A state-of-the-art review of the gravitational water vortex turbine for off-grid application and comparison with the existing water turbines

Md. Jubaet Rahman Sumit[1], Tasnuva Tabashhum Choudhury[1]
Mim Mashrur Ahmed[1], Md. Sohanur Rahman[1]
[1]Department of Mechanical Engineering, Rajshahi University of Engineering & Technology
E-mail: 2102044@student.ruet.ac.bd

Abstract

Hydroelectric power production system is as if a bliss in this present era, where the world faces both energy crisis and serious environmental degradation. However, the fact is that, while there are several hydroelectric power plants established in large scales in countries with available water flow, they mostly cover the areas surrounding it, such as the big cities or the main regions. On the other hand, the isolated or rural areas remain in darkness, being deprived of alleged facilities as result. Nonetheless, providing electricity supply to a portion of localities is possible, but the supply cost is in fact a matter of concern. Therefore, an independent off-grid hydroelectric power generation system can come in handy fulfilling the power production purpose in those areas having accessible water stream. However, there are multiple types of water turbine, and it is crucial to choose the suitable one which fits in that mini powerhouse supplying enough power to the local communities. In this paper, gravitational water vortex turbine (GWVT) is found as a potential candidate to be used in off-grid system through the literature survey on the performance analysis of water turbines, required off-grid characteristics for a turbomachine, comparison between GWVT and other turbines. Finally, recommendation of an outline for the off-grid power plant system operated by GWVT is provided that will be helpful for the researchers to conduct further investigation.

Keywords: GWVT, water turbine, renewable energy, sustainability.

1. Introduction

The universal energy market started to shrink in the wake of 2021, after which periodically came the world pandemic and not to mention the political clashes between nations [1]. Another problem is the global warming followed by the unlimited pollution of nature. It is said that the world temperature has increased about 1.36 degrees Celsius by the year 2023, warmer than the pre-industrial era [2]. While it is known that depending excessively on fossil fuels is one of the culprits behind mess, it is high time to think about clean energy technologies as a solution.

Many clean energy sources are available, such as solar, geothermal, wind and hydro (Fig.01.b). Though all of them have their own unique advantages and disadvantages, hydropower is more facilitating for its continuous service along the time. According to a study in the year 2023 (Fig.01.a), it's been found that, among the other sources of renewable energies, hydroelectric power possesses the largest share. This is because, solar, wind or other sources are either recurring or hard to harness, but it is hydropower which has both consistent and easy-to-extract nature. Though its cleanliness has been questioned by some, it possesses a potential to be the best option.

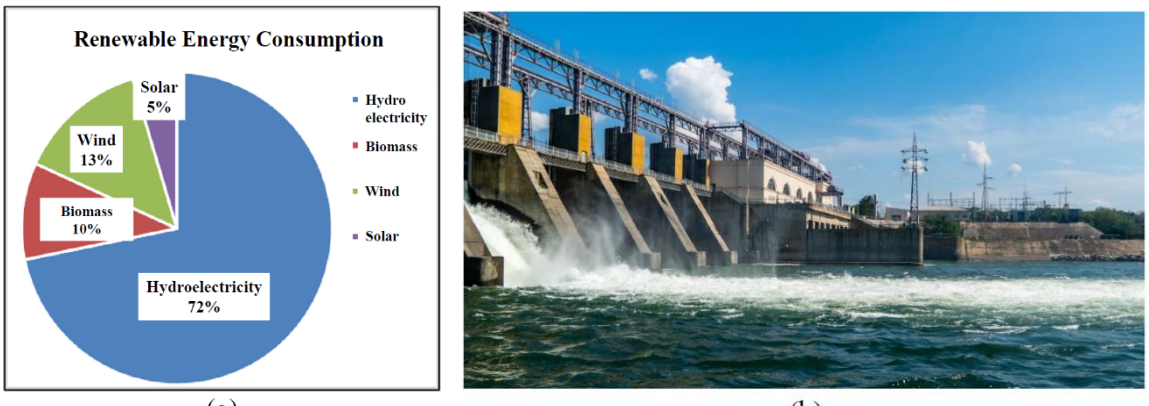


Figure 01: (a) The percentage share of Renewable energy consumption trend over (1997–2020) [3], (b) Hydroelectric power house.

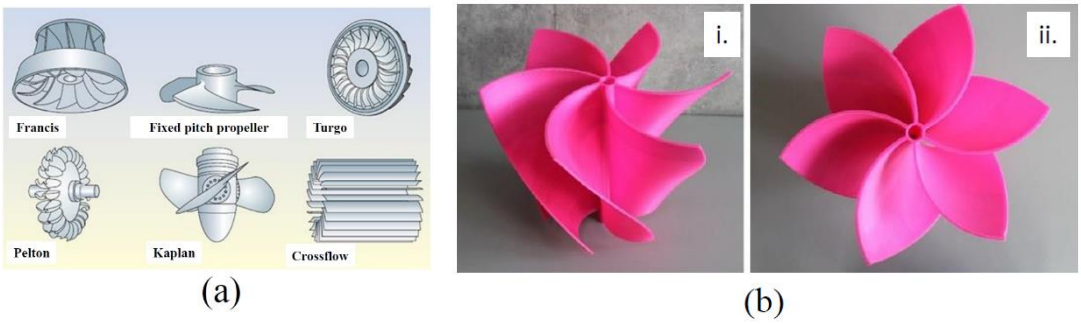


Figure 02: (a) Different types of hydro turbines, (b) Gravitational water vortex turbine (runner).

Then comes the issue of energy crisis. The world population is increasing day by day and so increases the demand of power. Though, a lot of gigawatts is producing every day, most of the share of generated power goes to the privileged main areas of a country and the majority of isolated, decentralized, rural areas remain in darkness. Though, if there is possibility of supplying them electricity, the transmission cost is very high [4]. As a result, their growth and development are seriously hampered, ultimately leaving them lagged behind, which nothing but challenges the overall progress of that country. Therefore, a clean off-grid (independent power grid) power generation system can be useful to solve both the problems of pollution and power sufficiency.

Gravitational water vortex turbine (GWVT) (Fig.02.b) has been chosen as a potential candidate for an off-grid mini-powerplant system in this paper. Many research works have been done to optimize the parameters of this kind of turbine for better performance. Like, Zamora et al (2022) have investigated the performance of a modified GWVT for using it in micro-scale power generation purpose [5]. Whereas, Edirisinghe et al (2022) have done flow simulation analysis on GWVT in order to enhance its efficiency [6]. Furthermore, Kueh et al (2017) have analyzed the impact of rotational speed and blade shape on turbine performance [7]. Also, many other works have been done in this field.

There are in fact many kinds of hydro turbines available (Fig.02.a). Thereupon, the objective of this literature survey is to operate a comparative surveillance on these turbines and logically show how GWVT possesses the largest potential as a candidate to be fitted in a consistent, efficient and sustainable off-grid energy generation system. Though there have been several research works done on GWVT (as can be seen in the upcoming review table), but there has been no literature review made with proposal of hypothetical powerplant system previously, in this paper, it has been strived to do so in an analytical manner.

The structural outline of the current paper can be represented such that, firstly the general turbine theory on which hydro turbines work and their classification have been presented. Later, the fundamental structure of GWVT and its working principle have been highlighted. After that, the required off-grid characteristics of a powerplant have been given, previous research works on both GWVT and existing turbines were recorded on a review table and a comparative analysis has been done between them. Lastly, a hypothetical rough outline has been given on an off-grid mini powerplant with GWVT and recommendations for future work have been included.

2. General Background

The theory behind mechanical hydro turbine system is simple. When there is head difference between two points and there is water at the higher point, because of gravity, it simultaneously flows to the lower one. If there is a turbine between those points, the falling water mechanically drives the turbine which further drives a generator producing electric power. By damming a river or flowing body, a turbine system is mainly built from where a huge amount of energy is harnessed. The rotation and power generation from the turbine is governed by Euler's turbomachinery equation and velocity triangle theorem.

Turbines can be classified based on several parameters, like impact of jet, head difference, flow type and speed. Furthermore, some of those turbines are conventional water turbines. Pelton turbine, Francis turbine, Kaplan turbine and propeller turbine are such conventional turbines used in typical hydroelectric plants. Whereas, Archimedes screw, cross-flow turbine and siphon tube turbine are nonconventional ones. They aren't that much popular in mass power generation. GWVT is an example of nonconventional water turbine.

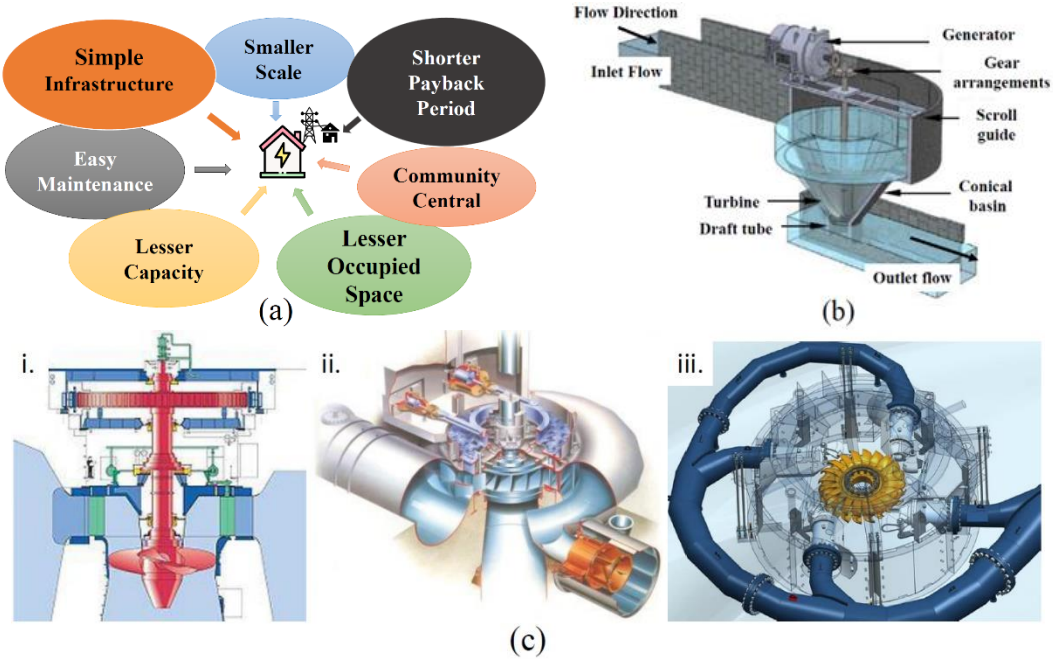


Figure 03: (a) Off-grid features, (b) Gravitational water vortex turbine system, (c) Existing hydro turbine systems: i. Kaplan turbine system, ii. Francis turbine system, iii. Pelton turbine system.

It's crucial to know how a GWVT is built, to explain how it works. A GWVT system contains a vortex chamber, a supply channel, a discharge channel, a draft-tube and a turbine rotor (Fig.03.b). When water flows through the supply channel, it produces an open surface free vortex in the chamber. The rotary motion of vortex makes the runner to rotate about its axis and so rotates the generator engaged with it, leading to power generation. After rotating the runner blades, the water is discharged in the discharge channel.
By nature, GWVT is an impulse type turbine, because, the rotating vortex flow attacks the turbine blades with an impact force causing the runner to whirl. This is how a GWVT can be characterized.

3. Comparative Overview of Water Turbines

Simply, off-grid powerplants are central grid independent power generation plants and are designed so to power up those areas which do not get the facilities of main-grid supply [8]. Therefore, it will have its own unique features dissimilar to that of the main-grid plants (Fig.03.a), such as, an off-grid powerplant is typically a small-scale power generating system having production capability as high as 100kW-1MW powering about 100-1000 houses [9]. Moreover, this kind of mini powerplants are simple in construction containing lesser amount of system components which are also easily made and fitted because of lesser demands of energy. And because of simple structure, the maintenance becomes easier, can be handled by local workers and therefore reduces cost. Simple structure gives another advantage of occupying small spaces, like, a space of approximately 10 to 25 square meters should be enough to build up a proper mini-hydro powerplant [10]. Furthermore, such type of off-grid power house can be community central, i.e. the rural community will have significant influence over the system, which gives them the opportunity to take major decisions, while problems making fruitful solutions acquiring the most beneficial outcome, leading to the prevention of remaining under ignorance. Finally, a project like this is potentially economical, as the installation and maintenance cost are low, the payback period is short, which would strengthen the community's economy.
A turbine having the closest resemblance with all the characteristics mentioned (Fig.03.a) would be the most suitable one to be selected as the best candidate. For this, a comparative analysis has been done on the features of different kinds of turbines, analysis type and output results from the corresponding research works for their optimization and development. Below, a review table has been given which denotes the previous investigations on the natures of the water turbines, impacts on their various parameters and improvements of their functional qualities. In the last portion, a rough outline has been provided for smoothening the path of further research works.

Table 1. A review over the recent works on hydro turbine characteristics and developments.

Year	Turbine Type	Analysis Type	Acquired Performance	Citation
2023	Pelton turbine (26 bucket)	Geometric designing, numerical modeling and experimental analysis	Efficiency obtained was up to 81.13%.	M. Á. Zamora-Juárez, Fonseca Ortiz, et al. (2023) [11]

Year	Turbine Type	Analysis Type	Acquired Performance	Citation
2022	Gravitational Water Vortex Turbine (GWVT)	CFD analysis	The model with 8 blades and largest impulse radius of 0.2 m showed the maximum efficiency of 64.23%, whereas the estimated efficiency was on average of 39.85%.	M. A. Zamora-Juárez et al. (2022) [12]
2022	Gravitational Water Vortex turbine (GWVT)	CFD Simulation	For vertical twist bladed turbine, the yielded efficiency showed to be 55.3% with a conical basin (it is noteworthy that the turbine with horizontal curved blade maintains efficiency over 51%).	Edirisinghe et al. (2022) [13]
2022	Gravitational water vortex turbine (GWVT)	Numerical simulation, experimental study and comparative analysis	Efficiency of the curved blade rotor improved by 3.65% and flat blade rotor by 1.69%.	Faraji et al. (2022) [14]
2022	Tubular Water-Bulb Turbine	Numerical Analysis	95.828% efficiency (at maximum flowrate of 13 L/s and speed of 1300 rpm).	Febri Budi Darsono et al. (2022) [15]
2022	Kaplan turbine	Theoretical designing and CFD simulation	The optimized maximum efficiency obtained was 93.01%.	Abeykoon, C. (2022) [16]
2022	Deriaz Turbine (Both pump and turbine mode)	Site Test (Using Sensor Fish)	Up to 93.6% optimum efficiency	Kassanos et al. (2022) [17]
2022	Francis turbine	CFD simulation and model testing	94% efficiency from CFD simulation having about 0.7% variation while compared with experimental result.	Umar et al. (2022) [18]
2021	Gravitational Water Vortex Turbine (GWVT)	Experimental Analysis	The maximum efficiency of single-stage GWVT was 54.44% at 0.70 m head and 0.004 m^3/s flowrate.	Sharif et al. (2021) [19]
2020	Gravitational Water Vortex Turbine (GWVT)	Laboratory test and CFD simulation	The maximum increase in efficiency obtained after adding the booster runner was 20.4% than that of the single main runner.	Dahal et al. (2020) [20]
2020	Gravitational Water Vortex Turbine (GWVT)	Experimental Analysis	The hydraulic efficiencies of SS-304, AA-5057 and PVC blade are 31.8%, 27.7% and 26.4% respectively.	Zariatin et al. (2020) [21]
2020	Gravitational Water Vortex turbine (GWVT)	CFD simulation and experimental analysis	Computational analysis showed maximum efficiency of 35.59% at the lowermost region of the vortex, whereas experimental efficiency was up to 10.51%, which was not obtained in the bottom-most position (the efficiency at the bottom-most position was 10.14%).	Kayastha et al. (2020) [22]
2017	Water Vortex turbine	Experimental study and theoretical analysis	The flat-blades turbine shoed maximum efficiency of 21.63% (at 3.27 rad/s) and the curved-blades turbine showed 22.24% (at 3.56 rad/s).	Kueh et al. (2017) [23]
2015	Water Vortex turbine (with five vertically twisted blades)	Theoretical analysis and experimental study	The maximum efficiencies of the steel and aluminum turbine were 33.56% and 34.79% respectively and it was found that the torque value and electricity production efficiency of aluminum turbine was higher than that of steel turbine at the average of 8.4% and 8.14% respectively.	Sritram et al. (2015) [24]
2013	Pelton and Turgo (Impulse)turbine	Laboratory-scale test	Efficiency around 85% (For Turgo turbine, in the speed ratio of 0.45 to 0.50)	Cobb & Sharp (2013) [25]

The given table represents a number of research works done on GWVT and existing conventional hydro turbines. From this, a comparison can be done between them. Such as, Abeykoon (2022) has analyzed Kaplan turbine obtaining an output efficiency of 93.01%, whereas Edirisinghe et al. (2022) have shown 51% efficiency of a GWVT. Again, Febri Budi Darsono et al. (2022) have worked on tubular water bulb turbine showing efficiency of 95.282%, but Kueh et al. (2017) achieved only 22.24% efficiency. If a review be done on the other conventional turbines, like Pelton and Turgo turbine (Cobb & Sharp (2013)), Deriaz turbine (Kassanos et al. (2022)) and Francis turbine (Umar et al. (2022)), it can be seen that their efficiency in each case is almost greater than 80%. On the contrary, overviewing the performance of GWVT, it comes out to be not more than 64.23% (obtained from research done by M. A. Zamora-Juárez et al. (2022)) thus always indicating a lower value than the existing hydro turbines. As a matter of fact, to establish off-grid powerplant systems in decentralized areas, which are mainly rural communities, cost is a crucial factor. The existing turbines, since they show higher degree of efficiency, may seem to fit in an off-grid power generation system. However, practically, it may not be feasible. This is because, their greater efficiency comes with increased cost. The conventional turbines (Kaplan turbine, Francise turbine or Pelton wheel) are designed to meet huge energy demand. Therefore, they are structurally intrinsic and complex (consisting penstocks, runner chamber, guide vanes, draft tube, link rods, spiral casing, control ring, stay ring, head cover and others (Fig. 03.c)), creating the possibility of higher maintenance cost and the requirement of expertise further increasing the expense, which won't be sustainable from the angle of rural economy. A simple turbine like the GWVT should be enough to power up a whole village with its modest performance solving the problem of both power availability and cost effectiveness. Furthermore, turbines like, Kaplan, Francis, Deriaz and Pelton wheel would require expensive and complex civil works (like making dams) to be installed in a power plant system, but a GWVT system needs only a few equipment, such as generator, rotor, inlet channel, outlet channel and a funnel shaped chamber for it's fulfill installation, which is easier and cost-effective. The scope of creating false tributary as water source eliminates the need to build a complex dam and the possibility of series arrangement of GWVT (Fig.04) gives the opportunity to increase efficiency (with lesser expenditure) in overall sense. Moreover, simple structure and scope of easy maintenance gives the rural community to independently operate the power plant, have significant influence on it and thus, getting the most benefit out of it, like, increased job opportunity for the community people will be created, possibility of complete power detachment will be lessened, leading to improved rural economy which is lot better than entirely depending on main grid power. From this discussion, it can easily be said that, GWVT has the highest potential to be implemented in the off-grid power generation system.

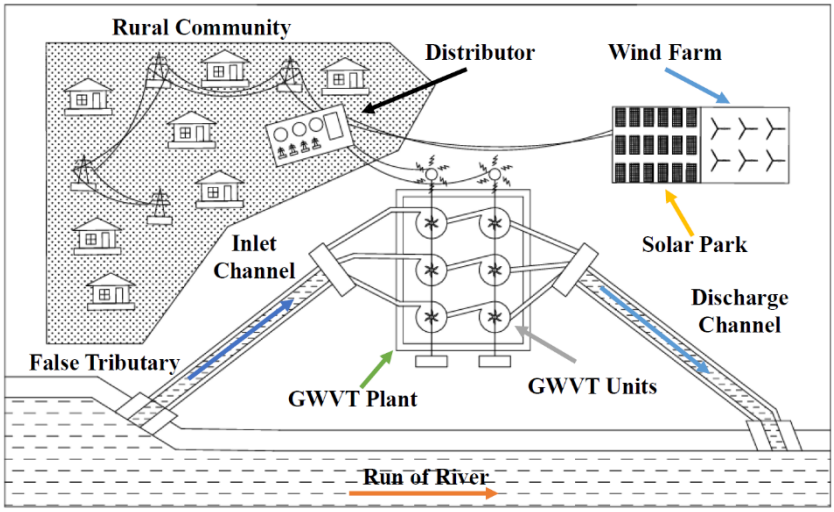


Figure 04: A hypothetical gravitational water vortex miniature hydro powerplant system.

Selecting a turbine for an off-grid system is not the only work to be done, rather a well-designed power generation system that's what is needed. For further research work, a rough outline of this kind of miniature plant is proposed (Fig.04). This includes a GWVT mini powerplant that is designed so to power up a small community, such as, a village where sufficient river-flow is present. A false tributary is used for inlet supply so that damming can be eliminated to prevent river damaging. There is provided a solar park and wind farm as back-up energy sources. A well-built distributor is given for well-distribution of energy throughout the whole area leaving not a single house without electricity.

4. Conclusions and Recommendations

There are pre-requisite key points to be followed to build up an effective power generating system in off-grid manner. For this, a handful of recommendations from not only the authors but also previous literatures may be considered in further research work. Such suggestions might be given as,

- First of all, an extensive load analysis should be done in order to get a clear conception of how much electricity is sufficient enough in order to power up a typical rural community, considering variation of conditions, such as number of consumers, available space and available water flow.
- Moreover, proper numerical and experimental study is crucial to do after the primary design is given.
- Furthermore, with addition to solar and wind sources (since they are recurring in nature) biogas plants can be used as a renewable source of energy, which are easy to be built up in the rural regions.
- Finally, a proper energy storage system can prove to be worth constructing for better energy handling preventing both wastage and deficiency of power, leading to better utilization of energy.

In this paper, only one type of turbine has been comparatively overviewed and selected to be used and a hypothetical layout of the system is given. Yet there are so many things are left to actually construct a real one, like optimizing the best blade design, selecting the most proper runner material, simulating and verifying the whole system in real time conditions. Now, the fact is that, it is no easy task to design a whole powerplant system, because, all decentralized localities are not the same. Nonetheless, if it is accomplished, it will both have a fair impact on the lives of people residing in those areas and the whole nation too.

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