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Systematic Review

A Systematic Review of Techno-Economic, Environmental and Socioeconomic Assessments for Vibration Induced Energy Harvesting

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Abstract: There is a growing need to ensure the resilience of energy and water systems through digitalization, retrofit these systems for cleaner energy systems, and protect public safety in terms of water quality. This resilience requires a reliable power supply that could be provided by harnessing unexploited energy hidden in the current water infrastructure through the deployment of vortex-induced vibration energy harvesters. Therefore, being able to understand the feasibility of deploying these devices across technical, socioeconomic and environmental scales could further enhance successful deployment and integration of these devices. This paper aims to provide a systematic review investigating the development of energy harvester technologies to understand the key methods used to assess their application feasibility. This study used the PRISMA guidelines, and 139 articles were reviewed and synthesized. The trends were visualized, illustrating the current direction in energy harvesting development and application and methods used to assess the feasibility of these devices and technology. The majority of the reviewed studies focused on technical feasibility, design configuration, limitation, and identification of the most optimal application environment. The results revealed a huge opportunity for energy harvesters, especially as a power supply for monitoring sensors. Nevertheless, the results also identified a knowledge gap when it comes to assessing the overall application feasibility of energy harvesting as most studies currently neglect economic feasibility, environmental impacts, social aspects and energy resilience. Assessment tools will help fill this knowledge gap by identifying the key barriers and benefits gained from integrating this technology into existing energy systems and water systems.

Keywords: systematic review; VIV-EH; micro-energy devices; technoeconomic assessment; socioeconomic assessment

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1. Introduction

The utilization of small- and micro-scale energy generation technology such as vortex-induced vibration (VIV) energy harvesters can play a critical role in digitalizing and enhancing monitoring of water and energy systems by providing reliable power to monitoring sensors. Enhanced monitoring facilitates the retrofitting of water and energy systems to be more reliable, sustainable and efficient, ensuring sustainable water supply through enhancing water [1] and energy system resilience and security [2–5]. Therefore, the ability to perform feasibility, impact and technology assessments of these small- and micro-scale energy generation technologies is vital to ensure the successful deployment of these technologies into existing energy systems [6].

In recent years, research into the application of alternative small- and micro-scale renewable energy technologies like VIV energy harvesters has been growing. This recent work is especially in relation to harvesting the hidden energy potential from oceans, seas, river currents and flow vibration events in water infrastructure [6–10]. Furthermore, the application of VIV energy harvesting technology provides an alternative and complement to current renewable technologies such as bioenergy, photovoltaic (PV), off-shore and on-shore wind, and geothermal and hydropower [10–13]). The application of a VIV energy harvester could allow for energy utilization and generation through harvesting the kinetic energy of flow-induced vibration in open water systems such as rivers, lakes and lagoons, as well as closed water systems like water pipe systems [6,11]. Another key aim of the growing research into the field of energy harvester technologies like VIV energy harvesters is to provide a self-sustaining micro- or small-scale electrical energy system. Through energy harvesting, these systems can be powered by an available natural or mechanical energy source such as mechanical vibration, wind flows, rivers and ocean currents [8,12–14]. For example, the application of energy harvester technology in micro or small electrical energy systems could power wireless sensors and communication devices, replacing conventional fossil fuel, batteries or intermittent renewable energy resources [8,12,15].

Assessing the feasibility of new energy generation technology integration into any infrastructure system is a part of infrastructure and system development or retrofitting. Information and outputs attained from assessing the multiple cross-dimensional factors are essential to secure sustainable, efficient and reliable water and energy services [16,17]. Therefore, understanding and identifying both the positive and negative economic, environmental, and societal impacts, as well as technological barriers or opportunities concerning the implementation of the energy system, is critical information and input for a whole system assessment framework [18–20].

Assessment frameworks and tools are often built around the ability to assess economic feasibility, such as payback time and costs of energy system development [21–23], socioeconomic impacts, such as job creation [24–26], and technical feasibility and impact, such as energy generation capacity increase and potential [27–29]. Understanding and being able to assess these major elements plays a critical role in the successful implementation of energy system development projects and is fundamental to any energy system development or retrofitting strategy [17,18].

Furthermore, assessment frameworks, models and tools often focus on larger-scale energy system feasibility analysis when it comes to energy system development. The integration of new PV or wind into a pre-existing energy system [30], large-scale energy storage facilities to mitigate the intermittency of renewable energy integration [31], retrofitting of buildings in urban areas or cities [32–34] and electric vehicle integration in cities and energy systems [35] are all examples of large-scale systems. Thus, the application of currently existing assessment frameworks is often limited to large systems. They are less applicable to feasibility and impact analyses related to the integration of small- or micro-scale energy technologies—such as a piezoelectric energy harvester or VIV energy harvesters—into an energy system, water system or other urban infrastructure.

The scope of this paper focuses on reviewing the literature to understand what kind of assessment methods and software are currently used to assess the feasibility and application potential of VIV energy harvesters in an existing energy system. In addition, this work aims to gain an overview of the potential opportunities for VIV energy harvester technologies to harness unexploited hydropower potential. Furthermore, this research intends to provide insights that strengthen the reasoning for the usage of cross-dimensional assessment approaches, especially when assessing the feasibility of energy harvesting technology and other emerging technologies. It does this through highlighting the key focus areas of current assessment methods and software used to assess energy harvester technology feasibility and identifying the lack of assessment methods specifically in the socioeconomic and environmental spheres. Additionally, it seeks to provide insight to the potential benefits of applying a cross-dimensional approach to feasibility assessment of energy harvesting technology and its further deployment.

The remainder of the paper is structured as follows. Section Two provides background on the VIV energy harvesting technology and its potential role in the renewable energy transition. Section Three presents the research methodology employed in this study. Section Four presents and discusses the results and key findings from this study, highlights the research gap, and shows the need for a comprehensive feasibility assessment. Section Five presents the conclusions of this study and provides insights into how assessment frameworks could be improved and describes the potential of VIV harvesters to enhance water-end energy systems.

1.1. Energy Harvester Technology

Bernitsas et al. [36] point out that VIVs have been studied by engineers to dampen and decrease the damage created by resonance on engineering structures [36,37]. Resonance events can cause significant damage and risks to the structural stability of buildings and other engineering structures, yet they also hold a critical potential for the utilization of unexploited kinetic energy [37]. Furthermore, the energy harvesting technologies that can be applied to harvest the energy potential associated with FIVs fall into four categories, which are classified by their different vibration characteristics and mechanisms [37,38], as shown in Figure 1. Two of the vibration characteristics are flutter and galloping. Technologies used to harness the energy from these two vibration characteristics function in a manner specific to the vibration type to generate energy. However, for the vibration characteristics of buffering and VIV, the technology used to harness energy uses pressure gradients resulting from vortexes to create oscillating movements to harness energy.

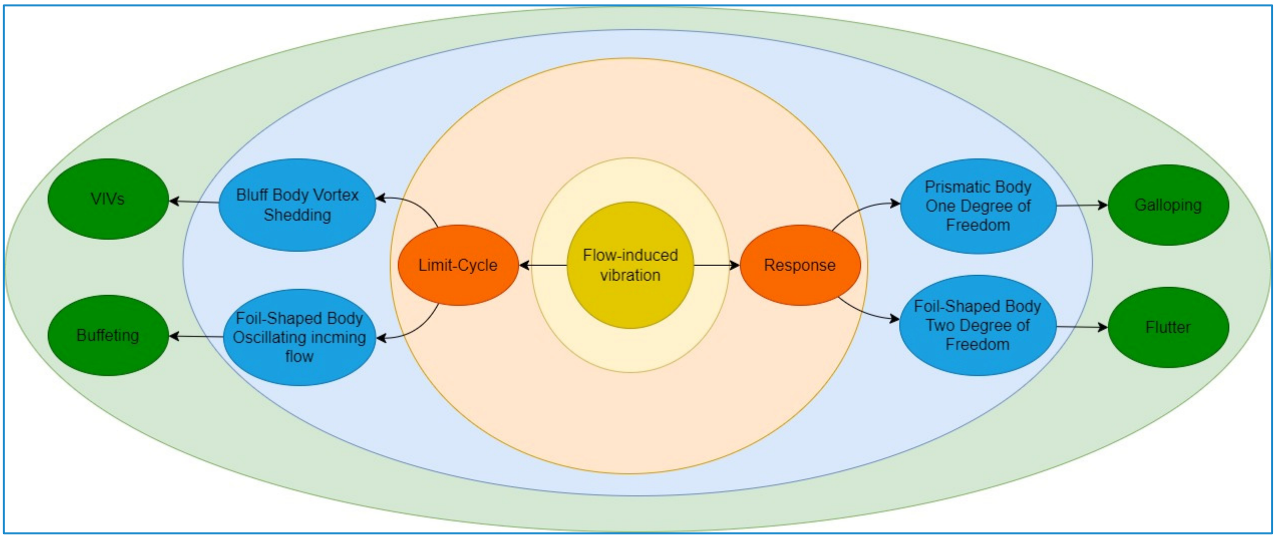

Figure 1. Categorization of different flow-induced vibrations.

Over the recent years, increased research focus has been on developing and testing various applications of energy harvester technologies to harness the unexploited renewable energy potential of kinetic energy in water systems and wind flow, as well as the various forms of ocean energy such as tides, currents, waves and thermal gradients [36,39].

Bernitsas et al. [36] proposed VIV devices that could be used to generate renewable energy from water systems and various forms of ocean energy called Vortex-Induced Vibration Aquatic Clean Energy (VIVACE). The VIVACE technology focuses on maximizing vortex shedding to exploit the vibrational energy and convert it into a clean and renewable energy source. Bernitsas et al. [36] point out that the application of VIV devices could harness and generate energy from currents as slow as 0.25 m/s, enhancing the viability of energy harvesting from ocean and river currents.

Various further testing has been conducted on the VIVACE harvester that was developed by Bernitsas et al. [36]. Dhanwani et al. [40] carried out experiments to improve the performance of the VIVACE device focused on optimizing both the spring stiffness and providing a rotational degree of freedom, achieved through asymmetric stiffnesses in the springs of the device. Allowing the system's natural frequency to vary based on the flow velocity generates vibration for energy generation for a specific flow regime. Xu et al. [41] tested the ability of a single-cylinder VIVACE device to harvest energy from FIV in shallow waters and near a free surface, showcasing the viability of a VIVACE device in these conditions.

Vasel-Be-Hagh et al. [42] present how using technologies such as VIVACE has the potential to improve and enhance the viability and efficiency of underwater compressed air energy storage (UWCAES). The experiments show that the application of VIVACE with UWCAES technology has the potential to increase the roundtrip efficiency of energy storage to approximately 97.75% in relation to the vortex hydro energy conversion efficiency rate of 37%. This shows that a hybrid VIVACE and UWCAES technology solution can potentially improve the viability of UWCAES technologies.

Aramendia et al. [11] present a novel technology concept for FIV energy harvesting in a water pipe system based on an oscillating U-shaped piezoelectric device rather than a cylinder-based device. This work highlights the deployment of a U-shaped oscillating piezoelectric device in testing scenarios where the Reynolds numbers are (Re = 3000, 6000, 9000, 12,000). These conditions have the potential to result in 34% to 65% higher energy generation capabilities in comparison to a cylinder-based device in the same scenarios. A U-shaped piezoelectric device could have significantly higher energy harvesting capabilities in water pipe systems with high energy outputs.

Kim et al. [38] explore the development of energy harvesting technology to utilize the buffering state of FIVs (see Figure 1). Kim et al. [38] propose the development of alternating-lift technologies (ALTs) using oscillating bodies like hydrofoils and/or cylinders to exploit the hydrokinetic energy from river and ocean currents. From the testing of various iterations of the ALT devices, the expected peak energy generation output was found to vary between 11 W and 194.1 W. The output depended on multiple factors such as flow velocity (m/s), size of the devices (diameter and length), technical features (spring stiffness) and number of cylinders in the device.

Qi et al. [43] present a novel hybrid piezoelectric–electromagnetic wave energy harvester (PEWEH), a device based on an encapsulated sphere design with three main components: piezoelectric sheets that move and deform in response to the movements of the waves, an electromagnetic component which is a fixed coil and a core that moves up and down and, finally, the energy storage component where the energy generated for the two components is stored. The testing shows that the PEWEH can generate electric power of 162 mW. The proposed device is seen as a tool to power sea crossing monitoring systems. It will be attached to a bridge or pier with an anchor that allows the device to move with the waves, thus generating electricity. The energy generated from this device is used to power monitoring sensors and allows for the sensor system to be self-powered and self-sufficient.

Cai et al. [44] present a small-scale piezoelectric energy harvester that could be used to harness wave motion to generate energy output. In the testing scenario, a single piezoelectric energy harvester was utilized to exploit the wave oscillations, generating a maximum output of 5 mW in field testing. In contrast, the software simulation testing scenario's maximum output was 7.3 mW.

Naqvi et al. [39] and Ma and Zhou [45] point out that in recent years, the research and development of energy harvesters that can exploit the FIV phenomenon has experienced increasing interest. This growth is resulting in various energy harvester concepts and applications being developed and tested for a wide scope of energy harvesting scenarios such as wind flow, water flow, and ocean waves [39,45].

Moreover, Ma and Zhou [45] highlight that the application and deployment of energy harvesters can be beneficial for our daily lives as well as, in some cases, national security. An energy harvester device that can harness and exploit mechanical and flow vibration for energy generation can enable further development of self-power technologies such as sensor and monitoring systems and replace the need for batteries for these kinds of systems.

1.2. Energy Harvester's Role in Energy Transition Towards Greener and Cleaner Energy Systems

The current discourse points out that energy harvesting technologies can play an enormous role in the energy transition when looking at the vast renewable energy potential held by the world's oceans. This potential is stored in the kinetic energy of the waves and tides [38,46,47], as seen in Table 1.

Table 1. Overview of the global oceans' estimated renewable energy reserves and energy generation potential [48,49].

	Wave Energy	Tidal Range (Barrage)	Tidal Stream	OTEC
Theoretical Energy Generation Potential (TWh/yr)	29,500	3	48	44,000
Current Capacity Deployment (MW/yr)	2.31	521.5	10.6	0.23

Moreover, there is estimated to be 3.1 TWh/yr of unexploited hydropower in water and wastewater networks in Europe, which can be harnessed by deploying low-impact micro hydropower technologies [50]. Also, hydrokinetic turbines in rivers have the potential of harnessing approx. 1.2 TWh/yr, and existing water wheels in old mills have the potential of harnessing approx. 1.6 TWh/yr [50].

Furthermore, there is an agreement among researchers working on energy harvesting technologies that these devices have a considerable role to play when it comes to the energy transition from fossil-based energy towards a cleaner and more sustainable energy system [13,37,40,47,51]. The application of energy harvester technologies and systems would contribute to the energy transition through, first, providing an additional renewable energy generation technology to the energy system portfolio and, second, providing access to green and renewable energy through harnessing various existing energy forces in our environment [13,41,45,52,53]. Therefore, the application of energy harvesters could enhance and ensure the supply of stable and reliable energy for some tasks and power systems that are critical to daily life. In addition, energy harvesters could improve infrastructure resilience through replacing the use of batteries in various devices and sensors. Thus, energy harvesters would enable monitoring systems to be self-sufficient and independent devices [11,13,39,43,53,54].

2. Research Methodology

This study adopted the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) [55] method for the search, review and selection of the literature [56–58]. The PRISMA framework is commonly used for systematic review and meta-analysis research activities to generate an understanding of a specific research field through gaining an overview of what has been written. This narrows the field of research and helps to identify research gaps or areas of interest [56,58].

2.1. Data Collection and Article Identification

The data collection process for this study focuses on the identification of the relevant literature to understand the application of assessment models, frameworks, and tools to assess the feasibility of integrating micro-scale energy generation technologies into an existing energy system. Scopus and Web of Science databases were used to identify peer-reviewed scientific articles using various search string combinations based on the following keywords: "Energy Harvesters", "Vortex-Induced Vibration", "Energy System", "PATs", "Feasibility", "Assessment", "Socioeconomic", "Techno-economic", "Technical", "Life Cycle Assessment", "LCA" and "Environmental Impact".

Search Strategies

The preferred keywords were identified and selected since they are closely linked to the objective of this study and were present in various articles' abstracts, titles, and keywords at the initial stage of the literature review. Table A1 in the Appendix A shows the keyword string combinations utilized in this systematic review. Consequently, these combinations with no restriction on the year of publication resulted in 1559 articles being identified during this initial keyword search as relevant to this study's objective.

2.2. Screening and Exclusion

The next step in the systematic literature process selects articles that are highly relevant to the scope and objective of this study through screening the identified articles for eligibility or exclusion based on a set of selection and exclusion criteria (See Figure 2).

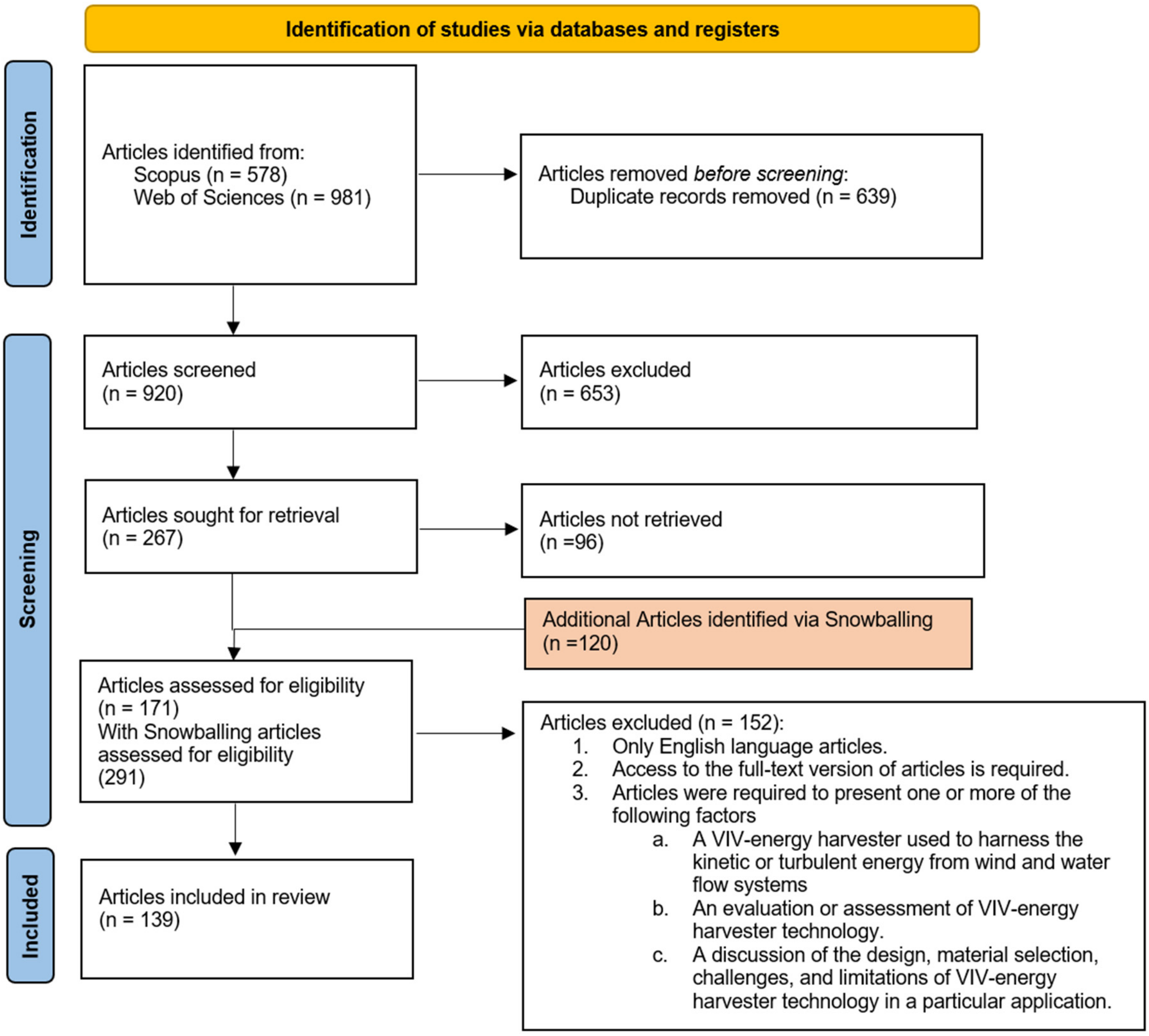

Figure 2. A PRISMA flowchart for systematic literature review was conducted in this study (Designed based on Page et al. [55]).

These criteria are as follows:

1. Only English language articles.
2. Access to the full-text version of articles is required.
3. Articles were required to present one or more of the following factors:
    (a) A VIV energy harvester used to harness the kinetic or turbulent energy from wind and water flow systems.
    (b) An evaluation or assessment of VIV energy harvester technology.
    (c) A discussion of the design, material selection, challenges, and limitations of VIV energy harvester technology in a particular application.

During the screening process, the title and abstract of the 1559 articles identified were reviewed, and the articles were divided into three categories: (a) relevant, (b) not clear, and (c) not relevant. The first round of the screening phase included three steps. The first step focused on removing duplicates with 639 articles being removed. The second step focused on screening the title and abstract, leading to the removal of a further 653 articles, and the third step focused on reviewing the remaining articles in relation to publisher restriction, i.e., paywalls. Due to a lack of access, a further 96 articles were removed. After the first round of the screening process, 171 articles remained and 120 additional articles were identified. Therefore, 291 articles were defined as eligible for the next phase in the literature review analysis process. The second step of the screening process focused on reviewing the remaining 291 articles in relation to the three eligibility criteria. As a result of these criteria, 152 articles were excluded from the analysis with the remaining 139 articles considered relevant. Then, these articles were analyzed to provide an understanding of the current field of VIV energy harvesters and the kinds of assessment frameworks used to assess their feasibility in an existing energy system.

2.3. Reviewing of Selected Articles

The selected literature was reviewed with a systematic approach accounting for geographic location, technical aspects and methods. These analyses were carried out using Microsoft Excel and VOSviewer ver. 1.6.20 [59]. They focused on gaining an overview of the assessment models, frameworks, and tools used to assess VIV energy harvesters' feasibility when integrated into existing systems. Additionally, the analysis aimed to understand if existing tools consider economic feasibility, as well as the potential environmental impacts of producing and installing VIV energy harvesters and the socioeconomic benefits of VIV energy harvesters.

Thus, the first step in the analysis was to summarize the selected articles to identify the scope of the current research on energy harvesters. This was performed in relation to a set of criteria (see Tables A2 and A3 in the Appendix A): (i) Type of study, (ii) Spatial scale of the application, (iii) Energy system dimensional scale, and (iv) Assessment dimensions–(a) Technical, (b) Environmental, (c) Economic, (d) Socioeconomic, (e) Stakeholder Engagement/Participation, (f) Risk assessment, and (g) Other dimensions. The first three steps were continuously carried out until all the selected articles were reviewed.

The second step focused on visualizing the results of the review using Excel and VOSviewer to classify the articles in relation to geographical location, application fields, journals, years, and applied methods. VOSviewer was used to map the various bibliometric linkages, such as keyword co-occurrence and overlay visualization.

The third step in the analysis was where the results were synthesized to address the focus of this study: to understand the scope of the current assessment approach for energy harvester technologies and to provide reasoning to support the development of a multidimensional feasibility assessment tool. It is significant to understand what assessment tools, methods, and models are currently being applied to conduct technical, socioeconomic and environmental impact assessment of VIV energy harvesters. Harvesters are used as additional elements to facilitate the transition towards renewable energy systems, harnessing hidden hydropower in our urban and water infrastructure and improving energy access in remote and rural communities.

3. Results and Discussion

3.1. Bibliometric Results

The PRISMA method allows for filtering and defining the relevant publications, but after that process, only 9% (139) was found to assess the feasibility of small- and micro-scale energy harvesting technologies. As stated above, 139 articles have been published on assessing the feasibility of energy harvesting technology using turbulent kinetic energy in fluid systems such as oceans, rivers, and water infrastructure. Figure 3 shows the number of publications on this topic for each year from 2006 to 2024. The data displayed in Figure 3 present the publication dynamics of articles related to the feasibility of energy harvesting technologies.

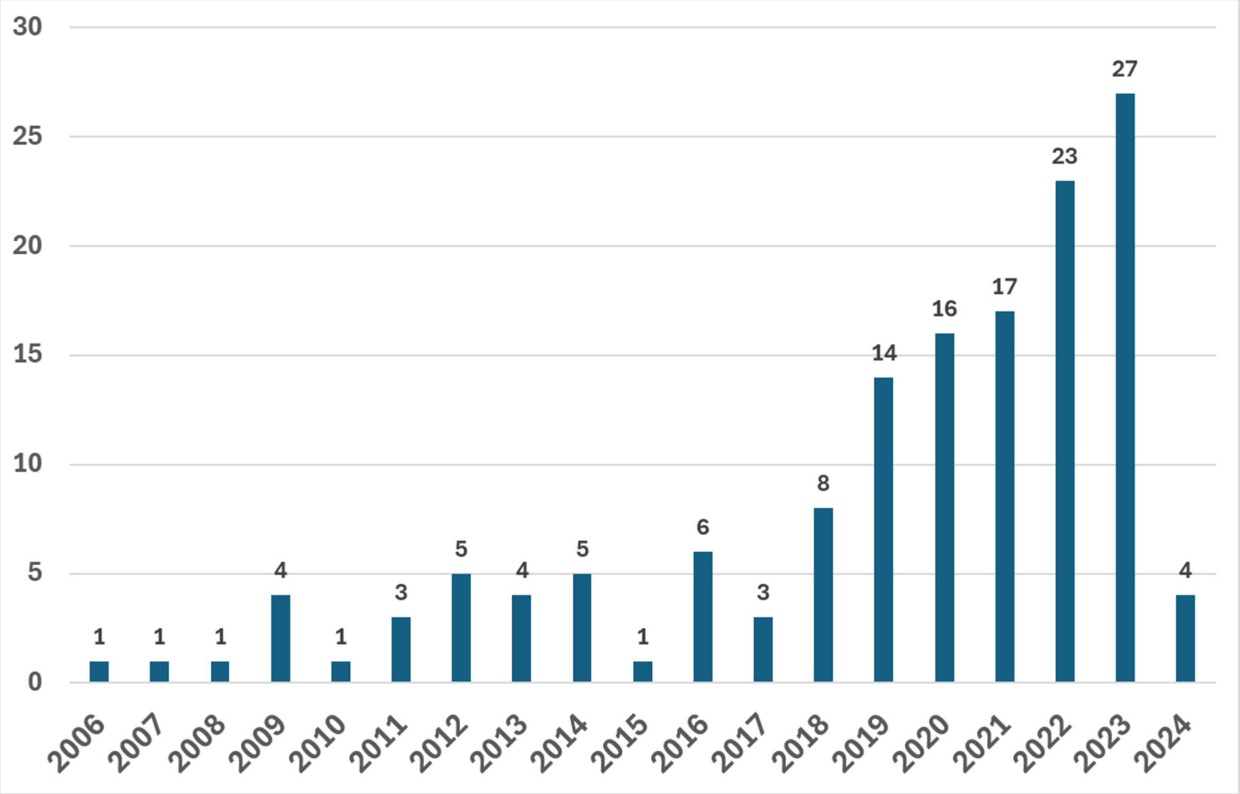

Figure 3. Number of publications assessing the feasibility of energy harvesting technologies per year.

Figure 3 shows that the publication numbers for research focusing on energy harvesting technologies and their feasibility were relatively low from 2006 to 2018. This period from 2006 to 2018 averaged three publications annually on this topic. However, from 2019 to 2023, this research area has been gaining more attention with, on average, 19.4 annual publications. This shows an exponential growth trend in publication output over this period compared with the period 2006 to 2018. This finding highlights a growing interest in energy harvesting research, which is a point highlighted in Naqvi et al. [39] and Ma and Zhou [45].

Additionally, this finding provides an indication that there is growing interest in the feasibility and application opportunities for small-scale and alternative energy generation solutions, such as the VIV energy harvester. There is interest in the potential roles these technologies can play in the energy transition, such as utilizing hidden hydropower potential in water systems [50] and bolstering resiliency in energy and water systems [43,54,60–63].

Based on looking at the geographical location of the institutional affiliation of the articles identified for the literature review and analysis, the most prolific country where researchers are looking into the feasibility and application of energy harvesting technology (see Figure 4 and Table 2 below) is China (published 55 articles), followed by the USA (published 13 articles), Italy (published 8 articles), and India (published 8 articles).

Moreover, Figure 4 shows that regionally, more researchers carried out research on this topic in Asia and other Global South regions (Articles 75), compared with North America, Europe, and other Global North regions (Articles 62).

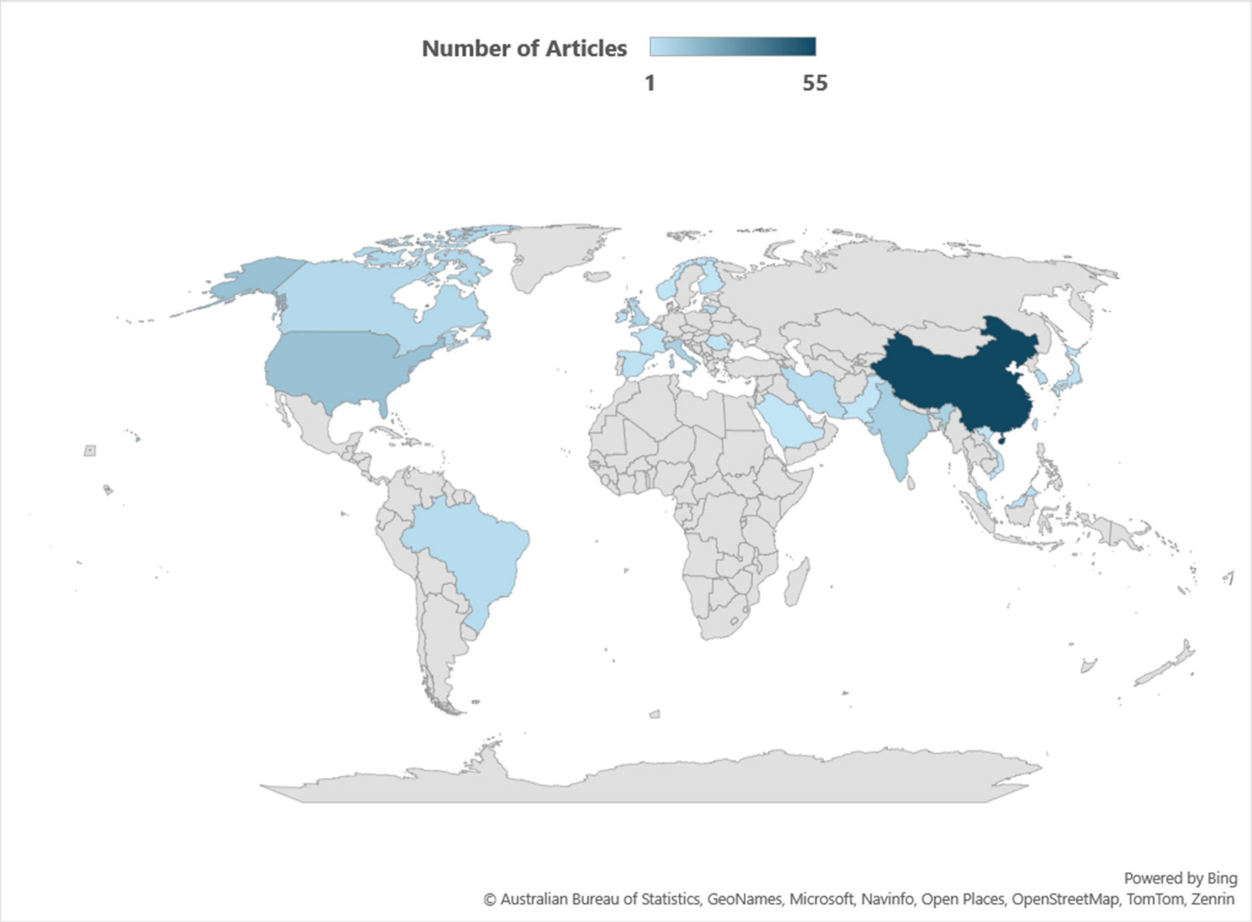

Figure 4. Geographical locations of selected publications on energy harvesters.

Table 2. Number of publications per country.

Country	Number of Articles	Country	Number of Articles
China	55	Malaysia	2
USA	13	Japan	2
India	8	Ireland	2
Italy	8	Spain	2
UK	6	Saudi Arabia	1
Singapore	6	France	1
Canada	5	Norway	1
Australia	5	Kuwait	1
Brazil	4	Romania	1
Iran	4	Pakistan	1
Republic of Korea	3	Vietnam	1
Lithuania	3	Finland	1
Taiwan	2		

The results shown in Figure 4 above highlight that Chinese authors and institutions are the most prolific when it comes to conducting research into energy harvesting technologies and their applications.

A co-authorship network analysis using VOSviewer allowed for the identification of two clusters of prolific authors working in the field of energy harvesting research. These clusters are (a) a red cluster, and (b) a blue cluster, and they are illustrated visually in Figure 5 below.

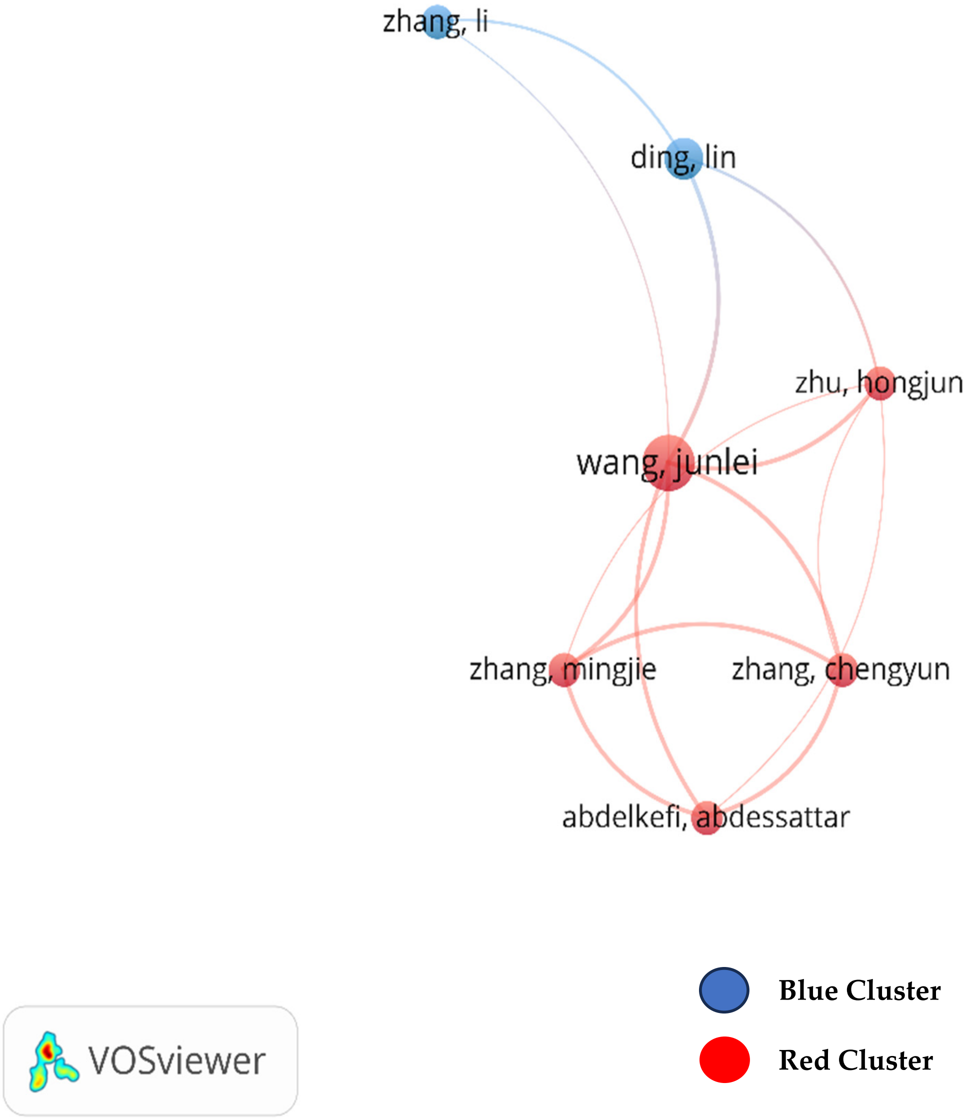

Figure 5. Author cluster—most prolific authors.

The results shown in Figure 5 above illustrate the degree of the collaborative relationship between the two clusters. For example, two authors in the red cluster tended to collaborate with authors in the blue cluster; this relatively high degree of collaboration is shown through their proximity on the diagram and number of publication co-authorships. The diagram also displays a color gradient in the link indicating the strength of this link between the authors. The red cluster indicates a higher degree of collaboration between authors, represented by the short distance between authors' nodes and strong color strength of the links between the authors. This degree of closeness between authors makes it easier for them to collaborate, share information and build a stronger collaborative research relationship. The author's article list and citation are presented in Table 3 below.

Table 3. Papers associated with the authors identified in most prolific authors' cluster.

Authors	Year	Title	Journal	Number of Citation
Abdessattar Abdelkefi; Muhammad R. Hajj; Ali H. Nayfeh	2012	Phenomena and modeling of piezoelectric energy harvesting from freely oscillating cylinders	Nonlinear Dynamics	127
Abdessattar Abdelkefi	2016	Aeroelastic energy harvesting: A review	International Journal of Engineering Science	503
Lei Zhang; H. L. Dai; Abdessattar Abdelkefi; Lin Wang	2019	Experimental investigation of aerodynamic energy harvester with different interference cylinder cross-sections	Energy	104
Junlei Wang; Linfeng Geng; Lin Ding; Hongjun Zhu; Daniil Yurchenko	2020	The state-of-the-art review on energy harvesting from flow-induced vibrations	Applied Energy	490
Junlei Wang; Zhen Su; Hang Li; Lin Ding; Hongjun Zhu; Oleg Gaidai	2020	Imposing a wake effect to improve clean marine energy harvesting by flow-induced vibrations	Ocean Engineering	58
Lin Ding; Xiangxi Mao; Lin Yang; Bowen Yan; Junlei Wang; Li Zhang	2021	Effects of installation position of fin-shaped rods on wind-induced vibration and energy harvesting of aeroelastic energy converter	Smart Materials and Structures	31
Mingjie Zhang; Chengyun Zhang; Abdessattar Abdelkefi; Yu Haiyan; Oleg Gaidai; Xiang Qin; Hongjun Zhu; Junlei Wang	2021	Piezoelectric energy harvesting from vortex-induced vibration of a circular cylinder: Effect of Reynolds number	Ocean Engineering	49
Junlei Wang; Chengyun Zhang; Mingjie Zhang; Abdessattar Abdelkefi; Yu Haiyan; Xiaomeng Ge; Huadong Liu	2021	Enhancing energy harvesting from flow-induced vibrations of a circular cylinder using a downstream rectangular plate: An experimental study	International Journal of Mechanical Sciences	44
Junlei Wang; Chengyun Zhang; Daniil Yurchenko; Abdessattar Abdelkefi; Mingjie Zhang; Huadong Liu	2022	Usefulness of inclined circular cylinders for designing ultra-wide bandwidth piezoelectric energy harvesters: Experiments and computational investigations	Energy	24
U. Latif; M. Y. Younis; Emad Uddin; Z. Ali; A. Mubashar; Abdessattar Abdelkefi	2023	Impact of solid and hollow bluff bodies on the performance and dynamics of flag-based energy harvester	Sustainable Energy Technologies and Assessments	9

Abdelkefi et al. [64] investigated the energy generation potential of harvesting the kinetic energy from VIVs of a rigid circular cylinder that can move without a high degree of restriction. The device has a piezoelectric transducer that extends across its degree of freedom to capture the kinetic energy from its movements. The results showed that changes in the load resistance do impact the onset of synchronization between the shedding frequency and cylinder frequency and that a higher resistance load allows the device to harness energy at higher freestream velocities. The conclusion pointed out that a VIV energy harvester with a piezoelectric transducer could be applied in different regions of freestream velocities. Abdelkefi [28] reviewed the different types of aeroelastic mechanisms and mathematical models used to assess the energy generation feasibility of the various aeroelastic mechanisms. VIV energy harvesting was one of the mechanisms reviewed by the authors. The author's analysis points out that the VIV energy harvester based on circular cylinder design generates only between 0.004 mW and 0.1 mW in comparison to other energy harvesting mechanisms reviewed in the study. For example, flutter generates 0.2 to 2.2 mW, and galloping 0.22 to 8.4 mW. The author also identifies that the key limitation to the cylinder-based VIV energy harvester is that these devices cannot operate in a system where there is a range of velocities with frequent changes. The energy generation capabilities of these devices are dependent on well-defined lock-in conditions of the velocity in the system, meaning that any changes in the system velocity can impact the energy generation capabilities and output of the device. The authors point out that energy harvesting devices could help replace the use of small battery-powered monitoring systems with self-powered devices and monitoring systems. Lastly, the authors highlight the wide range of applications and possibilities for energy harvester technologies such as urban areas and buildings, rivers and streams, high wind areas, and ventilation and air duct systems in buildings and streets.

Lei Zhang et al. [65] explore different designs of interference cylinders (ICs) to understand how these ICs would enhance the capabilities of piezoelectric energy harvesters to harness kinetic energy from aerodynamic oscillations. The authors investigate various designs of the IC cylinder, including square, circular, and triangular shapes, to determine the effectiveness of these designs in enhancing the harnessing capabilities of an energy harvester over a wide range of wind speeds and velocities. The findings highlight that the square configuration of the IC performs better than circular and triangular IC designs since those designs negatively impact wind speed and velocity, leading to significantly lower power output than the square design. The square design increases the synchronization region or lock-in state of the device by 380% compared to a device configuration without an IC. The average power output achieved by this configuration is 803.4 µW at a wind speed of 2.36 m/s with a spacing ration of 0.9 between the energy harvester and the IC. The findings point out that the deployment of IC as part of an energy harvester design and configuration could lead to improved effectiveness of the energy harvester device to harness the kinetic energy of vortex-induced vibrations.

Junlei Wang et al. [37] review the current literature and work on the development of hydro and wind energy harvesters based on the principles of flow-induced vibration. The authors highlight that the energy output from VIV energy harvesters can range between 0.0289 mW at a fluid velocity of 2.8 m/s and a maximum power output of 80 mW at 0.18 m/s based on device configuration and design. Additionally, the authors point out that the power output potential of an energy harvester harnessing the kinetic energy in flow-induced vibrations can range from 1.02 µW at 0.33 m/s to 470 kW at 5 m/s. These generating capabilities are closely connected to the device configuration design, the fluid velocity range and lock-in condition.

Next, the authors highlight the key limitations and challenges facing energy harvesting technology, such as the immaturity of the technology and the complexity of harnessing energy under complex conditions. These factors impact the energy-harvesting efficiency and size limitation of these devices, which leads to questions of feasibility and intermittency. Consistent power generation from these devices is necessary to provide stable energy sources for technologies like self-powered sensors and monitoring systems. There are several other challenging and limiting factors. First, the cost of energy harvesting technology in relation to energy output when compared to other renewable energy sources needs to be addressed. Specifically, maintenance and operation costs over the device's lifetime are uncertain. A second challenge is the deployment of devices in real conditions and environments, specifically protecting the devices and their equipment from damage in extreme conditions to ensure optimal lifetime and power generation of the devices. Minimizing the environmental impact on surrounding ecosystems also becomes an important consideration in real-world conditions. The author emphasizes that the field of energy harvesting technologies requires further research and testing of the devices in real conditions, the design and configuration, and the material selection of the devices to improve efficiency in power generation.

Junlei Wang et al. [66] explore the impacts of introducing stationary interfering cylinders (SICs) on the capability of energy harvesting devices. SICs can create various wake interference conditions that impact the harvester's ability to harness kinetic energy. Therefore, consequently, impacting the energy generation potential of the energy harvesting device. Thus, an energy harvesting device with a cylinder design accompanied by an SIC does enhance the energy harnessing capabilities and energy conversion efficiency of an energy harvester by 10.13%. The authors point out that the addition of interfering cylinders to energy harvesting devices has a beneficial impact on the efficiency of the energy harvesting of flow-induced vibrations such as in rivers, streams and oceans.

Lin Ding et al. [67] investigated the effects of placing fin-shaped rods (FSRs) on circular cylinder energy harvester devices in wind flows. The authors used experimental and numerical methods to assess the optimal placement of the FSRs and to understand the impacts of attaching FSRs to circular cylinder energy harvesting devices in terms of devices' vibration response. The findings highlighted that the placement of FSRs on circular cylinder energy harvesting devices can enhance the capabilities of the devices to harness energy from wind-induced cylinder vibration. Also, the optimal placement of the FSRs was found to be at an installation angle of 60 degrees, which results in a device output of 18.1 V and 1.645 mW at a wind speed of 6.8 m/s.

Mingjie Zhang et al. [12] investigated the relationship between the Reynolds number (Re) and the energy harvesting performance of piezoelectric and circular cylinder-designed devices in VIV conditions. The results highlight that increasing the Reynolds number leads to a wider lock-in region of the VIV energy harvesting device, which in turn leads to increased power generation capabilities. For example, at Re = 500, the maximum power output is 7.9 mW, whereas at Re = 30,000, the maximum power output is 34.5 mW. However, the VIV energy harvesting device is highly sensitive to mechanical damping at high Reynolds numbers, which has diminishing effects on the overall power output of the device. For example, a high mechanical damping ratio leads to exponential decay of device power output. The study highlights the importance of understanding and accounting for the Reynolds number effect when designing a VIV piezoelectric energy harvester.

Junlei Wang et al. [68] explore the effect of placing a small rectangular interfering plate downstream as part of a circular cylinder-based energy harvester to harness the kinetic energy from wind energy. The introduction of the rectangular interfering plate seems to enhance the energy harvester's capabilities to generate power at a wider range of wind speeds and higher velocities, thereby improving the overall power output from the energy harvester. The results point out that the optimal design configuration and placement of the rectangular interfering plate would be a plate with twice the cylinder diameter (2D [D = Cylinder Diameter]) of the energy harvester. The spacing between the energy harvester and the interfering plate would be 0.2D to 0.4D downstream. Altering the placement and configuration of the rectangular interfering plates would be an effective method to enhance the energy harvesting capabilities of the cylinder-based energy harvesters.

Junlei Wang et al. [69] investigated how the use of an inclined circular cylinder configuration can enhance the performance of a piezoelectric cylinder-based energy harvester in comparison to a vertical cylinder. The results pointed out that the inclined cylinder configuration increases the energy harvester's capabilities to harness kinetic energy at a wider velocity lock-in range, which enhances the robustness and usability of the energy harvester. This increased capability of enhanced power harnessing at a wider velocity range comes with a diminished maximum power output since the design is not optimized for power output but a wider velocity range.

Latif et al. [29] assess the energy harvesting potential and performance of a flag-shaped piezoelectric membrane when an IC is installed upstream of the energy harvester in a water channel. The results show that the installation of a C-shaped IC increases both the flapping amplitude and energy harvesting potential, with the energy harvesting potential increasing by 35% at a velocity of 0.26 m/s using a spacing ratio of 2.5D. This demonstrates that the installation of an inverted hollow C-shaped IC upstream improves the energy harvesting performance of a piezoelectric membrane-based energy harvester significantly and enhances energy harvester capabilities to harness the kinetic energy of fluid flows at a threshold velocity of 0.2 m/s.

Considering the research areas of the prolific authors presented in Table 3 and described above, it is possible to state that the optimal design of energy harvesters for harnessing flow-induced vibrational energy still requires further research before being tested in real conditions and environments. This is further supported by Table 4, which shows that most of the reviewed papers focus on experimental testing of various energy harvester configurations in different velocity conditions with a limited number conducting real-world case studies.

Table 4. Ratio of articles describing experimental data and case studies.

Type of Studies	Number of Articles	Relative %
Applications in Case Study	23	17%
Experimental Data	116	83%

These experimental studies, important when it comes to the development, design and application of energy harvesters, are experimental research activities that focus on identifying the optimal state for energy generation in terms of water velocity (m/s), shedding frequency (rad/s or Hz), power generation resistance (Ohm), and material composition.

Table 5 presents that current research into the potential application of energy harvester devices focus on the ability to deploy these devices as additional and secondary devices. The VIV energy harvesters are designed to harness the kinetic energy in both built and natural water distribution systems. Additionally, VIV energy harvesters can work in synergy with wind energy technologies to further harness the energy potential of wind, and they can also harness additional energy from the aerodynamic conditions on aircraft and fighter jets to power monitoring sensors.

Table 5. The application area of VIV energy harvesting research.

Application Area	Number of Articles	Relative %	Example of Research Area
Wind	15	11%	- Aerodynamics [65] - Aerospace [70,71]
Water	26	19%	- Tidal Energy [72] - Wave Energy [5,63] - Seabed [73] - Wastewater [74]
Unclear/Uncategorized	98	70%	

Table 6 illustrates that energy harvester devices are seen as additional and secondary electricity generation devices to power various types of small-scale systems. These types of systems currently rely on, for example, batteries as energy sources. In addition, this table highlights that a limited amount of research is being carried out looking at the whole system integration and application of energy harvester devices.

Small-scale systems can, for example, be monitoring systems for various critical elements of the existing energy and water system infrastructure [43,54,60]. The use of energy harvesting devices can improve the resilience of these monitoring systems since localized energy harvester devices would allow the systems to become self-powered and less reliant on batteries or other external energy sources [61–63]. Looking at the chronological development of the research field around energy harvesters, the general trend shows that the interest and research in energy harvesting technologies has grown in recent years. This is highlighted by increased publications in this field as shown in Figure 3 above and further supported by Figure 6 below.

Table 6. Number of articles assessing harvesters in energy systems and system analysis frameworks.

Spatial Scale on EH Application	Number of Articles	Relative %
Whole System	10	7%
Integration as a Large-Scale Solution	5	3.5%
Integration as a Small-Scale Solution	18	13%
Integration as Hybrid Solutions	7	5%
Micro-Scale Device	45	32%
Unclear/Uncategorized	54	39%

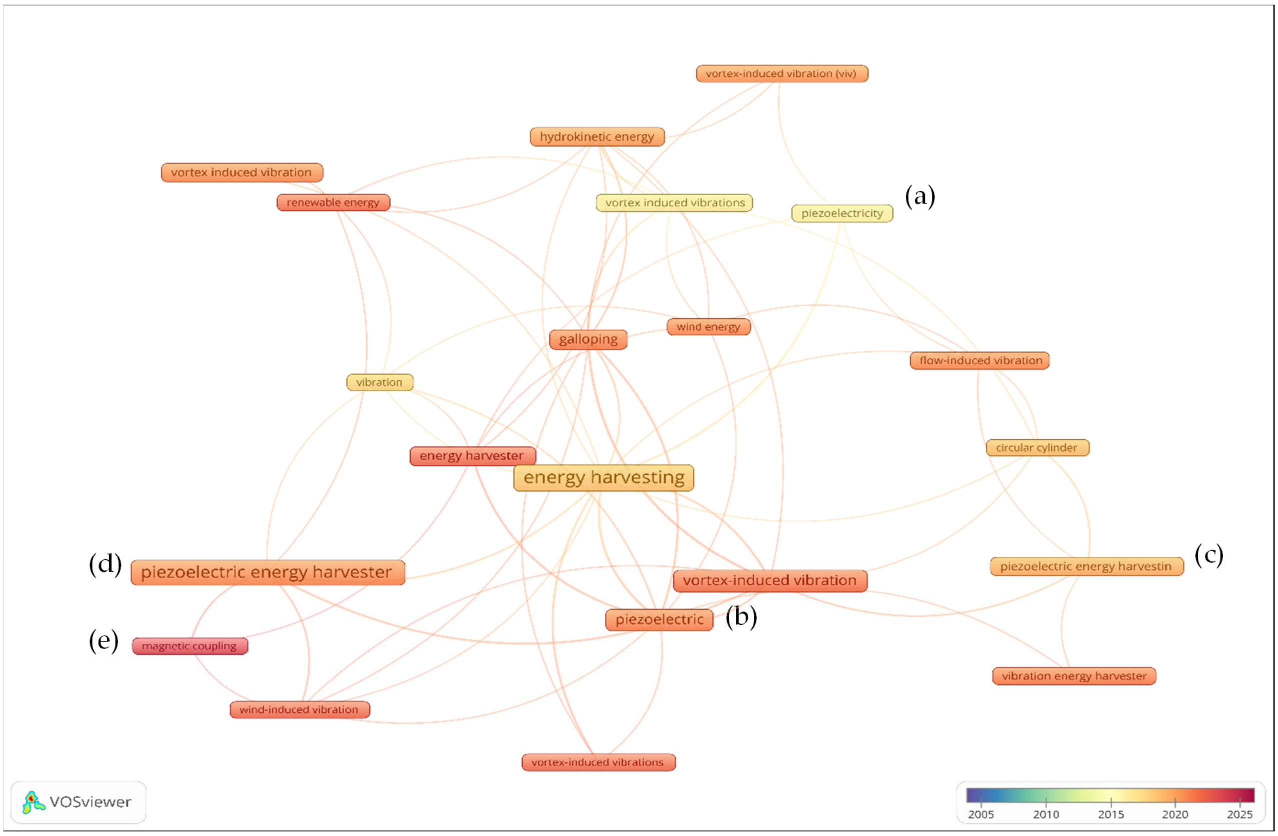

Figure 6. (**a**)–(**e**) Chronological illustration of interest and trends in the field of energy harvesters technology and energy harvesting of flow-induced vibration.

Figure 6 shows that, based on the reviewed papers, the focus on piezoelectric materials in energy harvesting has increased since 2015 [75–77]. This focus is visually illustrated in the figure by four boxes: (a) piezoelectricity in light yellow indicating research conducted before the year 2015, (b) piezoelectricity in light orange indicating research conducted between 2015 and 2020, (c) piezoelectricity in darker orange indicating research conducted around the year 2020, and (d) piezoelectricity in red indicating research conducted after 2020. Around 2020, additional research has focused on the impact of introducing a magnetic coupling component to the energy harvester configuration [78–80]. This focus is visually illustrated by one box in the left corner of Figure 7, (e) magnetic coupling in dark red indicating research conducted around and after 2020.

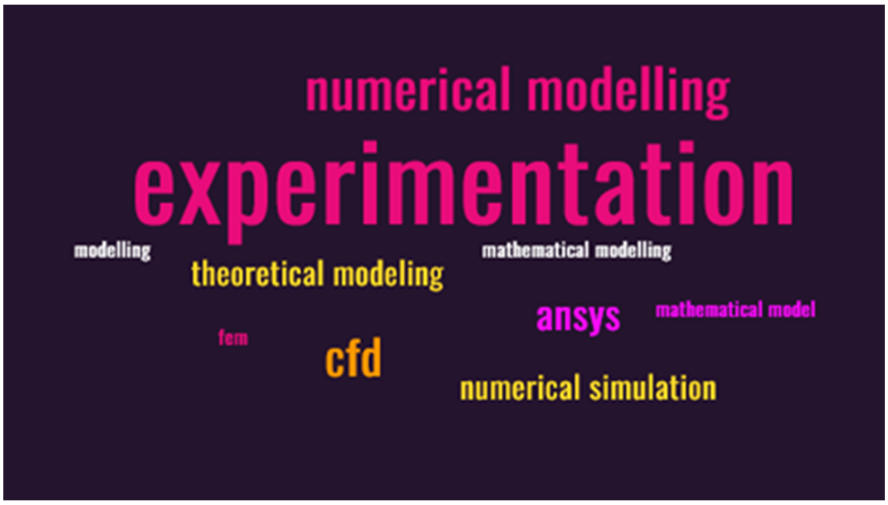

Figure 7. Wordcloud shows the most used methods and software used to assess the design configuration and technical feasibility of energy harvesters.

These years have been pivotal in creating an understanding of the stability and identifying the application area of energy harvesters as micro-scale renewable energy technologies in pre-existing modern infrastructure systems [28,37]. Research in the recent years has helped shape technological understanding, which has boosted further research and development of energy harvester technologies.

3.2. Reasoning for Developing a Multidimensional Technology Feasibility Assessment for Energy Harvesting Technology

Table 7 highlights the results of the content analysis. It shows that assessing and understanding technical feasibility is currently the core research focus of energy harvester development and deployment. In addition, it shows that a comprehensive feasibility assessment to support the successful deployment of energy harvesting technology requires a multidimensional approach. There are a range of factors that are important to decision-makers and users when it comes to understanding the overall feasibility of the devices, necessitating a more detailed framework than an isolated technical assessment.

It is understandable that most of the reviewed papers are technically oriented since the majority of piezoelectric energy harvester configurations are still considered early development. This technology tends to have Technology Readiness Levels (TRLs) of less than TRL3; hence, experiments and proof-of-concepts are still the focus of research. Figure 7 illustrates that analytical, mathematical, and theoretical modeling are the most prominent methods used to carry out computational fluid dynamics and finite element analysis in synergy with experiments (as shown in Table 2). Experimentation is the foundation of the technical assessments carried out to understand the feasibility of the energy harvester devices to harness the kinetic energy from flow-induced vibration. These methods and assessment tools allow for development of technical aspects such as material selection, interactions between the device and water environment and interactions between different components of the devices. They give an understanding of a device's robustness in simulated and controlled experimental environments that closely replicate the real conditions, a critical factor when it comes to technology development and design. Experimental tests help identify any potential issues in the design of an energy harvester as well as any potential failure points when it comes to deploying energy harvester technology in real conditions [61,74,81,82]. Therefore, understanding the technical feasibility of new technology, such as the VIV energy harvester, is an important research activity when it comes to developing energy harvesting devices that can play a part in supporting the system retrofitting that is required. Energy harvesters have a role in further digitalization of the energy, water, and urban infrastructure systems [39,44]. However, Table 5 highlights that understanding other dimensions—such as the technology's environmental impacts, ecological footprint and social benefits from the deployment of the device—can be critical for the successful deployment and application of an energy harvester.

Table 7. The current assessment area focuses on assessing energy harvester technologies.

Assessment Area	Number of Articles	Relative %	Key Assessment Metrics
Technical Scale	131	94%	Technical Metrics - Flow Characteristics - Energy Conversion Performance - Energy Extraction Performance - Cylinder Configuration and Design - Material Behavior - Predictive Failure Points
Social Scale	2	1%	Social Metrics - Community Preferences - Social Gains/Benefits
Economic Scale	6	4%	Economic Metrics - Level Cost of Energy - Capital Costs (CAPEX) - Operation and Maintenance Cost (OPEX) - Cost of Materials - Cost of Device Components
Environmental Scale	5	3%	Environmental Metrics - Impact from Material Extraction - Effect on Water Quality - Effect on Ecosystems
Risk Assessment	4	3%	
Stakeholder Engagement	1	1%	

3.2.1. Economic

Carrying out an analysis of economic factors can highlight the cost-effectiveness of a specific harvester design. This will be a function of the device's reliability, material selection, or power generation, which gives the potential user critical information for decision-making. The ability to provide this information on device design can clearly indicate whether a specific energy harvester device is suitable for a specific user application. Providing economic input during the design phase improves the successful deployment of the energy harvester device [4,72,74,83].

3.2.2. Environment

Analyzing certain environmental factors—such as the impacts of technology installation on the local ecosystems' fauna and flora—is often crucial information for a project in terms of understanding the environmental impact of the technology [10,84]. Furthermore, this type of analysis and information is often important when it comes to obtaining critical permits and licenses from the local governments for technology installation. Therefore, understanding the environmental impacts of the technology and devices is necessary when it comes to ensuring successful deployment of the devices [84].

3.2.3. Social

Including an analysis of the local community's perspective and attitudes toward new technology deployment helps to identify potential socioeconomic gains and benefits obtained from the installation of the technology. This knowledge can be critical for the successful implementation and application of technology within the local community [60].

The results and discussion highlight the complexity of assessing new technology and the importance of providing key information to the decision-maker and potential user that covers technical, economic, and environmental feasibility, as well as any social benefits attributable to the deployment of the technology.

3.3. Challenges

This systematic review highlights the need for the development of an assessment framework that can assess emerging technologies and their associated impacts and benefits. Assessment of VIV energy harvesters will require a wide range of assessment parameters. Xue et al. [85] point out that the selection of the most relevant assessment factors and parameters is the key challenge to developing any assessment tool. Especially when the objective is to deliver an assessment tool that gives insights into the impacts of a new technology or system retrofit, careful selection of assessment parameters is critical [85].

4. Conclusions and Limitations

This research carried out a systematic review and examined 139 publications focusing on alternative small-scale technologies for energy generation based on harnessing unexploited energy from flow-induced vibration. A thorough analysis was carried out to identify current trends in assessing the feasibility of these small-scale energy technologies as well as the status of energy harvester technology readiness. Research on energy harvesters emerged about a decade ago and has increased annually by about 10% in terms of published papers. In recent years, about 20 papers have been published per year in comparison to 3 papers published on average per year between 2006 and 2018. During the review process, it was identified that China has emerged as the most prolific country in terms of research output relevant to the development of energy harvester technology and assessment of the technical feasibility of energy harvesters.

The findings of this systematic review provide insightful information that further enriches the understanding of the current developments and trends in the domain of energy harvesters and technology feasibility assessment. The results highlight the current research trends towards understanding the technical feasibility of energy harvester devices by understanding (a) the design configuration of the energy harvester, and (b) the best suitable application environment or placement of the devices to ensure optimal power generation.

Moreover, the results presented identify that there is a lack of assessment tools and models to assess feasibility across all stages of development. In particular, the literature lacks multidimensional analysis frameworks accounting for social, environmental, economic, and risk aspects of VIV energy harvesters. Therefore, the results establish a grounded reason for developing an assessment framework to carry out a multidimensional assessment of the feasibility of VIV energy harvesters considering (i) technical feasibility, (ii) economic feasibility, (iii) ecological impact, and (iv) any localized societal benefits. The full potential of the deployment of small- or micro-scale energy harvesting technologies into a local energy system to harness the energy potential of local water infrastructure, rivers, and lakes could be assessed with such a framework.

Limitations and Next Research Steps

As with other systematic reviews, this study has certain limitations that are important to acknowledge. These limitations pertain to the keyword selection for the Boolean search in the systematic review process. Some may suggest that other keywords should have been used and/or question why certain keywords or search combinations were used in the identification of relevant papers during the initial steps in the review process. The keywords were selected based on the extensive pre-review of papers relevant to the research topic and through discussion with the research team to ensure that the keywords were highly relevant and fit the objective and scope of the research output. It is essential to keep in mind that this research involves the development of a multidimensional feasibility framework for energy harvesters designed by the H-Hope project and will be applicable to other energy harvester configurations. Therefore, this paper presents the reasoning for the development of the feasibility assessment framework, provides vital groundwork for the work ahead, and highlights the complexity of developing this framework. Further work in the development of the feasibility assessment tool will include close integration of technical and theoretical results from H-Hope energy harvester design and development. The initial work on framework development has started and is presented in Gudlaugsson et al. [86].

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

VIV	Vortex-induced vibration
FIV	Flow-induced vibration
UWCAES	Underwater Compressed Air Energy Storage
VIVACE	Vortex-Induced Vibration Aquatic Clean Energy
PEWEH	Piezoelectric–electromagnetic wave energy harvester
PRISMA	Systematic Review And Meta-Analysis
IC	Interference cylinder
FSRs	Fin-shaped rods
EH	Energy harvester
TRL	Technology Readiness Level

Appendix A

Table A1. Literature review keyword search string combinations.

	Search String Combination
1	"Energy System" AND "Feasibility Assessment"
2	"Vortex Induced Vibration" OR "Energy Harvester" AND "Technoeconomic" AND "Assessment"
3	"Energy Harvester" AND "Feasibility Assessment"
4	energy harvester OR "Vortex Induced Vibration" AND "Technical"
5	energy harvester OR "Vortex Induced Vibration" AND "Technical" AND "Assessment"
6	Energy Harvester OR "Vortex Induced Vibration" AND "socioeconomic" AND "Assessment"
7	Energy Harvester OR "Vortex Induced Vibration" AND "Technoeconomic" AND "Assessment"
8	Energy Harvester OR "Vortex Induced Vibration" AND "Feasibility" AND "Assessment"
9	"Vortex induced vibration" AND "life cycle assessment"
10	"Vortex induced vibration" AND "environmental impact"
11	"Energy harvester" AND "life cycle assessment"
12	"Energy harvester" AND "environmental impact"
13	"Energy system" AND "life cycle assessment"
14	"Energy system" AND "environmental impact"

Table A2. Overview assessment of identified assessment frameworks, models, and tools.

Reference:	Case Study	Experimental Data	Software or Method(s)	Geographical Location	Global	Geographic Regions	National	Local Region	Community and City Scale	Whole System	Integration as Large Scale Solutions	Integration as Small-Scale Solutions	Integration as Hybrid Solutions	Micro-Scale Devices
H. Farokhi and M.H. Ghayesh 2019		x	use of the nonlinear Euler–Bernoulli beam theory		x									x
J.Kan et al., 2023		x	CFD, two-degree-of-freedom (2-DOF) lumped parameter model	Jinhuan, China										x
L. He et al., 2023		x	ANSYS and experimentation	Jilin, China	x—focus on wider application of proposed design								x	
l. He et al., 2024		x	ANSYS and experimentation	Changchun, China									x	
Rostami and Armandei 2017			review paper	Rio de Janeiro, Brazil	x							x		
A.Barrero-Gil et al., 2012		x	CFD (1-DOF model)	Madrid, Spain										
Vasel-Be-Hagh et al., 2014		x	technical note paper	Windsor, Ontario, Canada				x					x	
Aabid et al., 2021			review paper			x—focus on the piezolectric material								
Abdelkefi 2016			review paper	USA	x									x
Abdelkefi et al., 2012		x	mathematical model, linear analysis (Pol equation and the Gauss Law)	Virginia Tech, USA										x
Abdulkhaliq et al., 2023		x	simulations, and experimentation—using a small-scale prototype	Cranfield, UK	x							x		

Table A2. *Cont.*

Reference:	Case Study	Experimental Data	Software or Method(s)	Geographical Location	Global	Geographic Regions	National	Local Region	Community and City Scale	Whole System	Integration as Large Scale Solutions	Integration as Small-Scale Solutions	Integration as Hybrid Solutions	Micro-Scale Devices
Hu et al., 2009		x	mathematical model	Wuhan, China										x
Marqui Junior et al., 2009	x	x	electromechanical FE plate model	Virginia Tech, USA, Sao Paulo, Brazil	x								x	
Erturk and Inman 2009		x	mathematical model—close-form analytical solution based on Euler–Bernoulli beam assumption	Virginia Tech, USA	x									x
Aramendia et al., 2019		x	Adaptive Differential Evolution (DE)-based (JADE) algorithm, Multivariable JADE algorithm, CFD software	Vitoria-Gasteiz, Spain	x									x
Araujo, da Silva and Marques 2022		x	Van der Pols wake model, particleswarm optimization (PSO) method	Sao Carlos, Brazil										x
Azam et al., 2019		x	prototype and experimentation; The National Instruments (USB-6211 Data acquisition device), Arduino Uno microcontroller, and LabVIEW	Kuala Lumpur, Malaysia										x
B.Zhang et al., 2018	(x)	x	CFD software fluent, time-step independence validation	Xi’an, China	x							x		

Table A2. *Cont.*

Reference:	Case Study	Experimental Data	Software or Method(s)	Geographical Location	Global	Geographic Regions	National	Local Region	Community and City Scale	Whole System	Integration as Large Scale Solutions	Integration as Small-Scale Solutions	Integration as Hybrid Solutions	Micro-Scale Devices
B.Zhang et al., 2022	(x)	x	Two-way CFD model, FSI simulation method	Beijing, China	x							x		
Bernitasa_and_Diaz_2006	x		project summary report	Michigan, USA	x							x		
Burda 2022		x	Matlab	Romania	x									x
Cepenas et al., 2020		x	COMSOL Multiphysics software	Lithuania	x									x
Ceponis et al., 2019		x	COMSOL Multiphysics software	Lithuania										x
Ceponis et al., 2022		x	Comsol Multiphysics	Lithuania										x
Chong Li and Lv 2023		x	COMSOL software	China	x									x
Costanzo et al., 2023		x	MatLab	Italy										x
Daqaq 2012		x	mathematical model	USA										
Lu et al., 2022		x	MatLab	Singapore, China	x									x
Del Priore et al., 2023		x	Simulink	Italy										x
Kim et al., 2023		x	experimental setup	China										x
E.S. Kim et al., 2021	x	x	case study analysis	South Korea, USA			x					x		
Li., H. et al., 2014			review paper	USA										
Erturk et al., 2009	x	x	electromechanical model	USA				x						x
Abrol and Chhabra 2018		x	experimental setup	India					x					x

Table A2. *Cont.*

Reference:	Case Study	Experimental Data	Software or Method(s)	Geographical Location	Global	Geographic Regions	National	Local Region	Community and City Scale	Whole System	Integration as Large Scale Solutions	Integration as Small-Scale Solutions	Integration as Hybrid Solutions	Micro-Scale Devices
Franzine and Bunzel 2018		x	Matlab and numerical Model	Brazil										x
Ghazanfarian et al. 2021			review paper	Iran and USA										
Han et al., 2022		x	COMSOL Multiphysics software	China					x					x
Erturk and Inman 2008			review and discussion paper	USA										
J. Wang et al., 2020			review paper	China and UK									x	
Jin et al., 2020		x	experimental setup	China	x									x
Narendran et al., 2016		x	experimental setup	India	x								x	
Kang et al., 2016			review paper	South Korea, USA					x					x
Khojasteh et al., 2023			review paper	Australia, UK, Finland, Iran, Ireland, USA										
Kong et al., 2010		x	experimental setup	USA										x
Kumar and Sarkar 2016			review paper	India	x								x	
Kumar and Sourav 2023		x	experimental setup and numerical model	India and USA	x									x
L.B. Zhang et al. 2019		x	experimental setup and numerical model	China and Singapore	x									x
L.B. Zhang et al. 2019		x	experimental setup	China and USA	x									x

Table A2. *Cont.*

Reference:	Case Study	Experimental Data	Software or Method(s)	Geographical Location	Global	Geographic Regions	National	Local Region	Community and City Scale	Whole System	Integration as Large Scale Solutions	Integration as Small-Scale Solutions	Integration as Hybrid Solutions	Micro-Scale Devices
Cimorelli et al., 2020	x	x	numerical model (nonlinear programming algorithm)	Italy	x									x
Lei and Sun 2023		x	experimental setup	China					x					x
Li et al., 2019		x	experimental setup	China	x									x
Modir and Goudarzi 2019		x	analytical modeling and experimentation	Florida, United States	x									
Li et al., 2021		x	numerical simulation and experimentation	Zhengzhou, China	x									
Kuriyama et al., 2020		x	prototype and experiementation	Kiryu, Japan	x									
Du et al., 2023		x	finite element simulation and experimentation	Huainan, China		x—for deployment in mines						x		
Deng et al., 2014		x	theoretical and computational modeling	Houston, United States	x									
Bowen et al., 2014		x	review paper	Bath, United Kingdom	x									
Zanelli et al., 2022	x		field test	Milan, Italy		x—deployment on power lines					x			
Naqvi et al., 2022		x	review paper	Haripur, Pakistan	x									

Table A2. *Cont.*

Reference:	Case Study	Experimental Data	Software or Method(s)	Geographical Location	Global	Geographic Regions	National	Local Region	Community and City Scale	Whole System	Integration as Large Scale Solutions	Integration as Small-Scale Solutions	Integration as Hybrid Solutions	Micro-Scale Devices
Park et al., 2023		x	experimentation	Ann Arbor, United States				x—tidal energy deployment			x			
Wang et al., 2020		x	numerical modeling and experimentation	Zhengzhou, China	x									
Wang et al., 2022		x	CFD modeling	Zhengzhou, China	x									
Younis et al., 2022		x	CFD simulation	Safat, Kuwait	x									
Mehdipour et al., 2022		x	CFD analysis	Arnesano, Italy	x									
Rabiee and Esmaeili 2023		x	numerical analysis	Arak, Iran	x									
Simiao and Bernitsas 2013	x		prototype and experiementation	Michigan, USA		x								
Weller et al., 2013	x		best practice report	Exeter, United Kingdom	x									
Wang and Ng 2023		x	CFD modleing	Nanyang, Singapore		x—tidal power					x			
Raghavan and Bernitsas 2011		x	experimentation	Michigan, USA	x									
Raghavan 2007		x	experimentation and prototype testing	Michigan, USA		x—ocean deployment					x			

Table A2. *Cont.*

Reference:	Case Study	Experimental Data	Software or Method(s)	Geographical Location	Global	Geographic Regions	National	Local Region	Community and City Scale	Whole System	Integration as Large Scale Solutions	Integration as Small-Scale Solutions	Integration as Hybrid Solutions	Micro-Scale Devices
Wang et al., 2021		x	modeling and experimentation	Zhengzhou, China	x—deployment on power lines									
Novara and McNabola 2021	x		own development, PAT selection software	Dublin, Ireland					x					x
Zhou et al., 2020		x	FEM, COMSOL 5.4	Harbin, China	x							x		
Zhang et al., 2021		x	theoretical modeling	Xi'an, China	x							x		
Zaarour et al., 2019		x	review paper	Shanghai, China	x									
Yu et al., 2023		x	FEM, numerical simulation	Harbin, China	x									
Wu et al., 2021		x	prototype and experimentation	Guangzhou, China	x							x		
Wu et al., 2012		x	FEM simulation (ANSYS) and experimentation	Singapore, Singapore	x									
Wang et al., 2022		x	CAE simulation, ANSYS	Jiaozuo, China	x									
Wang et al., 2023		x	ANSYS and experimentation	New Taipei City, Taiwan	x							x		
Usharani et al., 2018		x	analytical modeling	Tiruchirappalli, India	x									x
Tabil et al., 2019		x	review paper	Kajang, Selangor, Malaysia	x									
Sun et al., 2019		x	fabrication and experimentation	North Wollongong, Australia	x									

Table A2. *Cont.*

Reference:	Case Study	Experimental Data	Software or Method(s)	Geographical Location	Global	Geographic Regions	National	Local Region	Community and City Scale	Whole System	Integration as Large Scale Solutions	Integration as Small-Scale Solutions	Integration as Hybrid Solutions	Micro-Scale Devices
Su and Tseng 2023		x	theoretical modeling	Taipei, Taiwan	x									
Stefanizzi et al., 2018	x		preliminary assessment, three installation cases	Bari, Italy					x			x		
Shi et al., 2021		x	experimentation, wind tunnel	Wuhan, China	x									
Pecunia et al., 2023		x	roadmap, review	Surrey BC, Canada [piezoelectric chapter from Belvaux, Luxembourg]	x									
Shan et al., 2017		x	theoretical modeling	Harbin, China	x									
Rezaei et al., 2013			review paper	Edmonton, Canada	x									
Renzi et al., 2019	x		CFD, ANSYS	Bolzano, Italy	x—focused on one case study but with global application									
Pertin et al., 2022		x	mathematical modeling and FEM	Assam, India	x									
Noh et al., 2023		x	analytical modeling	Daejeon, Republic of Korea	x									
Mo et al., 2020		x	systematic analysis	Guilin, China	x									
Masana and Daqaq 2011		x	numerical modeling and experimentation	Clemson, United States	x									
Manoj et al., 2021		x	numerical simulation, ANSYS	Warangal, India	x							x		

Table A2. *Cont.*

Reference:	Case Study	Experimental Data	Software or Method(s)	Geographical Location	Global	Geographic Regions	National	Local Region	Community and City Scale	Whole System	Integration as Large Scale Solutions	Integration as Small-Scale Solutions	Integration as Hybrid Solutions	Micro-Scale Devices
Ma et al., 2020		x	numerical modeling, optimization	Huainan, China	x									
Lu et al., 2018		x	analytical and numerical simulation	Harbin, China	x									
Liu et al., 2020		x	theoretical modeling and experimentation	Suzhou, China	x									
Liu et al., 2011		x	theoretical modeling	Singapore, Singapore	x									
Liu et al., 2012		x	numerical modeling and experimentation	Singapore, Singapore	x									
Li et al., 2020		x	mathematical modeling	Nanning, China	x									
Li et al., 2022		x	numerical modeling and experimentation	Zhengzhou, China	x									
Li et al., 2022, 2		x	numerical analysis and prototype	Zhengzhou, China	x									
Laws and Epps 2016		x	literature review, feasibility assessment	Hanover, United States	x									
Manasseh et al., 2017	x		marine energy review	Melbourne, Australia				x			x			
Wu et al., 2022		x	comprehensive modeling survey	Waterloo, Canada	x									
Rehman et al., 2023			technical review	Dhahran, Saudi Arabia	x									
Yan et al., 2020		x	numerical modeling and experimentation	Shanghai, China	x									

Table A2. *Cont.*

Reference:	Case Study	Experimental Data	Software or Method(s)	Geographical Location	Global	Geographic Regions	National	Local Region	Community and City Scale	Whole System	Integration as Large Scale Solutions	Integration as Small-Scale Solutions	Integration as Hybrid Solutions	Micro-Scale Devices
Zhou and Yang 2018		x	numerical modeling	Ultimo, Australia	x									
Sun et al., 2018		x	modeling and experimentation	Xi’an, China	x									
Xu et al., 2020		x	modeling and experimentation	Tianjin, China	x									
Tamimi et al., 2022		x	empirical comparison	Harbin, China	x									
M.Zhang et al., 2021		x	numerical modeling and experimentation	Trondheim, Norway	x									
Shan et al., 2020		x	Prototype and experimentation	Harbin, China	x									
Liu and D’Angelo 2014		x	experimentation and analytical computation	San Diego, United States	x									
Qi et al., 2021		x	modeling and experimentation	Chengdu, China	x							x		
Li et al., 2023		x	mathematical modeling	Shanghai, China	x									
Rahmawati et al., 2018		x	numerical and theoretical modeling, experimentation	Hiroshima, Japan	x									
Ye and Soga 2012	x	x	energy system modeling	Cambridge, United Kingdom	x							x		
Lu et al., 2018		x	MSCA ITN VIPER program	Harbin 150080, People’s Republic of Chin	x									x

Table A2. *Cont.*

Reference:	Case Study	Experimental Data	Software or Method(s)	Geographical Location	Global	Geographic Regions	National	Local Region	Community and City Scale	Whole System	Integration as Large Scale Solutions	Integration as Small-Scale Solutions	Integration as Hybrid Solutions	Micro-Scale Devices
Behara et al., 2023		x		Andhra Pradesh 532201, India	x									x
Branch et al., 2022	x			Seattle, WA, United States		x						x		
Branch et al., 2022	x			Seattle, USA	x	x						x		
Li et al., 2020		x		Nanning 530004, China	x									x
Cai et al., 2021		x		Ontario, N9B 3P4, Canada	x									x
Ding et al., 2015		x		y, Chongqing, People's Republic of China	x									x
Ding et al., 2020		x		Xi'an 710049, China	x									x
Ding et al., 2021		x		Chongqing University, Chongqing, China	x									x
Falment et al., 2023		x		ONERA, Universit'e Paris Saclay, Chˆatillon, F-92322, FRANCE	x									x
Sun et al., 2019		x		University of Wollongong, Australia	x—high temperature operation (oil exploration) 150–200 °C									x

Table A2. *Cont.*

Reference:	**Case Study**	**Experimental Data**	**Software or Method(s)**	**Geographical Location**	**Global**	**Geographic Regions**	**National**	**Local Region**	**Community and City Scale**	**Whole System**	**Integration as Large Scale Solutions**	**Integration as Small-Scale Solutions**	**Integration as Hybrid Solutions**	**Micro-Scale Devices**
Renzi et al., 2019	x	x	computational fluid dynamics (CFD) simulations	Italy				x involves the installation of an axial Pump-as-Turbine (PaT) in a wastewater sewer of an oil refinery in Italy				x wastewater sewer within an oil refinery		
Lu et al., 2018		x	simulations based on Euler–Bernoulli beam theory.	Harbin Institute of Technology, China	x									
Li et al., 2020		x	equation based on the extended Hamilton principle	Guangxi University, Nanning, China	x									
Ding et al., 2021		x		Chongqing University, China	x									
Jiang et al., 2022		x		Wuhan University, China	x									x
Karami et al., 2022			theoretical analysis and numerical simulations, NETCOOP optimization algorithm	University of Isfahan, Iran	x									

Table A2. *Cont.*

Reference:	Case Study	Experimental Data	Software or Method(s)	Geographical Location	Global	Geographic Regions	National	Local Region	Community and City Scale	Whole System	Integration as Large Scale Solutions	Integration as Small-Scale Solutions	Integration as Hybrid Solutions	Micro-Scale Devices
Ding et al., 2015		x	open source CFD tool OpenFOAM	Chongqing University, Chongqing, China	x									
Ma et al., 2022			review paper	Xi'an, China	The paper summarizes studies and developments in flow-induced vibration energy harvesters from various regions worldwide									
Hamlehdar et al., 2019			review paper	Ho Chi Minh City, Vietnam										

Table A3. Identifying the assessment dimensions in the identified tools, frameworks, and models.

Reference:	Technical Scale	Social Scale	Economic Scale	Environmental Scale	Risk Assessment	Participatory—Engagement with Stakeholders
H. Farokhi and M.H. Ghayesh 2019	x					
J.Kan et al., 2023	x					
L. He et al., 2023						
l. He et al., 2024	x					
Rostami and Armandei 2017	x		x			
A.Barrero-Gil et al., 2012	x					

Table A3. *Cont.*

Reference:	Technical Scale	Social Scale	Economic Scale	Environmental Scale	Risk Assessment	Participatory—Engagement with Stakeholders
Vasel-Be-Hagh et al., 2014	x					
Aabid et al., 2021						
Abdelkefi 2016	x					
Abdelkefi et al., 2012	x					
Abdulkhaliq et al., 2023	x					
Hu et al., 2009	x					
Marqui Junior et al., 2009	x					
Erturk and Inman 2009	x					
Aramendia et al., 2019	x					
Araujo, da Silva and Marques 2022	x					
Azam et al., 2019	x					
B.Zhang et al., 2018	x					
B.Zhang et al., 2022	x					
Bernitasa and Diaz 2006	x		x			
Burda 2022	x					
Cepenas et al., 2020	x					
Ceponis et al., 2019	x					
Ceponis et al., 2022	x					
Chong Li and Lv 2023	x					
Costanzo et al., 2023	x					
Daqaq 2012	x					
Lu et al., 2022	x					
Del Priore et al., 2023	x					
Kim et al., 2023	x					

Table A3. *Cont.*

Reference:	Technical Scale	Social Scale	Economic Scale	Environmental Scale	Risk Assessment	Participatory—Engagement with Stakeholders
E.S. Kim et al., 2021	x		x	x		
Li., H. et al., 2014	x					
Erturk et al., 2009	x					
Abrol and Chhabra 2018	x					
Franzine and Bunzel 2018	x					
Ghazanfarian et al. 2021						
Han et al., 2022	x					
Erturk and Inman 2008						
J. Wang et al., 2020	x					
Jin et al., 2020	x					
Narendran et al., 2016	x					
Kang et al., 2016	x					
Khojasteh et al., 2023						
Kong et al., 2010	x					
Kumar and Sarkar 2016	x	x	x	x		
Kumar and Sourav 2023	x					
L.B. Zhang et al. 2019	x					
L.B. Zhang et al. 2019	x					
Cimorelli et al., 2020	x		x			
Lei and Sun 2023	x					
Li et al., 2019	x					
Modir and Goudarzi 2019	x					
Li et al., 2021	x					
Kuriyama et al., 2020	x					

Table A3. *Cont.*

Reference:	Technical Scale	Social Scale	Economic Scale	Environmental Scale	Risk Assessment	Participatory—Engagement with Stakeholders
Du et al., 2023	x					
Deng et al., 2014	x					
Bowen et al., 2014	x					
Zanelli et al., 2022	x				x	
Naqvi et al., 2022	x					
Park et al., 2023	x					
Wang et al., 2020	x					
Wang et al., 2022	x					
Younis et al., 2022	x					
Mehdipour et al., 2022	x					
Rabiee and Esmaeili 2023	x					
Simiao and Bernitsas 2013	x					
Weller et al., 2013	x					
Wang and Ng 2023	x					
Raghavan and Bernitsas 2011	x					
Raghavan 2007	x					
Wang et al., 2021	x					
Novara and McNabola 2021	x					x
Zhou et al., 2020	x					
Zhang et al., 2021	x					
Zaarour et al., 2019						
Yu et al., 2023	x					
Wu et al., 2021	x					
Wu et al., 2012	x					
Wang et al., 2022	x					

Table A3. *Cont.*

Reference:	Technical Scale	Social Scale	Economic Scale	Environmental Scale	Risk Assessment	Participatory—Engagement with Stakeholders
Wang et al., 2023	x					
Usharani et al., 2018	x					
Tabil et al., 2019	x					
Sun et al., 2019	x					
Su and Tseng 2023	x					
Stefanizzi et al., 2018	x					
Shi et al., 2021	x					
Pecunia et al., 2023	x					
Shan et al., 2017	x					
Rezaei et al., 2013	x					
Renzi et al., 2019	x					
Pertin et al., 2022	x					
Noh et al., 2023	x					
Mo et al., 2020	x					
Masana and Daqaq 2011	x					
Manoj et al., 2021	x					
Ma et al., 2020	x					
Lu et al., 2018	x					
Liu et al., 2020	x					
Liu et al., 2011	x					
Liu et al., 2012	x					
Li et al., 2020	x					
Li et al., 2022	x					
Li et al., 2022, 2	x					
Laws and Epps 2016	x			x	x	

Table A3. *Cont.*

Reference:	Technical Scale	Social Scale	Economic Scale	Environmental Scale	Risk Assessment	Participatory—Engagement with Stakeholders
Manasseh et al., 2017	x	x				
Wu et al., 2022	x					
Rehman et al., 2023	x			x	x	
Yan et al., 2020	x					
Zhou and Yang 2018	x					
Sun et al., 2018	x					
Xu et al., 2020	x					
Tamimi et al., 2022	x					
M.Zhang et al., 2021	x					
Shan et al., 2020	x					
Liu and D'Angelo 2014	x					
Qi et al., 2021	x					
Li et al., 2023	x					
Rahmawati et al., 2018	x			x		
Ye and Soga 2012	x				x	
Lu et al., 2018	x					
Behara et al., 2023	x					
Branch et al., 2022	x					
Branch et al., 2022	x					
Li et al., 2020	x					
Cai et al., 2021	x					
Ding et al., 2015	x					
Ding et al., 2020	x					
Ding et al., 2021	x					
Falment et al., 2023	x					

Table A3. *Cont.*

Reference:	Technical Scale	Social Scale	Economic Scale	Environmental Scale	Risk Assessment	Participatory—Engagement with Stakeholders
Sun et al., 2019	x					
Renzi et al., 2019	x		x			
Lu et al., 2018	x					
Li et al., 2020	x					
Ding et al., 2021	x					
Jiang et al., 2022	x					
Karami et al., 2022	x					
Ding et al., 2015	x					
Ma et al., 2022						
Hamlehdar et al., 2019						

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