Heliyon 9 (2023) e17753

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

A review on non-conventional hydropower turbines and their selection for ultra-low-head applications

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ARTICLE INFO

Keywords:
Conventional
Existing infrastructure
Hydropower
Resources
Turbine selection chart
Ultra-low-head

ABSTRACT

Very low-head water facilities are the salient resources for the development of hydropower using non-conventional hydro turbines. This review paper is concentrated on the collection and selection of turbines suitable for hydraulic heads between 0.5 and 3 m only defining them as the ultra-low-head. Turbines reviewed are feasible for new or existing infrastructure, drinking or waste-handled water, and able to function as a single unit, or parallel unit installation. From several earlier research and communication with 25 turbine manufacturers, thirty-eight different hydro turbines are discussed in this review with their operating range in most cases. The novelty of this review includes providing a comprehensive explanation of all the non-conventional hydropower turbines which were scattered in different literatures and providing a selection chart for classification of turbines. The distinct chart with four classification bases for hydro-static energy conversion of ultra-low-head turbines has been concluded and launched the category 'mode of action' to be the most comprehensive. The existing literature cover different basis for the selection but includes only few nonconventional turbines. This enforces the development of a specific selection chart comprising all such turbines with global scenarios.

1. Introduction

The power from water is the biggest and most economical source of renewable energy among all [1] and initially, the mechanical energy is produced after the potential or kinetic energy of flowing water. The machines applicable to translate energy from water to mechanical energy are hydraulic turbines [2]. This energy can be directly used or further converted to electrical through an electrical generator.

When classifying the hydropower based on working pressure head, ultra-low-head falls in the range of 0 m–3 m and is also referred to as extra-low-head [3] or micro head [4], or very-low-head [5]. Most of the published works emphasize the small category of hydropower technologies (static heads between 2m and 30 m) [6] or kinetic energy transformation technology [7]. Though water resources having hydraulic heads between 0m and 3m (termed as ULH) are technically feasible, not enough consideration has been established for water-energy conversion because of poor economic paybacks [3,5]. Some key benefits of ULH hydropower technology are: technology is environmentally gentle, low rotational speed and higher blade gaps can expressively decrease the effect for aquatic life flowing through the structure, the downstream water flow is ensured, no need for barriers for fish entry and separate path, requires reduced infrastructure that can be scattered broadly, can be developed near the social zone within a short duration [1,6,8].

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https://doi.org/10.1016/j.heliyon.2023.e17753
Received 2 August 2022; Received in revised form 20 June 2023; Accepted 27 June 2023
Available online 28 June 2023
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Abbreviation

ULH:	Ultra-low-head
SHPP:	Small hydropower plant
CEC:	Current energy conversion
TISEC:	Tidal in-stream energy converter
MCT:	Marine current turbine
RCECS:	River energy conversion system
WEC:	Wave energy conversion
PAT:	Pump as Turbine
ICOLD:	International Commission on Large Dams
HPM:	Hydrostatic pressure machine
GWVPP:	Gravitational water vortex power plant
SLHE:	Schneider Linear Hydro Engine
SRT:	Split reaction turbine
CPT:	Cross-pipe turbine
PVC:	poly venial chloride
RPM:	revolution per minute
kW:	kilowatt
USoDE:	United States Department of Energy
m:	meter
m/s:	meter per second
m^3/s:	meter cube per second
LPS:	liter per second
HyPER:	Hydropower Energy Resource

The development of a large quantity of small hydropower schemes took place in the beginning of nineteenth century and most of the developments were ignored on 1950s and 1960s. Now again, there exists a high necessity for the deployment of hydropower from low-head resources [9]. In the world, the small hydro potential having medium to high heads almost has already created already. But now, the remaining valued potential is ultra-low-head water resources which are undeveloped [3,5]. ULH technology will run out to be a modular, renewable, and justifiable resource through the advances in water turbine technology [8]. Presently, low-head hydropower has been an inspiring and noticeable technology for the concerned people in commercializing small-scale hydropower internationally [10].

Several types of research have been conducted by many researchers focusing on different concerns of low-head turbine technology for hydrostatic energy conversion. An extensive study conducted by E. Quaranta et al., 2020, in the “Hydropower case study collection: Innovative low-head and ecologically improved turbines” section contributed an explanation of a few typical cases of hydropower plant establishment from organizations of different countries covering environmentally enhanced and low-head waterpower converting devices. The conclusion drawn showed that the low-head hydropower is an area in progress in which the machineries and practices are being executed to improve flexibility, and productivity and to diminish conservational effects [11].

The contribution made by Zhang Yuquan et al., 2018, showed that there are no precise definitions of the different types of resources or their features and application of devices, on research trends of micro-head resource evaluation and hydropower turbines. The research recommended that the field is still in the premature periods of theoretic design and will necessitate noteworthy progress to match the established technology of conventional hydroelectric power production schemes [4]. Similarly, M. A. Sari, 2018, in “Recent Innovations and Trends in-conduit hydropower technologies and their applications in water distribution systems” presented an inclusive assessment of current technical novelties and inclinations in hydropower production from water conduits. Sixteen different turbine technologies (eight conventional turbines and eight evolving turbines) are assessed and compared based on their potential advantages and limitations, technological readiness levels, and installation locations in diversion structures, irrigation systems, and wastewater outfalls are all factors to consider [12].

According to a 2017 assessment of ultra-low-head hydroelectric technology by D. Zhou et al. the charts for turbine variety that are presented in certain books and published literature do not take into account cutting-edge turbine technologies that can function under ULH circumstances. According to the assessment, more trustworthy technology is becoming available for ULH resources and need to promote further expanding its utilization such that project cost can be lowered with the modular unit concept and utilization of local resources [8]. A Ph. D. dissertation by E. Quaranta, 2017, on “Investigation and optimization of the performance of gravity water wheels,” succeeded in providing a varied overview of all the categories of gravity water wheels. Physical tests to measure the water wheel’s performance under various hydraulic scenarios, theoretical models to gauge and forecast efficiency, and numerical simulations to enhance the design were all carried out [13].

Similarly, the explanation was made by M.B. Farriza et al., 2015, on “Evolution of simple reaction-type turbines for pico-hydro applications” [14]. Following an assessment of similar technologies in South African context, a research was done in 2015 b y I. Loots et al. on which areas where the technologies can be deployed and especially adapted to a South African environment were identified [15]. Another research conducted on “Low-head pico-hydro turbine selection using a multi-criteria analysis” by S.J. Williamson et al., 2014, provides a technique for choosing the best turbine architecture for a low-head pico-hydro specification by conducting quantitative and qualitative studies of 13 turbine systems that are determined from the particular requirements of the end user [16].

Improvements in the economic and ecological aspects of hydropower with VLH variations are promised by several fresh and intriguing solutions now being investigated, according to another study on “hydropower converters with head differences below 2.5 *m*” that was reviewed by S. Bozhinova et al., in 2013. This study revealed that a variety of interesting technologies were used and developed [17]. Also, I. Applegate Group and Colorado State University, 2011, completed a research on the feasibility of low-head hydro in Colorado’s current irrigation system, explaining over 20 low-head turbines appropriate for existing irrigation sites and selection chart for selected turbines [18]. In a similar way, J. Senior et al. (2010) in “New hydropower converters for very low-head differences,” presented two novel hydropower converters for very low-head differences and discovered that both devices appear to offer ecological benefits over existing hydropower converters and development potential. They provide continuation of the riverbed and enable sediment movement [19].

From the literature reviews conducted, different papers covered few different turbines that can be used for ULH hydropower generation, and also different turbine selection charts exist to select different turbines. So, it was necessary to accumulate those scattered information about turbine technologies critically focusing on the technological review of non-conventional turbines suitable for ULH hydropower generation and classify them on different basis and is the uniqueness of the research. Additionally, the selection chart for those turbines is varied and has to be gathered for further research and the production of standard charts.

To address those concerns, the contents of this paper have started with the explanation of hydro turbines for ultra-low-head technology, and potential existing low-head water resources and are followed by the operation of different non-conventional ULH turbines and their selection. A summary of a few concerned turbine manufacturers from the world is tabulated separately. The research findings are summarized at the end of the article. The contents are more focused on a variety of existing turbines and their selection for initial selection, and are anticipated to be more advantageous for all issues pertaining to ULH hydropower technology.

2. ULH hydropower technology and resources

2.1. Classification of ULH hydropower technology

The generation capacity of hydropower is ranged from pico to large where ULH falls on the range of pico to small hydropower plants. In most cases, they are run off the river type. Furthermore, the classification of small hydro can be sub-grouped based on the head such that the head range for the ultra-low-head category is below 3 m [20]. One of the main classifications of hydropower by head is remarkable because it defines the pressure due to incoming water on the runner of the turbine system. These parameters are the primary requirement for determining the kind of water turbine system to be implemented.

According to Zohu D. et al., 2017, ULH technology refers to power generation from locations with a vertical height of less than 3 *m* and a running water velocity of more than 0.5 m/s but no height [8]. From the various works of literature reviewed that are conducted by several researchers, ULH technology can be broadly explained under hydro-kinetic and hydro-static energy transformation technology.

2.1.1. Hydrokinetic energy conversion technology

Hydrokinetic technologies are mounted directly in natural watercourses like tidal inlets, marine currents, waves, rivers, human-made channels [21], and different water structures with a favorable velocity. This technology has many equivalents with wind technology regarding principles of working, electrical assemblies, and speed variability [22]. Generally, the water flow velocity for hydrokinetic turbines is 1.5–3 m/s. Though there are numerous benefits of using this technology, the turbine used on it has two key constraints; the first maximum theoretical efficiency is within Betz limit (59.3%) only, and the next is the cavitation issue [7].

- **Hydrokinetic technology with Turbine**: In this technology, turbines are the medium for energy conversion of flowing water in different positions as horizontal, vertical, cross flow, Venturi, and gravitational vortex [23].
- **Hydrokinetic technology without Turbine**: In this technology, instead of a turbine, different energy conversion equipment with concerned principles of operation is used that includes piezoelectric, flutter vane, oscillating hydrofoil, vortex-induced vibration, and sails [23].
- **Current energy conversion (CEC)**: This technology has made it possible to generate power from a moving watercourse using a turbine. Tidal in-stream energy converters (TISEC) [24], river energy conversion systems (RCECS), and marine current turbines (MCT) [25] fall under the category of CEC.
- **Wave energy conversion (WEC)**: The technique of response from a mechanism of reacting forces between two or more bodies that are concerning one another has made it feasible to harvest the energy of uneven waves [26]. The functioning principles and design methodologies of CEC and WEC systems are somewhat different.

2.1.2. Hydro-static energy conversion technology

The traditional method of generating electricity by dropping water from a given height and capturing water power using an appropriate water turbine is known as the hydro-potential or hydrostatic technique [27]. In ULH technology, the static head is between 0.5 and 3 *m* such that turbines are of non-conventional type [3]. From the several research literature reviews, the energy conversion on

ULH hydrostatic technology takes place mostly on existing infrastructure with minor modifications or new infrastructure in the form of multipurpose hydropower projects [18]. These can be divided into the following sub-groups based on the literary genres.

- **ULH hydrostatic conversion with impulse turbine**: In this technology, the transformation of the potential energy of water to mechanical power is due to purely impulse action of water using the non-conventional type of hydro turbines. Water with lost energy from the turbine housing flows to the outlet passage towards the tailrace [28]. Archimedean screw, water wheel, hydro engine, steff, and water vortex turbine are a few examples of this category.
- **ULH hydrostatic conversion with reaction turbine**: In this technology, the transformation of the potential energy of water to mechanical power is due to impulse action and pressure difference of water within the water-sealed framing and uses the non-conventional type of hydro turbines. Within the head range of the ULH technology, it can be further sub-categorized as low and high flow [14]. Different ULH turbines develop power utilizing either low or high flow rates depending upon the working principle of an individual system. Baker's mill, split turbine, siphon turbine, very low-head turbine, open flume Francis, dive, PAT, etc., are some of the examples.
- **ULH hydrostatic conversion with vertical shaft system**: In this technology, the position of the shaft is vertical on which the runner remains fixed. The water flow enters the runner based on their working principle [23]. Baker's mill, Split turbine, Propeller/Kaplan, water vortex, Siphon, open flume Francis, dive, Turgo, PAT, etc., fall under this category.
- **ULH hydrostatic conversion with horizontal shaft system**: In this technology, the runner remains attached to the horizontal shaft such that flow enters the runner based on their working principle [23]. For example, water wheels, cross flow, bulb, hydro engine, Steff, Turgo, PAT, etc., fall under this category.
- **ULH hydrostatic conversion with inclined shaft system**: In this technology, the runner remains attached to the incline-positioned shaft such that flow enters the runner based on their working principle [29]. Archimedean screw, very low-head turbine, Kaplan, etc., are some examples.
- **ULH hydrostatic conversion with closed or open water inflow line**: This is a sub-category on which either the water at the inlet of the turbine is through a closed pipeline or in contact with the atmospheric condition. For example, water-wheel, Archimedean screw, power pal, very-low-head, vortex, open-Francis, etc., are some open systems of ULH.
- **ULH hydrostatic conversion with double shaft system**: This is a sub-category in which the use of shaft used in the turbine is two in numbers; one is the main and the next is the ideal one. The rotation of the runner due to two shafts is a combination of a circle and line known as a composite path [30]. For example, the Steff turbine, hydro engine, Schneider fully flooded or free jet and Linear Pelton fall under the double shaft systems of ULH.

2.2. *Potential ultra-low-head water resources*

The advancement of large hydropower schemes has slowed in recent years because of worries about land acquirement costs, regulatory and approving hurdles, and environmental effects [31]. The geological distribution of ULH water-energy resources is massive around the globe [32]. The "sleeping" hydro potential plays a crucial market role. Though the water infrastructure is very small, it can produce a hydropower-like water supply system for homes or wastewater from home. If surplus pressure heads exist anywhere in water flow lines, there can be a better option to develop hydroelectricity [33].

A study conducted of 9266 hydropower stations worldwide by the International Hydropower Association, 2019 [34] with the ICOLD showed that 40% of hydropower stations are multi-objective type and 60% are only for hydroelectricity generation. From 1900 to 2018, the development of hydropower projects with single and multi-objectives is summarized in Fig. 1 [34].

According to Mhylab coordination with European Small Hydropower Association in 2010 [35], existing ULH water-energy resource

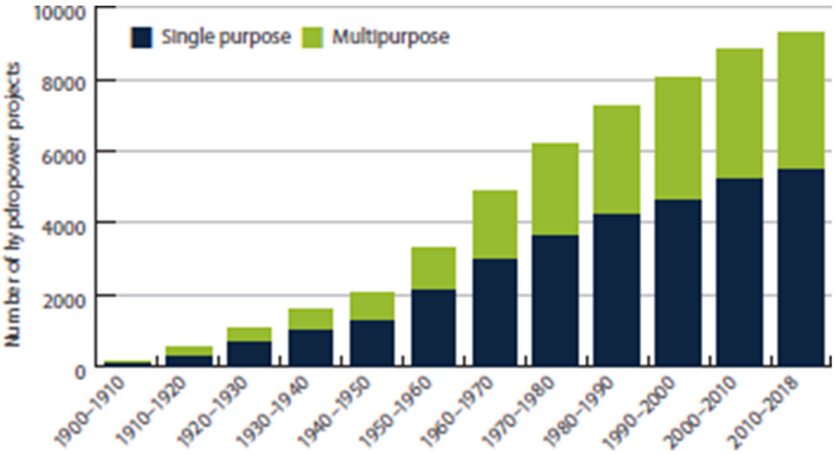

Fig. 1. Cumulative number of hydropower projects on a purpose basis [34].

potentials that prioritize electricity generation as a secondary goal are referred to as multifunctional systems. As a result, the power plant will be added to the existing infrastructure while maintaining its core role. Such potential sites can be classified [36] as in Fig. 2.

There are several prospects for hydropower generation utilizing small dams and barrages/weirs. [37], tailrace flow from hydropower stations [38], and old mills or similar structures [39].

2.3. *Different turbines for ultra-low-head hydrostatic energy conversion*

2.3.1. *Waterwheels*

Water wheels are the old-style technique of producing hydropower in low capacities for local use. The water wheels can still be a practical selection in many cases though they are less efficient than modern turbines. They are appropriate to construct and maintain, easy to control, and aesthetically attractive [40]. The classification of water wheels explained according to Quaranta E. 2017 [13] is summarized in Fig. 3.

- **Stream wheels**: The stream wheel was the first vertical type of wheel used in the past installed in flowing water (hydro-kinetic) with high flow rates to generate appreciable power output [41] as shown in Fig. 4a.
- **The Undershot wheel**: It is fixed on the top surface of the water with the wheel on the vertical plane. The wheel turns due to the flowing of water beneath the water wheel [13] as shown in Fig. 4b.
- **The Breastshot wheel**: It collects energy from dropping water hitting the blades at the center level of the water wheel [13] as shown in Fig. 4c.
- **An Overshot wheel**: It works due to the striking of water on the topmost blades towards the water wheel which makes it rotate and develop power [13] as shown in Fig. 4d.
- **Sagebien wheels**: These are radial blade undershot wheels with the blades inclined forward. Blades are designed on it to minimize upstream power loss [13]. The water enters the water wheel like in Fig. 4e.
- **Zuppinger wheel**: The blades designed on it are to reduce the energy losses on the downside of the water wheel. The modification in the profile of the blade empowers an improved filling and draining of the spaces resulting in upgraded efficiency [13]. Fig. 4f shows a diagram of the water wheel developed by Zuppinger.
- **Poncelet wheel**: The Poncelet has a large wheel having curved blades and water enters with an undershot passage of the gate. The blade design makes the waterfall out of the cells smoothly with a low horizontal velocity [13]. It is shown in Fig. 4g.
- **Hydrostatic pressure machine**: The HPM is a simple water wheel having radially placed straight blades. The arrangement of blades rotates in a curved and fixed bed segment that holds the water level to the top surface level. It also acts as a weir (Fig. 4h). In relation to the head difference and blade height, the hub diameter of HPM is roughly equal. The consequential hydrostatic pressure force developed on the blades runs the machine [19].

2.3.2. *Screw type turbine*

A hydrodynamic screw is a premature machine comprising helical surfaces attached to a shaft that acts as blades. Depending upon the site steepness between the higher and lower water surface, the inclination of the shaft on the turbine is 20°–35° as shown in Fig. 5 [49–52]. The configurations are in two assembly types: open and closed. The opened arrangements are for high flow rates whereas the closed systems are for lower flow schemes. A screw-type turbine works similarly to the Archimedes screw that gets active due to the pressure difference of water across the twisted blades [16]. High-flow and lower-head sites are suitable for these turbine systems [53]. The screw generally works at heads between 1 and 10 m and discharges between 0.2 and 15 m^3/s [54,55] with a maximum power of

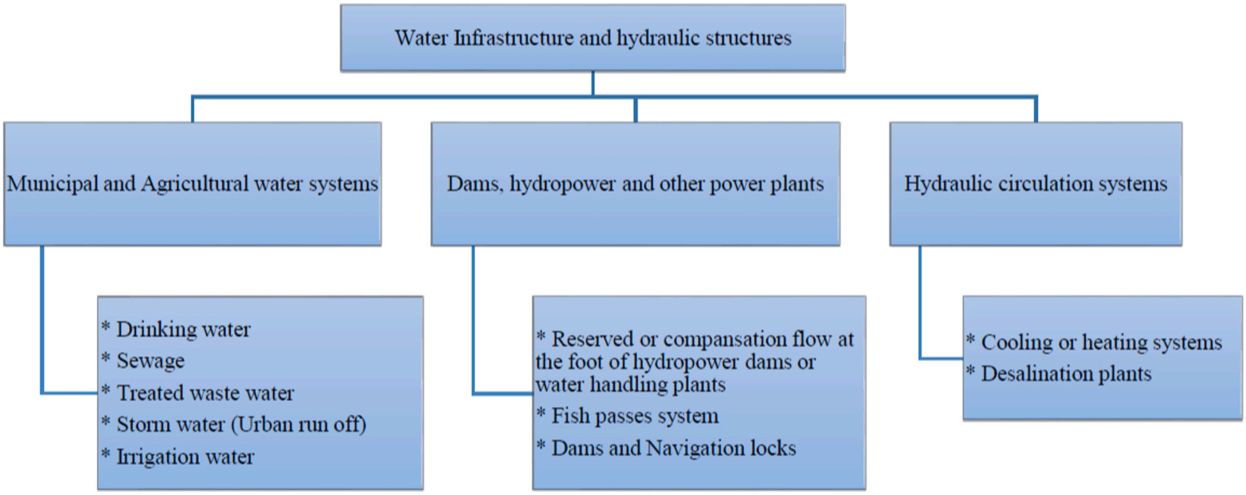

Fig. 2. Classification of Water Infrastructure and hydraulic structures, adapted from [36].

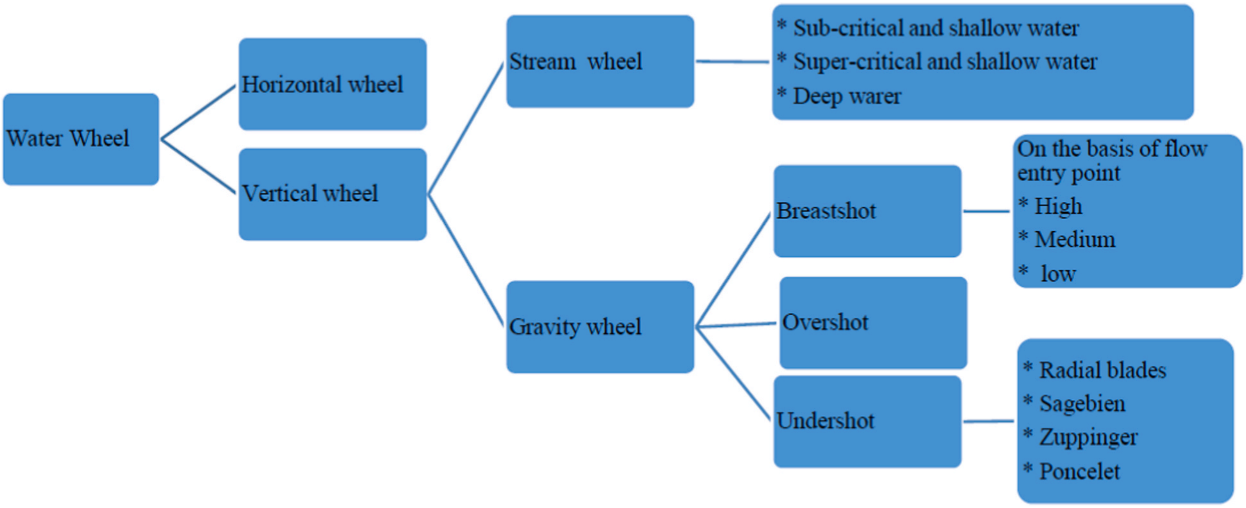

Fig. 3. Classification of water wheels, compiled from [13].

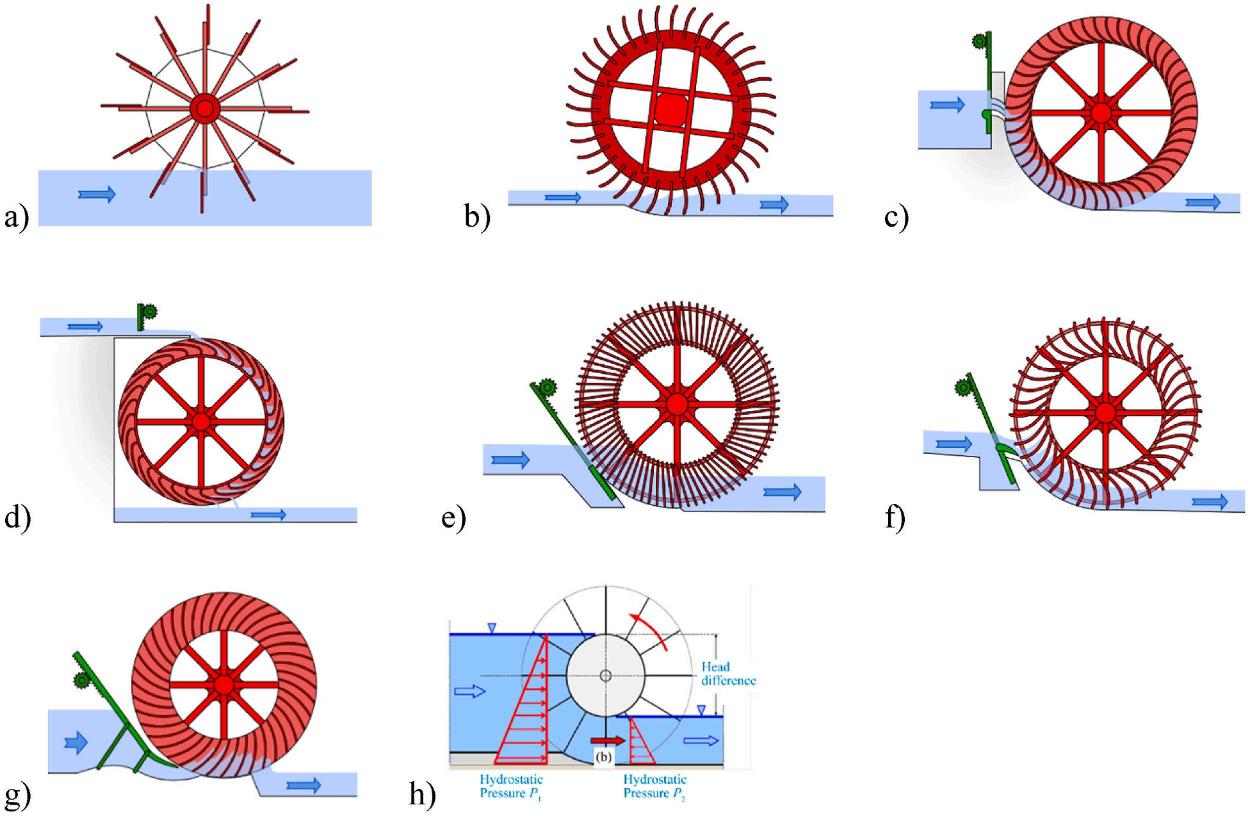

Fig. 4. Schematic diagram of different types of water wheels; 4. a) Stream [42] 4. b) Undershot [43] 4. c) Breastshot [44] 4. d) Overshot [45] 4. e) Sagebien [46] 4. f) Zuppinzer [47] 4. g) Poncelet [48] 4. h) Hydrostatic pressure machine, redrawn from [19].

around 1000 kW [55]. Weirs or channels with a head drop are often the regions of implementation, whether they are new or available structure. These have a relatively simple structure, low rotating speed, are fish-friendly, and can tolerate debris [56].

2.3.3. Cross flow turbine

The runner of crossflow turbines has two disks linked together by a series of inclined curved blades. Fig. 6 shows the water entering from one side of the blade series and passing through the blades. The blade series gets impacted twice resulting in the water having no

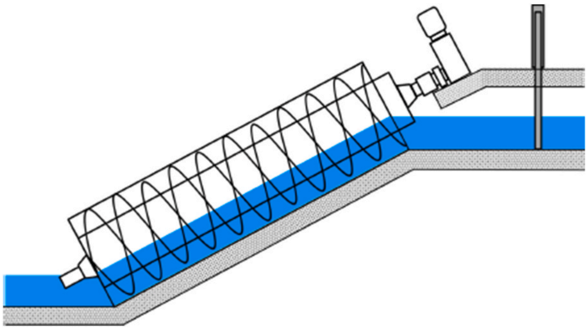

Fig. 5. Schematic diagram of Archimedean Screw Turbine, Adapted from [57].

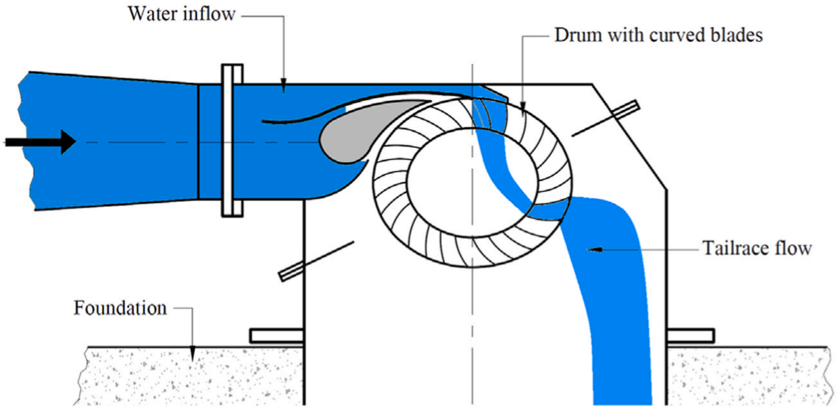

Fig. 6. Schematic diagram of the cross-flow turbine, Reused with permission from [58].

more energy and falling into the tailrace. It can be mounted horizontally or vertically and over a varied range of discharge rates [58]. Though the flow rate decreases, crossflow turbine efficiency does not significantly decline. So, Crossflow turbine systems are commonly selected when higher deviations on discharge are expected [59].

Structural requirements for this system are very simple and have a self-purification competency. The highest efficiency of a crossflow turbine is lower near Kaplan or Francis turbine [60]. The small size of crossflow turbines are in use in Nepal (Crosstric Set), Colombia, and the Philippines (Fireflies) utilizing 5–20 *m* head and discharge of 5–50 LPS [61].

2.3.4. Low-head turgo turbine

In the Turgo turbine, a water jet from a single nozzle enters a series of blades and exits at an acute angle that creates no interference with the incoming water jet, as shown in Fig. 7. Because of this configuration, the wheel diameter is lower for a given jet diameter, boosting rotational speed [62]. According to Harvey A. 1993 [37], if lower rotational speed and turbine runner size are not the problems, turgo turbines can be used in low-heads. In an experiment conducted by S.J. Williams et al., 2014, over several 13 turbines within a head range of 0.5–3.5 *m*, a Turgo turbine having only one jet above 1.5 *m* head has the highest weighted score [16]. In another research done by Williamson et al., 2013, the configuration of jet inclination angle was found optimum at 10° with an investigational

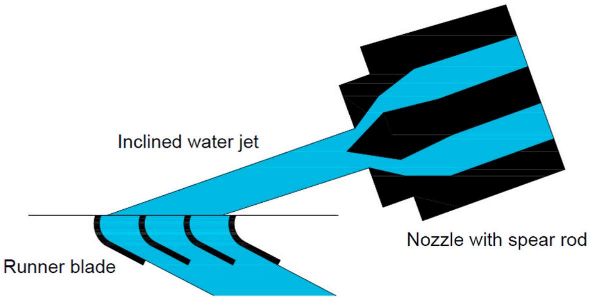

Fig. 7. Schematic diagram of Turgo turbine [63].

efficiency of 91% and 87% at 3.5 *m* and 1.0 *m* head respectively [62].

2.3.5. *Gravitational water vortex turbine*

The gravitational water vortex power system is an open canal type of plant designed to generate electrical energy from very low hydraulic heads. The system generally, consists of a tangentially guided water inlet to a cylindrical tank having a central bottom water outlet as shown in Fig. 8. Then the development of an artificial vortex above the center bottom outlet of the circular tank takes place. The turbine set placed vertically withdraws the mechanical energy and further into electrical energy utilizing a generator [65]. The Zotloeterer turbine for 0.7–3 *m* heads [65] and the Turbulent vortex turbine for 1–4.4 *m* heads [66] are the developed technology for gravitational water vortex power plants.

2.3.6. *Linear turbine*

Linear turbines have double shafts linked to blades following a composite path with the power developed during the travel of the blade in the linear motion portion. There exist two categories as Steff turbine and Hydro engines developed by two different organizations. In the case of the Steff turbine, installation of the structure is on an optimum incline of 30° that improves the capturing of potential energy within the enclosed system. The unit installed above the surface level of the water requires the minimum civil engineering input when developing a new design.

The circling chain that wraps around two sprockets is the main part of the Steff turbine. Chain-mounted paddles made of corrosion-resistant steel transfer the generated power to a built-in permanent magnet generator, as shown in Fig. 9 (a). The inclination of the Steff turbine can be fixed, as per landscape. Also, adjustments are possible to change the length of the chain used on it. This system is for a low-head high volume of flow rate applications for a wide variety of water and sewage sources that can be handled. In general, this turbine utilizes sewage outfall that has a minimum flow rate of 250 L/s with a height difference from 2.5 *m* to 5 m [67].

In hydro engines, water entering the turbine is focused to the first set of blades and successively guided to the next set [68]. The system has an exceptional design, claimed to be the first fully flooded two-step water impulse engine, so mentioned as a hydraulic engine instead of a hydraulic turbine. These are the first generation of Hydro Engine known as Schneider Linear Hydro Engine (SLHE) as fully flooded shown in Fig. 9 (b) and free jet as shown in Fig. 9 (c). These systems developed are installed in an existing drop, small dam walls, or structure anywhere between tail water and headwater elevation with a wide range of flows [68].

The Linear Pelton style is the improvement of the previous SLHE that has a multiple numbers of Pelton runner buckets on a system of composite path arrangement. As shown in Fig. 9 (d), a wide rectangular nozzle guides the water entering to the engine that transforms pressure into velocity. The water jet directs in the direction of a series of buckets and exits vertically downward [69].

2.3.7. *Simple reaction turbines*

A simple reaction water turbine follows a technique of thrust, where it utilizes the reaction developed due to the acceleration of water through a nozzle or opening to rotate an object in an advancing path [70]. The evolution diagram of simple reaction turbines reviewed by Farriz et al., 2015, is presented in Fig. 10 [14].

- **Hero's Turbine**: It is the first type of reaction turbine comprising a nozzle equipped with a spherical shape of hollow metal. The nozzles on it direct opposite directions tangentially to the sphere towards the same alignment. An airtight boiler produces steam by having a tube linked to the metal sphere. This arrangement leads the vapor to run into the sphere and exit from the nozzle causing the rotation of the metal sphere. This developed turbine was limited to demonstration only which showed that a device rotated by fluid can generate mechanical power (known as turbine) and can be used to run different machines [70].
- **Barker's Mill**: Barker's mill is an updated version, revised of Hero's turbine, capable of working with the potential energy of the water reserved [70]. The design of the tube arrangement was to enter the water entering from the topmost part of the turbine. When

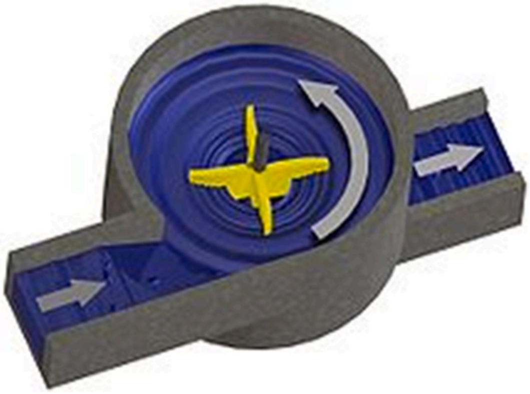

Fig. 8. Schematic diagram of GWVPP [64].

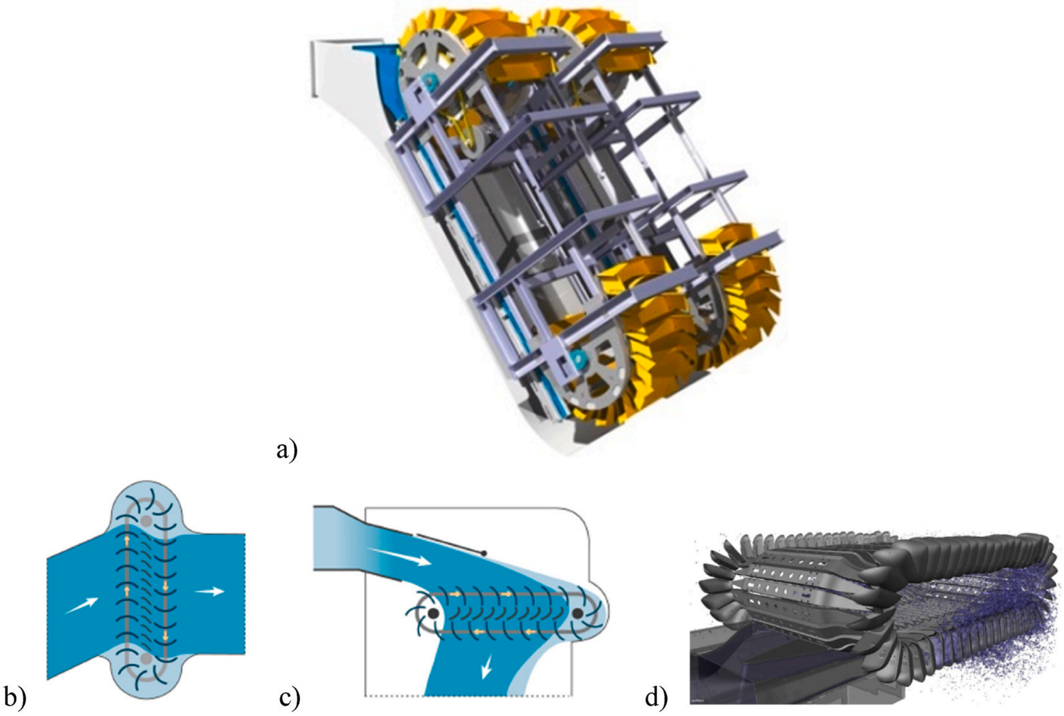

Fig. 9. Linear turbines: (a) Model of Steff Turbine [67] (b) Schneider fully flooded hydro engine [68] (c) Schneider free jet hydro engine [68] (d) Linear Pelton [69].

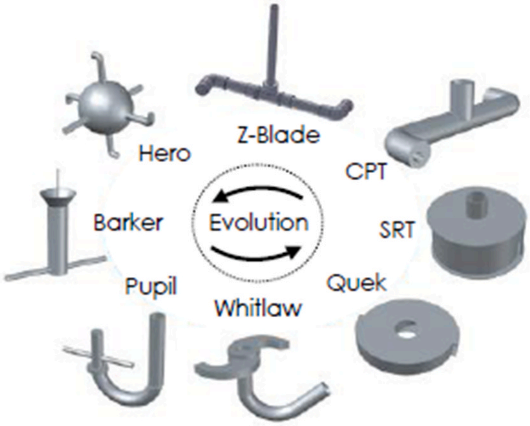

Fig. 10. Schematic of different simple reaction turbines, reused with permission from [14].

water leaves the nozzle peripherally, reaction energy is developed and causes rotation in the reverse direction. That makes the rotor rotate, producing mechanical power as in a water sprinkler [71].

- **Pupil's Turbine**: In Pupil's turbine, the water is entered into the turbine from the bottom. This method reduced the frictional force. This novelty allowed the pressure head to be in the reverse direction to the acting load of the rotating turbine. This load performs as a cushion, where increased water pressure from below the turbine provides resistance to the pressure from the water turbine [14].
- **Whitlaw's Mill**: In 1839, James Whitlaw redesigned the arm of Baker's mill without a nozzle, making it curved, thereby creating a higher velocity at the outlet resulting in the increased efficiency of the turbine [70].
- **Quek Turbine**: In 2003, Quek developed a turbine rotor having water passage in a solid metal disk. In the experimental research with the hydraulic head of water between 10 and 25 m, the efficiency obtained was less than 45% [70].
- **Split Reaction Turbine (SRT)**: In 2009, Date A. developed the cylindrical shape of the Split Reaction Turbine (SRT). The system demonstrated had high energy conversion efficiency under a low hydro-static head and flow rate starting from 2 m to 10 L/s,

respectively. The sealing of the inlet port and the flange coupling, the design and assembly of the top and bottom cover plates are critical on SRT [70].

- **Cross Pipe Turbine**: The Cross Pipe Turbine (CPT) uses standard pipe fittings with four major parts: one cross pipe set at the middle, two-unit reducing elbows, two-unit arms composed of male adapter fittings, and water jet nozzles at end of elbows through the reduction bush. CPT was found to be slow, thereby resulting in inefficient performance [70].
- **The Z-Blade turbine**: A few alterations of the CPT design prepared were to suit the Z-Blade with low discharge and low hydraulic head conditions [14]. This turbine uses standard PVC pipe fittings that have positively improved its performance and efficiency.
- **The single-arm centrifugal reaction water turbine**: The water from penstock using a flow control valve enters the intake fixed pipe further employing a rotating seal joint to connect to the intake rotary pipe, as shown in Fig. 11. Bearings are attached to the centrally placed power output shaft being the arm in the middle. The controlled size equals the circular tube at the entrance and leaving areas. This makes it rotate the conduit at the same speed. For the range tested, the turbine efficiency increased with an increased in arm radius [72].

2.3.8. Propeller and Kaplan turbine

Water is entered from the spiral casing towards the radially placed wicket gates on the inlet of the turbine to produce an inlet swirl ensuring improved efficiency. The axial entry of water is used in both Propeller and Kaplan turbines to create hydrodynamic forces that cause the runner to spin [60]. Propeller turbines have a runner with three to six fixed runner blades on the central hub connected to the shaft. The water axially exits the blades losing the water power towards the draft tube, as shown in Fig. 12. Double-regulated propellers, for example, are a more sophisticated technique for improving performance in small power plants.

The key-term difference between the Kaplan turbine from the propeller turbine is that the design regulates varying head and varying flow using adjustable pitch of runner blades at the central hub. These turbines are appropriate for installation in an outlet of a reservoir, within a weir, hydraulic control structure, or canals, or in an existing pipe. The Kaplan turbines exist with three to seven-bladed runners of any diameter with the installation can be in the horizontal, inclined, or vertical position [73].

2.3.9. Bulb turbine

The bulb turbine is sealed off in a large bulb-like structure composed of the horizontal shaft generator system. The bulb turbine has slightly higher efficiency than Kaplan since the route of the water flow is not needed to adjust [52]. The packing of this design is possible to install in water supply pipelines, as in Fig. 13. This compactness allows more flexibility in the structure of the powerhouse compared with Kaplan. But, it limits the approach for repair and maintenance actions [12]. These are very good choices for ULH locations with large water flow rates because water guided to the turbine results from minimum hydraulic losses. If the flow entering is minimum, a non-regulating system can be used in place of the dual-regulated system. It reduces the complication and overall cost of the system to be installed [75,76].

The bulb-turbine is a technologically advanced, more compacted axial flow type of turbine system, as an example, the Straight-Flow turbine (Straflo turbine) is in use. The design is complex as it has the generator built concentrically around the rim of the turbine runner [77]. When combinations of more such units, are arranged with horizontal axes, then that is known as a hydro-matrix. In the situation of run-of-river type of plant, installation of multiple such units are possible across the river.

2.3.10. Siphon turbines

Siphon turbine systems have also propeller blades attached to a turbine shaft that runs a generator. As a replacement for penstocks and draft tubes, it transports water between the upper and lower reservoirs, utilizing a siphon that extends over the dam, as shown in Fig. 14. For the initial operation of 30–60 s, the generator behaves as an electric motor that supplies water to the siphon until it reaches the desired level of priming. After that only, the system functions as a turbine generator. If there is more flow available for single turbine, a number of parallel systems near to each other can be installed. The outlet of the siphon may be beneficial if there is an

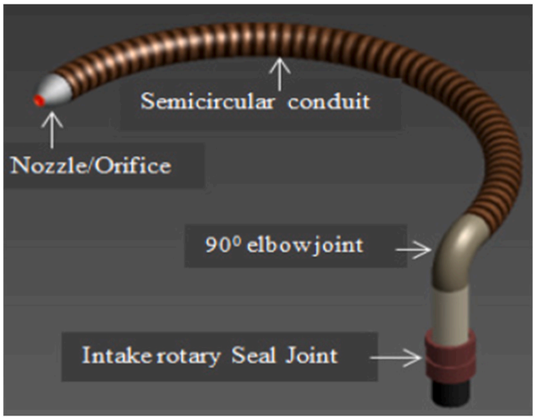

Fig. 11. Model of single-arm centrifugal reaction turbine [72].

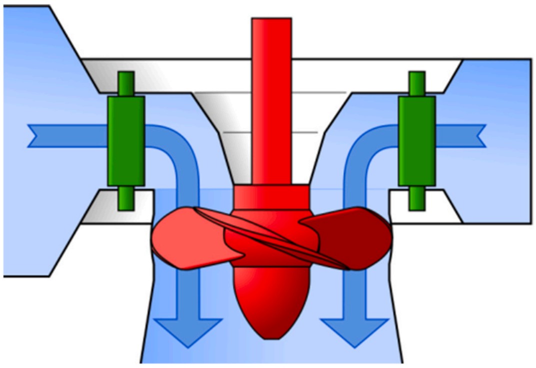

Fig. 12. Schematic diagram of Propeller/Kaplan turbine [74].

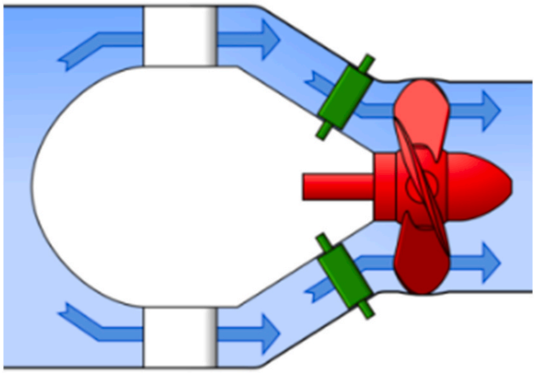

Fig. 13. Schematic diagram of Bulb turbine [78].

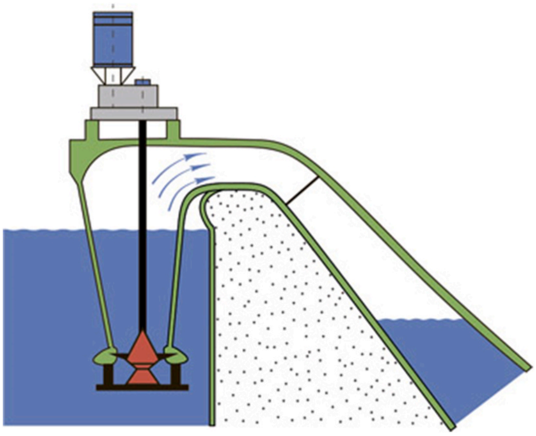

Fig. 14. Schematic diagram of Siphon turbine over dam [82].

existing structure that needs to be bridged. The siphon outlet may reduce installation costs if it is not feasible to adjust the available construction [79]. Among the turbine technology, the siphon turbine is a technology that is useful for adapting existing water resources which is different from the conventional installation [80,81].

2.3.11. Very low-head turbine

For ULH conditions, a very-low-head turbine has shown to be more viable as an imaginative axial-flow hydraulic turbine in present years [83,84]. The machine comprises a regulated propeller-generator unit fixed in a simple square channel. The turbine blades are covered safely by a fine trash rack provided on top of the system housing. This cover is possible to raise and lower. Depending on the available head of the site, the turbines are mounted at 15°- 45° [85], as shown in Fig. 15.

It has fixed guide vanes as well as stiffeners. An automatic garbage removal screen is included in the turbine assembly of this technology. Under the runner and inside the bulb, the runner connects the direct-driven variable-speed permanent-magnet generator. A range of machines are available in 3–5 *m* diameters size, head range of 1.5–4.5 *m*, discharge extends from 10 to 27 m^3/s, and power range per unit from 100 to 500 kW per unit [86]. Multiple units of this system are possible to install next to each other. Generally, this turbine is used in an open channel. The head of the turbine is the hydraulic head difference created across the turbine. This turbine is most likely best matched in an existing structure and larger canals to reduce the overall plant set-up costs [18].

2.3.12. Open flume Francis Turbine

For the low-head mill sites, most of the systems developed were using water wheels. However, as greater power and higher shaft speeds are required to operate contemporary power machines, they are switching to water turbines. To get all of the equipment upstairs flood level in open flumes below the mill, these turbines are placed with longer vertical power shafts, as shown in Fig. 16. Simple open flume Francis is easy to erect from vertical corrugated steel tubes or poured concrete where only the weir is left. Natel Energy and Nautilus offer varieties of open-flume Francis Turbine alternatives to satisfy various flow and power demands. These designs are available in both controlled and unregulated forms. Typically, these turbines are deployed in open flumes with a head range from 1 m to 10 m within the single unit range of power from a few hundred watts to 1200 kW [88,89].

2.3.13. Power pal turbine

The Power Pal turbine is a small open flume category low-head propeller-type turbine that can produce up to 1 kW of electricity. The turbine installed at the height of the incoming water has a draft tube lengthening below the turbine generating the head difference with suction. All or part of the water flow diverted into an open intake canal forms a vortex. It results in the propeller rotating as water exits through a draft tube to flow free downstream again. The generator above the water level is attached to an extended shaft of the propeller turbine, as shown in Fig. 17.

This system is generally installed nearby resources of water flow commonly available as small waterfalls, dams, or diversion channels. It is ideal for a hydraulic head of 1–2 m only [90]. A modified version of this turbine was settled in Indonesia by Cihanjuang Inti Teknik as a standard unit for heads less than 6 *m* known as Open-flume turbines. It is designed having a labor-intensive flow regulation technique and is simple to install and perform maintenance work [91].

2.3.14. Dive turbine

A dive turbine is an open flume type of compact propeller turbine and generator set entirely immersed in water without spiral type-of housing, as shown in Fig. 18. This combination makes the system less noisy and produce less vibration. Though it has fixed blades on the runner, double regulation is possible through the variable speed generator used on it and the pitching mechanism of the guide vanes. It is applicable for the head range of 2–60 *m*, discharge of 0.6–40 m^3/s, runner diameter to be 0.5–3.5 *m* and power from 30 kW to4000 kW. It can be planned for new hydropower plants or installed on existing water infrastructure or pressure pipes [93].

2.3.15. Pump as turbine

In the turbine mode of a PAT, the impeller rotates in a reverse direction than in pump operation mode. Pressurized water enters the pump from the casing and rotates the impeller. The rotation of the impeller shaft generates mechanical energy. Further, it exits from the center of the pump at minimum pressure [94–96] as shown in Fig. 19. There is minimal use of such turbines under the head below 3 *m*.

For this operation to exist and serve as a turbine, a conventional centrifugal pump is reversed to work under different flow and head conditions. Particularly in developing countries, PAT is a ready technology due to its production on a mass scale, easy availability, and low-cost than other turbines [15].

PATs generally function with lesser efficiencies at flow conditions when operated at lower range than the design condition. The major challenge of using a PAT is still the tussle on the output behavior of the turbine because the characteristic curves of pumps that function as turbines are not delivered by pump industrialists [97]. Presently, there are many recent works useful to estimate their

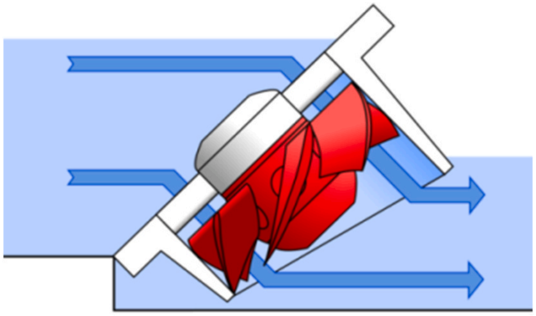

Fig. 15. Schematic diagram of VLH turbine [87].

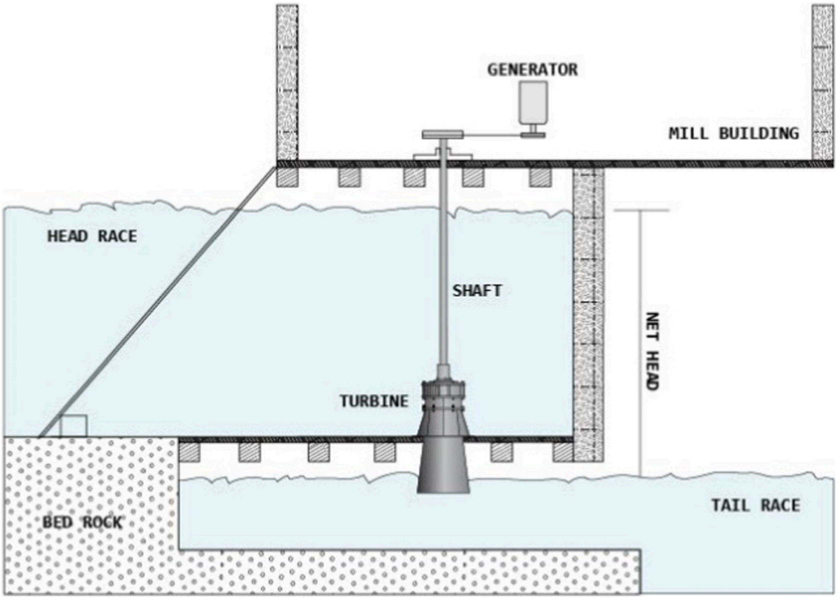

Fig. 16. Schematic diagram of Nautilus Open flume Francis turbine [89].

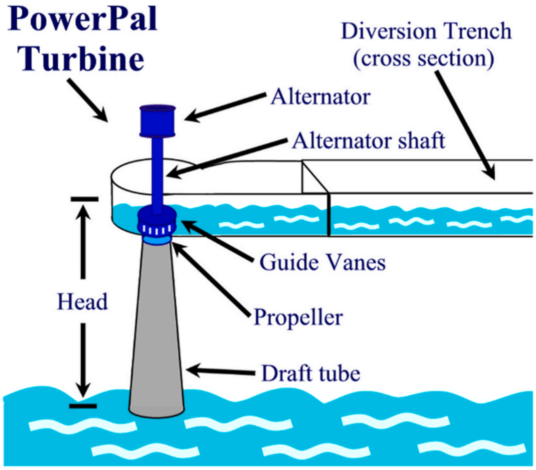

Fig. 17. Schematic diagram of low-head power pal turbine [92].

characteristics in turbine mode of operation.

2.3.16. HyPER harvester

The US Department of Energy has supported the HyPER harvester project to explore and develop a new hydropower technology. As a proof-of-concept, two units of 10 kW harvesters on the plant of 20 kW were constructed in 2014 at the Elephant Butte Irrigation District Drop 8 Station in Southern New Mexico, custom-fitted to a unique drop location.

It is a modular system creating a plug-and-play aspect for easy transportation and deployment. Among the four major components of the harvester, venturi-inlet, submarine, and discharge elbow are fabricated as two mirror-symmetric half-moldings, and a carbon-composite runner with a steel shaft is coupled with a sealed alternator supported vertically inside the submarine with a suitable thrust bearing. Two units of the turbine, which featured a 4-bladed Kaplan-like runner with a fixed pitch, were tested through a discharge of 3.5 m^3/s and a drop head of 1.5 m. It has the installation possibilities for either vertical drop, conduit, or penstock flow as shown in Fig. 20. This system is appropriate for existing structures of irrigation canals having low-head drops, as well as for weirs across streams and local rivers as a modular system [98].

2.3.17. Neptune hydro turbine

The Neptune is a form of Francis turbine that produces a lot of power in a small and compact package. It has a turbine in the open

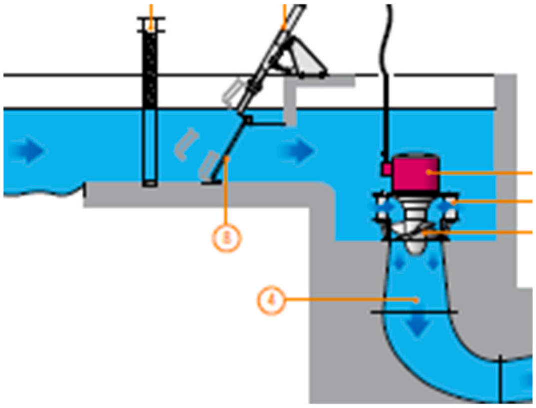

Fig. 18. Schematic diagram of dive turbine [93].

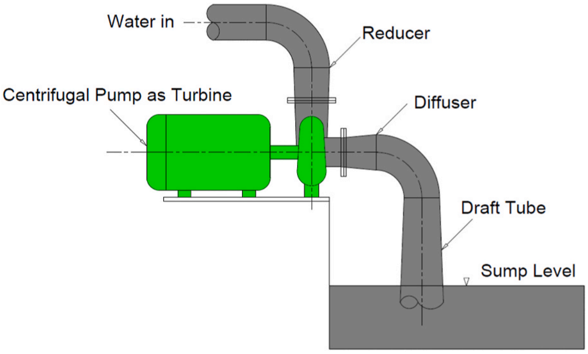

Fig. 19. Schematic diagram of Centrifugal pump as turbine.

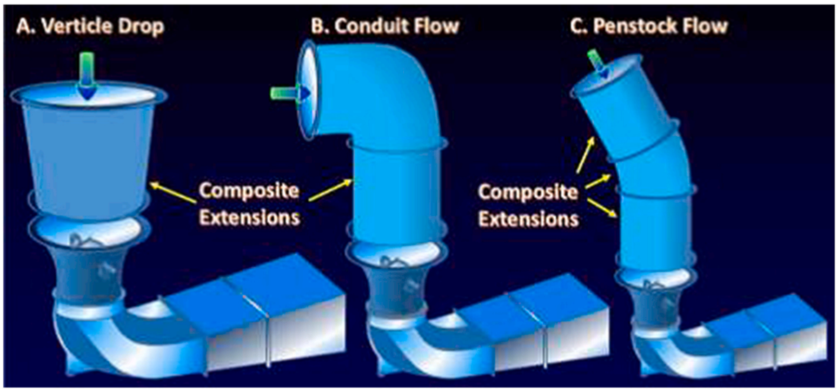

Fig. 20. Installation possibilities of HyPER Harvester turbine, Adapted from [98].

chamber on which the water is channeled through a pipe or open canal. This develops the 'pressure head' up to the headwater level in the chamber. The short 'draft tube' used at the outlet of the turbine produces a 'negative suction head'. There are several permanent magnet alternator choices for electricity generation. It is placed above the chamber through direct coupling or driven by a timing belt as in Fig. 21. It is available on two stainless steel runner diameters of 203 mm and 254 mm with an electrical output of 550–2200 W, head of 1.2 – 3 *m*, and flow rate of 85–135 LPS [92].

2.3.18. Niade hydro turbine

The Niade is a 'drop-in' installation type of ultra-low-head propeller turbine available in a complete housing as in Fig. 22. It is installed in an inclined position connecting two reservoirs on a different level through a 'draft tube' and produces a 'suction head'. It is

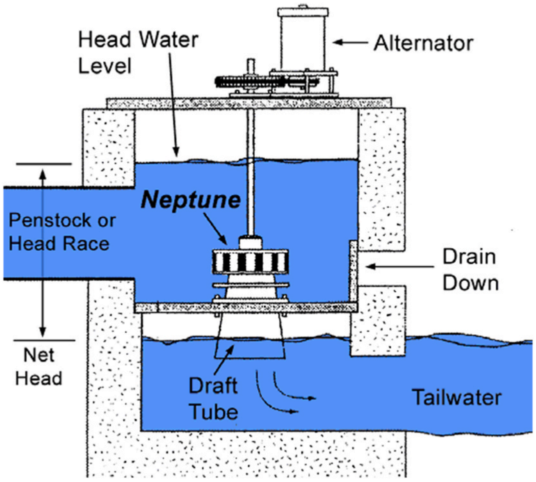

Fig. 21. Schematic diagram of Neptune Turbine [92].

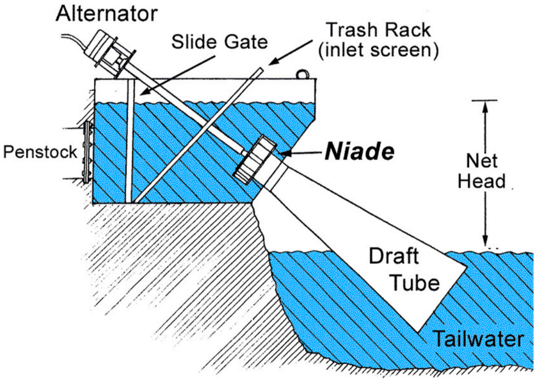

Fig. 22. Schematic diagram of Niade Turbine [92].

a modular unit that contains a protective inlet screen, a propeller turbine, the housing of cast iron, a slide gate, a draft tube, and an alternator.

The Niade turbine is available on a 175 mm and 225 mm cast iron runner. The output power ranges from 125 to 700 W, at a head of 0.6–1.2 m with a water flow rate of 44–115 LPS. This is the world's first turbine to generate useful power on a micro-hydro power range with a head less than 1.2 m [92].

3. ULH turbine selection chart

Each of the turbines developed has its concise working principle and range of applications. So, there requires an optimum technical selection for any particular site. Generally, the selection range of the turbines is likely to rely on different parameters as shaft speed, flow rate, head, power output and efficiency [16,99], as listed in Table 1. Here, the rotating speed of the runner shaft is the count of speed obtained while rotating the runner per minute at loading condition. The quantity of water flow per unit time available or required to drive the turbine is termed as discharge [28]. The gross hydraulic head is the perpendicular gap between the upper water superficial level and the downriver water superficial level for reaction turbines or the level of nozzle axis in case of impulse turbines on hydrostatic case whereas velocity of flowing water is responsible for head on hydrokinetic technology. Similarly the power output is the power available at rotating shaft and efficiency is termed as the relation of power output to the power input to the turbine [28].

Besides those parameters, some other factors are to be taken into consideration while finalizing the selection. That includes its performance, cost-effectiveness, and the depth at which the turbine should be placed [100]. Williamson et al. [16] suggested a technique to choose the utmost effective turbine for a low-head hydro-power employing quantifiable and qualitative considerations (as in Table 1). Any turbine suitable for a large hydro-power scheme can still be feasible for small schemes following certain alterations on those established turbines for fitness [59].

The standard turbine selection charts can be used as a starting point to explore which turbine may apply to a distinct site. The ranges presented on the chart are for approximation and further need to be contacted with the concerned turbine manufacturer to

Table 1
Range of Turbine Selection, Reused with permission from [16].

Quantitative criteria	Qualitative criteria
• Rated flow/head efficiency	• Environmental –weather-location
• Part flow/head efficiency	• Required civil works
• Cost	• Portability
• Turbine rotational speed	• Maintainability
• Power for a given site	• Reliability
• Size of the system	• Ease of manufacture
	• Design modularity

authenticate whether the turbine is suitable for the particular site condition or not. Basically, conventional turbine system is not feasible for schemes with the hydraulic head below 3 *m*. Modern equipment are in the developing stage to proceed advantage of those low altitude differences of water resources. But in general, these depend on the kinetic energy of flowing water which is different than the energy from the falling height [55].

As indicated in Fig. 23, the US Department of Energy (US DoE) [101] report presents the grouping of such technology with the measures of hydropower potential capacity and available hydraulic head of a probable scheme. It specifies that the traditional hydroelectric power plants use greater static-head and/or capacity in high-pitched difference to the non-conventional ultra-low-head or hydrokinetic schemes. Also, non-conventional turbine systems are required to produce energy through ultra-low-head water resources.

Generally, the selection of a water turbine categorized on the specific speed of the turbine is more famous which relates to the flow rate, head, output shaft speed, and output power [103]. According to this, the range of application for different turbines presented supports the selection, as in Fig. 24. It summarizes the flow rate, head, and power-producing range of several typical turbines in a single diagram. It is, furthermore, replicated in the commercially available water turbines for these head range [16].

According to Williamson et al., 2014 [16], when comparing various 13 turbines, the deviation obtained in the weighted scores throughout the head range is presented, as shown in Fig. 25. From Fig. 25a), among six different scoring criteria established, single jet Turgo turbine has the highest score. The radial and propeller turbines with draft-tube, compared with the propeller turbine without draft tube, has almost the same score. It is the value near the score of the single-jet Turgo turbine.

As shown in Fig. 25b), the most appropriate turbine between 0.5 and 1.5 *m* range head, is a propeller turbine using an outlet draft tube, and the best selection above 1.5 *m* head range is the Turgo turbine with a single-jet. Above 1.5 *m* head, radial, and propeller turbines having an outlet draft tube get a weighted score comparable to the Turgo turbine with single-jet. It resulted in justifiable choices for the requirement. While selecting the reaction turbine, there is an expectation of a draft tube on the system. That so why, draft tubes are offered with many of the low-head reaction turbines available commercially. According to Harvey 1993 [37], Turgo and Pelton turbines are able to implement in low hydraulic heads when low runner dimensions do not place major complications.

According to Zhou et al., 2017 [8], existing turbine selection diagrams don't include all varieties of turbine and operating ranges. Such diagrams do not deliver a suitable direction of selection for ULH water turbines. Therefore, Zhou et al., 2017 [8] developed a table to select turbines appropriate for the application at ULH sites as listed in Table 2 summarized from relevant research results.

The table reflects that turbines still can be selected to make the project feasible either technically or economically for the lowest hydraulic head of 0.5 *m* or slowest velocity of 0.5 m/s. The operation boundary of a turbine varies as circumstances alter. So, respectively the developed turbine systems tabulated should be frequently reorganized to reflect the advancement in concerned technologies [8].

Many of the hydro turbine manufacturers provide an operating range of their commercialized products for selection. List in Table 3, is the variety of ULH turbines discussed in this article. The table covers the type of turbine (grouped as impulse and reaction), manufacturer/supplier, models, the application range of head, flow, power, and efficiency. According to IS/IEC 41, 1991, the

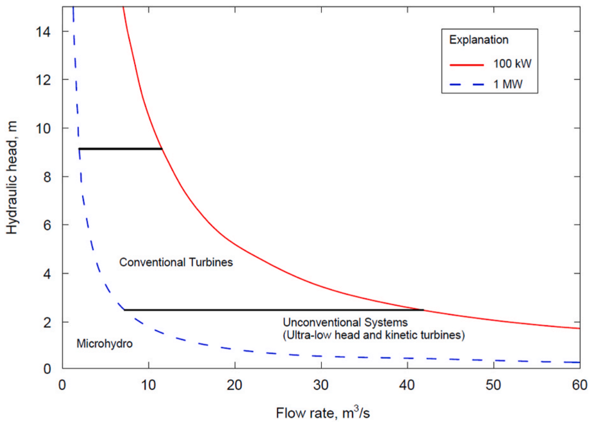

Fig. 23. Applicable range of conventional and un-conventional hydro turbine systems, Adapted from [101,102].

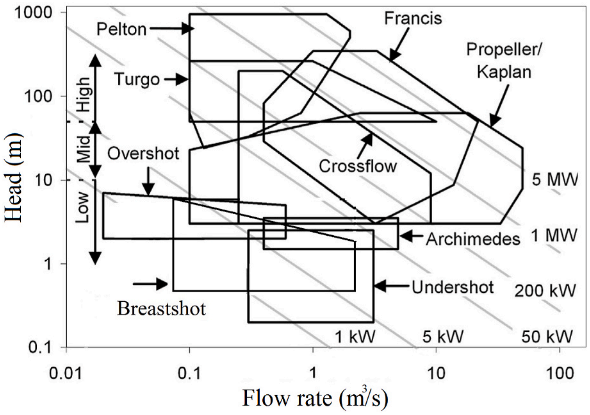

Fig. 24. Chart for turbine application range, Reused with permission from [16].

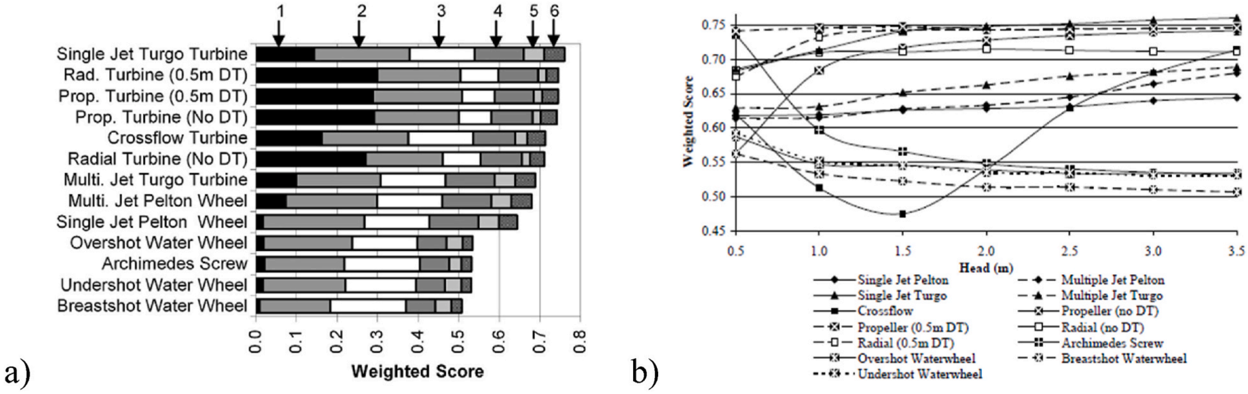

Fig. 25. The weighted scores for the 13 turbines: a) Criteria for scoring (1- Power density, 2- Rated flow efficiency, 3- Part flow efficiency, 4- Civil works, 5- Maintainability and serviceability, 6- Scope for modularity) b) Scoring over the head range 0.5–3.5 *m*, 'DT' = Draft Tube, Reused with permission from [16].

Table 2
Turbine selection table for ULH sites, Reused with permission from [8].

Turbine type	Rated head (or Velocity)
Open flume Francis	H > 2.0 *m*
Kaplan	H > 1.5 *m*
Propeller	H > 1.5 *m*
Tubular (double-regulated)	H > 1.0 *m*
Tubular (single-regulated)	H > 1.0 *m*
Tubular (non-regulated)	H > 1.0 *m*
Crossflow	H > 0.5 *m* or V > 2.0 m/s
Archimedes	H > 1.5 *m*
Hydro kinetic	V > 0.5 m/s

efficiency of the turbine is estimated using the mechanical power that was exchanged with the electrical device and the hydraulic power that was exchanged with the water [104] and is very critical during the design or selection of the system. Data presented are published by concerned manufacturers selected worldwide randomly.

Another selection of ULH turbines explained by Mutiara et al., 2018 [12] is according to the potential ULH resources. Different conventional and non-conventional turbine technologies are suitable for various existing infrastructures that can recover energy even in ultra-low-head sites. The summary of turbines for site-specific potential is in Table 4.

4. Discussion

The inclusive cost of electricity among all commercially existing renewable power generation technologies, hydropower is the

Table 3
Operating range of ULH turbines from diverse manufacturers.

Turbine	Manufacturer/Supplier	Model	Head (m)	Flow (m3/s)	Power (kW)/ unit	Efficiency (%)	Re-ference
ULH Impulse Turbine							
Water Wheel	Hydrowatt GmbH, Germany	Overshot	2.5–10.0	0.1–2.5	1.5–200	N/A	[105]
		Breastshot	1.0–3.0	0.5–5.0	1.5–200	N/A	[105]
	Smith Engineering (GB) Ltd, UK	Flat pack, overshot waterwheels	2.0–6.0	0.1–0.5	6 kW/m width	75	[106]
Screw based	Jash Engineering Ltd, India	Hydropower Screw	1.0–10.0	0.1–10.0	5.0–500.0	80–90	[107]
	Hydro turbine Technology Energy, Turkey	Arvida	1.0–10.0	0.1–10.0	1.0–500.0	80–90	[108]
	ANDRITZ Atro GmbH	Hydrodynamic Screw	1.0–10.0	0.2–10.0	upto 500.0	N/A	[109]
Crossflow	Ossberger GmbH, Germany	Through flow	2.5–200.0	0.04 to 13.0	15.0–10,000.0	84–87	[110]
	Cink Hydro Energy, Czech Republic	2 cell cross flow	3.0–200.0	0.03–16	10.0–7000.0	80–87	[111]
Gravitational water vortex	Zotloeterer Smart Energy Systems, Austria	Zotloeterer Turbine	0.7–3.0	0.05–20.0	0.2–500.0	80	[65]
	Turbulent NV, Belgium	Vortex Turbine	1.0–4.4	0.7–4.0	5.0–70.0	N/A	[66]
Linear	Natel Energy, Inc., USA	Hydro Engine: SLH10/ SLH100	2.0–18.0	0.2–11.0	upto 500.0	60–73	[112]
		Hydro Engine: Linear Pelton	3.0–20.0	0.02–10.0	10.0–1000.0	80	[113]
	Sewaco Limited, UK	Steff Turbine (Walter Reist)	2.5–5.0	0.25–0.4	12.0	78–90	[67]
ULH Reaction Turbine							
Propeller/Kaplan/ Bulb	Ossberger GmbH, Germany	Kaplan: A,B, R, T, K, S	1.0–25.0	0.2–60.0	10.0–3500.0	64–92	[114]
	Voith Hydro	Kaplan-Bulb/Pit/S	2.0–90.0	NA	upto 350,000.0	N/A	[115]
	Andritz Hydro	Bulb/Kaplan	0.5–90.0	NA	upto 230,000.0	N/A	[116]
	CleanPower AS	Kaplan-Turbinator: T series	3.0–55.0	0.5–11.9	75.0–3300.0	N/A	[117]
	Mavel, a.s.	Kaplan-Pit/S/Z/Bulb	1.5–35.0	1.0–200.0	20.0–20,000.0	N/A	[118]
	Gugler Water Turbines GmbH	Kaplan-Pit, Bulb	1.0–40.0	NA	5.0–25,000.0	N/A	[119]
	Toshiba International Corporation	Hydro e-kids: S, L, M, S3, S3C	2.0–12.0	0.03–3.5	1.0–200.0	N/A	[120]
Siphon	Mavel Microturbines, Czech Republic	Modular unit: TM series	1.5–6.0	0.15–5.0	5.0–160.0	N/A	[79]
	Lasca Group, Ukraine	Micro turbines-ST series	1.5–6.0	0.5–5.5	upto 100.0	N/A	[82]
Very Low-head	MJ2 technologies, France	VLH: DN series	1.5–4.5	10.0–27.0	100.0–500.0	N/A	[86]
Open flume	Natel Energy	Radial Open flume Francis	upto 10.0	1.4–17.0	100.0–1170.0	90	[88]
	Nautilus Water turbines	ULH Francis-660/T/ CMC	1.0–3.7	0.03–0.15	0.3–3.3	N/A	[121]
	Asian Phoenix Resources Ltd	Power Pal, propeller-MHG series	1.5	0.035–0.135	0.2–1.0	N/A	[122]
	Dive Turbinen GmbH & Co. KG	Dive turbine	2.0–60.0	0.6–40.0	30.0–4000.0	N/A	[93]
PAT	Andritz Hydro	ACT, FPT series	2.5–80.0	0.8–6.0	5.0–2000.0	N/A	[123]
	Voith Hydro	Pump-turbine	upto 700.0	NA	upto 500,000.0	N/A	[115]

cheapest one. Almost all of the hydro potential up to low-head in the world have already established, and the unsettled valued source is very low-head hydro schemes that are undeveloped. ULH water-energy resources are silent hydro potential because there is still a lot to be tapped, and even a very small water infrastructure is sufficient to produce hydropower. If there exists a surplus pressure head, either in drinking water or a waste-treated water supply line, there is always an opportunity to develop a hydropower scheme. This technology is possible to implement either for new infrastructures or for recovering the energy from the existing infrastructures with minor modifications. ULH sites are better for developing as multipurpose projects incorporating the primary operation not to be intermittent. ULH hydropower projects can be pico, micro, mini or small scale with single or parallel units at a place in the isolated or grid-connected plan, all depending upon the available resources.

Here, the explanation of different turbines for ultra-low-head hydropower technology has been covered in past research collections. From the kinds of literature covered, a broad approach has been established to classify the ULH turbines available globally. The basis of the classification of hydro-static energy conversion includes the mode of action, the orientation of the shaft, the water inflow line, and the number of turbine shafts which can be summarized as presented in Fig. 26.

Here, the technology of 38 different turbines under hydrostatic energy conversion was listed and compared under the four bases of classification. The category, mode of action, and the number of the turbine shaft, had distinct sub-grouping. But the rest of the two bases of classification as the orientation of shaft (vertical, inclined, horizontal) and water inflow line (open, closed) concluded with the placement of the same turbine on either sub-group resulting in a higher total quantity.

Table 4

Turbine selection according to potential sites, Reused with permission from [12].

Resources	Turbine
Built into the diversion structure wall and Canal drops	Kaplan
	Bulb
	Siphon
	Archimedean Screw
	Hydro Engine
Concrete-lined chutes	Pelton
	Turgo
	Crossflow
	Modular water wheel
Pipelines	In-line Francis
	Bulb
	Francis
	PAT
	Lucid Pipe
Waste Water Treatment Plant outfalls	Archimedean Screw
	Kaplan
Run-of-river Scheme	Archimedean Screw
	HydroEngine
Along canal section	Vertical axis hydrokinetic turbine
	Modular water wheel

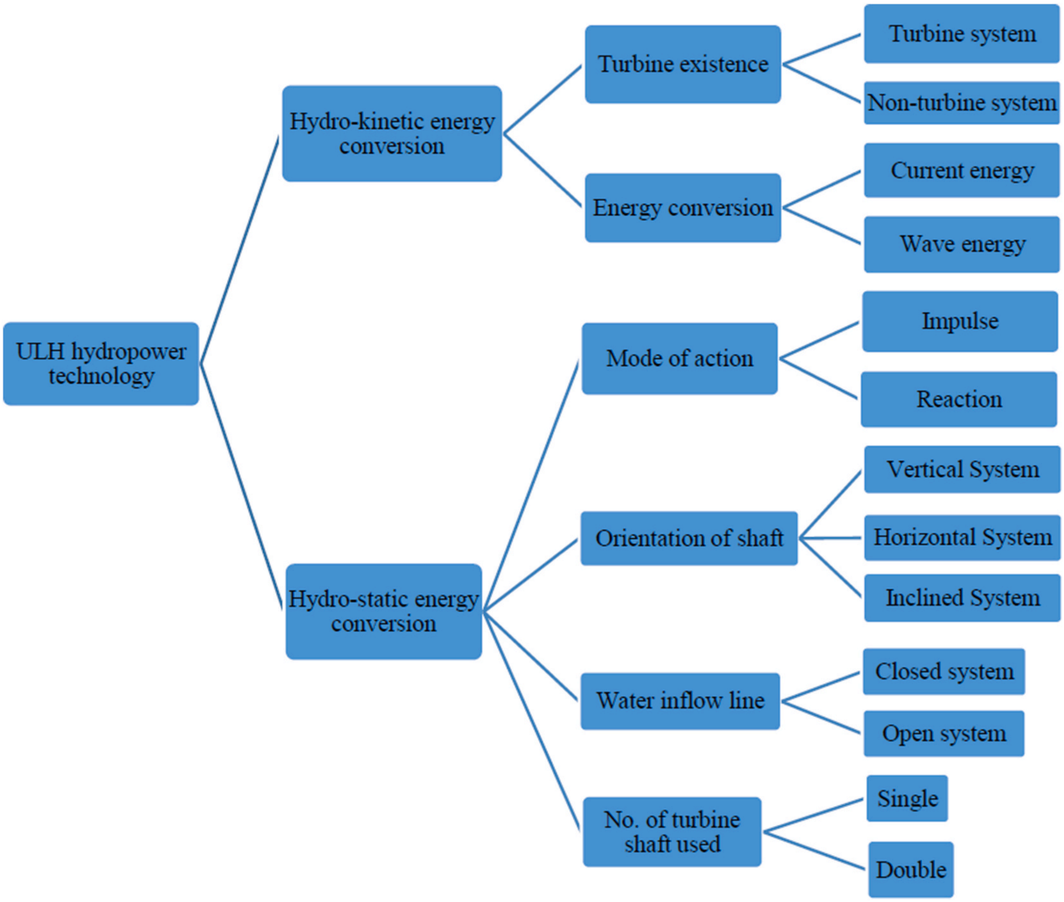

Fig. 26. Classification of ULH hydropower technology, compiled from [5,7,8,14,18,23–29,124].

The summary of the classification based on four categories for hydrostatic energy conversion is presented in Fig. 27. It shows the category, and mode of action, appeared here to be more comprehensive than others due to distinct working phenomena and equality of quantity coverage out of 38 turbines. In this sense, the higher the equality, the higher the probability to generalize the basis of

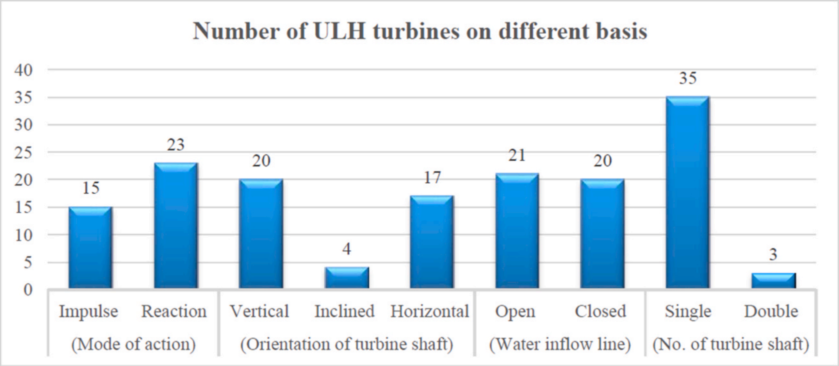

Fig. 27. ULH Turbine technology comparison on a different basis.

classification and the result is for the category mode of action. Reviewing, an impulse nature of the turbine may be exposed to the environment and just require a casing to prevent splash back. But the reaction turbine needs to be immersed in water and enclosed in a pressurized enclosure [125]. Low-head turbines are highly in use in Europe, South America, and Asia [126]. Generally, low-head water turbines are accepted to be of reaction category and need to be designed wisely for the particular site [126,127].

In the present scenario, ULH hydropower is a technology growing throughout the world and has more choices of turbine variety than conventional hydropower plants. The conventional type of selection chart for hydro turbines covers the operational choice of the turbines that developed in the past. But the turbines still can be selected for ULH sites with the less head being up to 0.5 *m* but the turbine being non-conventional. Since the ULH technology isn't the established one, presently, different charts and basis for the selection of ULH turbines are in existence. The aspects for grouping found are the minimum head, head-flow rate, head-weighted score, manufacturers' product operation range, and resource potentials. During the selection of the ULH turbine, more than one existing chart is needed to compare for preliminary optimization.

5. Conclusion

ULH water-energy resources are future salient hydro potential because of development in non-conventional hydro turbines today. Hydropower generation is possible from very small water infrastructures either of clean or wastewater flow in single or parallel units in isolated or grid-connected mode. The prime emphasis of this study was on the technological review of non-conventional turbines grouped under ULH hydrostatic potential with their range of operation. From the first part of the research, it has been concluded with a distinct classification chart that 38 different ULH turbines are more comprehensive to sub-group under a mode of action as impulse and reaction rather than the other cases covered. So, the conclusion on the classification basis of ULH turbines workable under 0.5 *m*–3 *m* is the main output of this research and is claimed as the novelty. Additionally, ULH reaction turbines explained are possible to be sub-grouped based on the flow rate or power but are outside the objective of this research. Furthermore, this research briefly reviewed the description of potential sites and randomly found 25 concerned turbine manufacturers from the global market. This research provides collective information on several scattered turbines for ULH condition for its' availability and the range of applications which was a gap in the past. So, now is expected to be more beneficial for project developers, site owners, investors, and decision-makers at the primary level to establish hydropower plants utilizing the ULH resources available nearby them. Furthermore, turbines with optimized concerns on efficiency, weight, materials, local manufacturability, installation time, reparability, and cost have a high commercializing future.

As the technology isn't a conventional one, like the ULH turbines, their selection charts are also in use with different basis of selection. From the second part of the research, the conclusion drawn is that no specific selection chart for ULH turbines exists to date. It is necessary to develop a chart covering a variety of commercialized ULH turbines. Also, it is essential to update with technological development from time to time. From this overall research conducted, future work needs to explore furthermore ULH turbines existing in the global market and develop a specific selection chart for those turbines covering the list of optimized classifications.

Authors contributions

Raj Kumar Chaulagain: Ph.D. Scholar- Conceptualization; literature collection and data generation; Funding acquisition; Writing - original draft.

Sanjeev Maharjan: Assistant Professor- Co-Supervision, Methodology development; Writing - review & editing.

Laxman Poudel: Professor- Supervision, Formal analysis; Concluding.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The writers would like to give thanks for the financial support received from University Grants Commission, Sanothimi, Bhaktapur, Nepal (Grant number Ph.D.-75/76-Engg-01) to complete this research. Also, the authors would like to recognize the reviewers for their appreciated suggestions.

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