RENEWABLE ENERGY RESOURCE, TECHNOLOGY, AND ECONOMIC ASSESSMENTS

Appendix L - Task 12: Technical Assessment of In-Conduit Small Hydro Power Technologies

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PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Technical Assessment of In-Conduit Small Hydro Power Technologies is the final report for the Technical Assessment of Small Hydro Power Technologies project (contract number 500 - 11 - 020, Task 12) conducted by the California Small Hydro Collaborative at UC Davis. The information from this project contributes to PIER’s Renewable Energy Technologies Program.

For more information about the PIER Program, please visit the Energy Commission’s website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.
ABSTRACT

This report provides a technical assessment of in-conduit small hydropower technologies and their deployment in California. It comprises an inventory of small hydropower turbine technologies available or under development with a focus on, but not strictly confined to, in-conduit applications. Also discussed are the simulation tools used for quantitative evaluation of in-conduit small hydropower technologies and evaluation criteria to assess their likely viability and usefulness. The status of in-conduit small-hydro deployment in California was estimated using a combination of publicly available records and databases and a limited survey of water agencies. The penetration of in-conduit small hydro in California’s water agencies was found to be relatively low. The report suggests a few factors that might be explored further to support future deployment.

Keywords: small hydro, in-conduit hydropower, California Renewable Energy Center.

Please use the following citation for this report:

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# NOMENCLATURE

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<tbody>
<tr>
<td>$C_f$</td>
<td>skin friction coefficient</td>
</tr>
<tr>
<td>$C_p, C_{pmin}$</td>
<td>(minimum) pressure coefficient</td>
</tr>
<tr>
<td>$D$</td>
<td>turbine rotor diameter</td>
</tr>
<tr>
<td>$g$</td>
<td>gravitational acceleration</td>
</tr>
<tr>
<td>$H$</td>
<td>total head, boundary layer shape factor</td>
</tr>
<tr>
<td>$J$</td>
<td>nucleation rate</td>
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<td>universal gas constant</td>
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<tr>
<td>$n$</td>
<td>rotational speed of turbomachine</td>
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<tr>
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<td>bubble-surface contact angle</td>
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<td>kinematic viscosity</td>
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<td>(critical) cavitation number</td>
</tr>
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EXECUTIVE SUMMARY

The energy used in California for water distribution is notoriously significant (up to one fifth of the state’s electricity use). It is possible to recover some of this energy by integrating in-conduit small hydroturbines at selected locations in the distribution network: the pressure release valves (PRVs). PRVs are flow control devices in which energy is expanded to bring pressure down to an acceptable value (typically after a drop in elevation). The power generated can be used to offset the energy needed to operate a water distribution system, thus improving its efficiency, or it can be fed back into the grid. This is a small hydropower technology and, as such, a renewable source of energy that can be harvested with minimal environmental impacts, particularly when since it is installed in existing conduits.

Purpose

This report provides an inventory of available in-conduit small hydropower technology and an assessment of the status of in-conduit small hydro deployment in California. The simulation needs for quantitative evaluation of in-conduit small hydropower and the evaluation criteria needed to assess the likely viability, performance, and usefulness of new in-conduit small hydroturbine technologies are also discussed. This report focuses on in-conduit small hydro and what differentiates it from the more mature small hydro field. Generators and grid connections issues are not within the scope of this study and neither are financial, policy, and permitting issues. The sources used include a variety of publicly accessible databases, trade publications, and manufacturers’ websites. In addition, a sample of water agencies were contacted with questions spanning topics relevant to this study, from the existence of an in-conduit small hydro installation on the system to the type of tools used to simulate the water distribution system.

Findings

Some of the devices identified in the hydroturbine technology inventory are being developed while others are already available. Many designs alter traditional hydro turbines to reduce cost or complexity for smaller sites with less energy. Pumps-as-turbines repurpose another commonly used hydraulic device to produce power at a lower cost. The technologies listed in this inventory utilize a variety of innovations to improve power production and lower the cost of energy from small hydro sites. Some turbine manufacturers have looked to history for technologies that were once used to produce mechanical water power that can be adapted to generate electricity. Others are inspired by wind turbine designs.

Water districts use a variety of simulation packages to model their water distribution network. In order to inform the development of in-conduit small hydro, the capabilities of the simulation tools must be expanded. These tools do not typically include the functionality to simulate in-line turbines. This limits the ability to model the difference between two set-ups and quantitatively express the differences. At the component level cavitation is a well-know issue and one that is incorporated in system design when considering pumps for example. Nevertheless, the proper inclusion of cavitation in the Computational Fluid Dynamics (CFD) codes used to develop new turbine designs for instance is still an active area of research.
When considering the installation of a turbine in a potable water distribution network, in addition to the certifications, approvals, permits, and standards pertaining generally to small hydro, water agencies must also follow the regulations relevant to water quality and public health. Test facilities for small hydroturbines could provide valuable information for turbine designers as well as contribute to building confidence for purchasers of hydropower equipment. Goals for improving turbine performance include flattening the efficiency curve to provide more uniform output in variable flow conditions, and increasing the overall turbine efficiency. Test facilities could also improve understanding of the performance of pumps when they are used as turbines.

The penetration of in-conduit small hydro was found to be low (10-25% of agencies with at least one in-conduit small hydro installed). There is significant potential for growth. Financial incentives are the top motivators with efficiency concerns and the desire to increase the fraction of energy used from renewable sources having important roles. Accordingly, the basis for the decision to install in-conduit small hydro on a water distribution system includes technical, financial, and environmental reports.

**Future Needs**

Topics of interest for future development of small hydropower include simplifying manufacturing and construction, improving turbine efficiency, and facilitating grid integration (National Hydropower Association et al., 2010). Standardization of turbine designs is a likely approach to reducing manufacturing costs by moving away from the model of customizing turbines to each site. This requires equipment that will connect to standard pipeline diameters. New materials could also improve manufacturability, reduce weight, or increase turbine lifetimes.

Independent testing facilities for new, in-conduit small hydro turbines would provide a valuable service to potential users. Existing Water Research centers in California could be leveraged to develop in-conduit small hydro testing and certification facilities.

Existing water distribution network simulation tools need to be adapted to accommodate the specificity of in-conduit small hydro. This is also the case for project analysis tools (that are not discussed herein).

Although this report does not discuss generators and grid integration, these are key areas for future work to improve power production and reduce project costs. The size of the necessary equipment could be scaled down to match the requirements of small hydro. Most interconnection equipment is designed for larger power plants and is correspondingly expensive. Small hydropower projects typically use synchronous generators, but variable speed generators could increase power production at sites with substantial variation in flow rates.

Finally, it is noted that the survey conducted as part of this investigation was necessarily limited, which constrained its accuracy. However, it addition to the qualitative insight that it provided, it also serves as a pilot, providing a template for a broader survey of potentially all agencies that would yield a wealth of information to guide the further deployment of in-conduit small hydro.
CHAPTER 1 — Overview

1.1 Introduction

Small hydropower is a renewable source of energy that can be harvested with minimal environmental impacts, particularly when installed in existing conduits. In-conduit small hydropower has been identified as a potential source of over 250 MW in generating capacity for the state of California (Kane, 2005). Water districts in California and elsewhere export 400 billion gallons of water everyday to their residents through gravity-driven flow distribution system consisting of 2.5 million miles of pipeline (Groeger, 2012; Spearrin, 2012). Procuring, treating, and transporting water through pipes requires significant amounts of energy. In 2005, the California Energy Commission (CEC) found that water-related energy consumption and demand accounted for nearly 20% of state’s electricity use (House, 2010). Some of the significant energy demand can be offset by recapturing energy lost in the water distribution systems (see for instance Chamberlain et al., 2005). Water distribution systems require several in-line pressure control facilities that are designed to regulate pressure and flow. Water agencies use pressure release valves (PRVs) in their water distribution systems to control pressure and avoid system damage. The energy dissipated using PRVs is lost energy.

The present study focuses on a strategy that aims at recovering some of that energy, known as the Pipeline Integrated Scheme (Zhanget al., 2012). In this scheme, hydro turbine units are placed at PRV locations in pipelines to recover the otherwise wasted water energy. Giugni et al. notes in 2009 that “turbine fitting in water networks is an unusual application requiring preliminary analysis to guarantee: optimal choice of the turbine, sufficient network pressure, suitable sanitary conditions, protection against potential pipes damage due to water hammer effects” (Giugni et al., 2009).

1.2 Scope

This report presents a study that aimed at investigating and assessing available small hydropower generation technologies and associated operating and performance parameters. The specific objectives of this study were to:

- Inventory small hydro technology
- Assess the simulation needs for quantitative evaluation of in–conduit small hydropower
- Identify evaluation criteria to assess the likely viability and usefulness of new in–conduit small hydropower technologies
- Evaluate the status of in-conduit small hydro deployment in California

Hydropower is a technically mature field with a broad science and technology literature base. This is also true of the sub-field of small hydro. Hence this report focuses on in-conduit small hydro. Ancillary information related to other small hydro implementations is only occasionally mentioned if relevant to the context. Generators and grid connections issues are not within the scope of this study. Finally, this study concentrates exclusively on the technical aspect: no attempt is made to discuss in any detail of the intricate financial, policy, and permitting issues. The recent and excellent work at ORNL to develop a cost reference model for small hydro is noted (Zhang et al., 2012).
1.3 Hydro Power Background

1.3.1 Fundamentals

The mechanical energy content of a flowing fluid is in the form of kinetic and potential energy. In open channels the potential energy is associated with elevation. In conduits both pressure and elevation contributed to the potential energy. The energy density $e$ (energy/volume) at a point of a fluid flow system is therefore expressed as:

$$ e = \frac{1}{2} \rho \alpha V^2 + p + \rho g z $$

where $\rho$ is the fluid density, $V$ its velocity, $p$ its pressure, $z$ its elevation, $g$ the acceleration of gravity and $\alpha$ is a kinetic correction coefficient (approximately 1 for turbulent flow). It is customary to consider the energy content per unit weight, $e/\rho g$, this quantity has a dimension of length and is called the Energy Grade Line (EGL):

$$ \text{EGL} = \frac{\alpha V^2}{2g} + \frac{p}{\rho g} + z $$

All terms on the left of the equal sign have dimensions of length as well and are consequently called: the kinetic head, the pressure head, and the elevation head, respectively. The sum of the pressure head and elevation head constitutes the Hydraulic Grade Line (HGL):

$$ \text{HGL} = \frac{p}{\rho g} + z $$

In an ideal, lossless system, the energy grade line would remain constant. In reality, friction losses and minor losses (associated with valves for example) occur as the fluid flows in the system, which reduces its energy content. This can be quantified by writing an energy balance for a flow system with a single flow path operating at steady state between two points (1) and (2):

$$ \left( \frac{\alpha V^2}{2g} + \frac{p}{\rho g} + z \right)_1 = \left( \frac{\alpha V^2}{2g} + \frac{p}{\rho g} + z \right)_2 + h_{12\text{loss}} $$

A turbine is a device placed on the flow path to extract some of the energy available in the flow. Let $e_t$ be the energy per unit volume extracted by a turbine. Then $h_t (= e_t / \rho g)$ is the turbine head, and the energy balance becomes:

$$ \left( \frac{\alpha V^2}{2g} + \frac{p}{\rho g} + z \right)_1 = \left( \frac{\alpha V^2}{2g} + \frac{p}{\rho g} + z \right)_2 + h_{12\text{loss}} + h_t $$

Furthermore, the power extracted from the fluid by the turbine ($P_{\text{t}}$) is obtained by multiplying the energy per unit volume extracted by the volume flow rate ($Q$):
Not all the power extracted from the fluid by the turbine is available for electricity generation however. The ratio between the power available for electricity generation, \( P \) and \( P_{\text{net}} \) is the turbine efficiency: \( \eta = \frac{P}{P_{\text{net}}} \).

Thus the power available for electricity generation is:

\[
P = \eta \rho gQh_f
\]

### 1.3.2 Small Hydro Definitions

“Small hydro” is intended to refer to projects that have minimal environmental impacts compared to the substantial civil works and reservoirs of large hydropower projects. Comparing relative environmental impacts between diverse projects is a complex task, so most governments and non-governmental organizations define small hydropower based on the generation capacity of an installation. These definitions are used to determine eligibility for benefits such as renewable energy grants, tax credits, or feed-in tariffs. There is no commonly accepted standard for “small hydro”, with the International Energy Agency (IEA) defining “small hydro” as \( \leq 10 \text{ MW} \), while the EU uses an upper bound of 20 MW, and Canada sets the maximum at 50 MW. In the United States, FERC grants exemptions from its licensing requirements for small conduit projects with a capacity of \( \leq 15 \text{ MW} \), or \( \leq 40 \text{ MW} \) for municipal
water projects. The state of California has defined “small hydro” as projects ≤30 MW for participation in the renewable portfolio standard. This report focuses on technologies that meet California’s definition of “small hydro”.

In addition to defining “small hydro” for regulatory purposes, other terms are also used to distinguish between projects at smaller and smaller scales. “Mini hydro” projects are typically defined as ≤1 MW, while micro hydro projects are ≤ 100 kW, and the smallest practical projects are called “pico hydro” at less than 10 kW. Micro and pico hydro projects may only be economically feasible in remote areas without access to grid-based electricity. In California, future projects will likely have capacities between 100 kW and 30 MW (Figure 1).

1.4 Data Sources

Information regarding small hydropower technologies in California and elsewhere has been gathered from a variety of sources. Some useful databases and source categories are listed below, while individual references on specific topics are provided throughout the text.

1.4.1 Small Hydropower Technologies

IEA Small Hydro http://www.small-hydro.com/

The US, Norway, Japan, France, Finland, China, and Brazil are signatories to the International Energy Agency (IEA) Hydropower Agreement, which includes collaborative research on technical and regulatory issues relating to small hydro projects (between 50 kW and 10 MW). The participants have identified a set of innovative technologies for small hydro and maintain a library of related information.

International Center on Small Hydropower www.inshp.org

The International Center on Small Hydro Power is co-sponsored by the United Nations and the Chinese government, with members from 78 countries. There is an emphasis on hydropower technologies for rural areas in developing countries. The center is compiling a report on the status of small hydropower worldwide, with some content already available on its website.

Trade Publications

For the hydropower industry, trade publications including Hydro Review (www.hydroworld.com) and International Water Power & Dam Construction (www.waterpowermagazine.com) provide information about new hydropower technologies. Information aimed at municipal utilities can be found in publications such as American City & County (americancityandcounty.com) or Water Technology (www.watertechonline.com).
Manufacturers’ Websites

Much of the information about specific technologies is drawn from the manufacturers’ websites. In particular, images and performance data for the majority of the technologies come from the manufacturers.

1.4.2 Small Hydropower installations in California

California RPS Eligible Facilities List

The California Energy Commission maintains a list of generation facilities that meet the requirements for the state Renewable Portfolio Standard, available online at www.energy.ca.gov/portfolio/documents/list_RPS_certified.html. The RPS includes conventional hydropower facilities with capacities up to 30 MW as well as small in-conduit facilities. The listing includes the plant name, capacity, date online, plant type, and owner, but does not provide more detailed information regarding the location or equipment type.

SGIP Quarterly Reports

The California Public Utilities Commission’s Self-Generation Incentive Program (SGIP) provides financial incentives for installing clean electricity generation to be used on-site. Small in-conduit hydro installations may qualify for rebates as “Pressure Reduction Turbines,” and the list of facilities applying for the incentives is available in statewide reports issued quarterly. These reports provide information on the capacity, type of turbine, and project costs. In-conduit hydro projects became eligible for SGIP only recently, as part of changes to the program in response to SB 412 in 2011, so there are currently very few applications by small hydro projects.

FERC eLibrary http://elibrary.ferc.gov/

The Federal Energy Regulatory Commission’s online library houses public records of official communications with FERC including applications for hydropower licenses and exemptions. These applications must contain (as Exhibit A) a project description including planned structures, water source, number and capacity of planned generating units, turbine type, an estimate of annual generation, hydraulic head, average flow rates, and a start date for construction. Exhibits F and G, which contain project drawings and maps, are also available unless they are considered Critical Energy Infrastructure Information. The eLibrary is a valuable source of information regarding specific projects in California, but it is limited to relatively recent activities. Materials dating before the early 2000s are kept on microfilm and are not readily available online.

Municipal Water and Power Utility Websites

The websites of municipal utilities have varying amounts of information about current and past hydropower projects.
1.4.3 Survey
A survey of water agencies was designed and conducted as a means to assess the status of in-conduit small hydro deployment in California. In addition to determining deployment, this survey also allowed the assessment of other relevant questions, e.g. simulation needs.

Approach
A list of California water agencies was kindly provided by the Water Resources Collections and Archives (UC Riverside and CSU San Bernardino). The list consists of a spreadsheet containing the contact information for 713 water agencies located in California. These agencies include municipal water districts, public utilities, irrigation districts, and wastewater treatment plants. A sub-set (sample) of 238 agencies was selected for the survey. These agencies were selected on the basis of geographic distribution (see Figure 2), size (from 4 to 3,784,000 acre-feet), and population served (from 500-3,863,839).

Figure 2: Geographic distribution of respondent to the Survey

The survey method was web-based. This choice made sense given the cost and time savings inherent to that method compared to more traditional methods (mail, phone). The main hurdle to implementing such a survey method, the potential bias that may be introduced by the lack of Internet connection or computer literacy of some of the individuals in the sample (Dillman et al., 2008), is immaterial here since the population is Water Agencies.

Email messages providing a short introduction to the survey and a link to the web-based form were sent to water agencies in the sample. Because web-based surveys tend to have a lower response rate than other methods (Monroe and Adams, 2012), some of the guidelines proposed
by Dillman were implemented including reminder emails and follow-up phone calls (Dillman et al., 2008).

The survey was kept short (9 questions, another strategy aimed at increasing the response rate) spanning topics relevant to this study, from the type of tools used to simulate the water distribution system to the existence of an in-conduit small hydro installation on the system or the factors that might prompt the agency to consider installing one. The responses are discussed throughout this report. Both close-ended and open-ended questions were used, sometimes in combination. Most close-ended questions had more than two unordered response choices, not necessarily mutually exclusive. The following questions were formulated for the survey:

**Challenges and Limitations**

The first challenge encountered in conducting the survey stemmed from the reliability of the contact information provided in the database. An email address was not necessarily provided for each agency, some email addresses were outdated and rejected the email message. This challenge alone reduced the survey sample to about 118 water agencies. The second challenge, common to every survey, was the limited response rate. The 118 email messages yielded 13 responses to the survey (~11%). This is a bit more than typically expected for Online surveys, but still too small to be useful. We addressed this challenge by implementing the reminder emails and phone follow-up strategy (Dillman et al., 2008) and we augmented the sample by 63 agencies selected following the same criteria. This brought the total number of respondents to 45. Because the characteristics of the non-respondents did not depart in a notable manner from those of the respondents, it is unlikely that a meaningful non-response bias exists.

This was effective as the response rate nearly increased to 25%. For an emailed survey, an average acceptable response rate is 40% (“Response rates,” 2011). We wanted to achieve a high survey response rate to ensure our results were representative of water agencies throughout California.

Though numerically our statistical accuracy is minimal (confidence interval 5-14% for a 95% confidence level), the responses we did were quite helpful in accomplishing our task. Much of data analysis discussed in this survey contains percentages of only the water districts that responded to the survey. This limited survey shows that there would be significant benefits in conducting a more extensive survey of all agencies as a means to assess technology deployment
CHAPTER 2 — Small Hydro Technologies

2.1 Technology Overview

The technologies included in this inventory represent the broad range of technologies available or under development for small hydropower projects, whether in-conduit or not. The inventory concentrates on turbines and does not consider generator technologies. Although in-conduit devices were the focus of the literature survey, devices for all types of small hydropower installation are reported in order to give a better sense for the range of turbines that have been designed. Some of the turbine geometries that are currently implemented only in open channels may contribute to future designs for in-conduit applications.

2.1.1 Technology Classifications

The choice of technology for a particular project is driven by characteristics of the site where it will be installed. The site configuration is a key factor in the types of environmental impacts that may occur, and places some limits on the type of turbine selected. The available hydraulic head is also an important factor in choosing a turbine. Alternatively, projects may be categorized according to the technology used. Most hydropower technologies fall into one of several classes of turbine geometry.

Classification by site configuration

Site configurations include storage, run-of-river, and pipeline integrated projects. Storage hydropower uses a reservoir (typically created by a dam) to store water and release it in a controlled manner for hydroelectric generation. The storage capacity of the reservoir allows the generator to minimize seasonal variations or to respond to changes in demand, with limits imposed by the downstream impact of flow variations. Dams are often associated with large hydropower projects, but there are also opportunities for small hydro with storage, in particular at existing non-powered dams. The US Department of Energy estimates California’s non-powered dam resource potential to be 195 MW (Hadjerioua, Wei, & Kao, 2012).

Run-of-river projects (which include projects installed in canals as well as natural streams) do not alter the seasonal flow pattern of the watercourse. They may incorporate a weir to maintain water depth and divert water into a penstock leading to a powerhouse. The outflow from the powerhouse is discharged back into the river or canal. Run-of-river projects may also be constructed in which there is no diversion from the existing watercourse; this configuration is also called in-stream. Turbines may be bottom-mounted, floating, or suspended at some height within the stream. The environmental impact of run-of-river projects is generally small compared to storage hydropower, which causes greater disruption of the natural water flows.

Pipeline integrated projects utilize closed conduits that are part of a water distribution system. The hydropower equipment is sited at a location with excess pressure that would typically be dissipated with a pressure release valve (PRV). The turbine and generator allow energy to be recovered that would otherwise be lost in the PRV. Because these projects are integrated into manmade conduits, additional environmental impacts due to hydropower are minimal.
California’s conduit small hydropower resource is estimated at 255 MW of nameplate capacity (Kane, Beyenne, & Previsic, 2005).

The characteristics of a particular site may determine which type of turbine is chosen. An important consideration for in-conduit hydro projects is whether pressure is required at the outlet. If the turbine is to be integrated within a pipeline, it must be designed to operate with pressurized output. At other sites such as a canal drop, there is no requirement for the outflow to be under pressure.

**Classification by available head**

From a turbine selection perspective, the two key parameters for any hydro site are the available head (turbine head, \( h_t \), more commonly denoted by \( H \)) and flow rate, \( Q \). Again, the total power \( P \) available for electricity generation depends on the product of the hydraulic head and flow rate:

\[
P = \eta \rho g Q H
\]

where \( \eta \) is the turbine efficiency, \( \rho \) is the water density and \( g \) is the acceleration of gravity. The relative head and flow rate for a given output power guides the selection of turbine geometry. Some turbines perform best at high flow rates and others require high-head sites. There are no commonly agreed-upon definitions of high, medium, or low head, but a suggested range is given in Table 1. The values should be considered as approximate guidelines rather than fixed limits.

<table>
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</tr>
<tr>
<td>Medium-head</td>
<td>25 – 70 m</td>
</tr>
<tr>
<td>High-head</td>
<td>&gt; 70 m</td>
</tr>
</tbody>
</table>

**Classification by turbine geometry**

Conventional hydroturbines are divided into two types: impulse turbines and reaction turbines. Small hydro projects may also use less conventional devices including pumps-as-turbines, Archimedes screw turbines, and hydrokinetic turbines. Small hydro turbines have typically been adapted form existing designs to the flow and head condition of a specific site. The particularities of in-conduit flow conditions (e.g. confinement) have also lead to strategies such as repurposing pumps as turbines (PATs) or yielded innovative designs, some inspired by other applications such as wind turbines. There is no standard turbine design yet for in-conduit applications. Performance ranges for several common turbine types are given in Figure 3. The diagonal lines indicating power output correspond to an efficiency \( (\eta) \) of 82%, which may be higher or lower than the actual efficiency of a given turbine.

In an impulse turbine, water is directed through one or more nozzles toward the runner. The momentum of the jets drives the runner’s rotation. The role of the nozzles is to direct the flow
and increase its velocity (convert potential energy to kinetic energy). Hence, the runner operates at atmospheric pressure, avoiding the need for a pressurized housing. This simplifies manufacture and maintenance of impulse turbines, but can be a disadvantage in closed conduits where pressure is required at the turbine outlet. Impulse turbines are best suited to high-head sites. They are advantageous for sites where there is significant variation in the flow rate as they can handle moderate departure from design flow without a significant decrease in efficiency (Kumar et al., 2011). Common types of impulse turbines include the Pelton, Turgo, and crossflow (or Banki) turbines.

Reaction turbines use the shape of the runner blades to convert water pressure at the inlet to rotational velocity for the generator. The runner is immersed in water and requires care in manufacturing to achieve the desired shape and avoid energy loss due to leakage between the runner and housing. The enclosed runner can operate at locations where pressure is required at the turbine outlet. Reaction turbines can operate at lower head sites than impulse turbines, but typically do not perform as efficiently at low flow rates (Kumar et al., 2011). Adjustable runner blades improve the efficiency at low flow, but also increase the complexity of manufacturing and operation. Compared to impulse turbines with the same generating capacity, reaction turbines can have a smaller diameter and higher shaft speed. This saves space and material and can allow for a smaller generator assembly.

Reaction turbines can be divided into radial flow and axial flow types. In radial flow turbines, water enters through a spiral casing that directs the flow radially inward. The flow is redirected as it passes through the runner, exiting axially via a draft tube. The Francis turbine is a widely-used example of a radial flow turbine. In axial flow turbines, water enters and exits parallel to
the shaft. The generator may be enclosed within the housing, along the perimeter of the runner, or the inlet may bend to keep the generator out of the water. Axial flow designs include bulb, Kaplan, and propeller turbines.

A common choice for in-conduit turbines is the pump-as-turbine (PAT) configuration. A typical PAT is a centrifugal pump operated in reverse to become a radial-flow turbine. The main advantage of a PAT is that it utilizes standard equipment that can be manufactured less expensively than a custom-designed turbine (Giugni et al., 2009), and water utilities may already be familiar with their operation and maintenance. Because they have not been designed to operate as turbines, pumps-as-turbines have lower efficiencies and a more restricted range of flow rates for efficient performance than comparable purpose-built turbines. More than two-thirds of the water agencies responding to the survey conducted in the context of this study (Section 1.4.3) report that a new turbine is likely to be more feasible than a PAT for their network (Figure 4). The actual selection would have to be informed by a thorough technical study of the water system conditions and possibly an extensive financial study to determine which choice is more viable for the specific water supply network.

![Figure 4: Which of the following options is more feasible for your water system.](image)

Archimedes screw turbines are a unique style of pump-as-turbine. They are essentially a reversal of the screw pump developed by Archimedes, which is commonly used in wastewater treatment plants and other applications where solid and semi-solid materials are being pumped. Screw turbines are typically partially submerged in open channels. They are used at low- and very low-head sites.

Hydrokinetic turbines approach the task of generating electricity from moving water from a somewhat different background than conventional hydroturbines. Designers of hydrokinetic devices have looked to wind turbines as a starting point to develop devices that are immersed in a fluid rather than having the fluid channeled into the device. Water provides a much higher power density than wind, allowing turbines to be much smaller, but they must withstand higher loads as well. Hydrokinetic devices have increasingly been researched for the purpose of harnessing energy from ocean waves, currents, and tides, and similar or identical devices can also be employed in rivers and manmade channels.

Hydrokinetic turbines do not require the large drop in hydraulic head that is the source of the energy harvested by conventional hydroturbines; instead, water velocity is the key requirement. As a result, hydrokinetic devices are not typically mapped onto a standard head-flow diagram, but power output is reported as a function of water velocity. Hydrokinetic turbines can be
divided into subcategories based on their geometry, specifically the orientation of their axis of rotation with respect to the incoming flow (Khan, Bhuyan, Iqbal, & Quaicoe, 2009). Axial turbines align the axis with the flow direction and may resemble horizontal axis wind turbines or propeller hydroturbines. Vertical axis and crossflow turbines are oriented vertically or horizontally, respectively, with their axes perpendicular to the incoming flow. Two basic vertical/crossflow turbine designs that have inspired many variants are the Savonius and Darrieus rotors. Savonius rotors have S-shaped blades that move due to drag force, while Darrieus rotors have aero- or hydrodynamic blade profiles that rotate due to lift forces. Blades on a Darrieus rotor are located at the rotor perimeter and the volume enclosed by the blades’ path may be cylindrical or spherical.

**Technology Readiness Levels**

Technology readiness levels (TRLs) were initially developed to assess new technologies for the space program. As a useful metric for comparing diverse technologies, they have been adapted by the US Department of Energy to describe emerging energy technologies. The DOE Wind and Water Program at Oak Ridge National Laboratory has further refined the TRL definitions to apply to small hydropower (Zhang et al., 2012). TRLs 0 – 3 indicate technologies still in the conceptual stage, while devices at TRLs 4 – 6 have begun product development and prototype testing. The highest TRLs (7 – 9) are assigned to technologies that are approaching or have reached commercial deployment.

<table>
<thead>
<tr>
<th>TRL</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRL 1</td>
<td>Ideas to form R&amp;D proposals</td>
</tr>
<tr>
<td>TRL 2</td>
<td>Formally funded R&amp;D proposals</td>
</tr>
<tr>
<td>TRL 3</td>
<td>Conceptual design—technical feasibility demonstration through theoretical analysis and/or computer modeling</td>
</tr>
<tr>
<td>TRL 4</td>
<td>Physical model validation in laboratory</td>
</tr>
<tr>
<td>TRL 5</td>
<td>Field validation and demonstration</td>
</tr>
<tr>
<td>TRL 6</td>
<td>Pilot plant operation</td>
</tr>
<tr>
<td>TRL 7</td>
<td>Verification and validation completed and ready for commercialization</td>
</tr>
<tr>
<td>TRL 8</td>
<td>Successfully applied and well performed in some countries/regions</td>
</tr>
<tr>
<td>TRL 9</td>
<td>Mature technology—good performance has been proved for decades</td>
</tr>
</tbody>
</table>
2.2 Specific Technology Descriptions

This section contains an inventory of small hydropower technologies with brief descriptions of each technology. A head/flow diagram is provided for each turbine (except hydrokinetic devices), as well as a list of existing projects, if applicable. The small icons used to indicate the turbine type are based on the classification chart in (Williamson, Stark, & Booker, 2014). The section is organized by type of turbine and TRL, following the order given in Table 2. Entries in the table include the following:

- **Product Name (Company)**
- **Turbine Type**: Reaction turbines are listed first, including Francis turbines, pumps-as-turbines, and axial turbines. Impulse turbines (Pelton, Turgo, and crossflow) and hydrokinetic turbines follow.
- **TRL**: Technology readiness levels have been estimated using the rubric shown in Table 2.
- **Site Type**: The type(s) of site each technology is suited for can be one or more of the following: “P” for pipeline, “D” for dam, and “RoR” for run-of-river or canal sites.
- **Power**: The output power range (in kilowatts) may span several different sizes of similar turbine models.
- **Activity Level**: Most technologies are considered “active,” while a few technologies do not appear to be currently active in production or development. Inactive technologies are not included in the descriptions following Table 2.
- **Installations**: The installations column indicates whether a particular technology has been installed in California, elsewhere in the United States, or elsewhere in the world. At lower TRLs, installations may include pilot projects or planned projects.

**Table 3. Quick reference guide to technologies discussed in this section**

<table>
<thead>
<tr>
<th>Product Name (Company)</th>
<th>Turbine Type</th>
<th>TRL</th>
<th>Site Type</th>
<th>Power (kW)</th>
<th>Activity Level</th>
<th>Installations CA</th>
<th>US</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Francis Turbine (various)</td>
<td>Francis</td>
<td>9</td>
<td>P, D, RoR</td>
<td>&gt; 500</td>
<td>Active</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Francis Plate Turbine (Small Turbine Partner)</td>
<td>Francis</td>
<td>8</td>
<td>P, D, RoR</td>
<td>500 – 4000</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Alden Turbine (EPRI / Alden / Voith)</td>
<td>Francis</td>
<td>5</td>
<td>D, RoR</td>
<td>10,000</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultra Low Head Turbine (Nautilus)</td>
<td>Francis</td>
<td>5</td>
<td>RoR</td>
<td>0.5 – 3</td>
<td>Active</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Reaction Turbine (Cornell Pump)</td>
<td>PAT</td>
<td>9</td>
<td>P, RoR</td>
<td>1 – 350</td>
<td>Active</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Difgen (Zeropex)</td>
<td>PAT</td>
<td>7</td>
<td>P</td>
<td>&lt; 110</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Product Name (Company)</td>
<td>Turbine Type</td>
<td>TRL</td>
<td>Site Type</td>
<td>Power (kW)</td>
<td>Activity Level</td>
<td>Installations CA</td>
<td>US</td>
<td>Other</td>
</tr>
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</tr>
<tr>
<td>Hydrokinetic Energy Recovery Opportunity (Rentricity)</td>
<td>PAT</td>
<td>7</td>
<td>P</td>
<td>15 – 55</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrodynamic Screw (Andritz Atro)</td>
<td>Archimedes screw</td>
<td>8</td>
<td>RoR</td>
<td>1 – 500</td>
<td>Active</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Screw Generator (Spaans Babcock)</td>
<td>Archimedes screw</td>
<td>8</td>
<td>RoR</td>
<td>50 – 250</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Screw Hydroturbine (Landustrie)</td>
<td>Archimedes screw</td>
<td>8</td>
<td>RoR</td>
<td>1 – 400</td>
<td>Active</td>
<td>✓</td>
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<td></td>
</tr>
<tr>
<td>Archimedean Screw (Rehart)</td>
<td>Archimedes screw</td>
<td>8</td>
<td>RoR</td>
<td>1 – 250</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HydroCoil</td>
<td>Archimedes screw</td>
<td>4</td>
<td>P, RoR</td>
<td>&lt; 2</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Axial / Propeller / Kaplan Turbine</td>
<td>Axial / Propeller</td>
<td>9</td>
<td>P, D, RoR</td>
<td>375 – 1000</td>
<td>Active</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Hydromatrix (Andritz)</td>
<td>Propeller</td>
<td>8</td>
<td>D, RoR</td>
<td>100 – 500</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very Low Head Turbine (MJ2)</td>
<td>Kaplan</td>
<td>8</td>
<td>RoR</td>
<td>100 – 500</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydro-eKIDS (Toshiba)</td>
<td>Propeller</td>
<td>8</td>
<td>P, D, RoR</td>
<td>1 – 200</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micro-tubular Turbine (Voith Fuji)</td>
<td>Bulb</td>
<td>8</td>
<td>P, RoR</td>
<td>3 – 250</td>
<td>Active</td>
<td>✓</td>
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<td></td>
</tr>
<tr>
<td>HydroAgri (Electric Power Development)</td>
<td>Kaplan</td>
<td>8</td>
<td>RoR</td>
<td>10 – 30</td>
<td>Inactive</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linepower (Kubota)</td>
<td>Bulb</td>
<td>8</td>
<td>P</td>
<td>3 – 90</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbinator (CleanPower)</td>
<td>Axial</td>
<td>6</td>
<td>D, RoR</td>
<td>100 – 3000</td>
<td>Active</td>
<td>✓</td>
<td>✓</td>
<td></td>
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<tr>
<td>Eco-Siphon (Galt Green Energy)</td>
<td>Propeller</td>
<td>6</td>
<td>D, RoR</td>
<td>10 – 200</td>
<td>Inactive</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ring Hydroturbine (Kawasaki)</td>
<td>Propeller</td>
<td>5</td>
<td>D</td>
<td>20 – 500</td>
<td>Inactive</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelton Turbine (various)</td>
<td>Pelton</td>
<td>9</td>
<td>D, RoR</td>
<td></td>
<td>Active</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>GPRV (SOAR)</td>
<td>Pelton</td>
<td>5</td>
<td>P</td>
<td>15 – 40</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turgo Turbine (various)</td>
<td>Turgo</td>
<td>9</td>
<td>D, RoR</td>
<td></td>
<td>Active</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Product Name (Company)</td>
<td>Turbine Type</td>
<td>TRL</td>
<td>Site Type</td>
<td>Power (kW)</td>
<td>Activity Level</td>
<td>Installations CA</td>
<td>US</td>
<td>Other</td>
</tr>
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</tr>
<tr>
<td>PowerPal (Asian Phoenix)</td>
<td>Turgo</td>
<td>8</td>
<td>RoR</td>
<td>0.6 – 20</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crossflow / Banki Turbine (various)</td>
<td>Crossflow</td>
<td>9</td>
<td>D, RoR</td>
<td>3 – 15</td>
<td>Active</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Ossberger Turbine (Ossberger)</td>
<td>Crossflow</td>
<td>8</td>
<td>D, RoR</td>
<td>15 – 3000</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrovolts Waterfall (Hydrovolts)</td>
<td>Crossflow (Banki)</td>
<td>6</td>
<td>D, RoR</td>
<td>50 – 500</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waterwheel (Hydrowatt)</td>
<td>Wheel</td>
<td>8</td>
<td>RoR</td>
<td>4 – 26</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poncelet Wheel (Poncelet Kinetics)</td>
<td>Wheel</td>
<td>3</td>
<td>RoR</td>
<td>3 – 5</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LucidPipe (Lucid Energy)</td>
<td>Hydrokinetic (Vertical)</td>
<td>7</td>
<td>P</td>
<td>14 – 100</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrovolts Canal (Hydrovolts)</td>
<td>Hydrokinetic (Crossflow)</td>
<td>6</td>
<td>RoR</td>
<td>1.5 – 12</td>
<td>Active</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>EnCurrent (New Energy)</td>
<td>Hydrokinetic (Vertical)</td>
<td>6</td>
<td>RoR</td>
<td>3</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modular Bulb Turbine (Hydro Green Energy)</td>
<td>Hydrokinetic (Axial)</td>
<td>5</td>
<td>D, RoR</td>
<td>100 – 750</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SmarTurbine (Free Flow Power)</td>
<td>Hydrokinetic (Axial)</td>
<td>5</td>
<td>RoR</td>
<td>5 – 40</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smart Kinetic Hydro System (Smart Hydro)</td>
<td>Hydrokinetic (Axial)</td>
<td>5</td>
<td>RoR</td>
<td>3 – 5</td>
<td>Active</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TREK (Renewable Energy Research)</td>
<td>Hydrokinetic (Axial)</td>
<td>5</td>
<td>RoR</td>
<td>4</td>
<td>Inactive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CycloTurbine (Boschma Research)</td>
<td>Hydrokinetic (Vertical)</td>
<td>4</td>
<td>RoR</td>
<td>3</td>
<td>Inactive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Underwater Electric Kite</td>
<td>Hydrokinetic (Axial)</td>
<td>4</td>
<td>RoR</td>
<td>3</td>
<td>Inactive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RivGen (Ocean Renewable Power Co.)</td>
<td>Hydrokinetic (Crossflow)</td>
<td>3</td>
<td>RoR</td>
<td>3</td>
<td>Active</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.3 Inventory of Small Hydro Power Generation Technology Types

A full list of these newly developed power generation technologies is provided here. The list contains an inventory of small hydropower technologies with brief descriptions of each technology. The list contains the following entries:

- Turbine Manufacturers’ Name, Location and Website
- Small icons used to indicate the turbine type
- A head/flow diagram for each turbine (except hydrokinetic devices), as well as a list of existing projects, if applicable

## Francis Turbines

<table>
<thead>
<tr>
<th>Manufacturers include: Alstom, Andritz, Canadian Hydro, Canyon Hydro, Cink, Dependable Turbines, Gilkes, Hitachi Power Systems, Mavel, Mecamidi, NorCan, Voith, Wiegert &amp; Bähr</th>
</tr>
</thead>
</table>

Francis turbines are reaction turbines with a radial inlet and axial discharge. The inlet is typically a spiral casing that directs the flow through a set of guide vanes that can be adjusted to maximize efficiency for different flow rates. Fixed guide vanes can be used to reduce the complexity of manufacture and operation, at the cost of lower efficiency at off-design flow rates. Francis turbines may be oriented with the outlet in a horizontal or vertical direction. Outflow frequently exits through an expanding draft tube which maximizes the pressure difference across the turbine.

Francis turbine in spiral casing with generator

Cut-away showing Francis runner (red) with adjustable guide vanes (yellow)

[image: commons.wikimedia.org]  [image: commons.wikimedia.org]
Small Turbine Partner originated in the Norwegian University of Science and Technology (NTSU) and is owned by several energy companies. They manufacture turbines with outputs up to 10 MW. The larger turbines are Pelton wheels or Francis turbines, while the smaller plate Francis turbines were identified by the IEA Small Hydro group as an innovative technology. The Francis plate turbine uses an optimized manufacturing method to simplify production and reduce costs.

**Installed Projects**

Several installations in Norway, ranging from 80 – 700 kW

A “fish-friendly” turbine designed for installation in a dam, avoiding the need for fish bypass equipment and the associated loss of power. A prototype was tested at the Alden Research Laboratory (results available at (Dixon & Dham, 2011)) and a pilot project is planned for the School Street dam in Cohoes, New York.

**Planned Project**

Brookfield Renewable Power, School Street, Cohoes, NY – 10 MW
Nautilus manufactures small Francis turbines for both medium head (1.2 – 12.8 m) and ultra-low head (1 – 3.7 m) sites. The turbines are designed for installation in open-flume settings as small, run-of-river power plants.

Selected Projects

Blairstown, NJ – 6 kW
Kennet Square, PA – 1.5 kW

Cornell pumps are a common choice for small in-conduit hydro in California as well as other states. The company’s primary products are pumps for a variety of applications including municipal water systems. When operated in reverse, the centrifugal pumps are marketed as reaction turbines.

Selected Projects

Cox Avenue, Saratoga, CA (2011) – 110 kW – two PATs
Burbank, CA (2002) – 300 kW – two PATs replacing a pressure release valve at a pumping station
Alameda, CA (1993) – 1,250 kW – six PATs in supply line to a water treatment plant

**Planned Projects**

Rialto, CA – 310 kW – two PATs on pipeline entering water treatment plant

University Mound, San Francisco, CA – 240 kW – three PATs in water delivery pipeline

<table>
<thead>
<tr>
<th>Zeropex</th>
<th>Stavanger, Norway</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><a href="http://www.zeropex.com">http://www.zeropex.com</a></td>
</tr>
</tbody>
</table>

The Difgen system includes a turbine, generator, and control system for installation in water delivery systems. The turbine is a positive displacement rotary lobe pump operating in reverse. The Difgen received ANSI/NSF 61 certification for use in drinking water systems.

**Installed Projects**

Denny, Scotland (2013) – 400 kW – Difgen system along water main

Devon, England (2012) – 120 kW – turbine at water treatment plant

Pen y Cefn, Wales (2012) – 17 kW – turbine at water treatment plant

**Planned Projects**

Avenal, CA – 110 kW – Difgen system replacing storage tank in water distribution system

Difgen turbine generator installed in water treatment plant  
[Image: www.zeropex.com](http://www.zeropex.com)  

Interior of turbine  
[Image: www.jnbentley-](http://www.jnbentley-)
## HYDROKINETIC ENERGY RECOVERY OPPORTUNITY

<table>
<thead>
<tr>
<th>Rentricity</th>
<th><img src="http://www.rentricity.com/" alt="Turbine" /></th>
</tr>
</thead>
<tbody>
<tr>
<td>New York, NY</td>
<td></td>
</tr>
</tbody>
</table>

Rentricity provides a water-to-wire package including a turbine (typically a pump-as-turbine), generator, grid connection, control system, and online performance monitoring. Their target market is municipal water utilities with opportunities to regain energy from head losses. As of mid-2013, there has been one pilot project in Connecticut and two commercial installations. Each operates in parallel with a PRV.

### Installed Projects

Aquarion Pilot Project, Stamford, CT (2006) – 40 kW  
Beaver Run Dam, PA (2010) – 30 kW – energy recovery at a mandated release point  
City of Keene, NH (2011) – 55 kW – two PATs installed at water treatment plant

### Planned Projects

Palos Verdes, CA (2013) – 350 kW

[Images: [www.rentricity.com](http://www.rentricity.com)]
The Archimedes screw turbine consists of a large central shaft with one to five blades that spiral down its length. Water enters the screw at the top of the slope and flows downhill, causing the screw to turn. The efficiency of the turbine depends on its slope (typically 20-22°) and the number of blades (Müller & Senior, 2009). Screw turbines are typically large, with diameters ranging between 1 – 5 m and lengths of 7 – 20 m. They can be used in rivers, where their fish-friendliness is an asset, or in artificial waterways such as the outlets of water treatment plants, power plants, or industrial plants (e.g. paper mills). Several manufacturers are currently supplying hydrodynamic screw turbines to low-head hydro sites in Europe, but none have been installed in the US. Six projects using screw turbines proposed by the New England Hydroelectric Company have received preliminary permits from FERC as of June 2013.

**Selected Projects**

Windsor Castle, UK (2012) – 316 kW – two turbines in parallel

Hirschthal, Switzerland (2011) – 110 kW

Stockton-on-Tees, UK (2010) – 520 kW – parallel installation of four reversible pumps/turbines

**Proposed Projects**

Newton, MA – 30 kW

---

**Schematic diagram of a screw turbine**

Two screw turbines installed in parallel
The HydroCoil is an enclosed screw-type turbine designed for portable use. The spacing of the coils becomes closer together as water travels from the inlet to the outlet, increasing the flow speed.

### AXIAL/PROPELLER/KAPLAN TURBINES

Manufacturers include: Alstom, Andritz, Canadian Hydro, Cink, Dependable Turbines, Hitachi Power Systems, Mavel, Mecamidi, NorCan, Voith, Weigert & Bähr

Several types of axial-flow turbines are commonly used at low-head hydro sites. The runner on a propeller turbine resembles a ship’s propeller operated in reverse. Guide vanes are used to direct the incoming flow. Kaplan turbines are a subset of propeller turbines that have adjustable runner blades (single-regulated) and may have adjustable guide vanes (double-regulated) as well. Propeller turbines without adjustable blades or vanes are simpler and less costly to build, but they operate efficiently across a smaller range of flows than Kaplan turbines.
In contrast with radial turbines or impulse turbines, both the incoming and outgoing flow travel along the turbine axis, which is also where the shaft connecting the turbine to the generator must be located. There are several options for positioning the generator for an axial turbine, leading to more names that are used for the various configurations. Bulb (or tubular) turbines encase the generator in a watertight housing behind the turbine. S-type turbines have a longer shaft that allows the generator to be kept dry by bending the water channel away from the generator. Rim generators are incorporated into the turbine by mounting the generator rotor on the perimeter of the turbine runner.

Kaplan turbine runner

Andritz Hydro GmbH
Vienna, Austria
http://www.andritz.com/hydro.htm

The Hydromatrix is a modular array of propeller-type turbines that can be installed at existing locks or dams. Each turbine has a diameter of 1.3 m within a square housing and several turbines can be assembled in a row or grid pattern. The topmost turbine must be located at least 1.5 m below the water surface at the outlet. The Hydromatrix uses a permanent magnet generator enclosed in a watertight bulb along the turbine central axis. The Straflomatrix variant locates the generator in a ring at the outer edge of the runner, which decreases the size and weight of the unit but also results in a lower power output due to friction losses (Schlemmer, Ramsauer, Cui, & Binder, 2007).

Selected Projects

Jebel Aulia, Sudan (2005) – 30.4 MW (80 units) – installed in existing irrigation dam
Chievo, Italy (2009) – 1.35 MW (5 units) – installed in existing lock
Lower St. Anthony Falls, MN (2011) – 10 MW (16 units) – installed in existing lock
### Very Low Head Turbine

<table>
<thead>
<tr>
<th>MJ2 Technologie SAS</th>
<th><img src="https://www.vlh-turbine.com/" alt="Diagram" /></th>
<th><img src="https://www.vlh-turbine.com/" alt="Graph" /></th>
</tr>
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<tbody>
<tr>
<td>Millau, France</td>
<td><a href="http://www.vlh-turbine.com/">http://www.vlh-turbine.com/</a></td>
<td></td>
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</table>

The Very Low Head (VLH) turbine is a Kaplan turbine with a large, slow-moving runner (for fish-friendliness) and a direct-drive variable speed permanent magnet generator. The VLH installs in a modular fashion that requires less space than conventional low head turbines. It is intended for installation in open channels and canals.

![Drawing of VLH turbine and support structure](https://www.vlh-turbine.com/)  
![VLH turbine installation before immersion](https://www.small-hydro.com/)

[images: www.small-hydro.com]
HYDRO-eKIDS

Toshiba International Corporation
Sydney, Australia

This is a compact propeller turbine for small hydro applications. Runner blades and guide vanes can be adjusted for site conditions. Information about existing installations is not readily available, although photographs on the Toshiba website show the turbines installed at an irrigation dam, water treatment plant, sewage treatment plant, and industrial water system. Toshiba International Corporation is the Oceania-based subsidiary of Toshiba.

Hydro-eKIDS turbine and generator

Installation at sewage treatment plant


MICRO-TUBULAR TURBINE

Voith Fuji Hydro
Kawasaki, Japan

The micro-tubular turbine was designed for installation in water supply lines and similar applications. It is an axial (tubular) turbine with a diameter between 29 and 76 cm.

Micro-tubular turbine diagram

Two micro-tubular turbines installed in parallel
Linepower is an axial turbine designed for installation in water supply lines.

The Turbinator is an axial flow design with fixed blades and fixed or adjustable gates. It utilizes a permanent magnet synchronous generator that rotates at the perimeter of the turbine runner. A pilot installation in Norway placed the turbine at the toe of a dam to capture energy from mandated water releases. A second pilot is planned for a canal in Oregon [3].

Installed Projects
Hegset, Norway (2010) – 280 kW – turbine at dam toe

Planned Projects
Culver, OR (2013) – 200 kW – turbine in irrigation canal

Turbinator installation at Hegset dam
[images: www.small-hydro.com]
PELTON TURBINES

Manufacturers include: Alstom, Andritz, Canyon Hydro, Cornell Pump, Cink, Dependable Turbines, Gilkes, Hitachi Power Systems, Mavel, Mecamidi, NorCan, Voith, Wiegert & Bähr

The Pelton wheel was invented in California in the 1870s by Lester Pelton. Water is directed into the turbine through one or more nozzles spaced along the perimeter of the wheel. Buckets on the runner are designed to split the jets of water into two streams, extracting around 90% of the available energy before the water falls away from the turbine. Pelton turbines are highly efficient and maintain their efficiency over wide range of flow rates. They are typically used at high head sites.

Installation of a Pelton runner

[Image: commons.wikimedia.org]

GENERATING PRESSURE REDUCING VALVE

SOAR Technologies, Inc.
Redmond, WA
http://www.soartechinc.com

The generating pressure reducing valve (GPRV) is a modification of the Pelton turbine that is able to operate when the outlet is under pressure (Maloney, 2010). Pelton turbines are advantageous because they are highly efficient over a wide range of flow rates below the design flow, but typically they must discharge into atmospheric pressure, which makes them poorly suited for pressurized water distributions systems. The GPRV consists of a standard Pelton wheel enclosed in a sealed housing in order to maintain a positive pressure at the turbine outlet. An Energy Innovations Small Grant from the Public Interest Energy Research (PIER) program in 2003 provided funding to test a prototype GPRV, leading to some modifications in the
design. The SOAR Technologies and Canyon Hydro manufactured and installed the new design at a site in Hawaii in 2008.

SOAR also manufactures an in-line Francis turbine and a multi-stage vertical turbine using Francis runners. These turbines are designed for in-conduit energy recovery applications.

**Patents**


**Installed Projects**

Waikaloa, HI (2008) – 40 kW

Bennington, VT (2010) – 15 kW

![GPRV installed in Hawaii](image: www.soartechinc.com)

![In-line Francis turbine installation](image: www.soartechinc.com)

![Multi-stage vertical turbine installation](image: www.soartechinc.com)

**Turgo Turbines**

<table>
<thead>
<tr>
<th>Gilkes</th>
<th>Kendal, UK</th>
<th><a href="http://www.gilkes.com">http://www.gilkes.com</a></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependable Turbines Ltd.</td>
<td>Surrey, BC</td>
<td><a href="http://www.dtlhydro.com">http://www.dtlhydro.com</a></td>
</tr>
</tbody>
</table>

Turgo turbines are similar to Pelton wheels, but the inlet nozzles are aimed at an angle (of approximately 20°) to the runner plane (Paish, 2002). In contrast, the nozzles in a Pelton turbine are in the same plane as the runner. The Turgo design allows water to exit the runner on the opposite side from the jets, avoiding interference between the discharge and the entering flow. This allows Turgo turbines to have smaller diameters than comparable Pelton turbines.
PowerPall turbines are small Turgo turbines intended for isolated rural areas without grid connections. They are designed to be portable and easy to install. Generation capacity for PowerPal turbines ranges from 1.5 to 20 kW.

In crossflow (also called Banki) turbines, water passes through the blades twice, first encountering a blade that directs the flow into the center of the runner, then hitting a second blade while exiting the runner. The direction of rotation imparted to the runner is the same in both cases. Crossflow turbines are used at medium-head, medium-flow sites.
The Ossberger turbine is a crossflow design for low-head sites.

**Installed Projects**


Blaenavon, Wales (2011) – 20 kW
Hydrovolts has developed two types of turbines for constructed waterways: canal and waterfall. The canal turbine has buoyant end caps that allow it to float, or it can be mounted on the canal bed. Two or more coaxial runners are suspended between the end caps. Initial installations have utilized pairs of Savonius runners (S-shaped profile), but other runner designs are proposed for sites with higher or lower average water velocities. The waterfall design is intended to connect to existing infrastructure at canal drops or at water treatment plants. It has a vertical flume leading to a Banki (crossflow) runner at the base. Both designs utilize permanent magnet generators that are enclosed in sealed housing attached to the turbines.

Installed Projects: Canal
Yakima, WA (2012) – 8 kW
Butte Water District, Gridley, CA (2012) – 12 kW

Installed Projects: Waterfall
Port Orchard, WA (2012) – 1.4 kW
Diablo Delta Sanitation District, CA (2013) – 12 kWHydroEngine
The hydroEngine is an impulse (crossflow) turbine designed for low head sites such as weirs and irrigation canals. The turbine has two parallel shafts, one at either pole of the drive belt. Water flows through the turbine in two stages, each consisting of a row of guide vanes followed by the rotating blades. A demonstration turbine was installed in an irrigation canal in Buckeye, Arizona in 2010 (Winner, 2013).

Installed Projects
Buckeye, AZ (2010) – 9.6 kW

Planned Projects
Madras, OR (2013) – 300 kW
Freedom, ME (2014) – 50 kW

HydroEngine diagram

[Image: www.natelenergy.com]
Waterwheels were historically used to produce mechanical energy from falling water. Modern installations use the wheel’s rotation to produce electricity. There are three basic types of waterwheels based on the height at which the water enters the wheel: overshot (inlet above the wheel), breastshot (inlet level with the axis), and undershot (inlet at the bottom of the wheel). HydroWatt manufactures overshot and breastshot water wheels for use at low-head sites.

Installed Projects

Several installations in Germany and elsewhere in Europe, ranging from 4.5 – 26 kW.

<table>
<thead>
<tr>
<th>PONCELET WHEEL</th>
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<tr>
<td><strong>Poncelet Kinetics</strong></td>
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</table>

An undershot waterwheel with curved blades mounted on a pontoon barge with mooring lines to shore. The wheel is 16 feet (5 m) in diameter and the float weights 10,000 lbs (Whitestone Power and Communications, 2010).

Rendering of proposed Poncelet wheel installation

[Image: www.akenergyauthority.org]
The LucidPipe is a spherical Darrieus-style vertical axis turbine for installation in water delivery pipelines. The turbine exterior diameters range from 0.6 to 2.4 m, but turbines may be installed in a pipeline of larger diameter (with contraction / diffusion) in order to boost water velocity at the turbine. The pressure drop across the turbine is approximately 1 m when the turbine is stopped, rising to 4 m at rated power. Multiple turbines can be installed in series to obtain a desired pressure drop. The recommended flow velocity range is 1.7 - 2.1 m/s, which corresponds to 1.0 - 5.6 m$^3$/s for the available pipe diameters. The LucidPipe is certified for use in drinking water supplies under ANSI/NSF 61.

**Patents**


**Installed Projects**

Riverside, CA (2012) – 20 kW

**Planned Projects**

Portland, OR (2013) – 200 kW
San Antonio, TX (2013) – 60 kW

Schematic diagram of LucidPipe turbines installed in series

[Image: www.lucidenergy.com]  
[Image: www.hydroworld.com]
## EnCurrent

**New Energy Corporation**  
Calgary, Alberta  
[http://www.newenergycorp.ca/](http://www.newenergycorp.ca/)

The EnCurrent is a vertical axis hydrokinetic turbine using a Darrieus-style rotor. A demonstration 5 kW turbine was tested in Ruby, Alaska in the summer of 2008 under the authority of the Yukon River Inter-Tribal Watershed Council. The 5 kW and 25 kW models were tested at Pointe du Bois at the University of Manitoba.

![EnCurrent Turbine Prior to Installation](http://www.newenergycorp.ca/)

## Modular Bulb Turbine

**Hydro Green Energy**  
Westmont, IL  
[http://hgenergy.com/](http://hgenergy.com/)

Hydro Green Energy’s hydrokinetic turbine may be installed in a dam tailrace or in a free-flowing river. The turbine is an axial (bulb) ducted design with a low rotational speed for minimal impact on fish.

**Pilot Project:**  
Hastings, MN (2009-2010) – 35 kW

**Planned Projects:**  
Braddock Locks & Dam, PA – 3.75 MW
Pilot project installation in Minnesota

[Image: hgenergy.com]

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**SMARTURBINE**

<table>
<thead>
<tr>
<th>Free Flow Power</th>
<th><img src="http://www.free-flow-power.com" alt="Image of SmarTurbine" /></th>
</tr>
</thead>
<tbody>
<tr>
<td>Boston, MA</td>
<td></td>
</tr>
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</table>

An axial, run-of-river hydrokinetic turbine designed to be installed in a matrix of similar turbines. The diameter of a single turbine is 1-3 meters, with matrices comprising 3 x 3 grids and installed at 50 m intervals in the river. The spacing between runner blades is intended to allow safe fish passage.

Pilot Project:
Dow Demonstration Site, Plaquemines, LA (2011) – 40 kW

Building a prototype SmarTurbine

[Image: www.akenergyauthority.org]

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**SMART KINETIC HYDRO SYSTEM**

<table>
<thead>
<tr>
<th>Smart Kinetic Hydropower System</th>
<th><img src="http://www.smart-hydro.de/" alt="Image of Smart Kinetic Hydro System" /></th>
</tr>
</thead>
<tbody>
<tr>
<td>Feldafing (Munich), Germany</td>
<td></td>
</tr>
<tr>
<td><a href="http://www.smart-hydro.de/">http://www.smart-hydro.de/</a></td>
<td></td>
</tr>
</tbody>
</table>
The Smart kinetic hydropower system is a floating hydrokinetic turbine for run-of-river systems. It consists of two floats (similar to a catamaran) above an expanding cylindrical shroud that recovers pressure and minimizes turbulence behind the rotor. Anchors are used to hold the system in place. The turbine is a three-bladed horizontal axis rotor with a permanent magnet generator. The system does not require a vertical drop, but it does require flow velocities between 1.5 to 3.5 m/s. It produces a maximum of 5 kW at 2.75 m/s.

Installed Projects:
Marisol, Peru – 5 kW

Prototype installation in Peru
[image: www.flussstrom.de]
The RivGen is one of three formats for installing ORPC’s turbine generator unit, which can also be installed in tidal and ocean current formats. The unit comprises a pair of helical Darrieus-style turbines with a shared generator in the center. The RivGen platform uses a pontoon structure with an upstream anchor to support the turbines. The pontoons are filled with air to float the turbines for installation and removal. Filling the pontoons with water causes the structure to sink and provides ballast to hold the unit in place.

Rendering of the RivGen system

[image: www.orpc.co]
CHAPTER 3 — Simulation Tools for Quantitative Evaluation of In–Conduit Small Hydropower Technologies

Almost two-thirds of the water agencies that responded to the survey conducted for this study indicated they use software to perform simulation of their systems (Figure 5). The type of software depends strongly on the specifics of the system of interest and what motivates the simulation effort: e.g. distribution optimization or major leak mitigation support. This chapter also provides introductory background regarding EPANET a public-domain code developed by the EPA for the simulation of water distribution systems. The R&D simulation needs associated with the particularity of in-conduit application, namely cavitation models, are also discussed.

![Figure 5: Software use to conduct simulation distribution systems by agencies that responded to survey.](image)

3.1 Overview of Current Tools Used

The table below provides names and descriptions of some of the software packages used by the water districts that responded to our survey as well as the citation frequency (some respondent cited more than one tool). Detailed descriptions of these packages are available on the websites provided listed in the Reference section. Most of these are commercial packages (four are products from the same company), with the notable exception of EPANET, a public domain software package developed by the Environmental Protection Agency (EPA). The associated toolkit is open-source and found at the core of various commercial software packages. A few more details are provided about EPANET in the next section.
### Table 4: Software packages used for water distribution system simulation

<table>
<thead>
<tr>
<th>Software Tool</th>
<th>Users (%)</th>
<th>Tool Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AutoCAD</td>
<td>22</td>
<td>Some water agencies report using AutoCAD to draft, design, and simulate their water distribution network systems. AutoCAD is a 2-D and 3-D computer-aided design (CAD) program (&quot;AutoCAD Overview&quot;, 2014). It is likely that the simulations are performed using other software packages provided by the same company (Autodesk) or modules provided by other vendors.</td>
</tr>
<tr>
<td>EPANET</td>
<td>26</td>
<td>EPANET is used for mimicking hydraulic simulation and water quality behavior over a period of time within pressurized pipe networks. It includes components such as reservoirs, pipes, tanks, and valves for simulation of water distribution networks (Rossman, 2000).</td>
</tr>
<tr>
<td>InfoWater®</td>
<td>30</td>
<td>Integrated with ArcGIS (geographic information system), InfoWater (by Innovyze) enables water districts to simultaneously perform hydraulic modeling with geospatial analysis of their water distribution networks (&quot;InfoWater Modeling Made Easy: Overview,&quot; 2014).</td>
</tr>
<tr>
<td>H2ONET®</td>
<td>15</td>
<td>H2ONET (by Innovyze) integrates with AutoCAD and is used to design, analyze, and model water distribution networks. In addition to the hydraulic analysis, it can be used to model water quality, and perform flow and energy cost analyses (&quot;H2ONET Modeling Made Easy: Overview,&quot; 2014).</td>
</tr>
<tr>
<td>H2OMap Water®</td>
<td>15</td>
<td>H2OMAP Water (by Innovyze) is a standalone package otherwise similar to InfoWater that allows the modeling of water distribution networks. It combines both spatial analysis tools and mapping functions (&quot;H2OMAP Water Modeling Made Easy: Overview,&quot; 2014).</td>
</tr>
<tr>
<td>InfoWorks®</td>
<td>4</td>
<td>InfoWorks WS (by Innovyze) is a “water distribution modeling and management” tool. In addition, it can be used to model water quality and sediment transport throughout a water distribution network (&quot;InfoWorks CS: Overview,&quot; 2014).</td>
</tr>
<tr>
<td>Synergi® Water</td>
<td>4</td>
<td>Synergi Water allows the simulation of pipe networks including elements such as pumps, valves, etc. (&quot;Synergi Water: Advanced Water Distribution Analysis,&quot; 2013).</td>
</tr>
</tbody>
</table>

The use of Supervisory Control and Data Acquisition (SCADA) systems is also reported. This is a real-time process operation, monitoring, and control strategy that can help detect and mitigate incidents such as leaks on pipelines (Galloway and Hancke, 2013).

#### 3.2 Technical Simulation Needs for In-Conduit Small Hydro Applications

In order to inform the development of in-conduit small hydro the capabilities of the simulation tools must be expanded. This section addresses two such needs, one at the system level, and the other at the component level: the ability to account for the addition of a turbine to the water distribution model (system level) and cavitation models (component level). Because the tools currently in use focus on distribution, they typically do not include former. Cavitation is a well-known issue and one that is incorporated in system design when considering pumps for...
example. Nevertheless, the proper inclusion of cavitation in the Computational Fluid Dynamics (CFD) codes used to develop new turbine designs for instance is still an active area of research.

3.2.1 System level simulation
EPANet is a public domain code developed by the US Environmental Protection Agency (EPA) for the simulation of water distribution system both in terms of hydraulics and water quality. It is available for download on the EPA website (EPA, 2014), together with the associated documentation (e.g. user manual). The EPANet toolkit (open source) also serves as the base for some commercially available packages. While only a Windows version is served by the EPA’s site, versions for other operating systems (e.g. OSX, Linux) are also available online. As is commonly the case with open source software, discussion groups exist and provide additional resources for users (e.g. Google group “EPANet and Development”). Resources are also available to help new users through the steps of setting up their first simulation (Clark and Pitt, 2014). Hence, EPANet is used here as an illustration to the basic functionality of water distribution simulation software.

Such software is used to investigate various scenarios associated with the operation of water distribution systems. Thus, when preparing a simulation, all necessary data must be gathered that describe the system: network configuration, pipe diameters, lengths, materials, pump performance curves, base demand for reservoirs, etc. The simulation yields outputs such as demand, head, pressure, water quality at the network nodes (if appropriate). Because the primary goal is water distribution, these software packages do not readily permit the consideration of an in-conduit turbine for power generation. In the case of EPANet, a “General Purpose Valve” can be defined, based on the desired turbine performance curve, to serve as a surrogate (Rossman, 2000). The power that can be extracted is then easily obtained from the difference between the head values calculated at the nodes that surround the turbine. Since EPANet toolkit is open-source, it would also be possible to add this functionality to the program.

3.2.2 Cavitation
The issue of cavitation and its implications in terms of the simulation needs for the development of in-conduit small-hydro turbine is discussed in details in Appendix. An abridged version of that discussion is provided here. The seminal work of Brennen (Brennen, 1969, 2013) is referenced extensively with other sources noted as appropriate.

The phenomenon of cavitation is a feature that distinguishes underwater turbines from those that operate in air, gas, or steam. Cavitation is the nucleation and growth of bubbles in a liquid as a result of a drop in pressure, below the vapor pressure caused by locally high velocity. Bubbles formed due to cavitation collapse implosively when they move into a higher-pressure region. When cavitation occurs in a turbine, it typically degrades the performance of the system and may cause material damage as well. Cavitation causes acoustic noise that may be undesirable but is also used to identify when cavitation is occurring. Cavitation can be used to advantage for some applications, such as reducing drag in high-speed propellers, cleaning teeth or homogenizing milk.
Cavitation Nucleation

The onset of cavitation is called cavitation nucleation. A cavitation nucleus is a microscopic void in a liquid, which may come from a variety of sources. Homogeneous nucleation is the formation of voids in a liquid due to thermal motion. Heterogeneous nucleation occurs at a liquid-solid boundary, which may be a boundary between the liquid and a solid wall, or between the liquid and a solid particle suspended within it. Heterogeneous nucleation is the most common type of nucleation seen in engineering applications.

Descriptions of heterogeneous nucleation at a solid surface rely on the contact angle, \( \theta \), measured in the liquid between the surface and the liquid-vapor boundary. Hydrophobic surfaces tend to reduce the effective tensile strength of a liquid, promoting heterogeneous nucleation.

Steady Flow Cavitation

In steady flow, the pressure coefficient:

\[
C_p(x) = \frac{p(x) - p_\infty}{\frac{1}{2} \rho U_\infty^2}
\]

is an important parameter for determining the likelihood of cavitation onset. The minimum value of the pressure coefficient, \( C_{p_{min}} \), generally has a negative value. \( C_p(x) \) depends on the geometry of the system and on the Reynolds number of the fluid. For inviscid flow, \( C_p(x) \) is only a function of the geometry. In a turbine, \( C_{p_{min}} \) is a function of the normalized flow rate, \( Q/(nD^3) \). The pressure coefficient is closely related to the cavitation number, \( \sigma \), which is defined by:

\[
\sigma = \frac{p_\infty - p_v(T_\infty)}{\frac{1}{2} \rho U_\infty^2}
\]

where \( p_v(T_\infty) \) is the vapor pressure of the liquid at reference temperature \( T_\infty \). Cavitation occurs when \( \sigma \leq \sigma_c \), where \( \sigma_c \) is the critical cavitation number.

The steady viscous effect is the name given to the influence of the Reynolds number on \( C_{p_{min}} \), which results in \( \sigma_c = f(Re) \). The presence of a contaminant gas (as microbubbles) or free stream nuclei (suspended solid particles or vapor bubbles due to upstream cavitation or recirculation) causes \( \sigma_c \) to increase. Turbulence, wall roughness and porosity all tend to increase \( \sigma_c \) as well.

Testing of prototype turbines often provides results that must be scaled up for a full-scale turbine. Scaling of the critical cavitation number is difficult because of the diverse factors that influence \( \sigma_c \). The size distribution of free stream nuclei is a difficult parameter to adjust, for example, while scaling of other parameters may conflict: maintaining a constant residence time near \( C_{p_{min}} \) requires a decrease in velocity, while maintaining an equivalent Reynolds number requires increased velocity. Cavitation that is firmly established, with \( \sigma \) well below \( \sigma_c \), can be expected to occur in full-scale as well as small-scale models. The International Electro-technical Commission (IEC:60193, 1999) has set standards for testing model turbines and the scaling of performance and cavitation data.
**Cavitation Types**

Cavitation occurs in a variety of forms that differ in appearance, sound level, and degree of performance degradation or material damage. The simplest is traveling bubble cavitation, which assumes spherical, non-interacting bubbles. Cloud cavitation is the periodic formation and collapse of clouds of bubbles. It is driven by periodic motion including vortex shedding and rotor blade rotation. Interactions between bubbles and solid walls is another cause of deviation from spherical bubble dynamics. The presence of a wall near one side of a bubble disrupts the symmetry that would otherwise cause it to take a spherical shape as it develops. Experimental observation of cavitation bubbles near surfaces confirm that the bubbles are typically hemispheric or cap-shaped. Attached cavitation is called by various names, including sheet cavitation, blade cavitation, and fully-developed cavitation. Unlike traveling bubble or cloud cavitation, attached cavitation is not composed of many small bubbles; instead, an entire wake or separated region is filled with vapor due to low pressure. Supercavitation occurs when a cavity begins on a hydrofoil and closes well downstream. High-speed propellers are designed to operate in supercavitation to reduce drag. Vortex cavitation occurs in the vortices that form behind propeller tips, pump impellers, and in turbine draft tubes. Vortex cores have lower pressure than the surrounding flow and often provide a site for cavitation.

Cavitation in a turbine, pump, water tunnel or other confined space can cause the flow to be choked. Analogous to flow through a nozzle, flow that is choked due to cavitation has a maximum velocity that is set by the tunnel width and tunnel pressure. For a given geometry, there is a critical cavitation number for which the cavity length becomes infinite, and the cavitation number cannot decrease below this value. The critical cavitation number can be used as an estimate for the breakdown cavitation number of a pump or turbine.

**Effects of cavitation**

Acoustic noise and material damage are the two most important effects of cavitation relevant to hydroturbines. Both are associated with the collapse of cavitation bubbles. When a bubble collapses, it causes a localized large-amplitude shockwave that is perceived outside the turbine as sound. The crackling sound of many bubbles collapsing can be used to detect cavitation in turbomachinery, as it is often the first indication that cavitation is occurring. When a collapse occurs close to a solid surface, the localized high pressure causes transient surface stresses that lead to fatigue damage if the surface is exposed to cavitation over a long period of time.

A second mechanism that can also produce surface damage is called a microjet or reentrant jet. Microjets occur during bubble collapse and are caused by a lack of spherical symmetry in the volume surrounding a bubble. When a bubble collapses near a solid boundary, a jet of liquid forms on the side of the bubble opposite the boundary, piercing the bubble and exiting through the other side, toward the solid boundary. In soft surfaces, individual microjets have been observed to cause pits and they are believed to contribute to surface fatigue damage in harder materials as well.

Surfaces exposed to cavitation shed flakes of material as the surface is repeatedly exposed to transient stresses. The coherent collapse of a cloud of bubbles is much more damaging than the collapse of individual bubbles, and is common in turbomachines due to the periodic motion of
blades and vortices inside and downstream of the machine. Turbine draft tubes can develop deep grooves at the location of cavitating tip vortices. (See figure below, from Arndt, 1981. Note man standing in groove towards the back.)

**Modeling and numerical simulation of cavitation**

Attached or fully-developed cavitation is the focus of much of the cavitation modeling relevant to hydroturbines. Models describe the extent and shape of an attached cavity in order to determine pressure distributions and hydrodynamic forces acting on turbomachines and the surrounding flow.

Computational models of cavitation can be divided into two broad categories: interface tracking models and multiphase models. Interface tracking models typically only model the liquid phase of the flow (even though this is not an inherent limitation) and determine the cavity shape through an iterative process. Multiphase models include both the liquid and vapor phases, which allows for modeling of more complex flows but also increases the computational intensity. While interface tracking and multiphase models are the most widely studied for turbomachinery applications, there are also other approaches. Models based on microbubble dynamics describe clusters of bubbles in the absence of attached cavitation. One recent example of a microbubble model with a survey of earlier works can be found in (Fuster & Colonius, 2011).

Interface tracking models of cavitation do not model the interior of the cavity; instead, they assume that the interface between the vapor and liquid phases is a surface of constant pressure equal to the vapor pressure of the fluid. The location of the interface is determined through successive iterations of modeling the dynamics of the liquid phase. Interface tracking models require a closure model to deal with the two-phase, turbulent wake at the end of the cavity, such as the Riabouchinsky closure model (C. Brennen, 1969) or a pressure recovery model (Lemonnier & Rowe, 1988). They are also restricted to attached cavities and cannot model more complex phenomena such as the release of clouds of bubbles associated with unsteady cavitation. In spite of these drawbacks, interface tracking models continue to be used for their efficiency and good first-order agreement with experimental results for supercavitating flows.

Multiphase models do not identify the location of the interface directly; it must be inferred from the properties of each individual cell. In systems where the cavity boundary is varying with time, a fine grid is required over a large domain in order to resolve the interface location accurately. These models are computationally expensive more difficult to implement than a mixture model and consequently there are few applications of multi-fluid models in the literature. (One exception is found in (Grogger & Alajbegovic, 1998).)

**Choosing a numerical model for cavitation**

The choice of cavitation model depends on the complexity of the system that is being modeled and the amount of computational time and resources that can be devoted to the problem. Interface tracking models are computationally efficient and can provide good models of systems with attached cavitation. The simplest codes use boundary element methods that can only model planar or axisymmetric bodies, but codes based on the Euler or Navier-Stokes equations can be used for more complex geometries. Interface tracking models cannot model a
system that is changing over time. If unsteady cavitation, meandering vortices or dynamic operation is being modeled, a multiphase model is more appropriate. Full multfluid models have so far been judged too difficult to apply to the complex geometry of a turbine, but mixture models have been applied to some cases. These require a full CFD code and a relatively fine mesh to capture the details of the cavitation interface. A comparison of three of the models implemented in commercial CFD codes (Morgut, Nobile, & Biluš, 2011) found that all could provide comparable accuracy when empirical coefficients are properly tuned.
CHAPTER 4 — Evaluation Criteria for In-Conduit Small Hydro

Installing a turbine in a potable water distribution network is not a simple task. Standards that protect potable water have to be met before any technology can be installed in the water supply system. Some of the standards that need to be considered and followed are summarized in this chapter. These standards are set up to protect human health and avoid harmful effects on the environment.

Consistent with the focus of this study, classical performance metrics and standards used for the assessment and deployment of small hydro plants are only mentioned in this Chapter. Rather, the emphasis is on the additional metrics and standards associated with the particularities of in-conduit configurations.

4.1 Performance Metrics

Performance parameters for turbines are classically derived from dimensional analysis for turbomachines as described in various textbooks (see, for instance, White, 2011). The relevant, non-dimensional parameters are also used in model/prototype characterizations. The relevant quantities include the flow rate \( Q \), the available head \( H \), the acceleration of gravity, \( g \), the fluid (water) properties (density \( \rho \) and viscosity \( \mu \)), and the turbine characteristics (material surface roughness, \( \varepsilon \); impeller diameter, \( D \), and speed, \( n \); and output brake horsepower, \( \text{bhp} \)).

In the context of performance assessment, the brake horsepower is chosen as an independent variable (desired quantity) and head and flow are treated as dependent variables:

\[
g H = f_1(\text{bhp}, D, n, \rho, \mu, \varepsilon) \quad \text{and} \quad Q = f_1(\text{bhp}, D, n, \rho, \mu, \varepsilon)
\]

The Buckingham Pi theorem (White, 2011) indicates that these can be re-written in non-dimensional forms involving fewer, dimensionless parameters:

\[
\frac{g H}{n^2 D^2} = g_1 \left( \frac{\text{bhp}}{\rho n^4 D^5}, \frac{\rho n D^2}{\mu}, \frac{\varepsilon}{D} \right) \quad \text{and} \quad \frac{Q}{n D} = g_2 \left( \frac{\text{bhp}}{\rho n^4 D^5}, \frac{\rho n D^2}{\mu}, \frac{\varepsilon}{D} \right)
\]

The last two independent parameters in both expressions are the Reynolds number, \( \text{Re} \), and the relative roughness. In the fully turbulent regime, \( \text{Re} \) effects are expected to be minimal. White (2011) also argues that relative roughness has a “constant effect”. Hence the non-dimensional expression can be approximated as:

\[
\frac{g H}{n^2 D^2} \approx g_1 \left( \frac{\text{bhp}}{\rho n^4 D^5} \right) \quad \text{and} \quad \frac{Q}{n D} \approx g_2 \left( \frac{\text{bhp}}{\rho n^4 D^5} \right)
\]

These expressions are commonly written as:

\[
C_H \approx g_1(C_\varepsilon) \quad \text{and} \quad C_Q \approx g_2(C_\varepsilon)
\]
where \( C_H = gH / n^2D^2 \) is the head coefficient, \( C_Q = Q / nD^3 \) is the capacity coefficient, and \( C_P = \text{bhp} / n^4D^3 \) is the power coefficient. The turbine efficient, defined as the ratio of the output break horsepower to the available hydraulic horsepower:

\[
\eta = \frac{\text{bhp}}{\rho g Q H}
\]

can be re-written in terms of \( C_H, C_Q \), and \( C_P \):

\[
\eta = \frac{C_P}{C_Q C_H}
\]

Finally, a size independent parameter, the power specific speed, \( n_s \), is often used to relate the output power to the available head (White, 2011):

\[
n_s = \frac{n_s \text{bhp}}{H^{1.6}}
\]

Note that this expression is not dimensionally homogenous: the impeller speed is in rpm, the bhp in horsepower, and the head in ft.

![Figure 6: Example of Francis Turbine Performance map. From Krueger and Bates (1966).](image)

The monograph by Krueger and Bates (1966) provides a good overview of hydraulic turbine performance characterization. Seltzer and Walters’ monograph on the performance of pump as turbines is relevant as well (Seltzer and Walters, 1977). Manufacturers provide a variety of data
to quantify turbine performance characteristics such as efficiency versus capacity and power (See Figure 6).

An independent facility that can test new, small hydro turbines specifically for in-conduit application would provide a valuable service to potential users. A large number of research centers that focus on water research exist in California. For example, the Water Resources Collections and Archives of UC Riverside and CSU San Bernardino libraries provide a list of the UC and CSU water centers (Haren, 2013). Such resources could be leveraged to develop an in-conduit small hydro testing center. In addition, the possibility of using these water centers to conduct certification tests pertaining to the utilization of new turbines in potable water network systems should be explored.

Table 5: Standards for new hydroelectric equipment in water distribution systems

<table>
<thead>
<tr>
<th>Standard</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Water Works Association (AWWA)</td>
<td>The AWWA is a nonprofit association that manages and treats water, and works to find solutions that protect the environment and improve the health of the public. To protect human health, AWWA has set up standards of minimum requirements for materials, equipment, and practices used in water treatment and supply (AWWA).</td>
</tr>
<tr>
<td>ASME PTC 18 (Rev. 2011)</td>
<td>ASME PTC 18 is a set standard for manufacturers of hydraulic turbines or pump-turbines of all sizes and types. The standard outlines testing procedures, methods of calculation, methods of measurement, etc. requirements that need to followed by manufactures (“Hydraulic Turbines and Pump-Turbines PTC 18-2011,” 2011).</td>
</tr>
<tr>
<td>EPA Safe Drinking Water Act (SDWA)</td>
<td>The SDWA is set up under EPA that sets standards to protect potable water and its sources such as rivers, lakes, reservoirs, springs, ground water wells (EPA). NOTE: SDWA does not regulate private wells that serve fewer than 25 individuals.</td>
</tr>
<tr>
<td>CA Department of Public Health (CDPH)</td>
<td>The California Department of Public Health enforces the Drinking Water Program, which regulates the public water systems. CDPH is set up to ensure the well being of people in California (CADPH).</td>
</tr>
<tr>
<td>NSF 60/NSF 61</td>
<td>If any agency that sells, manufactures, or distributes water must comply with the NSF/ANSI Standards 60 and 61 that set the minimum requirements for chemicals, products, and materials used in treating drinking water supply (NSF:60; NSF:61).</td>
</tr>
<tr>
<td>International Electrotechnical Commission (IEC)</td>
<td>IEC is the organization where industries, companies, and governments meet to discuss and develop standards for all electrotechnology (IEC).</td>
</tr>
<tr>
<td>Energy Recovery Devices (ERDs)</td>
<td>ERDs are used to recover the energy lost during desalination and other industrial processes (“Energy Recovery Inc Enhances Desalination Industry’s Most Efficient, Reliable Energy Recovery Devices,” 2011).</td>
</tr>
</tbody>
</table>

4.2 Standards

In addition to the applicable standards expected for the deployment of small hydro installations performance and implementation, in-conduit implementation in water distribution networks requires the consideration of water quality and public health and safety standards before a
turbine is introduced in the system. Certification following these standards as well as applicable local, regional, state, and federal laws, ordinances, regulations is needed. It is not within the scope of this study to analyze the certification and permitting requirements for in-conduit small hydro installation, but Table 5 above lists the main relevant standards.

Below is a list of publications relevant to the installation of a turbine in a potable water distribution network. The short descriptions of the content of these publications as listed on the websites of the various entities responsible for their development are reported here as well. In most cases, access to the full publication must be purchased. The list below is organized in four categories: performance standards, turbine implementation standards, water quality standards, and turbine testing standards.

**Performance-Related Standards**

IEC 61116 - Electromechanical equipment guide for small hydroelectric installations

For any hydroelectric installation with a power output of less than 5 megawatts and any turbine with a nominal diameter of 3 meters, the IEC 61116 standard must be utilized for guidance (IEC:61116, 1992).

ASME PTC 18 (2011) - Hydraulic Turbines and Pump-Turbines

ASME PTC 18 is a set standard for manufacturers of hydraulic turbines or pump-turbines of all sizes and types. The standard outlines testing procedures, methods of calculation, methods of measurement, etc. requirements that need to be followed by manufacturers ("Hydraulic Turbines and Pump-Turbines PTC 18-2011," 2011).

IEC 62097 - Hydraulic machines, radial and axial - Performance conversion method from model to prototype

When using model test results to create a prototype hydraulic machine, IEC 62097 must be used to assess the efficiency and performance of the machine, with consideration of scale effect including the effect of surface roughness (IEC:62097, 2009).

IEC 60609 - Cavitation pitting evaluation in hydraulic turbines, storage pumps and pump-turbines

IEC 60609 standard is used to measure and evaluate the amount of cavitation pitting on certain specified machine components for reaction hydraulic turbines, storage pumps and pump-turbines for given conditions that include specific hydraulic energy, speed, material, etc (IEC:60609-1, 2004).

IEC 62256 - Hydraulic turbines, storage pumps and pump-turbines - Rehabilitation and performance improvement

IEC 62256 is used to as a guide in rehabilitation and performance improvement of turbines, storage pumps and pump-turbines of all sizes but only of the following type: Francis, Kaplan, Propeller, Pelton (turbines only), and Bulb (IEC:62256, 2008).

IEC 60545 - Guide for commissioning, operation and maintenance of hydraulic turbines

IEC 60545 is used as a guide to commission, operate and maintain hydraulic turbines and associated equipment (IEC:60545, 1976).
**Implementation-Related Standards**

AWWA E102-06 - Submersible Vertical Turbine Pumps

For any pump manufactured and specified for use in the potable water with a driver horsepower of 5 hp (3.8 kW) or larger, this standard provides minimum requirements for submersible vertical turbine pumps utilizing a discharge column pipe assembly. In addition, this standard discusses only one type of prime movers: electric motors (Association & Institute, 2008a).

AWWA E103-07 - Horizontal and Vertical Line-Shaft Pumps

This standard is used in guidance for installations in wells, water treatment plants, water transmission systems, and water distribution systems of following pump types: horizontal centrifugal pumps and vertical line-shaft pumps (Association & Institute, 2008b).

**Water Quality-Related Standards**

ISO 8068 - Lubricants, industrial oils and related products (class L) - Family T (Turbines) - Specification for lubricating oils for turbines

ISO 8068:2006 is used for guidance to meet the minimum requirements set for lubricants for power generating turbines, which include steam turbines, gas turbines, combined-cycle turbines with a common lubrication system and hydraulic (water driven) turbines (ISO, 2006).

NSF/ANSI 61 - Drinking Water System Components - Health Effects

NSF/ANSI 61 is used by any agency that sells, manufactures, or distributes water to meet the minimum requirements set for drinking water system components that include indirect additives, products and materials. It also discusses the potential for leaching from plumbing system components (Backman).

NSF/ANSI 60 - Drinking Water Treatment Chemicals - Health Effects

NSF/ANSI 60 is used by any agency that sells, manufactures, or distributes water to meet the minimum requirements set for any direct additives such as any chemicals used to treat the drinking water supply (Backman).

**Testing-Related Standards**

IEC 62006 - Hydraulic machines - Acceptance tests of small hydroelectric installations

IEC 62006 outlines the test, the measuring methods and the contractual guarantee conditions for field acceptance tests for small power generating hydroelectric installations that include impulse or reaction turbines with unit power up to about 15 megawatts and reference diameter of about 3 meters (IEC:62006, 2010).

IEC 60041 - Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines

This standard outlines field acceptance tests, which are used to determine the hydraulic performance of any size and type of impulse or reaction turbine, storage pump or pump turbine (IEC:60041, 1991).
IEC 60193 - Hydraulic turbines, storage pumps and pump-turbines - Model acceptance tests

IEC 60193 is used as a guide for laboratory models of any type of impulse or reaction hydraulic turbine, storage pump or pump-turbine (IEC:60193, 1999).

IEC 60308 - Hydraulic turbines - Testing of control systems

IEC 60308 provides the definition and the characteristics of control systems. In addition, it includes other tasks that may be assigned to a control system, such as sequence control tasks, safety and provision for the actuating energy (IEC:60308, 2005).
CHAPTER 5 — In-Conduit Small Hydro Deployment in California: Status and Challenges

The deployment status of in-conduit small hydro in California was assessed using both publicly available records and the survey of water agencies described in Section 1.4.3.

5.1 Small Hydropower Installations in California

Small Hydro sites were primarily identified using the Federal Energy Regulatory Commission’s (FERC) eLibrary which contains a list of all small hydropower projects along with information such as issue date of the project license, authorized capacity (in kW), name of water district applying for the license, waterway location, and whether the project received conduit or non-conduit exemption. From the projects with exemptions for small hydro from the FERC database, we mapped projects that generated power under 2 MW and projects that received conduit exemptions (built waterways rather than natural). A few additional sites were identified by researching information pertaining to newer projects available on-line typically from the companies building the projects. Other sources are listed in Section 1.4.2. The sites identified are mapped below (Figure 7).

![Figure 7 Map of Small Hydro in California](image)

There is a notable and expected higher concentration in areas with higher population densities (San Diego, LA basin, San Francisco Bay area). Figure 2 shows the fraction of water districts that
responded to the survey that have currently installed or projected in the near future small hydro turbines in their water supply network.

**Figure 8: Are there small hydro turbines currently installed or projected on your system?**

Despite the relatively wide confidence interval of the survey (discussed in Section 1.4.3) the penetration of in-conduit small hydro as reported (~25%) is commensurate with the data obtained statewide form the public sources listed above. Clearly there is significant potential for more growth. It is therefore important to clarify the reasons that motivate deployment and the elements that enter the decision making process.

**Figure 9: Factors that prompt a district to install a small hydroturbine on its network.**

Figure 9 shows a few of the factors that may prompt a water district to consider installing a turbine on their water supply network, as reported by the survey respondents (multiple answers were possible). Financial incentives are evidently the top motivator as they shorten the return on investment. The responses also show that the improved efficiency that will result from recovering some of the energy wasted in PRVs using in-conduit turbines as well as the fact that it would increase the proportion energy from renewable sources used also contribute significantly. It is also noted that while tax credits seem to play a smaller role, they are likely to be part of the evaluation of financial incentives and the present survey does not address these
two factors in a completely independent manner. Consistent with these motivations and with regulatory requirements, the basis for the decision to install in-conduit small hydro on a water distribution system includes technical, financial, and environmental reports (Figure 10).

![Figure 10](image)

**Figure 10: On what basis is the final decision based on for installing a hydro turbine on your system**

Prior to installing an in-conduit turbine, it is important to determine whether the power output from the turbine will be fed to the electric grid or will be used on-site to contribute to the water distribution energy needs in effect improving the energy efficiency of that system. Respondents to the survey indicate a clear preference for a grid-connected implementation of in-conduit small hydropower (see Figure 11). Challenges inherent to grid-connection include issues associated with: the interconnected nature of the water distribution networks, which means that more than one agency may be affected by the installation thus requiring consultation; geographic location, i.e. additional expenditures that may have to be incurred in more remote areas. Although not within the scope of this study, generator technology (e.g. synchronous generators vs. inverters) and the lack of interconnection tariffs such as those that exist for other renewable technologies are also relevant to the issue of grid-connection.

![Figure 11](image)

**Figure 11: How is the power from existing or new hydro turbines used?**

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CHAPTER 6 — Conclusions

This task provides an inventory of available in-conduit small hydropower technology and an assessment of the status of in-conduit small hydro deployment in California. The simulation needs for quantitative evaluation of in–conduit small hydropower and the evaluation criteria needed to assess the likely viability, performance, and usefulness of new in–conduit small hydroturbine technologies are also discussed.

The technologies listed in this inventory utilize a variety of innovations to improve power production and lower the cost of energy from small hydro sites. Development levels (TRLs) for in-conduit devices are mostly high (near commercialization) with some new designs still at the stage of laboratory validation. The simulation tools used by water agencies are typically designed for water distribution simulation and would require minor additions to support the decision making process. At the component level, the issue of cavitation remains an open research topic. The specificity of in-conduit applications (confined environment, potable water) adds to the performance metrics, standards, certifications, approvals, and permits that are needed for generic small hydro. The penetration of in-conduit small hydro was found to be low. Financial incentives are the top motivators with efficiency concerns and the desire to increase the fraction of energy used from renewable sources having important roles.

Topics of interest for future development of small hydropower include:

- Standardization of small hydroturbines for in-conduit applications.
- Development of independent testing and certification facilities for new, in-conduit small hydro turbines.
- Adaptation of water distribution network simulation tools to accommodate the specificity of in-conduit small hydro.
- Although not discussed in this report, generators, grid integration, and project analysis tools are key areas for future work to improve power production and reduce project costs.
- Conduct a broader survey of potentially all agencies. The enhance accuracy of such a survey would yield a wealth of information to guide the further deployment of in-conduit small hydro.
APPENDIX: Cavitation

Vapor pressure is the pressure at which a liquid boils and is in equilibrium with its own vapor pressure. When local liquid pressure falls below the vapor pressure, vapor bubbles begin to appear in the liquid. When liquid pressure is dropped below the vapor pressure due to a flow phenomenon, we call the process cavitation (White, 2011). Bubbles formed due to cavitation collapse implosively when they move into a higher-pressure region. Cavitation collapse can rapidly spall and erode metallic surfaces and eventually destroy them. Avoiding cavitation in pipe flow is important so that bubbles do not erode the turbine in place to extract energy. Once a turbine becomes eroded, it causes harmful substances to fall into potable drinking water. This can have harmful health effects on humans when they drink the water with those harmful substances. Not only is cavitation harmful to potable water, it also reduces the overall efficiency of the hydroturbine. Cavitation is further described in a paper titled Cavitation Background for Hydroturbines. The paper describes different types of cavitation that can occur and their effects in far more details. In addition, the paper discusses ways to model cavitation.

The phenomenon of cavitation is a feature that distinguishes underwater turbines from those that operate in air, gas, or steam. When cavitation occurs in a turbine, it typically degrades the performance of the system and may cause material damage as well. Cavitation causes acoustic noise that may be undesirable but is also used to identify when cavitation is occurring. Cavitation can be used to advantage for some applications, such as reducing drag in high-speed propellers, cleaning teeth or homogenizing milk.

Cavitation occurs in a liquid when the local pressure drops below the vapor pressure. It is similar to boiling in that it is a phase transition from the liquid to the gas phase, but it is caused by a change in pressure rather than an increase in temperature. Differences between heat transfer and pressure transmission in liquids mean that boiling and cavitation can appear quite dissimilar in their onset and location.

The following overview of material on cavitation nucleation and the types and effects of cavitation is drawn primarily from the work of (C. E. Brennen, 2013), with other sources as noted.

Nucleation

The onset of cavitation is called cavitation nucleation. A cavitation nucleus is a microscopic void in a liquid, which may come from a variety of sources. Homogeneous nucleation is the formation of voids in a liquid due to thermal motion. Heterogeneous nucleation occurs at a liquid-solid boundary, which may be a boundary between the liquid and a solid wall, or between the liquid and a solid particle suspended within it. Suspended bubbles of a gas other than the liquid (water nearly always contains microbubbles of air) may also provide nucleation sites. Cosmic radiation can produce cavitation nuclei as well--this is the principle underlying a bubble chamber--although in general this is of more interest to physicists than turbine designers. Heterogeneous nucleation is the most common type of nucleation seen in engineering applications.
Homogeneous nucleation theory describes the formation of cavitation nuclei in a liquid starting from basic physical properties. The difference in pressure between a bubble and the surrounding liquid is:

\[ p_{\text{bubble}} - p_{\text{liquid}} = 2 \frac{S}{R} \]

where \( S \) is the surface tension and \( R \) is the bubble radius. The tensile strength of a liquid can be defined from this as:

\[ \Delta p_c = 2 \frac{S}{R_c} \]

where \( R_c \) is the critical radius, which is the maximum size of a vacancy within the liquid. The net energy required to form a bubble is:

\[ W_{CR} = \frac{4}{3} \pi R_c^2 S = \frac{16}{3} \pi \frac{S^3}{\Delta p_c}. \]

This expression for the energy can be used to define the nucleation rate, \( J \), which is the number of events per volume per time:

\[ J = J_o e^{-W_{CR}/kT} \]

where \( J_o \) is an empirically determined proportionality factor.

Descriptions of heterogeneous nucleation at a solid surface rely on the contact angle, \( \theta \), measured in the liquid between the surface and the liquid-vapor boundary. On a flat surface, \( \theta < \pi/2 \) for hydrophilic surfaces, while \( \theta > \pi/2 \) for hydrophobic surfaces. Hydrophobic surfaces tend to reduce the effective tensile strength of a liquid, promoting heterogeneous nucleation. On a microscopic level, most surfaces are not flat but have small pits in which bubbles may form. These pits are typically modeled as conical cavities with the vertex of the cone spanning an angle of \( 2\alpha \). The half-angle \( \alpha \) is used to find the critical contact angle, \( \theta = \alpha + \pi/2 \), at which the tensile strength goes to zero. If \( \theta > \alpha + \pi/2 \), then bubbles are able to form at pressures higher than the vapor pressure. Deep, narrow pits therefore have a greater effect on cavitation than wide, shallow pits. Heterogeneous nucleation occurring away from walls is caused by nuclei traveling in the free stream—suspended particles and microbubbles—which vary with the incoming flow and are difficult to characterize for a given system.

**Cavitation in steady flow**

In steady flow, the pressure coefficient:

\[ C_p(x) = \frac{p(x) - p_\infty}{\frac{1}{2} \rho U_\infty^2} \]

is an important parameter for determining the likelihood of cavitation onset. The minimum value of the pressure coefficient, \( C_{p_{\text{min}}} \), generally has a negative value. \( C_p(x) \) depends on the geometry of the system and on the Reynolds number of the fluid. For inviscid flow, \( C_p(x) \) is only a function of the geometry. In a turbine, \( C_{p_{\text{min}}} \) is a function of the normalized flow rate, \( \frac{Q}{nD^3} \). The pressure coefficient is closely related to the cavitation number, \( \sigma \), which is defined by:
\[ \sigma = \frac{p_{\infty} - p_v(T_{\infty})}{\frac{1}{2} \rho U^2_{\infty}} \]

where \( p_v(T_{\infty}) \) is the vapor pressure of the liquid at reference temperature \( T_{\infty} \). Cavitation occurs when \( \sigma \leq \sigma_c \), where \( \sigma_c \) is the critical cavitation number. In a liquid with no surface tension, \( \sigma_c = -C_{p\text{min}} \). The critical cavitation number may refer to the incipient cavitation number, \( \sigma_i \), which is the value of \( \sigma \) at which cavitation begins while pressure is gradually decreased. An alternative measure is the “desinent” cavitation number, \( \sigma_d \), which is found by raising the pressure in a cavitating system until cavitation stops. The “desinent” cavitation number has been observed to be more repeatable in laboratory settings than the incipient cavitation number (Arndt, 1981).

While the minimum pressure coefficient can provide an approximation to the critical cavitation number, there are many factors that may cause \( \sigma_c \neq C_{p\text{min}} \). Tensile strength in a liquid (\( \Delta p_c > 0 \)) causes \( \sigma_c \) to decrease. The residence time effect also decreases \( \sigma_c \), as fluid parcels move out of the area of minimum pressure before bubbles form. The steady viscous effect is the name given to the influence of the Reynolds number on \( C_{p\text{min}} \), which results in \( \sigma_c = f(Re) \). The presence of a contaminant gas (as microbubbles) or free stream nuclei (suspended solid particles or vapor bubbles due to upstream cavitation or recirculation) causes \( \sigma_c \) to increase. Turbulence, wall roughness and porosity all tend to increase \( \sigma_c \) as well.

Testing of prototype turbines often provides results that must be scaled up for a full-scale turbine (see also section 4.1). Scaling of the critical cavitation number is difficult because of the diverse factors that influence \( \sigma_c \). The size distribution of free stream nuclei is a difficult parameter to adjust, for example, while scaling of other parameters may conflict: maintaining a constant residence time near \( C_{p\text{min}} \) requires a decrease in velocity, while maintaining an equivalent Reynolds number requires increased velocity. Cavitation that is firmly established, with \( \sigma \) well below \( \sigma_c \), can be expected to occur in full-scale as well as small-scale models. The International Electrotechnical Commission (IEC:60193, 1999) has set standards for testing model turbines and the scaling of performance and cavitation data.

(Arndt, 1981) discusses various empirical scaling factors that account for the influence of free stream nuclei, contaminant gas or wall roughness. Each takes the form of an additive correction to the critical cavitation number. For free stream nuclei described by a critical radius, \( R_* = \left( \frac{9}{8\pi} \frac{NkT}{S} \right)^{1/2} \)

where \( N \) is the mass of gas in a typical nucleus, \( k \) is the universal gas constant, \( T \) is the temperature and \( S \) is the surface tension:

\[ \sigma_c = -(C_{p\text{min}} + \frac{4S}{3R_*} \frac{1}{\rho U^2}) \]

When a contaminant gas is present in vortex flow:

\[ \sigma_c = -C_{p\text{min}} + \frac{K\alpha}{\frac{1}{2} \rho U^2} \]
where $\alpha$ is the dissolved gas content, $\beta$ is Henry’s constant, and $K$ is a constant that takes a value between 0.3 and 1. The effect of wall roughness can be described by:

$$\sigma_c = -C_p + (1 - C_p)\sigma_{cfp}$$

where $\sigma_{cfp}$ is a function of the boundary layer shape factor, $H\frac{h}{\delta}$ and $Re_h$ for an isolated bump of height $h$. For distributed roughness, $\sigma_{cfp} = 16C_f$ where $C_f$ is the skin friction coefficient.

Due to the complexities involved in a precise determination of $\sigma_c$, other numbers are used to provide a simpler estimate of when cavitation may occur. One is the Thoma number:

$$\sigma_T = \frac{H_{sv}}{H}$$

where $H_{sv}$ is the net positive suction head and $H$ is the total head. Another number that is commonly used for pumps is the suction specific speed:

$$S = \frac{\omega\sqrt{Q}}{[gH_{sv}]^{3/4}}$$

where $\omega$ is the pump rotational frequency, $Q$ is the flow rate, and $g$ is the acceleration due to gravity. The suction specific speed is nondimensional as written above, but in US units, $g$ is often set to unity and $\omega$ is replaced by rotations per minute, with $H_{sv}$ in feet and $Q$ in gallons per minute.

**Types of cavitation**

Cavitation occurs in a variety of forms that differ in appearance, sound level, and degree of performance degradation or material damage. The simplest is traveling bubble cavitation, which assumes spherical, non-interacting bubbles. The bubbles are primarily generated from free stream nuclei, with a small proportion generated at solid walls. In some situations, there may also be bubbles entering the volume of interest via recirculation from downstream cavitation. The bubbles typically travel near a surface or along the stagnation streamline.

The Rayleigh-Plesset equation describes the growth and collapse of spherical bubbles. It is derived from the Navier-Stokes equation under the assumption of spherical symmetry and can be written as:

$$\frac{p_B(t) - p_\infty(t)}{\rho_L} = R \frac{d^2R}{dt^2} + \frac{3}{2} \left( \frac{dR}{dt} \right)^2 + \frac{4\nu_L}{R} \frac{dR}{dt} + \frac{2S}{\rho_L R}$$

where $R(t)$ is the bubble radius and subscripts $B$, $L$ and $\infty$ denote bubble, liquid, and free stream, respectively. The pressure in the bubble depends on the bubble temperature, $T_B$, and the partial pressure of contaminant gas in the bubble, $p_{Go}$ at reference size $R_0$, as follows:

$$p_B(t) = p_V(T_B) + p_{Go} \left( \frac{T_B}{T_\infty} \right) \left( \frac{R_0}{R} \right)^3.$$
driven by periodic motion including vortex shedding and rotor blade rotation. Bubbles within a cloud interact, altering their natural frequencies and modes of oscillation. Clouds collapse in a coherent fashion that is noisier and more damaging than individual bubble collapse.

Interactions between bubbles and solid walls is another cause of deviation from spherical bubble dynamics. The maximum-modulus theorem requires that the minimum pressure in inviscid, steady, potential flow must occur at a boundary such as a solid wall. Viscous effects do not cause significant change in the minimum pressure location, except in the introduction of vortices. As a result, cavitation often occurs near a solid boundary. The presence of a wall near one side of a bubble disrupts the symmetry that would otherwise cause it to take a spherical shape as it develops. Experimental observation of cavitation bubbles near surfaces confirm that the bubbles are typically hemispheric or cap-shaped.

Attached cavitation is called by various names, including sheet cavitation, blade cavitation, and fully-developed cavitation. Unlike traveling bubble or cloud cavitation, attached cavitation is not composed of many small bubbles; instead, an entire wake or separated region is filled with vapor due to low pressure. Traveling bubble cavitation in a region can transition to attached cavitation as the operating pressure is dropped. A sharp edge on a surface or at the trailing edge of a bluff body can provide a starting point for an attached cavity. Predicting the starting point of attached cavitation on a smooth surface is a more difficult task. Attached cavitation can be divided into three categories: partial cavitation, supercavitation and unstable cavitation. When a cavity begins and ends on the surface of a hydrofoil, producing a large closed bubble, it is described as partial cavitation. Supercavitation occurs when a cavity begins on a hydrofoil and closes well downstream. High-speed propellers are designed to operate in supercavitation to reduce drag. Cavity lengths between $\frac{3}{4}$ and $\frac{4}{3}$ of the hydrofoil chord length are unstable and oscillate between the upper and lower limits of cavity size. Each time the cavity shrinks, it releases a cloud of bubbles.

Vortex cavitation occurs in the vortices that form behind propeller tips, pump impellers, and in turbine draft tubes. Vortex cores have lower pressure than the surrounding flow and often provide a site for cavitation. Helical vortex cores can be seen multiple rotor diameters downstream of a propeller or turbine.

Cavitation in a turbine, pump, water tunnel or other confined space can cause the flow to be choked. Analogous to flow through a nozzle, flow that is choked due to cavitation has a maximum velocity that is set by the tunnel width and tunnel pressure. For a given geometry, there is a critical cavitation number for which the cavity length becomes infinite, and the cavitation number cannot decrease below this value. The critical cavitation number can be used as an estimate for the breakdown cavitation number of a pump or turbine.

**Effects of cavitation**
Acoustic noise and material damage are the two most important effects of cavitation relevant to hydroturbines. Both are associated with the collapse of cavitation bubbles. When a bubble collapses, it causes a localized large-amplitude shockwave that is perceived outside the turbine as sound. The crackling sound of many bubbles collapsing can be used to detect cavitation in
turbomachinery, as it is often the first indication that cavitation is occurring. The pressure within the shockwave is quite large; experimental observations suggest

\[ p_{peak} \approx 100R_{M}\frac{p_\infty}{r} \]

where \( R_{M} \) is the maximum bubble radius before collapse, \( p_\infty \) is the freestream pressure and \( r \) is the distance to the center of the bubble. Within the bubble at the last stages of collapse, this high pressure causes the vapor to reach a very high temperature, possibly as high as 6000 K in the last microseconds of collapse. Gas at such a high temperature emits visible light, known as sonoluminescence. When a collapse occurs close to a solid surface, the localized high pressure causes transient surface stresses that lead to fatigue damage if the surface is exposed to cavitation over a long period of time.

A second mechanism that can also produce surface damage is called a microjet or reentrant jet. Microjets occur during bubble collapse and are caused by a lack of spherical symmetry in the volume surrounding a bubble. Asymmetry may be due to the presence of other bubbles or a solid boundary. When a bubble collapses near a solid boundary, a jet of liquid forms on the side of the bubble opposite the boundary, piercing the bubble and exiting through the other side, toward the solid boundary. In soft surfaces, individual microjets have been observed to cause pits and they are believed to contribute to surface fatigue damage in harder materials as well.

Surfaces exposed to cavitation shed flakes of material as the surface is repeatedly exposed to transient stresses. The coherent collapse of a cloud of bubbles is much more damaging than the collapse of individual bubbles, and is common in turbomachines due to the periodic motion of blades and vortices inside and downstream of the machine. Turbine draft tubes can develop deep grooves at the location of cavitating tip vortices. (See figure below, from Arndt, 1981. Note man standing in groove towards the back.)

**Cavitation modeling**

Attached or fully-developed cavitation is the focus of much of the cavitation modeling relevant to hydroturbines. Models describe the extent and shape of an attached cavity in order to determine pressure distributions and hydrodynamic forces acting on turbomachines and the surrounding flow.

Assuming that a cavity is present, two key questions that a cavitation model needs to address are where does it start? and where does it end? If the surface on which the cavity begins has a sharp edge, the cavity typically detaches from that point. On a smooth surface, the detachment point (which is distinct from the boundary layer separation point) must be identified by the cavitation model. Inviscid models do not do a good job of predicting the detachment point, but viscous models can provide better predictions. Experimentally, the detachment point has been observed to occur downstream of the separation point and quasi-empirical models (Arakeri, 1975; Franc & Michel, 1985) can be used to find the distance between the two points.

Closure models are used to model the downstream end of a cavity. The (Riabouchinsky, 1921) model places an image of the cavitating body near the end of the cavity, which causes the streamlines to close smoothly. This model is popular for axisymmetric and planar bodies because it is simple to determine the correct image and easy to implement computationally. Streamlines generated using the Riabouchinsky model are symmetric in the direction of the
flow, which is inaccurate in failing to model the widening of streamlines in the wake. The symmetric streamlines also lead to d’Alembert’s paradox, which implies zero drag contrary to experimental observations. The (Joukowsky, 1890) model (or open wake model) takes the contrasting approach of extending the streamlines to infinity in the wake. This model is also computationally simple and it avoids d’Alembert’s paradox, but the wakes calculated by this method are larger than those observed in practice. The reentrant jet model (Efros, 1946; Kreisel, 1946) places a jet of liquid directed into the cavity at the downstream end, which is supported by observations of attached cavitation. Unlike real flows, however, the modeled jet disappears within the cavity, resulting in a negative wake thickness. Finally, the single and double spiral vortex models (M. Tulin, 1953; M. P. Tulin, 1963) are computationally tractable for two-dimensional planar flows. These models place a pair of vortices at the end of the cavity, in which the cavity streamlines end and two new streamlines begin that extend downstream to form the wake, eventually merging farther downstream.

Linearized models have been applied to hydrofoils and cascades of hydrofoils, starting with the work of (M. Tulin, 1953). The simplest case is the flat plate hydrofoil with an attached cavity, which is analyzed in textbooks such as (C. E. Brennen, 2013) in ch. 8.8. Two regimes are defined based on \( l \), the ratio of the cavity length to the chord length: partial cavitation when \( l < 1 \) and supercavitation when \( l > 1 \). For partial cavitation, the lift coefficient and cavitation number are found as:

\[
C_L = \pi \alpha [1 + (1 - l)^{-1/2}]
\]

\[
\sigma = \frac{2 - l + 2(1 - l)^{1/2}}{l^{1/2}(1 - l)^{1/2}}
\]

Both of these values become infinite as \( l \to 1 \), while the flat plate solution \( C_L = 2\pi \alpha \) is regained as \( l \to 0 \). The cavitation number, \( \sigma \), has a minimum at \( l = 0.75 \), which marks the maximum cavity length before unsteady cavitation begins. For supercavitation:

\[
C_L = \pi \alpha l \left[l^{1/2}(l - 1)^{-1/2} - 1\right]
\]

\[
\sigma \left(\frac{2}{\sigma} + 1\right) = (l - 1)^{1/2}
\]

which also become infinite as \( l \to 1 \).

**Numerical modeling**

Computational models of cavitation can be divided into two broad categories: interface tracking models and multiphase models. Interface tracking models typically only model the liquid phase of the flow (even though this is not an inherent limitation) and determine the cavity shape through an iterative process. Multiphase models include both the liquid and vapor phases, which allows for modeling of more complex flows but also increases the computational intensity. While interface tracking and multiphase models are the most widely studied for turbomachinery applications, there are also other approaches. Models based on microbubble dynamics describe clusters of bubbles in the absence of attached cavitation. One recent example of a microbubble model with a survey of earlier works can be found in (Fuster & Colonius, 2011).
Interface tracking models of cavitation do not model the interior of the cavity; instead, they assume that the interface between the vapor and liquid phases is a surface of constant pressure equal to the vapor pressure of the fluid. The location of the interface is determined through successive iterations of modeling the dynamics of the liquid phase. Interface tracking models require a closure model to deal with the two-phase, turbulent wake at the end of the cavity, such as the Riabouchinsky closure model (C. Brennen, 1969) or a pressure recovery model (Lemonnier & Rowe, 1988). Many of the initial interface tracking models used potential flow boundary element methods. While these codes are computationally efficient, they are restricted to 2D planar or axisymmetric flows. The use of Euler or Navier-Stokes equation based models has allowed for more complex geometries and more realistic wake closure models. The iterative nature of all interface tracking models means that they are unable to provide time-accurate solutions or to model travelling cavitation. They are also restricted to attached cavities and cannot model more complex phenomena such as the release of clouds of bubbles associated with unsteady cavitation. In spite of these drawbacks, interface tracking models continue to be used for their efficiency and good first-order agreement with experimental results for supercavitating flows.

Multiphase models do not identify the location of the interface directly; it must be inferred from the properties of each individual cell. In systems where the cavity boundary is varying with time, a fine grid is required over a large domain in order to resolve the interface location accurately. Models can be classified as multi-fluid models or mixture models. Mixture models use a single fluid whose density varies sharply between liquid and vapor regions. Multi-fluid models treat the liquid and vapor phases separately, which is computationally expensive and more difficult to implement than a mixture model and consequently there are few applications of multi-fluid models in the literature. (One exception is found in (Grogger & Alajbegovic, 1998).) Mixture models can be further subdivided, with some models applying a single set of conservation equations for mass, momentum and energy to both phases while others use separate conservation equations for each phase.

Mixture models using separate conservation equations are called homogeneous mixture models, due to the fact that a no-slip condition is imposed between the two phases. Some are based on a modified form of the Rayleigh-Plesset equation for bubble dynamics as expressed in the bubble two-phase flow model of (Kubota, Kato, & Yamaguchi, 1992). More commonly, a mass transport model is used in which the transfer of mass between the liquid and vapor phases is expressed as a source term for the continuity equations.

Choosing a numerical model
The choice of cavitation model depends on the complexity of the system that is being modeled and the amount of computational time and resources that can be devoted to the problem. Interface tracking models are computationally efficient and can provide good models of systems with attached cavitation. The simplest codes use boundary element methods that can only model planar or axisymmetric bodies, but codes based on the Euler or Navier-Stokes equations can be used for more complex geometries. Interface tracking models cannot model a system that is changing over time. If unsteady cavitation, meandering vortices or dynamic operation is being modeled, a multiphase model is more appropriate. Full multifluid models
have so far been judged too difficult to apply to the complex geometry of a turbine, but mixture models have been applied to some cases. These require a full CFD code and a relatively fine mesh to capture the details of the cavitation interface. A comparison of three of the models implemented in commercial CFD codes (Morgut, Nobile, & Biluš, 2011) found that all could provide comparable accuracy when empirical coefficients are properly tuned.
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