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Research Article

Energy Generation from Water Systems: A Technical and Cost-Benefit Analysis

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Abstract

The production of energy from the flow of water in drinking water supply pipes is an emerging field globally, and particularly novel in Kosovo. This method involves integrating water turbines with generators directly into water pipes, utilizing the water flow to rotate blades and drive the rotor, thereby producing electricity. Such systems not only generate renewable energy but also reduce excess pressure within the pipeline network, providing a dual benefit. Although similar technologies exist worldwide, their practical application in potable water systems remains limited, with experts yet to fully embrace their potential for reliable power generation. This paper explores the feasibility of implementing such a system in the Regional Water Company "PRISHTINA," with the aim of using the generated electricity to power monitoring equipment in the water supply network. The proposed approach has the potential to enhance operational efficiency, generate additional revenue, and mitigate risks associated with high pipeline pressure. This paper provides novel insights into the technical, financial, and environmental benefits of harnessing energy from existing water distribution systems in underdeveloped regions.

Keywords: Water pipes; Flows through turbines, Electrical energy; Sustainable energy; Micro-hydro turbines; Environmental impact; Water systems.

INTRODUCTION

The recovery of energy from potable water distribution systems by the integration of small-scale hydro turbines into pipelines has been the subject of numerous studies and pilot projects conducted globally in recent years. Installing inline turbines or micro-hydropower units at high-pressure locations has been shown to generate renewable electricity while also lowering excess pressure in the network, according to research conducted in nations like the US, UK, Italy, and Japan [1-5]. These systems have been effectively used to run off-grid facilities, support local grid supply, and power monitoring equipment. But even with these developments, the technology is still not widely used in underdeveloped nations, and many areas have not yet fully tapped into its potential.

Energy represents the second-largest operating cost for the water sector in Kosovo. During the provision of water services, electricity is required for raw water transportation, treatment processes, storage, and distribution. Energy consumption in water utilities depends on several factors, including the source of water, treatment type, facility age, storage capacity, topography, and system size, which encompasses both production volume and service area.

Despite these high costs, many water companies in Kosovo do not fully recognize the importance of reducing energy consumption as a means of optimizing overall system performance, improving operational efficiency, and ensuring a secure water supply. One key strategy for lowering electricity expenses is the integration of renewable energy technologies into utility operations [6-10].

Kosovo's energy sector faces significant challenges due to its developing-country status, unstable economic and political conditions, and limited investment in infrastructure. The country relies heavily on outdated power plant technology, has not built new major power facilities in decades, and remains dependent on energy imports during peak demand. Investment in renewable energy has also been insufficient.

Moreover, the management and technical staff of regional water companies often lack full awareness of available strategies for managing energy budgets or for identifying, prioritizing, and funding energy efficiency projects. By implementing targeted efficiency measures and renewable energy solutions, the water utility sector can establish effective energy management programs and achieve substantial cost savings.

This paper aims to assist water companies in Kosovo and comparable regions by exploring opportunities for electricity generation from existing assets. Specifically, it examines the feasibility of harvesting energy from potable water flowing through pipelines via integrated turbine systems. This research work provides novel insights into the technical, financial, and environmental benefits of harnessing energy from existing water distribution systems in underdeveloped regions.

RESEARCH APPROACH

Kosovo has seven Regional Water Companies that supply potable water, with the Regional Water Company (RWC) "PRISHTINA" being the largest in the country [11]. Current total water demand in its service area is approximately 49 million m^3 per year and is projected to increase to 66 million m^3 by 2040. RWC "PRISHTINA" currently serves about 554,000 inhabitants (approximately 132,000 customer connections). Supported by the German Development Bank (KfW), the company plans to expand its coverage to serve an estimated 938,000 inhabitants by 2040. The schematic representation of the study area is shown in Figure 1.

The "ALBANIK" Water Treatment Plant, the largest potable water production facility in Kosovo, plays a central role in the national water supply sector. Located at an elevation of 705 m above sea level, the plant delivers treated drinking water through a DN 900 steel pipeline with a length of 24,584 m. The pipeline then splits into two DN 600 steel branches that supply the “Arbëria” and “Kodra I” reservoirs. These two reservoirs provide water to approximately 60 % of the population of Kosovo’s capital, Prishtina.

From the “ALBANIK” plant, water flows by gravity through the DN 900 pipeline. At a distance of 15,557 m from the plant, the pressure in the pipeline reaches 14 bar at an elevation of 541 m above sea level. The available gross head is calculated as equation (1):

$$Hgeo = (705 \text{ m a.s.l} - 541 \text{ m a.s.l}) - \sum h_{\xi} = 164m - 17m\ losses = 147m. \quad (1)$$

Where:

$\sum h_{\xi}$ – Energy losses through pipes are calculated by equation (2):

$$\sum h_{\xi} = \sum h_{\xi loc} + \sum h_{\xi fric} \approx 17\ m' \quad (2)$$

Here, $\sum h_{\xi loc}$ represents local head losses, and $\sum h_{\xi fric}$ represents distributed (friction) head losses along the pipeline.

This section of the DN 900 pipeline operates under a constant pressure of more than 13 bar and remains in service nearly year-round. Figure 1 illustrates the pipeline’s layout in the field. At location “Point A”, the installation of a turbine is proposed to enable electricity generation.

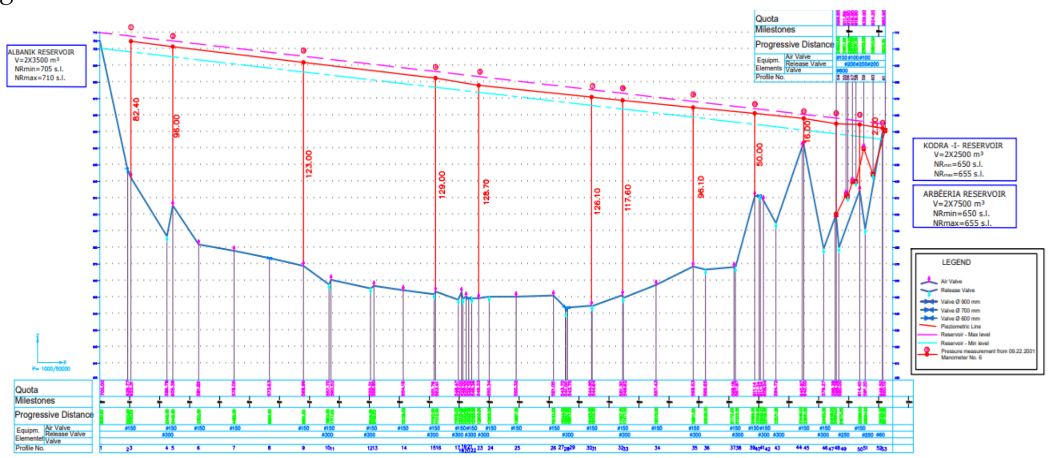

Figure 1. System diagram of the pipelines layout

AIM OF THE STUDY

Determining the hydraulic energy generated from day to day in the drinking water supply structures is proving to be more attractive and necessary [12, 13]. Therefore, the purpose of this study is to evaluate the electricity produced from the predetermined amount of water released in accordance with the drinking water requirements for the city of Pristina, as shown in figure 2, this will be achieved through the following steps [14]:

- Electricity generation from the turbine installed in the drinking water pipe (hydropower in a pipe),
- Increase of revenues for the water company "PRISHTINA",
- Protection of that part of the pipe from over pressure,

- Preservation of the environment and surroundings in that of the pipe,
- As well as the contribution in the field of employment and the reduction of unemployment in Kosovo.

Figure 2. Scheme of hydropower in a pipe

Since ancient times, ancient Rome used water wheels to grind grain and pump water. Water wheels are gradually replaced by hydraulic turbines (Francis, Pelton and Kaplan) that had much higher efficiency. Thus, in 1882, the first hydroelectric power plant was built in Appleton, Wisconsin, USA, using water turbines to generate electricity for lighting in the vicinity of this hydroelectric power plant.

The first hydroelectric power plants were local and supplied cities or factories near rivers. The production of energy from Hydro Turbines is a traditional method of producing renewable energy (Hydro Energy). Energy is produced by the gravity flow of water in pipes from higher to lower sea levels and there is a potential for energy production. The turbine is driven by the flow of water, meaning the hydropower of the water is transformed into mechanical energy. This mechanical energy drives the generator connected to the turbine, and here the mechanical energy is converted into electrical energy.

The drinking water production report from the "ALBANIK" factory is provided in Table 1. Based on it, the Regional Water Company "PRISHTINA" provided the water flow data used in this research work via a combination of utility records and field measurements. Installed flow meters and pressure sensors that run continuously as part of the supervisory control and data acquisition (SCADA) system were used to monitor flow rates and pressure values at key nodes of the DN 900 pipeline. In order to account for seasonal fluctuations in demand, measurements were taken across a representative twelve-month period during the years 2022 and 2023. Cross-referencing with previous operating records and removing outliers brought on by transient disruptions like pipeline maintenance or unusual consumption peaks allowed for the validation of the data quality. Two important factors were taken into consideration when choosing the proposed installation location (Point A, Figure 1): (i) year-round high-pressure conditions (above 13 bar) and (ii) closeness to existing utility infrastructure, which makes it easier to integrate turbines without requiring significant network reconfiguration. To ensure that the installation wouldn't jeopardize downstream service levels, EPANET 2.2 was used to perform hydraulic modelling of the distribution system. Other sites were considered but disqualified due to their greater risk of service interruption or lower possibility for energy recovery.

Table 1. Drinking water production report, "ALBANIK" factory

Date	Raw water (m^3)	The amount of water for Pristina (m^3)	The amount of water for Podujeva (m^3)	The amount of water for Villages (m^3)	Level of the Lake (s.l.)
31.01.2022	1831970	1525600	168390	137980	631.49
28.02.2022	1626050	1346900	157320	121830	632.46
31.03.2022	1816360	1509800	168390	138170	633.15
30.04.2022	1754540	1440200	171750	142590	634.55
31.05.2022	1843090	1548400	180920	113770	634.15
30.06.2022	1920190	1652500	183410	84280	633.45
31.07.2022	1964410	1673800	194250	96360	632.75
31.08.2022	1944410	1624200	181830	83470	631.92
30.09.2022	1915700	1568600	176310	90990	631.8
31.10.2022	1953300	1633600	189090	108710	631.14
30.11.2022	1923600	1612900	173420	104680	632.42
31.12.2022	2052500	1600100	186240	108170	634.97
Total 2022	**22546120**	**18736600**	**2131320**	**1331000**	
			22198920		
31.01.2023	2164800	1635700	186880	94540	634.99
28.02.2023	2008700	1611300	166800	96680	635
31.03.2023	2076700	1635500	182250	111750	365
30.04.2023	1916500	1549500	174400	115140	634.99
31.05.2023	1969100	1531100	173460	112600	634.74
30.06.2023	1956700	1447500	175180	113550	634.95
31.07.2023	1951100	1463000	184400	97110	634.57
31.08.2023	1927100	1426300	187420	100290	633.91
30.09.2023	1844700	1501500	197150	95550	633.19
31.10.2023	1887500	1436300	172250	93710	632.44
30.11.2023	1911100	1426700	172410	102560	632.14
31.12.2023	1989100	1448400	169650	134440	633.05
Total 2023	**23603100**	**181112800**	**2142250**	**1267920**	
			184522970		

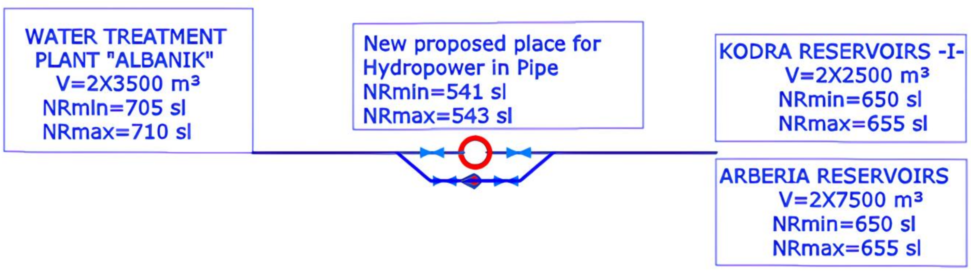

Figure 3. Schematic of the main pipeline system of "ALBANIK"

POWER ANALYSIS

The potential electric power of the water in terms of flow and head can be calculated from the following equation (3).

$$P(kW) = 9.81 \cdot Q \cdot H \cdot \eta \quad (3)$$

Where:

- P - electric power output in kilowatts (kW),
- Q - quantity of water flowing through the hydraulic turbine in (m^3/s),
- H- Net available head in (m)
- η - overall efficiency of the hydro power plant (0.85) [15, 16]

In accordance with performance standards documented for contemporary microturbine designs functioning under steady flow circumstances, the efficiency factor was fixed at η = 0.85. Under ideal operating conditions, axial and crossflow turbines of similar size can attain efficiencies in the 80–88% range, as shown by [16, 17]. The representativeness of the selected parameter is supported by similar values that have been verified in other micro-hydropower applications integrated into water distribution networks. Additionally, the discharge (flow rate) of water in a stream available for power generation varies daily and seasonally due to natural hydrological changes. The optimum discharge for power generation is determined by balancing potential energy output against the associated generation costs, ensuring the most cost-effective use of the available water resource.

In preliminary assessments, detailed head loss calculations are frequently replaced by the assumption that about 10% of the gross head is lost due to friction and related effects, as shown in Equation (4)

$$H_{net} = H_{gross} \cdot 0.9 = 164 \cdot 0.9 = 147.6\, mm \quad (4)$$

The theoretical calculations from Equations (5) to (10) were applied to assess the feasibility of implementation in our case study.

From formulas (1) we have:

$$P\ (kW)\ =\ 9.81\ \cdot\ Q\ \cdot H_{net}\ \cdot\ \eta \quad (5)$$

- H_{net} -the net head. This is the gross head physically measured at the site, less any head losses. To keep things simple head losses can be assumed to be 10%, and we have [18]:

$$H_{net} = H_{gross} \cdot\ 0.9\ = 164\ x\ 0.9\ =\ 147{,}6\, m \quad (6)$$

- η - the product of all the component efficiencies, which are normally the turbine, drive system and generator [19].

$$\eta = 0.85 \cdot 0.95 \cdot 0.93 = 0.751 \quad i.e., 75.1\% \quad (7)$$

For amount of water in main pipe $Q = 560\ l/s$ if we use total amount of water, we can produce electricity:

$$P_{max}\,(kW) = 9.81 \cdot 560 \frac{l}{s} \cdot 147 \cdot 0.751 = 606\,476\ W : 1000 = 606\ kW \tag{8}$$

For amount of water in main pipe $Q = 750\ l/s$, if we use total amount of water, we can produce electricity:

$$P_{max}\,(kW) = 9.81 \cdot 750\ l/s \cdot 147 \cdot 0.751 = 812\,245\ W : 1000 = 812\ kW \tag{9}$$

For amount of water in main pipe $Q = 850\ l/s$, if we use total amount of water, we can produce electricity:

$$P_{max}\,(kW) = 9.81 \cdot 850\ l/s \cdot 147 \cdot 0.751 = 920\,545\ W : 1000 = 920\ kW \tag{10}$$

This calculation is theoretically possible but not practical because the water would be cut off for the customers of the Regional Water Company Prishtina.

The prerequisites for selecting the Scenario are:

- The scenario must be selected in such a way that it does not jeopardize the water supply for the city of Prishtina and.
- The pressure in the pipe behind the turbine must not be reduced below 12 bar.

Since we have overpressure in the main pipe around 30 m then we have predicted some scenarios of how electricity can be produced from drinking water pipes by reducing the pressure.

We always keep in mind not to jeopardize the regular supply of the company's customers with drinking water.

Since pipe flows may vary inside the pipe, below are some electricity generation scenarios:

Table 2. Electricity production scenarios based on the amount of water in the pipe.

No.	**Flow 560 (l/s)**	**Pipe diameter (mm)**	**Geodetic height of the position (m)**	**Pressure reduction (m)**	**Electric power (kW)**
			Flow 560 (l/s)		
Scenario I	560	900	147	10	41
Scenario II	560	900	147	20	82.5
Scenario III	560	900	147	30	123.7
			Flow 750 (l/s)		
Scenario I	750	900	147	10	55
Scenario II	750	900	147	20	110
Scenario III	750	900	147	30	165
			Flow 850 (l/s)		
Scenario I	850	900	147	10	62
Scenario II	850	900	147	20	125
Scenario III	850	900	147	30	187

Based on the prerequisites, the scenario must be selected in such a way as not to endanger the water supply for the city of Prishtina, and the pressure behind the turbine can't be below 12 bars.

Based on the above paragraph and from the tables above we see that the most optimal scenario for us is scenario II with Flow 560 $(\frac{l}{s})$ flow and pressure drop of 20 m [20]. This scenario is optimal which produces energy with a capacity of 82.5 kW/h and the pipe is still shaved and the pressure in this part of the pipe is below 12 bar which is the nominal pressure of the DN 900 pipe.

At the same time, it does not cause problems in the supply of the city of Prishtina with the capacity desired by the company.

If we make a financial calculation of this annual energy production, we will have calculations as follows:

$$P = 82.5\ kW\ \cdot 24 \cdot 30 \cdot 12 = \ 712{,}800\ \text{kWh/year}$$

FINANCIAL IMPACT OF HYDROPOWER PRODUCTION

The financial impact, together with the operational and production costs of generating energy from water flow, makes this approach a practical and valuable source of energy [21].

Using either project-specific input data provided by the user or predefined values based on industry standards, the model estimates both the water flow capacity through the pipeline and the corresponding rate of energy production.

The following table presents the financial impact assessment of energy generation from water flow, highlighting the potential economic benefits derived from the generated income. By analysing different scenarios, the study identifies which variant is most suitable for energy production through the water pipeline in the 'ALBANIK' project [22].

Table 3. Total revenues according to hydropower production

No.	Flow 560 (l/s)	Pipe diameter (mm)	Geodetic height of the position (m)	Pressure reduction (m)	Electric power (kW)	Adjusted price in (€)	Total income (s)
	A	B	C	D	E	F	G = E x F
	Flow 560 (l/s) in total revenues according to energy production						
Model I	560	900	147	10	41	0.0295	1.21
Model II	560	900	147	20	82.5	0.0295	2.43
Model III	560	900	147	30	123.7	0.0295	3.65
	Flow 750 (l/s) in total revenues according to energy production						
Model I	750	900	147	10	55	0.0295	1.62
Model II	750	900	147	20	110	0.0295	3.24
Model III	750	900	147	30	165	0.0295	4.86
	Flow 850 (l/s) in total revenues according to energy production						
Model I	850	900	147	10	62	0.0295	1.82
Model II	850	900	147	20	125	0.0295	3.68
Model III	850	900	147	30	187	0.0295	5.51

The regulated tariffs for household consumers in Kosovo are the source of the electricity price of 0.0295 €/kWh [23]. The estimated electricity price of 0.0295 €/kWh is regarded as a cautious estimate, reflecting potential cost reductions and efficiency advantages from integrating renewable energy sources, since the proposed micro-hydropower system is meant to serve a narrow segment of the water distribution network.

Pipeline volume handling 560 l/s; 750 l/s and 850 l/s to produce energy in bringing income into the annual aspect [24].

Based on the table above, considering a pipeline flow rate of 560 L/s and analysing the different scenarios for electricity production efficiency, it can be observed that the production scenarios of 560 L/s, 750 L/s, and 850 L/s, with a pipe diameter of 900 mm and pressures of 10, 20, and 30 bar, demonstrate high efficiency in maintaining both stable water flow and consistent energy production. Under these conditions, energy output remains largely unaffected by variations in pressure.

The annual revenues benefited from the pipeline volume scenario of 560 L/s according to the third case are as follows:

- P – Production
- H – hour
- M – month
- P – price
- D – Day

Treatment of the first case of pipeline volume 560L/s with energy production of 123.7kW
P = 123.7 kW x 0.0295= 3.65 €/s = 3.65 x 1h = 219 €/h = 19 x 24h = 5,256 €/24h
5,256 x 30 Day = 157,680 €/1 month
157,680 x 12 months = 1,892,160 total annual income

Treatment of the first case of pipeline volume 750 l/s with energy production of 165.7kW
P = 165 kW x 0.0295= 4.86 €/s = 4.86 x 1h (60min) = 292 €/h = 292 x 24h = 7,009 €/24h
7,009 x 30 Days = 210,276 €/1 month
210,276 x 12 months = 2,523,312 total annual income

Treatment of the first case of pipeline volume 850L/s with energy production of 187kW
P = 187 kW x 0.0295= 5.51 €/s = 5.51 x 1h (60min) = 330 €/h = 330 x 24h = 7,943 €/24h
7,943 x 30 Days = 238,312 €/1 month
238,312 x 12 months = 2,859,753 total annual income

Based on our analysis, Table 4 depict the suitable scenario which is accompanied with their model.

Table 4. Suitable scenario for hydropower production

No.	Flow 560 (l/s)	Pressure reduction (m)	Electric Power (kW)	Adjusted price in (€)	Euro/s (kW)	Total income (Euro/month)	Total income (s)
	A	**B**	**C**	**D**	**E = C x D**	**F = E x 24hours x 30days**	**G = F x 12 Months**
Model III	560	30	123.7	0.0295	3.65	157,680	1,892,160

Additionally, a break-even study was carried out to evaluate the suggested micro-hydropower system's financial feasibility, see equation (11).

$$Payback\ Period\ (Years) = \frac{C_{install}}{R_{annual} - C_{O\&M}} \tag{11}$$

Where,

- $C_{install}$ - Total installation cost of the turbine and pipeline modifications (€)
- $C_{O\&M}$ - Annual operation and maintenance cost (€)

R_{annual} - Annual revenue from electricity generation (€), calculated via equation (12):

$$R_{annual} = E_{annual} \times P_{elec} \tag{12}$$

with:

- E_{annual} = 712,800 kWh/year
- P_{elec} = 0.0295 €/kWh
- $C_{O\&M}$ = 1,500 €

Based on our data analysis, with an annual production of 712,800 kWh, the system is projected to reach the break-even point in approximately 7.3 years.

Socio-economy benefits

Significant socio-economic and environmental advantages can result from integrating hydropower plants into current water delivery networks. Analysis of the variables indicates that water volume and pressure significantly influence potential revenues, which, in turn, directly impact the country's economic activity. Regarding hydropower production, the scenarios analysed suggest that the primary beneficiaries are the local communities. These benefits may include increased employment opportunities, enhanced energy supply security, additional income sources for farmers and ranchers, and a cleaner environment.

Furthermore, the following impacts are evaluated using methods like [25], and expressed as follows:

- *Employment Creation*: Between two and four full-time equivalent (FTE) jobs may be created per installation as a result of the installation and upkeep of micro-hydropower systems. This covers positions in construction, engineering, and continuing maintenance.
- *Reduction of CO_2 Emissions*: Since each micro-hydropower system replaces fossil fuel-based electricity generation, it can offset between 300 and 500 tonnes of CO_2 emissions per year.

These numbers are in line with research from comparable settings, where small-scale renewable energy initiatives have shown beneficial socio-economic effects.

SUMMARY AND CONCLUSION

The recovery of energy from water flowing through water supply systems is an increasingly relevant topic. Beyond large turbines installed in major transit pipes, solutions for smaller distribution pipes have emerged, enabling electricity generation to power monitoring devices such as sensors. However, the implementation of microturbines within water distribution systems requires a comprehensive approach, including the development of a reliable power supply, contingency measures for turbine blockage, optimization of turbine design with minimal moving components, and operation at flow rates compatible with microturbine and generator start-up requirements.

This paper presents an initial framework addressing these challenges. The proposed solutions offer several advantages, including a simple design, reduced mechanical complexity, and no need for external electricity to control water flow. While these solutions have yet to be widely implemented, their potential benefits are significant. The most suitable model of all proposed scenarios corresponds to Model III with a flow of 560 l/s, and a pressure reduction of 30 m. Based on it, with an annual production of 712,800 kWh, the system is projected to reach the break-even point in approximately 7.3 years.

Key benefits of generating energy from potable water pipelines, exemplified by systems such as LUCIDPIPE™, include:

- Clean and Renewable Energy: Utilizes existing water flow to produce electricity without additional resource consumption. Reduces dependence on fossil fuels, lowering carbon emissions.
- Easy Integration with Existing Infrastructure: Can be installed in existing drinking water pipelines, minimizing construction costs and complexity.
- Reliable and Continuous Energy Production: Generates electricity without interrupting the water supply, ensuring stability for local communities.
- Energy Efficiency and Loss Reduction: Exploits the natural kinetic energy of water flow, minimizing mechanical intervention and energy loss.
- Low Operating Costs and Minimal Maintenance: Designed for minimal upkeep, reducing operational and human resource requirements.
- Contribution to Community Sustainability: Enhances environmental and economic outcomes, improving energy efficiency and lowering costs.
- Localized Energy Production: Produces energy close to consumption points, reducing transmission losses.

Despite these benefits, some limitations must be considered:

- Steady water flow is required for optimal energy generation.
- Turbines may slightly reduce water pressure (1-5 PSI per turbine).
- Initial installation costs can be substantial.
- Not all pipelines are suitable; modifications may be necessary.
- Periodic maintenance is required to ensure optimal operation.

Careful planning and assessment are essential to maximize benefits while addressing these limitations. Overall, the LUCIDPIPE™ system demonstrates strong potential to improve sustainability, enhance local energy production, and support economic and environmental objectives. The conclusions and recommendations presented in this paper aim to inform both researchers and relevant institutions about the practical and theoretical considerations of implementing such systems.

Future research work will focus on comparative analysis to other renewable energy sources in Kosovo.

AUTHOR CONTRIBUTIONS

Conceptualization, G.V.; Methodology, G.V. and M.I.; Validation, M.I. and Z.S.; Investigation, G.V.; Resources, Z.S.; Data Curation, G.V.; Writing – Original Draft Preparation, G.V. and Z.S.; Writing – Review & Editing, M.I.; Supervision, G.V.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

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