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A CASE STUDY OF: IoT-BASED SMART SUSTAINABLE HYDROPOWER DEVELOPMENT FOR A RURAL DISTRICT CALLED LAKSHMIPUR LOCATED SOUTHERN PART OF BANGLADESH

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ABSTRACT: The framework of this research paper will highlight how electrification is possible in rural areas of Bangladesh through the implementation of IoT-based hydropower. The main goal of this research is to demonstrate how electrification is possible in Lakshmipur, a rural area located in the southern part of Bangladesh, through modeling, simulation, optimization, and operation services using IoT implementation. This IoT-enabled hydropower system will integrate solar power systems, wind turbines, micro-hydro systems, and diesel generators. Each system will have IoT-based sensors that will be able to send real-time data to the control system via SCADA, so that the amount of electricity generation required for the next day or the next month can be determined in advance. The cost of this proposed model will be analyzed using current market prices and the results show that IoT is a viable hydropower system for rural sustainable development compared to conventional hydropower systems.

KEYWORD: *IoT, Hydropower, Solar Panel, Wind turbine, Sustainable Development, Energy management system*

1. INTRODUCTION

Every country's government believes that sustainable energy production is essential for socio-economic development. The Bangladesh government has been trying to increase energy production capacity every year for sustainable economic development, and this is being done not only in urban areas but also at the rural level [1]. Since Bangladesh is a densely populated country, there is a huge demand for electricity in the country, from garment manufacturing factories to the private sector, and the Bangladesh government has always been trying to meet this huge electricity demand, which has consistently included about 71% of the total population of Bangladesh [2,3]. The distribution of electricity is uneven. 86.16 percent of the total distribution is distributed to metropolitan areas and 13.14 percent to rural areas. As a result, many people in rural Bangladesh do not receive adequate electricity during the day [4].

The demand for electricity is a very important factor in the economic development of the people of southern Bangladesh, especially Lakshmipur, and the biggest problem with electricity is its availability. Several rivers flow through Lakshmipur, a southern region of Bangladesh, one of which is the Meghna River. It is possible to generate electricity at low cost by easily installing turbines at the mouth of this river [5]. Moreover, it is possible to generate electricity by installing wind turbines on the banks of the river and diesel-powered generators can be used. The current power system is not based on modern IoT. If the power generation system here can be fully brought under IoT implementation and power can be supplied through effective optimization, then the power shortage in this region can be easily eliminated [6,9]. If the region's energy management system needs to be improved, the plan can be implemented by implementing IoT with SCADA and adding real-time IoT based sensors to each dependent power generation sector such as solar panels, winter bins and diesel generators.

Since this region is located in the south of Bangladesh and is close to the Bay of Bengal, the wind speed in this region is always high. In this case, if the wind turbines can be properly replaced under IoT, a mega solar panel installation center with sufficient lighting can be created, then it is possible to supply a very good amount of electricity from here [7,5]. Nowadays, IoT is being implemented almost everywhere and hydropower is no exception. In this field too, there are many implementations of IoT. For example, in this paper, we will present how it will be possible to send real-time data to SCADA by installing 'ESP' in various hydropower sectors [8]. The proposed hybrid system includes micro hydroelectric power plants, wind turbines and photovoltaic panels (PV). The diesel generator, as its capacity, is an important component of a backup system. The hybrid energy system's mathematical model was analyzed and carried out in this paper [9,10].

2. SOURCE OF ENERGY

Our proposed system will use solar power, wind power, diesel power, and all this equipment will be integrated with IoT, which will make it possible to send accurate information to the energy management system (EMS).

2.1. Solar Energy Potential

Of all the renewable energy sources currently available or offered to consumers, solar energy is the best and most sustainable source. Lakshmipur district is located in the southern part of Bangladesh and during summer the temperature of this district ranges from 34°C to 35°C and sometimes from 37°C to 40°C and there is ample light and air because it is located near the Meghna, the largest river in Bangladesh. Figure-1 below shows the daily solar radiation (kwh/m2/day) in Lakshmipur.

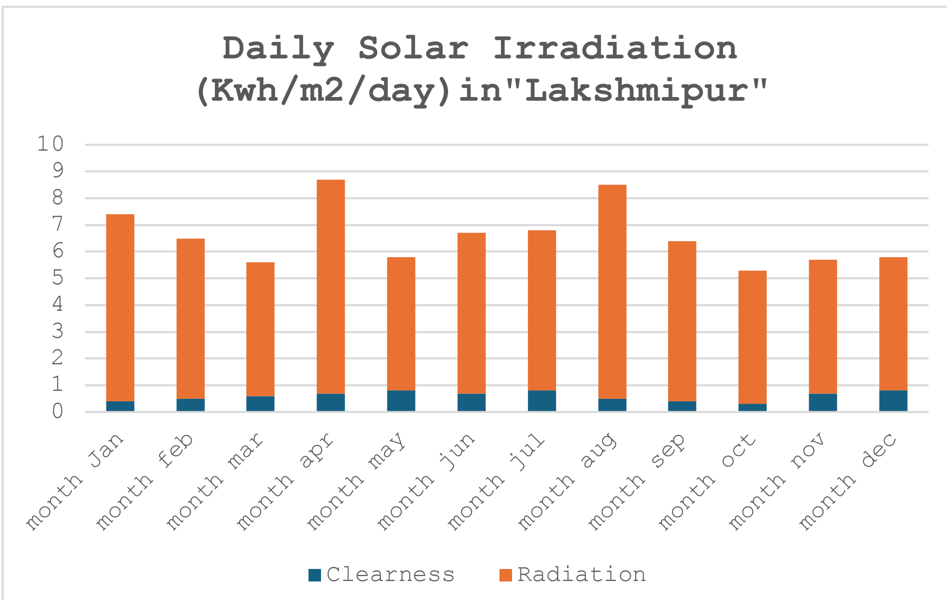

Fig.1. Daily Solar Irradiation in Lakshmipur

2.2. Wind Energy Potential

A very effective and acceptable renewable energy source, Lakshmipur experiences a good level of wind speed from January to December, with an average annual wind speed of 13 Km/h. In the country, the average speed is 10 km/h and the maximum increase is observed in June up to 16 km/h and it is expected that the highest level of power will be available from wind turbines during this summer period of June-July [10]. The Figure-2 showed the wind speed in Lakshmipur from January to December.

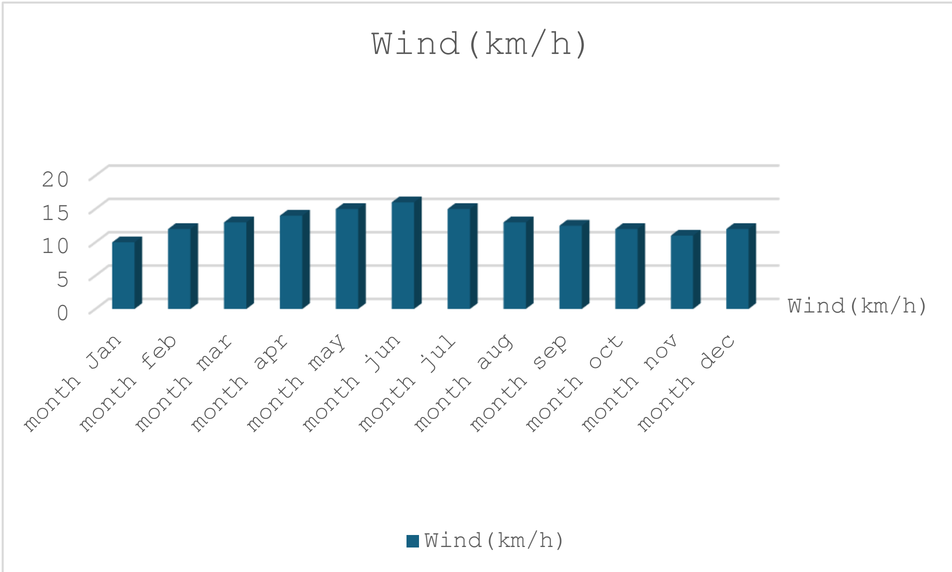

Fig.2. Wind Speed in Lakshmipur (jan-Dec)

2.3. Hydro Energy Potential

Fig. 3 shows the monthly water flow data critical to micro hydro power generation in the southern part of Bangladesh. The water flow, measured in cubic meters per second (m3/s), steadily rose from January at 500 m^3.s to 800 m^3.s in August and slowly declined toward December [11]. The data reveal seasonal fluctuations in water availability, which significantly impact the operational efficiency of micro hydropower plants.

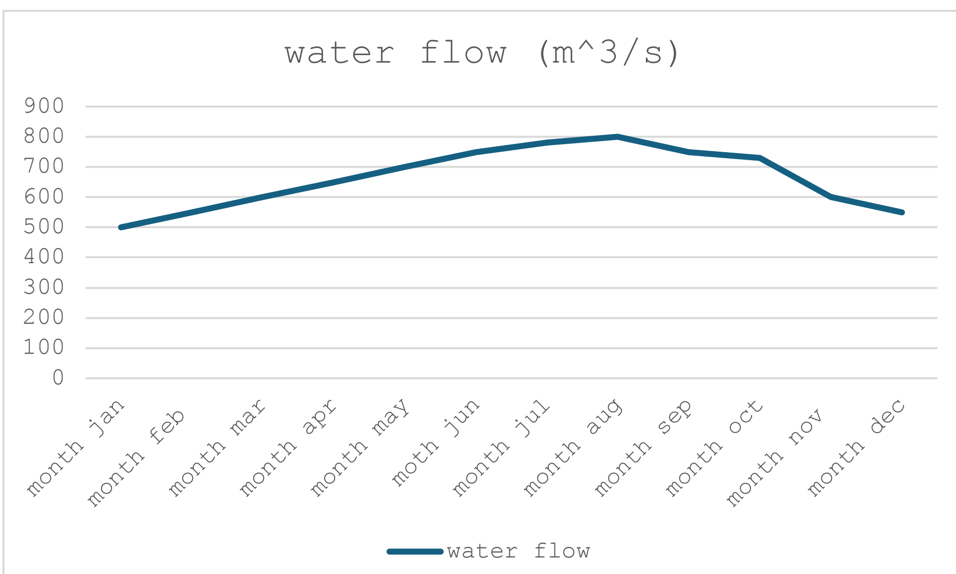

Fig.3. Water flow southern part of Bangladesh

Understanding these patterns allows for better energy generation planning, optimal resource allocation, and long-term sustainability in the region. This underscores the vital role of hydroelectricity in Bangladesh's renewable energy landscape. However, challenges in enhancing micro hydropower systems persist, including technical limitations, logistical hurdles, and high costs. Key technical constraints involve site suitability and the difficulties of transporting heavy machinery to remote locations [12]. Additionally, bureaucratic obstacles arise from the complex permitting processes required before project implementation.

2.4. Others Elements

i. Converter: A converter will be used here and this converter will work as an inverter and rectifier and the lifetime of this converter will be 15 years and its efficiency will be 90%. Different types of converters are used in which case a 300 kW converter will be used here according to the variation and it will depend on the direction of water flow.
ii. Battery: The Surrett 6CS25P Battery is employed to maintain stable power distribution in solar and wind energy systems, preventing fluctuations in the battery bank's output direction. The battery stack consists of multiple units, ranging from 0 to 300 in capacity. Each unit is a 4V battery with an energy storage capacity of 7.6 kWh.

3. METHODOLOGY

The methodology section will explain how IoT integration works within this system, its working principles, mathematical calculations, and cost analysis of the system.

3.1 Working Principle

The proposed IoT based Smart hybrid power system, illustrated in Fig. 4, integrates multiple renewable energy sources such as solar PV, wind, diesel, and hydropower to ensure a reliable and sustainable energy supply for rural development.
This diversified approach enhances system resilience and meets the energy demands of rural communities efficiently. Since it is an IoT-based smart power system, the energy or power generated from generation systems such as PV arrays, wind turbines, and diesel-powered generators will go to the Energy Management System (EMS). This energy management system will be mainly operated through the IoT Based Cloud System. After receiving the data, the cloud system will analyze the data received from each generation system and decide in advance how much generation is needed per day. This IoT based system is capable of performing weekly data analysis, as well as monthly and annual power generation calculations, allowing the operator to easily understand which time of day produces the most power and store energy in advance to supply it during peak times of the day [13].
This system integrates renewable energy sources with a backup diesel generator to ensure reliable power supply during periods of low renewable energy generation or high demand caused by supply fluctuations. An IoT-based cloud control system intelligently monitors and manages power generation in real-time, optimizing energy distribution based on demand and available resources. It also minimizes environmental degradation due to carbon emissions, and the system can help reduce the use of fossil fuels. The proposed Hybrid power system is also scalable and flexible, making it a suitable option for rural residents because of its ability to diversify their lifetime energy needs. The resource capacity is considered solidarity. Sub-frameworks are considered to continue to flow in small lakes. Available power sometimes depends on various sources [14,12].

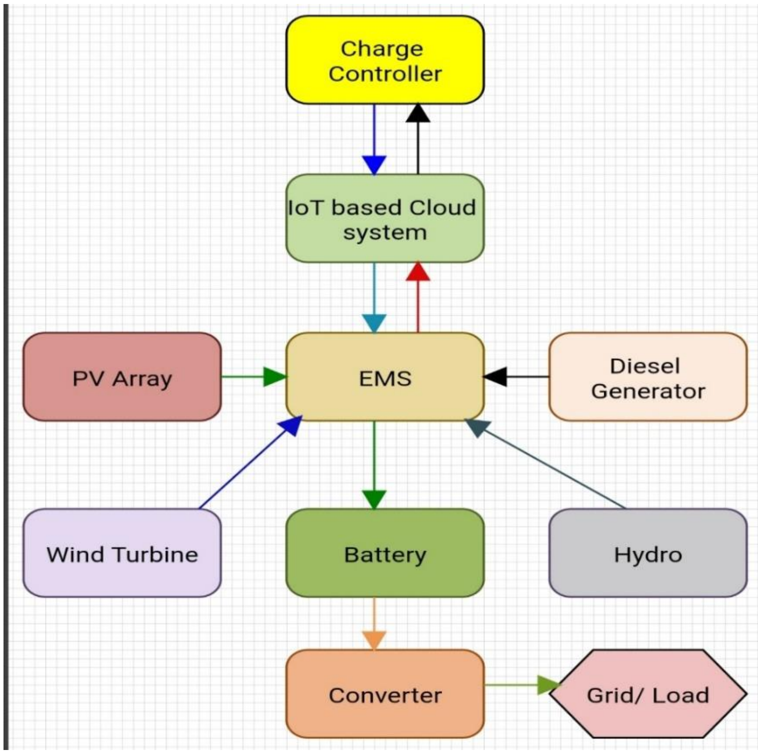

Fig.4. System Flow chart

3.2. MATHEMATICAL MODEL

In this proposed system, a complete IoT based hydro power model has been mentioned in the mathematical model section through a number of different mathematical equations.

i. Hydropower:

$E\_hydro = \rho \times g \times Q \times H \times \eta\_h$ ……………………(equation -1)

ρ = Water density (kg/m³)

g = Gravity (9.81 m/s²)

Q = Flow rate (m³/s)

H = Effective head (m)

η_h = Efficiency of the hydro turbine

ii. Solar Power:

$E\_solar = A\_s \times G \times \eta\_s \times t$ ……………………………..(equation- 2)

A_s = Area of the solar panel (m²)

G = Solar irradiance (kW/m²)

η_s = Efficiency of the solar panel t = Time (h)

iii. Wind Power:

$E\_wind = 0.5 \times \rho\_air \times A\_w \times v^3 \times \eta\_w \times t$ ………………… (equation – 3)

ρ_air = Air density (kg/m³)

A_w = Swept area of wind turbine blades (m²)

v = Wind speed (m/s)

η_w = Efficiency of wind turbine

t = Time (h)

iv. Energy Storage (optional):

$E\_storage = \eta\_storage \times E\_stored$ ………………………. (equation-4)

$\eta\_storage$ = Storage efficiency (battery or pumped hydro)

E_stored = Energy stored during off-peak or excess generation

V. Final Mathematical Equation

From the above mentioned Equation-1, Equation-2, Equation-3 and Equation-4, we can collectively form a complete mathematical equation which is written below.

E_total = E_hydro + E_solar + E_wind + E_storage - E_losses

3.3. COST ANALYSIS

From (table-1) and (Figure – 5) below, we can see that the total cost of this proposed system is mentioned. In the mentioned total cost, we can see that the initial cost is slightly higher than the traditional hydropower system, while the later replacement cost is significantly lower than the traditional hydro-power system. Hydropower is a reliable renewable energy source, but traditional systems face inefficiencies in monitoring, maintenance, and energy optimization. IoT-based smart hydropower introduces automation, real-time data analytics, and predictive maintenance, improving efficiency but with different cost implications. IoT-based systems are 10-30% more expensive due to sensors, connectivity, and AI software [15]. O&M Savings, IoT reduces operational costs by 20-40% through predictive maintenance and remote monitoring. Efficiency Gains, Smart systems boost energy output by 5-15%, increasing revenue. IoT hydropower has a shorter payback (6-10 years) vs. traditional (10-15 years). Long-Term Value, Higher upfront IoT costs are offset by lower O&M and better efficiency, making it more cost-effective over time [16,6].

Tab. 1. Initial vs Replacement Cost

Equipment’s	Initial cost ($)	Replacement cost ($)	O & M cost per year
PV	5700	5000	12
Diesel Generator	19000	18500	1
Wind turbine	13000	10000	125
Converter	200	120	2
Battery – 5V, 7.6kwh	600	450	20

Figure 5 shows the initial and replacement costs.

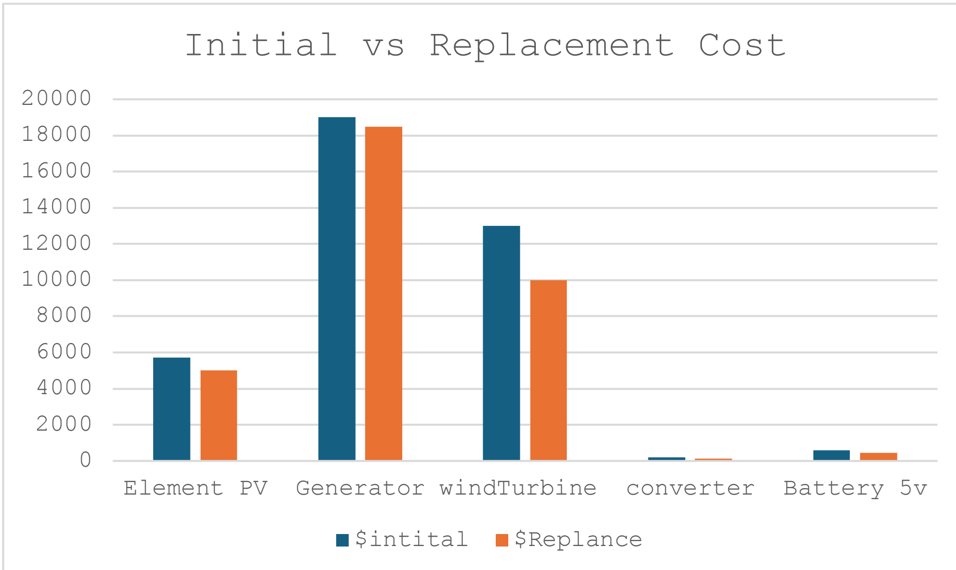

Fig. 5. Initial Vs Replacement Cost

4. RESULT

4.1. Hybrid System Operation Strategy Corporation With IoT

A hybrid system that uses renewable energy generators can be characterized by two basic configurations: a series-based and a parallel hybrid framework. Both frameworks have distinct attributes. The proposed scheme implements a parallel hybrid structure, where wind turbines serve as the primary energy supplier. Variations in wind power, influenced by domestic demand, act as the main external factors affecting the system over time [17,4]. The base load is secured by a small hydropower station, enhanced with IoT-based monitoring and control systems for real-time performance optimization, predictive maintenance, and efficient energy management. This integration ensures higher reliability and adaptability to demand fluctuations [18,11].
Additionally, the PV framework, coupled with a battery bank, shares part of the load, while diesel generators and battery banks serve as backup power sources. The case study is based on virtual data, which can be analyzed using HOMER software to evaluate system performance under different operational scenarios.

4.2 Comparison Between Traditional vs. IoT-Based Hydropower in Southern Part of Bangladesh

Tab.2. Traditional vs IoT-Based Hydro-power System

Aspect	Traditional Hydropower (Kaptai Dam)	IoT-Based Hydropower (Potential Smart Systems).
Monitoring & Control	Manual checks, delayed response to faults.	Real-time sensors (water flow, turbine health, grid load)
Energy Efficiency	~70-75% (fixed operations).	Real-time sensors (water flow, turbine health, grid load).

Maintenance Cost	High(reactive repairs, downtime).	Low (predictive alerts, remote diagnostics)
Environmental Impact	Disrupts fish migration, sedimentation issues.	Smart flow control reduces ecological harm.
Grid Stability	Prone to fluctuations (manual adjustments.	Stable (automated load balancing with solar/wind).
Scalability	Limited (dependent on dam capacity).	Flexible (micro-hydro + IoT integration)
Data Usage	Minimal (historical logs only)	Big Data analytics for weather & demand forecasts
Cost of Deployment	Lower upfront, higher operational costs.	Higher initial IoT setup, but 20-30% savings long-term
Suitability for Southern BD	Works but inefficient in monsoon/dry seasons.	Adapts to seasonal changes (e.g., monsoon floods)

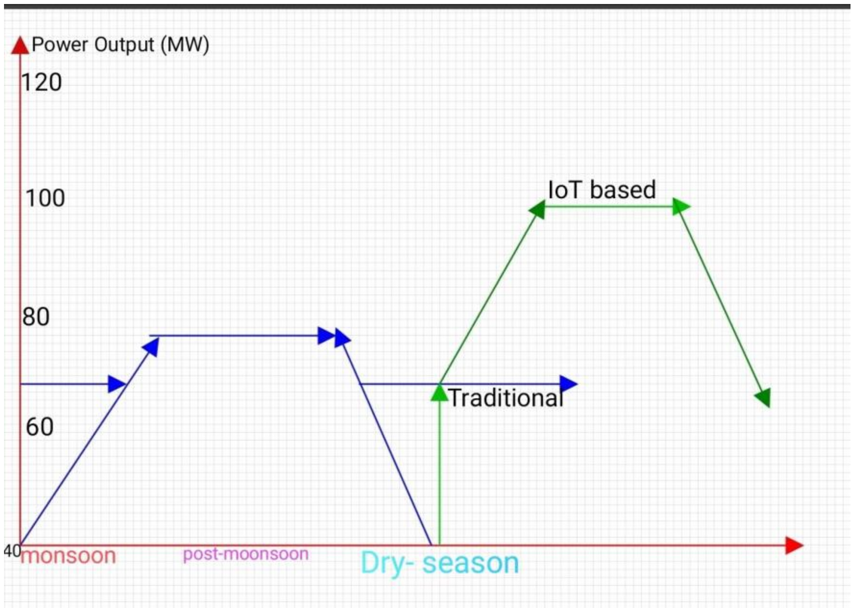

Fig.6. Traditional vs IoT based hydro-power system Power Output(MW)

From the above table we can see that the long-term cost of IoT-based hydropower system is 20 to 30% less than traditional hydropower system and when we consider its efficiency, we can see that traditional hydropower system works better in dry season. However, IoT-based hydropower system works better in other two seasons.

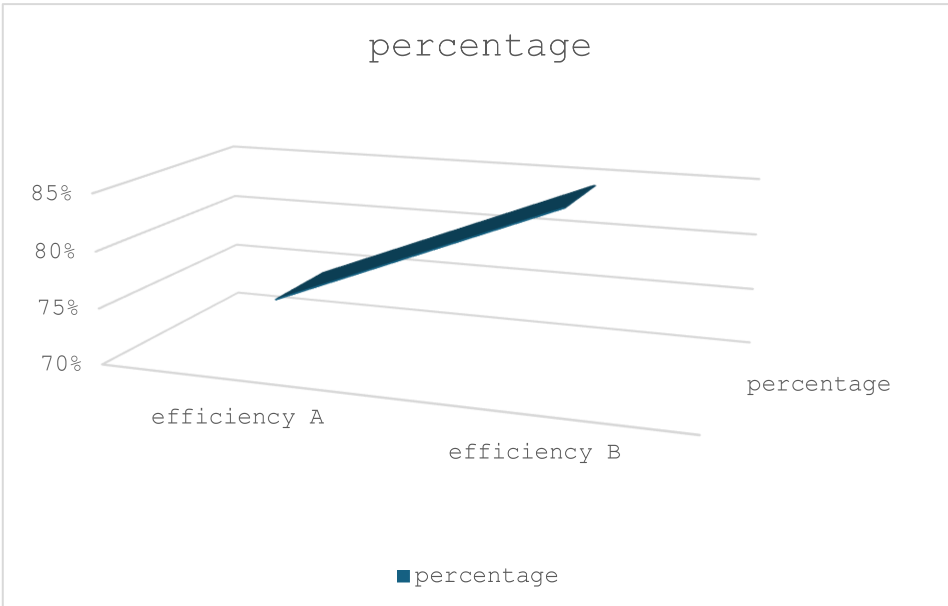

Fig.7. Efficiency Traditional Vs IoT-Based hydro-power

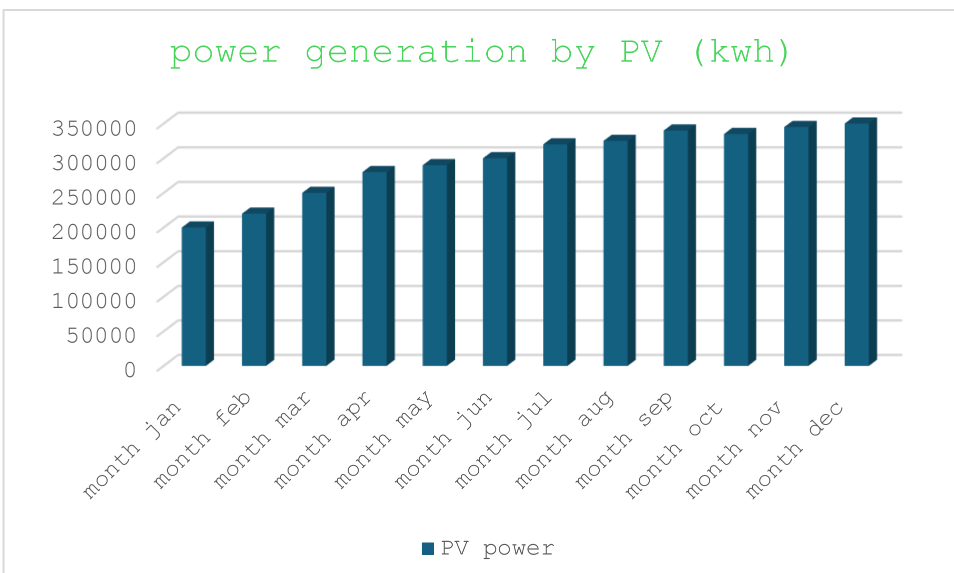

Fig.8. Yearly Power Generation by PV

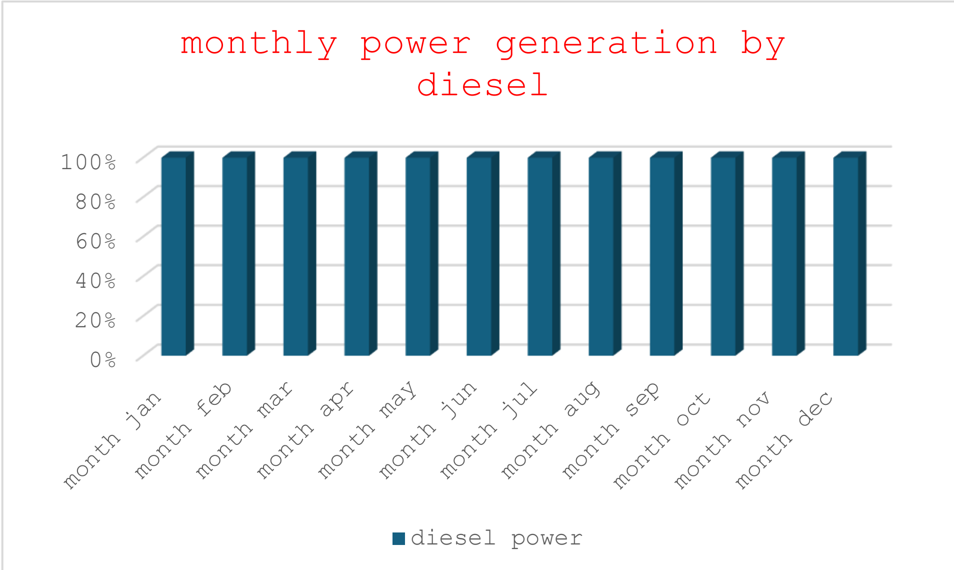

Fig.9. Yearly Power Generation by Diesel

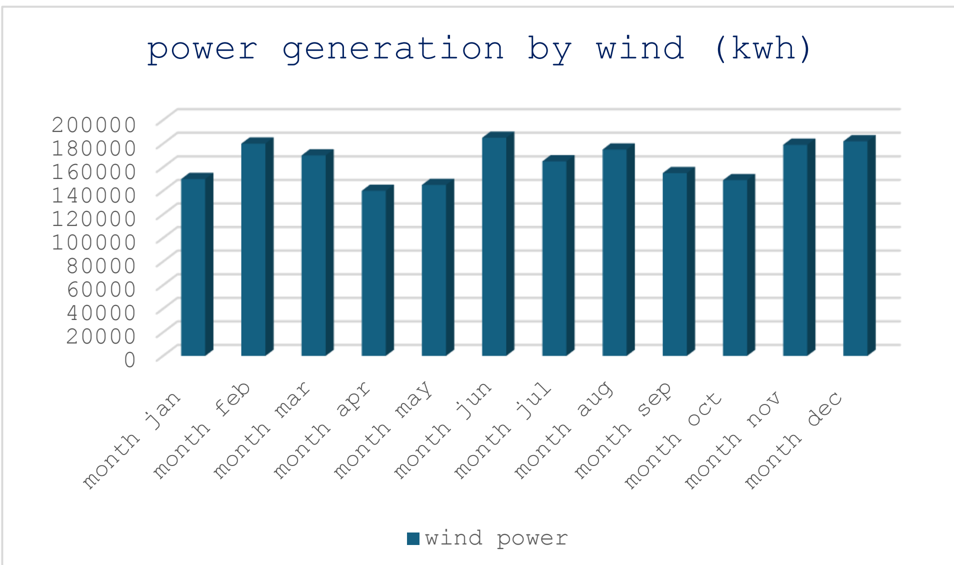

Fig.10. Yearly Power Generation by Wind Turbine

The above-mentioned features 8-10 show that different types of electricity generation occur each year, such as diesel electricity, PV electricity, and electricity from wind turbines. We can say that by combining all the power generation through this proposed model, it will be possible to meet the electricity needs of other districts in the southern part of Bangladesh, including Lakshmipur. The proposed model is IoT-based in terms of efficiency as shown in the above fig-7, which shows that its efficiency is 10 to 20% higher than the traditional hydro power system, making it a very effective link for possible implementation in Lakshmipur district [19,15].

5. DISCUSSION

Through the combination of IoT implementation and hydropower optimization, it is possible to meet the electricity demand for sustainable economic development in Lakshmipur or the southern region of Bangladesh, through the model proposed above**.** Since Lakshmipur can be called the economic district of Bangladesh and this district has more business, commerce, industry and factories than other districts of Bangladesh and the population in this district is also higher than other districts, the demand for electricity in this district is high. Since the district needs a lot of electricity, the hydroelectric system will play a very important role in economic development through the growth of IoT. Because this IoT based hydroelectric system is cost-effective in the long run and its efficiency is 15 to 20% higher than the traditional system [20].

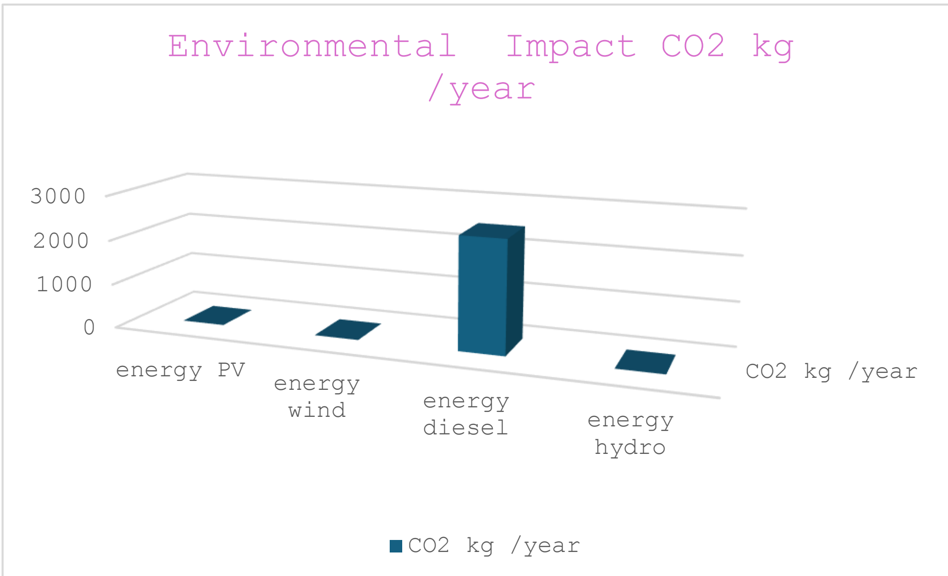

Fig.11. CO2 Emission kg/per year

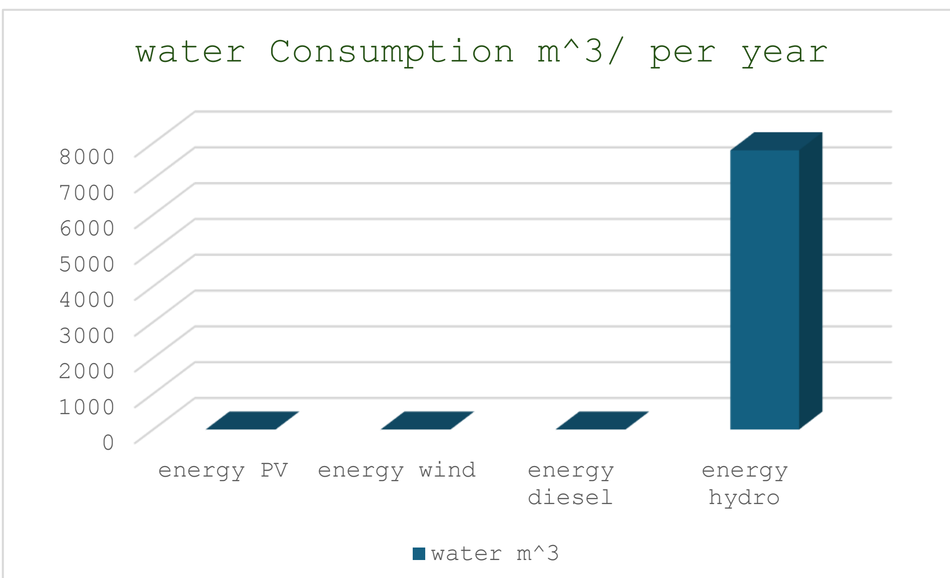

Fig.12. Water Consumption m^3/per Year

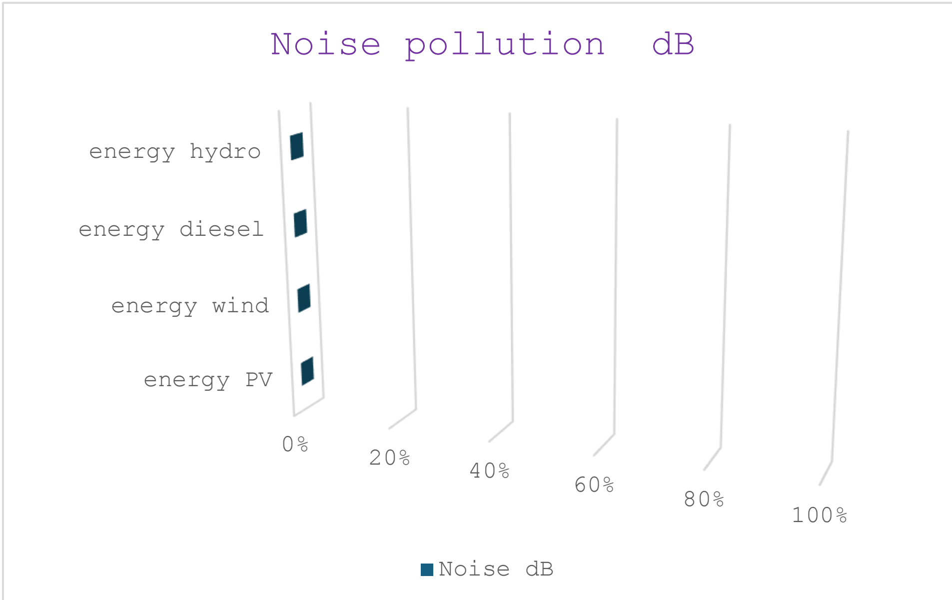

Fig.13. Noise Pollution dB

Since this is an IoT implementation of hydroelectricity, it uses renewable energy generation which will play a very important role in environmental issues. As a result, carbon dioxide emissions will be reduced to a great extent, which will be a boon for the people of this region as air pollution is increasing day by day in this part of the country. The above figure 11-13 highlights the environmental impact of this proposed IoT based hydropower system in this region. From the above figures, we can see that although there is some carbon-oxide emission through diesel-powered generators, the air pollution and noise pollution are almost zero, so we can say that this is a very effective system for sustainable rural development.

6. CONCLUSION

In conclusion, IoT-enabled smart hydropower presents a viable pathway for sustainable energy development in rural Bangladesh, fostering economic growth, environmental conservation, and improved quality of life for the residents of Lakshmipur. Future research should focus on scalability, cost optimization, and long-term impact assessment to replicate this model in similar regions. For a region like Lakshmipur, where energy scarcity and unreliable power supply hinder socio-economic progress, this smart hydropower approach offers a sustainable and scalable solution. The IoT framework ensures optimal resource utilization, improves grid stability, and empowers local communities through clean energy access. Additionally, the project aligns with Bangladesh's renewable energy goals and global sustainability targets, contributing to climate resilience and rural development.

However, successful implementation requires addressing challenges such as initial investment costs, technical expertise, and infrastructure readiness. Public-private partnerships, government incentives, and community engagement will be crucial in overcoming these barriers. The case study of IoT-based smart sustainable hydropower development in Lakshmipur, Bangladesh, demonstrates the transformative potential of integrating modern technology with renewable energy solutions in rural areas. Finally, it can be said that IoT based systems in the combined process of energy sources such as solar wind turbines and hydroelectricity will play a very effective role in the sustainable socio-economic development of Lakshmipur in the southern region of Bangladesh.

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