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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