Future Energy
Open Access Journal
ISSN 2832-0328

November 2023| Volume 02 | Issue 04 | Pages 31-37

Journal homepage: https://fupubco.com/fuen

https://doi.org/10.55670/fpll.fuen.2.4.4

Future Publishing LLC

Article

Load analysis of an off-grid hybrid power system using micro-hydro and diesel power technology in the remote areas of Bangladesh

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ARTICLE INFO

Article history:
Received 05 January 2023
Received in revised form
07 February January 2023
Accepted 09 February 2023

Keywords:
Hybrid power, Vortex, Remote
Micro-hydropower, Generator, Electricity

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DOI: 10.55670/fpll.fuen.2.4.4

ABSTRACT

Hybrid power technology plays an important role in the field of energy systems. This technology can be used with or without a grid by merging renewable and non-renewable sources. This study analyses electricity generation through an off-grid hybrid technology, which is composed of micro-hydro power and diesel generator power in a remote area of Bangladesh. In this investigation, some of the crucial cases will be examined, which are the optimum turbine placement with the aid of fluid flow simulation using the flow parameters, electric power production in a single power unit and hybrid power system unit, and cost analysis of the hybrid power system unit in order to inspect the feasibility of the system.

1. Introduction

The generation of power through a hybrid system is one of the reliable technologies for meeting the load demand. Besides, the generation of power through renewable sources bears an enormous role in reducing environmental pollution with low operating and maintenance costs. Establishing a hybrid system using micro-hydro and diesel power technology is one of the vital methods for electricity production. Some of the research has been done regarding micro-hydropower and diesel power technology. In Bangladesh, there are several remote areas on the border and especially on the hilly sides, where electricity has not been reached properly. This study aims to investigate load analysis in a particularly remote area of Bangladesh by setting up an off-grid hybrid power system through micro-hydro and diesel power to observe if it is a feasible technology to go and can be applied in other remote areas of the country based on available sources.

2. Literature review

Bangladesh is blessed with lots of rivers and lakes. Despite having a sufficient amount of hydro resources, the utilization of these resources is not much. Bangladesh has got only one large-scale hydroelectric power plant of 230MW in Kaptai [1]. BPDB and BWDB have found some potential micro-hydro sites on the southern sides of Bangladesh where power can be generated for electricity production. Some of the investigations have been carried out by utilizing the hydro resource. For example, a 10kW micro-hydro power unit has been established at Bamarchara at Chottogram. But it was not that much feasible as almost 41% of potential energy was lost by the penstock, turbine, generator, and transmission line [2]. Md. Golam Kader et al. [3] described low-head hydropower and investigate the possibility of micro-hydropower establishment. Ayesha Zaman and Taslima Khan designed a low-head micro hydropower system for measurable families where family members can use household appliances when there is no power from the national grid line [4].

3. Methodology

3.1 Geographical area

For electricity production, an ideal place needs to be selected where a proper source of water is available with the necessary head and water flow. Taking into account the remote areas of Bangladesh, the Sailopropat waterfall can be selected, which is located in the Banderban in the Chattogram division (Figure 1). The waterfall has a flow rate of 100 L/s with an available head of 6m, which is sufficient to generate electricity through a micro-hydro system.

Figure 1. The geographic location of Sailoprapat Waterfall

3.2 Overall Investigating Process

First of all, an entire micro-hydropower system has been designed using SolidWorks. Then the system was simulated with the help of ANSYS Fluent CFD simulation software to observe the ideal turbine position. Finally, the micro-hydro unit has been taken into HOMER Pro software for load observation for a residential area by adding a generator and an energy storage system (ESS) in order to make it a feasible hybrid power system unit. Besides, cost-effectiveness has also been observed to get a better idea about its feasibility for the people of remote areas. In Figure 2, the overall study methodology has been shown according to a flowchart diagram to get an overview of the project based on which the study has been conducted.

3.3 Designed model of micro-hydropower unit

Before modeling the hybrid power system, a micro-hydropower unit needs to be designed, which is the prime power generation source. This micro-hydropower unit consists of four main sections, which are the channel, turbine or vortex chamber, vortex turbine, and outlet section, which is also called the orifice. A channel has been designed for the incoming water from the waterfall of Sailoprapat. As the average available head is 6m, a cylindrically shaped chamber has been attached to the channel where the turbine needs to be installed, and there is an outlet section at the bottom middle end of the chamber from where the water will come out and again merges with the water flow. Based on the location of the waterfall, the micro-hydropower unit has been designed according to the necessary geometrical parameters (Table 1). The design has been done using SolidWorks by taking fundamental syntaxes (Figure 3).

3.4 Mathematical equations for CFD simulation

To conduct fluid flow simulation, the behavior of fluid in the system must be understood. The fluid flow in the turbine chamber where the turbine will produce power generates a certain formation called vortex which is the rotational mass of fluid. For this phenomenon, the governing equations that can be viscous, incompressible, steady, and in addition to a turbulent flow can be claimed as the continuity equation, and also the Navier Stokes equation associated with the coordinates of a cylinder that is placed as the continuity equation is used to obtain the vorticity. The equation has been given on the basis of cylindrical-shaped parameters [5, 6].

$$\frac{\partial V_r}{\partial r} + \frac{\partial V_z}{\partial z} + \frac{V_r}{r} = 0 \quad (1)$$

$$\partial V_r \frac{\partial V_\theta}{\partial r} + VZ\frac{\partial V_\theta}{\partial z} - \frac{V_r V_\theta}{r} = v\left(\frac{\partial^2 V_\theta}{\partial r^2} + \frac{\partial V_\theta}{r\,\partial r} - \frac{V_\theta}{r^2} + \frac{\partial^2 V_\theta}{\partial z^2}\right) \quad (2)$$

$$V_r \frac{\partial V_r}{\partial r} + VZ\frac{\partial V_r}{\partial z} - \frac{V_\theta^2}{r} + \frac{\partial \rho}{\rho\,\partial r} = v\left(\frac{\partial^2 V_r}{\partial r^2} + \frac{\partial V_r}{r\,\partial r} - \frac{V_r}{r^2} + \frac{\partial^2 V_r}{\partial z^2}\right) \quad (3)$$

$$\partial V_r \frac{\partial V_z}{\partial r} + VZ\frac{\partial V_z}{\partial z} + \frac{\partial \rho}{\rho\,\partial z} = g + v\left(\frac{\partial^2 V_z}{\partial r^2} + \frac{\partial V_z}{r\,\partial r} + \frac{\partial^2 V_r}{\partial z^2}\right) \quad (4)$$

Systematically, it is an immense complex equation that can be solved through. Therefore, ANSYS CFD Fluent simulation software has been used to decode the equation [7].

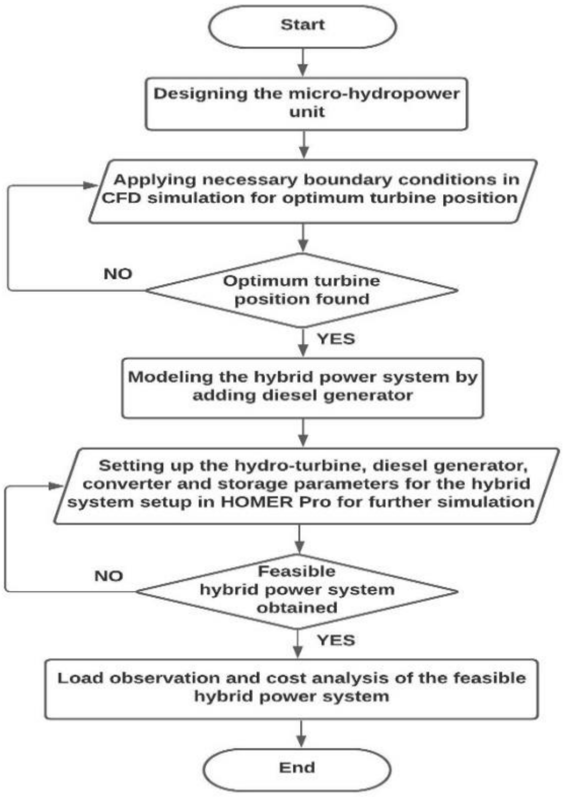

Figure 2. Overall Investigation Process

Table 1. The geometrical configuration of the micro-hydropower unit setup

Section	Dimension (mm)
Channel Width	500
Channel Height	750
Total Channel Length	9141.46
Chamber Diameter	2500
Chamber Height	3000
Outlet Section Diameter	500
Outlet Section Height	500

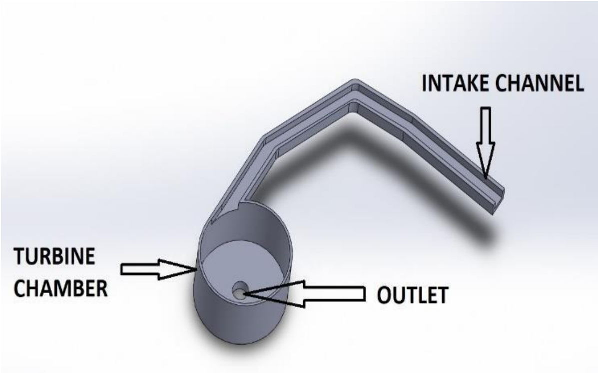

Figure 3. 3D Model of Micro-hydropower unit setup

3.5 Meshing analysis of micro-hydropower unit

For CFD simulation, proper meshing is needed for the micro-hydropower unit in order to conduct the fluid flow simulation. The entire 3D geometrical model of the unit has been taken to the proposed section of the simulation, where the tetrahedron mesh has been applied. The element size has been taken at 0.1m with a growth rate of 1.2, and the total number of the element has been found to be 64,157 after the mesh generation. Adaptive sizing has been used in this mesh by taking high smoothing quality. In terms of the mesh metrics, the average skewness has been found at 0.26872. The average aspect ratio was found to be 1.9505. The 3D meshed body of the micro-hydropower unit is depicted in Figure 4.

3.6 CFD solving parameters

In terms of the viscous model, a standard k-epsilon model has been set for this unit with standard wall functions. The overall body has been taken as a water fluid domain as this simulation has been conducted by turning the multiphase off. For the boundary conditions, the inlet velocity of water has been set to 0.2 m/s for the inlet condition, and the outlet pressure has been taken to 0 Pa for the outlet condition. The free surface was considered as a wall because the entire simulation will be run through a single phase by taking the entire domain as filled with water. All the residual convergence criterion was set at 0.001, and the 3000 number of iterations were set for the simulation through hybrid initialization (Figure 5).

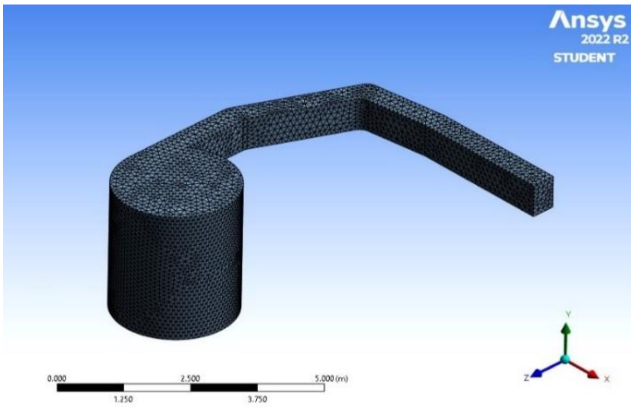

Figure 4. 3D Meshed model of the micro-hydropower unit

3.7 Simulation of the hybrid power unit for load test

A hybrid power unit setup has been modeled for the power generation where an Autosize Genset diesel generator has been added with the micro-hydropower unit (Figure 6). An energy storage system (ESS), a Generic 1kWh Li-Ion battery, has been added to the system for backup power when both renewable and non-renewable power sources are unable to deliver power. A converter has been included for AC to DC current conversion and vice versa. The overall setup has been modeled and simulated in HOMER Pro optimization software. Figure 6 shows the overall schematic diagram of the proposed hybrid power system plant which has been discussed in this study. Before the simulation, an average daily load profile of Banderban was taken for the month of January on load consumption of around 4 kWh (Figure 7) [8].

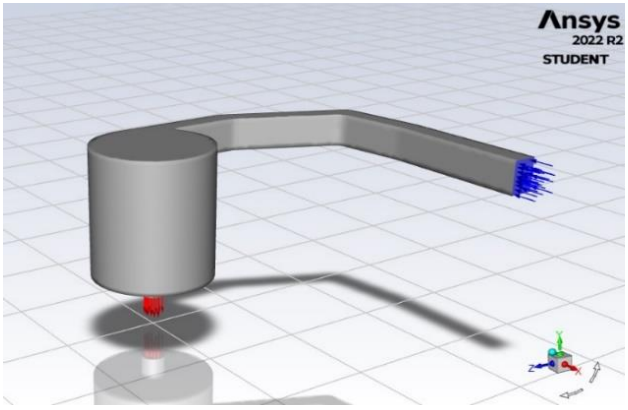

Figure 5. 3D Solver model of the micro-hydropower unit

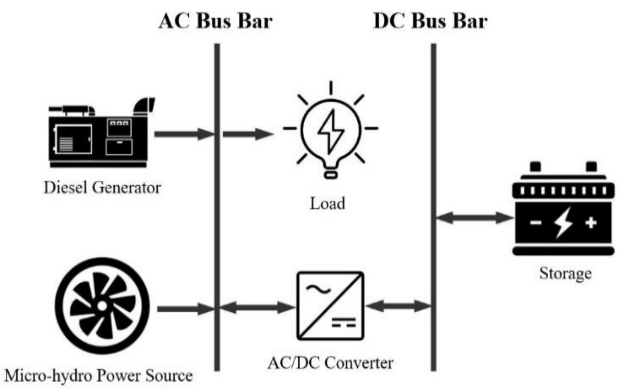

Figure 6. Schematic diagram of hybrid power system

4. Results and discussion

4.1 Generation of vortex

From Figure 8, it has been observed that there is a conical formation of water streamlines which is the vorticity. The inlet section of the channel allows the water to flow through the entire channel. Then the water falls spirally into the vortex chamber, which generates the vorticity. The particle tracker in Figure 8 shows the fluid has been directed to the turbine chamber from the intake channel resulting in vortex generation. In Figure 9, the cross-sectional view of the generated vortex has been shown along the y-z axis. Here, the air-core formation has been clearly observed from the velocity contours where the blue colour represents the formation of the air-core. The color bar indicates the range of velocity of the vortex formation inside the vortex chamber.

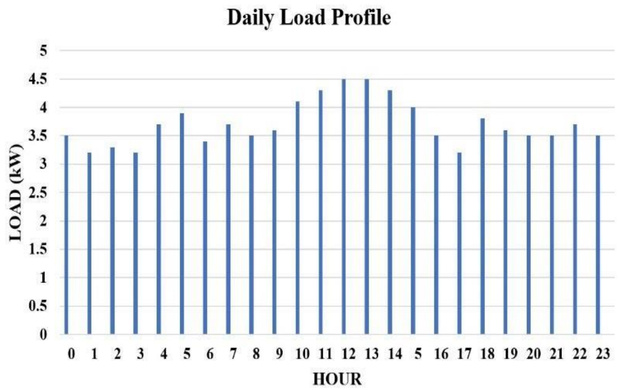

Figure 7. Graphical representation of daily load profile in Banderban district

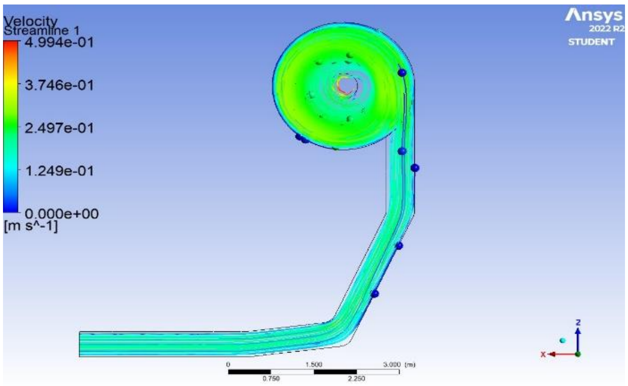

Figure 8. 3D Fluid particle tracker of micro-hydropower Unit

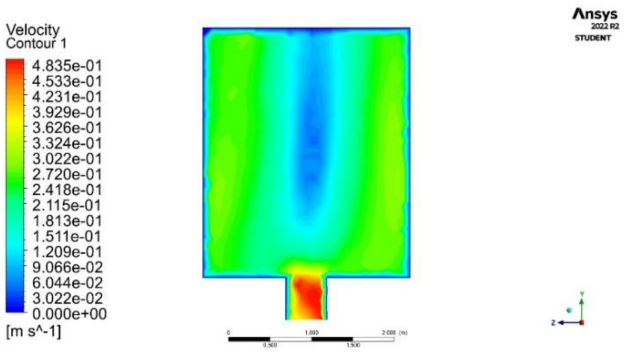

Figure 9. Velocity contour of the chamber along the Y-Z axis

[Figure 10](#), [Figure 11](#), and [Figure 12](#) are the visual representation of the air-core formation of a generated vortex. Figure 10 shows the swirling strength of the vortex core that will assist the vortex turbine in rotating for power extraction. Figures 11 and Figure 12 are the velocity and pressure formation of the vortex core where the velocity is higher and pressure is lower at the bottom of the chamber. Figures 13 and Figure 14 represent the absolute velocity and static pressure curves of the vortex chamber in the center, where it is clearly observed that the absolute velocity rises as the center line approaches the bottom of the chamber. On the other hand, there is a drop in static pressure due to the increase in absolute velocity.

4.2 The optimum position for the turbine

After forming a suitable vortex in the vortex chamber, an ideal spot is needed to place the turbine to extract the maximum possible amount of energy from the vortex core. Therefore, CFD simulation has been conducted through the channel and turbine chamber by taking the necessary boundary conditions and flow parameters [9]. Figure 15 shows the velocity contours of the turbine chamber from the bottom section. The post-CFD result shows that the velocity profile is much stronger at 28% of the total chamber height with respect to the bottom. Therefore, the turbine can be installed in this position to extract the maximum amount of power for electricity generation.

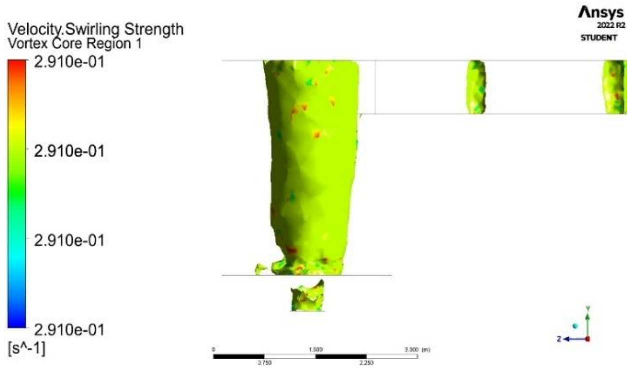

Figure 10. Swirling strength of the vortex core

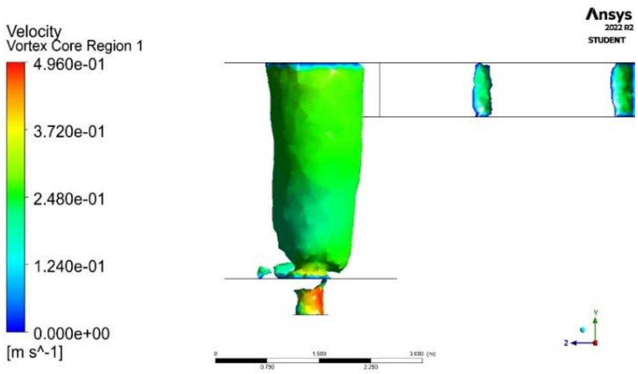

Figure 11. The velocity of the vortex core

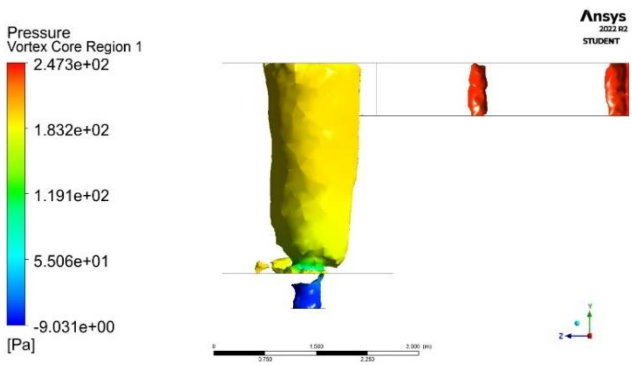

Figure 12. The pressure of the vortex core

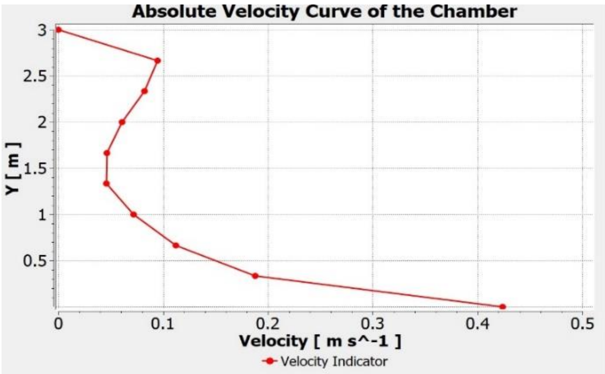

Figure 13. Absolute velocity curve at the centre of the chamber

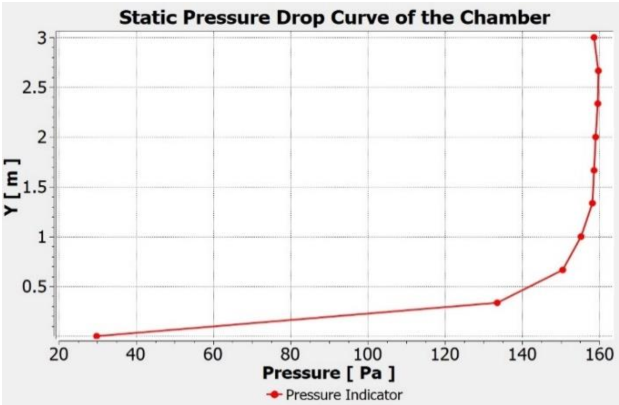

Figure 14. Static pressure curve in the center of the chamber

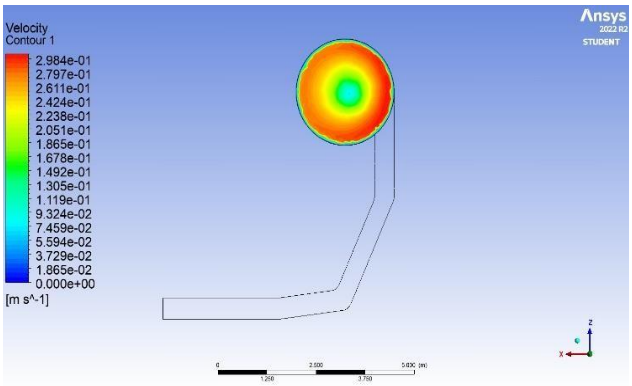

Figure 15. Velocity contours at the chamber at 28% height from the bottom

4.3 Load behavior of diesel generator power

Figure 16 depicts the annual electricity generation from diesel generators only. But going with this process is not a feasible option at all as the excess electricity is 94.4 kWh/yr. i.e., 0.301%, which is a considerable loss.

4.4 Load behavior of hybrid power system

With the inclusion of a micro hydropower system, the load behavior is more balanced. The load ratio of the generator has been to 25% as this becomes the secondary power source. With this system, the generated excess amount of electricity is 8.46 kWh/yr, equivalent to 0.0254% only. This means a minimal amount of electricity loss can be obtained from the hybrid power system (Figure 17).

4.5 Production of energy by renewable sources

The production of energy from a renewable source, which is the micro-hydropower source, has been found 55.9%, which is a positive outcome for the hybrid power system. Also, the renewable power source has the capacity to distribute 59.5% of the load (Figure 18).

4.6 Fuel Consumption of the Hybrid Power System

It is necessary to observe the fuel consumption of the diesel generator while the hybrid power system is operating. From the simulation data, it has been observed that the average diesel consumption of the generator only is 31.4 L/day. The fuel consumption by the diesel generator annually is shown in Figure 19. On the other hand, if the power system runs through both of the sources, the average consumption of diesel by the generator reduces enormously and comes down to only 12 L/day, which is more than 2.5 times less than the single case as the hydropower generation is backing up along with the diesel generator according to the demand of the load. Yearly fuel consumption by diesel generators while the hydropower is activated is depicted in Figure 20.

From Figure 19 and Figure 20, it can be seen that this hybrid power system can able to save a lot of fuel as the dependency on the non-renewable power source is less.

4.7 Charged state of ESS

The energy storage system (ESS) is used to deliver backup power when both renewable and non-renewable power sources fail to produce power. Throughout the year, the energy storage system delivers 9223 kWh of power and receives 10,247 kWh of power. The annual loss from the ESS is 1025 kWh / year, as observed from the result of the simulation. From Figure 21, it has been observed that the energy storage device remains charged more than 30% for almost a maximum of the time. This proves that the storage system is always ready to deliver the backup power whenever needed and will not run out of charge.

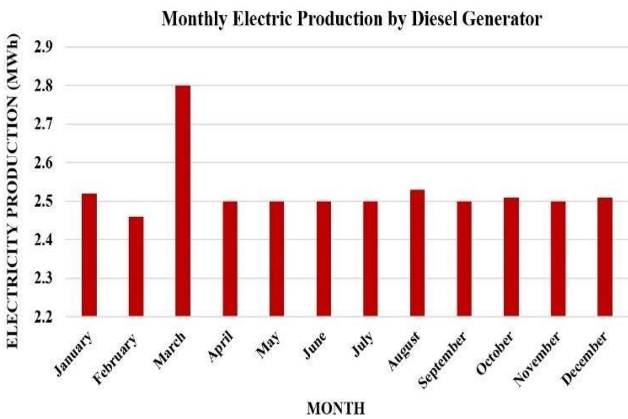

Figure 16. Annual electricity production by diesel generator

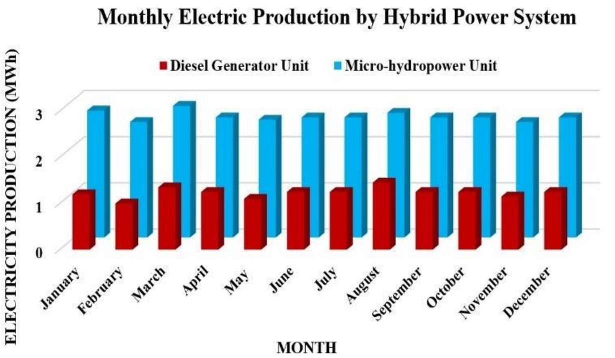

Figure 17. Annual electricity production by hybrid power system

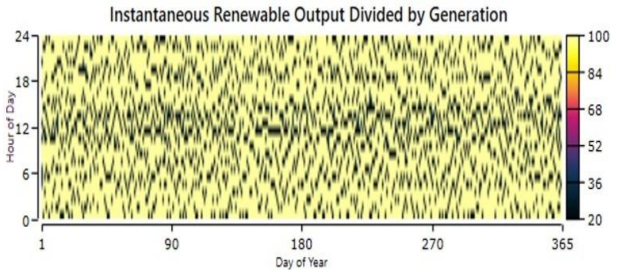

Figure 18. Annual power output percentage from the renewable power source

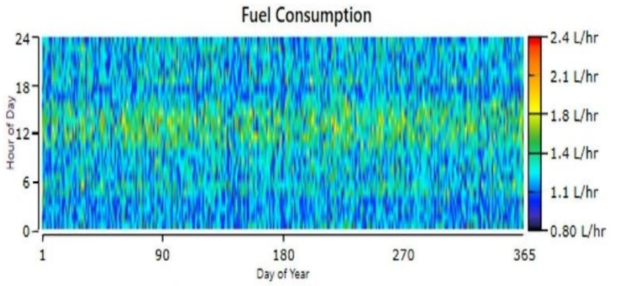

Figure 19. Annual fuel consumption by diesel generator only

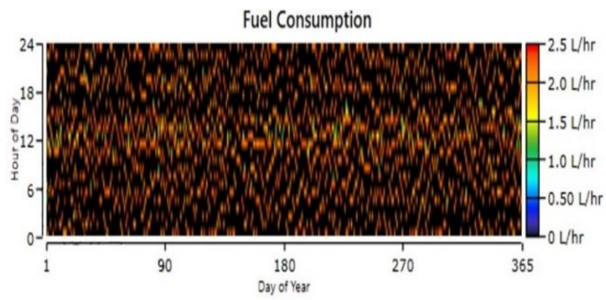

Figure 20. The annual fuel consumption by a diesel generator, along with renewable power source

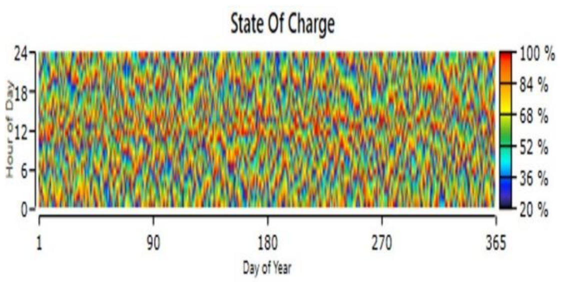

Figure 21. The annual charging state of ESS

4.8 Cost analysis of hybrid Power system

Hybrid power systems bear great economic value (Figure 22), which have been seen in recent times. Considering the fact this hybrid power system of micro-hydro power and diesel generator power has been designed and simulated in the HOMER Pro software to see the cost-effectiveness. It has been observed that the simple payback duration is 7 years after the hybrid system installation with an internal rate of return (IRR) of 14% and return on investment (ROI) of 10% and which is a commendable outcome. In Table 2, the cost summary has been provided where the lowest cost system is generated for the hybrid power system.

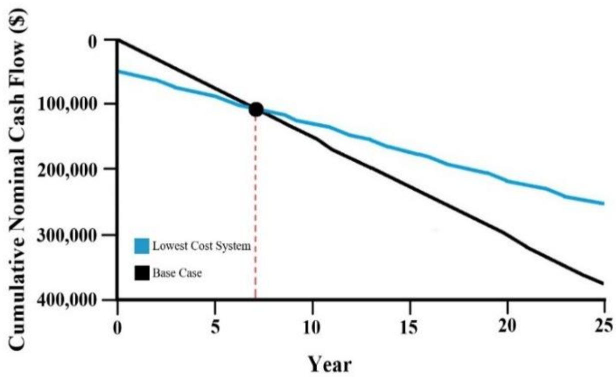

Figure 22. Representation of project lifetime of hybrid power system

Table 2. Cost Summary

	Base Case (USD)	Lowest Cost System (USD)
NPC	195,406	155,614
Initial Capital	4,150	50,958
O&M	14,794/yr.	8,096/yr.
LCOE	0.483/kWh	0.385/kWh

5. Conclusion

Among all renewable energy sources, hydropower is one of the most enforceable power sources from which electricity can be produced in a convenient way. Bangladesh, which is a land of rivers and lakes, has many opportunities to use hydro resources. There are numerous remote areas in this country where electricity can be distributed among those people by using hydropower. Since the hybrid power system has been one of the exemplary power generation technologies, a system has been designed including two power sources of micro-hydropower and a diesel generator for a remote area in Bangladesh. Taking the Sailoprapat waterfall as the suitable spot for the implementation of the hybrid power system, several simulations were carried out to evaluate the load and cost analysis of the system. Optimized turbine power has been found at 2.5 kW for the micro-hydropower unit that extracts the energy from the water vortex for the maximum amount of time. The overall system has been seen to be more practical when the cost analysis was observed where the operation and maintenance and levelized cost of energy (LCOE) were good enough. Satisfactory outcomes were obtained after carrying through multiple investigations of the hybrid power system where both of the sources were generating a good amount of electricity. As this hybrid power system can bring out some fruitful outcomes, installing this off-grid hybrid power system can be an impactful project for electricity distribution in the remote and rural areas of Bangladesh.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

Datasets analyzed during the current study are available and can be given following a reasonable request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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