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Multidimensional feasibility assessment of pico-scale hydropower technology deployment in water infrastructure

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ABSTRACT

Pico-scale hydropower technologies based on vortex-induced vibration energy harvesting offer a promising solution for exploiting hidden energy potential in existing water infrastructure and powering low-power monitoring devices. However, their deployment requires a feasibility assessment that goes beyond technical and economic indicators and also includes environmental, risk-related and social aspects. This paper presents a multidimensional feasibility assessment framework for evaluating vortex-induced vibration energy harvesters in water distribution networks. The framework integrates technical, economic, environmental, risk and social-perspective assessment layers and is applied to a pilot case in Turkey. The results show that feasibility strongly depends on device design, hydraulic conditions and expected energy output. Mechanical power generation ranges from 2.7 W to 133 W, while the levelized cost of energy ranges from 11 to 1036 EUR/kWh. Environmental impacts vary from 0.012 to 1.16 kgCO_2eq/kWh. Although the technology is not yet economically competitive with conventional renewable energy systems, selected cases indicate potential for powering IoT-based monitoring devices and improving the resilience of water infrastructure.

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1. INTRODUCTION

The transition towards cleaner and more resilient energy systems has increased interest in small-scale renewable energy technologies capable of exploiting locally available and previously unused energy sources. In this context, energy harvesting from flow-induced vibrations (FIV) and vortex-induced vibrations (VIV) has attracted growing attention, particularly in water infrastructure where continuous fluid flow may provide a hidden source of recoverable energy [1–4]. Although the generated power is usually limited, such technologies can be highly relevant for low-power applications, including autonomous sensors, monitoring devices and Internet of Things (IoT)-based systems used in water distribution networks.
Existing water infrastructure contains a considerable amount of unexploited hydropower potential. Previous studies have indicated that European water systems may contain hidden hydropower potential that can be recovered without constructing large conventional hydropower plants [5]. In this regard, pico-scale hydropower and energy harvesting devices may represent a complementary solution for improving the energy autonomy of monitoring systems installed in pipelines, wastewater channels, remote water infrastructure and other locations where direct grid connection is unavailable or economically unjustified. The energy generated by VIV-based energy harvesters can be used to support low-power monitoring systems for measuring flow, pressure, water quality and other operational parameters [4,6].
Improved monitoring of water distribution networks is becoming increasingly important due to the need for higher system resilience, better resource management and improved drinking water quality. Disruptions in water supply systems may cause significant economic and social consequences for households, commercial users and critical infrastructure [7,8]. In addition, water quality deterioration and contamination events can lead to

increased treatment costs and broader public health concerns [9,10]. Therefore, technologies that can provide local energy for distributed monitoring devices may contribute not only to energy efficiency, but also to more reliable operation, earlier detection of failures and better decision-making in water infrastructure management.

However, the successful deployment of pico-scale hydropower and VIV energy harvesting technologies cannot be evaluated only through energy generation potential. In many feasibility studies, the assessment is mainly focused on technical performance and economic indicators, such as energy output, investment costs and levelized cost of energy. Although these aspects are essential, they provide only a partial understanding of the overall feasibility of emerging energy harvesting technologies. Environmental impacts, risk factors, social acceptance and socioeconomic benefits are often insufficiently considered or analysed separately, without integration into a unified decision-support framework [11–15].

This limitation is particularly important for technologies that are still at an early stage of development. VIV-based energy harvesters are expected to operate under specific hydraulic conditions and their performance strongly depends on device geometry, material selection, installation location, flow velocity and long-term operational stability. At the same time, their practical value may be associated less with large-scale electricity production and more with enabling self-powered monitoring, digitalization and resilience of water infrastructure. For this reason, a multidimensional feasibility assessment is required in order to identify where and under which conditions such devices may provide technical, environmental and social benefits despite current economic limitations.

Another important aspect is that the feasibility of pico-scale hydropower technologies should be interpreted in relation to their intended application. Unlike conventional hydropower systems, these devices are not primarily designed to contribute significantly to the overall electricity supply, but to provide local and autonomous energy for specific low-power functions. Therefore, their value should be assessed through their ability to support monitoring, data acquisition, early warning and infrastructure resilience. This application-oriented perspective justifies the need for a broader assessment approach in which technical performance and economic indicators are considered together with environmental effects, operational risks and potential social benefits.

The aim of this paper is to present a multidimensional feasibility assessment framework for evaluating the deployment of pico-scale hydropower technology based on vortex-induced vibration energy harvesting in water infrastructure. The proposed framework integrates technical, economic, environmental, risk-related and social-perspective assessment layers. It is applied to a pilot water distribution network case in Turkey in order to analyse the feasibility of VIV energy harvesters under different operating and design conditions. The contribution of the paper is reflected in providing a broader assessment approach that supports decision-makers, infrastructure operators and technology developers in identifying feasible deployment scenarios and future development priorities for pico-scale hydropower technologies.

2. H-HOPE PROJECT

The H-HOPE project is a European Horizon-funded research project focused on the development of hidden hydropower technologies for existing water infrastructure. The main idea of the project is to identify and exploit small, previously unused energy potentials that occur in water systems during regular operation. In particular, the project investigates energy harvesting from vortex-induced vibrations, which appear when flowing water interacts with submerged or partially submerged objects. Instead of treating these vibrations only as an unwanted phenomenon, the H-HOPE concept considers them as a possible source of useful mechanical energy that can be converted into electricity for low-power applications [4], [16].

The project develops different energy harvester concepts intended for application in water distribution networks, wastewater channels and remote water infrastructure. These locations are especially important because they often require continuous monitoring of flow, pressure, water quality and other operational parameters, while access to a stable electrical power supply may be limited or economically unjustified. In such cases, pico-scale energy harvesting devices can provide local energy for sensors and Internet of Things (IoT) monitoring units, thereby supporting the digitalization and resilience of water infrastructure [4], [6], [17]. Several design concepts have been developed within the H-HOPE project for different water distribution network applications, as shown in Figure 1.

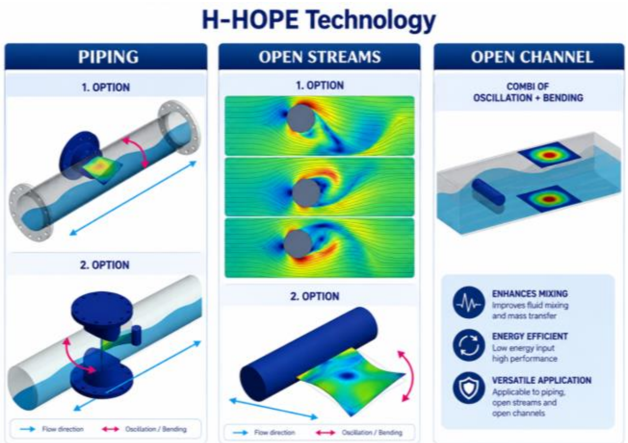

Fig. 1 H-HOPE energy harvesters design options for three WDN applications [16].

A key characteristic of the H-HOPE approach is that the technology is intended for integration into already existing infrastructure, rather than for the construction of new hydropower facilities. This makes the concept particularly relevant for water distribution networks, where energy generation can be achieved as a positive by-product of normal water flow. The generated energy is not expected to replace conventional renewable energy sources, but to support specific low-power functions such as autonomous monitoring, data collection and early detection of system irregularities. In this way, H-HOPE energy harvesters may contribute to improved operation, maintenance and long-term resilience of water systems [4], [17].

Within the project, several design options are considered depending on the type of water infrastructure and the hydraulic conditions at the installation site. The performance of the energy harvester depends on parameters such as flow velocity, pipe diameter, device geometry, material selection and operational lifetime. Therefore, the assessment of H-HOPE devices requires not only technical analysis of energy generation potential, but also economic, environmental, risk-related and social evaluation. This is particularly important because the technology is still under development and its practical feasibility depends on the balance between expected energy output, installation costs, environmental impacts and benefits for infrastructure monitoring.

3. TECHNOLOGY FEASIBILITY ASSESSMENT

The technology feasibility assessment applied in this paper is based on a multidimensional framework developed to evaluate the potential deployment of vortex-induced vibration energy harvesters in water infrastructure. The framework is structured around three main assessment layers: technical, economic, and socioeconomic and environmental assessment. These layers are used to analyse the feasibility of the technology from different perspectives and to identify the main factors that may support or limit its practical implementation. A more detailed description of the assessment modules and key equations is provided in Gudlaugsson et al. [17].

The structure of the proposed assessment framework is shown in Figure 2. The technical layer focuses on the operational and design-related characteristics of the energy harvester, including device geometry, material properties, hydraulic conditions, expected energy production and operational lifetime.

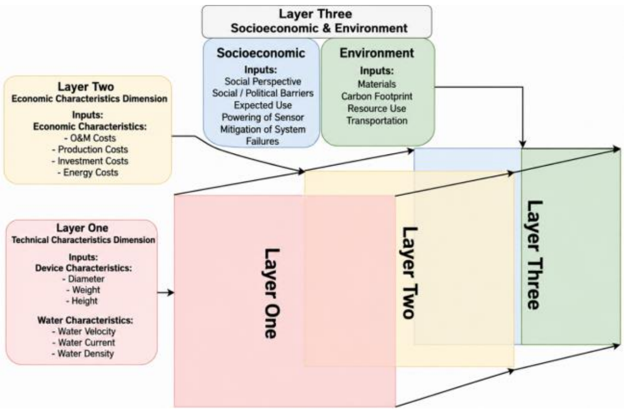

Fig. 2 Structure and assessment layers of the H-HOPE assessment framework.

This part of the assessment is important because the energy output of VIV-based devices depends strongly on local water velocity, pipe dimensions, device size and the interaction between the flowing water and the harvester structure.

The economic layer evaluates the financial aspects related to the development and deployment of the energy harvester. It includes capital costs, installation costs, operation and maintenance costs, and the levelized cost of energy. Since pico-scale hydropower devices are still emerging technologies, economic assessment is particularly important for understanding whether the generated energy can justify the required investment. However, in this study, economic feasibility is not interpreted only in comparison with large-scale renewable energy systems, but also in relation to the specific function of powering low-power monitoring devices in water infrastructure.

The socioeconomic and environmental layer extends the assessment beyond technical performance and direct costs. It considers environmental impacts associated with material selection, manufacturing and energy generation over the device lifetime, as well as social and stakeholder-related aspects. This is important because the value of pico-scale energy harvesting technologies may be reflected not only in the amount of electricity produced, but also in their contribution to infrastructure monitoring, digitalization, early warning, resilience and improved management of water systems.

The assessment framework uses a set of key parameters that describe the energy harvester, the water system and the installation environment. These parameters include device height, diameter, weight, width, length, material type, material density, installed number of devices, device lifetime, Reynolds number, pipe geometry, water depth, flow velocity, water density, water flow, pressure and other relevant hydraulic and operational variables. The main parameters used in the assessment are presented in Table 1.

The parameters presented in Table 1 provide the basis for calculating and comparing different feasibility indicators. Technical indicators are used to estimate energy production potential and capacity factors under specific hydraulic conditions. Economic indicators are used to estimate the total costs and levelized cost of energy. Environmental indicators are used to calculate the global warming potential and carbon footprint per unit of generated electricity. In addition, risk-related and social-perspective indicators are used to identify potential barriers, operational challenges and wider benefits connected with the deployment of the technology.

By combining these assessment layers, the framework enables a more comprehensive interpretation of feasibility than conventional one- or two-dimensional assessment approaches. Instead of focusing only on energy output or cost, the framework makes it possible to evaluate whether a specific deployment case is technically possible, economically reasonable, environmentally acceptable and socially beneficial. This is especially relevant for VIV-based pico-scale hydropower technologies, where the main practical value may be associated with supporting autonomous monitoring and improving the resilience of water infrastructure rather than producing large quantities of electricity.

Table 1 – *Key assessment parameters used for the feasibility assessment.*

ID	Evaluation criteria	Variable	Unit
T.1	Device height	XHeight	mm
T.2	Device diameter	XDiameter	mm
T.3	Device weight	XWeight	mm
T.4	Device width	XWidth	mm
T.5	Device length	XLength	mm
T.6	Device size	XSize	mm
T.7	Installed devices	InDevices	Number of devices
T.8	Device lifetime	XLifetime	Years
T.9	Reynolds number	Re	Numerical value
T.10	Device material	XM	Type of material
T.11	Device material density	XMD	kg/cm³
T.12	Pipe geometry factor	GPipe	%
T.13	Pipe height percentage	X%ofPlateLength	%
T.14	Device cylinder volume	XCyl_V	cm³
T.15	Device plate volume	XPlate_V	cm³
WS.1	Width	Ywidth	m
WS.2	Water depth	YDepth	m
WS.3	Velocity	Yv	m/s
WS.4	Density	YDensity	kg/m³
WS.5	Water flow	YQ	m³/s
WI.1	Piping length	PLength	m
WI.2	Piping friction	PFriction	Fraction
WI.3	Piping drop	PDrop	m
WI.4	Piping pressure	PPressure	Pa
WI.5	Piping diameter	PDiameter	mm
WI.6	Piping water flow	PQ	m/s
T.7	Installed devices	InDevices	Number of devices
E.1	Energy production	EPDevice	Watts or Joules
E.2	Capacity factor	CFDevice	Fraction
E.3	Actual output	AOutput	Watts/hour
E.4	Maximum possible output	MPOutput	Watts/hour
E.5	Total energy generation	EPOverall	Watts or Joules
R.1	Velocity changes	i	m/s
R.2	Pipe friction*	ii	–
R.3	Water temperature*	iii	Degrees
R.4	Pressure changes*	iv	Bar
R.5	Device robustness	v	–
R.6	Device lifetime	vi	Years
R.7	Pipe lifetime*	vii	Years

In Table 1 parameters marked with an asterisk are primarily related to the piping system. The symbols (i)–(vii) refer to the following risk-related and operational aspects: (i) change in water velocity in the system; (ii) change in pipe friction affecting water flow; (iii) change or increase in water temperature affecting the operational integrity of the device; (iv) change in water pressure; (v) device resilience, mechanical robustness and stability under the corresponding water environment and operating conditions; (vi) operational lifetime of the device; and (vii) operational lifetime of the pipe under the corresponding water environment and operating conditions.

4. RESULTS

The application of the proposed assessment framework focuses on evaluating the feasibility of deploying vortex-induced vibration energy harvesters in an existing water distribution network in Turkey, referred to as Case Area 103. This case was selected to examine how different hydraulic conditions, device characteristics and operational assumptions influence the technical, economic, environmental, risk-related and social feasibility of the proposed pico-scale hydropower technology. The results are presented through five assessment dimensions: technical performance, economic feasibility, environmental impact, risk assessment and social perspective.

4.1 Technical Assessment

The technical assessment considers the hydraulic and design conditions of the selected pilot case. The analysed piping system has a pipe diameter of 150 mm, while the optimal cylinder diameter of the VIV-EH device is determined to be 141.8 mm. The main technical assessment results for the five analysed cases within Case Area 103 are presented in Table 2.

The results presented in Table 2 show that the frequent water velocity ranges from 0.573 m/s to 2.135 m/s, while the energetic velocity ranges from 0.578 m/s to 2.157 m/s. These values are important because the energy generation potential of VIV-based energy harvesters depends strongly on the interaction between the device and the local flow conditions. By identifying the dominant and energy-relevant velocity ranges, the device can be better calibrated to operate within realistic hydraulic conditions and to improve its capacity factor.

The total energy production over the expected device lifetime is shown in Figure 3. The results indicate that three out of the five analysed cases have more favourable energy generation potential. In Case 103-1, the estimated energy production ranges from 66 to 101 kWh for a 12-year lifetime and from 110 to 169 kWh for a 20-year lifetime. In Case 103-4, the estimated energy production is significantly higher, ranging from 1531 to 1596 kWh for a 12-year lifetime and from 2552 to 2660 kWh for a 20-year lifetime. Case 103-5 also shows favourable potential, with estimated energy production ranging from 440 to 445 kWh for a 12-year lifetime and from 733 to 741 kWh for a 20-year lifetime.

Table 2 – *Key technical assessment results for piping application Case Area 103 (derived from [19]).*

Case study	Capacity factor +	Capacity factor *	Intermittency indicator	Frequent velocity +	Energetic velocity *	Pipe diameter	Cylinder diameter
103-1	31.25%	37.50%	0.530	0.990 m/s	1.068 m/s	150 mm	141.8 mm
103-2	34.38%	26.04%	0.613	0.778 m/s	0.899 m/s	150 mm	141.8 mm
103-3	47.92%	45.83%	0.426	0.573 m/s	0.578 m/s	150 mm	141.8 mm
103-4	56.25%	52.08%	0.121	2.135 m/s	2.157 m/s	150 mm	141.8 mm
103-5	34.38%	34.38%	0.150	1.693 m/s	1.698 m/s	150 mm	141.8 mm

These findings suggest that the technical feasibility of VIV-EH devices is highly case-dependent. In locations with more favourable flow conditions, the generated energy may be sufficient to power low-power monitoring sensors or IoT devices. Such devices can support the monitoring of pressure, flow velocity, water quality and other relevant parameters in water distribution networks. Therefore, from a technical perspective, VIV-EH technology shows potential for supporting autonomous monitoring applications, especially in locations where grid connection is unavailable or difficult to provide [4], [6], [19].

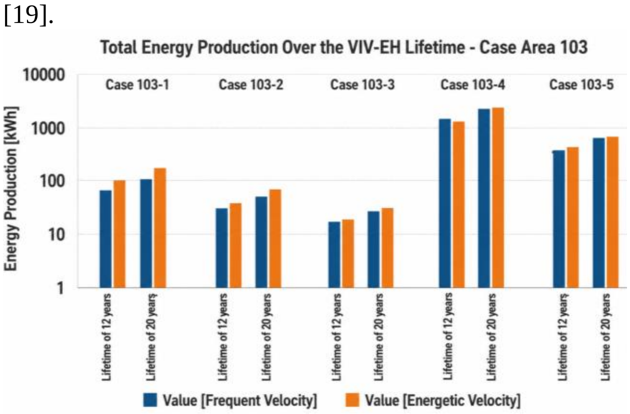

Fig. 3 Total energy production over the EH device lifetime.

4.2 Economic Assessment

The economic assessment evaluates the costs associated with the development, installation, operation and maintenance of the VIV-EH device. The assessment is divided into two main phases. The first phase includes capital expenditures related to manufacturing, installation and licensing, while the second phase includes annual operation and maintenance costs. The main economic input assumptions used for the levelized cost of energy calculation are presented in Table 3.

As shown in Table 3, the total capital cost for the initial deployment phase is estimated at 7451.28 EUR. This includes manufacturing costs, installation costs and licensing costs. The annual operation and maintenance costs are estimated at 820 EUR per year. Over a 12-year device lifetime, the total operation and maintenance costs amount to 9840 EUR, while over a 20-year lifetime they increase to 16,400 EUR. Consequently, the total costs are estimated at 17,291.28 EUR for a 12-year lifetime and 23,851.28 EUR for a 20-year lifetime.

The levelized cost of energy for the analysed VIV-EH cases is shown in Figure 4. The results indicate that, for a 12-year lifetime, the LCOE ranges from 11 EUR/kWh to 1037 EUR/kWh, depending on the energy generation output of the specific case.

Table 3 – *Key assessment parameters used for the feasibility assessment.*

Cost category	Cost item	Value
CAPEX	Capital costs — manufacturing	4,021.28 EUR
CAPEX	Capital costs — installation	2,680.00 EUR
CAPEX	Capital costs — licenses	750.00 EUR
CAPEX	Total CAPEX	7,451.28 EUR
OPEX	Operation and maintenance	670.00 EUR/year
OPEX	Fuel costs	–
OPEX	Fixed costs	150.00 EUR/year
OPEX	Variable costs	–
OPEX	Total year 1	820.00 EUR
OPEX	Total year 12	9,840.00 EUR
OPEX	Total year 20	16,400.00 EUR
Total costs	Total costs for 12 years	17,291.28 EUR
Total costs	Total costs for 20 years	23,851.28 EUR
Cost category	Cost item	Value
CAPEX	Capital costs — manufacturing	4,021.28 EUR
CAPEX	Capital costs — installation	2,680.00 EUR

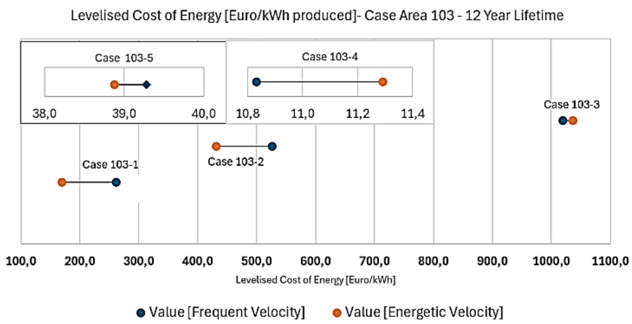

Fig. 4 LCOE range for VIV-EH devices with a 12 year lifetime.

The economic results show that the current LCOE values of VIV-EH devices are considerably higher than those of established renewable energy technologies, which typically range from approximately 0.05 to 0.25 EUR/kWh [21], [22]. However, this comparison should be interpreted carefully, because VIV-EH devices are not intended to compete with large-scale renewable energy systems in terms of bulk electricity generation. Their potential value lies in providing local energy for low-power monitoring devices in specific infrastructure locations. In addition, the technology is still at an early development stage, and further improvements in design, manufacturing, installation procedures and energy conversion efficiency may reduce costs and improve economic feasibility in future applications [17], [23].

4.3 Environmental Assessment

The environmental assessment focuses on the global warming potential associated with material selection, manufacturing, transportation and energy generation over the device lifetime. The environmental impact results for the analysed pilot case are presented in Table 4.

Table 4 – *Environmental impacts of EH devices for pilot Case Area 103.*

Case	Parameter	Frequent velocity	Energetic velocity	Unit
All	GWP material selection	9.05	9.05	kg CO_2eq/device for materials
All	GWP of the device	19.48	19.48	kg CO_2eq/device
103-1	GWP per unit of electricity produced	0.29	0.19	kg CO_2eq/kWh
103-2	GWP per unit of electricity produced	0.59	0.48	kg CO_2eq/kWh
103-3	GWP per unit of electricity produced	1.14	1.16	kg CO_2eq/kWh
103-4	GWP per unit of electricity produced	0.0122	0.0127	kg CO_2eq/kWh
103-5	GWP per unit of electricity produced	0.0442	0.0438	kg CO_2eq/kWh

The results presented in Table 4 show that the total global warming potential for producing one VIV-EH device is 19.48 kg CO_2eq. Material selection accounts for 9.05 kg CO_2eq, while manufacturing and transportation account for 10.43 kg CO_2eq. When the environmental impact is expressed per unit of generated electricity, the results vary significantly between the analysed cases. The carbon footprint ranges from 0.0122 kg CO_2eq/kWh in the most favourable case to 1.16 kg CO_2eq/kWh in the least favourable case.

The relationship between carbon footprint and mechanical power generation is shown in Figure 5. The results indicate that higher energy generation leads to a lower carbon footprint per unit of electricity produced. This means that the environmental feasibility of VIV-EH devices depends strongly on whether the installation location provides sufficient energy output over the device lifetime.

The most favourable cases, particularly 103-4 and 103-5, show carbon footprint values ranging from approximately 11.2 to 44 g CO_2eq/kWh. These values are comparable to those reported for other renewable energy sources [24], [25]. In contrast, cases with low energy output show considerably higher carbon intensity, approaching or exceeding values associated with fossil-based electricity generation. Therefore, the environmental feasibility of VIV-EH technology is strongly linked to appropriate site selection and sufficient long-term energy production.

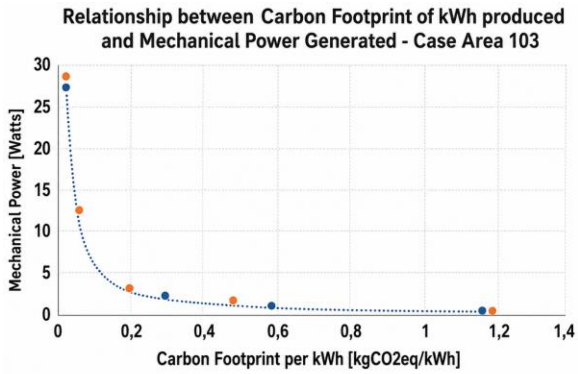

Fig. 5 Relationship between carbon footprint and mechanical power generation.

4.4 Risk Assessment

The risk assessment evaluates potential risks associated with the development and deployment of the VIV-EH device. The analysed risks are grouped into factors related to design and manufacturing, and factors related to the installation environment and water characteristics. The main risk assessment results are presented in Table 5.

Table 5 – *Risk assessment of key risk variables associated with EH device development and deployment.*

Risk parameter	Risk rating	Numerical value
Structural design	Critical	15
Installation	Moderate (high)	8
Material corrosion	Moderate (high)	8
Manufacturing quality	Moderate (high)	9
Fouling	Sustainable	4
Sediments	Moderate (low)	6
Velocity — high	Moderate (low)	6
Velocity — low	Sustainable	4

The results in Table 5 show that the most critical risks are associated with the development phase of the technology. Structural design is rated as critical, while installation, material corrosion and manufacturing quality are rated as moderate to high risks. These results indicate that the successful operation of VIV-EH devices depends strongly on design robustness, material selection and manufacturing precision. Since the device must operate in a water environment over a long period, mechanical stability and resistance to operational degradation are essential.

In contrast, risks related to fouling, sediments and velocity changes are generally rated as sustainable or moderate to low. This suggests that, under the analysed conditions, the water environment itself is not considered the dominant source of operational risk. However, these factors should still be monitored because long-term exposure to variable hydraulic conditions may influence device performance, maintenance needs and operational lifetime.

4.5 Social Perspective Assessment

The social perspective assessment is based on the evaluation of stakeholder views regarding the potential benefits and relevance of VIV-EH deployment in water infrastructure. The ranking of social perspective parameters is presented in Table 6.

Table 6 – *Ranking of social perspective parameters in terms of relevance to society.*

Social perspective parameter	Score
Support for remote communities	0.750
Contribution to environmental sustainability	0.625
Improved infrastructure monitoring and maintenance	0.500
Cost-effective services for communities	0.500
Enhanced resilience	0.375
Promotes technological innovation	0.250
Prevention of water loss and environmental impact	0.125
Environmental monitoring for public safety	0.125
Diverse applications	0.125
Long-term resilience and security	0.125
Economic impact on families	0.125
Better collaboration with municipalities and stakeholders	0.125
Educational opportunities	0.125
Improving water network resilience	0.125

The results presented in Table 6 indicate that VIV-EH technology is perceived as particularly relevant for supporting remote communities, contributing to environmental sustainability and improving infrastructure monitoring and maintenance. The highest score is assigned to support for remote communities, which reflects the potential of the technology to provide local energy in areas without stable grid connection. Other relevant benefits include enhanced resilience, cost-effective services for communities and the promotion of technological innovation.

These findings show that the social value of VIV-EH technology is not limited to energy generation. Its broader contribution is related to enabling more reliable monitoring, improving infrastructure resilience and supporting better management of water systems. From this perspective, even if the technology is not yet economically competitive as a conventional energy source, it may still provide important social and operational benefits when applied in suitable locations.

5. DISCUSSION

The application of the multidimensional feasibility framework provides important insight into the overall feasibility of VIV-EH devices in water distribution networks. The results show that not all analysed cases are equally suitable for deployment. The main limitations are related to low energy generation potential in some cases, high levelized cost of energy, and environmental performance that strongly depends on lifetime electricity production. Therefore, the feasibility of VIV-EH technology must be interpreted through combined technical, economic, environmental, risk-related and social assessment results.

From the technical perspective, VIV-EH devices can be feasible for powering low-power monitoring and IoT devices only in selected cases. The most favourable cases show sufficient lifetime energy generation to support monitoring functions, while cases with lower energy output have limited practical application. This confirms that local hydraulic conditions, especially water velocity and operational stability, are critical for successful deployment.

The economic assessment shows that VIV-EH devices are currently economically challenging. Their LCOE values are high compared with conventional renewable energy technologies, mainly due to relatively low energy output and costs related to design, manufacturing, installation, operation and maintenance. However, this should be interpreted in relation to the intended application of the technology, which is not large-scale electricity generation, but local energy supply for low-power monitoring systems.

The environmental assessment shows that feasibility strongly depends on the selected case. In high-energy-output cases, the carbon footprint per unit of electricity can be comparable to other renewable energy sources, while low-output cases may have a significantly higher carbon footprint. This confirms that environmental feasibility is closely connected with technical feasibility and appropriate site selection.

The risk assessment indicates that the development phase represents a critical point for successful operational deployment. Structural design, installation, material corrosion and manufacturing quality are important risk factors that may influence long-term device performance. In contrast, risks related to the water environment and deployment conditions are generally assessed as moderate or sustainable in the analysed case.

The social perspective assessment shows that VIV-EH devices may provide benefits beyond direct energy generation. The technology is relevant for supporting remote communities, improving infrastructure monitoring and maintenance, contributing to environmental sustainability and enhancing resilience. In this role, VIV-EH devices may support better resource management, early detection of failures and more reliable water supply services.

Overall, the discussion confirms that VIV-EH deployment in water distribution networks should be considered selective rather than generally feasible. If the devices are evaluated only as electricity generation units, their feasibility remains limited. However, if they are considered as enabling technologies for autonomous monitoring and water system resilience, their potential becomes more relevant. Future development should focus on improving design, reducing costs, increasing energy output and identifying locations where technical, environmental and social benefits are strongest.

6. CONCLUSIONS

This study confirms that the deployment of pico-scale hydropower technology in water infrastructure requires an integrated assessment approach. The proposed multidimensional framework enables the simultaneous consideration of technical performance, economic requirements, environmental impacts, operational risks and social relevance, which is particularly important for emerging energy harvesting technologies.

The main contribution of the paper is the application of this framework to VIV-EH devices intended for water distribution networks. The results demonstrate that the practical value of these devices is not primarily related to large-scale electricity production, but to their ability to support autonomous monitoring functions. In suitable hydraulic conditions, VIV-EH devices can provide local energy for sensors and IoT-based systems, contributing to improved data collection and infrastructure monitoring.

The findings also indicate that further development is necessary before wider deployment can be expected. The most important priorities are the improvement of device design, reduction of investment and maintenance costs, increase of energy conversion efficiency and verification of long-term reliability under real operating conditions.

Future research should focus on experimental validation in different water infrastructure environments, optimization of device geometry and materials, and a more detailed evaluation of maintenance requirements and lifecycle performance. In this way, pico-scale hydropower technologies could become a useful supporting solution for the digitalization, monitoring and resilience of water system

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REFERENCES

[1] Chen, Z., Alam, M. M., Qin, B., & Zhou, Y. (2020). Energy harvesting from and vibration response of different diameter cylinders. Applied Energy, 278: 115737.

[2] Wang, J., Geng, L., Ding, L., Zhu, H., & Yurchenko, D. (2020). The state-of-the-art review on energy harvesting from flow-induced vibrations. Applied Energy, 267: 114902.

[3] Gudlaugsson, B., Bronkema, B. M., Stepanovic, I., & Finger, D. C. (2024). A Systematic Review of Techno-Economic, Environmental and Socioeconomic Assessments for Vibration Induced Energy Harvesting. Energies, 17(22): 5666.

[4] Karapici, V., Trojer, A., Lazarevikj, M., Pluskal, T., Chernobrova, A., Nezirić, E., ... & Rudolf, P. (2024). Opportunities of hidden hydropower technologies towards the energy transition. Energy Reports, 12: 5633–5647.

[5] Quaranta, E., Bódis, K., Kasiulis, E., McNabola, A., & Pistocchi, A. (2022). Is there a residual and hidden potential for small and micro hydropower in Europe? A screening-level regional assessment. Water Resources Management, 36(6): 1745–1762. https://doi.org/10.1007/s11269-022-03084-6

[6] Hayes, M. H., Fagas, G. F., Donnelly, J. D., Salot, R. S., Savelli, G. S., Spies, P. S., Vom Boegel, G. B., Konijnenburg, M. K., Stenzel, D. S., Romani, A. R., Gerbaldi, C. G., Cottone, F. C., & Weddell, A. W. (2021). Enables - European infrastructure powering the internet of things: Research Infrastructure Position Paper. Retrieved January 27, 2025, from https://www.enables-project.eu/wp-content/uploads/2021/02/EnABLES_ResearchInfrastructure_PositionPaper.pdf

[7] Heflin, C., Jensen, J., & Miller, K. (2014). Understanding the economic impacts of disruptions in water service. Evaluation and Program Planning, 46: 80–86.

[8] Sjöstrand, K., Klingberg, J., Zadeh, N. S., Haraldsson, M., Rosén, L., & Lindhe, A. (2021). The value of water—estimating water-disruption impacts on businesses. Water, 13(11): 1565.

[9] Hopland, A. O., & Kvamsdal, S. F. (2023). Drinking water contamination and treatment costs. Water Resources and Economics, 43: 100225.

[10] Snelson, P. B. B. (2024, October 15). Europe's water crisis needs urgent attention, says EEA's State of Water report. Retrieved February 27, 2025, from https://eeb.org/europes-water-crisis-needs-urgent-attention-says-eeas-state-of-water-report/

[11] Blanco, H., Codina, V., Laurent, A., Nijs, W., Maréchal, F., & Faaij, A. (2020). Life cycle assessment integration into energy system models: An application for Power-to-Methane in the EU. Applied Energy, 259: 114160.

[12] Braimakis, K., Charalampidis, A., & Karellas, S. (2021). Techno-economic assessment of a small-scale biomass ORC-CHP for district heating. Energy Conversion and Management, 247: 114705.

[13] Wali, S. B., Hannan, M. A., Ker, P. J., Abd Rahman, M. S., Tiong, S. K., Begum, R. A., & Mahlia, T. I. (2023). Techno-economic assessment of a hybrid renewable energy storage system for rural community towards achieving sustainable development goals. Energy Strategy Reviews, 50: 101217.

[14] Vélez Godiño, J. A., & Torres García, M. (2023). Techno-Economic Assessment of an Innovative Small-Scale Solar-Biomass Hybrid Power Plant. Applied Sciences, 13(14): 8179.

[15] Gudlaugsson, B., Bronkema, B. M., Stepanovic, I., & Finger, D. C. (2024). A Systematic Review of Techno-Economic, Environmental and Socioeconomic Assessments for Vibration Induced Energy Harvesting. Energies, 17(22): 5666.

[16] H- H-Hope: H-HOPE: Hidden Hydro Oscillating Power for Europe. (2023). Retrieved May 6, 2024, from https://h-hope.eu/

[17] Guðlaugsson, B., Hočevar, M., Sečnik, M., Bronkema, B., Rak, G., Stepanovic, I., & Finger, D. (2025). Assessment and Feasibility Analysis Framework for Vortex-Induced Vibrations Energy Harvesters. Available at SSRN: http://dx.doi.org/10.2139/ssrn.5126391

[18] Gudlaugsson, B., Finger, D., Stepanovic, I., & Bronkema, B. (2024). Criteria for evaluating the hydropower application for H-Hope in Europe.

[19] Bronkema, B., Guðlaugsson, B., Bermejo, D., Escaler, X., & Finger, D. (2025). Energy Recovery, Enhanced Resilience, and Sustainability in European Water Networks: Harnessing the Water-Energy Nexus. SSRN. https://doi.org/10.2139/ssrn.5208128

[20] Eurostat. (2025, March 28). Eurostat statistics explained: Hourly labour costs. The European Union. Retrieved April 12, 2025. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Hourly_labour_costs

[21] Klein, S. J. W., & Fox, E. L. B. (2022). A review of small hydropower performance and cost. Renewable and Sustainable Energy Reviews, 169: 112898.

[22] Kost, C., Müller, P., Sepúlveda Schweiger, J., Fluri, V., & Thomsen, J. (2024). Levelized Cost of Electricity Renewable Energy Technologies. Fraunhofer Institute for Solar Energy Systems ISE. Retrieved February 24, 2025, from https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/EN2024_ISE_Study_Levelized_Cost_of_Electricity_Renewable_Energy_Technologies.pdf

[23] Saber, M., Abdelall, G., Ezzeldin, R., AbdelGawad, A. F., & Ragab, R. (2024). Techno-economic assessment of the dethridge waterwheel under sluice gates in a novel design for pico hydropower generation. Renewable Energy, 234: 121206.

[24] Nicholson, S., & Heath, G. (2021). Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update. National Renewable Energy Laboratory. Retrieved November 30, 2024, from https://www.nrel.gov/docs/fy21osti/80580.pdf

[25] Amponsah, N. Y., Troldborg, M., Kington, B., Aalders, I., & Hough, R. L. (2014). Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations. Renewable and Sustainable Energy Reviews, 39: 461–475.

[26] Stepanovic, I., Garcia-Santos, G., Guðlaugsson, B., & Finger, D. C. (2025). Assessing enablers and challenges for the deployment of energy harvesters in water networks through stakeholder interviews. EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-18505. https://doi.org/10.5194/egusphere-egu25-18505