

HYDROKINETIC POWER:
AN ANALYSIS OF ITS PERFORMANCE AND POTENTIAL IN THE ROZA AND
KITITAS CANALS

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ABSTRACT

Hydrokinetic energy, the power of moving water, is a promising new, vast, and renewable resource that is unhindered by many of the weaknesses experienced with other clean energy sources. The recent installation of a prototype hydrokinetic turbine at Yakima, WA's Roza Canal serves as an example of this, as the turbine produced over 5,000 kWh in one month, exceeding expectations. This thesis analyzes this turbine's performance while also looking at two canals in eastern Washington's Kittitas Reclamation District as potential sites for hydrokinetic turbines. The estimates demonstrate hydrokinetic turbines to not only be a clean, reliable, and continuous power source, but to also be a cost-effective investment in ideal sites.

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The research and data for this thesis were conducted and collected over a span of six months from February to August 2012. Several details, particularly concerning Hydrovolts products, have changed since this writing. Therefore, this paper should be viewed only as a snapshot in time of hydrokinetic technology and Hydrovolts products. The dimensions, power estimates, and cost estimates reported in this thesis are rough estimates for products that have since evolved. Though I was employed at Hydrovolts midway through this research, this thesis was reviewed and edited by independent sources.

There are many people without whom this thesis would not have been possible. My parents, the Hydrovolts team, and the MES family have all been an amazing help and have made the past year a wonderful experience. I'd like to give special thanks to the following people for their incredible support: Michelle Holmes, Judy Cushing, Ken Hasbrouck, Maryann Miyashiro, and John Tennert. Thank you all so much.

1. INTRODUCTION

The need for alternative methods in how we generate power has become increasingly apparent given the role of fossil fuels in climate change and the rate at which those fuels are being depleted. With this understanding has come the development of many forms of renewable energy. Solar, wind, nuclear, and hydropower among many others, are thriving in certain environments, resulting in yearly increases in clean-energy technology venture capital investments, which saw a 30% jump from 2010 to 2011¹. However, renewable energy sources currently account for only 11.7% of U.S. power production, with 85% of that consisting of hydropower and biomass².

Hydropower has become the leading power source in Washington, comprising almost 70% of the state's energy³. The U.S. Energy Information Administration (EIA) reported in 2009 that hydropower accounted for 65.5% of all renewable energy, a figure that hints at the small contribution of other clean energy sources. It also highlights the fact that Washington's leadership in hydroelectric energy production creates its own unique set of environmental problems, as many argue that hydropower is not even a truly clean energy source⁴. Hydroelectric dams encroach upon nature, harm fish stocks, and lower the water level, which in turn impacts water flow and sedimentation⁵. In addition to these concerns, the Electric Power Research Industries has projected that no new hydropower greater than 30 MW will be generated

¹ Romm, 2011

² Gies, 2012

³ Pratt, 2012

⁴ Ibid

⁵ Environmental Impacts of Dams, 2012

by hydroelectric, meaning the need for additional renewable energy generation will have to largely rely on other sources. Despite this projection, vast amounts of untapped clean energy can be found in our waterways, and this is where hydrokinetic energy, one of the best potential ways we can curtail our dependence on fossil fuels and move towards a sustainable future, comes into play.

Hydrokinetic energy is a promising new technology still in the research and development stages. This thesis will address some of the many questions and uncertainties still surrounding this new technology. Many companies are approaching commercial distribution of various hydrokinetic energy systems, most of which are capable of providing clean energy off and on grid. One of these companies is Hydrovolts, located in Seattle, WA, which is currently testing a smaller variation of their C3 (class 3 - large) hydrokinetic turbine in the Roza Canal in Yakima County, WA. This thesis will use experimental data from this turbine to illustrate the potential uses and benefits of this new technology. The analysis will address the following:

- A literature review of hydrokinetic energy, its current state, and an overview of the existing technology
- An analysis of how the C3 Canal turbine performs at Roza, focusing on the turbine's power output compared to the water rates in the canal, as well as its consistency, installation, and maintenance
- Projections for how the same turbine would perform at the Kittitas Reclamation District (KRD) Main Canal and North Branch Canal, giving insight into the turbine's potential at these sites
- Analysis of the turbine's projected cost-effectiveness for the Roza and KRD canals; and

- A recommended course of action for the Kittitas Reclamation District

This thesis also contains background information on hydrokinetic energy, the various hydrokinetic turbines under development, and the Roza and KRD Canals. This is a site specific study and does not aim to make projections for other locations. However this analysis may shed light on the potential of small-scale hydrokinetic energy in irrigation canals.

Projections and a course of action will be determined for the Kittitas Reclamation District after examining the feasibility and cost-effectiveness of hydrokinetic turbines. Multiple scenarios will be investigated such as the optimal turbine size and placement, the preferred method of installation, and other factors that will aid in KRD's assessment of hydrokinetic energy.

2. HYDROKINETIC ENERGY

Hydrokinetic energy, at its most basic, is the energy of moving water. Hydrokinetic turbines harness energy from the motion of water, whether from waves, currents, or canals. Producing power from the speed of water is what distinguishes hydrokinetic energy from hydropower, which uses the pressure of water, created by a large vertical height (also referred to as “hydraulic head”) such as a dam, for power generation. Hydrokinetic energy works similarly to wind power in that a turbine uses the flow of water to drive a rotor, which is connected to a generator. Hydrokinetic energy's key difference to wind power is that water is over 800 times denser than air, making it a highly concentrated, reliable, and largely untapped resource⁶.

Hydrokinetic energy has several distinct advantages over other clean energy sources. Perhaps most notable is hydrokinetic energy's ability to adapt to existing infrastructure, rendering expensive, long-term construction projects unnecessary. This is a big advantage over other clean energy technologies such as wind or solar, given that the start-up costs for small-scale hydrokinetic projects are much lower and power production begins much sooner. For most clean energy sources, large plots of land are required, while many potential locations already in place are ready to produce hydrokinetic power. The current project in the Roza Canal is a good example. The turbine was scaled to the canal's size and required no more than several hours of installation and no manipulation of the canal's structure⁷. Many canals and similar structures are available for relatively easy and burden-free use by hydrokinetic turbines to produce renewable energy. The high costs associated with infrastructure and necessary land are rarely obstacles for hydrokinetic energy.

⁶ How Hydrokinetic Energy Works, 2010

⁷ Case Study: Roza Canal, 2012

One of the biggest hurdles facing almost all renewable energy sources is inconsistent output⁸. Businesses and investors are generally reluctant to fund weather dependent sources of renewable energy because they produce fluctuating amounts of energy that are difficult to accurately predict. The high risk for investors of these sources has slowed their growth in the energy market. Conversely, hydrokinetic turbines can be installed in man-made structures which produce consistent, controllable, and measurable water flows. Aside from planned dry periods for some canals, there will never be drought periods and the canals can accurately predict energy output⁹. This is a major advantage over other clean energy sources, and makes hydrokinetic energy more appealing to investors, giving it more potential for substantial growth.

While these factors have set hydrokinetic energy apart from some other renewable energy sources, it remains in the shadow of hydropower. Hydrokinetic energy does pose a viable alternative to hydropower as it doesn't include any of hydropower's environmental problems (the overall environmental impact of hydrokinetic turbines is still relatively unknown)¹⁰. Despite these differences, traditional hydro and hydrokinetic power can work very well together, as there are many places within a dam where hydrokinetic energy can "piggyback" on hydropower generation and efficiently produce power¹¹.

Piggybacking off of existing hydropower is one way for hydrokinetics to break into the market because it eases the grueling permitting process. Piggybacking occurs when a hydrokinetic turbine is placed downstream from an existing hydropower plant, generating power

⁸ Solar Energy Advantages Disadvantages, 2011

⁹ Ankum, P

¹⁰ Hydrokinetic Electric Power Generation

¹¹ Neville, 2009

from the water leaving the dam. If a site is already generating hydropower, it has already completed much of the required permitting, meaning there are fewer obstacles for hydrokinetic facilities, as agencies and studies have already been conducted on these sites. This qualifies sites for an exemption (FERC's "piggyback exemption") for projects "under 5 MW off an existing dam."¹² While this exemption eases the process and prevents the need for an entirely new application, it still has a set of time-consuming procedures. Permitting is a major hurdle, and methods such as piggybacking help to create more opportunities for new renewable energy technologies.

-The Current State of Hydrokinetic Energy

As with any new technology, many hurdles face hydrokinetic energy as it is commercialized. A major obstacle is the lack of testing of hydrokinetic devices, which causes many issues, including largely unknown environmental impacts, the technology's durability, and the true overall cost¹³. These unknowns make investing a risky decision for some business owners, and unfortunately, most of these questions won't be definitively answered until more hydrokinetic units are actually licensed and operated for substantial periods of time. The solution to this problem is more research (this thesis being one small example), development, and demonstration (RD&D), which will require funding¹⁴. Unfortunately, many of the remaining questions about hydrokinetic technology will require long-term testing, something that needs strong funding support as most start-up companies can't afford extended testing. New and experimental technologies often find themselves in a catch-22, where they need research and

¹² Neville, 2009

¹³ Hydrokinetic Electric Power Generation

¹⁴ Ibid

testing to get funding, yet need funding to conduct research and tests. This hesitation towards new and unproven technologies has drastically slowed the progress of renewable energy.

-Incentives

Many clean energy projects rely on outside sources to receive the necessary funding. These can range from grants to renewable energy incentives such as utility rebates, performance based incentives, expedited permitting, tariffs, and more¹⁵. Some of these incentives can be restricted to specific irrigation districts or countries, but can still help determine the best sites for early testing when funding is still hard to come by.

Hydrokinetic power is such a new technology, that the Government has not officially recognized it as “renewable” yet. This keeps hydrokinetics from benefiting from the same incentives as other clean energy sources such as wind, biomass, and solar, adding yet another roadblock to its development. Washington State provides two incentives for small hydroelectric (including hydrokinetic power), both of which are performance based¹⁶. These are the Sustainable Natural Alternative Power Producers Program and the MORE Green Power Program, both of which provide financial support based on the kilowatt hours generated¹⁷.

-Permitting

The Federal Power Act of 1920 requires all hydroelectric projects to submit permitting and licensing applications to the Federal Energy Regulatory Commission (FERC)¹⁸. The

¹⁵ Database for State Incentives for Renewables and Efficiency, 2012

¹⁶ Ibid

¹⁷ Washington, 2012

¹⁸ Oram, O’Connell, and McKinsey, 2010

application process requires approval from sometimes hundreds of relevant agencies, which almost always requires additional research, staff, and money¹⁹. A few examples of entities from which approval is frequently required are: U.S. Army Corps of Engineers, U.S. Coast Guard, National Marine Fisheries Service, Fish and Wildlife Service, any impacted tribes, land owners, local governments, and many more²⁰. Getting such approval can be difficult considering that hydrokinetic technologies are still very new and there is not yet sufficient research on subjects such as environmental impacts, especially long-term. Adding to the considerable time FERC can take to respond to submitted applications, seeking approval for installation sites turns into a crippling process for many prospective companies.

The current regulatory framework in place is simply not compatible for many small energy companies, including small hydro. The permitting process involves many kinks, making it difficult for start-up companies working with a new technology. The current process for a hydrokinetic turbine starts with a preliminary permit, which allows the company to apply for a license²¹. FERC has had trouble handling the increasing number of permit requests, and uses a random draw method to select which applications to approve²². While this method does highlight the strong interest in hydrokinetic energy, it also shows that many solid projects are rejected simply due to high demand in a broken permitting system. Fixing the permitting system is a high priority for Congress, as a clean energy source with high potential is severely limited by the current time-consuming, unreliable, and unfair process.

¹⁹ Oram, O’Connell, and McKinsey, 2010

²⁰ Ibid

²¹ Griset, 2011

²² Griset, 2012

There are many proposed solutions for making the permitting process more efficient. One straightforward, if not always feasible, solution is to simply open up and hire more personnel, including outside experts, as the California State Department of Fish and Game did in June 2011. In addition, they also implemented a 60 day deadline for accepting or rejecting a proposal, an immense improvement over previous wait times of up to a year²³. This has saved time and greatly benefited those researchers seeking permits.

Hydrokinetic applications have been increasing year over year. These increases further demonstrate the need for an easier permitting process, signaling that FERC's process needs to be changed. Below is a map showing the issued hydrokinetic permits as of June 2011:

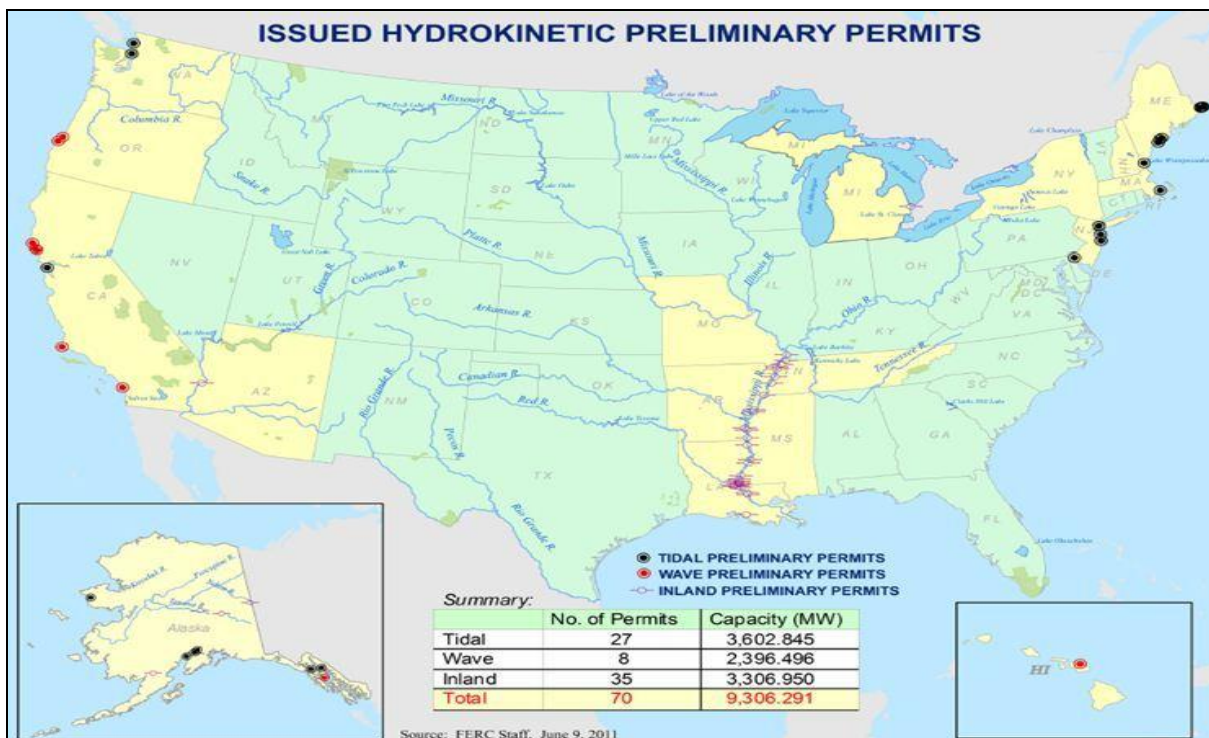


Figure 1: A map of FERC's issued hydrokinetic permits as of June 2011

²³ Kraemer, 2012

The environmental impact of hydrokinetic turbines is one of the biggest unknowns surrounding their use, but several recent and current studies are beginning to answer some of these questions. The Department of Energy (DOE), Pacific Northwest National Laboratory (PNNL), and the Electric Power Research Institute (EPRI) are funding and implementing various studies, including a risk evaluation process that can be used to calculate the impact of a hydrokinetic turbine at different locations²⁴. Tests on the impacts of the rotor blades on fish populations are perhaps top priority for many locations. There is concern not only because of the harm the blades might inflict on the fish, but of simply how the fish will respond to the turbine's presence. Preliminary results from one of these studies, which involved over 500 fish, resulted in no deaths or injury, with final results, including video, to be released in 2012²⁵. Another test on fish survivability, conducted on the Mississippi River, examined impacts to roughly 680 fish and reported no injuries due to rotor blades, and found that the turbine had no noticeable impact on the fish in the area²⁶. While more research and data collection is needed, early indications point to hydrokinetic turbines being a safe and environmentally friendly technology.

Research, development, and permitting are not the only hurdles for hydrokinetic energy. The social perception of hydrokinetics, or lack thereof, will influence investors and partly determine its success. In a 2010 survey of various water resources and environmental protection agency professionals revealed that 87% of participants had little or no knowledge of hydrokinetics²⁷. The word "hydro" has also led to public confusion, causing hydrokinetics to

²⁴ Arango, 2011

²⁵ Ibid

²⁶ Kessler, 2010

²⁷ Stafford, Sweet, and Wiessmeyer, 2010

absorb some of the negative perception surrounding hydropower and its environmental impacts²⁸. This obscurity puts more pressure and responsibility on developers to raise awareness and earn investments, as most investors likely aren't currently pursuing hydrokinetics.

-Potential

As with many other clean energy sources, solar in particular, the raw potential for hydrokinetic energy is very high. The DOE claimed that our oceans could theoretically supply over 50% of the U.S. energy demands through hydrokinetics, a figure that does not take into account other considerable resources such as irrigation canals, which are abundant in the U.S. and the focus of this thesis²⁹. Needless to say, hydrokinetics is a largely untapped resource with no shortage of sites where significant amounts of power could be efficiently extracted. One concern is over power storage, as it is unclear how turbines will handle power production if a grid is unable to take in more power. However, the generated power from these turbines can be used directly on site by hooking items, such as heaters or batteries, directly to the turbine. This feature gives the smaller models great potential in undeveloped, off-grid areas.

Many natural and man-made sites are fully ready for hydrokinetic power. The Roza canal is just one example. The infrastructure and water flow for sites like Roza have been in place for some time. Similar man-made structures that need no manipulation in order to support a hydrokinetic turbine are available all over the U.S. and the rest of the world. Many hydrokinetic turbines, such as those that are the focus of this study, have design features that allow them to adapt and fit many structures regardless of differences in width, length, and depth.

²⁸ Stafford, Sweet, and Wiessmeyer, 2010

²⁹ Fitz-Gerald, 2012

The flexibility of these turbines and the high availability of accommodating infrastructure is a strong incentive to put more focus on hydrokinetics as a major player in the clean energy market.

3. TURBINES

There are many different existing designs for hydrokinetic turbines. Hydrokinetic power can be extracted from a variety of locations such as river channels, ocean waves, waterfalls, and canals, and there are turbine models designed to accommodate all of these locations and their unique nuances.

-Hydrovolts Turbines

This project will focus on two of the four Hydrovolts turbines in development: the C2 (medium) Canal, and specifically the C3 (large) Canal, as it's the largest turbine and a smaller variation (the C3 prototype) is currently being tested in the Roza Canal. An overview of the 4 Hydrovolts turbines as well as the prototype C3 follows.

Prototype C3 (Used for testing at Roza Canal)



Figure 2: The C3 Prototype Turbine being lowered into Roza Canal

- Measurements: 8.5' tall, 14' wide, 8' deep
- Features up to 4 rotor sections of 5' long and 7.5' high
- Weight: 6,000 pounds

- Originally projected to produce 5 kW at a 2 m/s water velocity
- Used for testing at the Roza Canal

C3 (large) Canal Turbine

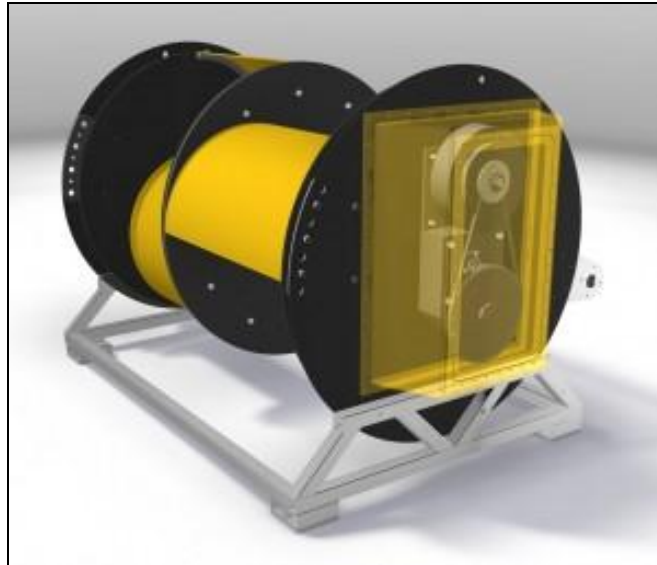


Figure 3: The C3 Canal Turbine

- Output: 5-20 kW
- Measurements: 8' tall, 25' wide, and can hold up to 4 rotors of 5' x 7.5'
- Weight: 8,000 pounds
- Unlike other turbines, the C3 is not meant to be buoyed near the surface of the water but is designed to be completely submerged at the bottom of the canal
- Canal requirements: 10' of depth and 15' of bottom canal width
- Lifespan: 20 years
- Estimated cost: \$40,000 - \$50,000

C2 (medium) Canal Turbine



Figure 4: The C2 Canal Turbine

- Output: 1.5–12 kW
- Measurements: 5' tall, 12' wide (10' base stand)
- Can hold up to 3 rotors (5' each)
- Weight: 5,000 pounds
- Canal requirements: 6' of depth and 13' of bottom width
- Lifespan: 20 years
- Estimated cost: \$20,000 - \$30,000

Portable Turbine

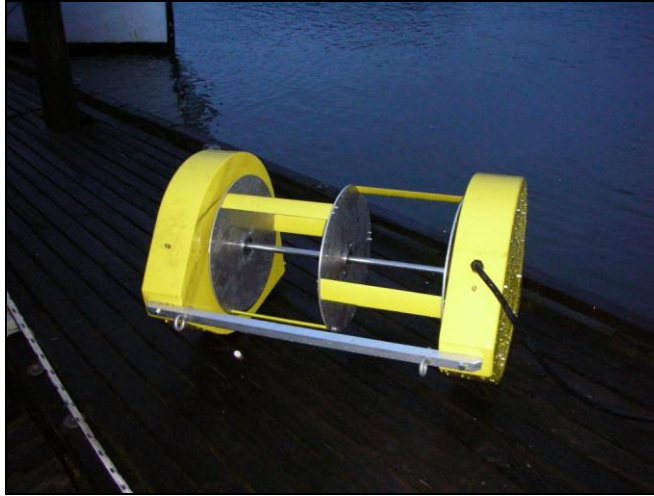


Figure 5: The Portable Turbine

- Output: 75 – 1,000 watts
- Measurements: 3' tall and 3' wide
- Weight: 160 pounds
- Can be packed into two 80 pound portable parcels
- Canal requirements: 4' deep and 5' wide
- Designed for local loads
- Lifespan: 20 years
- Estimated cost: \$5,000 - \$7,000

Waterfall Turbine

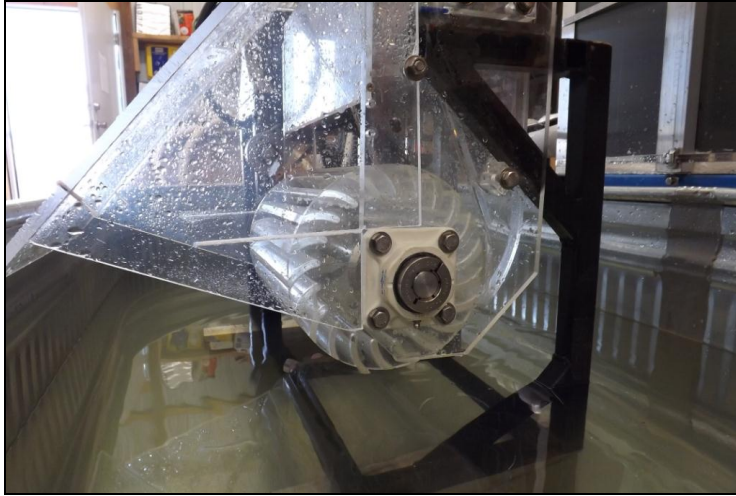


Figure 6: A small demonstration of the prototype Waterfall Turbine

- Output: 5-30 kW
- Designed for Wastewater Treatment Plants
- Measurements: 6' tall, 5' wide, 3' deep
- Weight: 600 pounds
- Requirements: 6' drop, 5' wide, and a water flow of at least 5 million gallons per day (MGD)
- Lifespan: 20 years
- Estimated cost: \$20,000

One major design attraction of the C2 and C3 turbines is their scalability, which means that sections can be added to a turbine, adjusting its size so that it can best fit its waterway and maximizes energy production. These turbines are also designed to produce power on or off grid since their generators are located in the turbine's endcaps, providing greater flexibility in where they are installed. This feature also makes these turbines strong candidates for producing clean

energy in developing countries and areas located off-grid. The Portable Turbine’s capabilities also make it a good fit for off-grid, rural communities.

-Other Hydrokinetic Turbines

Many other kinds of turbines are also on the market, with more under design and development. Despite many companies still in the development phase, there have been successful deployments of several different turbines. Though this thesis does not examine these other turbines in its analysis, below are details on other recent turbines to highlight the range and current state of hydrokinetic technology. Table 1 provides a brief look at the basics for these turbines, with more in-depth information found later.

Hydrokinetic Power Product Information

Company	Type	Power (kW)	Status
Free Flow Power	Rivers	40	Testing
Hydro Alternative Energy	Tidal	N/A	Testing
Hydro Green Energy	Tidal	N/A	N/A
Lucid Energy	Pipes	100	N/A
Natel Energy	Canals	50-500	Small unit available
New Energy Corporation	Canals	5-250	N/A
Ocean Renewable Power Corporation	Tidal	50	N/A
Smart Hydro Power	Rivers	5	Available for sale
Tocado BV International	Rivers	10-500	N/A
Verdant Power	Tidal	60-80	Testing
Vortex Hydro Energy	Rivers	N/A	N/A

Table 1: Shows the hydrokinetic power products and their variety in power outputs, intended installation sites, and current market status

The Oceanus Power Generation System:

- Designed to work in slower water velocities such as 1 meter per second (2 knots).
- Requires only 1m per second, or 2 knots, of speed to produce 1MWh of power.

- Has great potential to harness hydrokinetic power in previously untapped areas through a system that magnifies the water velocity as it enters the turbine. This system features two modules, one to magnify the speed of the water, and another to generate power.
- Currently being tested and is not currently available for distribution.
- Developed by Hydro Alternative Energy.

The Free Flow System Turbines:

- 3 bladed horizontal axis turbines
- Produces an estimated 40 kW at an average flow rate of 3m per second.
- Tested in NYC. Successfully produced 70 Megawatt hours of grid-tied energy.
- Testing, not currently available for distribution.
- Developed by the Free Flow Power Corporation.

Ocean Renewable Power Company (ORPC) Systems:

- These larger hydrokinetic systems are not intended for canals but for larger river channels and deep water bodies. The ORPC uses their Turbine Generator Unit (TGU) to create three different hydrokinetic systems: The RivGen Power System, TidGen System, and OCGen System. Each TGU can produce up to 50 kW depending on the river's velocity.
- The RivGen Power System is intended for small river sites. The system was designed to allow for parts to be shipped and easily installed on site. These systems are scalable, and can contain up to several dozen TGUs.
- The TidGen Power System is designed to operate at deeper water depths of 50 to 100 ft. The TGUs in this system must be connected to a power station via a transmission

line. These systems can withstand high speeds and pressure, with each TGU potentially generating more than 150 kW in fast currents.

- The OCGen Power System is an incredibly large system designed for areas exceeding a depth of 80 feet. Stacks of TGUs are placed at this depth and then connected through underwater cables to power stations. This system can generate large amounts of power, with a stack of four TGUs estimated to produce 600 kW in a 6-knot current.

The Tocardo Turbines:

- Four different sizes of turbines: the T50, T100, T200, and T500.
- The T50 produces 10-53 KW of power and requires a minimum flow rate of 1.5 m per second and a maximum of 4 m/s. Its small size makes for easy installation. This turbine is currently installed at a demo site in the Netherlands.
- The T100 produces 43-86 kW of power and requires a minimum 1.5 m/s flow rate. The blades can be adjusted from 3.2-6.4 m depending on the site. This turbine has a 20 year lifespan.
- The T200 produces 87-174 kW of power and was deployed in spring 2011. Blades ranging from 4.6 to 9.2 m can be used depending on the site. This turbine is currently installed at several locations.
- The T500 produces 350-500 kW of power and is designed for sites with great depth and high velocity. Blades for this turbine can range from 7 to 20 m. This turbine is currently in development and will soon be deployed for testing in Scotland.
- The 3 smaller sizes are currently available for sale, while the T500 is expected to be available late 2012.
- Developed by Tocardo BV International.

Natel Energy's Turbines:

- Currently developing 5 sizes of turbines with their hydroEngine™ technology.
- This technology is designed for drops between 2 and 6 meters.
- Small and medium sized turbines are designed for man-made conduits such as irrigation canals, while the large scale turbines can work in streams or in existing dam structures.
- Natel estimates that their small and medium sized turbines can generate from 50 to 500 kW of power.
- Natel's first commercial project of its SLH10 hydroEngine™ produced 9.6 kW at 2.6 meters of head and 0.5 m³/s of flow.
- These turbines are still in development and not currently available for sale.

The Smart Hydro Power Turbine:

- A 5kW turbine built with a horizontal axis generator system.
- Designed for rivers and can work in any such stream.
- Intended for water flow speeds of up to 3.5 m/s.
- Currently being tested and is not available for sale.

The New Energy Corporation Turbines:

- Develops five turbines: The 5, 10, 25, 125, and 250 kW Power Generation Systems. These turbines can work as independent or grid-connected energy sources.
- The 5 kW turbine is available in 3 different models: The High Velocity, Low Velocity, and Restricted Flow Models. These models all accommodate various water velocities. This turbine generates enough power for 2 to 5 "average" homes.

- The 10 kW turbine is available in the High Velocity and Restricted Flow Models.
- The 25 kW turbine is available in all 3 models. These can be built downstream from hydropower dams to contribute to the facilities' output, in irrigation canals, tidal farms, or large rivers.
- The 125 kW turbine is available in High and Low Velocity Models. The High Velocity turbine's rotor height is measured at 3.8 m and the diameter at 7.6 m, while the Low Velocity has a diameter of 10.4 m and a height of 5.4 m. This turbine was developed only for power plants with a large enough capacity.
- The 250 kW turbine also has both a High and Low Velocity Model. The High Velocity Model has a rotor height and diameter of 7.6 m. Data for the Low Velocity Model is unknown. These turbines are designed for tidal applications.

The Hydro Green Energy Turbine:

- Hydro Green Energy installed the first hydrokinetic turbine in the Mississippi River in 2008. This was a large, 35 kW turbine installed downstream from a dam.
- The current status of these turbines is unknown, as the company appears to be changing its focus. Full data from the project has not been released.

The Lucid Pipe Power System:

- Features a "lift-based vertical axis spherical turbine design" that generates power from water pipelines with a 24"- 96" diameter.
- Several LucidPipe turbines can be installed in the same pipeline at only 3-4 turbine lengths apart.
- Output depends greatly on site characteristics.
- Developed by Lucid Energy.

-Turbine Installation and Maintenance

Ease of installation is an important design factor, in addition to the turbine's ability to work with existing infrastructure. In an irrigation canal such as Roza and KRD for instance, a C3 Canal turbine will only require several hours of installation before it is operational and producing power. This quick process greatly helps reduce installation costs, a factor that can go a long way with potential clean energy investors. The time and cost of installation differs for each turbine and company. However all the various models considered to be quick installations and none require additional infrastructure to be built. Every current hydrokinetic turbine is designed to work within a pre-existing infrastructure or body of water.

Hydrokinetic turbines are designed to have a long lifespan, even in harsh environments. As a result regular maintenance is required to maintain operational efficiency. For example, C2 and C3 Canal Turbines require a particular set of maintenance procedures roughly every 3 years. The turbine's shaft seal cartridge and belts should be replaced, and the turbine should be lubricated and receive an oil change. In addition to this, the rotor shaft bearing requires maintenance every 6 years. Over a 20 year lifespan, projected maintenance costs are estimated to be *roughly* \$7,000 for the C2 and C3 Turbines. Manuals will be included with turbine purchases detailing the parts used, and the steps for routine maintenance. Most of the required maintenance is considered standard, and does not require company expertise. Considering these turbines operate non-stop in what can be rough conditions, this maintenance is not time-consuming or expensive.

-Site Location

Hydrokinetic turbines are similar to most other clean energy technologies in that locating a compatible site with the greatest potential for power production determines the overall effectiveness³⁰. Understanding water flows, densities, and size is essential to an efficient and economically successful project. Other important factors to consider include whether or not the canal is earth or concrete-lined (impacting water flow and debris), whether the passage is straight or curved, whether there is easy road access, access to a power grid (not an issue with most manmade canals), whether there are check structures or drops (impacting velocity), canal dimensions, and many other factors that can impact turbine efficiency. Site selection becomes trickier in natural waterways such as river channels, as not only must one locate a site with a high enough velocity and great enough depth to support the device, but one must also consider the strong variations in shape and size, not to mention the frequent obstructions (such as rocks), sedimentation, and potential debris³¹. All these variables play a big role in the amount of power a turbine can produce.

One should also note that hydrokinetic energy can be found in many areas other than canals or river channels. This technology is receiving a lot of attention for use in waterfalls, marine environments, tidal areas as well as deep ocean sites. There are products being developed to extract hydrokinetic energy from a wide variety of water sources. Development is even underway to extract hydrokinetic energy from pipelines from companies such as Zeropex and Lucid Energy.

-Rotor Blades

³⁰ Arango, 2011

³¹ Will Your Site Work?, 2012

There are many types of rotor blades for hydrokinetic turbines, all of which affect performance and power generation. The C2 and C3 turbines examined in this thesis are "switchblade" enabled, which allows the user to change the rotor blades to adjust the turbine to the site's flow characteristics, maximizing power production³². Rotor blade exchange is enabled via modular generator endcaps and a generator design that accommodates different sets of blades. Though there are a large number of different rotor blades for turbines in general, there are currently three blades designed for the two turbines discussed in this study.

Darrieus Blades:



Figure 7: A C2 Canal Turbine equipped with Darrieus rotor blades

- Designed for fast moving water currents
- Requires a cut-in speed of at least 2 m/s
- Operates at a 30% efficiency rate
- More expensive than other blades

³² Case Study: Roza Canal, 2012

Savonius Blades:



Figure 8: A Turbine with Savonius rotor blades

- Works well in flow rates between 1.5 and 3 m/s (lower cut-in speed than Darrieus blades)
- Designed with durability in mind
- Efficiency rate of 20%

The Flipwing Rotor:

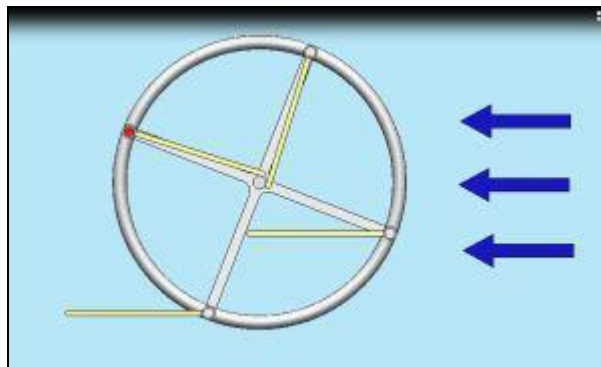


Figure 9: The Flipwing Rotor

- Designed to work in remote and unpredictable locations, as it better handles slower, inconsistent speeds and debris
- Requires a cut-in speed of only 1 m/s
- Efficiency rate of 10%

Savonius blades are being used by the C3 Canal turbine at Roza, and offer a good compromise between performance and durability and can be ideal for long-term projects such as Roza. They also operate well at low to medium velocities, making it a practical blade for sites that fluctuate with their flow rates.

4. THE CANALS

The Roza, KRD Main and KRD North Branch Canals are all located in Eastern Washington. The canals are primarily used for irrigation purposes though Roza also supplies water to a local power plant. These canals are part of the Yakima Project, which is operated by the U.S. Bureau of Reclamation. The canals were built to provide irrigation water to over 464,000 acres on a 175 mile stretch of land by the Yakima River in Central Washington. Together, these two canals are 121.2 linear miles long. Roza and Kittitas make up two of the seven divisions in the project and irrigate 131,500 acres of land. The five other divisions are Storage, Sunnyside, Tieton, Kennewick, and Wapato³³.

-Roza Canal

The 95-mile Roza canal is located in Yakima County and provides water to a local power plant as well as irrigation water for local farmland. Roza's diversion dam (a dam that directs water from its water source into a canal) is a concrete weir located 10 miles north of Yakima, diverting water from the Yakima River³⁴. The diversion dam has an elevation of 1,205', giving it a strong slope for water velocity³⁵. The canal also alternates between earth-lined and concrete lined to control the flow rate. Concrete lined areas have faster flow rates and less debris, making them more ideal for hydrokinetic turbines than the earth-lined sections of the canal.

The Roza canal has several locations where a hydrokinetic turbine is ideally suited, particularly in the first 11 miles of the canal where there is more water before it splits in two

³³ Yakima Project

³⁴ Ibid

³⁵ Ibid

directions and begins delivering the water to its destinations. The sections along the first 11 miles are typically wider and deeper and accommodate a higher cubic feet per second rate, which presents greater opportunities for power production. This section is also concrete lined and has several easy access points. For example, a Hydrovolts C3 Canal Turbine is located along this section of the canal near the intersection of Hwy 821 and I-82, allowing for accessible and practical installation and maintenance. This location is roughly 5 miles from the diversion dam (the point at which the river water is directed into the canal), and is also close to a siphon, which helps eliminate debris, thus minimizing wear and tear to the turbine. The turbine is placed in a straight section of the canal, as water velocity tends to be higher in these areas than in the curved sections. Roza Canal also has "gates" and check structures placed throughout the canal, which can be used to regulate the velocity and amount of water through the system. These systems are especially useful when dealing with more severe weather fluctuations, as the water flow can be adjusted to ensure a steady and reliable output.

-Kittitas Reclamation District Main Canal

The Kittitas Reclamation District consists of over 330 miles of canals and laterals, with the Main Canal stretching 26.2 miles³⁶. These waterways irrigate roughly 60,000 acres of land in Kittitas County, making it the 6th largest irrigation district in the state³⁷. Kittitas County is located in Central Washington, and ranges from the Cascade Mountains to the Yakima and Columbia Rivers with a total of 2,315 square miles and a population over 40,000³⁸. One immediate advantage of the KRD Main Canal is that it features a large variety of sizes and

³⁶ The Kittitas Reclamation District

³⁷ Ibid

³⁸ The Kittitas Reclamation District

flows. There are slower, earth-lined sections with widths over 30 feet, as well as faster and smaller concrete-lined sections. This variety facilitates different approaches as to where and what kind of turbine is installed. The concrete sections are heavily curved and have many siphons. Turbines should not be placed close to siphons for a variety of safety reasons, which slightly decreases the number of turbines that can be installed.



Figure 10: A siphon in the KRD Main Canal

The canal was constructed from 1926 to 1929 at the same time as the Easton Diversion Dam. Water is diverted into the Main Canal from the Yakima River and then divides into the North and South Branch Canals. The Kachess and Keechelus Lake reservoirs provide additional water for irrigation use in Kittitas³⁹.

-Kittitas Reclamation District North Branch Canal

The North and South Branch Canals split from the Main Canal. The South Branch stretches 14 miles with just over half concrete lined. The North Branch is connected to the Main

³⁹ Ibid

Canal through a mile long pipe siphon, and is 36 miles long⁴⁰. The South Branch is not included in this analysis because it is much smaller and not suitable for the C2 or C3 Turbines.

These canals not only feature very different characteristics, but also vary in dimensions and water velocity. While these results should be applied only to these locations and turbines specifically, it provides an idea of what potential there is for hydrokinetic turbines in already existing infrastructure such as the Roza and KRD Canals.

⁴⁰ Yakima Project: Project Data

5. RESULTS AND ANALYSIS FOR THE PROTOTYPE C3 CANAL TURBINE AT ROZA CANAL

Before analyzing the turbine's performance data, it is important to describe where and why the turbine was installed. The Roza Canal presents many ideal features for turbine installation, such as adequate widths at both the bottom and top of the canal, low depths, concrete lining, easy canal access (for installation and maintenance purposes), and a large capacity for CFS (cubic feet per second) rates of up to 2,200. Many canals, including Roza, feature both concrete and earth lined sections, as well as varying widths, depths, slopes, and flow rates. Concrete sections prevent erosion (leading to fewer environmental complications) from faster-moving water, which usually means that these sections have the highest velocity in the canal. It should be emphasized, however, that these turbines are designed to work well in earth-lined sections as well. Roza's long wet season is another bonus for hydrokinetic turbines. Most canals have dry periods, some of which are quite long, but Roza is typically dry only one month a year, giving a long window for power production. Every canal's wet season is different and is crucial in projecting a turbine's power output.

-Roza Installation

The C3 Canal Turbine was successfully installed in the Roza canal for testing on March 8, 2012. This was the first major canal installation of a Hydrovolts turbine, with the prototype C3 weighing 6,000 pounds (full-size C3 weighs 8,000). Installation was completed in less than two hours, demonstrating the efficiency of hydrokinetic installations⁴¹. Smaller turbines,

⁴¹ Case Study: Roza Canal, 2012

especially the portable turbine, should present fewer complications and result in even simpler installations.



Figure 11: A road running alongside the KRD Main Canal providing easy access for maintenance and installation

The turbine was transported to the site in the back of a pick-up truck⁴². Lifting cables were used to transport this turbine from a truck to the canal, with drag and lateral lines used to center and stabilize the turbine⁴³. Many canals, including Roza and KRD, have operation and maintenance roads running alongside them, allowing turbines to be taken right up to the installation point and then easily dropped in via a boom crane. A potential turbine site being accessible by road is a major advantage as it makes installation and maintenance a quick and easy process.

Once in operation, the power generated from the hydrokinetic turbine is transmitted to the Power Control Center, which also contains a data collection system and other monitoring systems to track every facet of the turbine's

⁴² Case Study: Roza Canal, 2012

⁴³ Hydrovolts, 2011

performance. Data were tracked on the following parameters:

- Rotor speed
- DC voltage
- DC current
- Generator temperature
- Amps
- Time and date

Another factor contributing to the convenience and practicality of this installation is Roza's local load banks. A transmission grid next to the canal and electric loads located near the installation site provide several options for power generation and transmission. This also eases the process of feeding power back into the grid. Features such as these can be found in irrigation canals all over the U.S., making the often complicated procedures of installation and connecting to a grid as streamlined as possible. These site characteristics are in no way required, but Roza serves as an example of smooth and easy power production.

-Power Output

The turbine began producing power and data immediately. The Bureau of Reclamation tracked CFS (cubic feet per second) water data and Hydrovolts tracked all power generation data (frequency, rotor speed, voltage, amps, and watts). Data were logged every 15 minutes from the date of installation, showing a detailed look at the turbine's consistent performance under different rates, as Roza's CFS rate changed several times over the sampling period which began on March 10th (the first complete day of data collection), and ended on April 14th around 2:30 p.m. when the turbine's generator overheated and stopped producing power. The turbine itself is

still functioning properly while Hydrovolts prepares a new generator for use. This disruption is minor and not expected to continue after the necessary modifications, so it will have no effect on expected power generation.

As implied by the turbine's power generator overheating, the C3 canal turbine performed above expectations during the sampling timeframe. Originally designed to produce 5 kW at 2 m/s, the turbine provided up to 8 kW at 1.8 m/s⁴⁴. Had the turbine been installed with Darrieus rotor blades, this figure would be even higher. The data show the turbine to be a remarkably consistent power source as long as the water velocity and CFS levels also remain consistent, which is typical of manmade canals such as Roza. The turbine also adjusted appropriately to several different CFS rates, proving to be a remarkably constant and consistent source of renewable energy.

A simple linear regression was used to determine the relationship between the canal's CFS rates and the turbine's power output. The two variables are highly correlated, but what is important to note is how the turbine responded to the significant fluctuations in CFS rates. The CFS rates had a wide range from 1100 to 1936 CFS, an increase of 76%. The turbine's power generation ranged from 3065 watts (3.1 kW) to 8913 watts (8.9 kW), a 190% increase. After removing outliers (discussed below), the range becomes 4979 to 8913 watts, a 79% increase, close to the 76% increase of the CFS rates. This percentage illustrates how reliably the turbine's power output adjusted with the CFS rates in the canal.

⁴⁴ Case Study: Roza Canal, 2012

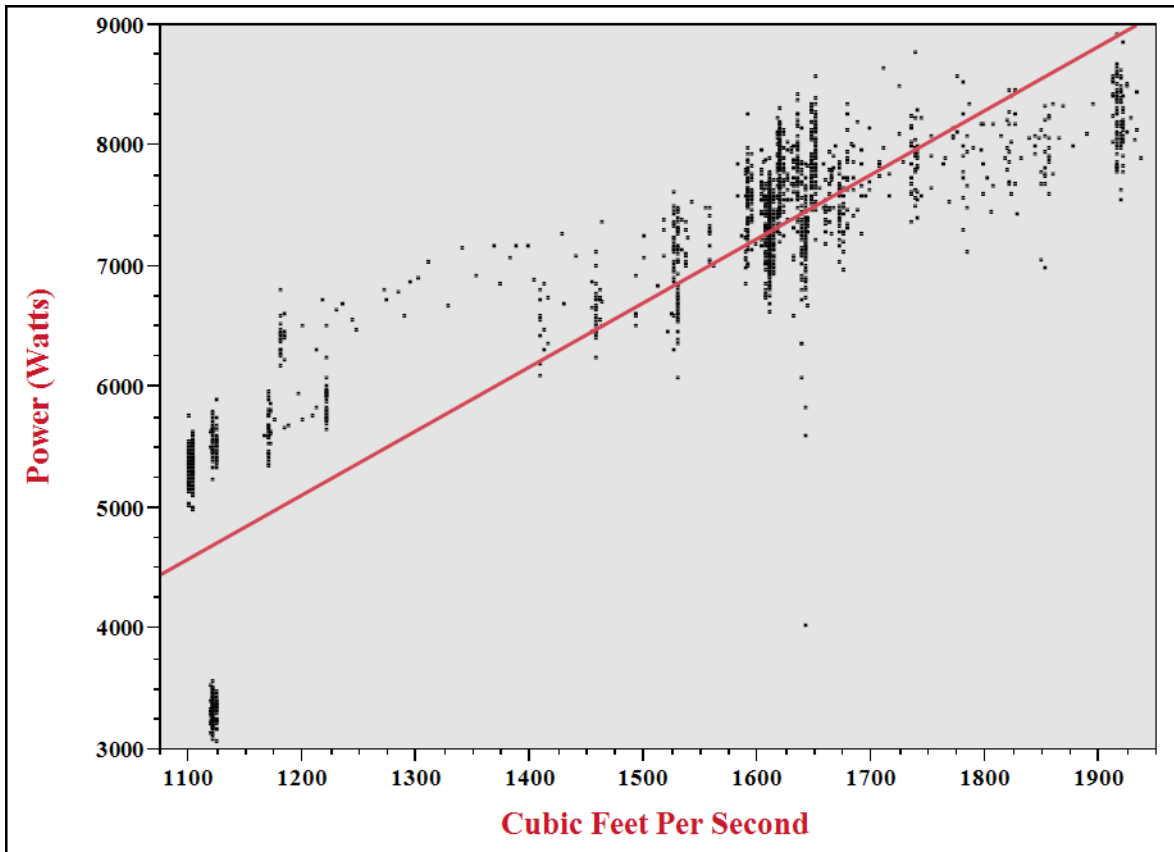


Figure 12: Graph illustrating the power output data from Hydrovolts’ C3 Canal Turbine at Roza Canal, including outliers, with the canal’s cubic feet per second rate at the turbine’s location. The graph shows a strong correlation between the canal’s CFS rate and the turbine’s power output.

The graph in Figure 1 includes all the raw data from the turbine’s initial run at Roza, including outliers such as those in the bottom left corner. These outliers were caused by a faulty heating element which caused a spike in voltage and a decrease in power. The element was repaired several days after installation on March 12, resulting in several hours of missed data. Because these outliers were simply the result of minor technical malfunctions, they were removed from the data analysis and will not be taken into account for future projections. Three other data points influenced by the oncoming generator shutdown and do not accurately reflect the turbine’s performance were removed from the very of the study period. Figure 2 shows the adjusted graph:

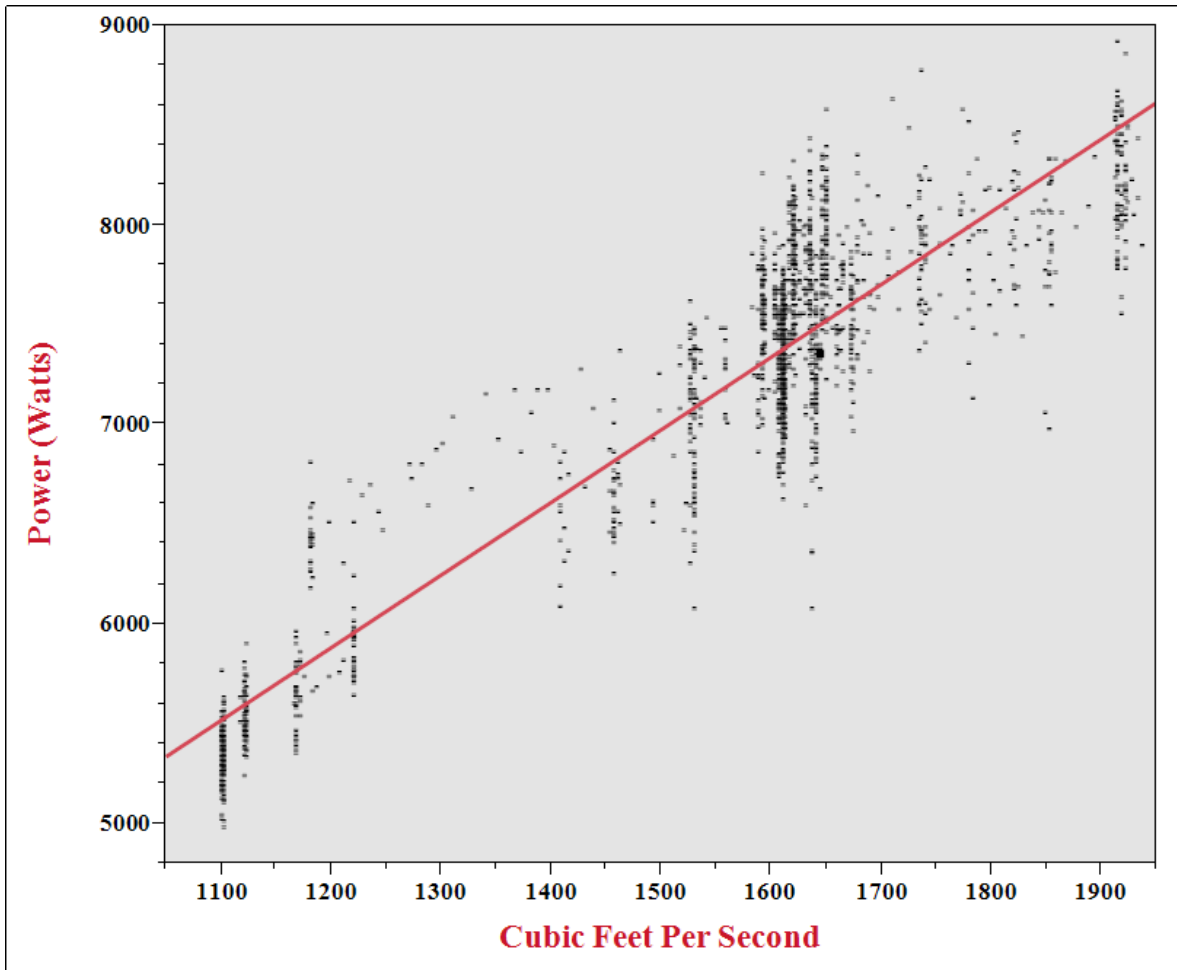


Figure 13: Graph illustrating the power output data from Hydrovolts’ C3 Canal Turbine at Roza Canal, not including outliers, with the canal’s cubic feet per second rate at the turbine’s location. The graph shows a strong correlation between the canal’s CFS rate and the turbine’s power output.

The adjusted data details how the CFS rate for the Roza Canal relates to the power generation of the C3 Canal Turbine during its initial month’s run. The turbine’s power output increased consistently with the CFS rate and was strongly correlated ($r=.85$); any minor inconsistencies can be attributed to a number of factors, most notably small shifts in water velocity. To predict a turbine’s power output using the canal’s CFS rate, we computed the linear relationship between Power and CFS for Roza; this can be found using the following formula:

$$Power (Watts) = 1505.6687 + 3.6456381 * CFS$$

To look in depth at the consistency of the turbine's power output, small ranges of CFS rates were examined. The CFS rates range from 1100 to 1936. These rates were separated into 8 categories: 1100-1199, 1200-1299, and so on up through the 1900s (there were no CFS rates in the 1300s). Water velocity data, though it was measured at select times, was not tracked every 15 minutes as was CFS and power output, and therefore is not a part of this section of the analysis, though it is an important variable. Though a notable omission, the water velocity in this case is expected to be fairly consistent with the CFS rates and does not significantly impact the integrity of this analysis.

The graph in Figure 2 shows consistent increases for every CFS group. Each group had a different sample size, with some CFS rates obtaining less than 100 data elements while other CFS rates obtained more than 1,000. The mean wattage for the 1100-1199 CFS group was 5535 watts, for 1200-1299 CFS, the mean was 6070 watts, and for 1900-1999 CFS, the mean was 8241 watts.

While the power output for the C2 and C3 turbines depends on a variety of factors such as CFS and site dimensions, water velocity is the most important variable. Because the speed of the water is not as important for irrigation as is the volume of water, most canals track CFS rate rather than water velocity. The lack of in-depth and precise data on Roza's water velocity prohibits us from any extensive analysis on how the turbine performed under different velocities. In light of this gap in Roza data, velocity figures provided by Hydrovolts for the C2 and C3 turbines will be used here and for projections at the KRD canal. This Hydrovolts data are based on a number of factors, including previous tow-testing (where a turbine is attached at the end of a boat and dragged through water) and design factors.

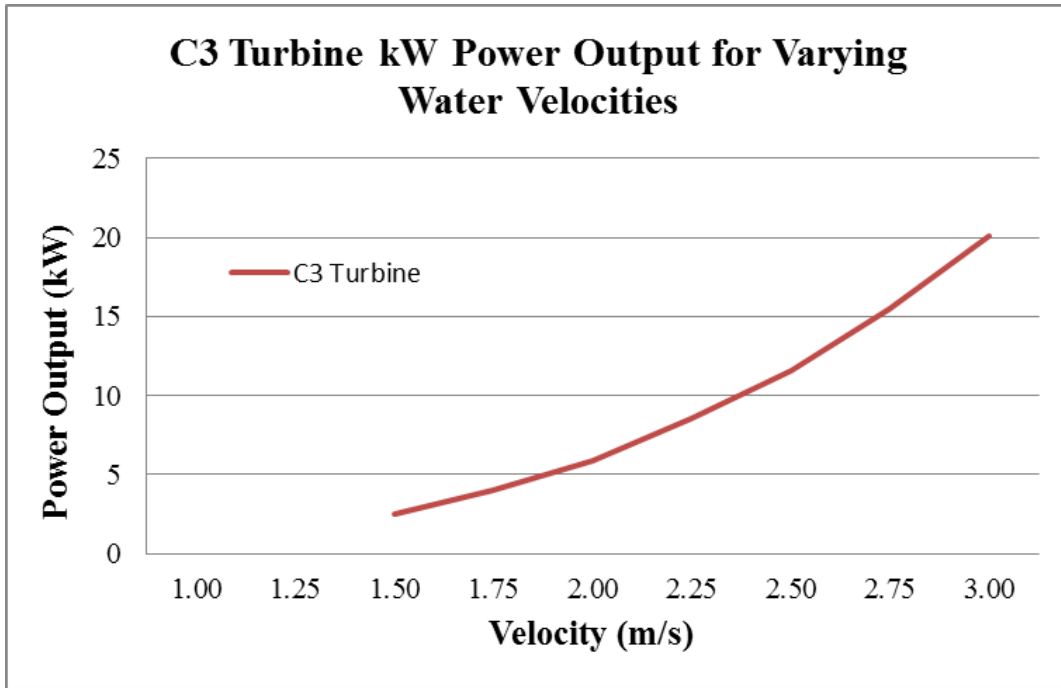


Figure 14: The Class 3 Canal Turbine’s projected power output for varying water velocities when equipped with Savonius rotor blades

The data used in Fig 15 was collected from a turbine using Savonius rotor blades, which are also used at Roza. Figure 15 shows the impact that relatively small changes in velocity can have on the turbine’s power output. Small increases in speed can lead to substantially higher output rates, as seen by the 100% velocity increase on the chart (1.5 to 3 m/s) and the 700% increase in power output (2.5 kW to 20 kW). These projections change significantly with the use of different rotor blades (seen in Figure 16). Turbines cannot be 100% efficient, as that would completely capture all of the available kinetic energy and therefore would completely stop the water flow. For this reason, a turbine’s efficiency rate tends to be no more than approximately 30% so as that a canal’s water flow is not overly impacted. Turbine efficiency rates also affect how far apart turbines can be spaced within a site, which should be considered when choosing rotor blades.

From figure 16 we see the estimated power outputs for two additional rotor blades: Darrieus and FlipWing. Neither blade was used at Roza, but they present additional options for other potential turbine sites. Considering that there is currently little data for the Darrieus and FlipWing blades on the C2 and C3 turbines, it should be emphasized that these are estimates and that this product is still in the testing phase.

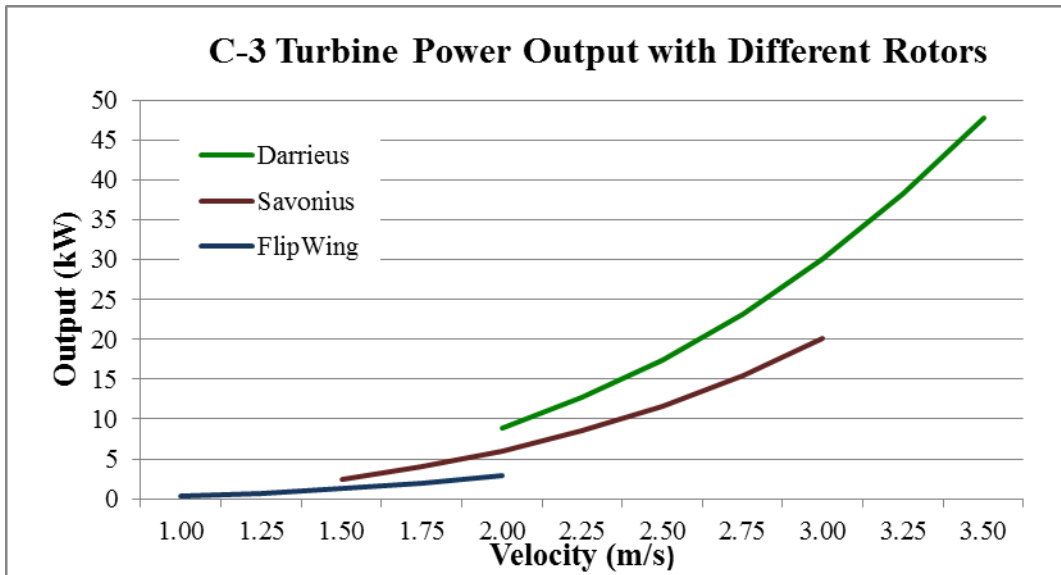


Figure 15: Graph illustrating the projected kW outputs for the C3 Canal Turbine with different Rotor Blades under water velocities ranging from 1 to 3.5 m/s

Figure 15 compares power output from the C3 Turbine using different rotors. The average power output with the fluctuating CFS rates (and water velocities) was 7170.47 watts (7.17 kWh), or 172.08 kWh per day, 5334.48 kWh per month and 64013.76 kWh (64.013 MWh) per year. Taking Roza’s month-long dry period into account, power output is adjusted to roughly 58679.28 kWh (58.679 MWh) per year. By using these figures with the various kWh electricity prices in each state, we can project how much money the C3 Canal Turbine would generate and therefore judge its cost-effectiveness as a clean energy source.

In 2011, Washington had the second lowest electricity price per kWh in the U.S.⁴⁵. At a price of 8.04 cents for residential customers, the only state to charge less than Washington in 2010 was neighboring Idaho at 7.99 cents per kWh⁴⁶. These two figures are well below the U.S. average of 11.54 cents, with Hawaii being the highest charging 28.1 cents⁴⁷. Using these figures, we can roughly calculate how much money the C2 and C3 turbines can generate, as well an estimated return on investment (ROI). Below is an assessment of the turbine's cost effectiveness if it were to be installed in several other states.

To examine the cost-effectiveness of the C3 Turbine we will first use the average power output from Roza Canal and the average 2011 price per kWh in the U.S. of 11.4 cents. Supposing the turbine were to produce its Roza average of 7.17 kWh, it would generate roughly \$608.13 per month and \$7,297.57 per year at the average U.S. price per kWh. Extend this figure for the turbine's 20 year lifespan, and the estimate is roughly \$145,951.37. While many canals do flow year round (or only have dry periods once every 3 to 4 years), many canals operate with extensive dry periods. To address this possibility, the analysis was repeated assuming operation of 11 months per year, similar to Roza. Under this scenario, the turbine would generate approximately \$6,689.44 per year or \$133,788.80 over its 20 year lifespan.

It is important to note that over the 20 year lifespan of these turbines, the changing prices of electricity and inflation must be taken into account, although power prices are not expected to decrease over time. For example, Washington's electricity price per kWh jumped 24% from

⁴⁵ Cauchon, 2011

⁴⁶ Ibid

⁴⁷ Ibid

2007 (6.5 cents) to 2010 (8.04 cents)⁴⁸. For this reason these long-term figures should be considered very rough although they give an idea of the turbine's lifetime performance.

-Cost and Return on Investment (ROI)

The C3 Turbine is currently estimated to cost between \$40,000 and \$50,000, while the C2 is between \$20,000 and \$30,000. These are early and rough estimates, as these turbines are not expected to hit the market for at least another six months from the time of this writing. It is unclear if the turbine's price will vary by state to adjust to variations in electricity price, if there will be a single price point based largely on manufacturing costs, or if the price will vary based on the turbine's power output at each site. The scalability of these turbines will also make price estimates tricky at this early stage. It is likely that each turbine site will require its own analysis to determine an accurate price.

This study assumes the most conservative estimates, and so we will use the high price of \$50,000 for a C3 Turbine and \$30,000 for a C2. It is very possible, and even likely, that when these turbines are available the cost will be significantly lower. Based on these conservative estimates, if the C3 Turbine were to produce its Roza average power over its 20 year lifespan (11 month wet season), it would earn \$44,356.28 above cost in Washington State, paying for itself almost twice. At this rate it would take 9.7 years for a ROI. A similar ROI can be expected for the C2. This is an especially conservative estimate for four reasons:

1. The Roza turbine is not full-size but is a smaller variation of the C3. A C3 Turbine (especially one at the high range of the current price estimate) is likely to produce significantly more power than the turbine installed at Roza.

⁴⁸ Electricity Cost

2. The turbine is equipped with Savonius rotor blades, not Darrieus. If Darrieus blades were being used, the turbine would produce significantly more power. The Darrieus blades *will* be ready by commercialization and will be ideal in man-made environments such as Roza and KRD.
3. The \$50,000 price tag is the highest estimated and could be significantly lower.
4. The estimates are using a wet season of 11 months, as is the case at Roza. In many cases the turbine will be operating year round.

These estimates should ease the minds of potential investors of such a new technology. With the highest available cost estimate, a power output estimate of a smaller sized variation of the C3 turbine equipped with Savonius blades, and an estimated dry period, the C3 turbine is still a strong, if long-term, investment.

To complete our assessment of the financial potential of this turbine, consider the following calculations for the states with the lowest and highest electricity price per kWh: Idaho (7.99 cents) and Hawaii (28.1 cents). If this turbine were to produce its Roza average in Idaho, it would generate \$5,114.70 per year (operating year round) and \$102,293.99 in 20 years. Even at the minimum electricity price, the turbine still produces a strong profit of \$52,293.99 (operating year round) or 47,179.29 (operating 11 months per year). Conversely, in Hawaii, the turbine would generate \$17,987.87 per year and \$359,757.33 over 20 years, resulting in returns of roughly \$309,757.33 (year round) and \$291,769.46 (11 months per year). It is important to stress that prices fluctuate between states and project locations, so my estimates use the highest estimated cost to give a strong idea of the profits this turbine would earn. With easy installation,

strong profit, no loss of needed infrastructure or space, and the generation of much-needed renewable energy, the C2 and C3 Turbines are sound investments.

Estimated Earnings of the C3 Canal Turbine in the United States

State	Price Per kWh (cents)	\$ Per Year	\$ Per 20 Years
U.S. Average	11.40	\$7,297.57	\$145,951.37
Alabama	10.67	\$6,830.27	\$136,605.36
Alaska	16.26	\$10,408.64	\$208,172.75
Arizona	10.97	\$7,022.31	\$140,446.19
Arkansas	8.86	\$5,671.62	\$113,432.38
California	14.75	\$9,442.03	\$188,840.59
Colorado	11.04	\$7,067.12	\$141,342.38
Connecticut	19.25	\$12,322.65	\$246,452.98
Delaware	13.80	\$8,833.90	\$176,677.98
Florida	11.44	\$7,323.17	\$146,463.48
Georgia	10.07	\$6,446.19	\$128,923.71
Hawaii	28.10	\$17,987.87	\$359,757.33
Idaho	7.99	\$5,114.70	\$102,293.99
Illinois	11.52	\$7,374.39	\$147,487.70
Indiana	9.56	\$6,119.72	\$122,394.31
Iowa	10.42	\$6,670.23	\$133,404.68
Kansas	10.03	\$6,420.58	\$128,411.60
Kentucky	8.57	\$5,485.98	\$109,719.58
Louisiana	8.98	\$5,748.44	\$114,968.71
Maine	15.71	10,056.56	\$201,131.23
Maryland	14.32	\$9,166.77	\$183,335.41
Massachusetts	14.59	\$9,339.61	\$186,792.15
Michigan	12.46	\$7,976.11	\$159,522.29
Minnesota	10.59	\$6,779.06	\$135,581.14
Mississippi	9.87	\$6,318.16	\$126,363.16
Missouri	9.08	\$5,812.45	\$116,248.99
Montana	9.16	\$5,863.66	\$117,273.21
Nebraska	8.94	\$5,722.83	\$114,456.60
Nevada	12.36	\$7,912.10	\$158,242.01
New Hampshire	16.32	\$10,447.05	\$208,940.91

New Jersey	16.57	\$10,607.08	\$212,141.60
New Mexico	10.52	\$6,734.25	\$134,684.95
New York	18.74	\$11,996.18	\$239,923.57
North Carolina	10.12	\$6,478.19	\$129,563.85
North Dakota	8.13	\$5,204.32	\$104,086.37
Ohio	11.32	\$7,246.36	\$144,927.15
Oklahoma	9.14	\$5,850.86	\$117,017.15
Oregon	8.87	\$5,678.02	\$113,560.41
Pennsylvania	12.70	\$8,129.75	\$162,594.95
Rhode Island	15.92	\$10,190.99	\$203,819.81
South Carolina	10.50	\$6,721.44	\$134,428.90
South Dakota	8.97	\$5,742.03	\$114,840.69
Tennessee	9.23	\$5,908.47	\$118,169.40
Texas	11.60	\$7,425.60	\$148,511.92
Utah	8.71	\$5,575.60	\$111,511.97
Vermont	15.57	\$9,966.94	\$199,338.85
Virginia	10.45	\$6,689.44	\$133,788.76
Washington	8.04	\$5,146.71	\$102,934.13
Washington D.C.	14.01	\$8,968.33	\$179,366.56
West Virginia	8.79	\$5,626.81	\$112,536.19
Wisconsin	12.65	\$8,097.74	\$161,954.81
Wyoming	8.77	\$5,614.01	\$112,280.14

Table 2: Data showing the estimated earnings of the C3 Canal Turbine in all 50 states by year as well as over the turbine's 20 year lifespan. Data is based off the turbine's average power output from the Roza Canal and each state's residential price per kWh in 2010.

-Turbine Spacing

How far apart turbines can be spaced in one site is one of the most important remaining questions for many hydrokinetic products. This will allow for companies to install multiple turbines throughout lengthy canals, maximizing power output. As yet, no reliable figure can be given on how far apart turbines need to be spaced. Each site will have a different spacing length depending on the type of turbine, its rotor blades, the water velocity, and so on. It is not essential

that the canal regain its complete laminar flow and velocity in order to install another turbine. The canal only needs to recover most of its velocity, which is another reason why spacing will change from site to site, as each site's velocities will differ. The little existing data on turbine spacing has led to a range of estimates. For this reason, this thesis will use a very conservative spacing estimate of 300 ft. for the C2 and C3 Turbines.

The particular section of the Roza canal where the C3 turbine is placed stretches 11 miles. The Bureau of Reclamation owns and operates roughly 50,000 miles of canals in addition to Roza, which is still a small portion of canals in the United States that are amenable to turbine installation⁴⁹. The sheer number of man-made irrigation canals, as well as the ability to space these large C3 turbines roughly 300' apart opens many significant power opportunities. It is likely that smaller turbines will require considerably less separation since they have a smaller impact on the water. In addition to the turbines being scalable, they can also be installed side by side. As long as a site meets at least the minimum dimension requirements for the C2 turbine, modifications can be made to maximize power output for that site.

The appropriate spacing for the C3 Canal Turbine was determined by tracking velocity data at several checkpoints around the turbine. Velocity data were calculated by using the sonar product "Streampro," developed by Teledyne and RD Instruments. This product features a red raft with attached sonar processing equipment. The raft was strapped to cables and guided by hand at various sites in the canal to determine water velocity before and after the C3 turbine's installation. Before the turbine's installation, measurements were taken 61.5 ft. upstream from the turbine, 112 ft. upstream, 145 ft. downstream, and at turbine's location. After the turbine's

⁴⁹ Opportunity

installation, measurements were taken at these same locations, resulting in readings from 7 locations. These data were uploaded into Teledyne's Winriver II program for analysis to calculate overall water velocity, the turbine's impact on water velocity, and the distance at which the velocity recovers enough for subsequent turbines to be placed thereby optimizing generating capacity of the canal.

In an 11-mile stretch with turbines placed every 300 feet, approximately 193 turbines could be installed. If these turbines each produced power output of the Prototype C3 Turbine installed at Roza, 11325.1 MWh of clean and reliable energy would be produced in an 11 month wet season. In 2011, this amount of power would be worth over \$910,500 in Washington.

6. PROJECTIONS FOR THE KITTITAS RECLAMATION DISTRICT'S MAIN AND NORTH BRANCH CANALS

The analysis below focuses on three different sections of the Main and North Branch canals. One of the Main Canal sites meets the installation requirements for the C3 turbine, while the others meet the minimum requirements for the C2 turbine. Differences in canal dimensions among these three sites provide several strong options for possible turbine installations. The following analysis estimates the projected power outputs for various water velocity rates to estimate the potential of the C2 and C3 turbines in these canals.

The KRD Main Canal has a maximum capacity of 1,320 CFS and the North Branch a maximum of 925. These are both substantial and more than enough to support a full-size C3 Turbine, if the canal's dimensions permit. The KRD Main Canal had a range of 814 to 1,138.17 CFS based on data during the month of July⁵⁰. The CFS rate increased gradually and consistently throughout the month, with only one minor dip of approximately 100 CFS. This is a strong CFS rate in which hydrokinetic turbines can operate.

The KRD canals switch between fast concrete-lined sections and slow earth-lined sections. The wider and deeper earth-lined sections of the Main Canal feature dimensions feature a bottom width of 30', a top width of 64.2', and a depth of 11.4'. The thinner but faster section of the canal features dimensions of 12' bottom width, 25' top width, and a depth of 9.75'⁵¹. The North Branch Canal section has dimensions of 10' bottom width, 20.5 top width, and 7.9' depth. These dimensions are detailed in table 3.

⁵⁰ Yakima Hydromet Real-Time (DAYFILES) Data Access, 2012

⁵¹ Yakima Project

The KRD canals have a 6 month wet season stretching from mid-April through October 15th of each year. Therefore, the following projections will assume a similar 6-month wet season. Other factors of note are that trout are present in the canals, as well as occasional debris such as branches or logs. The table below shows all three KRD sites as well as the Roza site for quick comparison.

Dimensions for the Roza and KRD Canal Sites

Site	Top Width	Bottom Width	Depth	Concrete?	Easy Access?
Site A	64.2'	30'	11.4'	N	Y
Site B	25'	12'	9.75'	Y	Y
Site C	20.5'	10'	7.9'	Y	Y
Roza	48'	14'	11'	Y	Y

Table 3: The dimensions of the four canal sites examined in this thesis. The table also includes whether the site is earth or concrete lined, and whether there is a road providing easy access to the site.

-Site A



Figure 16: Site A of the KRD Main Canal

This wider, earth-lined section, which will be referred to as “Site A,” has a slow water velocity but does have a high CFS and is large enough to install the C3 Canal Turbine. Velocity

was measured on August 9, 2012 using Global Water’s flow monitoring instrumentation which recorded water flow at speeds of only 0.9 to 1.0 m/s. The figure was used as the basis for making power output projections displayed below.

Figure 16 outlines the projected power outputs for the C3 Turbine with three different rotor blades. However, 1.0 m/s was too slow for both the Darrieus and Savonius rotor blades as they require minimum cut-in speeds of 2.0 and 1.5 m/s, leaving the Flipwing rotor blade as the only option for Site A. This would produce an estimated .4 kW. With Washington’s 2011 price per kWh of 8.04 cents, this equals 297.6 kWh per month, 1,785.6 kWh every 6 months (KRD’s wet season), and 35,712 kWh over the turbine’s 20 year lifespan (operating 6 months per year). The prototype C3’s performance at Roza, however, indicates that these figures are lower than they should be, and that the full-size C3 would likely produce more power than estimated here. However, to keep the estimates conservative, we will use the projections in Figure 16.

Table 4 depicts the projected power outputs, as well as the associated earnings (using Washington State’s 2011 price of 8.04 cents) for the C3 Turbine in Site A with the measured water velocity of 1.0 m/s. Projections for all 3 sites will include all 3 types of rotor blades:

Projected Power Outputs and Earnings for Site A

Rotor Blade	Power Output (1.0 m/s)	\$ Per 6 months	\$ Per 20 Years
Darrieus	N/A	N/A	N/A
Savonius	N/A	N/A	N/A
FlipWing	.4 kW	\$143.56	\$2,871.24

Table 4: The projected power outputs and financial earnings for the C3 Canal Turbine with a 1.0 m/s water velocity at Site A of the Kittitas Reclamation District’s Main Canal. Earnings are shown for every 6 months (KRD’s wet season) and for 20 years.

Table 4 shows yearly earnings of \$143.56. Analysis of every site’s projections can be found in the next section. However, in this case it is clear that the C3 Canal Turbine is not a good option for Site A as the water velocity is simply too slow, yielding too little power output.

-Site B



Figure 17: Site B of the KRD Main Canal

The KRD Main Canal's second site, Site B, is thinner, concrete lined, and comprises approximately half of the canal's 26.2 mile length, though the canal does frequently switch between the earthen and concrete-lined sections. Site B has a top width of 25', a bottom width of 12', and a depth of 9.75', meeting the minimum installation requirements of the C2 Turbine, but not the C3. Below are the projected power outputs for the C2 Turbine:

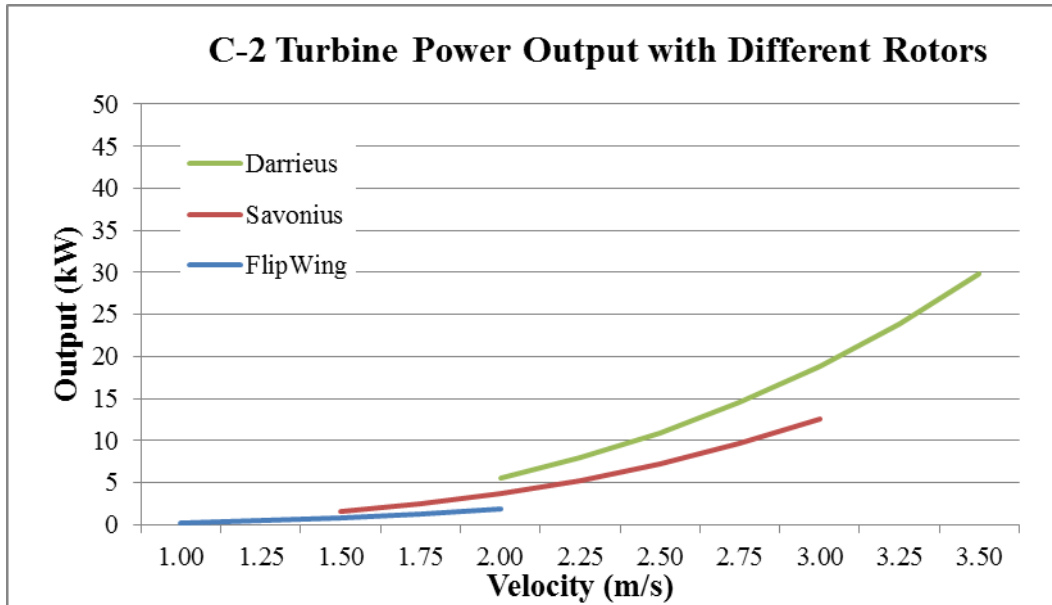


Figure 18: Chart illustrating the projected kW outputs for the C2 Canal Turbine with different rotor blades under water velocities ranging from 1 to 3.5 m/s

Velocity measurements at Site B recorded readings ranging from 2.0 to 2.7 m/s, with an average of 2.5. With this average, the C2 Turbine with Darrieus rotor blades would produce 10.9 kW of power, producing 8,109.6 kWh per month or 48,657.6 kWh per 6 months. Based on Savonius rotor blades, the estimates increase to 7.3, 5,431.2, and 32,587.2 kWh. The velocity at this site is too fast for Flipwing rotor blades so those estimates were not calculated. As discussed above, these figures are potentially lower than they would be as indicated by the C3 prototype turbine's performance in the Roza Canal. The following chart depicts projected power outputs, as well as the associated earnings (using Washington's 2011 price of 8.04 cents) for the C2 Turbine at Site B:

Projected Power Outputs and Earnings for Site B

Rotor Blade	Power Output (2.5 m/s)	\$ Per 6 months	\$ Per 20 Years	ROI (years)
Darrieus	10.9 kW	\$3,912.07	\$78,241.42	7.67
Savonius	7.3 kW	\$2,620.01	\$52,400.22	11.45
FlipWing	N/A	N/A	N/A	N/A

Table 5: The projected power outputs, financial earnings, and ROI for the C2 Canal Turbine, with 3 different rotor blades, at Site B of the Kittitas Reclamation District’s Main Canal. These projections are made using a 2.5 m/s water velocity and a 6 month wet season.

-Site C



Figure 19: Site C of the KRD North Branch Canal

Site C is part of the KRD North Branch Canal, which splits from the Main Canal along with the South Branch Canal. The South Branch is much smaller, and cannot accommodate either the C2 or C3 Turbines given its 5’ bottom width, 3.8’ depth, and maximum 220 CFS rate⁵². The North Branch, however, is very similar to the Main Canal, though slightly smaller. This canal also switches between earthen and concrete-lined sections over its 36 miles. The

⁵² Yakima Project: Project Data

larger, earthen sections have a width of 30' and a depth of 8.2', while the concrete sections have a top width of 20.5', a bottom width of 10', and a depth of 7.9'. The North Branch has a capacity of 925 CFS⁵³.



Figure 20: A velocity reading taken at Site C

Site C encompasses the North Branch's concrete lined sections. The velocity measurements there reported readings from 2.2 to 2.7, with an average of 2.5 m/s, the same as Site B. Once again, with Darrieus blades, a 2.5 m/s velocity is estimated to produce 10.9 kW, or 8,109.6 kWh per month, 48,657.6 kWh per 6 months, and 973,152 kWh over the turbine's 20 year lifespan. Savonius blades are estimated to produce 7.3 kW at 2.5 m/s, or 5,431.2 kWh per month, 32,587.2 kWh every 6 months, and 651,744.2 kWh over 20 years. Flow rates in this section are too fast for Flipwing blades. The following chart depicts the projected power outputs, as well as the associated financial earnings for the C2 Turbine in Site C:

⁵³ Yakima Project: Project Data

Projected Power Outputs and Earnings for Site C

Rotor Blade	Power Output (2.5 m/s)	\$ Per 6 months	\$ Per 20 Years	ROI (years)
Darrieus	10.9 kW	\$3,912.07	\$78,241.42	7.67
Savonius	7.3 kW	\$2,620.01	\$52,400.22	11.45
FlipWing	N/A	N/A	N/A	N/A

Table 6: Projected Power Outputs and Earnings for the C2 Canal Turbine at Site C of the KRD Main Canal with a 2.5 m/s Flow Rate. Projections are given for 3 types of rotor blades.

-Comparison with Other Renewable Energy Sources

To see how these figures relate to other renewable energy options, a brief comparison will be made with solar energy, one of the most popular and well-known clean energy sources. A 5 kW solar system with no tax credits is currently estimated to cost between \$25,000 and \$35,000 with an estimated ROI of roughly 20 years⁵⁴. This comparison, notably without maintenance costs factored in, shows solar to be more expensive than the C2 Turbine with a longer ROI while producing less power. The C3, which is estimated to produce a minimum of 5 kW, costs more than the solar unit, but has a shorter ROI and produces considerably more power. While these two technologies use different sources to generate energy, this comparison shows that hydrokinetics, even in its development stage, has potential to be more efficient and cost-effective than other leading energy sources. It is also worth repeating that hydrokinetics produce energy consistently and around the clock, while solar's output, along with many other clean energy sources, depends on weather and is therefore subject to unpredictable fluctuations and drops in output.

⁵⁴ Devlin, 2012

-Impact

The average household energy consumption in the United States is 30 kWh per day⁵⁵. The C2's projected output of 10.9 kW (261.6 kWh per day) at Sites B and C could be used for a number of important services. According to this figure, a C2 Turbine at Site B or C would be enough to power almost 9 homes. This by itself is a significant amount of power, but if we look at the maximum potential for this site, we find that theoretically 547 C2 Canal Turbines could be installed in the KRD Main Canal and North Branch Canals. Altogether, these turbines would produce 142,095.2 kWh a day, enough to power 4,736 homes. Of course, it is unlikely that all of these turbines could actually be installed, not only due to the incredibly high initial cost, but due to other factors such as siphons and check structures. These figures do however provide a strong example of the potential of hydrokinetic energy.

⁵⁵ How Much Electricity Costs, and How They Charge You

7) RECOMMENDED COURSE OF ACTION FOR THE KITTITAS RECLAMATION DISTRICT

Based on available data, investing in the C2 Turbine at Sites B and C at the Main Canal and the North Branch would be beneficial in a number of ways for KRD. First, the projections show a strong rate of return over the turbine's lifespan, even based on conservative cost estimates. Second, the turbine would be installed in areas that would otherwise be essentially unused. Unlike some other energy sources, installing a hydrokinetic turbine would not take needed space. From an operational perspective, the canals would be unaffected by the addition of one or more turbines.

The only impact a C2 Turbine would have on these canals is a small rise in water level (Roza's was increased by about 6 inches with the Prototype C3) and a slightly decreased water velocity for several hundred feet downstream of the turbine⁵⁶. Both of these impacts should be minor and will only affect a small area downstream from the turbine.

-Site A

Though the dimensions in Site A are large enough to accommodate the powerful C3 Turbine, its water velocity is too slow to produce enough power. The 1.0 m/s velocity barely meets the cut-in speed for the Flipwing, which would fail to produce a significant amount of power and would not net a profit. While the dimensions at this site are big enough to possibly even chain turbines together or install them side by side, the water velocity is simply too slow. If the velocity could be increased, and maintained, Site A would be ideal for a C3 Turbine (possibly even two side by side).

⁵⁶ Case Study: Roza Canal, 2012.

-Sites B and C

At both of these sites a C2 Turbine equipped with Darrieus rotor blades would produce an estimated 10.9 kW of power. This turbine would pay for itself after 7.67 years of its 20-year lifespan, eventually making \$48,241.42 in profit with the current WA price per kWh and a conservative cost estimate of \$30,000. In its lifetime, this turbine should produce an estimated 973 MW of clean energy.

Site B has large enough dimensions to add rotors to the C2 to maximize power. Little testing or power estimates with scaling have been completed on these turbines. However, Site B does have opportunities for possible scaling which should be considered should KRD decide to invest. These large dimensions will also cause the C2 to have an even smaller impact on the canal's water height and velocity.

Installing a C2 Turbine at Sites B or C is a solid investment for several reasons:

- The turbine has an ROI of 7.6 years, less than half its lifetime.
- A turbine could be easily installed by Hydrovolts and will not significantly impact the canal's water velocity or height. Overall, the District should not be inconvenienced.
- A turbine would produce approximately 973 MW of 100% clean energy in its lifetime.
- Lastly, a turbine would assist with long-term research of hydrokinetic products, helping to further an important new technology.

-Notes about Site C

Site C features smaller dimensions and a lower CFS rate than Site B. It is possible that water height and velocity might be affected more by the presence of a turbine, though this would not be expected to be significant enough to affect operation of the canal. Overall, sites B and C

are ideal locations for a C2 Turbine and it is highly recommended that the Kittitas Reclamation District strongly consider the C2 Canal Turbine when it is available in 2013.

-Risks and Other Factors

Despite hydrokinetic power being a new technology, there are relatively few risks associated with hydrokinetic turbines. There is the possibility of clogging due to debris, but even this is highly unlikely in that these sections are concrete lined (less overall debris) and the C2 Turbine is designed to handle fair amounts of debris. The turbine would also not be taking up entire sections of the canal, leaving plenty of room for any existing debris to easily pass through. Hydrovolts turbines, unlike Smart Hydro's for example, are designed to deal with such issues, meaning debris in any irrigation canal is manageable and shouldn't result in any additional maintenance or clogging.

There are still the many unknowns that come with all new technologies. Questions regarding the turbine's environmental impact remain, though early signs point to that impact being minimal, if non-existent. Perhaps the biggest risk is the turbine's long-term performance and maintenance, for which there is no data. Hydrovolts, however, confidently estimates the turbines to have a 20 year lifespan even in relatively harsh conditions, which may ease concerns over long-term performance. It is also still unclear at this time how Hydrovolts and other hydrokinetic companies plan to handle maintenance for their products.

8. FUTURE RESEARCH

Because hydrokinetic technology is very new, and nearly every company is still in the research and development phase, there will be considerable research opportunities for some time, particularly on long-term performance. Environmental research still needs to be done on hydrokinetic turbines, including the C2 and C3 turbines. Despite preliminary tests already mentioned in this thesis, more extensive research is needed on turbines' environmental effects. The variety of turbines, installation sites, and rotor blades create many environmental questions. Environmental research is especially important to ease not only the permitting process, but also the transition into commercialization. Unknown environmental factors could complicate or halt potential permits or sales and hurt the future of a promising technology.

The permitting process needs more research to help fix what is generally considered a broken system. Research to demonstrate easier permitting methods that remain effective could lay down a major step for hydrokinetic energy to expand and reach its potential. Significant reforms may be on the way for hydrokinetic permits, but regardless research on permitting delays and the impacts it has on prospective companies needs to be thoroughly addressed so that permitting doesn't continue to be a roadblock for technological and commercial progress in the hydrokinetic market.

A crucial but difficult research topic is the long-term performance of hydrokinetic turbines in various situations. This research cannot easily be carried out because hydrokinetics is such a recent technology. When turbines are purchased and installed for long periods of time, however, it will be important to track the consistency and longevity of the turbine, especially in harsher natural environments where damage, wear and tear are more likely. Data on this subject

could help greatly with future turbine designs and projected power outputs, leading to more accurate turbine pricing, which would help create a more reliable and sturdy market.

Turbine spacing represents an area of study that could drastically change the hydrokinetic market. More research on how turbines impact water velocity and how far they need to be apart will allow companies to sell and install the maximum number per site, increasing power output and profit.

Lastly, much research needs to be done on the impact different rotor blades have on hydrokinetic turbines. These blades will likely have a direct effect on many issues, making it arguably the most important research topic for hydrokinetic energy. Choosing a rotor blade will greatly affect a turbine's power output, while also possibly affecting the turbine's longevity and any environmental impacts.

9. CONCLUSIONS

Hydrovolts' C3 prototype turbine performed exceptionally well during its first run at Roza Canal. Not as large as the traditional C3, and only expected to produce 5 kW, the turbine's 7.17 kW average power output and an 8.9 kW peak, all with Savonius blades, demonstrate that the turbine performed well and was consistent, especially for a renewable energy source.

Even with the conservative estimates for the cost and power outputs of the C2 and C3 turbines, this thesis still showed them to be financially sound investments for the KRD and Roza Canals. Installing the C2 Turbine at Sites B and C in the Kittitas Reclamation District would produce a large amount of clean energy with an ROI of less than half the turbine's lifetime. In addition to the financial benefits, these turbines could be easily installed in hours within existing infrastructure, would produce power consistently regardless of the weather, and would produce 100% renewable power. This study showed that these turbines should be seriously considered by both the KRD and Roza Canals when they become commercially available in 2013.

Without more in-depth testing and research on how hydrokinetic turbines affect water velocity and how far apart they must be spaced, it's difficult to gauge the true potential of the technology. However it is still clear that the potential is considerable, as just within Roza's 11 mile stretch where the prototype C3 is installed, there lies potentially 1,381.81 kW (1.4 MW) worth of power if the turbines were to be placed 300' apart and produce the prototype's 7.17 kW average. Irrigation canals and other water channels can be found throughout the world and contain great amounts of renewable power. Hydrokinetic turbines such as the C2 and C3 represent a simple and cost-effective way to extract and harness that power, and should be considered a major factor in the rise of clean energy technologies.

The installation at the Roza Canal serves as an example of the reliability and consistency of hydrokinetic turbines and of how this technology has fixed the main weaknesses that have hindered other clean energy sources such as wind and solar, which produce power infrequently and inconsistently. Political hurdles remain, but hydrokinetic technology has demonstrated it can tap a vast energy source that's already present in waterways across the world.

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