Electricity Generation from Rooftop Rainwater Flow Using Downpipe Micro-Hydro System: A Comprehensive Analysis

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Abstract - *The feasibility of utilizing a downpipe micro-hydro system in harnessing electrical energy from the rainwater flowing over the rooftop is examined in this project. With the increasing demand for sustainable and alternative sources of energy, the potential of harnessing energy from existing sources in urban areas presents an interesting area of research. The proposed project aims at harnessing the kinetic and potential energy of rainwater flowing through the gutters and downpipes of buildings using a micro-turbine generator. The proposed system includes rainwater diversion, a micro-hydro turbine located inside the downpipe, a DC generator, and an energy storage device. During rainy days, rainwater is collected and directed to turn the turbine blades, thereby producing electricity using a DC generator. A prototype model of the system was developed using light materials and a miniaturized turbine designed to function effectively in low-head and fluctuating flow rates. The prototype was tested under artificial rainfall conditions. The findings show that the system is capable of producing adequate electrical power that can be used in low-power devices such as LED lighting and powering sensors. However, despite the fact that the power is only supplied intermittently, depending on the rain, the use of energy storage makes the system more reliable. It can, therefore, be concluded that the use of micro-hydropower in the harvesting of rainwater as an alternative source of energy is not only possible but also environmentally friendly and an efficient means of harvesting energy, which can be improved by making improvements to the system.*

Keywords: Rooftop Rainwater Harvesting, Downpipe Micro-Hydro power, Micro-Turbine Generator, Low-Head Energy Conversion, Runoff Flow Rate, DC Power Generation, Urban Renewable Energy, Energy Storage System.

1. INTRODUCTION

The last ten years have seen a sharp rise in the world's energy demand due to both rapid technological advancements and an expanding population. Global energy consumption is predicted to increase by 77% between 2000 and 2040, to 740 million terajoules **[1]**. Fossil fuels contributed 84% of global primary energy consumption in 2019 **[2]**. Environmental pollution, greenhouse effects, and CO2 emission are only a few of the alarming effects of these non-sustainable resources on the globe. The UK has set goals to generate all of its power from renewable energy by 2035 **[3]**. Governments have understood the need to invest in green energy to ensure a clean environment for future generations. Renewable energy sources are now among the most competitive energy sources in many nations due to quick technological advancements, declining costs of renewable energy supplies, and rising battery storage competitiveness **[4]**. Energy harvesters that transform ambient energy into electrical energy have attracted a lot of research interest from a variety of areas. For usage in low-power electronic devices, the energy harvester gathers and stores ambient energy from outside sources like solar panels, thermal energy, and kinetic energy. Recently, scientists have begun to use a variety of methods, including as hydroelectric **[5]**, electromagnetic **[6]**, piezoelectric **[7]**, solar **[8]**, and thermoelectric **[9]**, to harvest electrical energy from the environment. In 2020, renewable energy accounted for 43% of the 312 TWh of domestic power generated in the UK **[3]**. Wind and hydro only contributed 11% and 3%, respectively, whereas solar (photovoltaics) accounted for about 81% of the total **[10]**. The UK's flat terrain helps to explain the modest hydro contribution given the abundance of potential and kinetic energy from heavy rains and the accessibility of ocean waves around the country each year. With an annual rainfall of roughly 1154 mm, it rains on average for 156.2 days of the year **[11]**. It is believed that the rainwater that enters the downspouts from the gutters is a waste of enormous potential energy. An alternative form of recycling should be developed to prevent this form of energy waste. It is more environmentally friendly to harness rainwater as a form of energy, such as electrical energy, instead of letting it go down the drain. One way to turn rain energy into electricity is to collect it and run it via a micro-hydro turbine (MHT). Raindrops that fall are captured by a rooftop rainwater energy collection system and used to create electricity. Raindrop energy is harvested using revolving machinery like hydro turbines **[12]**. Conventional rainwater harvesters frequently use hydro turbines as spinning generators. Impulse turbines (Pelton and Turgo) and reaction turbines (Kaplan and Francis) are two common categories for hydro turbines **[12]**. Depending on different water-head conditions (adjusted for building height) and other real-time environmental considerations, a variety of water turbines have been developed and installed to harvest rooftop rain energy **[13]**. Attaching piezoelectric materials to elastic structures to capture vibration energy **[14]** and putting a turbine in the flow to capture its kinetic energy **[15]** are the two primary approaches used in the past to harvest potential energy from rain. Because it was more efficient than the piezoelectric material, the turbine design was selected to move on to the product design phase. The comparatively poor efficiency of the turbines is the primary obstacle to the wider application of hydro-kinetic power for energy production. No matter the type of turbine, Albert Betz **[16]** came to the conclusion that the theoretical maximum efficiency is 59.3%. The head, flow rate, and stream characteristics of the flow determine which hydro turbine is most suited to the design. There have been many sectors that have generated notable interest in the field of energy harvester, which converts the surrounding energy into electrical energy. The energy harvester is used to absorb the energy that is present in the surroundings, such as solar energy, thermal energy, or kinetic energy, in order to power low power electronics. Scientists have recently begun to draw electricity from the surrounding environment in several ways, one of which is hydroelectric. The water that drains from the gutters to the downspouts can be referred to as the waste of high potential energy. In this regard, there is an important alternative recycling process that can reduce the effects of this potential energy waste. It is better for the water to drain in a manner that converts it to electricity rather than flowing freely to the drains. Rainwater collection and passage through a Micro-Hydro Turbine (MHT) is one such technique of exploiting rain energy in the form of electricity. Rainwater energy harvesting through a rooftop system uses rain droplets for the generation of power by utilizing rotational devices such as hydro tunnels in rain droplets The design and implementation of a downpipe micro-hydro system for electricity generation represent an innovative approach to harness renewable energy from rooftop rainwater runoff.

2. METHODOLOGY

The process of implementing the project is structured, starting from the collection of rainwater to the generation of electrical energy and its utilization or storage. This methodology is based on the utilization of the potential and kinetic energy of the rainwater flowing through the existing downpipe of the building. This is achieved by connecting it to a micro-hydro turbine generator.

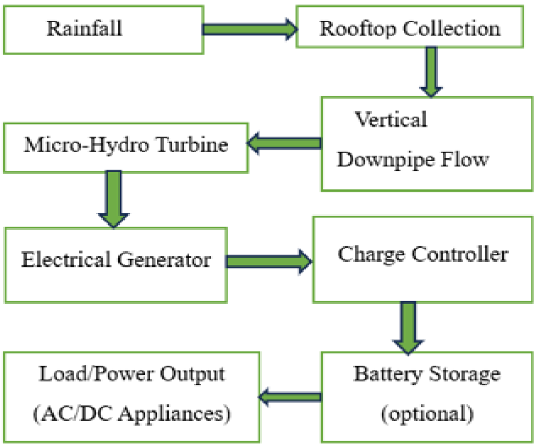


Fig -1: block diagram of proposed system

2.1Rooftop Rainwater Harvesting: The natural harvesting of the rainwater occurs on the roof of the building surface during the raining period. The roof surface of the building becomes the catchment area for the rainwater harvesting process. The rainwater that gets harvested on the roof surface of the building is passed to the gutter system. Afterward, the collected rainwater on the gutters is passed through vertical downpipes such as PVC or metals, which lead to the drainage point at ground level.

2.2 Calculation of Rainfall Runoff: Find out the rate of water discharge due to rainfall.

Formula:

$$Q = C * I * A \text{ ...... } (1)$$

Q = discharge of rainfall runoff in m^3/s

C= Runoff coefficient, the value of C ranges between 0.75 to 0.95 for rooftop

I= Intensity of rain. Its units are either in m/s or mm/hr.

A= area of the rooftop, in m^2

2.3 Water Potential Energy (Head):

Formula:

$$P = \eta * \rho * g * Q * H \text{ ...... } (2)$$

P = Output power, in Watts

η= Efficiency of generator-turbine system.

ρ= Density of water. The density value is 1000 kg/m^3.

g= Gravity. Its value is 9.81 m/s^2.

Q = Discharge rate of runoff water in $m^3/$

H = Vertical height.

2.4Downpipe System Design & Analysis: The downpipe is the main structural component where the energy conversion system will be integrated. It is positioned vertically; hence, the rainwater will gain kinetic energy due to the acceleration caused by gravity.

2.5 Pipe Flow and Losses: In order to determine the size of the downpipe required and minimize pipe losses:

Bernoulli's Equation (Simplified):

$$V^2 / 2g + H = \text{Total Head} \;\ldots\ldots (3)$$

Darcy-Weisbach Equation for head loss:

$$hf = f * L/D * v^2 / 2g \;\ldots\ldots (4)$$

hf= head loss due to friction (m)

f= Darcy friction factor (dependent on pipe roughness, Re number)

L= length of pipe (m)

D= diameter of pipe (m)

V= velocity of water in m/s

2.6 Micro-Turbine Selection and Integration: The micro-turbine is selected or designed depending on the space available in the downpipe. The micro-turbine is then rotated by the power of flowing water. The mechanical rotation is the first stage of conversion.

2.7 Generator coupling: The generator used here is small and works on the principle of the DC generator. The mechanical energy gets converted into electrical energy by this generator, owing to its coupling with the micro-turbine.

2.8 Power Conditioning Circuit: The power that comes from the generator is then processed before being used. The components in this circuit are:

1.The conversion of AC into DC if an AC generator is utilized.

2.Voltage regulation to produce a constant voltage supply.

2.9 Energy Storage or Direct Utilization: The power generated by the micro-turbine can be stored in a battery for future use or can be used directly for the following: LED lights for indoor and outdoor usage, Environmental sensors, USB devices, Emergency lights, etc.

Fig -2: Hardware model of proposed system

3. RESULT & DISCUSSION

To evaluate the performance of the proposed downpipe micro-hydro system, experimental observations were recorded under varying head and flow rate conditions. The performance of the proposed downpipe micro-hydro system was evaluated using fundamental hydraulic and electrical power relations. The mathematical formulation used for analysis is given below:

$$P = \rho * g * Q * H \ldots\ldots (5)$$
$$P_o = P * \eta_t \ldots\ldots (6)$$

where:

P=Hydraulic Power (W)

Po=Electrical Output Power (W)

ρ=Density of Water (1000 kg/m3)

g=Acceleration Due to Gravity (9.81 m/s2)

Q=Flow Rate (m3/s)

H=Head(m)

ηt=Turbine Efficiency

The data derived from the prototype tests are shown in the Table (Figure 2). The following is a detailed analysis of these data.

3.1Introduction to Experimental Results: An experimental analysis was done based on variation in effective head from 2.10 ft to 14.0 ft. The parameters measured include the flow rate, speed (RPM), output voltage, hydraulic power, and electrical power generated by the system.

3.2 Relationship Between Increasing Head and Flow Rate & RPM:

As the head increased:

1.The flow rate increases significantly from 7.8 L/min to 27.63 L/min.

2.The rotational speed increases from 480 RPM to 1670 RPM.

Clearly, there is an indication that an increase in head leads to an increase in potential energy, leading to conversion to kinetic energy and increasing the performance of the turbine.

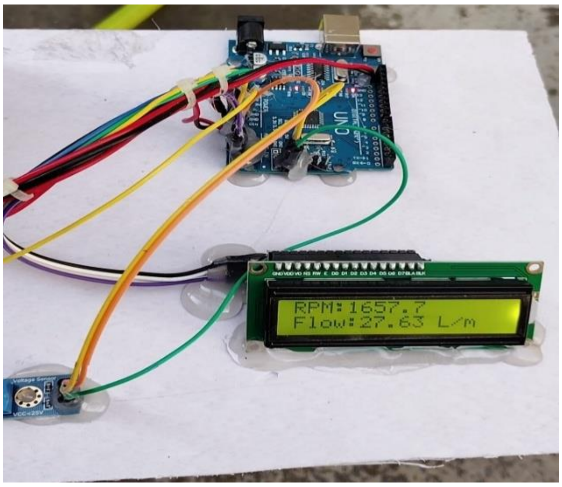


Fig - 3: Experimental setup showing RPM and Flow rate measurement of the Micro-Hydro system

3.3 Characteristic Voltage Generation:

An increase in the generated voltage with an increase in head and flow rate:

1. A minimum head of 2.10 ft gave 2.7 V of output voltage.

2. A maximum head of 14.0 ft gives an output voltage of 11.8 V.

This means that there exists a proportional relationship between the RPM and the output of the turbine.

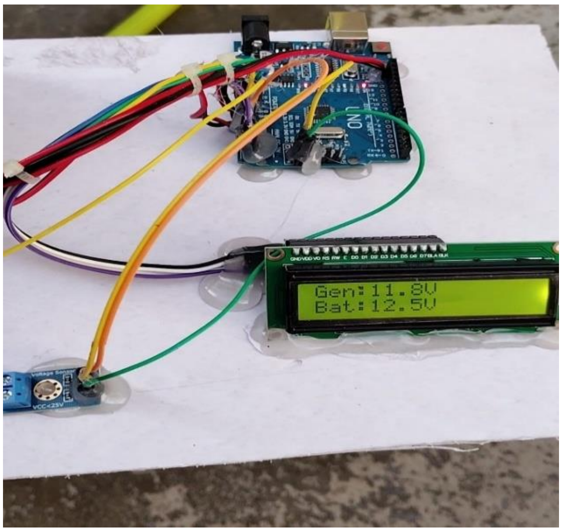


Fig - 4: Real-time monitoring of Generator and Battery voltage using Arduino Uno

3.4 Power analysis for Hydraulic and Electrical Output

The hydraulic power and the electrical output power were determined using the common equations in micro-hydro power. From the analysis, the following is noted:

1. Hydraulic power increased from 0.82W to 19.26W.

2. Electrical power output was increased from 0.80W to 18.94W

The closeness of hydraulic and electrical power indicates:

1.High level of efficiency of the system

2.Little or no loss of energy between the turbine and generator.

3.5 Efficiency of the system:

From the results above:

$$\eta = \frac{P_o}{P_{hydraulic}} \approx 98\%......(7)$$

The high efficiency indicates that:

1.Turbine is suited for low head hydro energy

2.Mechanical and electrical energy loss is minimal in the system.

3.6 Practical Applications: According to the findings of the experiment:

1.The device is capable of generating energy for low power consuming devices like LEDs, sensors, etc.

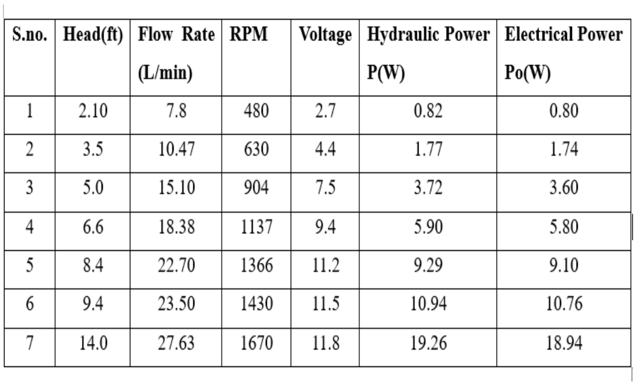
2.At high intensity rainfall (higher water flow rate), the energy generation from the device is possible and constant.

3.The addition of energy storage devices (such as batteries/supercapacitors) could increase usability even during dry days.

3.7 Table and Graphs:

3.7.1Experimental Performance Analysis of Downpipe Micro-Hydro System Under Varying Head Conditions:

The performance of a downpipe micro-hydro system is highly dependent on hydraulic parameters such as available head and flow rate. In rooftop rainwater harvesting systems, the vertical height of the building (head) plays a crucial role in determining the potential energy available for conversion into electrical energy. As rainwater flows through the downpipe, this potential energy is converted into kinetic energy, which drives the micro-turbine and subsequently generates electricity through a coupled generator.



S.no.	Head(ft)	Flow Rate (L/min)	RPM	Voltage	Hydraulic Power P(W)	Electrical Power Po(W)
1	2.10	7.8	480	2.7	0.82	0.80
2	3.5	10.47	630	4.4	1.77	1.74
3	5.0	15.10	904	7.5	3.72	3.60
4	6.6	18.38	1137	9.4	5.90	5.80
5	8.4	22.70	1366	11.2	9.29	9.10
6	9.4	23.50	1430	11.5	10.94	10.76
7	14.0	27.63	1670	11.8	19.26	18.94

Fig -5: Performance parameter of downpipe micro-hydro system

To systematically evaluate the system behaviour, experiments were conducted under varying head conditions ranging from low to high values. Key performance indicators including flow rate, turbine rotational speed (RPM), output voltage, hydraulic power, and electrical power were measured and recorded. This analysis provides a clear understanding of how variations in head influence the overall efficiency and output of the system. The results presented in Table 1 highlight the direct relationship between hydraulic input conditions and electrical output performance, thereby validating the effectiveness of the proposed energy harvesting system.

3.7.2 Graphical Analysis

To better understand the performance characteristics of the proposed downpipe micro-hydro system, graphical analysis is carried out using the experimental data presented in Table 1. Graphs provide a clear visual representation of the relationship between key hydraulic input parameters (such as head and flow rate) and output performance parameters (such as RPM, voltage, and power).

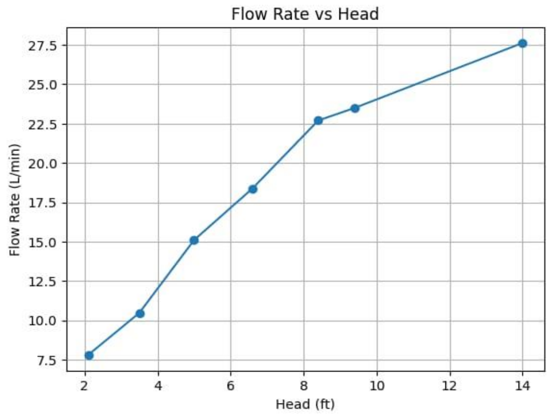


Chart -1: Flow Rate vs Head Relationship

Flow rate is directly proportional to head. Higher head results in a higher flow rate and increases the potential energy conversion efficiency.

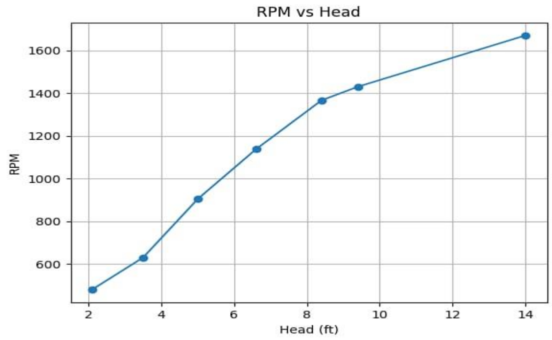


Chart -2: RPM vs Head Relationship

The RPM of the turbine is directly proportional to the head. This means that higher pressure will result in an increased rotation speed.

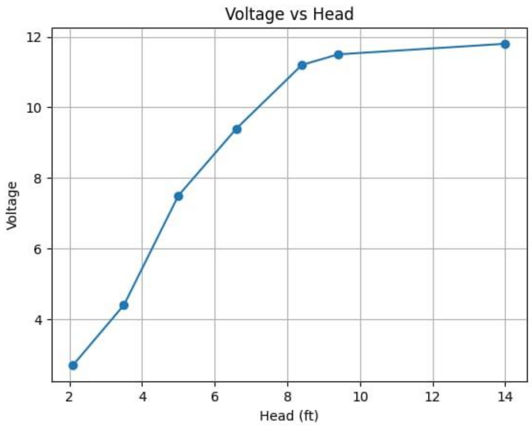


Chart -3 Voltage vs Head Relationship

Voltage is directly proportional to the increase in head. An increase in head means that the generator will produce more voltage until it reaches saturation.

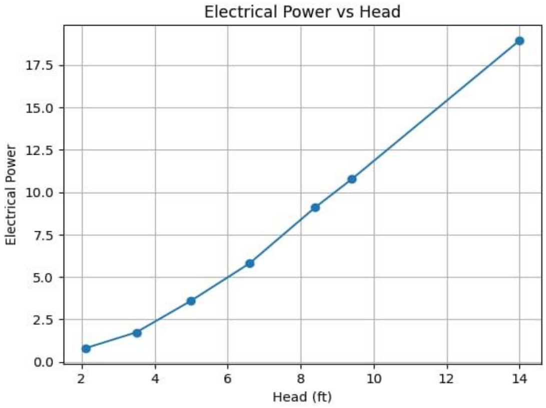


Chart -4: Output Power vs Head Relationship

There is a high level of increase in power when the head increases. This indicates that there is higher energy conversion due to water pressure.

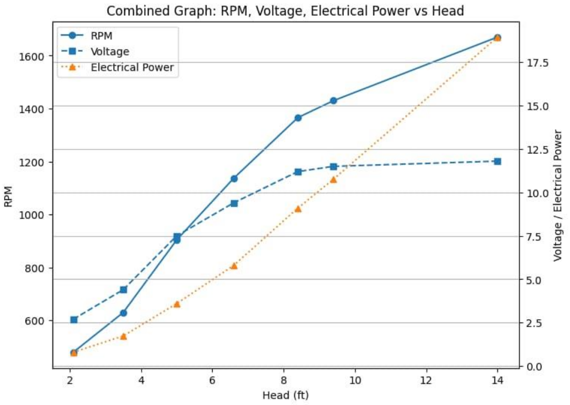


Chart -5: Combined Performance Analysis vs Head

RPM, voltage, and power are all directly proportional to the head. Increased head increases the rotational speed, generator output, and electrical performance efficiency.

4. CONCLUSION

As can be seen, the suggested downpipe micro-hydro energy production model is proven feasible for the generation of electric energy from rooftop water flow at low heads. In particular, the obtained experimental data prove the existence of the positive correlation between increased head, flow rate, turbine speed, generated voltage, and produced power. This allows us to affirm the validity of the theoretical relations applied throughout the analysis. The highest power output of 18.94 W was observed with about 98% efficiency. Accordingly, it is worth noting that while the power generated may be intermittent and weather-dependent, the use of energy storage systems ensures its reliable utilization. This type of power is particularly useful in powering equipment of low consumption, for instance, LED lights and sensors. Therefore, the proposed system could be considered an effective and eco-friendly way of energy production for modern cities.

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