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Review

Water Lifting Water: A Comprehensive Spatiotemporal Review on the Hydro-Powered Water Pumping Technologies

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Received: 20 June 2019; Accepted: 9 August 2019; Published: 12 August 2019

Abstract: Water pumping systems driven by renewable energies are more environmentally sound and, at times, less expensive alternatives to electric- or diesel-based ones. From these, hydro-powered pumps have further advantages. Nevertheless, these seem to be largely ignored nowadays. More than 800 scientific and nonscientific documents contributed to assemble their fragmented storylines. A total of 30 pressure-based hydro-powered pumping technologies worldwide have been classified and plotted in space and time. Although these do not present identifiable patterns, some noticeable clusters appear in regions such as Europe, South–Southeast Asia, and Eastern Africa, and in timeframes around 1960–1990, respectively. Some technologies have had a global impact and interest from their beginnings until contemporary times, others have been crucial for the development of specific countries, and other ones barely had almost imperceptible lives. All of them, nonetheless, have demonstrated to be a sound alternative to conventional pumping technologies, which can be unaffordable or inaccessible, particularly in remote and off-the-grid areas. Currently, hydro-powered pumping technologies face a regained momentum, hence a potentially promising future. However, researchers, manufacturers, and users need to be aware of the importance that management systems, as well as business models, pose for these technologies beyond their mere performance.

Keywords: hydro-powered; water-powered; water-driven; hydro-mechanical; self-reliant; water lifting; water raising; water pump

1. Introduction

Given the considerable number of smallholders farms worldwide [1], intensification of their crop farming is key for local and global food security [2]. However, smallholders face many uncertainties linked to weather events, crops diseases, and market fluctuations. In addition, on-farm conditions are often suboptimal because of low availability of inputs and lack of control/information to decide on their use. Although access to water is not the only factor influencing farming, improving water control for small-scale farming is a major option to secure smallholder production [3]. Pressure-based irrigation technologies, either introduced as a new choice or as the result of former gravity-based systems converted into (water-saving) drip and sprinkler irrigation, are one option. Another option is to use pumping technologies to allow water delivery to fields that used to be otherwise unirrigated.

Pumped irrigation is ruled worldwide by electricity- and diesel-based systems. They bear high operation and maintenance costs because of continuous use of electricity from the grid and expensive fuels, respectively. As a consequence, these technologies might be eventually (too) cost-intensive for most smallholders—which makes them less accessible and/or suitable for small farmers. Furthermore, they are strongly linked to air pollution due to their gaseous emissions and noise [4,5]. More environmentally sound and, at times, less expensive alternatives would be pumping systems based on renewable energy (RE) sources, i.e., solar power, wind power, biomass/biogas, and hydropower [6].

Hydro-powered pumping (HPP) technologies, namely those driven by the energy contained in the water they lift, correspond to a concept as ancient as effective [7,8]. Non-direct lifting (i.e., pressure-based) HPP devices started being envisaged by Al-Jazari in the early 13th century [9], and later on by Taqi Al-Din [7,10], Agricola [11], Ramelli [12], and other authors [13] during the 16th century. These pumping systems pose further advantages over their other RE-based counterparts: (i) Their energy source is generally available 24 hours a day, seven days a week, relatively concentrated and more predictable; (ii) they have a higher power-to-size ratio, thus are more cost-effective; (iii) they are mechanically simpler and more robust, hence less maintenance-demanding and long-lasting; and (iv) they are typically more efficient (up to 85%) [14].

Nevertheless, and despite their advantages and long history in water lifting, HPP systems seem to be largely disregarded nowadays. On one hand, there are some contemporary studies [15–21] and literature reviews [4–6,22,23] on RE-based water pumping systems. However, none of them address hydropower as a sound source of energy. On the other hand, there are several old publications [14,24–31] that considered it to a bigger or lesser extent, though completely overlooking many other then-contemporary HPP technologies that were relevant—and, in some cases, even predominant—for other (non-Western) contexts. Therefore, and considering such knowledge fragmentation and consequent gap, this review constitutes the first worldwide-scale depiction of the past and present trends on the documented research, development, application, and commercialization of the HPP technologies. In turn, such information provides a general yet solid basis for scholars, (industry) researchers, managers, manufacturers, and users, with respect to the future uses these technologies (as well as new ones derived from them) might have under different sets of physical and social conditions.

It is so that two universities, namely Delft University of Technology and Comillas Pontifical University, from The Netherlands and Spain, respectively, are currently carrying out the DARE-TU (Developing Agriculture and Renewable Energy with the TUrbine pump) project. It aims to research the cocreation and implementation of affordable clean irrigation systems, based upon novel HPP technologies [32] developed in collaboration with the Dutch start-up company aQysta. Within this context, the objectives of the present article are:

1. To summarize and classify the HPP technologies researched, applied, and eventually commercialized globally over time;
2. To define their state-of-the-art by synthesizing their respective storylines and highlighting the highest level of their developments;
3. To identify global spatial and temporal patterns on the (re)invention, application, and spread of HPP technologies.

2. Methods

2.1. Selection Criteria for HPP Technologies

Relevant HPP technologies, within the context of the present review, fulfilled the following criteria:

1. Exclusively driven by the kinetic and/or potential energy of water;
2. Rely exclusively on hydro-mechanical energy, hence not relying whatsoever on electro/electrochemical conversion processes;

3. Work by building up pressure (i.e., must not be a direct lift technology);
4. Pose any form of actual or potential use for supplying water, preferably to agricultural activities and human consumption, thus must ensure a relatively constant and reliable flow. As a consequence, devices such as the superhydrophobic pump [33] were neglected;
5. Operate with the same (fresh) water to be supplied, therefore technologies such as ocean-driven turbines, firefighter ejector turbo-pumps [34,35], water-driven foam pumps, or the hydraulic turbocharger™ [36] were not taken into account.

2.2. Sources of Information

To look for relevant data, the following literature and sources of information were considered:

1. Peer-reviewed literature, from online academic databases through Google Scholar search engine (https://scholar.google.com/) and Google Books digital library service (https://books.google.com/);
2. Peer-reviewed and grey literature (i.e., non-peer-reviewed), retrieved from online databases, accessed through Google search engine (https://www.google.com/);
3. Documents bibliographically referenced in the two previous sources (particularly old ones)—yet not indexed in the previous search engines—from different academic databases and libraries worldwide (through TU Delft library services);
4. Personal communication from other authors.

Initial search iterations made evident that, unlike other RE-based pumping technologies, there is a considerable lack of scientific literature regarding HPP. This was the main driver to expand the screening process toward grey literature, thereby filling information gaps that could not have been considered otherwise, hence increasing information bias [37]. Furthermore, a triangulation of sources/databases was performed (i.e., not using a single source), in order to overcome implicit accuracy limitations that the Google search engines pose regarding systematic reviews [38].

2.3. Literature Screening

2.3.1. Keywords and Terms

The complete set of keywords used in the search engines was gradually enlarged as the iterative search process took place. To produce more accurate results based on generic and broad terms, these were combined with the words "water", "irrigation", and "pump". In some iterations, terms were expressed as exact phrases by making use of quotation marks.

The final set of terms was: "hydro-powered", "water-powered", "water wheel", "water-driven", "turbine-driven", "hydro-mechanical", "hydraulic ram", "hydram", "impulse", "spiral", "coil", "manometric", "Wirtz", "Plata", "Chinese turbine-pump", "water-turbine", "sling", "HyPump", "Barsha", "no power", "self-powered", "self-propelled", "river-current turbine", "hydrokinetic turbine", "fuel-less", "powerless", "Glockemann", "High lifter", "pump as turbine", "Hydrobine", "PowerSpout PHP", "Filardo", "Markovic self-propelled", "zero-energy", "PAPA", "Garman turbine", "river turbine", "water-current turbine", "Tyson turbine", "Mangal turbine", "Bunyip", "Linear turbine", "Tuapeka turbine", "tidal turbine", "Cherepnov water lifter", "hydropulsor", "hydrautomat", and "pulser".

To ensure higher accuracy of results from the search engines, some words were intentionally and explicitly ruled out during the search. These terms were gradually set depending on the initial results of each iteration. For instance, searching only with the term "water-turbine pump" returned too many inaccurate results linked to a technology out of the scope of this paper. However, when excluding the terms "-vertical" and "-deep well", the accuracy eventually became higher. The ruled out terms were: "desalination", "solar", "vertical", "deep well", "wind", "sump", "ocean", "generator", and "coronary" (linked to the Filardo surname within the cardiology field).

Although the main screening of literature was conducted in English, it was necessary to perform iterations with terms in other languages to look for other HPP technologies otherwise absolutely overlooked. In Spanish: *"bomba de río"*, *"río-bomba"*, *"turbo bomba"*, *"turbo bombeo"*, *"bomba funcionando como turbina"*, and *"ariete multipulsor"*; in Italian: *"elevatore idraulico"* and *"elevatore di Cigliano"*; in Portuguese: *"roda d'água"*; in Romanian: *"transformatorul hidraulic"*, *"turbotransformatorul hidraulic"*; in Russian: "Черепнов водоподъемник", "водоподъемник токаря Черепнова", "Автономных водоподъемников", and "Аэрогидравлического водоподъемника"; in German *"Brunnhäuser"* and *"Lambachpumpe"*; in Mandarin: "水轮泵", "水锤泵"; in Vietnamese: *"bơm thủy luân"*; in Indonesian: *"pompa air tenaga hidro"*; in Thai *"เครื่องสูบน้ำกังหันน้ำแบบ"*. It is worth mentioning that the technologies screened and analyzed here might not be limited to the aforementioned languages. Nevertheless, true to the authors' knowledge, these were the ones whose keywords provided consistent results within the scope of the present review.

2.3.2. Selection of Results

The first search iterations depicted several temporal gaps in the literature, i.e., not all the relevant technologies, in accordance with the selection criteria, could be found around the same period but in heterogeneous time frames (decades, centuries) throughout the history. Therefore, to increase the likelihood of gathering valuable data, the process of search and subsequent selection of information was not restricted to any specific time range (e.g., only 20th and 21st centuries), but from the present until the origin of the first-ever recorded HPP technologies.

Results of search engines, for both peer-reviewed and grey literature, were taken into consideration as long as they provided any of these aspects: (i) Technical information and applicability of the technologies; (ii) the description of a particular case study and/or its uniqueness worldwide; (iii) the development of an innovative design; and/or (iv) unique facts that contribute in understanding the storyline of evolution, success or failure of the technologies.

Literature from search engines was selected by consecutive sampling, i.e., all the relevant subjects were considered. In consequence, each search iteration was explored thoroughly until its outcomes became out of scope of the selection criteria, usually beyond the first 40 results. Notwithstanding the previous technique, snowball-sampling (through bibliographic references and hyperlinks) was also used in the case of technologies whose documents were not indexed in any database or did not respond to the set of keywords.

2.3.3. Data Classification and Processing

Results of iterative searches showed a wide diversity of HPP devices in terms of shapes, sizes, prime movers, pumping principles, prime mover—pumping device integration, working conditions, benefits, and applicability. Due to this heterogeneity, HPP technologies were grouped and classified not based on a single criterion, but on the combination of a series of properties related to their morphological/mechanical characteristics.

In line with the proposed classification, two datasets were built from the selected documents, namely bibliography and application cases, respectively (see Appendix A in Supplementary Materials) [39]. The bibliography dataset grouped and quantified documents according to their nature (scientific or grey literature), type of document, year of publication, and language, among other bibliographic information. Furthermore, scientific literature consisted of: Articles published in high- and low-impact factor journals, books and books sections, conference proceedings, and encyclopedias. Grey literature involved: Working papers, research newsletters, theses, magazine articles, reports, research bulletins, brochures, websites, information in social networks, presentations, patents, newspaper articles, videos, and others. The application cases dataset, on the other hand, was built from all the instances found in the bibliography where HPP devices have been reported under any kind of actual use (e.g., agricultural irrigation, water supply, research, others) within the selection criteria. It encompassed year of implementation, country, and type of end-use. It must be noticed, nevertheless, that there is not any quantitative relation between the number of documents and number of reported cases, i.e., a single article might report thousands of HPP devices in use, whereas some documents could triangulate few application cases in a specific context.

Some assumptions were made while building the datasets. Regarding the literature, certain documents were recorded as many times as different technologies they addressed. On the application cases, whenever it was not possible to determine the number of devices (i.e., literature refers to "some" or "few") either/or their year of application, a number of two and/or the year of the corresponding document were allocated, respectively. Manufacturers of technologies have been assigned only as one case, whereas neither retailers nor distributors were considered. Repowered and renovated cases were accounted for again, as long as they posed an upgrade or change in the technology.

Statistical analyses of the datasets were performed with Microsoft® Excel® 2016. Due to considerable differences between reported cases of HPP technologies (order of magnitude of six), these were plotted in space and time on the basis of a customized logarithmic scale.

3. Main Findings

3.1. HPP Technologies

In total, 30 technologies were identified and grouped into eight classes: (i) Manometric pumps, (ii) hydro-pneumatic water lifters; (iii) hybrid turbine-pumps; (iv) water turbine pumps; (v) tubular multi-propeller turbines; (vi) water current turbines; (vii) generic integrations; and (viii) other devices. Figure 1 shows the classification of HPP technologies. Their timeframe and presence worldwide, as well as some of their technical properties, are summarized in Table 1. The narrative on the origins, evolution, and fate of each technology is contained in Appendix B (see Supplementary Materials).

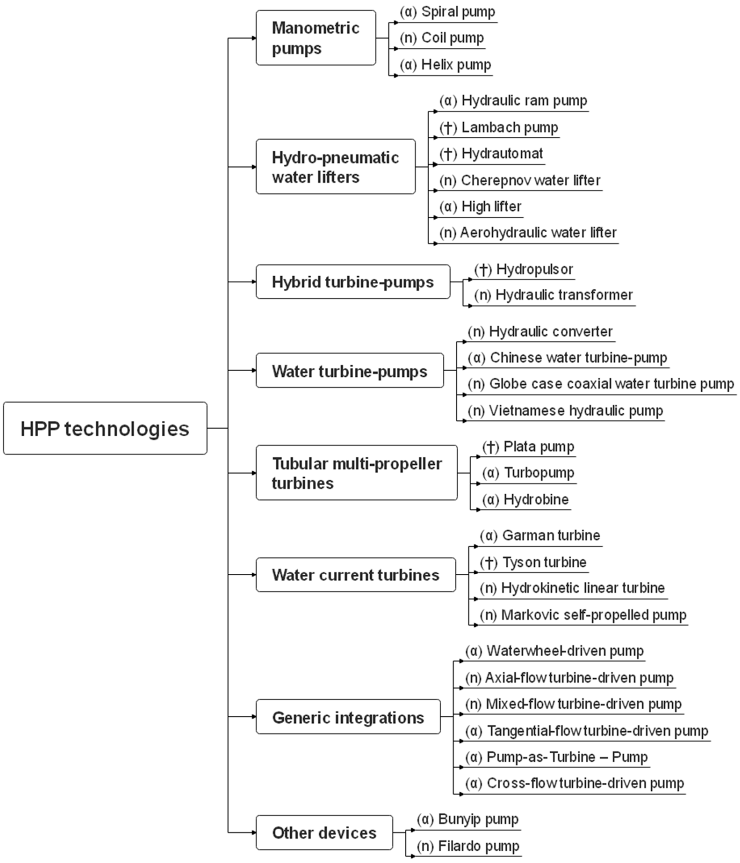


Figure 1. Classification of hydro-powered pumping (HPP) technologies and their latest development/production stage. The symbols (α), (†), and (n) stand for commercially available, commercially extinct, and noncommercial technologies, respectively.

Table 1. Summary of HPP technologies.

Class	Technology	First Record	Last Record	Reported Devices	Nr. of Countries	Prime Mover	Pumping Device	Pumping Principle	Integration	Required Head	Location in Water
Manometric pumps	Spiral pump	1746	2018	192	19	Waterwheel	Spiral pipe	PD	DA, CS	ZH	SS
	Coil pump	1778	1997	14	8	Waterwheel	Coil pipe	PD	DA	ZH	SS
	Helix pump	1987	2017	27	12	Axial-flow propeller	Helix pipe	PD	DA	ZH	SS
Hydro-pneumatic water lifters	Hydraulic ram pump	1796	2017	~6840	42	Compressed air	HT, SARP	PD	VS, Diaphragm	LH	OS, SS, SU
	Lambach pump	1880s	1961	35	3	Compressed air	SARP, DARP	PD	PS	LH	OS
	Hydrautomat	1920s	2013	13	6	Compressed air	HT	PD	VS	LH	SU
	Cherepnov water lifter	1960	1996	6	5	Compressed air	HT	PD	VS	LH	OS
	High lifter	1984	2016	4	1	Compressed air	SARP	PD	PS	LH	OS
	Aerohydraulic water lifter	1998	1998	4	1	Compressed air	HT	PD	VS	LH	SS
Hybrid turbine-pumps	Hydropulsor	1909	1912	5	2	Turbine-pump impeller	Turbine-pump impeller	VH	Integrated impeller	LH	OS
	Hydraulic transformer	1940	1999	12	1	Turbine-pump impeller	Turbine-pump impeller	VH	Integrated impeller	LH	OS
Water turbine-pumps	Hydraulic converter	1921	1921	1	1	Axial turbine	CP	VH	CS	LH	SU
	Chinese water turbine-pump	1954	2007	~81500	15	Kaplan turbine	CP	VH	CS, TS	LH, MH	SU
	Globe case coaxial water turbine pump	1999	2014	4	1	Kaplan turbine	CP	VH	CS	LH	OS
	Vietnamese hydraulic pump	2009	2014	9	1	Kaplan turbine	CP	VH	CS	LH	SU
Tubular multi-propeller turbines	Plata pump	1972	1990	17	8	Multi-propeller turbine	SARP	PD	TS	ULH	SS
	Turbopump	1983	1992	~300	1	Multi-propeller turbine	SARP	PD	TS	ULH	SS
	Hydrobine	1998	2014	7	4	Multi-propeller turbine	SARP	PD	TS	ULH	SS

Table 1. *Cont.*

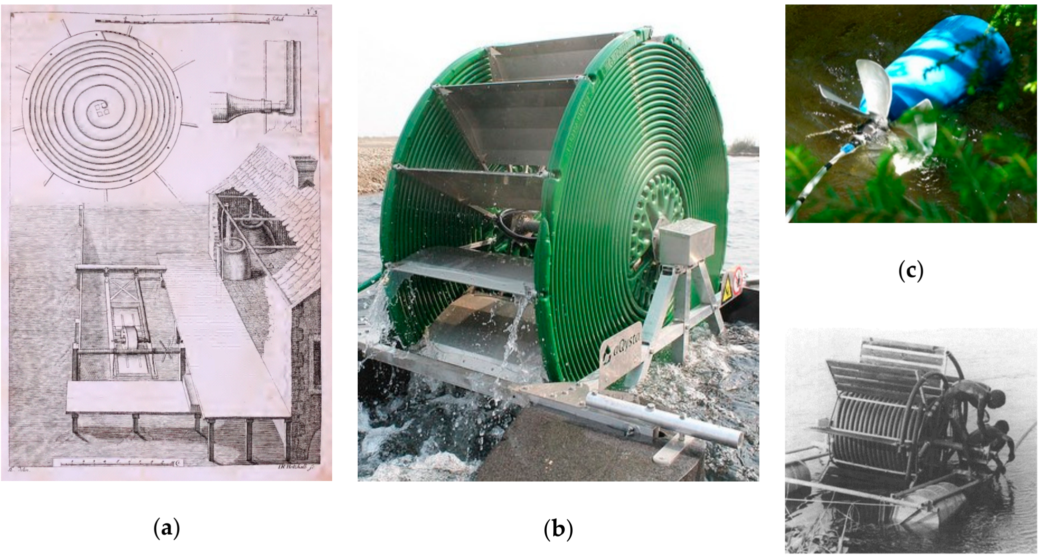
Class	Technology	First Record	Last Record	Reported Devices	Nr. of Countries	Prime Mover	Pumping Device	Pumping Principle	Integration	Required Head	Location in Water
Water current turbines	Garman turbine	1976	2018	69	6	3-bladed propeller turbine	CP	VH	TS	ZH	SS
	Tyson turbine	1982	2009	28	9	7-bladed turbine	DARP	PD	TS	ZH	SS
	Hydrokinetic linear turbine	1984	2017	13	4	Linear turbine	SARP	PD	Slider-crank	ZH	SS
	Markovic self-propelled pump	1993	2009	3	1	Mixed flow propeller turbine	SARP	PD	Slider-crank	ZH	SU
Generic integrations	Waterwheel-driven pump	1528	2018	139	19	Waterwheel	SARP, DARP, DP, CP	PD, VH	TS	ZH, LH	OS, SS
	Axial-flow turbine-driven pump	1851	2011	88	9	Axial-flow turbines (Kaplan, Tubular, Bulb, S-shape, Jonval, Girard)	DARP, CP, DP	PD, VH	CS, TS	LH	SS, SU
	Mixed-flow turbine-driven pump	1897	2005	18	4	Mixed-flow turbines (Francis, Samson, S. Morgan Smith, Leffel)	CP, DARP	PD, VH	CS, TS	LH	SS
	Tangential-flow turbine-driven pump	1900	2018	17	7	Tengential-flow turbines (Pelton, Turgo, Ghatta)	CP, Plunger pump, Progressive cavity pump, DP, SARP, DARP	PD, VH	CS, TS	HH	OS
	Pump-as-Turbine - Pump	1952	2018	47	10	Pump working in reverse	CP, DP	PD, VH	CS, TS	LH	OS
	Cross-flow turbine-driven pump	1979	2018	26	10	Cross-flow turbine (Michell – Banki, Ossberger, BYS)	CP, DP	PD, VH	CS, TS	LH	OS
Other devices	Bunyip pump	2006	2018	6	1	Rubber tire	SARP	PD	DA	LH	OS
	Filardo pump	2012	2013	5	1	Ribbon frond mechanism	Peristaltic pumping pipes	PD	DA	ZH	SU

On pumping devices: HT, SARP, DARP, CP, and DP stand for hydraulic tank, single-acting reciprocating pump, double-acting reciprocating pump, centrifugal pump, and diaphragm pump, respectively. On pumping principles: PD and VH stand for positive displacement and velocity head, respectively. On integration: DA, CS, VS, PS, and TS stand for direct attachment, coaxial shaft, valve system, piston system, and transmission system, respectively. On required head: ZH, LH, MH, ULH, and HH stand for zero-head, low-head, medium-head, ultra-low-head, and high-head, respectively. On location regarding water: SS, OS, and SU stand for semi-submerged, on-surface, and submerged, respectively.

3.1.1. Manometric Pumps

These devices consist of any kind of semi-submerged curved pipes winding around a fixed central point or axis, which rotates continuously, thereby alternatively taking in both water and air packets through an open end in each revolution. The other extreme (i.e., the outlet), which matches the center/axis, is connected to a water-tight rotary fitting joined to a fixed pipe [40]. They are named after their resemblance to a wounded cascading manometer, thus operating on its principle, where the series of loops of the pipe act as manometers separated from one another by the trapped air columns [41–44]. The total lifting head at the outlet results from the addition of the manometric head difference in each loop. Several authors have thoroughly studied the hydraulics of this water lifting principle [40,41,45–49].

The shape of the curved pipe can be either planar [50], convolved in a three-dimensional cylindrical surface [51], or in a conical one [49]. Besides, regarding the water stream, the axis of the pipe can be cross-flow or axial-flow. These different shapes give rise to manometric pumps that acquire several names throughout the literature, sometimes being used interchangeably or even as synonyms. For convention of the present work however, cross-flow planar, cross-flow non-planar, and axial-flow non-planar pipes will be referred as hydro-powered spiral pump (HSP), hydro-powered coil pump (HCP), and hydro-powered helix pump (HHP), respectively. Figure 2 depicts different types of manometric pumps.



(a) (b) (c) (d)

Figure 2. Different types of manometric pumps: (**a**) First ever known hydro-powered spiral pump (HSP) from 1746 in Zurich [52]. CC BY-NC 3.0; (**b**) Modern HSP—aQysta's Barsha pump [53]. © USAID (https://securingwaterforfood.org/innovator-news/hydro-powered-pump-offers-eco-friendly-irrigation-solution). Cropped from the original; (**c**) Hydro-powered helix pump (HHP) [54]. Reproduced with permission from Rife Hydraulic. © Rife Hydraulic Engine Manufacturing Company (https://www.riferam.com/pumps.html); (**d**) Hydro-powered coil pump (HCP) [51]. Reproduced with permission from Practical Action Publishing Ltd. © Otto Clemensen (https://doi.org/10.3362/0262-8104.1985.030).

The HSP, HCP, and HHP generally harness the required energy by means of waterwheels (frequently stream shot ones), radial paddles, or axial-flow propellers, respectively. Therefore, these devices do not usually rely on the water potential head but on the velocity of the water stream (i.e., kinetic head). Both the curved pipe and prime mover can be joined either by attaching them together [55,56] or either by transmitting the rotational movement from one to another through a shaft or transmission system. More than one curved pipe can be assembled to the whole device [57,58].

3.1.2. Hydro-Pneumatic Water Lifters

These HPP devices lift water at the expense of potential energy from falling water and pneumatic compression [59,60]. They are usually self-oscillatory, thus relying on automatic draining components (e.g., valves, floating devices, magnetic switches, counterweights) that allow the lifting cycles to recommence [61–65]. However, other less common variants operate without any moving component [66–68]. Hydro-pneumatic water lifters can be built in the form of compact machines [69–74] or very large and complex systems [61,67,75,76]. Technologies within this class are the hydraulic ram pump (HRP) and its many variants (e.g., multipulser, Platypus, Dingo™, Glockemann, PAPA, Venturo), Lambach pump (LP), hydrautomat, Cherepnov water lifter (CWL), High Lifter, and aerohydraulic water lifter. From these, the most common and widely applied is the HRP. Several types of hydro-pneumatic water lifters are shown in Figure 3.

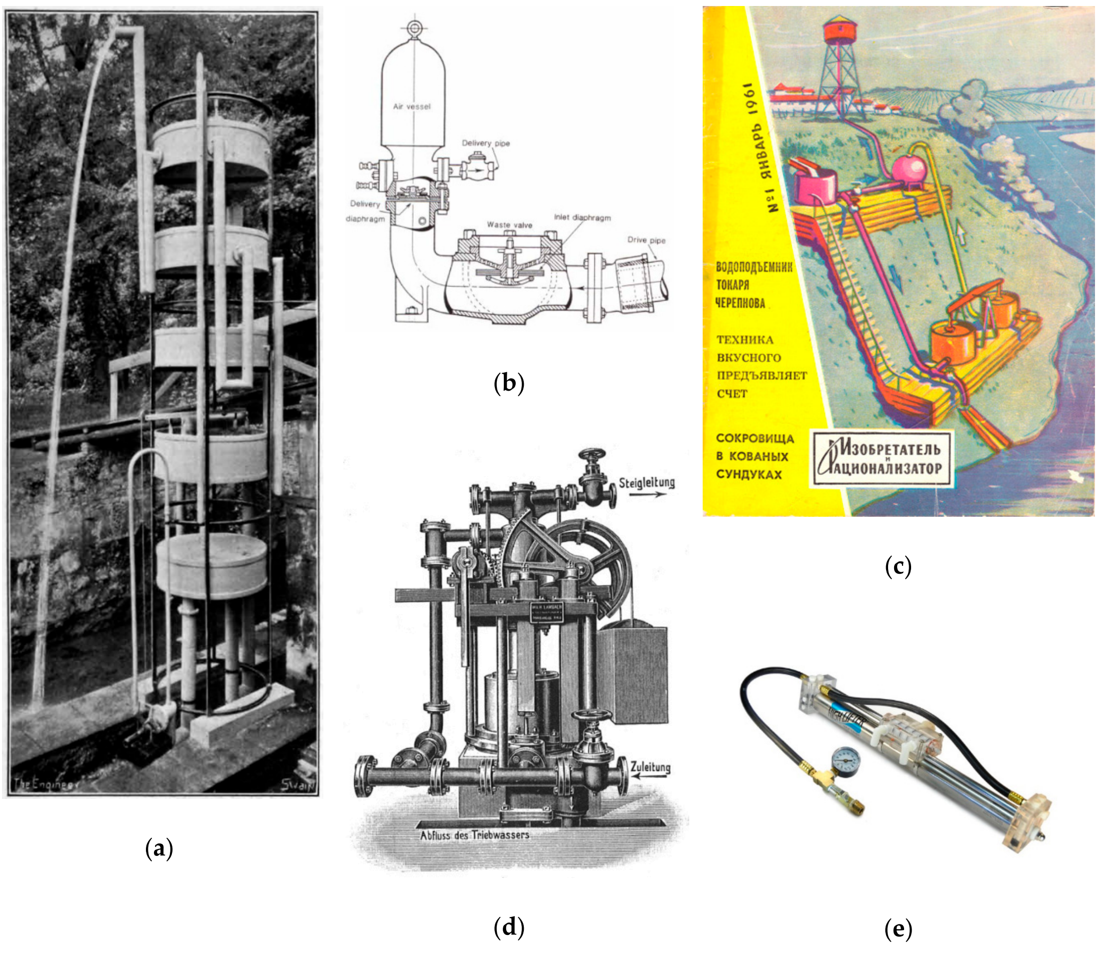
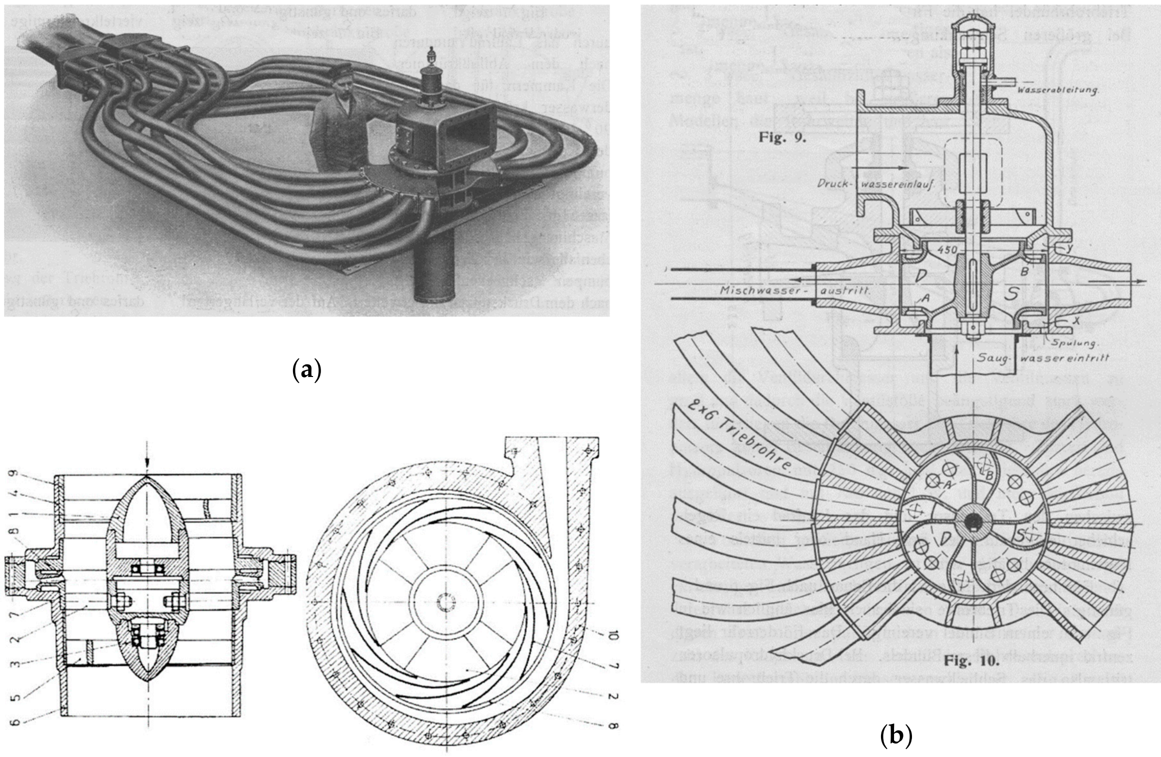


Figure 3. Different types of hydro-pneumatic water lifters: (**a**) Hydrautomat [77]. © Grace's Guide Ltd. (https://www.gracesguide.co.uk/The_Engineer_1922/07/07). CC BY-SA 4.0; (**b**) Scheme of an hydraulic ram pump (HRP) [78]. Reproduced with permission from Jeremy Milln. © The National Trust (https://industrial-archaeology.org/wp-content/uploads/2016/04/AIA-News-93-Summer-1995.pdf); (**c**) Illustration of the Cherepnov water lifter (CWL) installed at the former Gorky Oblast, Russia [75,79]. Reproduced with permission from "Inventor and Innovator" magazine. © Изобретатель и рационализатор(http://i-r.ru/article/2254/); (**d**) Early model of Lambach pump (LP) [62]. © Hauptverein Deutscher Ingenieure in der Tschechoslowakischen Republik; (**e**) High lifter [80]. Reproduced with permission from Humboldt Solar Water Pump. © Humboldt Solar Water Pump (http://www.humboldtsolarwaterpump.com/high-lifter-gravity-water-pump-for-your-off-grid-water-system/).

3.1.3. Hybrid Turbine-Pumps

Hybrid turbine-pumps, unlike many other HPP technologies, do not join two different machines (i.e., prime mover and pump), but they physically integrate both of them in a single, different hydraulic device. Therefore, they must be understood as the hybridization of a type of water turbine and a centrifugal pump, hence fulfilling both functions at the same time [81]. Hybrid turbine-pumps are usually compact devices [82,83], though they have been also implemented in large-scale versions, able to reach lifting heads of even hundreds of meters, for waterworks and irrigation systems [84,85]. These machines are very versatile [85–88], though require complementary civil works to operate properly [83]. The Hydropulsor and the hydraulic transformer (HT) are in this group. Figure 4 illustrates the different types of hybrid turbine-pumps.



(**a**) (**b**) (**c**)

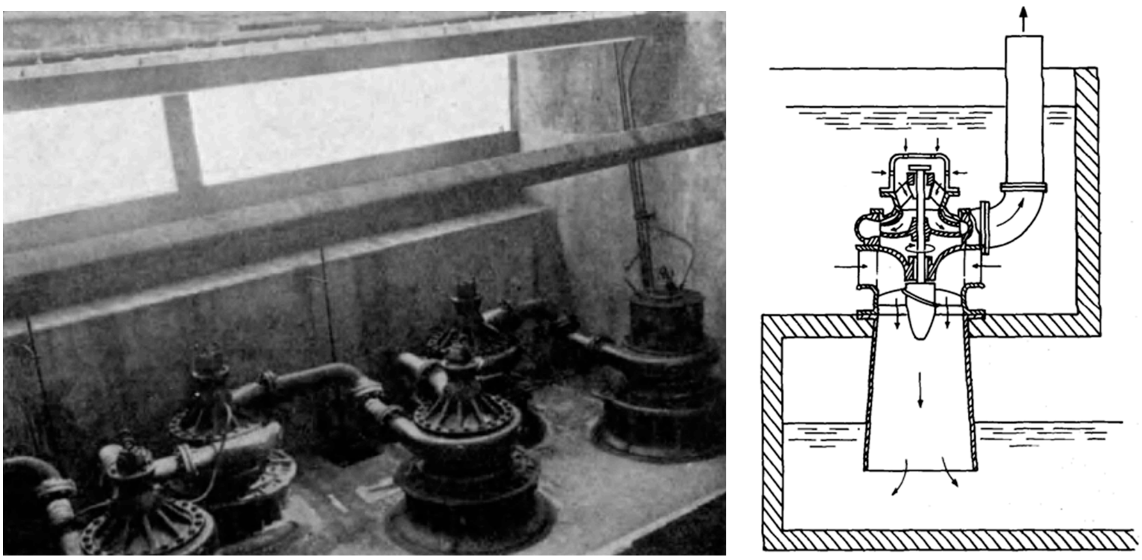
Figure 4. Different types of hybrid turbine-pumps: (**a**) Hydropulsor installed at Dretzel, Germany [85]. © Digitalisierung des Polytechnische Journal (http://dingler.culture.hu-berlin.de/article/pj327/ar327220). CC BY-NC-SA 3.0; (**b**) Impeller/runner of the Hydropulsor installed at Dretzel, Germany [85]. © Digitalisierung des Polytechnische Journal (http://dingler.culture.hu-berlin.de/article/pj327/ar327220). CC BY-NC-SA 3.0; (**c**) Longitudinal and transversal section of an hydraulic transformer (HT) [89]. (http://www.afst.valahia.ro/images/documente/2010/issue2/2010-2-4-3-Man-Eugen-Teodor.pdf). CC BY.

3.1.4. Water Turbine-Pumps

The water turbine-pump (WTP), largely referred to the literature as a machine unique to China, results from embodying in a single case, and coaxially joining–through a single shaft [90–95] or transmission system [96,97]-an axial-flow turbine (usually a Kaplan type) and a centrifugal pump. Both components are usually fully submerged, hence operating with the same water body, though some models [98,99] operate on surface, by means of water-tight pipes. The head difference in the water drives the turbine, whose vanes and blades can be either fixed or adjustable, and which in turn transmits its rotational mechanical energy directly to the pump [26,100]. Due to this characteristic, some authors consider WTPs highly efficient machines [25,93,94,96]. The WTP group encompasses the hydraulic converter, Chinese water turbine-pump (CWTP), Globe case coaxial water turbine pump, and Vietnamese hydraulic pump.

WTPs are quite modular, thus prone to be installed in a wide variety of setups [91,93,101,102], fulfilling different requirements: Stand-alone or in batteries (pump stations); with single-stage or multistage pumping configurations [97,103,104]; placed either horizontally, vertically, or mixed; in parallel and/or in series; as single-purpose devices, only for lifting water, or multi-purpose ones [94,97,105–107], combined with electricity generation and other machinery [14,90,91,93,96,97,108]; installed in dams, canal drops, and excavated diversion canals [107,109]; and in both low-land tidal rivers and mountainous areas [93,97,108,110]. Although they are generally better suited for low-head conditions [14,90,111–114], there are few reported cases that make use of medium- and high-working heads [99,113]. Furthermore, WTPs cover a broad range of models able to lift water from a few up to hundreds of meters [14,28,90,94,99]. Commercially, WTPs are classified in regard to the diameter of the turbine runner (given in cm) and the head ratio (pumping head: Working head) [90,93]. A 40-6 model, for instance, will have a 40 cm-diameter runner and a 6:1 head ratio. Devices of 10-160 cm diameter, from 4:1 to 20:1 head ratio, and maximum efficiencies of 70%, exemplify the wide variety of solutions [93,96,115].

Unlike other ready-to-use HPP devices, WTPs are highly demanding in complementary civil works [93,107]. They frequently require dams, weirs and/or gates to create artificial drops, thus augmenting the working head, as well as pits to hold the machine. Additionally, a draft tube is also built to amplify the effect of the hydrostatic head [95]. As stated by some authors [14,26,50], albeit the WTP by itself bears relatively low production costs, investments of complementary constructions [96,107,110] largely outpace them. Several WTPs and their installations can be seen in Figure 5.



(a) (b)

Figure 5. *Cont.*

(**c**)

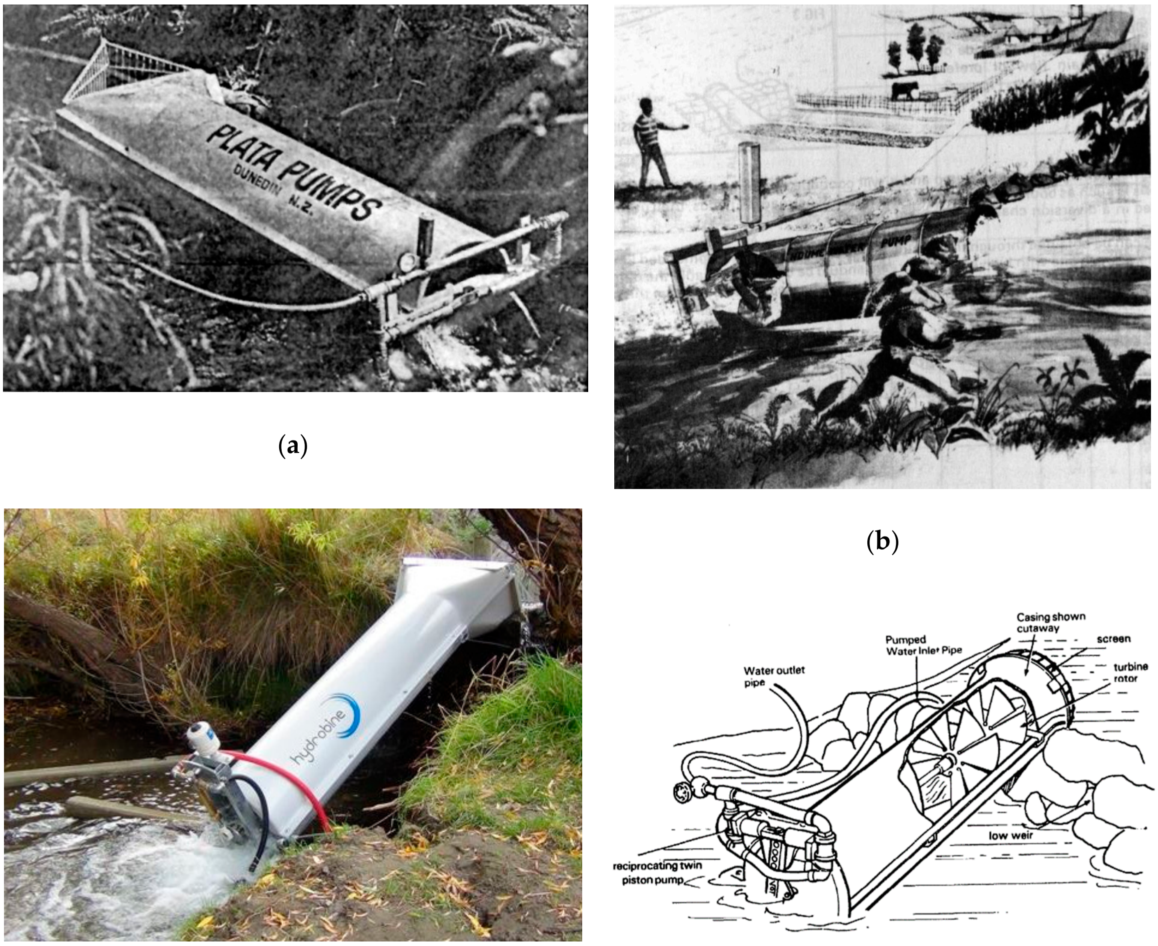
(**d**)

(**e**)

Figure 5. Different types of water turbine-pumps (WTPs): (**a**) Hydraulic converters installed in in the Muffatwehr at the Isar River in Munich [81]. Reproduced with permission from Springer Nature. © Springer Nature (https://doi.org/10.1007/978-3-642-50802-8_18); (**b**) Schematic view of the typical installation of a WTP [14]. Reproduced with permission from Food and Agriculture Organization of the United Nations © FAO (http://www.fao.org/3/ah810e/AH810E12.htm#12.1). A from the original; (**c**) Mass production of Chinese water turbine-pump (CWTP). Reproduced with permission from Gejing Jiang. ©有 金华天阳电子有限公司 (http://www.jiaxiangwang.com/cn/guizhou.htm); (**d**) Multi-stage Vietnamese hydraulic pump [116]. © Viện Khoa học Thủy lợi Việt Nam (http://www.vawr.org.vn/index.aspx?aac=CLICK&aid=ARTICLE_DETAIL&ari=2314&lang=1&menu=&mid=-138&pid=1&title=cong-nghe-bom-thuy-luan-bom-nuoc-tu-dong-phuc-vu-nong-nghiep-mien-nui-va-trung-du); (**e**) Globe case coaxial water turbine pumps commissioned in the Mae Phum Reservoir, Phayao province, Thailand [117]. © Royal Irrigation Department. CC BY-NC-SA 3.0. Cropped from the original.

3.1.5. Tubular Multi-Propeller Turbines

The tubular multi-propeller turbines (TMPT), which include the Plata pump, Turbopump, and Hydrobine, as shown in Figure 6, are semi-submerged, axial-flow, ultra-low head (0.25–1.0 m) pumping devices [14,24,118] encased in a cylindrical body made out of metal [118] or fiberglass [29,119]. They consist of a series of coaxial propeller turbine rotors joined through a single shaft, coupled to one/two single-action reciprocating water pumps by means of a slider-crank mechanism [14,27,119]. TMPTs are meant to be installed laying on a slight slope angle to make water flow through the cylinder, thereby usually requiring basic site preparation [14,24,27]. Furthermore, TMPTs are able to be installed either in parallel or in series [27]. Their maximum power is developed when the turbine works about half full of water, but it can operate well in a range of three-quarters full to almost empty [14,27]. Additionally, modern versions [120,121] of these devices are designed for both water pumping and electricity generation.



(**a**) (**b**) (**c**) (**d**)

Figure 6. Different types of tubular multi-propeller turbines (TMPTs): (**a**) Plata pump [119]. Reproduced with permission from Alternative Technology Association Inc. © The Alternative Technology Association (https://www.jstor.org/stable/softtechaltetech.13.18); (**b**) Illustration of a Turbopump in operation [122]. © S.C. White (http://www.wossac.com/search/wossac_detail.cfm?ID=2076); (**c**) Hydrobine in operation [123]. Reproduced with permission from Wayne Perkins. © EB Engineering Solutions (https://www.facebook.com/Hydrobine/photos/pcb.789312184518066/789311851184766/?type=3&theater). Cropped from the original; (**d**) Schematic view of a TMPT [14]. Reproduced with permission from Food and Agriculture Organization of the United Nations © FAO (http://www.fao.org/3/ah810e/AH810E12.htm#12.1).

The operation of TMPTs can raise some issues due to particles and floating debris. A grid before the turbine intake will prevent them, though it might require daily clearance. Frequent silting can contribute to undesired changes in the working head of the structures, thereby requiring periodic removal of deposits [27,118,122].

The performance and benefits of TMPTs are a point of disagreement. Whereas some literature mentions excellent lifts [29,119] of even hundreds of meters [118], others authors [14,27,42,111,122] point them out as relatively expensive, less robust, and less efficient machines compared to other HPP technologies.

3.1.6. Water Current Turbines

Water current turbines (WCTs) lift water by harnessing kinetic energy from free-flowing streams [124–127]. WCTs, comprising the Garman turbine (GT), Tyson turbine (TT), Hydrokinetic linear turbine, and Markovic self-propelled pump, consist of a fully submerged turbine, coupled to a centrifugal or reciprocating water pump by a transmission system. These devices are frequently moored in nontidal (unidirectional flow) rivers, though tidal ones are considered as well [128,129], particularly in locations where damming water is impractical due to economic or engineering reasons [124,127]. Less common WCTs incorporate piston pumps by employing crankshaft-and-connecting rod systems, as well as vertical Darrieus-type water turbines [24]. Figure 7 shows several types of WCTs.

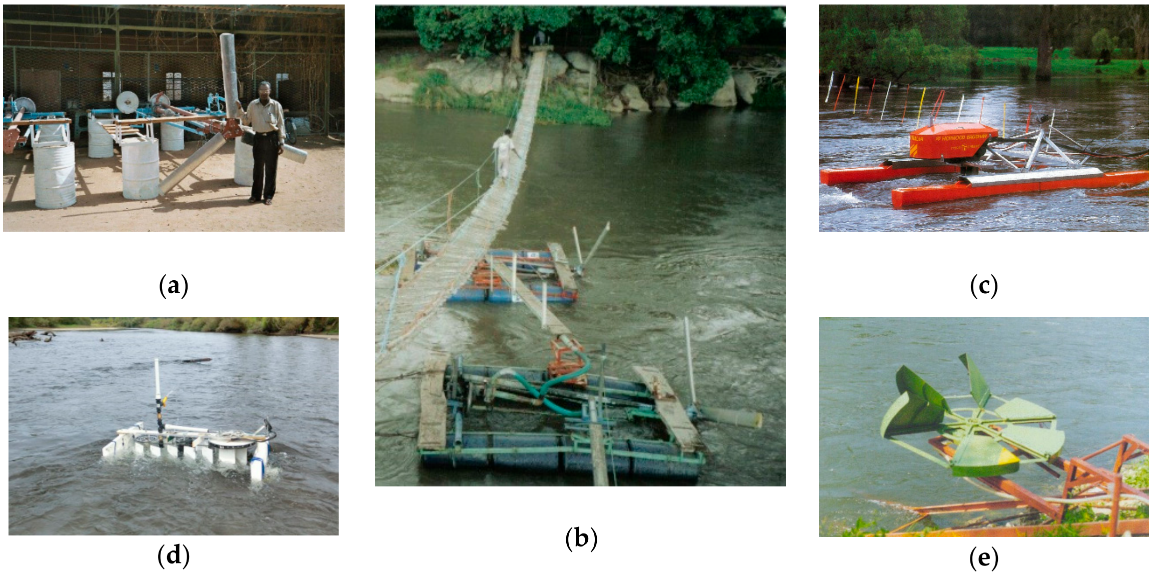


Figure 7. Different types of water current turbines (WCTs): (**a**) Construction of a Garman turbine (GT). © Thropton Energy Services. Courtesy of Dr. Barbara Sexon; (**b**) Two GTs in operation. © Thropton Energy Services. Courtesy of Dr. Barbara Sexon. Cropped from the original; (**c**) Tyson turbine (TT) in operation. Reproduced with permission from Museum of the Riverina. © Wagga Wagga City Council. Courtesy of Mr. Luke Grealy; (**d**) Hydrokinetic linear turbine operating [129]. Reproduced with permission from John Service. © Tuapeka Turbines (http://tuapeka-turbines.com/blog/mini-linear-turbine-test-whakatane-river-new-zealand-14-march-2014/). Cropped from the original; (**e**) Markovic self-propelled pump [130]. Reproduced with permission from Nataša Markovič. © Vladimir Markovič (http://izumi.si/doc/ENERGY_AS_ENEMY.pdf).

WCTs are relatively simple to build with readily available materials, yet are sturdy and long lasting. Besides, they do not require additional civil works, thereby reducing costs and favoring their versatility [124,126,127,131–133]. However, WCTs present problems and interferences with weed (e.g., water hyacinth) and floating debris [134–139], which in turn determine their maintenance frequency, though this largely depends on the type of river [140]. There are cases of turbines cleaned several times a day [124], and other ones only every few days or weeks [140,141]. In this respect, some efforts have been done in improving the design to counteract this issue [134–136].

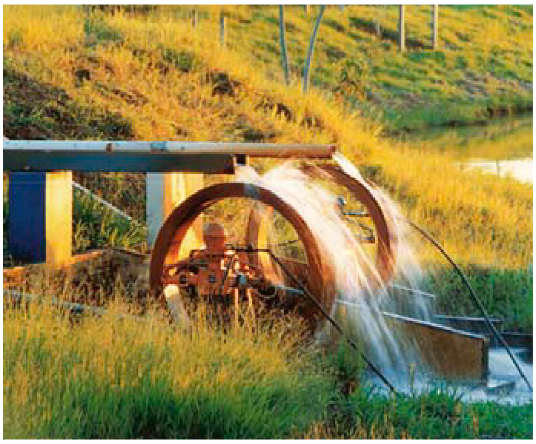
WCTs are used for water pumping and/or electro-generation. Nonetheless, current research on these devices focuses mainly on the latter [135,136,142–146], whereas the pumping purpose is barely addressed by few authors [147].

3.1.7. Generic Integrations

Besides the specific HPP technologies previously addressed, there are cases in which generically coupling a prime mover and a pumping device works effectively. Moreover, these arrangements are usually more flexible for a number of conditions compared to specific devices. Due to their generic nature, however, it is not possible to trace back the origin or evolution of each of these inventions.

Among the prime movers used for these purposes are: Waterwheels, the most primitive form of water turbine, hence more used in the remote past; axial-flow turbines; mixed-flow turbines; tangential-flow turbines; pumps working in reverse, often known as pump-as-turbines; and cross-flow turbines. On the other hand, a wide variety of pumping devices can be coupled: Single and multistage centrifugal pumps, plunger pumps, progressive cavity pumps, and single and double action piston pump, among others. Both off-the-shelf [148–152] as well as tailor-made [153–156] setups are used for these purposes, and usually their implementation requires extra infrastructure to work properly [150,155,157–160].

In regard to the type of prime mover, these generic integrations are waterwheel-driven pump (WDP), axial-flow turbine-driven pump (ADP), mixed-flow turbine-driven pump (MDP), tangential-flow turbine-driven pump (TDP), pump-as-turbine-pump (PAT-P), and cross-flow turbine-driven pump (CDP). Figure 8 depicts different types of these generic integrations.



(a)

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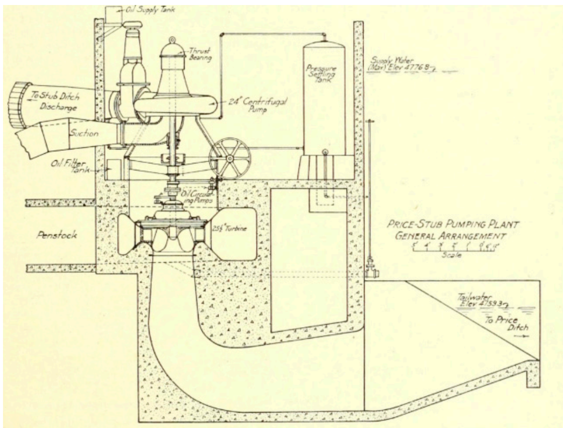
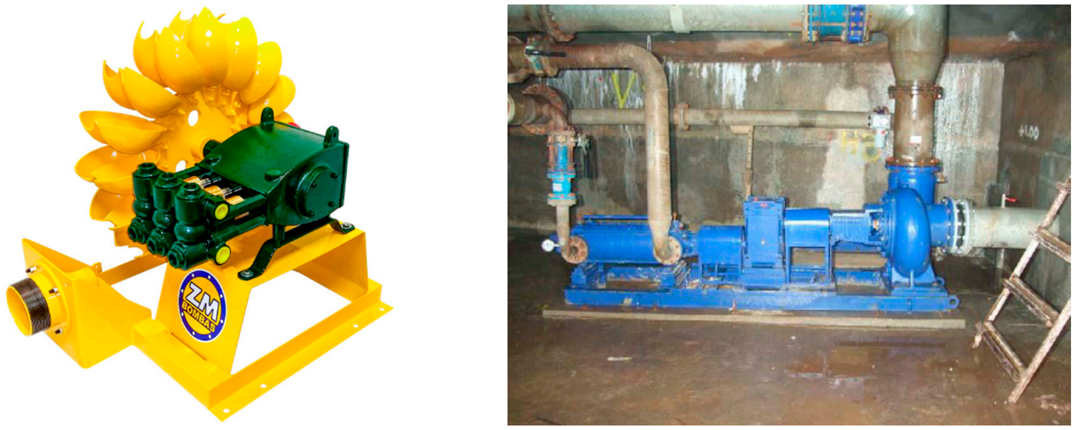


(d)

Figure 8. *Cont.*

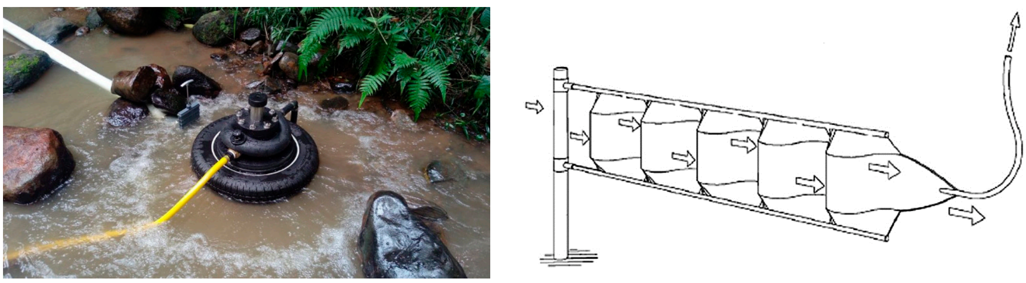


(e) **(f)**

Figure 8. Different types of generic integrations of HPPs: (**a**) Waterwheel-driven pump (WDP) system in Brazil [161]. Reproduced with permission from Agropress. © AGROTEC (https://dl.uc.pt/bitstream/10316.2/29970/1/Agrotec7_artigo35.pdf). Cropped from the original; (**b**) WDP type "Mangal Turbine" [162]. Reproduced with permission from Bharat Dogra. © Bharat Dogra, as authorized by the author Mangal Singh (https://thewire.in/agriculture/mangal-singh-bundelkhand-turbine). Cropped from the original; (**c**) Cross-flow turbine-driven pump (CDP) system in Indonesia [163]. Reproduced with permission of the author. © Isnugroho (https://publikasiilmiah.ums.ac.id/xmlui/handle/11617/4447). Cropped from the original; (**d**) Mixed-flow turbine-driven pump (MDP) in the Price-Stub pumping plant, Grand Valley Project, Colorado [155]. Document under public domain (https://archive.org/details/reclamationrecor11unit/page/308); (**e**) Off-the-shelf tangential-flow turbine-driven pump (TDP) unit. © ZM Bombas (http://zmbombas.com.br/turbobomba). Reproduced with permission of the author. (**f**) PAT-P system in an underground karst cave system in Gua Bribin, Indonesia [164]. © Franz Nestmann et al. (https://doi.org/10.1016/j.proeng.2013.03.006). CC BY-NC-ND 3.0.

3.1.8. Other Devices

This group comprises two HPP devices that, due to their mechanical characteristics and energy harnessing method, do not fit in any of the other groups. These, which are the Bunyip pump and the Filardo pump, are characterized for being relatively novel inventions, though their commercial and research status are mutually opposite to each other. The former results from the integration of a conventional rubber tire (which provides elastic potential energy) and a piston pump, while the latter harnesses kinetic energy from running water by means of a so-called ribbon frond mechanism, which acts as a linear peristaltic pump. Both devices can be seen in Figure 9.



(**a**) (**b**)

Figure 9. Other HPP devices: (**a**) Bunyip pump [165]. Reproduced with permission of the author. © Brett Porta (https://www.facebook.com/portasaffordablepumps/photos/a.835289806627751/1033397573483639/?type=3&theater). Cropped from the original; (**b**) Concept of Filardo pump [166]. Reproduced with permission of Elsevier. © Elsevier (https://doi.org/10.1016/j.renene.2016.01.089). Cropped from the original.

3.2. Literature Analysis

A total of 854 documents of different nature, in 17 languages, either as a whole or sections of them, were selected and classified. From these, 418 and 436 correspond to scientific and grey literature, of which 156 and 125 are non-English documents, respectively. As represented in Figure 10, the number and distribution of these documents per HPP technology are neither homogeneous nor follow any identifiable pattern.

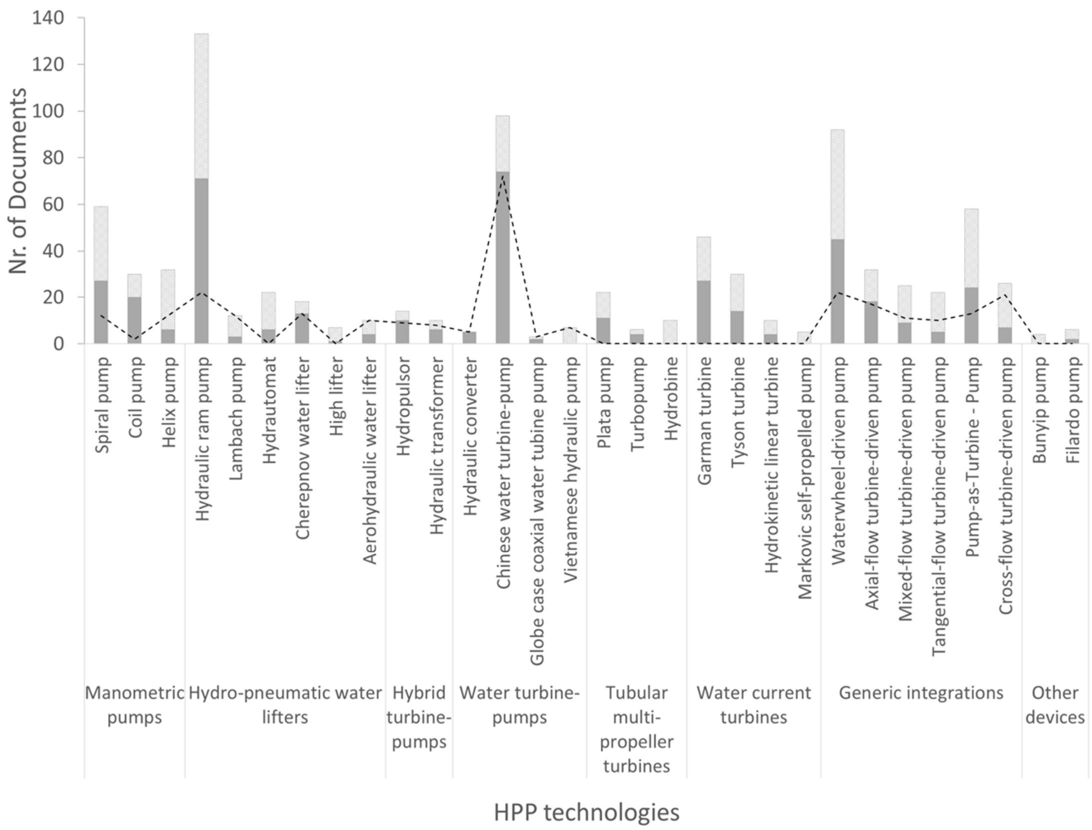


Figure 10. Number of selected documents per HPP technology. The grey solid bars, grey diagonal pattern bars, and black dashed line correspond to scientific literature, grey literature, and non-English literature (both scientific and grey), respectively.

Although roughly half of the total selected documents belongs to scientific literature, this is mostly concentrated in only three technologies, namely the CWTP, HRP, and WDP (18%, 17%, and 11%, respectively). In relative terms, however, the Hydraulic converter, CWTP, CWL, and Hydropulsor are the largest holders of these sources (100%, 76%, 72%, and 71%, respectively). On the opposite side, the HRP and WDP are the main bearers of grey literature (14% and 11%, respectively), though its biggest relative concentration relies on the HHP, High lifter, Vietnamese hydraulic pump, Hydrobine, Markovic self-propelled pump, and Bunyip pump. In point of fact, the five latter only exist in that domain of information, i.e., they are not reported at all in scientific documentation.

Notably, documents from sources usually neglected in scientific research (e.g., low-impact factor journals, commercial literature, nonscientific websites, social media) offered large fragments of information not found otherwise. Such is the case of the HHP, LP, High lifter, Vietnamese hydraulic pump, Hydrobine, Markovic self-propelled pump, and Bunyip pump. Furthermore, the mapping of certain case studies and/or research worldwide (3.3) was only possible due to those sources.

One-third of the total documents corresponds to non-English literature, thus cannot be considered negligible. Out of that quantity, 26% belongs only to CWTP, whereas roughly 23% is evenly distributed between the HRP, WDP, and CDP. Albeit five technologies (i.e., LP, Aerohydraulic water lifter, Hydraulic converter, Globe case coaxial water pump, and Vietnamese hydraulic pump) contribute to barely 13% of the total, those pose the particularity of being exclusively reported in non-English documents. Other technologies with a high relative non-English representation are the CDP, HT, CWTP, CWL, and Hydropulsor (81%, 80%, 74%, 72%, and 64%, respectively).

All these documents, which belong to the 30 HPP technologies and their respective categories, have been published in different years throughout history. However, as seen in Figures 11 and 12, there are certain periods in which noticeable boosts of literature took place. The hydro-pneumatic water lifters, though showing a steady increase over time, have two particular moments: The former around the early 1920s and the latter since the early 1980s, due to the punctual and momentary interest of the Hydrautomat and the sustained production on the HRP, respectively. Documents addressing technologies such as the HSP, WDP, and PAT-P gained a particular rebound during the 21st century (though the two former existed since few centuries ago), thus providing an evident increase to their respective categories, i.e., manometric pumps and generic integrations. The WTPs, thanks to the CWTP, present a remarkable peak in their literary production during the late 1970s and 1980s which, during the present century, has flattened drastically. The documentation on WCTs, mainly linked to the records on the GT, presents the particularity of increasing during the last decade, despite those technologies having been actively researched/applied during the 1980s and 1990s.

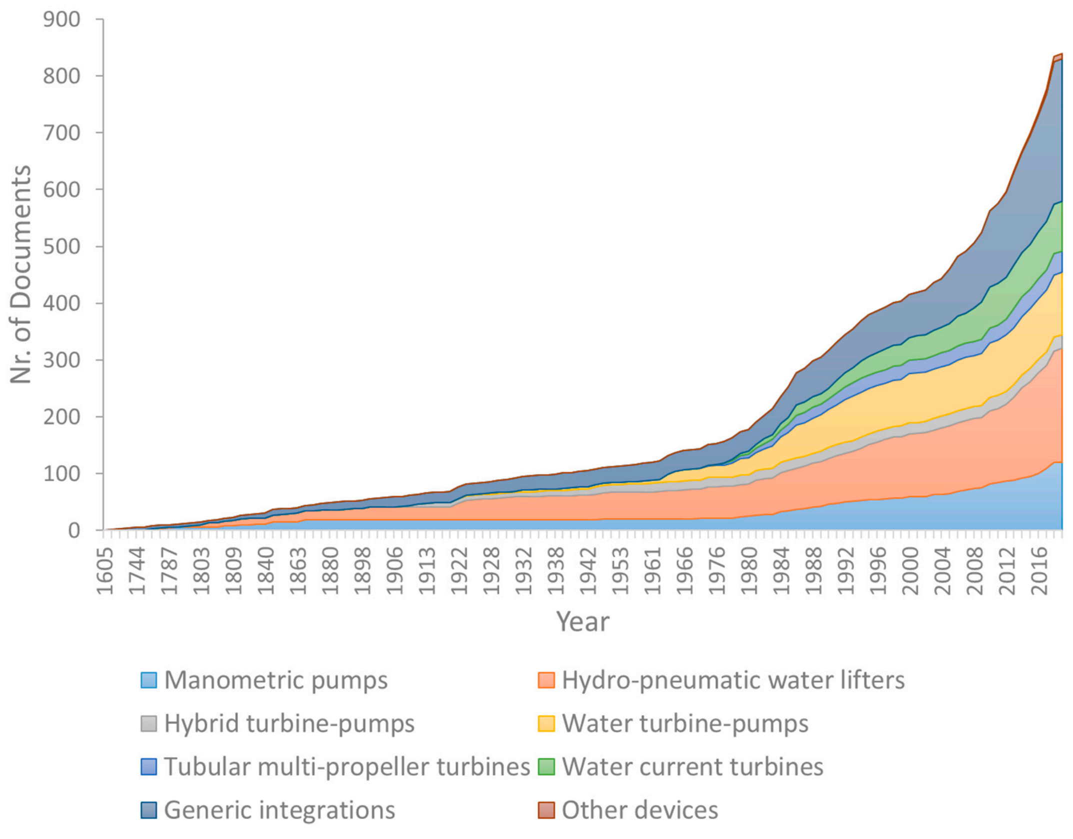


Figure 11. Cumulative number of selected documents published over time. The different colored areas depict the running total of documents produced per category of technology per year.

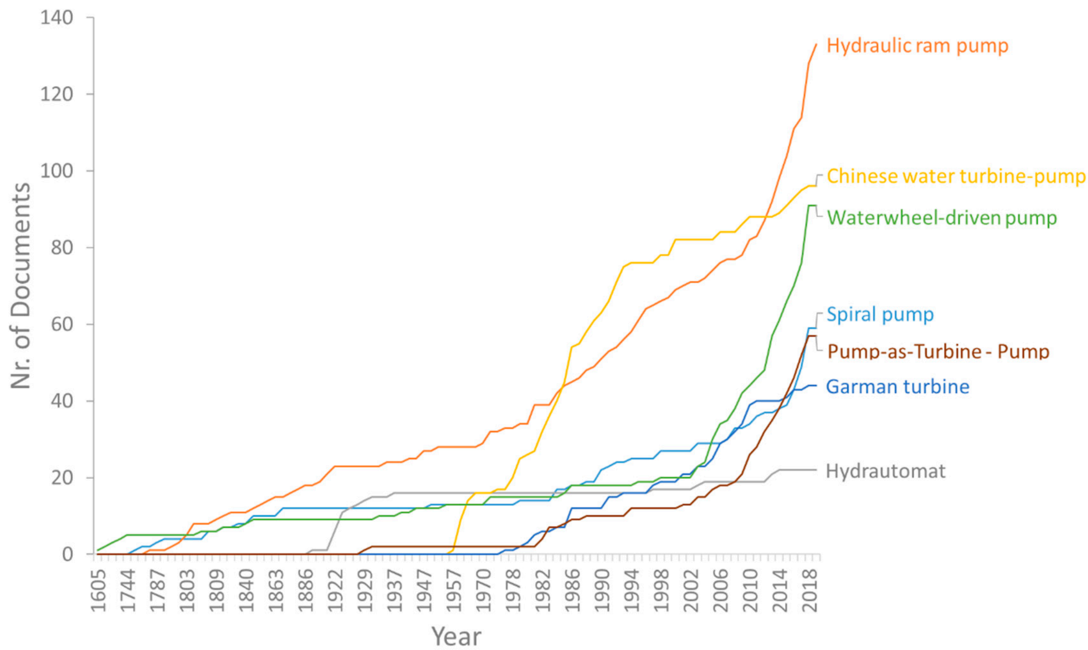


Figure 12. Noncumulative number of selected documents published over time. The different colored lines depict the running total of documents produced per technology per year. Only the most noticeable ones are represented.

These numbers, as well as their distributions amongst the different HPP technologies, offer solid evidence in understanding: (i) How scientific production has (historically) focused in certain–to the detriment and neglect of other ones–regardless their development stage and benefits; (ii) how some HPP technologies (e.g., High Lifter, Hydrobine, Bunyip pump) exist, scale out, and thrive commercially, unnoticed by the written scientific sphere; and (iii) how, despite the long history of HPP systems, room still exists for further scientific studies focusing on old, as well as relatively new, HPP technologies.

3.3. Spatial Analysis

The worldwide spread of HPP technologies, as can be seen in Figure 13, has not been followed any recognizable spatial pattern. On the contrary, literature shows their places of origin, density of application, end-use, and propagation, are as heterogeneous (and, at times, even contradicting one another) as diverse are the technologies themselves. Moreover, they have faced different fates in both very high and high-human development index (H-HDI) and medium and low-human development index (L-HDI) countries, under a number of contrasting conditions.

At a continental and subcontinental level, there are noticeable agglomerations of HPP technologies. The three main global clusters take place in Europe, South–Southeast Asia, and Eastern Africa. None of them are in coincidence with areas in which other RE-based pumping systems (e.g., solar-powered) have been installed [4]. The first one depicts an even distribution, mainly in western European countries such as the United Kingdom, Germany, The Netherlands, France, and Spain, which group a number of developers, manufacturers, and research centers linked to HPP technologies. On the other hand, the Asian and African clusters seem to be associated to areas of intensive traditional agriculture (i.e., southeast China, Indo-Gangetic plain, Indochinese peninsula), and to main transboundary river basins (e.g., Nile, Jubba, Zambezi), respectively. From these three groups, as presented in Figure 14, the Asian group is the only one with a consistent predominance of the agricultural irrigation as main end-use, whereas the European and African groups present a mix of water supply–agricultural irrigation uses.

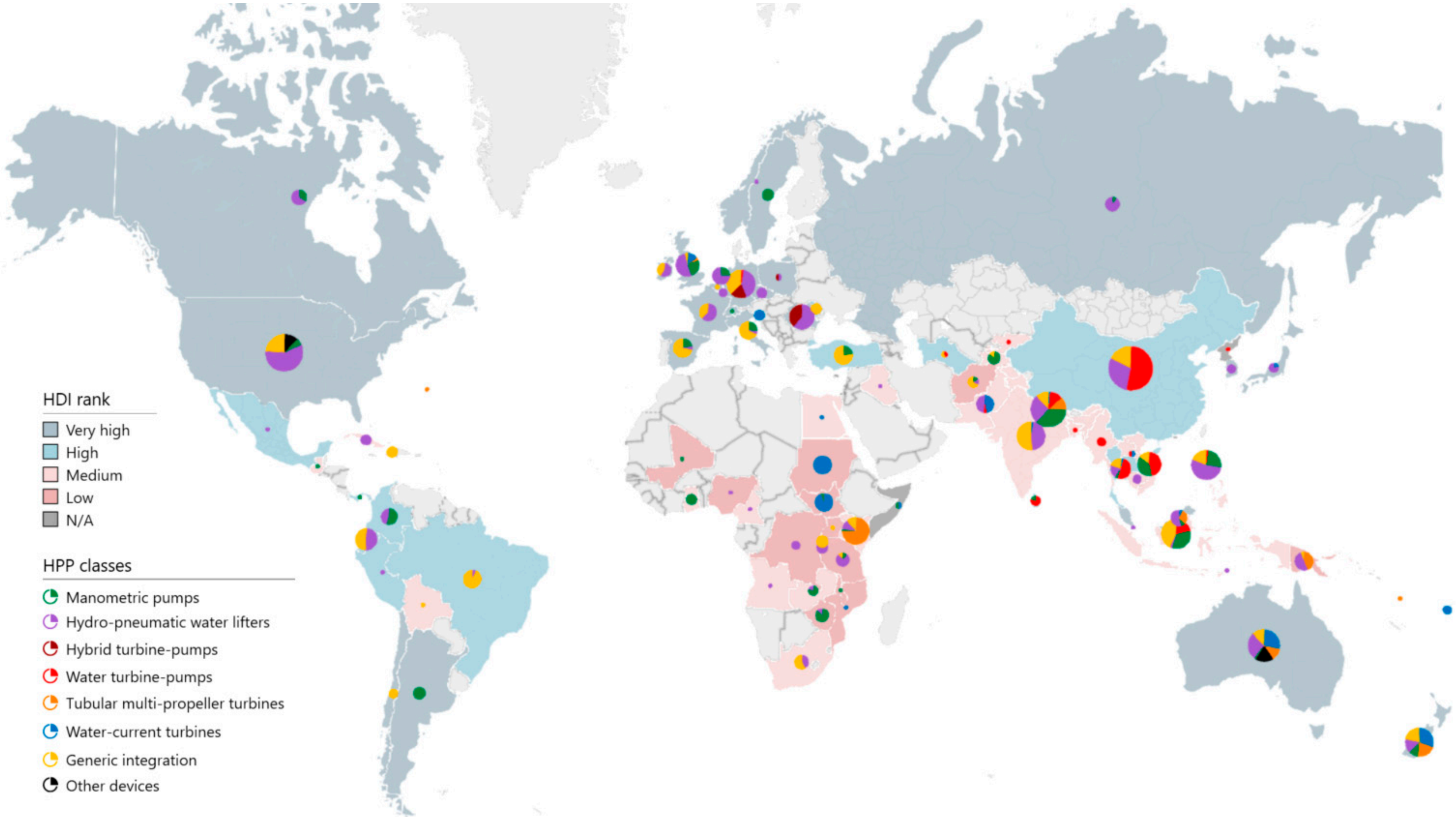


Figure 13. Worldwide mapping of HPP technologies per country. The size of each circle and the arc length of each colored slice represent, proportionally based on a logarithmic scale, the total number of reported devices and the number of reported devices per HPP classes, respectively. The background color of each country depicts its rank regarding the Human Development Index (HDI).

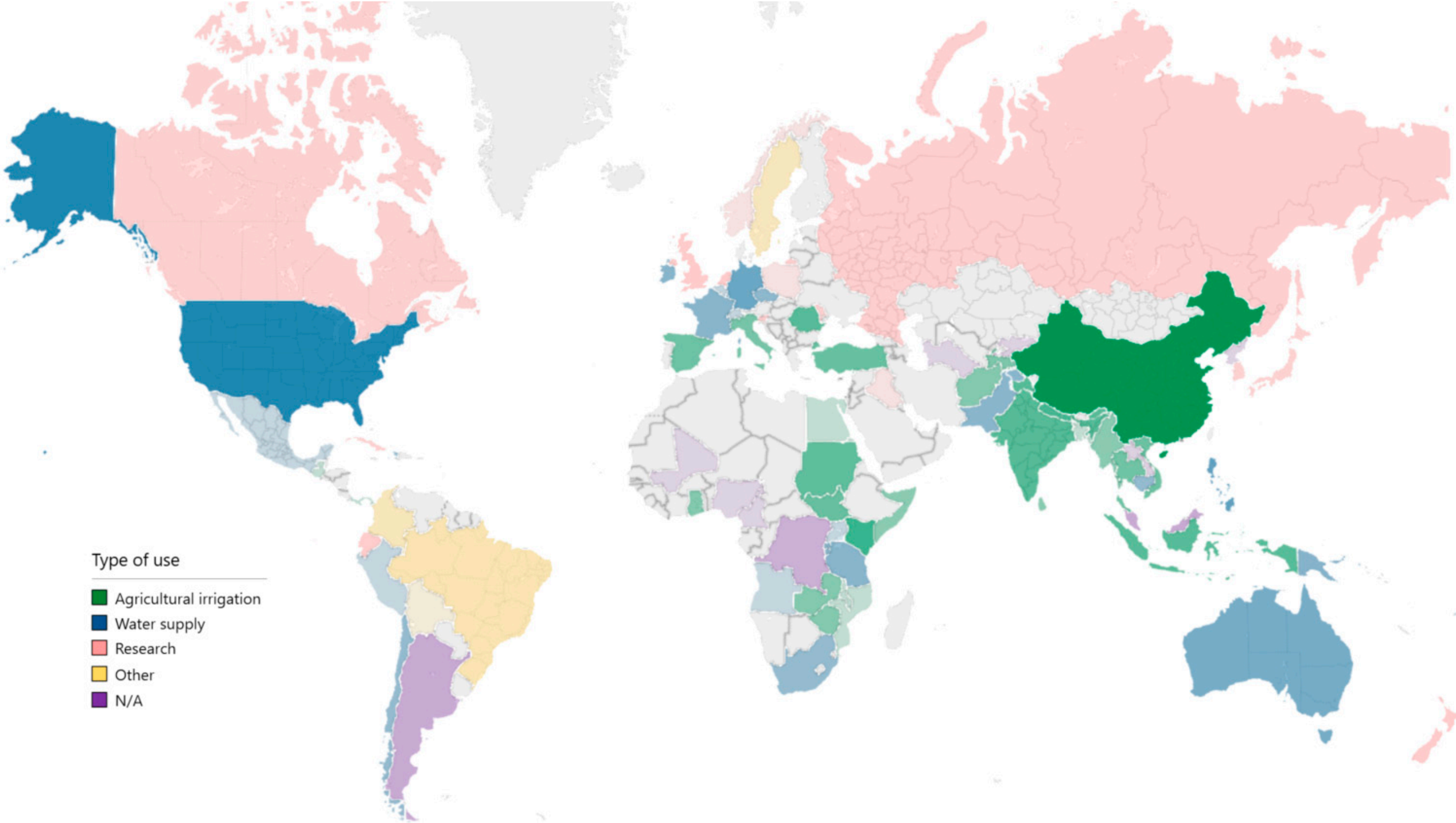


Figure 14. Worldwide mapping of predominant HPP technologies end-uses per country. The intensity of the colors represents, proportionally based on a logarithmic scale, the total number of reported HPP devices serving that end-use. The category "Other" groups the presence of manufacturers, as well as other less-common reported uses: Livestock water supply, aquaculture, land drainage, sewage pumping, landscape irrigation.

With respect to a country scale, both quantitative and qualitative concentrations of technologies can be distinguished, i.e., number of reported cases and distinct technologies, respectively. The number of installed units per country is amply dominated by the CWTP in China and the HRP in the United States, both H-HDI countries, as shown in Figure 13 and Table 2. Nevertheless, as seen in Figure 14, these technologies predominantly fulfilled two different end-uses, i.e., agricultural irrigation and water supply, respectively. The former resulted from an immense undertaking of the Chinese government, whereas the latter was a product of the proliferation of American manufacturers and the consequent popularization of the HRP. Other technologies that show a high nationwide density are the Turbopump and HSP in Kenya and Nepal, respectively, both serving agricultural irrigation, and the HRP in Philippines, mainly used to supply water in rural villages. These three cases, all within L-HDI countries, are the sole result of the efforts of their respective manufacturers.

Table 2. Top-five ranking of countries in regard to different categories.

Ranking	Density of Technologies	Concentration of Diverse Technologies	Nr. of Manufacturers
1	China (CWTP)	USA (11)	UK (8)
2	USA (HRP)	Australia (9)	China, USA (7)
3	Kenya (Turbopump)	New Zealand (8)	Brazil, New Zealand (6)
4	Nepal (HSP)	Indonesia, Nepal, Thailand (7)	Australia (5)
5	Philippines (HRP)	Germany, Kenya, UK (6)	Colombia, Nepal (4)

The top-five ranking of countries are ordered from highest (1) to lowest (5). The density of technologies, concentration of diverse technologies, and number of manufacturers, are expressed regarding the predominant technology, number of distinct technologies, and number of distinct manufacturers, respectively.

On the other hand, both H-HDI and L-HDI countries have been fertile land for the application and coexistence of many diverse HPP technologies, as depicted in Figure 13 and Table 2. With 11 different technologies the USA is the country bearing the highest diversity. However, the Australasian and South-Southeast Asian regions hold other important contenders: Australia, New Zealand, Indonesia, Nepal, and Thailand. In contrast, the concentration of manufacturers of HPP technologies is led by UK, USA, China, New Zealand, and Brazil, i.e., mainly H-HDI countries. Nevertheless, technologies such as the GT, Vietnamese hydraulic pump, Turbopump, and HRP are flagships of effective local production in L-HDI countries (e.g., Nepal, Philippines, Afghanistan, Kenya, Vietnam).

A number of technologies have been able to move across political boundaries, though with different destinies: The HRP, whose presence is reported in 42 countries, became the most cosmopolitan, ubiquitous a nd diversified HPP technology. The expansion of the CWTP, nonetheless, is unique amongst HPP devices: Although it bears the biggest number of reported applied cases ever, vastly outpacing any other technology, it just moved discreetly to other 14 countries (besides China), where it did not flourish at all. Other technologies that show certain degree of global presence are the HSP, WDP, HHP, CDP, and PAT-P. In contrast, the Plata pump (turning into the Kenyan Turbopump) and the GT quickly moved from their original H-HDI countries to L-HDI ones, modestly thriving within their new limits, possibly thanks to effective transfer of knowledge.

Technologies such as the HHP, the TT, and the Hydrobine, for example, arose completely within H-HDI countries (Sweden, Australia, and New Zealand, respectively), whereas other devices like many HSPs, HCPs and CDPs found their way in L-HDI ones. Interestingly, the HT, Bunyip Pump, Globe case coaxial water turbine pump, and the High Lifter on one hand, and the MT and Vietnamese hydraulic pump on the other hand, are technologies that have virtually remained within their original boundaries in H-HDI and L-HDI countries, respectively, without having experienced any further expansion.

3.4. Temporal Analysis

Unlike what occurs with their worldwide spread, evolution of HPP technologies over time follows noticeable patterns of peaks and depressions, as depicted in Figure 15. During the 16th and

17th centuries, the earliest HPP technologies (e.g., WDP, HSP, HCP) consisted mainly of large-scale waterworks for urban settings (e.g., Paris, London, Philadelphia, Munich) or for nobility buildings (e.g., Toledo, Versailles, Modave, Arkhangelskoye). Their number was very limited, mainly due to their complexity in construction and the high investment costs involved. During the 18th and 19th centuries, however, the invention of the HRP provided a considerable boost to HPP systems by fulfilling the function of a small-scale, affordable pumping technology that contributed in changing the lifestyle of many European and American households [167].

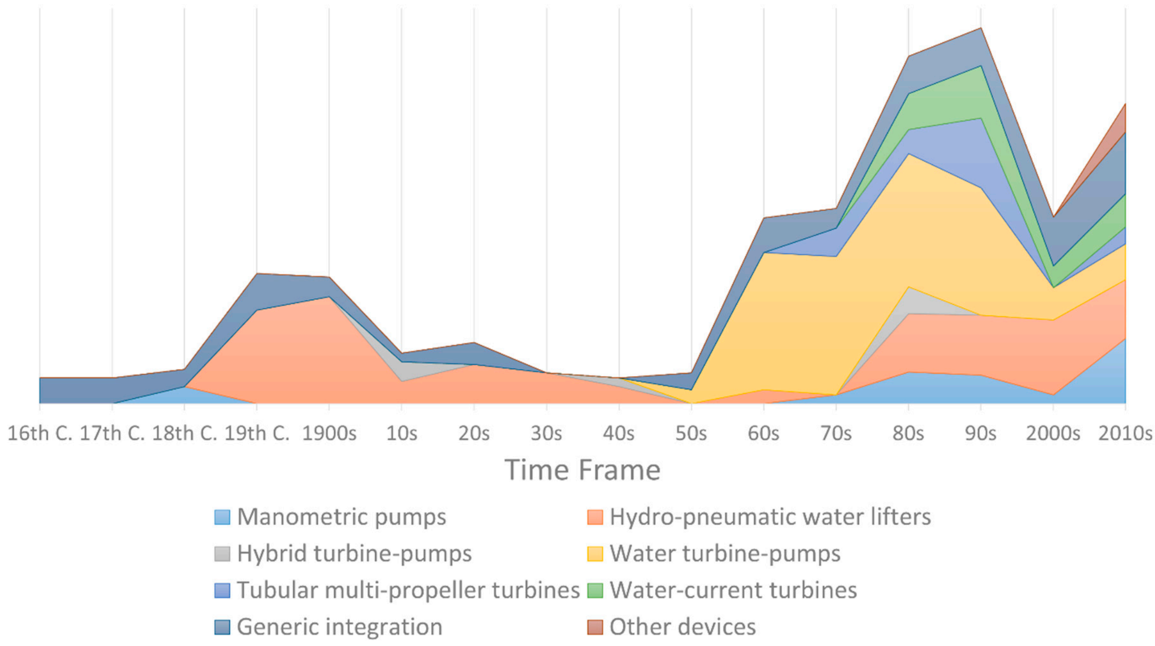


Figure 15. Number of reported cases of HPP technologies over time, depicted proportionally based on a logarithmic scale. The different colored areas represent each of the HPP classes.

This first peak was gradually overshadowed during the first half of the 20th century by the rise of forms of readily available energy (e.g., steam, electric) different from hydraulic. Nevertheless, its second half was the most prolific period for HPP technologies, when many of them arose as a direct response to either scarce, unaffordable, or inaccessible fossil-based energy [168–170], in which high global oil prices due to critical events (e.g., oil embargos, Iran/Iraq War, Gulf War) seemed to be a main game-changer [171]. The main contributor to this unequalled peak in history was the aggressive spread of the CWTP over China during two continuous decades [114], though the rebound of the HRP [167] and the quick, yet focalized rising of the Turbopump [118] became non-negligible additions as well. This period is also characterized by the emergence of many other technologies such as the GT, PAT-P, TT, CDP, HT, and HCP, among others.

During the 2000s, however, HPP technologies faced a slump apparently linked to the drop of international oil prices [171], hence to more affordable fossil-origin energy, which in turn partially dragged down the interest for RE-based technologies [172]. Nowadays, there has been a regained HPP momentum, which could be the indirect result not only of fossil-fuel trends, but also of an increasing environmental awareness and more affordable RE-based technologies [172,173]. Although no other technology has ever reached the numbers of the CWTP, many of them altogether provide this current impulse: HSP, HRP, ADP, CDP, PAT-P. Nonetheless, the fluctuation of international oil prices can jeopardize the progress of RE [172], thus HPP along with it.

At an individual level, HPP technologies present very dissimilar storylines in regard to their survival, growth, application, and fate. The LP, Hydrautomat, Hydropulsor and Plata pump declined despite their benefits, good reception, and commercial status. Moreover, devices such as the Platypus

HRP and the Plata pump left the stage almost without any traceable information. Some technologies became marketable only after long research and prototyping processes (e.g., HSP, HRP, CWTP, GT), whereas other ones went commercial almost without research and development phase (e.g., HHP, Plata pump, Turbopump, High Lifter, Bunyip pump, Hydrobine). On the other hand, another group of technologies has not aroused any apparent commercial interest, thus being relegated to the research realm: CWL, HT, hydrokinetic linear turbine, hydraulic converter. Furthermore, a last group corresponds to potentially promising technologies incipiently researched in contemporary times: Filardo pump, aerohydraulic water lifter.

Some technologies thrived despite adversities, while other ones sunk even while counting on favorable conditions. Inherent properties, like simplicity of manufacturing, robustness, and sound functioning, have been key for the worldwide spread and persistence of the HRP over time, whose principle has remained virtually unchanged for more than two centuries. In the same line, a globally ubiquitous, well-developed market and affordable off-the-shelf units have been a solid ground for the more recent expansion of PAT-P throughout the second half of the 20th century. By contrast, complexity, uniqueness, and highly concentrated expertise of the LP resulted in crucial weaknesses when facing threats like world wars and market collapses.

Factors belonging to the management systems of HPP technologies have been also gravitating. Seemingly proper business models for the HHP seem a sound reason for its discreet, yet sustained use, especially in H-HDI countries (e.g., USA, Canada, Sweden). Contrariwise, mismanagement issues such as stakeholders' misalignments, weak supply chains, lack of spare parts, and stagnation in development were deadly for the Plata pump and for the once-acclaimed and officially supported CWTP. Moreover, the firm will of the people involved has led to push forward some causes against odds. Peter Garman, for instance, practically devoted his life to develop and spread the GT in L-HDI countries in Africa, despite civil wars, discontinuation of the research program, and local-manufacturing issues. Mangal Singh and Auke Idzenga are other examples of standing against many sociopolitical constraints, though the expansion of their Mangal Turbine WDP and HRP have found opposite destinies in India and Philippines, respectively. On the other hand, the constancy and endeavoring of Warren Tyson was eventually not enough for the TT to cope with world market crashes that led to an eventual commercial crumbling.

The appropriate technology movement and many of its related research centers and agencies (e.g., ITDG–Practical Action, VITA, SKAT, CICAT, GIZ) largely contributed to the expansion and implementation of some HPP technologies during the 1970s, 1980s, and 1990s. Several cases of HCPs, HRPs, GTs, and CDTs are direct products of their undertakings. In most of these instances, there was a strong component on expertise transfer, local manufacturing, and technology empowerment, aiming to create more resilient technologies rather than profit from patented ones [51,74,124,173–178].

4. Conclusions

HPP technologies have a long history, though having experienced different levels of prominence. More than 800 documents, different in nature and content, have been thoroughly reviewed to shape their role in space and time. Some of these technologies, such as the HRP and the WDP, have had global impact and interest since their origins until contemporary times, whereas other ones, like the Hydraulic converter, Hydropulsor, and HT, have had short and almost imperceptible lives. On the other hand, the CWTP, albeit with a relatively short lifespan, was one of the backbones of rural development in China, and a unique case worldwide. To a bigger or lesser extent, all of them have demonstrated to be a sound alternative to conventional water pumping systems, which can be unaffordable or even inaccessible, particularly in remote and off-the-grid areas.

In this sense, and in accordance with the objectives previously raised in the present document, three main following concluding remarks can be drawn:

1. The concept of pumping water by only relying in hydro-mechanical power–at least due to the amount of readily available "westernized" literature–is something seemingly reserved for

few well-known technologies like the HRP, WDP, CWTP, GT, and HSP. Nevertheless, after an exhaustive and systematic search process, up to 30 HPP technologies were screened and analyzed. However, due to the wide range of features and applicability, their classification became eventually a main challenge for the present study. It is so that eight classes were defined, not based on one single property on the technologies, but on the combination of several of them (i.e., working principle, pumping principle, prime mover, pumping device, integration of the parts).

2. HPP technologies are not currently the main protagonists globally in water lifting. Some of them, however, mainly off-the-shelf devices within the class of generic integrations (i.e., CDP, PAT-P, TDP, WDP) applied in low-income countries, keep being the standard-bearers of their development, commercialization, and application. Moreover, and despite their more than two century-long existence, both HRP and HSP pose a sustained interest from manufacturers and researchers, who persistently find in them low-cost, robust, and environmentally sound means of delivering water to new heights.
3. Individual HPP technologies do not present any apparent global spatial and temporal patterns. However, their aggregated analysis does say much more, not only on what has been done before, but on the current, as well as possible future, directions of research, application, and commercialization. For instance, nowadays, many South American countries show an incipient, yet growing interest in working with these technologies in both academia and industry. On the other hand, Sub-Saharan Africa remains a region where HPPs have the potential to create a higher social impact by improving livelihoods through sustained water supply. Last, yet not least, the baggage of expertise on design and manufacturing, as well as a higher capacity of adoption and use of HPPs in other regions (i.e., Europe, South and Southeast Asia), will be always a valuable capital for academics and manufacturers while exploring new insights in their respective domains.

HPP technologies still have a potentially promising future to keep supplying water in different contexts, particularly due to their current regained momentum. However, researchers, manufacturers, and users need to be aware of the importance that management systems, as well as business models, pose for these technologies beyond their mere performance. Their adequate implementation can represent higher resilience and adaptability capacities, while their lack or an open mismanagement could turn into their weakest point. The synthesis presented in this document serves as a reference starting point for other researchers in fields such as hydraulics engineering, water and irrigation management, and industrial archaeology, as well as others interested in the world of HPP systems.

Supplementary Materials: Datasets related to this article can be found at https://dataverse.nl/privateurl.xhtml?token=88727bbc-838f-4cfc-b311-cf81d2943016, an open-source online data repository hosted at DataverseNL [39].

Author Contributions: Conceptualization, J.C.I.Z. and M.W.E.; methodology, J.C.I.Z. and M.W.E.; formal analysis, J.C.I.Z., investigation, J.C.I.Z., J.M. and E.A.P., writing—original draft preparation, J.C.I.Z.; writing—review and editing, J.M., E.A.P., J.C.D. and M.W.E.; visualization, J.C.I.Z.; supervision, J.C.D. and M.W.E.

Funding: This research was funded by the TU Delft | Global Initiative, a program of the Delft University of Technology to boost Science and Technology for Global Development.

Acknowledgments: The authors express their gratitude to the Delft University of Technology library services for making possible the access to otherwise hidden, uncommon literature. Particular thanks to Zhiling Zhang and Krissada Tundulyasaree, for contributing in translating some documents written in Mandarin and Thai, respectively.

Conflicts of Interest: One of the authors belongs to aQysta B.V., manufacturer of the Barsha Pump, one of the HPP technologies addressed in the present document.

Acronyms

RE	Renewable energy
HPP	Hydro-powered pumping
HSP	Hydro-powered spiral pump
HCP	Hydro-powered coil pump
HHP	Hydro-powered helix pump
HRP	Hydraulic ram pump
LP	Lambach pump
CWL	Cherepnov water lifter
HT	Hydraulic transformer
WTP	Water turbine pump
CWTP	Chinese water turbine pump
TMPT	Tubular multi-propeller turbine
WCT	Water current turbine
GT	Garman turbine
TT	Tyson turbine
WDP	Waterwheel-driven pump
ADP	Axial-flow turbine-driven pump
MDP	Mixed-flow turbine-driven pump
TDP	Tangential-flow turbine-driven pump
PAT-P	Pump-as-Turbine – Pump
CDP	Cross-flow turbine-driven pump
H-HDI	Very High and High-human development index
L-LDI	Medium and Low-human development index

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