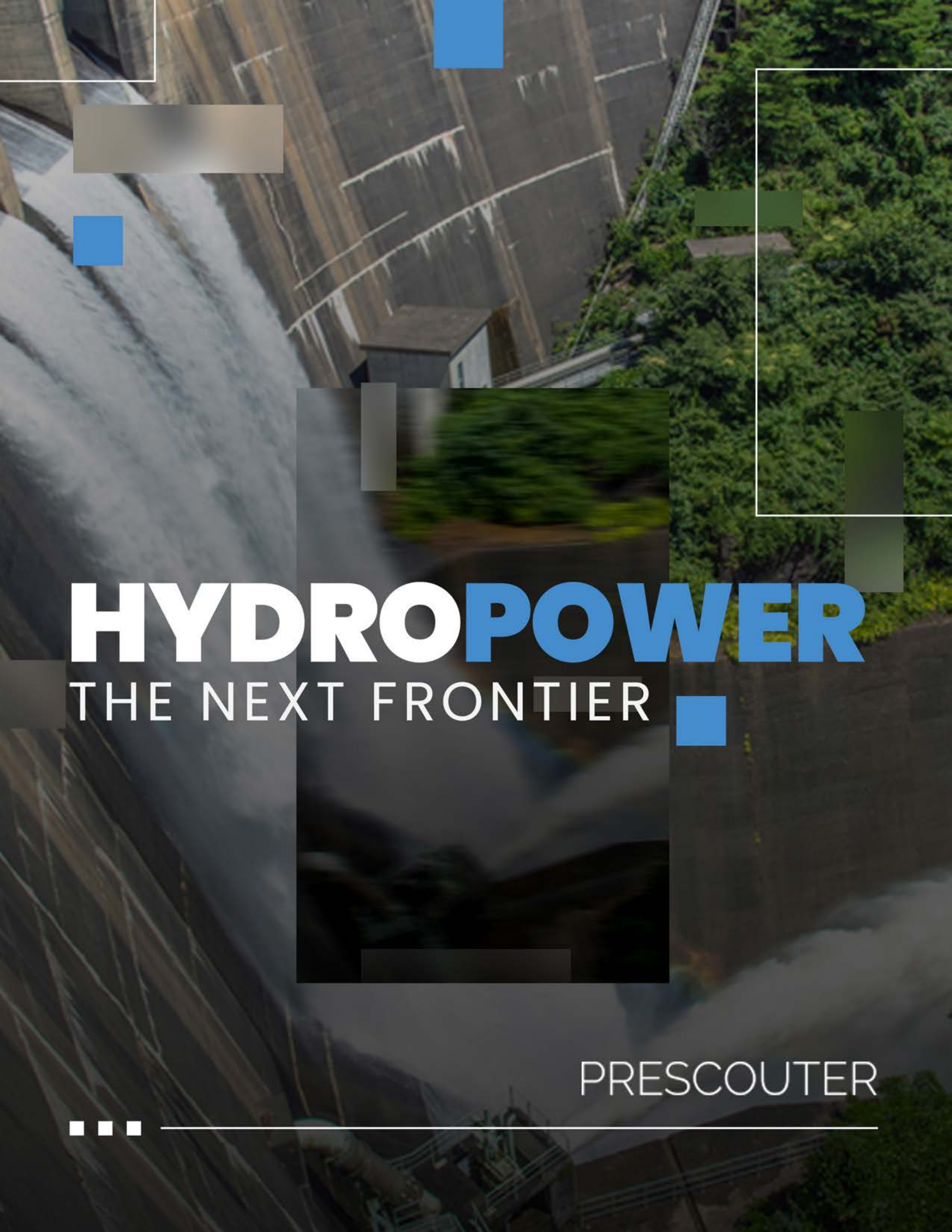

HYDROPOWER
THE NEXT FRONTIER

PRESCOUTER

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INTRODUCTION

In recent years, renewable energy sources have increasingly contributed to global energy production with a total supplement of around 2,200 GW (approximately 34% of global installed power capacity). Hydropower is the largest contributor, with approximately 1,200 GW (approximately 18% of global installed power capacity). It is hence a key energy source.

The aim of the present paper is to discuss some recent and future trends of hydropower, identifying challenges, open debates and new technologies. This document is an interesting reference to understand how the future of hydropower will be, and the changes that it is undergoing, rather than a basic assessment of existing hydropower technology and general hydropower operation.

Hydropower is shifting from a flexible source of energy covering peak loads in a fossil fuel/ dominated energy mix, towards a function of supporting the more flashy solar and wind sources available during the day. At the same time, pumped-hydropower has emerged as a key energy storage and valorization option. Hence, there is the need to better understand hydropower future potential, roles and market opportunities.

CONTENTS

CHAPTER 1

MARKET, CHALLENGES & EMERGING TECHNOLOGIES

The Hydropower Market

The small hydropower market (up to 10MW) was estimated to be USD 2.6 billion in 2019 and is projected to reach USD 3 billion by 2024, at a CAGR of 2.4% during the forecast period.

Asia pacific dominated the small hydropower market in 2018 (42%), followed by Europe (33%) and North America (18%). The highest CAGR is expected to be in the rest-of-the-world section (4.1% vs the overall of 2.4%) as shown in figure below [1].

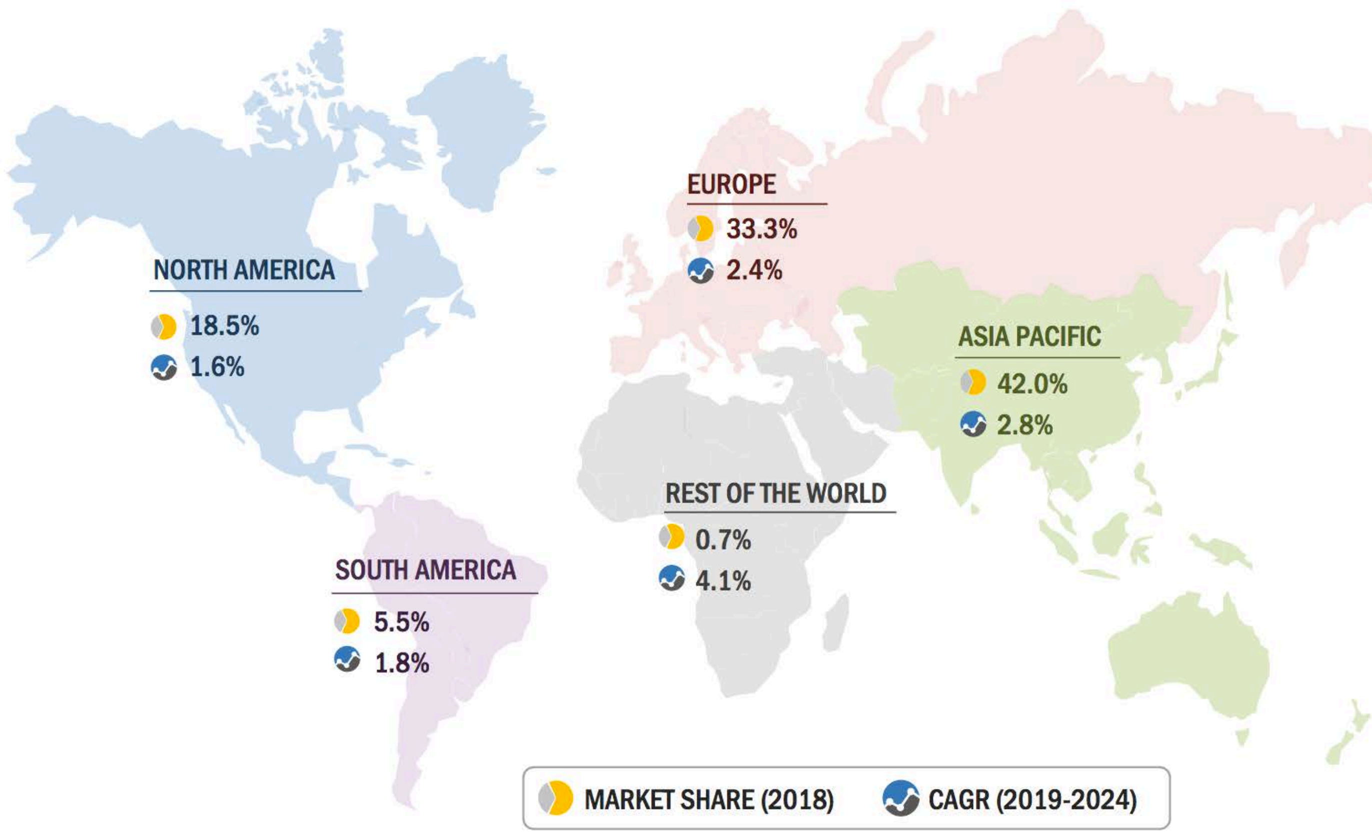

FIGURE 1 Market share and CAGR in the different world regions for small hydropower.
Source: ©2020 MarketsandMarkets Research Private Ltd. All rights reserved.

Increasing investments in rural electrification and renewable energy are expected to drive the small hydropower market during 2019-2024, while some of the restraints of this technology is the unstable supply, as the energy generated depend on seasonal highs and lows, which can act as a deterrent for small hydropower installations.

Emerging Technologies and Challenges in Hydropower

Throughout the world, 16% of electricity production is generated by hydropower plants [2]. Compared to wind and solar energy sources, hydropower is by now technologically mature. However, novel approaches in the design, operation, and planning of hydropower plants still exist, aiming at increasing hydropower flexibility, efficiency, lifetime, and cost effectiveness [3].

Increasing hydropower flexibility

Modern hydraulic turbines are faced with new challenges associated with the variable demand of the energy market. This necessitates new technologies to ensure greater flexibility over an extended range of regimes far from the best efficiency point of turbines.

Some of these technologies include:

- Stabilizer fins
- J-grooves
- Stator installed immediately downstream of the runner
- An adjustable diaphragm installed in the draft tube cone
- Air injection/admission
- Tangential water injection at the cone wall
- Axial water injection with high/low velocity and low/high discharge
- Axial water injection with counter-flow tangential component
- Ejector power plants for the excess flow rate
- Two-phase air-water injection along the axis

FIGURE 2 Examples of a draft tube, where turbulent phenomena occur:

picture of Zeco Hydropower (top) and Carmine Fioravante, Artingegneria (bottom).

Hydro generators with current-controlled rotors

Inline with the increased hydropower flexibility, frequent start and stop actions are required to provide regulation of turbines, which leads to additional wear on the energy-conversion components. Modern power electronics with current-controlled power supplies can provide new opportunities for the control of electrical machines. This is, for example, the case of the hydropower plant Frades II in Portugal, which is equipped with two pump-turbines and with an induction-motor generator with rotor power controlled by an AC-excitation system [4].

Digitalization of hydropower operation

The objective is to gather and analyze real-world data and apply them to the actual working conditions of turbines, providing advanced grid supporting services without compromising their safety and reliability. The annual energy production coming from the world's hydropower sector (1,225 GW) could increase by 42 TWh by investing in hydropower digitalization [3]. This production increase corresponds to USD 5 billion annual operational savings and a significant reduction of greenhouse gas emissions. One example is within the HYPERBOLE research project, granted by the European Commission, on the 444-MW MICA hydropower plant located on the British Columbia in Canada [5].

Hydroelectric energy storage and variable speed turbines

The increase of renewable energy in the electrical power system is requiring the need for energy storage power plants such as pumped storage hydropower plants (PSHPs, see Chapter 3). PSHPs continue to evolve to respond to the need for turbines to more quickly and more frequently pass from pump mode to turbine mode and vice versa. These turbines are called pump-as-turbines (PAT). Variable speed PATs are able to start up in pump mode and change the operation mode in a shorter time than turbines with constant rotational speed. Instead, the speed variation is possible thanks to the use of power electronic converters, in either of the two following ways: synchronous machines whose stator is driven with a variable frequency (converter-fed synchronous machines), and electric machines that are fed by AC currents into both the stator and the rotor windings (double-fed induction machines).

> By investing in digitalization, the annual global energy production from the hydropower sector could increase by 42 TWh.

Another interesting turbine that can work both in pump and turbine mode, and with adjustable blades, is the Deriaz turbine, currently under investigation by the Author and by the hydraulic laboratory Mhylab in Switzerland.

Novel technologies in small-scale hydropower

Small-scale hydropower is generally more eco-friendly and can potentially offer an alternative clean energy solution in the variable electricity market for local and remote areas development. Small hydro plays an important role in mini-grid and rural electrification strategies. The cost of small hydropower is lower and environmental impacts are not as significant as large hydro plants , although the cumulative impact of small hydropower plants in cascade may be appreciable. Nevertheless, there are a series of small hydro plants installed on existing hydraulic infrastructure, or in irrigation canals, that do no add additional impacts on river connectivity, and with also a good ecological behavior in relation to fish passage. In particular, novel designs of gravity hydraulic machines and turbines (see Chapter 2), along with advanced designs and operation strategies for PATs (see Chapter 3), are being introduced. For example, the 378-kW variable-speed Kaplan tubular turbine with fixed guide vanes, was installed in Ingelfingen small hydro to deal with head variation.

Fish-friendly hydropower technologies

The environmental and ecological sustainability of hydropower plants should be always considered in hydropower design, with a focus Sustainable solutions include for example fish-friendly turbines (like water wheels, the vortex turbine and the VLH turbine in low head applications and the Alden turbine for higher heads, see chapter 3) andthe development of water-lubricated bearings to mitigate water pollution risk. Therefore, hydropower companies and public authorities are continuing to invest in the hydropower sector, making hydropower a potential source of profit and business. For example, through 2020, in the state of New York there will be 47 projects encompassing 62 hydroelectric developments located on 29 different rivers in nine watersheds.

New materials in hydropower

The first used material in hydropower was wood, used to build water wheels, and that sometimes is used nowadays in composite water wheels with a steel structure and wooden blades. In the Nineteenth century, the development of new turbines led to the diffusion of steel, due to high fatigue loading and resistance to cavitation erosion and corrosion. With the development of micro turbines in the last decades, the need of more cost-effective material has been more and more perceived.

Modern fiber-reinforced composites have the stability and fatigue strength that can rival steel components, like those constructed with a polymer matrix and synthetic or natural fiber reinforcement. For example, the 1.2 MW SeaGen tidal turbine being installed in Northern Ireland uses a combination of fiberglass and carbon fiber to produce stiff and lightweight blades. They are chosen for their strength-to-weight ratio and economy of scale for complex shapes. US Syntethics is developing new polycrystalline diamond (PCD) bearing-shaft assembly for the RivGen Power System in an hydrokinetic context.

Composite bearings are also finding applications in conventional hydro as thrust bearings for runners, wear plates and trunnion bearings on spillway gates. Nowadays, innovative materials have been introduced also for water wheels, like high density polyethylene (HDPE), that is lighter and stronger than steel [6].

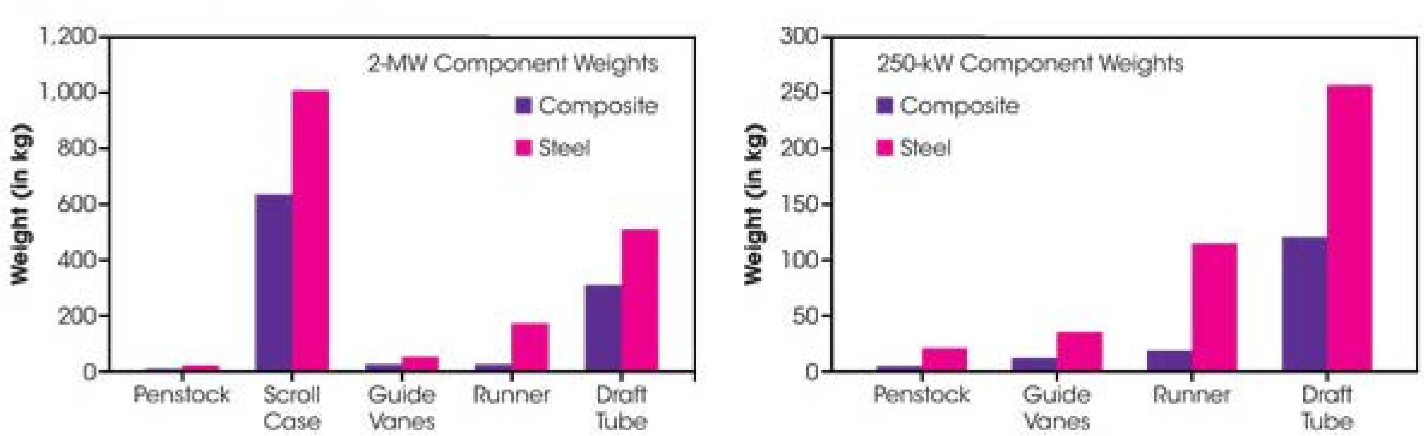

FIGURE 3 Component weights: Weights were calculated for the five turbine components for parts made from composite and steel materials. These numbers are based on 50% fiber weight. *Source: Hydroreview.*

CHAPTER 2

NEW MINI-HYDROPOWER TECHNOLOGIES

Gravity Water Wheels

Water wheels have been used for thousands of years to pump water, forge iron, grind grain, saw wood and many other applications. The most ancient water wheels exploited the kinetic energy of flowing water and were called stream water wheels. Water wheels that used the potential energy of water were introduced later and were called gravity water wheels (the water exerts a pressure on the blades due to its weight). Water wheels were in widespread use until the end of 19th century, when large hydropower plants replaced them.

Can water wheels be reinvented?

Nowadays, water wheels are being recognized once again as a promising technology, especially in the micro hydropower field for electricity generation (installed power typically lower than typically below 50 KW. Water wheels work well with very low heads and flow rates, for example in irrigation and mill canals, where conventional turbines (such as Kaplan turbines) are economically not viable. Water wheels are eco-friendly machines because fish can pass through them unharmed. Furthermore, their payback periods are shorter (7-12 years or lower) concerning Kaplan installations. The European Small Hydropower Association estimates that in Europe about 350,000 sites suitable for similar micro hydropower plants exist.

Are water wheels ancient or attractive machines?

With the aim of both filling the gap of engineering information on water wheels and shedding more light on their hydraulic behavior and efficiency, researchers from Politecnico di Torino, Turin, Italy built an experimental channel to test gravity water wheels. Scientists , and Emanuele Quaranta in first line, firstly investigated a breastshot water wheel, installing in the laboratory a 1:2 scale model of an existing one as seen in the adjacent images. In breastshot wheels, water enters into the buckets from the upstream side of the wheel, near or under the rotation axle, and they are used for head differences between 1.5 to 4 m, and flow rates below 600-800 l/s per metre width

FIGURE 4 The existing breastshot water wheels, for which a 1 : 2 scale model was investigated. The original diameter is 4 m.

The experiment showed a maximum hydraulic efficiency of 75% constant over a wide range of flow rates; the efficiency can improve up to 80% using an inflow weir instead of a sluice gate at the inlet. Theoretical and dimensionless models to predict the power losses and the power output were also elaborated as engineering tools, and Computational Fluid Dynamic (CFD) simulations were performed to investigate the effect of the blade number and shape on the performance [7]. These results have shown that the filling process of the buckets is the most important process to optimize in the engineering design.

The scientists then investigated the efficiency of overshot water wheels [8]. In this kind of water wheel, the water enters into the buckets from the top, exerting the pressure which drives the wheel on the blades along the downstream side of the wheel. Overshot wheels are used for head differences between 3 to 6 m, and flow rates below 200 l/s per metre width. The researchers again found that the maximum efficiency was constant over a wide range of flow rates and rotational speeds, with a maximum of 85%. They also developed a theoretical model to estimate the power losses and efficiency. The experimental results have shown that at rotational speeds higher than the maximum optimal one, the efficiency decreases. Therefore, they are currently performing simulations to improve the efficiency in these conditions.

A cooperation between Politecnico di Torino and Southampton University (UK) was also carried out to test the performance of undershot water wheels, where the authors tested in the laboratory two kinds of undershot water wheels: the Sagebien and the Zuppinger wheels, finding hydraulic efficiency up to 80% [9].

FIGURE 5 Overshot water wheel (Gratia Hydro)

To conclude, water wheels are competitive and efficient hydropower converters in low head applications. The vast diffusion of suitable sites and their low cost make them very attractive and promising. The design of a water wheel is not banal: an optimal one is what distinguishes a good water wheel plant from an ancient one.

Floating Water Wheels & Hydrostatic Pressure

Stream water wheels and floating mills

Stream water wheels are hydraulic machines that are installed in flowing water. The kinetic energy of the flow determines the rotation of the water wheel, generating mechanical energy and, eventually, electricity [6]. When a stream wheel is supported by boats on its sides, it is called a floating mill. Water wheels that instead use the potential energy of the flow (the water weight) are called gravity water wheels, as in Quaranta and Revelli, 2016 [10], see previous chapter.

FIGURE 6 Floating water wheel (AIAMS, Silvano Bonaiuti) *on the left, and gravity water wheel (breastshot type) on the right (Marco Gatta).*

From kinetic energy to the hydrostatic force of water

In a previous study, a stream water wheel was investigated in a channel which was as wide and deep as almost the blades of the wheel. In this case, it was observed that the efficiency was higher, since a water wheel set closely along the channel performs like a weir; the difference of water level between upstream and downstream acts in addition to the stream kinetic energy.

This obstruction effect was later better investigated by Batten and Müller, 2011 [11]. A body with a base plate and a bow section was constructed around the wheel; the contraction region was designed for maintaining a constant flow velocity and for the development of a head in front of the turbine.

Downstream of the wheel, there was a stern section with an expansion section that was designed for the flow to exit at a shallower depth and at higher velocity. There were also separators to generate a region of low pressure and to reduce the water level downstream of the rotor, facilitating the discharging process.

> This design generates the hydrostatic force (the higher water depth upstream of the blades) which drives the wheel; the maximum hydraulic efficiency is 65%.

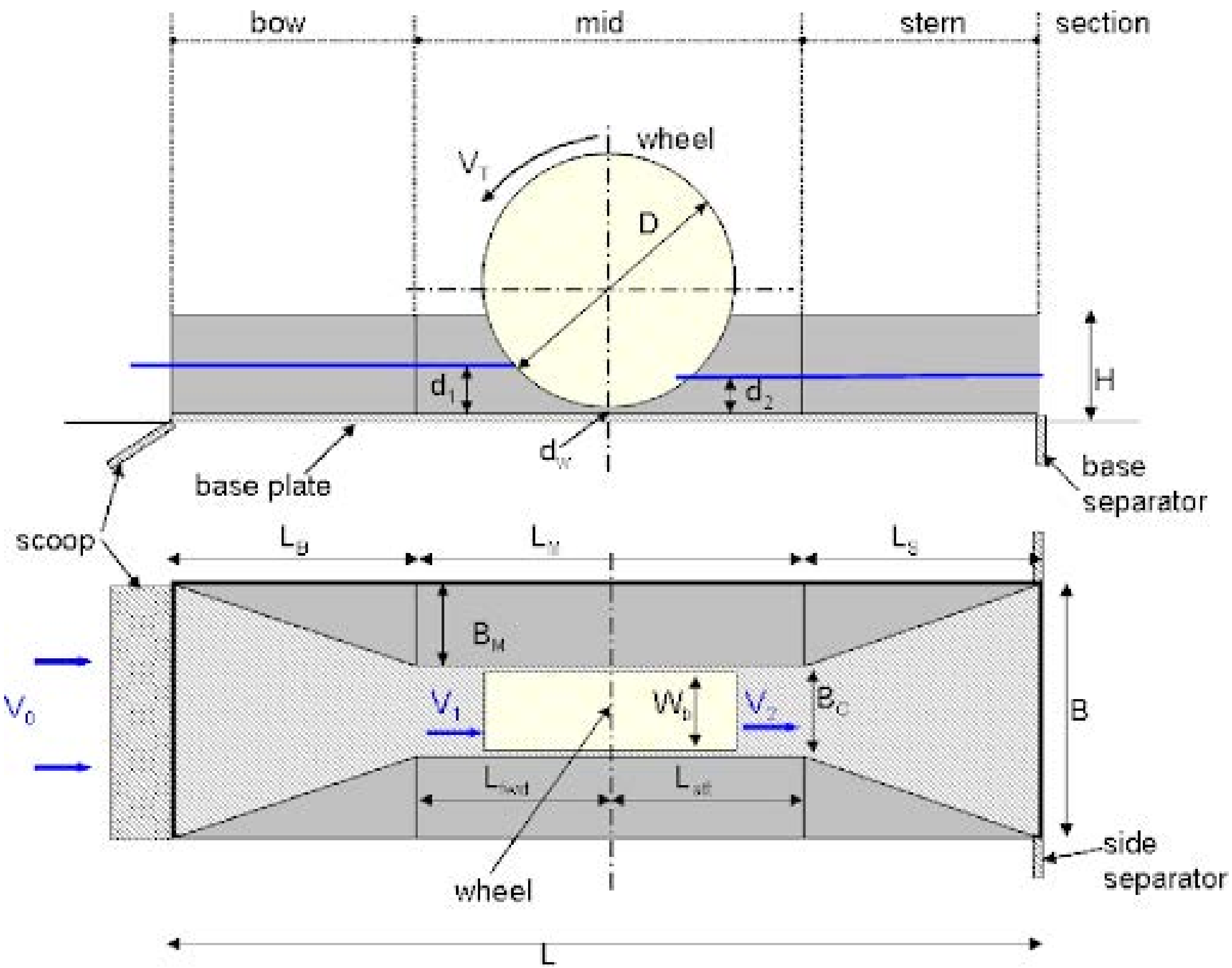

FIGURE 7 General schematic showing principle dimensions - *Source: Batten and Batten, 2011 [12].*

The hydrostatic pressure machine (HPM) in zero head applications

The damming-up effect generated by the water wheel is a principle which has also been effectively exploited in the rotatory hydrostatic pressure machine (HPM) by Senior et al., 2007 and Butera et al., 2020 [13,14]. HPM is a hydropower converter which acts as a weir, since the hub diameter is equal to the head difference, and the blades depth and width are similar to the downstream flow ones. An interesting video of experiments can be found *here.*

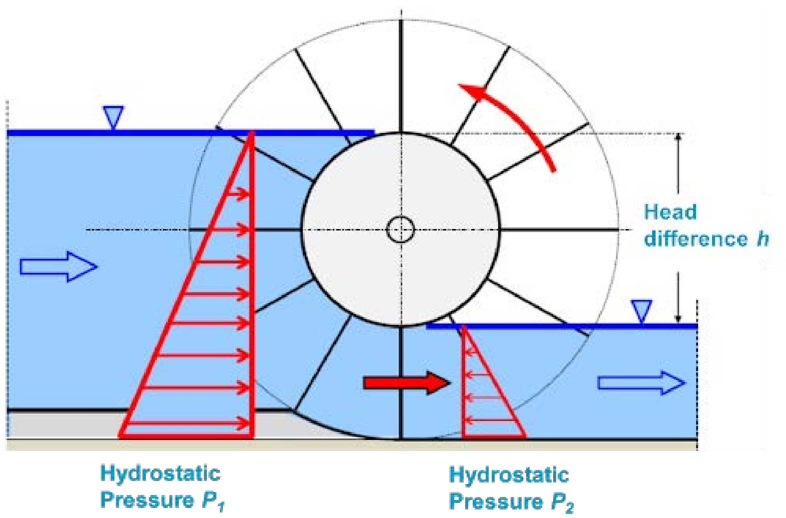

FIGURE 8 Concept of the HPM. Source: University of South Hampton [15].

The upstream flow depth ranges up to the top hub level. The water level difference generates hydrostatic pressure which acts on the blades, with maximum hydraulic efficiency that can be assumed 60-65% in practical applications to avoid very low rotational speed. This machine can be used in sites with a maximum flow rate of 2 m3/second/meter width, while the hydraulic head (generally from 1 m to 2.5 m) can be generated by the wheel itself. Therefore, the design has to take into account that the upstream water level increases when the wheel is in operation.

Future applications

The advantage of a HPM is that it can be used in a straight channel where bed drops do not exist, since the hydraulic head which drives the wheel can be auto-generated. This can also be a strategy in irrigation canals to raise the water level by the damming effect, carrying the water from a location to a higher one. At the moment, some HPMs are installed mainly for scientific purposes, and experimental and numerical research is in progress. The main challenge in water wheel operation is their low rotational speed. Optimization int his context are under investigation, like new power take off systems.

Hydrodynamic Screws

The Hydrodynamic Screw is one of the oldest hydraulic machines still in use today. One theory regarding its creation supposes that the King of Egypt asked Archimedes to design a machine to remove water from his ships. A second theory suggests that the device was created hundreds of years prior to the birth of Archimedes and he adapted it to make it popular around the known world. Hence, this machine is also called Archimedes screw.

Development and early applications

The hydrodynamic screw was initially used for pumping water from one location to another, of higher altitude. Hence, it can be used as a fish ladder to provide a method to allow fish to pass over a potential danger or obstruction, such as a dam or turbine. In 2001, John Burland used the Archimedes screw to stabilize the leaning tower of Pisa: using an Archimedes screw, soil was removed from the foundations without any damage and reduced the inclination angle of the tower by approximately 0.5°. The screw was also used in the Netherlands to create polders (reclaimed land that is under sea level), where excess water is pumped from the area of interest towards the sea.

Furthermore, the Archimedes screw is employed during injection molding to deliver the compound material to the mold. The technology of this screw has been also used in the medical field in over 20,000 patients in need of a heart transplant, keeping them alive until a donor heart can be found, with the aim of replacing the left ventricle.

The hydrodynamic screw for electricity generation

At the end of the 20th century, the hydrodynamic screw started to operate as a turbine, thus in the reversed way with respect to the pump principle. The first hydrodynamic screw turbines were installed in Europe in 1994. The torque is created by the hydrostatic force of water in the buckets, which makes the screw rotate around an inclined axis, typically 22°-35° on the horizontal. They can be used up to a hydraulic head of 8 meters and at maximum flow rates of 6 cubic meters per second. With a maximum hydraulic efficiency of 80-85%, Archimedes screws can represent an interesting technology in the micro-mini hydropower field. Archimedes screws exhibit maximum hydraulic efficiency of 80-85%, constant over a wide range of flow rates. Therefore, like water wheels, Archimedes screws can represent an interesting technology in the micro-mini hydropower field. The only drawback is that they need a gearbox to match the electric grid frequency, since they generally turn at less than 50 revolutions per minute.

With a maximum hydraulic efficiency of 80-85%, Archimedes screws can represent an interesting technology in the micro-mini hydropower field.

Future prospects: More than just a hydropower converter

The tidal barrage in the Severn Estuary is the most discussed tidal range project in the UK; it was suggested almost 100 years ago. However, each time that it was discussed, it was dismissed due to the very high initial costs and adverse environmental effects. The Archimedes screw turbine (one of the considered technologies) can also operate in this way, and thanks to the simple design, the initial costs can be reduced. It can also be used with a horizontal rotation axle as tidal stream turbines in series across a waterway.

FIGURE 9 Hydrodynamic screw installation in Italy (Carmine Fioravante, Artingegneria).

Spiral Pumps for Sustainable Irrigation

The spiral pump (also known as water wheel pump) is a hydraulic machine that pumps water without electricity. With the global efforts to reduce carbon emissions, the increased focus on renewable energy is making the spiral pump a viable option for pumping water, especially in rural areas and developing countries. Simple installation and low maintenance costs make the spiral pump a favorable, environmentally-friendly alternative.

What is a spiral pump and how does it work?

A spiral pump is constituted of a pipe wrapped around a horizontal axle, generating a spiral tube that is fastened to a water wheel. The water wheel is in flowing water, so that the water in the river provides the energy necessary for the rotation of the wheel. Hence, the spiral tube also rotates. When the inlet surface of the tube (the tube's external extremity) passes into the river, water enters into the tube. This water volume moves toward the outlet of the tube (the internal extremity), at the center of the wheel, where a straight tube is connected to the end-user.

Several water columns are generated inside the spiral tube, separated from each other by columns of compressed air trapped between the water columns. These columns of compressed air push against the water columns, so that at the outlet (the center of the wheel) the water achieves energy and velocity. In this way, it can be pumped at a higher elevation or at a certain distance from the river *(http://www.lnec.pt/fotos/editor2/hydrolink_2-2018_v4.pdf, pg.60).*

FIGURE 10 The spiral pump. Image courtesy of Jaime Michavila (aQysta).

Where & how can it be applied?

The possible users are irrigation consortia and civil people, in both developing and developed countries, especially for drip irrigation and partially for drinking water in developing nations. The largest application of the pump, and in general of water withdrawal, is irrigation. Although there have been past attempts to build such pumps in an artisanal way, aQysta developed a patent that allows to manufacturer this pump cost-effectively and as a commercial product. aQysta says that spiral pumps are able to pump to a maximum height of at least 20 meters and a maximum flow rate of at least 43.6 m3/day. As of October 2016, aQysta installed over 40 pumps worldwide in countries like Nepal, Indonesia, Turkey, Zambia and Spain [16]. Optimizations are in progress to improve the performance (HyPump H2020 project).

Environmental and economic benefits: Future development

Spiral pumps work without fuel or electricity, since the needed energy is supplied by flowing water (preferably a flow velocity faster than 1 m/s). The spiral pump saves up to 70% of overall lifetime costs compared to diesel pumping. The spiral pump requires no operation costs and it is environmentally friendly.

Therefore, spiral pumps can represent an interesting technology, especially for irrigation. This is the motivation that has encouraged Politecnico di Torino (Polytechnic University of Turin, Italy) and Southampton University (UK) to start scientific research on spiral pumps, in collaboration with the industry.

New Action Turbines

Hydraulic turbines for hydropower plants have been used since the nineteenth century. However, new and innovative turbines are being introduced to the market, in order to improve efficiency, and to extend the operational range of existing turbines. The so called M turbine was developed and patented in Italy (Patent 0000282352) by Eng. Mario Mariucci in October 2016, who is now scientifically cooperating with Eng. Emanuele Quaranta (Turin, Italy, author of this white paper), to overcome the deficit of standard action turbines.

Innovation of the M turbine

The M turbine is an action turbine, thus a hydraulic turbine that exploits the kinetic energy of a water jet, differently from reaction turbines like Francis and Kaplan turbines, that exploit the water pressure [17]. Furthermore, it is an axial flow machine, since the water jet flows parallel to the vertical rotation axis of the turbine. The M turbine that can work in hydraulic conditions where common action turbines (Pelton and Turgo turbines) cannot be convenient and efficient. Existing action turbines in very low head sites can exploit very small flow rates (few tens of liters per second), with very low power output. The M turbine can be employed in sites with heads (difference between the water level upstream and downstream of the turbine) less than 3 m and flow rates less than 3 m3/s (Source: Teti srl). The efficiency is between 85% and 90% for a wide range of flow rates. Hence, the M turbine represents a suitable alternative to common action turbines in the micro hydropower field (power less than 100 kW), especially in sites with head differences less than 10 m.

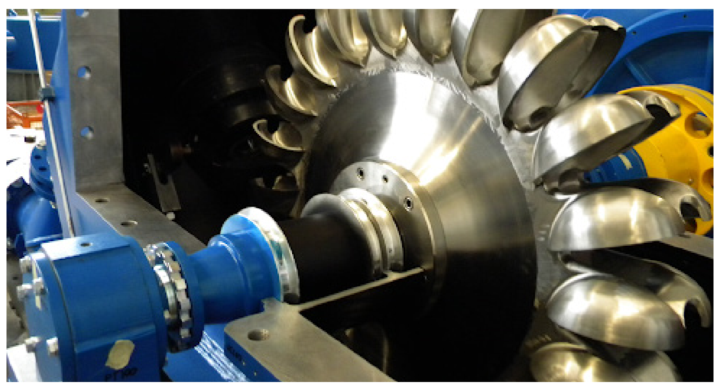

FIGURE 11 The M turbine observed from the top *(Mario Mariucci, left)*, and a Pelton turbine *(Zeco Hydropower, Riccardo Bergamin, on the right)*

How does the M turbine work?

The M turbine is installed with a vertical rotation axis inside a tank, which is filled with water. The water free surface level of this tank corresponds to the upstream water level, while the downstream water level corresponds to the tailrace, as well as the water free surface in the river just under the turbine. At the center of the tank is an orifice, where the turbine is installed. Along the periphery of the wheel, there are the blades.

The water flows from the tank to these blades, exerting a force on them, and determining the rotation of the turbine. The cross section through which the flow rate passes is a circular crown as large as the blades. Thanks to movable sheets, it is possible to regulate the portion of this cross section through which the water jet can flow (called effective area), so that the flow rate can be regulated. This means that when the available flow rate reduces, the effective area is also reduced by an external control; in this way, the head in the tank is maintained constant, as well as the flow velocity. As a consequence, the rotational speed of the turbine can be maintained constant, thus expensive electro-mechanic equipment to change the turbine velocity or blades inclination are unnecessary.

When the downstream water level increases, a lifting system lifts the turbine to avoid the turbine becoming immersed in water. In this way, the draft tube used in common reaction turbines is not required. A similar technology, the VLH turbine, is an axial flow and reaction turbine, without spiral case and draft tube, but with no possibility to be moved on the vertical direction, although it can be moved away from water for maintenance.

CHAPTER 3

DIFFERENT TYPES OF HYDROPOWER (PLANTS)

Tidal Energy

Oceans cover over two thirds of our planet's surface. The energy contained in the oceans has tremendous potential, including in the form of waves and tides. These sources have an estimated 337 GW. New technologies and projects represent a significant opportunity for renewable energy development in several countries [18].

The basics of tidal energy

Tidal power is created using a head difference between two bodies of water. To create this difference, a wall separates the two water bodies. As the tide flows in or out, the wall blocks the flow of the tide and generates this head difference. When the head difference has reached the optimum design level, the water is forced to pass through holes in the wall, where turbines are placed to generate power. Since two tidal cycles occur per day, this head difference develops four times each day (in one cycle, the tide comes in and out).

Turbines convert the water energy into mechanical energy, and then into electricity by means of an electric generator.

Since tidal head differences generally measure a few meters, typical turbines are low head turbines, e.g. water wheels, Archimedes screws and bulb turbines. One other way to generate power from tides uses turbines on the seabed, driven by the kinetic energy of the moving tidal flow, similar to wind turbines in airflows [19].

Tidal power projects exist in France, South Korea, Russia, the UK and China, among other places. Research suggests that in the UK over 20% of the national energy demand could be satisfied by exploiting tidal and wave energy sites around the country [20]. Famous tidal power plants include:

- La Rance in France (240 MW)
- Lake Sihwa in South Korea (254 MW)
- Annapolis in Canada (20 MW)
- Jiangxia in China (3.9 MW)

FIGURE 12 La Rance tidal plant in France (240 MW). Courtesy of George Aggidis.

The latest projects and innovations in tidal energy

Tidal energy offers a long-term, predictable form of clean energy. Ongoing projects like the Swansea Bay tidal lagoon in the UK (320 MW) has generated positive interest from local people and government institutions. New tidal projects are under consideration throughout the world, including locations that were until now considered unsuitable [21]. Some tidal plants under construction include the Meygen Tidal Project (398 MW) in the UK, while others are in development in Russia, South Korea, India and the Philippines [22].

To support these projects, tidal power engineers are refining existing technologies, with a special focus on the improvement of turbines. Modified bulb turbines with an additional set of guide vanes allow better management and control of the flow through the turbine. Bulb turbines can reach very high power output. Two examples include:

1. The 7 meter diameter bulb turbines in the Swansea Bay tidal lagoon that can produce 16 MW.
2. The innovative Straflo turbines can reach values of 20 MW, as in the Annapolis plant.

Archimedes screws could be employed as a fully submerged tidal stream device, or they can be enclosed in a pipe system. Archimedes screws also have the additional advantage of “fish friendliness”. Finally, water wheels under testing use inflow hydraulic structures to better control flow and power [23].

The future of tidal energy

In the short term, tidal energy will likely represent a small share of total renewable energy. But these projects and new technologies demonstrate its growing relevance in specific locations, complementing more traditional sources like wind and solar.

The theoretical global tidal resource is estimated to be 8800TWh/yr. Technically recoverable tidal energy potential is 800TWh/yr. Total theoretical power available along the U.S. coasts is estimated to be 50 GW.The technical resource is estimated to be 250 TWh/yr. Alaska shares the vast majority of this amount. The theoretical potential in UK ranges from 50 to 94 TWh/y. Finally,Canada has 110TWh/y of theoretical potential [24].

Micro Hydropower in Water Distribution Networks

Water distribution networks (WDN) are present in all developed cities. Their aim is to deliver drinking water to citizens. New technologies, however, could also allow them to function as renewable energy sources.

What is a water distribution network? Why are they a source of energy?

A water distribution network is a net composed of nodes, where water is injected or collected, and pipes where water flows, which link the nodes. Maximum and minimum thresholds on water pressure and flow velocity must be respected in a WDN in order to avoid technical and engineering complications along pipes and at the nodes. This means that, in certain points, where pressure is higher than the maximum threshold, the excess pressure has to be dissipated. Overpressure is dissipated by installing valves which generate power losses in the water flow (so-called head losses), reducing water pressure. Valves mainly act by reducing locally the cross section of the pipe, generating an obstacle to water flow. Water encounters resistance flowing across this obstacle, losing energy and pressure. Head losses represent an amount of water energy which is lost and wasted.

Recovering excess water energy and pressure

To avoid dissipating water power, pressure reduction can be generated by installing hydraulic turbines. The excess water pressure is converted into mechanical and electrical power by the turbine. The effect is the same as installing valves—a reduction in water pressure—but now the original surplus of pressure is converted into electricity.

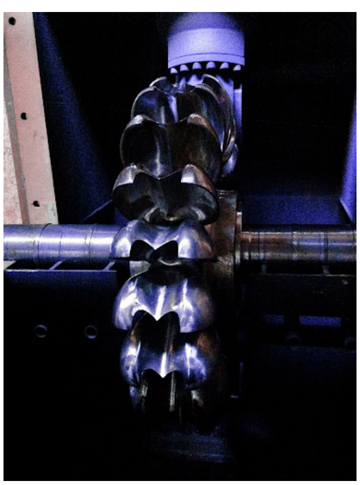

FIGURE 13 Pelton *(photo of Carmine Fioravante, Artingegneria, left)* and Bulb *(photo of Riccardo Bergamin, Zeco Hydropower, right)* turbines.

Considering typical turbine efficiency, only 20-40% of the surplus water pressure is lost, and 60-80% is converted into electricity. Typical turbines are bulb and Pelton turbines, or pumps operating as turbines (PAT).

Bulb turbines are hydraulic machines which rotate around a rotational axis parallel to the flow direction. They are composed of a certain number of blades installed around the axis.

PAT are conceived to work as pumps (hence with the aim of lifting water, giving energy to water instead of taking energy from water). If they rotate in the opposite direction, PAT can work as turbines, extracting energy from water.

Bulb turbines and PAT are installed inside pipes. Pelton turbines are installed outside of the pipe. Water is squirted into the turbine blades installed along the turbine external circumference. After that the water has been used by the Pelton turbine, water is reintroduced into the pipe with less energy and pressure [25]. These are the most used turbines in WDN because hydraulic conditions in aqueducts involve high pressures and low flow rates (generally tens/hundreds liters per second).

A similar concept can be seen in irrigation networks/canals, where the excess natural head is dissipated by drops in the channel beds. In order to exploit these drops, as head differences to drive hydropower plants, low head turbines, like water wheels can work in a somewhat similar way. There, water is used both for irrigation purposes and for energy production.

All of these options should be seen in the wider context of smart cities. As cities look for ways to generate power and carefully manage their water, the integration of electricity production into water pressure management represents a mostly untapped opportunity.

Pumped-Storage Hydropower Plants

Pumped-storage hydropower plants (PSHPs) are spreading worldwide and are at the center of engineering goals. PSHPs can act both as an energy supply and storage to stabilize the electrical grid, depending on the energy demand. They can allow the further spread of wind and solar power plants, which are the renewable-based power plants most responsible for the variability of electricity delivered to the grid. Finally, considering the trend of energy prices during the day, PSHPs are also considered an attractive solution for new market opportunities worldwide.

Advantages and drawbacks of renewable resources

The operation of wind and solar plants depends on atmospheric conditions, which cannot be managed by human control. Wind and solar sources exhibit the highest variability in time and their production can be predicted, but with great difficulty. Instead, hydropower plant operations are more flexible, since hydropower output can be easily managed. More than 50% of renewable energy is generated by hydropower plants [25].

In the last decades, due to the spreading of wind and solar plants and the diversification of human activities, there is frequently a surplus of energy delivered to the grid. This surplus of electricity has to be stored or intentionally wasted in order to not destabilize the electrical grid. The best solution to deal with this problem is represented by using pumped-storage hydropower plants (PSHPs), i.e. hydropower plants that can operate also in reverse to not only create energy, but also to store it.

Pumped-storage hydropower plants are hydropower plants that can both create energy and store energy.

FIGURE 14 Installation of a pump-turbine. *Photo courtesy of Voith GmbH & Co. KGaA.*

Fish-Friendly Turbines

Hydropower plants convert the power of water into mechanical and electrical power. The hydraulic turbine allows for this conversion. However, fish generally cannot pass through the turbines unharmed. The primary exceptions include some low head (<6m) turbines, like water wheels and Archimedes screws. However, these do not work for large hydropower plants. Therefore, two strategies have been developed for higher head hydropower: fish passage facilities and fish-friendly turbines.

Improved fish passages

Fish passages are hydraulic structures that allow the upstream and downstream migration of fish when a dam impedes their migration. For example, fish ladders consist of a channel with typical bed slope between 5% and 10%, with pools separated by transversal baffles. Fish ladders mostly enable upstream migration. Fish passages also exist for downstream fish migration, coupled with screens behind the turbine that prevent fish entrance and divert fish to the fish passage [26].

> While effective should be supported by fish-friendly, fish passages add cost to hydropower dam construction. Improved and necessary turbines offer to a potentially better alternative.

Fish friendly turbines

The Alden turbine specifically works with higher head sites. The Alden turbine has spiral blades wrapped around the shaft [27]. The shaft rotates around a vertical axis. Maximum efficiency can reach 90%, with fish survival rate of more than 90%.

Alternatively, the Minimum Gap Runner turbine (MGR) has a modification of the Kaplan turbine. The gaps between the adjustable runner blade and the hub, and between the blade tip and the discharge ring, are minimized at all blade positions. Such modifications decrease fish injury and mortality caused by grinding and by local high shear stresses and turbulence. Additionally, the modifications improve turbine efficiency.

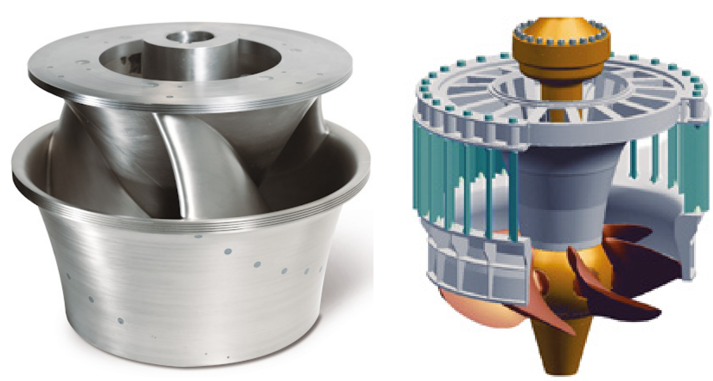

FIGURE 15 The Alden turbine; (B) The MGR turbine *(courtesy of Voith GmbH & Co. KGaA)*

Hydrokinetic Turbines

Wind turbines exploit the kinetic energy of an air flow, i.e. wind velocity, to rotate and generate energy. In recent times, wind turbines have also been developed to work in a water flow, like natural streams, tides, ocean currents and artificial water networks, requiring flow velocities generally higher than 1 m/s. When a water flow is used instead of wind, the turbines are called hydrokinetic turbines (HT). Since water density is almost 800 times higher than that of air, HTs can produce more energy than wind turbines for the same flow velocity and turbine dimensions. Different research projects are currently under development in order to make HTs a standard market product.

HT potential in the USA is estimated to be 120 TWh/year in rivers, 210 TWh/year from waves and 250 TWh/year from tidals.

Types of hydrokinetic turbines

Hydrokinetic turbines are categorized into Cross Flow and Axial Flow, depending on the orientation of their rotation axis.

Cross Flow HTs

Cross Flow HTs have either a horizontal axis, or a vertical axis, perpendicular to the flow direction. Cross Flow HTs can be further classified into drag type (like the Savonius turbine, which exploits the impact of the water flow, or the floating water wheel) and lift type (like the Darrieus turbine, where the airfoil effect is used to push the blade).

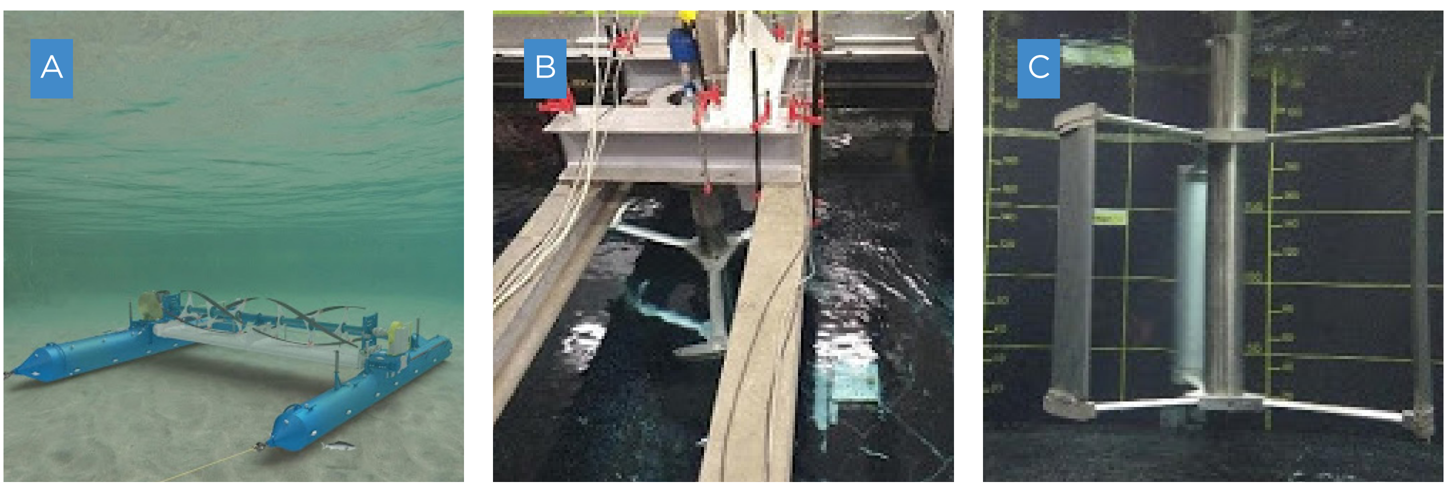

FIGURE 16 A) Igiugig-RivGen® Project. This is a Cross flow HT with horizontal axis, Darrieus type with helical blades. *Photo courtesy of Susy Kist of ORPC;* (B and C) Vertical axis Darrieus turbine with straight blades. *Photo courtesy of Tommaso Morbiato, Windcity.*

Axial Flow HTs

Axial Flow HTs have a horizontal axis, parallel to the water flow, similar to bulb turbines [17]. HTs are completely immersed in water. Nevertheless, the first HT to be used has been the floating water wheel, a drag type and cross flow HT.

FIGURE 17 Installation of an axial flow HT from Guinard Energies *(photo courtesy of Flavien Martine)*. The turbine, installed in a duct, can generate 20 kW.

Hydrokinetic turbine power generation

The maximum power that a hydrokinetic turbine can generate is defined by the Betz limit. The Betz limit claims that the ratio of the maximum power P generated by the HT, to the kinetic power K of the fluid flow that passes through the turbine, exhibits a maximum limit: this ratio is called power coefficient Cp = P/K, and the maximum value established by the Betz limit is Cp,max = 16/27 = 59.3%, independent of design configurations. The kinetic power is defined as K=0.5 Av3, where rho=1000kg/mc is the water density, A is the frontal area of the turbine interacting with the flow and v is flow velocity.

A well optimized HT can exhibit a power coefficient equal to 50%, although classical HTs usually exhibit a power coefficient of 20-25%. However, optimized HTs enclosed inside a duct can exceed the Betz limit because the pressure energy is used in addition to the kinetic one. This is the case that was published in the journal Renewable Energy [28], where the power coefficient of a turbine inside a duct reached Cp = 86.5%.

Developments

The International Electrotechnical Commission is currently developing standards for HT applications, with specifications and design requirements for river applications, to help the promotion of hydrokinetic turbine international market.

The United States Department of Energy *states*: Hydrokinetic energy from flowing water in open channels has the potential to support local electricity needs with lower regulatory or capital investment rather than impounding water with more conventional means.

Since 2013, more than 300 projects have been developed from 280 different companies. Among the biggest companies, 194 companies are based in the USA, 45 in the UK, 19 in Australia and 19 in Canada. In the European Union, 8 are in Ireland, 6 in Denmark and most of the developed HTs are axial flow turbines [29]. Some of them are Guinard Energies, Ocean Renewable Power Company, Verdant Power and Marine Current Turbines.

Real hydrokinetic turbine installations

The Seagen turbine is an axial HT, 18 m in diameter installed in Strangford (Ireland), with rated power of 1.2 MW and producing 6000 MWh/year of electricity.
The Verdant Power turbine is an axial HT, 5 m in diameter, 35 kW of power and power coefficient between 0.38 and 0.44; the installed 6 HTs generate 70 MWh of electricity at East River, New York [30].

HTs can also be used to power off-grid irrigation pumps, like the axial HT in Neiva (Colombia), that is 1 m in diameter and 1.1 kW of power (similar to the spiral pump). One other example is the Darrieus turbine installed in the Roza Canal (USA), 3 m in diameter and 10.9 kW [31].

Engineering challenges and studies

Hydrokinetic turbines are under investigation by research and commercial companies. The most important challenges are:

- Cost optimization (Niebuhr et al., 2019, estimated a payback period of 6.5 years for the Groblershoop HT plant in South Africa, made of a system with 4 HTs)
- Performance evaluation (power coefficient) at different geometric configuration
- Deflectors and shroud to better direct the water flow into the turbine
- Hydraulic behavior when more HTs are used (array of HTs)
- Requirement for diffusers and channel modifications to control flow velocity and direction

Installation of HTs can generate some small environmental impacts, like blocking of navigation and fishing; turbine components, noise and vibration can affect the river habitat, although fish mortality through HTs is generally very low, because fish tend to avoid HTs.

Although the structural requirements are minimal, cavitation and high installation costs per kW remain an open research topic. Since HT technology is in its infancy, the cost can vary a lot among different installations. For example, a 500 kW HT was estimated to cost between 950-1150 $/kW, with respect to 700 $/kW of an analogous wind turbine. The US Department of Energy has defined a levelized cost of energy (LCOE) calculation method to allow comparisons across HEC technologies, ranging between 25 to 80 cents/kWh.

The interest of the scientific and engineering communities on hydrokinetic turbines will continue to grow. HTs will have a key role both as a local source of energy for householders in rural areas, for remote localities and villages in emerging countries, and as a powerful technology to exploit wave and tidal energy. Several companies are emerging as HT manufacturers and different research and industrial projects are under development, making HTs a rapidly developing sector. However, the common low speed of rivers is at the moment the most challnging factor in their wide development in the river context.

Photovoltaic-Hydropower Hybrid Plants

Hydropower and solar power plants were developed separately in the past. Recently, hydro and solar plants have started to merge into photovoltaic-hydropower hybrid plants [32], where floating solar panels are installed on the water surface of hydropower reservoirs and/or on the dam surface. This represents a cost-effective strategy for allocating new PV plants without occupying natural lands, protecting dams from insulation and increasing hydropower generation by reducing evaporation losses.

In photovoltaic-hydropower hybrid plants, PV panels are incorporated into the hydro plant mainly in two ways: installation of PV panels on the downstream face of the dam [33], an option only possible in certain plants where the face slope of the dam is below 40° (like in gravity and embankment dams), or floating PV panels on the water surface of the hydropower reservoir [34].

FIGURE 17 A) Foating PV on Mettur Dam, India. Credit: Marco Rosa-Clot of Upsolar Floating
B) Floating solar plant. Credit: Silvano Pinter, Hydrosolar srl

In hybrid systems, several benefits are achieved with respect to the independent operation of the solar and hydro plants. In general, hydro plants are easy to access and already grid-connected, thus the installation of PV panels requires less work and infrastructure.
In the former case (PV on dams) the benefits are the following:

- PV panels protect the dam surface from direct solar radiation that may negatively affect the stability of the dam itself, reducing thermal excursion of the dam surface and increasing dam durability
- PV panels are installed on an existing structure (the dam surface), reducing land use
- Energy generated by PV can be used for pumping in pumped-storage hydropower plants
- PV panels are mounted on an inclined area, minimizing the distance required between two panels with respect to an analogous installation on a flat area, thus increasing solar energy generation

In the case of floating solar panels on hydropower reservoirs, the benefits are the following:

- Land use is minimized
- The cooling effect provided by water below the panels increases panel efficiency
- The shading provided by PV panels on the water reduces algae growth and water evaporation, improving hydro energy generation and water quality
- The water surface provides areas free of shading objects along with higher sunlight reflection, improving PV generation

Floating panels can increase the capacity factor of a hydropower plant by 50% to 100%, where the capacity factor of the hydro plant is the ratio of total generated energy to the maximum energy than can be generated if the hydro plant would always work at its maximum installed power capacity [35]. Floating panels can gain 7% to 14% more energy than a land installation due to the reduction of temperature.

However, floating PV has an important limit: It cannot resist strong wind gusts, necessitating a very large number of mooring points in order for it to remain intact. The solution devised by the company Upsolar Floating is based on a much more robust concept where rafts are built with polyethylene pipes and steel beams supported by 20 to 24 panels. They have been shown to resist damage by wind up to 140 km per hour.

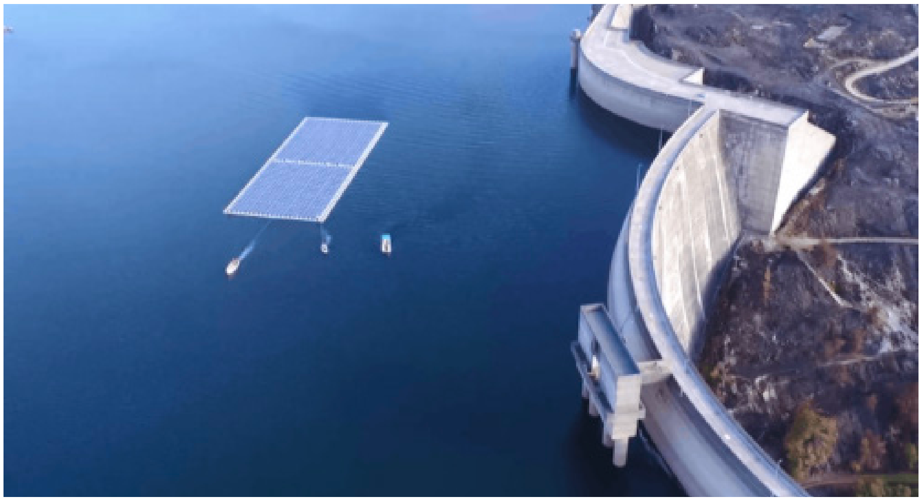

FIGURE 18 Floating PV at the Alto Rabagão pumped-storage reservoir, Portugal. Credit: Michaela Costes, Ciel & Terre USA

Real cases and costs

Floating solar panels installed on a dam surface can be applied to several dams across the globe. For example, a recent study carried out by the European Commission's Joint Research Center revealed that the application of such hybrid systems to 10 selected dams in South Africa can generate an annual electricity amount of 72 GWh from PV from an installed peak power of 42 MWp. An example of a real project can be found in Japan's Kutani Dam, with an installed PV capacity of 4.99 MWp and a 20-year revenue of ~ $5.4 million.

FIGURE 19 PV powered dam transformation in Japan. Credit: Kougias, I., Bódis, K., Jäger Waldau, A., Monforti Ferrario, F., & Szabó, S. (2016). Exploiting existing dams for solar PV system installations. Progress in Photovoltaics: Research and Applications, 24(2), 229-239.

An interesting example of floating PV is at the Alto Rabagão pumped-storage reservoir in Portugal, with an installed capacity of 220 solar kWp. One other example is the 200-kWp floating solar project in Suvereto, Italy.

Today, a floating solar project costs 10% more than a solar plant on the ground, but this higher cost is overcome by the increased efficiency. The final kWh cost is 20% lower than a ground-based project. The cost for large projects is about ~ $763 per kWp, all included (mooring, cable, inverters, electric cabinet), while the final kWh price is in the range of $33 to $54 per MWh, depending on the local radiation conditions.

FIGURE 20 200-kWp floating PV in Suvereto, Italy. Credit: Marco Rosa-Clot of Upsolar Floating

Potential estimation and conclusion

By assuming coverage of 25% of the 265.7 thousand sq. km that represent all existing hydropower reservoir surfaces with floating PV, 4,400 GW could be generated (6,270 TWh) that can reach 5,700 GW (8,000 TWh) using all existing reservoirs, both for hydropower and for other purposes. Floating solar could prevent about 74 billion cubic meters of water evaporation, increasing water availability by 6.3% and hydropower generation by 142.5 TWh. This application to water reservoirs worldwide has already been considered, for a total installed capacity of floating PV of 376 MW in China, 22.7 MW in Japan, 9.3 MW in the United Kingdom, 6 MW in South Korea, 4 MW in Australia, 0.77 MW in Italy and 0.67 MW in the United States. Other examples, but at a minor scale with respect to the previously mentioned countries, can be found in Spain, Portugal, France and India.

Due to the advantages of this type of combined hybrid plant, the potential and market opportunities are expected to grow in the future, especially the floating solution, thus reducing the combined (hydro + solar) GHG emissions per kWh produced, particularly in tropical regions.

CONCLUDING THOUGHTS

Hydropower energy is the most spread renewable energy sources that exist nowadays. The resources (bodies of water) are widely spread and available throughout the whole world. If sustainable technologies like fish friendly turbines and fish passages are used (as we presented here), environmental impacts are reduced, while the use of existing structures (typically for low head hydropower) can allow better water and resource management, optimizing water use and minimizing impacts. What is more, hydro technology can be combined with other renewable sources in at least two ways: Pumped-storage hydropower plants (for those intermittent energy sources like solar and wind) and hybrid systems (solar-hydro as presented in this paper).

Hydropower is one of the most versatile sources in terms of installed capacity and flexibility since it can be installed for outputs bigger than 1 GW, but also can supply small rural communities (below 100kW, up to few kW) that have today difficulties in getting their energy from other sources or distribution grids. Technological advances in design, materials and system optimizations, multipurpose uses of hydropower such as flood control and electric grid stabilization, and installations inside existing structures (like irrigation ones) have converted hydropower into an attractive investment option. This is confirmed by many research projects being funded by the European Commission that aim at the retrofitting of existing plants, to increase flexibility and sustainability.

Sustainable solutions should be always considered in order to limit environmental impacts, especially when new barriers are planned to be installed, in order to not reduce the ecological status of rivers.

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