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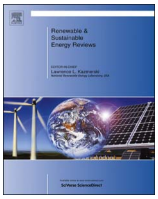

Ultra-low-head hydroelectric technology: A review

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ABSTRACT

In recent years, distributed renewable energy-generation technologies, such as wind and solar, have developed rapidly. Nevertheless, the utilization of ultra-low-head (ULH) water energy (i.e., situations where the hydraulic head is less than 3 m or the water flow is more than 0.5 m/s with zero head) has received little attention. We believe that, through technological innovations and cost reductions, ULH hydropower has the potential to become an attractive, renewable, and sustainable resource. This paper investigates potential sites for ULH energy resources, the selection of relevant turbines and generators, simplification of civil works, and project costs. This review introduces the current achievements on ULH hydroelectric technology to stimulate discussions and participation of stakeholders to develop related technologies for further expanding its utilization as an important form of renewable energy.

1. Introduction

Although hydropower is considered to be a renewable energy resource, its sustainability is sometimes questioned because of the impacts of dams on the environment, which is a major barrier for the deployment of large- or mid-sized hydropower projects [1]. Interest in using small hydropower resources is increasing, and the technology is being developed worldwide because of its advantages in terms of scale (i.e., small), deployment time (i.e., short), and impact on the environment (i.e., low) [2]. To date, most published literature focuses mainly on small hydropower technologies that use low hydraulic heads between 2 m and 30 m [3–6] or on hydrokinetic energy conversion technology [7–9]. Nevertheless, not enough attention has been paid to water-energy development in situations where the hydraulic head is between 0 m and 3 m (i.e., ultra-low head [ULH]) because of the poor economic benefits of these resources [10].

ULH hydropower will become an attractive, renewable, and sustainable resource through advances in hydraulic turbines, simplified civil works, and reduced project costs. In addition, this type of water-energy technology is advantageous in that it can be distributed widely and implemented near human activities, and it is generally regarded as environmentally benign. Specifically, the low environmental impact of ULH hydropower is reflected in two main points: 1) the wide blade passages and low rotating speed can significantly reduce collision damage for fish; and 2) because no dam or a very low dam is involved, barriers for fish migration and navigation are avoided and water flow downstream are ensured. Although generally considered to be environmentally benign, inappropriate applications of the technology can result in harmful impacts to the environment [7,8]. In this review, ULH water energy refers to situations where the hydraulic head is less than 3 m or the flow velocity is more than 0.5 m/s with zero head. Based on the classifications defined by Singh and Kasal [11], ULH hydropower can be pico-hydro (less than 5 kW), micro-hydro (5 kW~100 kW), mini-hydro (100 kW~1 MW), small-hydro (1–15 MW), or medium-hydro (15–100 MW) depending on the output. Many low-head projects seek to minimize infrastructure and costs, and as a result, low-head hydropower projects are almost always “run-of-the-river” installations (i.e., water-storage capabilities are small to nonexistent) [12].

This paper focuses on ULH water-energy deployment and provides an overview on ULH hydropower technology. It begins with the introduction of existing ULH water-energy sites, followed by discussions of turbine and generator selection for ULH hydropower sites. Then, we discuss ways to simplify implementation of the technology and provide a breakdown of project costs. Finally, we summarize future development objectives for ULH hydropower projects.

2. Sites of ULH water-energy resources

A comprehensive assessment based on the temporal and spatial flow properties of water-energy resources should be performed to confirm the economic value of candidate sites. However, it would be difficult to conduct a survey for reliable statistics because ULH water-energy resources are widely distributed geographically throughout the world. Thus, existing ULH water-energy sites are introduced within the following categorized examples: 1) Rivers and Streams; 2) Canals, Locks, and Pumping Stations; 3)

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Fig. 1. Two turbines deployed in New York City's East River. The diameter of each turbine is 5 m. (Used with permission of Verdant Power).

Piping Systems; 4)Wastewater Hydropower; 5) Tailrace Flows from the Power Station; 6) Tidal Energy; and 7) Other Sites.

2.1. Rivers and streams

Many undeveloped rivers or streams throughout the world contain abundant ULH resources that could be used to generate electrical energy via suitable hydro-units installed in simple, onsite structures [13–15]. Meier and Fischer [16] reported that in Vietnam, block and support construction utilizing locally sourced wood and bamboo have been used, and several 200-W, low-head, pico-hydro units have been installed to generate power. Water current alone (i.e., no hydraulic head) can be used to produce power using a hydro-kinetic turbine [17,18]. The power available from a potential hydro-kinetic site is dependent on the speed and depth of the flow, which determine the size of the turbine that can be used. A study conducted by the Electric Power Research Institute (EPRI) estimated the hydro-kinetic technically recoverable power from rivers in the United States to be 119.9 TWh/yr [19]. For example, using water turbines (Fig. 1), 1 MW of electric power could be generated in the East Channel of the East River in New York City, with minimal impacts on the river mean water velocity in the channel [20].

2.2. Canals, locks, and pumping stations

Canals and other artificial waterways with water flow velocities greater than 1.5 m/s are ideal sites for ULH energy conversion because of their controllable, predictable, and relatively clean characteristics [21–23]. The U.S. Department of Energy Wind and Water Power Technologies Office supported hydro-kinetic energy development within existing canal systems [22] such as the Roza Canal in Washington State (Fig. 2). British Waterways reported on plans to 1) exploit 3541 km of Britain's canals and rivers and 2) build 25 small-scale hydroelectric schemes with a total generating capacity of 40 MW, which would be enough to power 40,000 homes [24]. Botto et al. [25] considered water hydro-kinetic turbine technology applicable to small and medium-sized channels as a breakthrough in clean energy production, and analyzed the database of Piemonte regional (Northwestern Italy) irrigation canals to map the energy potential production of that resource. Micro-hydropower systems using irrigation water in an agriculture canals have been built in Taiwan [26] and the Lao People's Democratic Republic [27]. Overall, water current hydro-kinetic generation is viable in waterways and canals with sufficient water velocities. Furthermore, the faster the water flows, the more potential there is for generating electrical power. In some pumping stations, pumps can be used as turbines to generate power under special conditions. For example, pumping units work as turbines to generate 3 MW of power in Jiangdu irrigation and drainage stations in China when the Huaihe River has excess inflow [28].

Fig. 2. Structure to support testing of a turbine that produces electricity from flowing water. Instream Energy Systems of Vancouver, B.C., built this structure over the Roza Canal in the Yakima Basin in Washington State to support testing of a turbine that produces electricity from the flowing water. (Used with permission of Instream Energy Systems Corporation).

2.3. Piping systems

The piping in industrial cooling water circulation systems, waterworks, and water supply lines in hydropower plants have varying amounts of surplus water head. Zhou et al. [29] described a case in which surplus pressures ranging from 39 to 147 kPa existed in a cooling tower piping system. A modified Francis turbine was installed to harvest the previously wasted energy in the cooling system. Zheng et al. [30] researched 300-kW small turbine units that could be used to replace pressure-relief valves in water supply systems of hydropower plants. Excess pressure in the diversion pipes of many water treatment plants also can be exploited to generate power [3]. The use of micro-hydro systems in water supply networks can control the system pressure while producing power [31]. However, when potential energy recovery in a city water supply network is explored, care must be taken to avoid impacts to the water quality [32]. In addition, the bypass pipe can be set up to prevent accidents that could affect the normal water supply. Therefore, optimal planning, design, implementation, and management of the proposed approach are important for obtaining maximum environmental, social, and economic benefits [33].

2.4. Wastewater hydropower

Although implementation of hydroelectric power in wastewater plants is still in the developmental stage, the water-energy extant in those facilities has been receiving more attention as new low-head turbine system technologies have emerged. In a recent investigation of seven states in the United States (i.e., California, Texas, Florida, Pennsylvania, New Jersey, New York, and Massachusetts), Torrey [34] identified both high energy prices and an abundance of wastewater plants that would make these sites attractive candidates for wastewater hydropower installations. Capua et al. [35] studied eight wastewater treatment plants in Massachusetts and reported average flow volumes ranging from 0.05 to 15.99 m^3/s and available hydraulic heads ranging from approximately 1.22 to 5.18 m. The Deer Island Wastewater Treatment Facility located near Boston, Massachusetts, has been recovering energy from water flowing from the plant since 2002 [35]. The two 1-MW hydroelectric generators installed in this plant can produce over 6 million kWh annually, leading to savings of approximately $600,000 per year. A wastewater treatment facility in Millbury, Massachusetts, has an available head of 1.7 m and an average flow volume of 1.4-m^3/s, which can generate about 20 kW of power [34].

Generally, there are two schemes for hydro-units installed near wastewater plants [36]. In the first scheme, the hydro unit is installed upstream of the wastewater plants. In this case, the turbine components should be more corrosion resistant, and the diversion pipe entrance must be equipped with a thin trash rack. In the second scheme, the hydro unit is installed downstream where the hydro unit encounters cleaner water so component materials used in the unit can be less corrosion resistant; however, space limitations at the site can become an important issue.

2.5. Tailrace flows from the power station

Reserved flows or compensation flows at the foot of hydropower dams or the water exiting from the draft tube still have considerable hydro-kinetic energy [37,38]. Use of these flows to generate electricity would result in lower flow rates and, thus, reduced erosion on downstream hydraulic structures along the shoreline. Rozumalski and Fullarton [39] used a three-dimensional computational fluid dynamics model to simulate flow rates in the tailrace at Milford Dam in Kansas. The results indicated that velocities of strong currents in the tailrace could reach 1.4–1.7 m/s [39]. A quantitative flow-field visualization of the tailrace region at Wanapum Dam in southeast Washington State provided the distribution of flow vectors and provided useful reference points for siting the hydro unit (Fig. 3) [40]. Jose et al. [41] confirmed the viability of a small hydroelectric project at the tailrace of the Poringalkuthu Powerplant in India. In addition to extracting energy from the tailrace flows, cooling water from the thermal power station was conveyed to the hydropower plant to produce electricity by a Kaplan turbine and generator [36]. Overall, by extracting 0.1% of the water energy from the total hydroelectric generation, an additional 12 GW of power could be generated worldwide via tailrace hydropower by 2020 [38].

2.6. Tidal energy

Tidal energy contains potential and kinetic components that can be harnessed by tidal barrages and tidal current turbines, respectively [42]. The theoretical global tidal resource is estimated to be 8800 TWh/yr [43]. Technically recoverable tidal energy potential is predicted to be 800 TWh/yr [44]. The National Renewable Energy Laboratory and EPRI estimate that the total potential of all the combined ocean renewable energies in United States currently exceeds the national electric energy needs [45]. A total of 13 GW of new hydro-kinetic technologies could be deployed by 2025, supplying at least 10% of the electrical needs of the United States [45]. There are many potential current energy sites including Ireland, the Amazon River, the English Channel, the Strait of Gibraltar, Fiji Island, the Strait of Messina, the southern coast of Iran, and South Korea [46]. In Europe, the EU-JOULE CENEX project [47] included a resource assessment and compiled a database of European locations in which over 100 sites ranging from 2 to 200 km^2 of sea-bed area were identified, many with power densities greater than 10 MW/km^2. Abundant tidal energy resources in China have great potential to be exploited. More than 80% of China's tidal energy resources are distributed in Fujian and Zhejiang Provinces, and sea areas to the south of Yangtze River Estuary are rich in current energy [48]. However, at present, tidal energy development is still facing the challenges related to the complex ocean hydrodynamic environment, short equipment life, maintenance obstacles, construction difficulties, and the significant capital investment required [49].

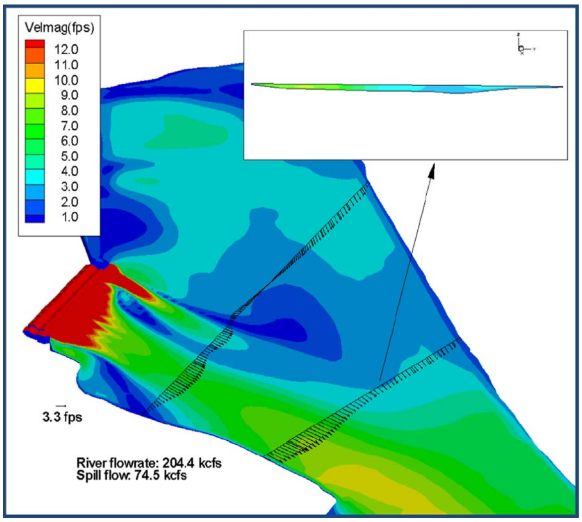

Fig. 3. Graphical representation of water flow through the Wanapum Dam Tailrace. Discharge of 2100 m^3/s going through the spillway (clearly demarked by the high velocity contour) and a total flow rate of 5800 m^3/s. (Used with permission of Grant County Public Utility District).

2.7. Other sites

Water energy for exploitation may exist at other sites. Check dams are installed in streams to control floods and gravel transport and to mitigate erosion [50]. The resultant water reservoir stores a certain amount of water and forms a low hydraulic head, which can be used to generate electricity via hydro-units installed through the dams or connected with siphon pipes. Desalination plants use reverse osmosis to separate water from dissolved salts through semi-permeable membranes under high pressures of around 7 MPa [51]. Water residue from the process still at high pressure can be passed through a turbine to recover part of the energy used to drive the reverse osmosis process [51]. In another example, an attraction flow must be installed so fish migrating upstream can find the entrance of the fish-passage system. This attraction flow can be created by placing a penstock from the upstream basin to the entrance of the fish pass system. In this case, energy recovery would involve installing a turbine that would use the attraction discharge and the difference of the water levels between the upstream basin and the fish-passage entrance [36].

3. Turbine selection for ULH applications

It is important to select a suitable hydro-turbine for ULH water-energy exploitation. Conventional water turbines can be classified as impulse turbines or reaction turbines. The main types of conventional hydropower turbine types include Pelton turbines, Turgo turbines, cross-flow turbines, Francis turbines, Kaplan turbines, and tubular turbines [4]. In addition, there are more than 20 types of emerging hydro-kinetic turbines for current energy conversion [52]. These emerging hydro-kinetic turbines can be classified as lift or drag types, with the type being based on either the principle of the hydraulic force acting on the blades or, for horizontal axis and vertical axis turbines, the relationship between the flow direction and the rotation axis [7]. A turbine selection chart usually is used to select turbines for consideration and to perform technical and economic comparisons among them.

3.1. Available and updated turbine selection charts

Turbine selection charts can provide basic information useful for determining a turbine that may be suitable for a particular site. The charts also can help a manufacturer verify that a turbine is appropriate for site-specific conditions. Turbine selection charts are provided in some textbooks [53] and in the published literature [54–56]. As a typical example, the turbine selection chart in the Fig. 4 [57] shows turbines types that can be used for hydraulic heads ranging from 1 to 1000 m and discharge scopes ranging from 1 to 100 m^3/s. However, it does not consider innovative turbine technologies that can operate in ULH and discharge conditions. It has been reported that some structure-simplified Francis turbines can be applied in situations where the head is less than 3 m [58], and the re-designed cross-flow turbine can operate as a hydro-kinetic turbine in situations where there is no hydraulic head [59].

Generally, traditional turbine technology is not viable for projects in which the head is less than 2 m. New technologies are being developed

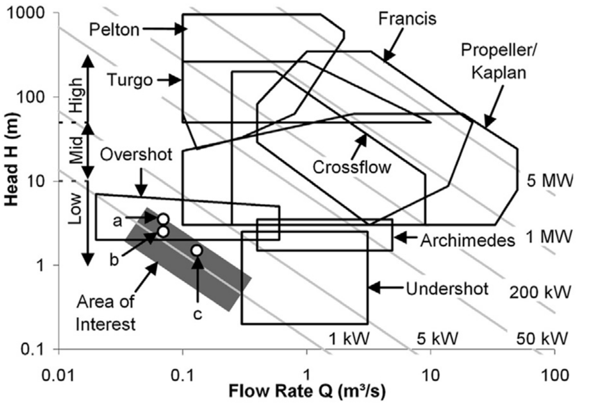

Fig. 4. Typical turbine application range chart. (Used with permission of SJ Williamson).

to take advantage of these small water elevation differences, but they generally rely on the kinetic energy in the streamflow as opposed to the potential energy associated with the hydraulic head [60]. Available turbine selection charts are not comprehensive in terms of turbine types and application ranges included, so the charts do not provide satisfactory selection guidance for ULH turbines. Therefore, we used relevant research results [4,9,54,57,61–64] to create a turbine selection chart suited for use at ULH sites (Table 1). The table considers the viabilities of technology and economy, and even under extreme conditions of the lowest hydraulic head (0.5 m) or slowest velocity (0.5 m/s), turbines still can be selected. Certainly, the use-range of a turbine can change as circumstances change, and the turbine types in the chart should be regularly updated to reflect the emergence of new technologies.

3.2. *Pros and cons of typical turbines*

Generally, open-flume Francis turbines are seldom used in ULH applications. At discharge rates less than 1 m^3/s, Francis turbines are difficult and expensive to machine because of their small size and large number of blades. Compared to Kaplan turbines, Francis turbines exhibit poor flow capacity and lower power output under the same ULH conditions. Francis turbines are superior to propeller turbines because of their good stability and high efficiency over wide head ranges or discharge fluctuation ranges. Kaplan turbines also perform better over a large range because of their double-regulation capability (i.e., the runner blades and guide vanes both are adjustable). However, the blade adjustment mechanism is complex and requires adequate installation space in the runner hub. Thus, because of this complexity, Kaplan units are expensive and, to be economical, are more suitable for larger flow capacity situations in which hydraulic heads are very low. Fixed-blade propeller turbines are much more cost-effective than Kaplan turbines and are more appropriate for ULH applications; however, the optimal power operating ranges are more limited for propeller turbines.

Table 1
Turbine selection table for ULH sites.

Type	Rated Head (or velocity)	Rated Output (or capacity)
Open flume Francis turbine	H > 2.0 m	N > 100 kW
Kaplan turbine	H > 1.5 m	N > 100 kW
Propeller turbine	H > 1.5 m	N > 10 kW
Tubular turbine (double-regulated)	H > 1.0 m	N > 100 kW
Tubular turbine (single-regulated)	H > 1.0 m	N > 50 kW
Tubular turbine (non-regulated)	H > 1.0 m	N > 10 kW
Cross-flow turbine	H > 0.5 m or V > 2.0 m/s	N > 1 kW
Archimedes turbine	H > 1.5 m	N > 10 kW
Hydro-kinetic turbine	V > 0.5 m/s	N > 10 W

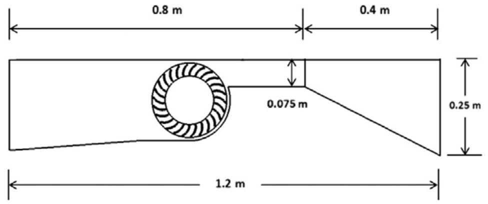

Fig. 5. Schematic diagram of a cross-flow turbine installed in a channel. (Used with permission of Elbatran AH.).

Tubular turbines are good selections for ULH conditions and for large discharge conditions because water passes straight through the turbine, resulting in low hydraulic losses. For sites where the total flow capacity is lower, single- or non-regulated tubular turbines can be used instead of double-regulated types to reduce the complexity and resulting system cost. Furthermore, the geometry and number of guide vanes and runner blades can be reasonably simplified to reduce manufacturing costs of Kaplan and tubular turbines [65,66]. In recent years, a very-low-head turbine has been demonstrated to be suitable for operating under ULH conditions as an innovative axial-flow hydraulic turbine [67,68].

Conventional cross-flow turbines (Fig. 5) pushed by water jets usually are used for a wide range of hydraulic heads ranging from 5 to 200 m [69]. The best efficiency of a cross-flow turbine is somewhat less than for a Kaplan or Francis turbine. However, the cross-flow turbine has a flat efficiency curve under varying load, and its structural requirements are simple and it has a self-purification capacity [70]. Furthermore, cross-flow turbines can be improved to be semi-submerged or fully submerged to convert current energy with a much higher efficiency [54,71–73]. Therefore, cross-flow turbines may be an ideal hydro-energy converter to be used at ULH sites.

A new series of Archimedes screw turbines have been designed for low-head conditions (i.e., 1–10 m) and large discharge ranges (i.e., 0.1–15 m^3/s). A significant advantage these screw turbines is their tolerance for debris [60]. Archimedes screw turbines are potentially fish-friendly, have low environmental impact, low rotating speed, and relatively simple structural requirements [74]. Ak et al. regard the Archimedes screw as the most suitable turbine for low-head hydropower using a multi-criteria analysis tool [75]. However, Archimedes screw turbines are volumetrically large and, as a result, are less desirable with respect to transportation and installation. Based on the principles of water energy converted by these turbine blades, more tests should be performed to verify the efficiencies reported in the literature [54,60,76].

Hydro-kinetic turbines are driven by free flow when ultra-low or zero head conditions exist. This type of turbine usually is applied in natural streams (e.g., rivers), tides, ocean currents, artificial waterways, and other sites with sufficient water velocities [7]. A hydro-kinetic system can convert the energy of flowing water to electricity, and power production can be increased by deploying multi-unit arrays like wind farms [62]. In addition, the structural requirements for these systems are minimal [77]. However, their relatively low efficiency, cavitation [7], high installation costs, and maintenance difficulties are the biggest challenges to advancing hydro-kinetic technologies.

4. Generator matched with turbine

It is very important to select the right generator for efficient ULH water-energy conversion under different head and flow velocity conditions. Usually, the characteristics of ULH hydropower generation are similar to those of wind power generation, such as low output power and slow fluctuating rotation speeds. Therefore, for generator selection, much can be learned from the wind power industry [78]. Two common types of generators are reported in the literature [79–82]: 1) squirrel-cage induction generators and 2) permanent-magnet synchronous generators. Both types have been adopted as cost-effective choices for ULH power generation [83].

4.1. Squirrel-cage induction generator

The name of squirrel-cage induction generators was derived from the similarity between its rotor structure and a squirrel cage [78]. Despite being less efficient than an equivalent permanent-magnet synchronous machine and the need to run at a more-or-less fixed speed [80], this type of induction generator is an attractive option for pico-/micro-/mini-scale hydropower generation because of the following advantages [84,85]: low cost, robustness, simpler startup, and simpler control. In addition, a squirrel-cage generator requires the least amount of maintenance because of its simple and rugged brushless rotor construction [86]. However, a reliable controller should be installed to regulate the voltage and frequency [11].

4.2. Permanent-magnet synchronous generator

Low-head hydro installations usually experience extreme variations in flow and hydraulic head, which requires a generator that can tolerate input power variations [87]. Generators that are based on permanent-magnet machines are very suitable for slow and variable-speed conditions because their performance can be maintained at different rotating speeds [88]. Davila-Vilchis and Mishra [89] demonstrated a type of axial-flux permanent-magnet generator that was improved to produce the following advantages: minimum maintenance, no heat problems inside the bobbins, high efficiency at lower RPMs, and improved electricity production cost. However, permanent-magnet generators have disadvantages related to magnetic degradation [79]; that is, the excitation is fixed and, hence, the output voltage varies with load [90].

4.3. Other generators

Other promising generator technologies are used to exploit ULH water energy. Marques et al. [91] reported that cascaded induction generators require lower maintenance because slip rings and brushes are not used. Nakamura and Ichinokura [92] designed a super-multi-polar permanent-magnet reluctance generator that can be connected directly to a low-speed turbine without the use of a gear box. To eliminate the need for a powerhouse, waterproof turbo-generators are designed to allow the entire power unit to run safely while submerged in the flow [4]. Efforts to develop different types of generators to meet the special requirements in ULH power systems should be continued.

5. Structural requirements

Structures in conventional hydropower facilities mainly include water-storage structures, water-diversion facilities, a powerhouse, and a tailrace passage. Costs for these structures often account for more than half of the total project cost. Therefore, it is very important to find some ways to reduce the costs of structures for ULH power projects.

5.1. Using local resources

Water-retaining and conveyance structures and structural support frames can be made with abundant local materials (e.g., wood, bamboo, stone, etc.), which can reduce costs for construction, maintenance, and replacement. Water can be a diverted from a river or it can come from a small dam or weir made from locally available materials. These types of installation are frequently used in the mountainous districts of Kham, Mai, and Kuah in Laos, where there is an abundance of suitable small streams (Fig. 6.) [27]. In Thailand, mostly local materials have been used to construct small, portable, and low-cost check dams to store water collected during the rainy season for use in the dry season [93].

Fig. 6. Standing Pico-Hydro Unit in Khaivieng Village, Kham District, Xieng Khouang Province.(Used with permission of M Smits [27]).

5.2. Using existing facilities

It is more economically viable to develop water power projects at existing sites, such as sluice gates, irrigation canals, water pressure release valves, and municipal wastewater outfalls, and at sites in rivers with existing dams [60]. A siphon hydroelectric plant can be especially attractive for adding hydropower capability at existing dams or similar sites (Fig. 7). This approach has often proven to be a cost-effective, timesaving option because a siphon plant moves the water over, not through, the dam [3]. This avoids the often time-consuming and expensive work of developing a water passage if modifying the existing structure is not feasible. During the planning phase, it is important to determine that adding ULH hydropower into an existing infrastructure does not negatively impact the original primary function of the site [36].

5.3. Modular units

Modular units integrate the turbine, generator, control and protection equipment, and support structure. Modular units also are known as “plug-and-play” or “self-contained” units. These new technologies can minimize or eliminate the traditional powerhouse and simplify construction. A modular small hydro system combining a modified bulb turbine design has been developed for use at low-head, non-powered dams and lock sites (Fig. 8) [87]. The very-low-head turbine often is installed in an existing channel, so structural modifications are minimized or nonexistent (Fig. 9) [94]. Some other innovative turbine technologies are available from Power

Fig. 7. Eight siphon-type Kaplan turbines. The units were installed by North Side Canal Company in Idaho, United States, in 2015. The site has a 6 m of head and a total of 1.28 MW installed capacity. (Used with permission of A Hansten of North Side Canal Company).

Fig. 8. A 100-kW Nameplate Capacity hydro-kinetic unit. This unit is located at the U.S. Army Corps of Engineers Lock and Dam No. 2 in Hastings, Minnesota. (Used with permission of Hydro Green Energy, LLC).

Pal [57], Natel Energy, Mavel [3], Kössler [95], Turbinator [87], Instream Energy Systems, Amjet Turbine Systems [96], Canyon Hydro, Obermeyer Hydro, etc. These new technologies make it possible to lower investment cost and shorten construction time.

6. Project costs

The costs of a ULH hydropower project are a major concern for a developer or an investor. The costs include not only the expected costs and benefits, but also the sensitivity (i.e., the corresponding economical risk and uncertainty) [97]. Because of the complexity of an economic assessment, our review focused only on project cost. At this time, the cost of ULH hydropower is nearly equal to the cost of a wind energy plant but less than that of a solar energy plant [54,98].

6.1. Breakdown of costs

The main cost of a ULH hydropower project includes civil engineering costs, electromechanical costs, transmission, engineering and approvals, and operations and maintenance (O & M) costs. The approximate breakdown of the low-head hydro project costs are listed in Fig. 10 [60]. The costs are highly dependent on the site and are included for illustrative purposes only. All costs are larger for greenfield (i.e., environmentally friendly) sites except for the electromechanical costs [60]. Because of the high standards of greenfield sites, civil engineering costs are a large proportion of total costs, more than 40% in most cases [99]. Installing hydropower capability at existing dam projects could significantly decrease civil engineering costs and lead to an increase in the electromechanical cost proportion due to the decrease in total costs [60]. Annual O & M costs are often quoted as a percentage of the investment cost per kilowatt. For small-scale hydropower installations, typical values range from 1% to 6% and, in some cases, can be even higher [100]. According to LaBonte et al. [101], the cost breakdown for hydro-kinetic energy conversion systems covers all lifecycle expenditures including project planning and permitting, generating equipment, supporting infrastructure, and O & M.

Fig. 9. A 410-kW very-low-head turbine unit in the Tarn River, Millau, France. (Used with the permission of MJ2 Technologies S.A.S.).

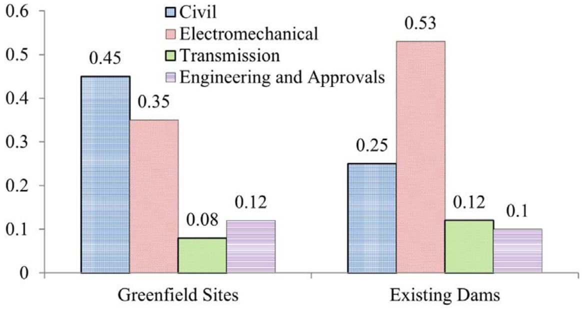

Fig. 10. Approximate breakdown of low-head hydro project costs. (Source: [60]).

6.2. Costs of conventional small hydropower projects

The wide investment cost bands for hydropower projects within countries and between countries (Fig. 11) are determined by factors such as the resource availability, site-specific considerations, and the cost structure of the local economy [100]. For a low-head hydropower project, the total initial project costs can range from U.S. $1800 to $8000 per kilowatt [87]. However, by using localized expertise and technology, costs can be reduced to below $1000 per kilowatt [4].

A series of empirical equations have been established to estimate overall project cost, civil engineering costs, and electromechanical costs [4,100,102,103]. For example, the initial capital cost equation, based on existing non-powered dams and conduit sites, is given by Eq. (1) [87]:

$$C_P = 566.9H^{0.01218} P^{1.1452} \tag{1}$$

where H is the water head (m) and P is the power (kW). Singal and Saini [104] performed research to develop a methodology for correlating the total cost using regression analysis that considered head and capacity as cost-sensitive parameters for alternative layouts having one to four turbines. Actual project costs may vary significantly when detailed design and construction are carried out. Unsuitable turbine selection, a lack of experience with pico-hydro technology, or a failure to execute a good cost-effective approach will dramatically increase costs [105].

6.3. Hydro-kinetic turbine system costs

Hydro-kinetic technologies are still in the early developmental phase,

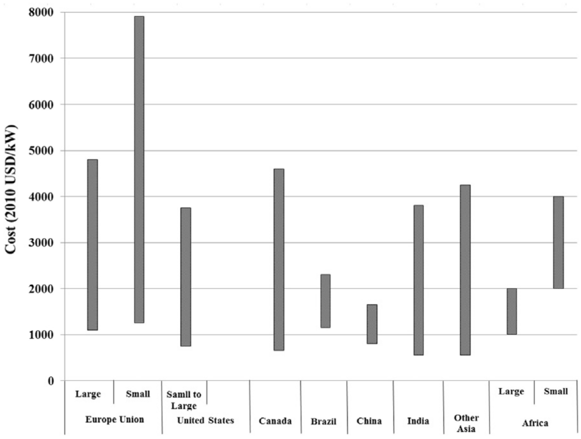

Fig. 11. Total Installed Hydropower Cost Ranges by Country. (Source: [106–108]:).

Table 2
Estimated economics of hydro-kinetic power generating devices in Alaska. Used with permission of Jerry Johnson, compiled from Previsic 2008, Polagye and Previsic 2006; Previsic and Bedard 2009.

Study Locations	Power Production (kW)	Capital Cost (2010 $)	Cost per kWh (2010 $)	Annual O & M Costs (2010 $)
Igiugig	40	315,000	0.68	12,600
Eagle	60	283,000	0.38	6800
Whitestone	590	1,900,000	0.19	135,00
Knik Arm	17,000	123,000,000	0.11	4,500,000
Yakutat	5200	48,000,000	0.28	1,400,000

which makes it difficult to conduct accurate economic analysis for proposed installations. When more devices have been built and deployed, specific estimates for costs can be made. EPRI conducted preliminary economic analyses for several proposed hydro-kinetic projects in Alaska (Table 2) [17]. The estimated O & M costs ranged between 2.45% and 7.08% depending on the size and location of the deployment [40].

7. Conclusions and prospects

Although ULH hydro-resources are abundant in many countries, the survey task is difficult because no comprehensive database has been established to collect relevant information from wide-ranging sources. Because of different site conditions and deployment methods for each ULH hydropower project, a more accurate cost-assessment model of ULH hydropower projects need to be established in the future. For ULH turbines, future development objectives are summarized below:

- First, high-efficiency turbines with large flow capacities should be designed to produce more electricity.
- Second, lightweight, inexpensive materials should be investigated and adopted when feasible to reduce the costs of manufacturing, transportation, and installation while being able to meet the mechanical specifications.
- Finally, to prolong service lives, turbines must be made of corrosion-resistant materials and be equipped with good seals, and bearing lubrication systems.

Non-regulated turbines with variable-speed generators have a wide tolerance for head or flow fluctuations and, thus, can obtain maximum power outputs. Ideal generators for ULH power systems need to be small, direct-driven, and variable speed, and must have good self-protection capabilities. The use of modular units, locally available materials, and existing facilities can significantly reduce project costs. Overall, it is no doubt that the availability of reliable technology and low implementation costs will be the two key factors that will influence the adoption of the ULH hydropower.

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