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Review of energy harvesting techniques in wireless sensor-based pipeline monitoring networks

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ABSTRACT

With the ever-increasing use of Wireless Sensor Networks (WSNs) in scientific and industrial applications, the users' desire to ensure their uninterrupted operation over long periods of time could not be fulfilled by relying solely on batteries with finite energy supply, storage, and lifetime. In pipeline monitoring networks, the finiteness of these resources engenders unavoidable downtimes caused by the replacement of spent batteries, inspection and repairs of resulting failures, including pipe leaks and ruptures. All of this would result in costly operational interruptions, leading to concomitant disruptions in fluid transport logistics, and crippling production losses in the monitored systems. This spurred an ongoing and vigorous research effort into devising a suitable logistics-aware energy management scheme to ensure an uninterrupted and cost-efficient operation. At the core of this scheme, lies energy harvesting which provides monitored networks with vital operation-sustaining energy gathered from natural sources emanating from the sensors' surroundings. This paper therefore aims at giving a comprehensive review of these alternative energy sources, the mechanisms behind harvesting their energies and various ways of integrating each of them into WSNs. This review is vital in providing engineers with an up-to-date comparative study and a valuable roadmap of, and selection guidelines for, the state-of-the-art energy harvesting technologies used. This study reviews the pros and cons of different harvesting technologies and concludes with some pointers towards some research gaps that need to be addressed to facilitate the development of reliable and cost-effective leak detection schemes, with longer operational lifetimes, better reliability, cost efficiency and logistical support.

1. The important role played by pipeline networks in the energy sector

Pipelines, and in particular pipeline networks, play an important role in different industries pertaining to the energy sector, by carrying different fluids not only over small distances (as is the case in an infrastructure, e.g. inside industrial or domestic buildings) but also over long distances ranging up to hundreds of kilometers, as is the case when transporting fluids to different widely-spread geographical areas. In the oil and gas industry, crude oil is transferred from an upstream sector that includes crude oil reservoirs and petroleum wells to a midstream sector including for example oil Refineries where the crude oil is refined and purified into different petroleum products [1].

With the rapid increase in the demand for petroleum products, the production had to be increased several times over, thus leading to an increase in the size of the pipeline network needed to serve both new and old customers scattered over a wide geographical area, including areas across continents where *trans*-continental pipelines are already installed to supply petroleum products to far-off places. The ever-increasing spread of pipeline networks across the face of the earth is clearly depicted by Table 1 which tabulates the largest currently operational pipelines as well as those that are still under construction, along with some related technical details and reference work which this information was sourced from.

Beside the petroleum and hydrocarbon industry, pipelines are also heavily used in carrying water, including sewage sludges, and gas. In the

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water Industry where the upstream sector includes the main water sources, pipelines are used to carry the available water to various desalination plants, if it is coming from oceans and seas, or chemical treatment plants, if it is coming from rivers, underground sources or large septic tanks, to be finally channeled to various distribution centers providing either clean drinking water, fit for human consumption in adherence with the high quality standards mandated by the water industry, or possibly raw water for irrigation purposes to the agriculture sector. In urban areas covering large towns and cities, this water is carried to different large water reservoirs mostly in different big cities from where it is then distributed to subscribed consumers. A similar distributional setup applies to gas transportation, processing, and distribution over large urban areas.

Clearly, regardless of the nature of the fluid being distributed by these pipeline networks, the pivotal role that these networks play in various domestic and industrial sectors, including the energy one, requires that they be closely monitored for a timely detection of any faults, including incipient ones, or a possible malfunctioning that would call for a maintenance task to be initiated at the earliest. The continuous monitoring of such vastly-spread pipeline networks is needed to ensure a continuous successful performance, whilst avoiding either pecuniary losses and/or fatalities or other dangers to either the personnel operating these networks or to the population being served by them. The use of a wired monitoring scheme is clearly impractical, if at all feasible, when vast expanses to be covered are involved. Various techniques that were proposed and tried are discussed below and their merit-demerits discussed in some detail. An additional and crucial advantage gained by the use of Wireless Sensor Network (WSN)-monitored pipeline-monitoring networks is that these render the transport of the particular fluid being used, more reliable and, as such, effectively and cost-efficiently target a major activity, namely “transport”, of the logistics of the monitoring process. By the same token, they also fulfil the much-desired 7 R's of a sound logistics management scheme for the leak monitoring process, namely: Getting the Right fluid, in the Right quantity, in the Right condition, at the Right place, at the Right time, to the Right customer, and at the right price [2].

Carrying different reactive, inflammable and hazardous fluids to long distances in harsh weather conditions and remote environments, is bound to adversely affect, in the long run, the structural health of the pipelines used. Other causes of such damages may also be due to some violent natural events (e.g. storms and earthquakes) or to some accidental punctures inflicted on the pipelines by some heavy machinery carrying some needed work near these pipelines. Whatever the nature of these damages may be, their severities cause corrosion and cracks in pipelines. These cracks end up causing leakages that disturb not only the production rate and adversely affect the economic aspects of the production process, but also cause severe damages to the surrounding environment, with sometime unbearable human and pecuniary costs. Statistics for different areas of the world show huge loss of fresh water, due to the deterioration of pipelines [13,14]. Different studies show that about 20–40% of the total water present in the system gets lost because of the unchecked water leakage in pipelines in different countries [15]. Furthermore, given the fact that the pecuniary losses incurred in these unchecked leak detections, be they in domestic or industrial sectors, can be simply phenomenal, this has then spurred both sectors involved onto developing and taking quick and decisive remedial actions to at least mitigate these losses whenever possible, or preferably stem them altogether. The vital importance of this aspect of leak detection and its deleterious effects on both the surrounding environment and the growth of the industries fighting this problem, are well described and reported for domestic applications in [77] for water network in UK, where the staggering cost of repair of water distribution pipelines are estimated to be UK £7billion (around 10 billion US$) annually.

The vital role pipeline networks carrying various fluids, play in various sectors, urban and otherwise, may be appropriately likened to their being the key supply lines that sustain the life of the different industrial sectors they serve. As such, their continuous monitoring and, if need be, their quick maintenance, are of the utmost importance if their operations are to proceed smoothly, uninterruptedly, reliably, safely and cost-effectively. For all these important reasons, the key issues of monitoring these pipeline networks and ensuring their safe and continuous supply of energy are discussed next, after giving a brief description of the content of our paper.

The organization of the paper is as follows: After a detailed introduction in Section 1 setting the stage for the vital role played by pipeline networks in different sectors, Section 2 discusses the important task of ensuring a continuous and reliable monitoring of their operations, with a view to detecting any leakages that may cause operational disruptions, pecuniary losses, possible personnel injuries as well as some environmental damages that could range from small to epic proportions. This section also addresses the energy supply aspect of PMS (Pipeline Monitoring System) and highlights their acute need of a more sustained

Table 1
Pipeline with longest lengths.

#	NAME OF THE PIPELINE	CONNECTING		CAPACITY	REFERENCE	TOTAL LENGTH OF THE PIPELINE (KM)	DIAMETER (M)	FLUID	STATUS
		Area 1	Area 2						
1	West-East (Petro China)	Tarim Basin, Xianjing, China	Shanghai, China	17 billion m^3/year	[3,4]	4000	1.016	Natural Gas	Functional
2	Enbridge Pipeline system	Edmonton, China	Montreal, China	2 million bbl/d	[5]	3057.75	0.3048 to 1.22	Crude oil	Functional
3	East-West pipeline	Abqaiq, Saudi Arabia	Red sea, Saudi Arabia	795 million L/d	[6]	1200	1.22	Crude Oil	Functional
4	GASUN (BRAZIL)	Rio Grande, Bolivia	Porto Alegre, Brazil	11 billion m^3 (units)	[3,7]	5000	varying	Natural Gas	Under Construction (2026)
5	Yamal-Europe (Gazprom(Russian) And PGNiG (Polish))	Western Siberia, Russia	Austria	33 billion m^3	[3,8]	4196	1.42	Natural gas	Functional
6	Trans-Saharan	Nigeria	Hassi R'mel, Algeria	30 billion m^3	[3,9]	4127	1.22 to 1.42	Natural gas	Under construction
7	Eastern Siberia-Pacific Ocean Oil Pipeline (ESPOOP)	Taishet, Central Siberia	Kozmino, Eastern Siberia	1.6 million barrels per day	[3,10]	4857	1.22	Crude Oil	Functional
8	Druzhba pipeline	Almetyevsk, Central, Russia	Schwedt, North Germany	1.2–1.4 bbl/d	[3,11]	4000	0.42–1.02	Crude Oil	Functional
9	Keystone Pipeline	Keystone Hardisty, Alberta, Canada	Patoka Oil Terminal, Illinois, USA	830,000 bbl/d	[3,12]	3456	0.914	Crude Oil	Under construction

supply of energy if they are to be WSN-based and deliver sustainable long operational durations despite the intrinsic limitation in energy storage of their component wireless sensors. Section 3 makes a strong case for the need of energy harvesting in WSN-based PNM if the desirable aim to make them operate uninterruptedly over long durations of time, is to be achieved, thus paving the way to Section 4 which gives a practical taxonomy and a critical review of various energy harvesting techniques, either currently in use or been proposed in the literature, which rely on different physical phenomena and whose benefits can be readily leveraged from the workings of the wireless sensors used. Section 5 concludes the paper by summarizing the main contributions of this comprehensive, critical and engineer-centric review paper and offering some suggestions for some future work to tackle some challenges in this vital filed.

2. WSN-based pipeline networks: leakage monitoring and energy supply aspects

Undetected and unattended leakages in pipeline networks, regardless of the fluid carried in them, lead to a slew of adverse effects, ranging from loss of production, through environmental damages to loss of lives in the population living in nearby or even in faraway places.

As a testament to this, hundreds of accidents have occurred that have been reported in different research studies carried out for different countries [17]. Only 7000 incidents were recorded in USA from 1986 to 2012. Tons of natural gas, oil and other hazardous liquids were disastrously released into the environment as reported in Ref. [18].

To prevent these problems from re-occurring, and to ensure the operational continuity, integrity and safety of pipelines, continuous monitoring is required, if not mandatory. As the pipelines are widely spread and mostly located in rough terrains like vast deserts, mountainous regions and under seas, where it is not easy to continuously monitor them with the help of maintenance personnel, the detection of the location of leaks or the rate at which the pipe is corroding in any particular area is a hideous and difficult job to carry out. Due to this reason, continuous research throughout the world is carried out for developing different schemes that can effectively address the problem of continuous monitoring of pipelines to make sure that not only a sound structural health of the pipelines is ensured but also that it is maintained over time so as to support an uninterrupted operation of the whole process, through continuous monitoring, to avoid any future damages and pre-empt, through a proper and timely maintenance program, any incipient faults or cracks from developing further and becoming real dangerous and costly ones.

Different techniques have been proposed for monitoring pipelines for any leakages or damages. One such effective technique leveraging the advantages of the recent technology of unmanned vehicles, including drones, is to use unmanned ground, aerial or underwater vehicles for continuous surveillance of pipelines. Different strategies are proposed for monitoring of pipelines using Unmanned Aerial Vehicles (UAVs), as can be found, for example, in Refs. [19–22].

Despite their technological superiority, the use of UAVs in pipeline monitoring may bring with it some potential problems which may put them out of the reach of several companies in the area. These problems include first obtaining the necessary legal approvals for air flights, ensuring the availability of expert operational knowledge from specialists in the area(s) involved, weather limitations due to uncertain climate changes, and the need for sophisticated expensive instruments to be that require a high-level of training from its operators. Although nowadays, recent advances in advanced robotics, drone technology and machine learning are being leveraged to provide fully autonomous inspection of large infrastructures, such as pipeline networks and turbines, it is still only those large companies with financial clout that can afford the use of UAVs for monitoring purposes. It is however expected that, as this new technology matures, it will become accessible to small-to-medium companies, thus ushering in a new era of fully automated inspection and monitoring of large infrastructures found in various industrial sectors. Moreover, the use of UAVs can be extended beyond their mere application to continuous monitoring of infrastructures or other cyber-physical installations. Coupling WSNs with UAVs can make the former facilitate the use of the latter in the vital areas of communication [23], data collection [24] and in wireless charging for power management [25]. Further details on the different aspects of UAVs in monitoring pipelines can be found in Ref. [26]. Similar approaches are reviewed and proposed for underwater pipelines, in Refs. [27,28]. Unmanned underwater vehicles (UWVs) are used for the collection of data from sensor nodes that are linearly placed on the pipelines located under water [29].

A direct and typical use of WSNs in pipeline monitoring is to deploy wireless sensors at key positions all along the pipeline stretching over distances of tens-to-hundreds of meters for domestic applications, to several hundreds of kilometers for large desert-, or ocean-based, monitoring applications, with a view to collecting some vital flow-related information for leak detection purposes, as well as and location-related data for possible pipeline mapping useful for leak localization. As such, this monitoring solution would lend itself to an easy and affordable implementation which, while requiring no special and expensive knowledge, installation and operation expertise, does enjoy the advantages of lower cost, lower energy consumption and faster communication than their wired counterparts. Moreover, these wireless sensor nodes enjoy further advantages of adaptability and ruggedness as they can work in almost any environment, with only small modifications and adjustments to carry out.

These wireless sensor nodes can also easily communicate with other sensor nodes as well as with the base or main control stations, depending on their network topology. The data obtained from these sensor nodes can also be easily interpreted at the control stations and with the help of different approaches and detection algorithms, leakages can be timely detected. The state of the art in the monitoring, detection and localization of leakages is constantly evolving with the evolution of new technologies and measurement techniques. A good review of different vibration-based leakage detection techniques with a historical analysis can be found in Ref. [30]. For the localization of leakages, different other methods have also been proposed that can localize single or multiple leaks with a good precision. Some of the most recent techniques that have been proposed in the literature, in this area, are given in Refs. [31–33].

All of the above-mentioned advantages of wireless sensors are based on the premise that they are continuously supplied with the required energy they need for a reliable operation. Unfortunately, being mostly battery-operated, their energy supply is inevitably limited and therefore calls for some solution to this energy problem. Solutions relying on sing back-up batteries and/or interrupting the pipeline operation for battery replacement purposes have their own limitation in eradicating the limited energy supply problem, and/or problem in causing downtime (while replacing the spent batteries) and loss of production and lowering of profit. It is at this stage that the importance of Energy harvesting techniques (EHTs) comes into its own, in that if the operation of these EHTs is made to rely on some physical phenomena that are continuously taking place either within the pipeline or in its surroundings, and while the pipeline is in operation, then this setup can, at least in theory, provide a continuous supply of energy to the wireless sensors and thereby prolong their operation for much longer than would other non-EHT-aided solutions.

As such, EHT-aided, WSN-based pipeline monitoring offer an attractive, reliable and cost-efficient solution that ensures a sustainable energy supply and an uninterrupted operation with all its concomitant advantages. These EHTs, powered by their own specific energy harvesting mechanisms that convert energy that is readily available in the surroundings of WSN, will therefore act like virtual uninterruptible power sources for the WSNs. After converting the harvested energy into a useable form of energy for the sensor nodes, the Energy Harvester (EH) device either stores it in a suitable energy storage e.g. a battery or a super capacitor etc. or directly supply it to the sensor node. The use of extra storage depends on the architecture of the EH that relies on the availability, predictability and controllability of the energy source available in the surroundings of the energy harvester [34]. In Ref. [35], a solar-powered cloud-based WSN with battery storage was designed for monitoring and communication in a crude oil pipeline facility whereby an android app was also incorporated for easy access to the sensor logs. In addition to solar power source [36], combines wind and water flow energy sources with battery storage capability to supply power to a ZigBee-based WSN in agricultural application. Although, the redundant power ensures consistent and reliable supply to the sensor nodes, environmental factors might affect the reliance on all of these three natural energy sources. A self-powered flexible thermoelectric generator wrapped around heat pipes was fabricated to power a long range (LoRa) WSN in Ref. [37], this system works well at a temperature of 70° Celsius but deteriorates below 50° Celsius which calls for an incorporation of battery storage system in this temperature range.

For water quality monitoring [38], maximization of the energy harvested from radio frequency sources by sensor nodes together with information transmission rate using the sum-throughput technique was presented. In Ref. [39], a magnetic induction (MI)-based wireless sensor network with multiple sensors was used for leakage detection and localization in underground pipelines. The use of the available RF energy is exploited in the following 2 pieces of work. First, the thesis work of [40] focusing on the feasibility of using RF energy harvesting to power a wireless outdoor ground-level sensor network. Next, in Ref. [41], a smart pipe prototype was designed with an intelligent wireless node hosting miniaturized sensors to provide both distributed and real-time monitoring of a water contamination plant.

In [42], a multi-parameter sensing node embedding a miniaturized slime was used to address surface fouling issues for the purpose of predictive maintenance and management with the help of a kinetic energy-harvesting turbine (Gaoxing Tech F-50 turbine) and battery storage. In Ref. [43] a leakage detection technique, involving a wavelet-based approach and statistical methods, was discussed and shown to be capable of determining leakage occurrence, its location and size. Table 2 gives the details of relevant research work reported in the literature that involves energy harvesting using various techniques as well as development of the required WSN setup used in them.

With the ever-present urge to increase the operational lifetime of wireless sensors, EHTs are becoming a common feature of about all WSNs proposed in the literature. This has fueled further research in this area, especially in the water and oil industries, to achieve the development of PMS offering an uninterrupted monitoring of pipelines in various hostile and rugged environments. Hence, the current evolving state of this important area and the dire need for better and longer-lasting PMS provided us with the prime motivation to undertake here the review of EHTs and mechanisms that have so far been developed and used for supporting WSNs in PMS. Although there are some existing studies [34,44–48] that have been published before on the topic of EHTs for PMS, none of these cover all the recent available techniques, especially those used for the continuous monitoring of pipelines.

It is important to point out, in the following, the incompleteness of some published reviews, as they lack coverage of the important area of EH-aided, WSN-based continuous PMS targeted by our review. In section 3 of [44], a brief survey of the energy harvesting mechanisms is carried out. Although the paper reviews WSNs and some EHTs that can be used for monitoring water distribution pipelines, the area of EH covered by this work is quite narrow and focusses mainly on vibration-based EHTs. Similarly, section 5 of [45] also gives a brief one-page survey of EHTs for PMS, in which they generally discussed only the harvesting mechanisms that can be used for general WSNs but not particularly for PMS. Moreover, one of the major areas of EHTs for

Table 2
Energy harvesting using various WSN-aided techniques.

Ref	Details of Pipeline and Fluid, Also pipe material, diameter, flow rate etc	Type of physical anomaly detected	Type and detail (also power) of Energy harvesting	WSN hardware/software details	Main Contribution
[35]	Above ground pipeline/Oil	Fluid levels, fire, and smoke sensor status	Photovoltaic (6 V, 600 mA)	Temperature, fire, smoke, level sensing Communication module: CC3100 which is based on 802.11 b/g/n radio Connected to Amazon Web Server (AWS)	Integrated WSN with System on Chip (SoC) for monitoring and communication protocols to connect to cloud
[36]	Above ground for hydrogenerator		solar radiation, wind and water flow (58mAh)	ZigBee network	MPWiNodeX prototype developed helps manage redundant energy sources for charging NiMH battery pack for WSN network.
[37]	heat pipes of various diameters		flexible thermoelectric generator (272 mW)	TPipe sensor (NTFS-1); TAmb. & rH sensor (HTU21D); CO2 & VOCs sensor (CCS811); LoRa transceiver (SX1276) with data transmission of 500 m radius.	A self-powered WSN driven by a flexible thermoelectric generator (f-TEG) which can be wrapped around heat pipes was developed.
[38]			radio frequency sources (3000 mW)	Formulation of a time-division multiple access (TDMA)	A unique simulation approach to maximization of energy and throughput in a WSN
[39]	Underground pipe		Magnetic Inducion (MI) (2.5 mW)	soil property sensors, MI transceivers and relay coils, pressure sensors and acoustic sensors	(MI)-based wireless sensor network with multiple sensors for leakage detection.
[40]	ground-level		Radio Frequency (1.5 μW)	Radio Frequency	Work focuses on the feasibility of using RF energy harvesting to power a wireless outdoor ground-level sensor network.
[41]	Ground level pipe with 8 cm diameter and 10 m length and a flow speed up to 2.5 m/s.		Green Valve supply	pH, conductivity, biofilm, temperature sensor and conductivity probes. Arduino/GSM	Smart pipe prototype with an intelligent wireless node hosting miniaturized sensors, for distributed and real-time monitoring of water contamination
[42]	0.5″ pipe		Temperature, conductivity, pH, pressure, flow rate sensors (110 mA)	GSM/GPRS cellular network communication.	A multi-parameter sensing node embedding a miniaturized slime monitor for estimating micrometric thickness and type of slime.
[43]	Ground level. 12″, 20 km pipeline	Leakage occurrence, size and location.	–	–	Leakage detection including leakage size and location.

PMS which is an in-pipe hydro power-based EH, was missing from this review. Likewise, a short review paper [46] also discussed the EHTs but solely for general WSNs. Although some modern techniques are also discussed in this paper, like thermal energy harvesting, it does not however cover the complete area of EHTs and its latest development. Another work published in 2015 in Ref. [47], also review EHTs particularly as used in in-pipe hydro systems. A comprehensive and detailed study is carried out, but it mostly includes the commercially-available EH mechanisms. While a lot of research has been published in literature where different research groups throughout the world have presented novel ideas and solutions for powering EHTs, these have unfortunately not been practically realized yet so as to be fully commercially assessed and exploited. Mubashir Rehmani et al. [48] also presented, in 2015, a detailed review of energy harvesting for general WSNs. Besides covering the EHTs, they also reviewed wireless recharging and Energy storage devices used for facilitating the use of WSNs in practice. However, their review is also focused on general WSNs only and does not cover all the available EHTs that can be used for PMS, which reveals yet another gap in literature.

Recently, a comprehensive work [34] has been presented on energy harvesting techniques used for WSNs, where energy prediction models were also provided. This work also covered some of the techniques that can be used for PMS but lacked coverage of a lot of other important recent techniques. In contrast to these reported studies, our work here, as tabulated below in section 3, presents a detailed and updated comprehensive survey of most of the recent energy harvesting techniques, spanning various energy harvesting mechanisms, that have recently been proposed for WSN- based PMS.

Because of its centrality in our review here, the theme of energy harvesting for WSN-based systems, and in particular those aimed at supporting continuous PMS, warrants providing it a separate coverage in section 2, to review its need and bolster its key role towards achieving the holy grail of WSN-based systems, namely their uninterrupted supply of energy to ensure their continuous operation.

3. The need for energy harvesting to support long WSN-Based PMS operation

As discussed earlier, different approaches for continuous monitoring of pipelines using WSNs are presented in the literature. This area includes vital tasks such as monitoring for, and timely detection of, leakages, including incipient ones, and corrosion detection. For monitoring, different factors, sensors and approaches are proposed in the literature [1]. These approaches vary, based on the selection of sensors that are used in those nodes and particularly on the scheme or algorithm used for detecting leaks, their rates, etc. Both the sensor nodes and the algorithms that are proposed for such problems are mostly energy-hungry and hence require a large amount of energy to work continuously, reliably and effectively. This high-energy requirement arises mainly due to the need to collect, over long periods of time, large data sets at high sampling rates from the sensors placed on the pipelines, and also to the use of long and complex algorithms to process and analyze these data for continuous monitoring of long pipelines. While the energy demand in ordinary WSNs is satisfactorily fulfilled by the use of small batteries, continuous charging or replacing of the batteries is also quite time-consuming, expensive as well as operationally impossible to carry out in most cases [34]. This serious disadvantage limits the practical application and actual implementation of WSNs in industrial applications, especially for PMS, if a long and uninterrupted monitoring is required.

To cope with this problem of limited energy, different solutions like energy conservation schemes and energy harvesting mechanisms have been proposed in the literature. The energy conservation schemes proposed in the literature in Refs. [49,50] include duty cycling, power management strategies, data reduction and modelling, efficient data acquisition. Besides this, energy-aware algorithms and techniques have also been developed in Ref. [51] and shown to be able to detect leaks and to find their exact locations using smaller data sets and fewer sensor nodes for any particular length of pipeline. The latest research in the field of machine learning (ML) allowed researchers to use different ML models for various applications. The benefit of using these models over others, is their ability to find hidden traits and trends from a larger data set and to learn patterns that may reveal either an existing leak or an incipient one that has escaped detection by other conventional leak detection schemes.

As discussed earlier, another efficient and cost-effective way to support the energy demands of WSN-based pipeline networks over long periods of time, is to use energy harvesting techniques (EHTs). These Techniques use energy harvesting mechanisms to either generate or at least supplement, the required energy, by extracting it from sources surrounding the wireless sensor nodes used [48]. The mechanisms also convert the raw energy into a useable form so that it can be used either directly to power the WSN's sensing and communication tasks or to be stored in batteries or super capacitors, so that it can be used later on when it is needed.

Depending on the surroundings, and for pipeline monitoring applications, different forms of energy are available for harvesting. For example, fluid flow energy, thermal energy (in case of hot fluid pipelines), vibration energy, pressure energy, solar energy and wind energy (for open air pipelines) and even radiation energy. These forms of energy can be used for the purpose of energy harvesting and can be converted into useful forms of energy that can be provided to efficiently operate WSNs. Due to their large variety, EHTs for PMS are classified in the taxonomy provided in the next section, where they are separated into different classes depending on their effect on pipeline, i.e., invasive, or non-invasive, and on the basis of the type of harvested energy they lead to.

4. Energy harvesting techniques for PMS: taxonomy and critical review

Energy harvesting techniques that are used for supporting WSN-based PMS can be broadly classified into two main categories: Invasive Energy Harvesting Techniques (IEHTs) that are invasive to pipelines and require some modifications in the existing pipeline structure and Non-invasive Energy Harvesting Techniques (NEHTs) that are not invasive to the pipelines and hence do not require any big modification that might negatively affect production (Fig. 1). Within each of these 2 major classes, a further classification can be obtained based on the form of energy that is harvested. The following subsections will describe several EHTs proposed in the literature and will briefly describe their mode of operation and provide a critical assessment of each of them.

4.1. Invasive Energy Harvesting Techniques (IEHTs)

These EHTs require big modifications in the pipelines at the initial installation stage. This is a major drawback of these techniques as it disturbs the normal operation of the existing pipelines, and hence will adversely affect the production and distribution of the fluid being transported. But once these IEHTs have been installed on the pipelines, their strength is that the energy harvested by them is far greater than the one achieved by the rest of the EHTs. These IEHTs usually harvest hydro power either directly by using turbines or indirectly by using microfilms as will be discussed next.

4.1.1. Turbine-based IEHTs

Turbine-based IEHTs exploit the hydro power that exists naturally in fluids in the form of kinetic energy. Different turbines and architectures are presented for different diameter pipelines. These are reviewed as under.

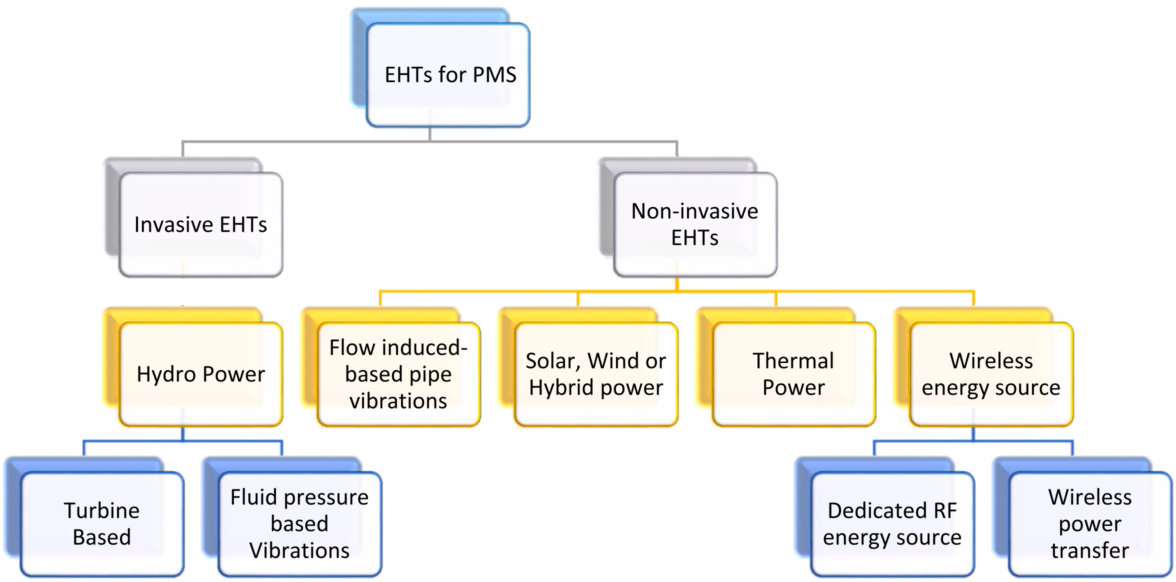

Fig. 1. Taxonomy of energy harvesting techniques for pipeline monitoring systems.

4.1.1.1. Acoustic data communication system for in-pipe Wireless Sensor Networks (2006) [52]. In this paper, an acoustic digital data communication system is proposed for freshwater pipelines for 3 pipeline structures: straight, bend and branch. For experimental verification of their techniques, the authors used a 101.6 mm diameter PVC pipe with a length of up to 9 m. Air at atmospheric pressure is considered as the acoustic medium. A hybrid mechanism of turbines (Fig. 2) is designed to encapsulate the Gorlov's Helical turbine model and Savonius turbine models. This combination gives better efficiency and a high initial start-up torque. The power requirement of the system was 0.95 W, and the dimension of the turbine setup was 50.8 mm in diameter and 228.6 mm in height. It generates 1 W energy at a water flow velocity of 1 m/s with a 35% efficiency of the mechanism. The focus of, and advantage achieved by this research was to provide digital data communication so as to improve operational efficiency and increase the amount of harvested energy.

4.1.1.2. A novel vertical axis water turbine for power generation from water pipelines (2013) [53] [54]. A 100 mm drinking water pipeline is considered in this research which mainly focuses on the development of efficient turbines to generate maximum energy. Different types of turbines with different numbers of blades are designed, fabricated and tested for different scenarios. A vertical-axis water turbine having a hollow shaft and an eye-shaped slanted block with 12 blades is designed (Fig. 3(a)), fabricated (Fig. 3(b)) and used to generate energy from flowing water within the pipeline. This turbine is successfully tested in real scenarios and the generated power is measured. The power output obtained from the final design is 88.2 W at a water velocity of 1.5 m/s and at a pressure drop of 4.85 m. Design parameters such as the tilted angle of the turbine blades, folium of turbine blades and the hollow shapes of the turbines requires thorough investigation which could lead to improved design.

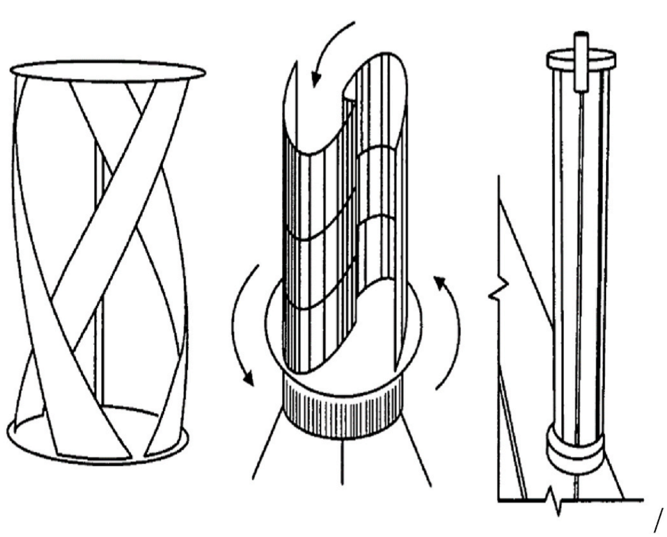

Fig. 2. A design that encapsulates Gorlov's Helical turbine model and Savonius turbine models proposed.

4.1.1.3. Green valve: hydrodynamics and applications of the control valve for energy harvesting (2016) [55] [14]. A Green valve is a type of a modified valve that not only controls the pressure, but also generates energy by using a built-in turbine. It controls the flow and harvested energy with the help of a vertical axis-based water turbine that can be planted inside the body of the green valve. Multiple models of vertical-axis water turbines (Fig. 4) have been designed and tested. The effectiveness of the Green valve is verified experimentally for different scenarios and the amount of harvestable energy calculated. The maximum energy obtained is 409 MJ/week at a valve diameter of 80 mm for mountain environment and 306 MJ/week at a valve diameter of 100 mm for district heating plant environmental conditions. The great advantage of this scheme is the dual-action Green pipe is used, which is providing both control and energy harvesting in a single compact unit, thus saving both cost and space in space-critical applications. However, rotational regime and driving moment depends on the differential pressure which is tied to the efficiency of an electric machine. Therefore, for increased performance within a small working range, there is need for improved control specifications.

4.1.1.4. Lucid pipe systems (2018) [56]. Drinking water pipelines are mainly focused upon in this paper. They provide energy harvesting solutions for commercial purposes and their products are available on the market for small-level energy harvesting needs, thus very suitable for domestic applications. Inline cross-flow turbines (Fig. 5) are also used for harvesting energy with different diameter-dependent power outputs. For 600 mm, 1050 mm and 1500 mm pipeline diameters, the power outputs are 18 kW, 50 kW and 100 kW at water flow rates equal to 1.0

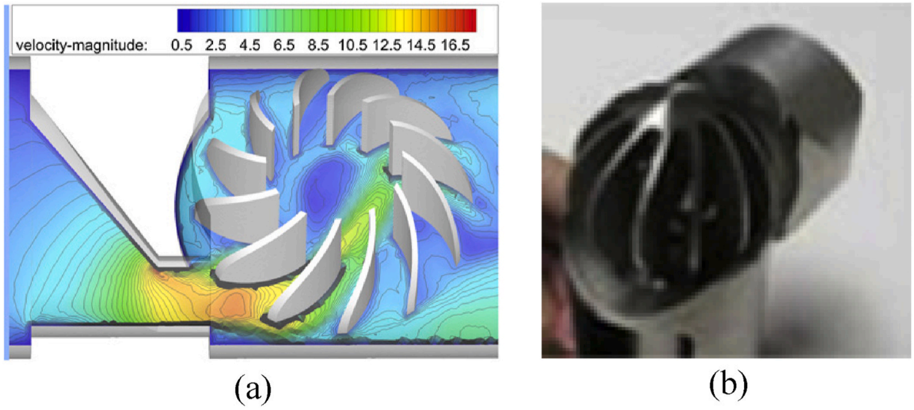

Fig. 3. A design that encapsulates Gorlov's Helical turbine model and Savonius turbine models [54].

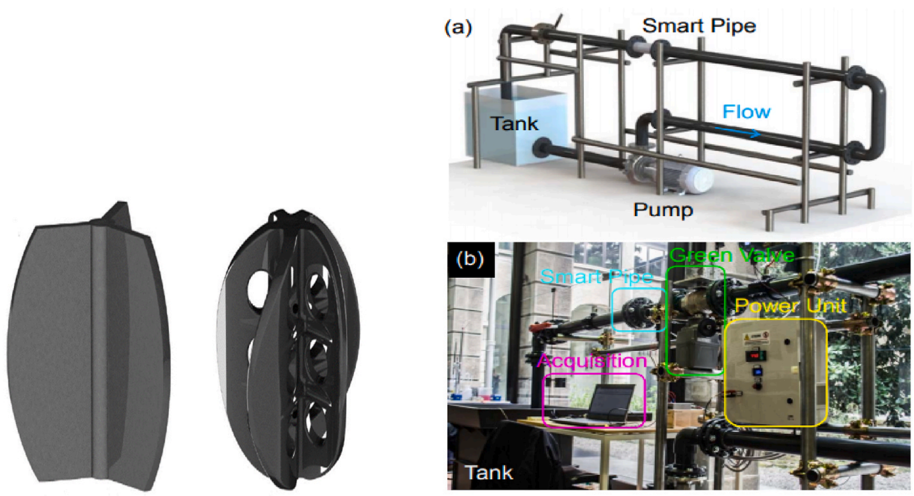

Fig. 4. On the left-hand side are 3 and 5 blades impellers that are used inside the Green Valves for energy harvesting [55], On the right-hand side (a and b) is a prototype system called Smart Pipe that uses the Green Valves [14].

m^3/s, 2.7 m^3/s and 5.6 m^3/s, respectively.

4.1.1.5. Development of inline hydroelectric generation system from municipal water pipelines (2018) [57]. Pipeline Monitoring Systems for municipal water pipelines are discussed in this study. Turbine fabrication, testing of turbine prototypes and design of controllers are the topics that are mainly focused upon in this paper. Inline hydro-electric generation is presented for harvesting energy. Drag-type turbines (Fig. 6(a) and (b)) and lift-type turbines (Fig. 6(c) and (d)) are proposed for medium size ($\Phi = 250$ mm) and large size ($\Phi = 600$ mm) pipelines, respectively. The power generated using drag-type turbines ranges from 25 W to 100 W at 1.14 m/s velocity of water. On the other hand, lift-type turbines are claimed to be able to harvest better energy for a large diameter, i.e. 600 mm, pipelines, since the use of drag-type turbine for the large diameter pipeline would make its solid block very heavy. For energy storage, batteries and super-capacitors are used.

4.1.1.6. Development of an inline vertical cross-flow turbine for hydropower harvesting in urban water supply pipes (2018) [58]. In this work, an inline vertical-crossflow turbine (Fig. 7) is developed for monitoring water leakage in pipelines in urban areas that harvests energy from hydropower. Pipelines with diameters of 200 mm–250 mm are considered, and the objective is to avoid excess water-head loss through the developed mechanism. In general, the head losses can be reduced by decreasing the pipe flow, and increasing the diameter and roughness coefficient of the pipe, which is based on Hazen-Williams relationship [59]. The proposed solution includes a special self-adjustable vane that limits the head loss at high flow velocities.

The energy requirement of the PMS is assumed to be within the range of 40 W–100 W. In the test running for 1 month, the results show that the system can generate about 600 Wh of electricity at a water flow velocity of 1.3 m/s and, in this same test period, the head loss was found to be as small as 5 m.

The following table (Table 3) gives a quick and clear summary of the main features of the above-mentioned Energy Harvesters that use hydro power for generating energy. This table serves as a helpful tool in aiding engineers in their choice of the appropriate technique to choose based on the application area at hand.

4.1.2. Fluid pressure-based vibrations

This type of Energy harvester utilizes the fluid pressure in moving the film attached to its piezoelectric or electromagnetic material. By moving the film, the energy thus generated is harvested.

4.1.2.1. Piezoelectric energy harvesting from flow-induced vibrations (2010) [60]. Here an energy-harvesting mechanism is developed for small (Pipe diameter = 2.4 mm) oscillatory fluid pipelines. The focus is on developing the vibration-based energy harvester and its corresponding mathematical model. An experimental mechanism is designed that generates electricity by harvesting flow-induced vibrations using a piezoelectric film (Fig. 8). It uses pressure oscillations of the fluid

Fig. 5. Commercially-available harvester that is designed for 3 different pipe diameters [56].

flowing in the pipe to generate electricity. The dimensions of the piezoelectric film is 13 × 25mm. The open-circuit voltage of the EH is 2.2 V and its instantaneous output power is 0.2 μW at an excitation pressure of 1.196 kPa and at a frequency of 26 Hz. As such, the low-power requirement of this EHT makes it suitable for domestic applications or in a small subsystem of a large infrastructure.

4.1.2.2. Electromagnetic energy harvesting from flow-induced vibration (2010) [61]. The focus of this study was also to develop the vibration-based Energy Harvester for small (8 mm diameter) pipelines with flow-induced oscillations. A mini experimental energy harvester was developed that uses vibrations produced by the oscillations in the fluid flowing inside the pipe, to generate electricity (Fig. 9). The deflections in the pressure of the fluid produce periodic oscillations in the piezoelectric diaphragm that is attached to a permanent magnet surrounded by an induction coil. The oscillations in the piezoelectric diaphragm cause the magnet to oscillate and a voltage is induced inside the coil. The voltage obtained from the EH is recorded as 10.2 mV at an excitation pressure of 254Pa and at a frequency of 30 Hz. The instantaneous power is 0.4 μW at a frequency of 30 Hz and a pressure of 254Pa. Here too, this EHT lends itself well to domestic applications or in a small subsystem of a large infrastructure.

4.2. Non-invasive energy harvesting techniques (NEHTs)

These types of EHTs do not require any major modifications to be made to the existing pipeline structure and hence are more suitable to be applied directly on operational pipelines without causing any interruptions and loss in production and hence no down time to be incurred. These NEHTs are further classified below, based on the type of harvested energy.

4.2.1. Flow induced-based pipe vibrations

This type of NEHTs are rarely found in PMSs and are still in the research phase. No practical solution for powering WSN-based PMS has been presented yet in the literature. The major reason behind this is the presence of very small vibrations on the surface of the pipelines that are difficult to harvest energy from. However, due to the continuous development in materials science and engineering and the availability of fast ultra-low power electronics, it is, in principle, possible to harvest energy even from this source of low vibrations. Some of the research results that are provided in the literature in this regard are discussed next. These research works used piezoelectric materials, and directly applied them to pipelines to harvest energy from them.

4.2.1.1. Energy harvesting techniques for structural health monitoring and indicators for control of a damaged pipe structure (jan 2018) [62]. The piezo energy harvester used in this study, is based on Lead Zircon-ate Titan-ate (Fig. 10(a)) and is studied for harvesting energy in the cantilever pipe under forced vibrations. The Energy Harvester (EH) is used to find any leakage and to indicate the structural health of the pipeline for control purposes. Mainly, the voltage response and power output of the EH are studied both theoretically and experimentally by changing different loading conditions. The length and outer radius of the steel pipeline are 4.725 m and 0.03667 m, respectively. Two techniques were proposed for detecting single and multiple damages as well as the magnitude of the damage in the pipelines, firstly by directly using the output of the EH (Fig. 10(b)), and secondly, by utilizing the energy-harvesting damage index EHDI (Fig. 10(c)), which is defined as the ratio of the output power of the damaged model to the output power of the undamaged one.

4.2.1.2. Evaluation of energy-harvesting potential in water pipelines to power sustainable monitoring Systems(March 2018) [63]. The energy harvesting capability of a piezoelectric film is studied and verified for different locations on two looped drinking water pipelines with different diameters (Fig. 11(a)). Piezoelectric films (MIDE PPA 1021) are mounted on the surface of the two looped PVC pipelines (Fig. 11(b)) with diameters 76 mm and 102 mm having multiple bends, T-joints and valves. It uses flow-induced vibrations to generate electricity. To supply water, a Dayton model 3KV80A pump is used along with a 420-L reservoir placed on an elevated platform. A magnetic flowmeter (FMG3002-PP-D) is attached to measure the volume of water flowing in the system. In order to make the piezoelectric film work with different pump frequencies, a tip-mass combination is used. To fasten the piezoelectric film with the pipe, a clamp kit (PPA 9001) is used. After examining different scenarios, it was found that maximum RMS voltages of 0.15 V and 0.12 V are obtained at the T-junction (Piezo 7) and at the 90°-bend (Piezo 9), respectively, and at the pump frequency of 23 Hz that best matches the resonance frequency of the piezoelectric film. Also, changing the diameter of the pipe contributes to increasing the turbulence that produces more vibrations and hence more energy to be harvested.

4.2.2. Solar, wind or hybrid power

NIEHTs related to these types of natural energy sources, are rarely proposed for supporting WSN-based PMSs because of the following 2 primary reasons:

- A lot of the pipelines are located underground where these natural energy sources are not available.
- These energy sources are unpredictable and are therefore not continuously available.

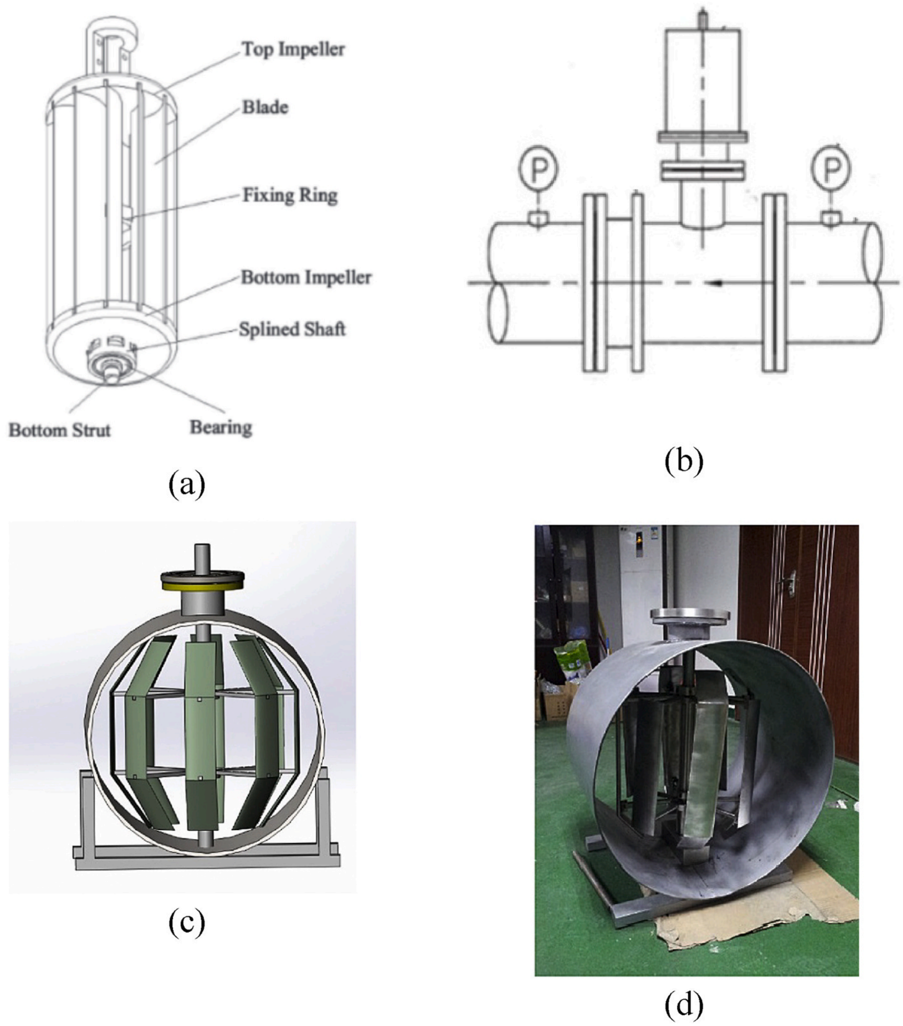

Fig. 6. (a) and (b) shows a drag-type turbine that is designed for 250 mm diameter; (c) and (d) shows lift-type turbines for 600 mm-diameter pipelines [57].

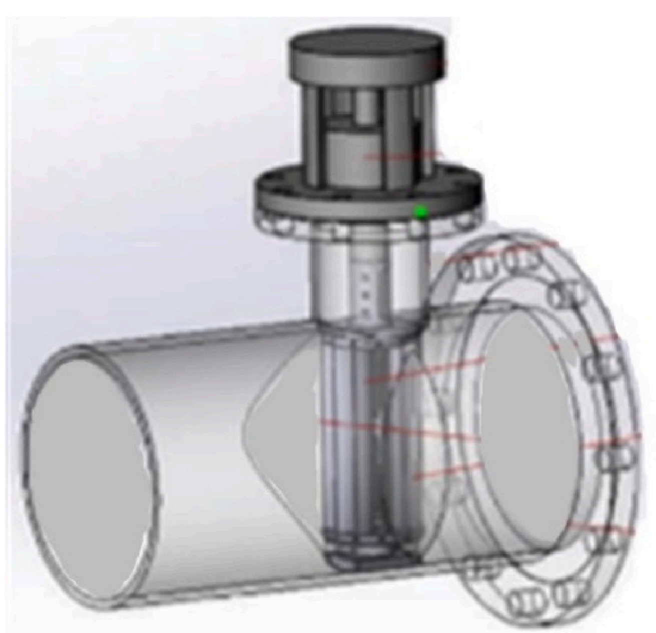

Fig. 7. Inline vertical crossflow turbine purposed for 200–250 mm diameter [57].

However, for those areas where pipelines are located in the open air, and where sunlight and wind energy are likely to be abundantly available, hybrid solutions, combining these natural sources and batteries are proposed. These hybrid techniques are reviewed as under:

4.2.2.1. Integrated WSN for crude oil pipeline monitoring (2018) [64]. Crude oil pipelines that are most likely expected to be in a desert environment are considered in this research. The system monitors several process variables such as temperature, smoke, fire, fluid level and leakage in the pipeline. The focus of this study was to develop such a system that can monitor pipelines as well as also communicate with the field engineers in an efficient manner. A monocrystalline solar PV cell whose schematic operational diagram is shown in Fig. 12 is used to generate electricity for the WSN used. The voltage and current produced by the harvester are 6 V and 600 mA, respectively, and a lead-acid battery is used for storing this energy. The battery needs 7 V for effective charging, therefore, a DC-DC converter is used to boost the voltage to the required level. As such, such WSN-based pipeline monitoring system is well suited to applications involving large geographical areas and rough terrains.

4.2.2.2. Sun, wind and water flow as energy supply for small stationary data acquisition platforms (2006) [65]. The practical example of a testbed considered in this research is a practical hybrid pipeline monitoring system which is applied to an irrigation system. The parameters monitored are solar radiation, air humidity and wind speed using EH modules

Table 3
Energy Harvesters that use hydropower for generating energy.

#	Author/System (Year)	Ref.	Pipe dia. (mm)	Pipeline details	Water vel. (m/s)	Energy harvester	Energy Harvester details	Additional features	Application
1.	G. Kokossalakis (2006)	[52]	102	PVC	1	0.95 W	Combination of Gorlov's Helical turbine and Savonius turbine models	Mechanism Efficiency 35%	Acoustic data communication system
2.	J. Chen, H.X. Yang et al. (2013)	[53]	100	Experimental Test rig	1.5	88.2 W	Vertical-axis turbine having hollow shaft and an eye-shaped slanted block with 12 blades	Pressure drop = 4.85 m	Underground pipeline monitoring system
3.	Lucid Pipe System (2018)	[56]	600 1050 1500	Any[a]	3.54 3.12 3.17	18 kW 50 kW 100 kW	Lift-based Spherical turbine	Neither reduces pressure nor requires any additional bypass loops for installation	Any[a]
4.	Tao Ma et al. (2018)	[57]	250	Drinking water pipelines	1.14	100 W	Drag-type turbine with 12 vertical blades	Tilted flexible vanes were used for over-speed safety of turbine	Data monitoring system for urban environment
			600		–	–	Lift-type turbine with 8 bend blades with 80 cm chord length	Found that power output for DN600 is proportional to chord length	
5.	Du Jiyun et al. (2018)	[58]	200–250	Experimental Test rig	1.3	$600\ \frac{Wh}{month}$	Inline vertical cross-flow turbine	An auto- adjustable vane is used to reduce pressure drop (Head Loss) up to 5 m	Urban water monitoring system

[a] Can be deployed in any pipeline-based application but are not designed for any other application.

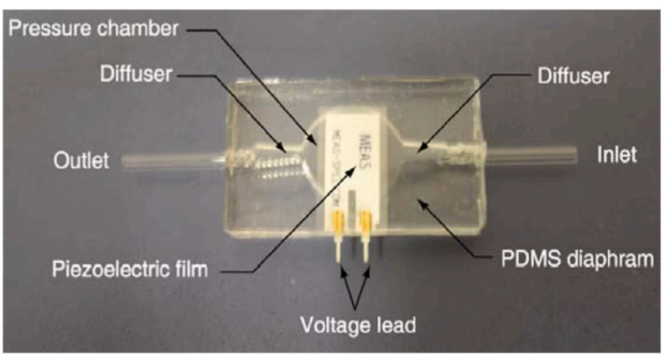

Fig. 8. A piezoelectric film-based vibration harvester for 2.4 mm pipeline with oscillatory fluid [60].

(Fig. 13(a)). A commercial Hydro Generator (HG) by VULCANO (Fig. 13 (b)) is used for harvesting Hydro Energy. For solar energy generation (SG) and wind energy generation (WG), a small PV and a vertical wind turbine (Fig. 13(c)) are used, respectively. A complete sensor network consisting of eight different sensors and a data transmission unit was used. The data transmission rate or the duty cycle is set at 16.7% (10 s in 60 s time frame). The total requirement of the WSN is 39mAH. The energy harvesting details are as follows: Energy harvested using HG at a water flow rate of 0.5 m^3/s is equal to 15mAh. The WG scheme generates about 32mAh at a wind speed of 6.52 m/s and the SG scheme generates 11mAh. For energy storage, 3 NiMH rechargeable cells with 1.45 V each were used.

4.2.3. *Thermal power*

Certain pipelines are designed to carry high-temperature fluids. For such pipelines, the energy harvesting mechanisms are used to harvest the thermal energy carried in the hot water by the pipelines. This section will review the studies that have designed thermal-based energy harvesters for pipelines.

4.2.3.1. Modelling, experiments and optimization of an on-pipe thermo-electric generator (2016) [66]. This research focuses on modelling a thermal energy harvester. It involves the design of a TEG (Thermo--Electric Generator) for high-temperature pipelines with temperature ranging from 275 °C to 295 °C and with a pipe outer diameter of 0.5 m. A thermo-electric harvester is designed that comprises of two thermo-electric modules. Firstly, a wicked copper-water heat pipe is used to conduct heat from high-temperature fluid pipelines to the TEG unit (Fig. 14(a)). Secondly, finned heat sinks are applied on the cold side of the thermoelectric material to dissipate heat to the surroundings (Fig. 14 (b)). Two 1.1″ x 1.1” Bi2Te3 thermo-electric generators are used. The power output achieved is (2.25 ± 0.13) W over a temperature difference of (128 ± 1.12)°C and with the source temperature range of (246 ± 1.9)°C. An increase of power output by 6 times was shown for this approach compared to the conventional designs.

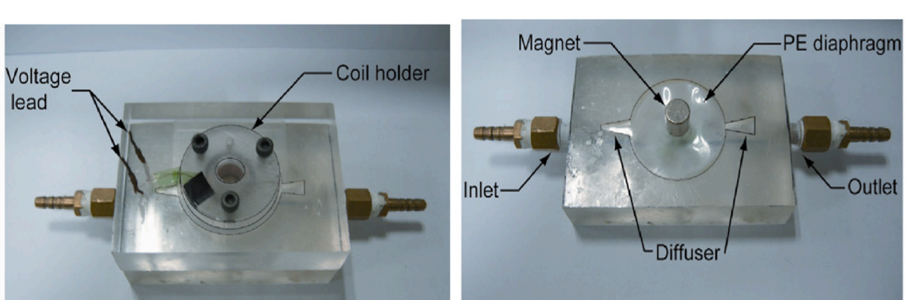

Fig. 9. Piezoelectric diaphragm and magnetic coil mechanism for harvesting vibration energy from 8 mm pipeline [61].

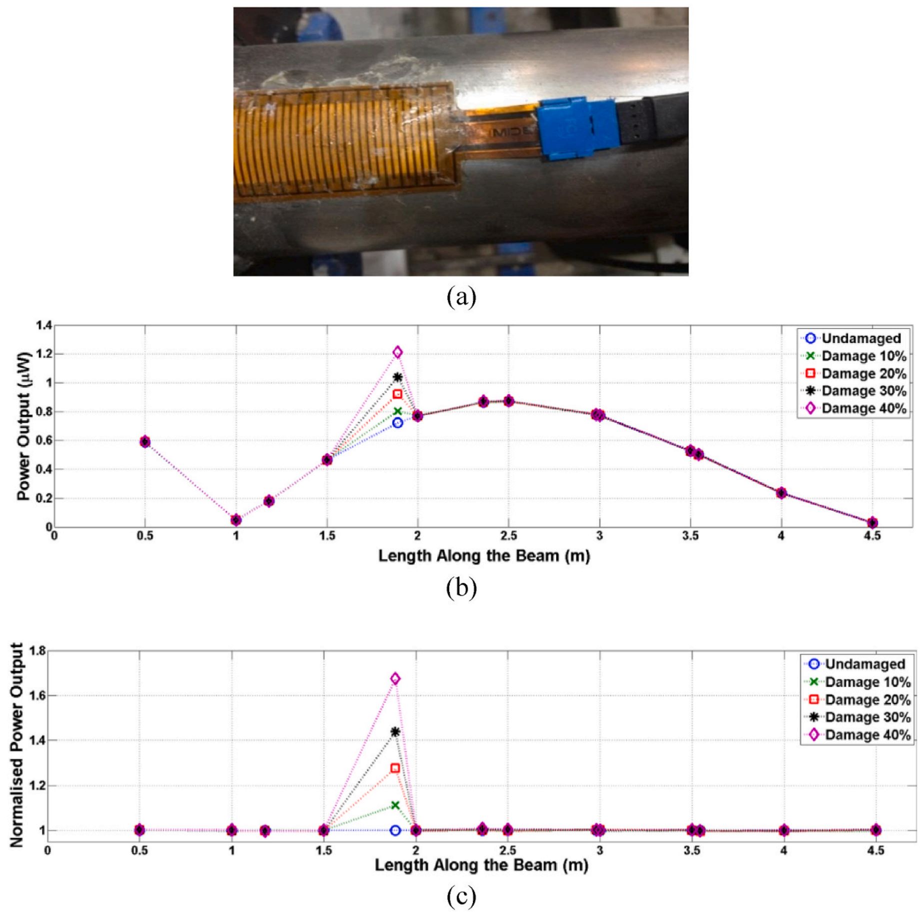

Fig. 10. (a) Piezoelectric diaphragm and magnetic coil mechanism for harvesting vibration energy from 8 mm pipeline, (b) Power output for different damage cases, (c) EHDI for one position of damage for different damage cases [62].

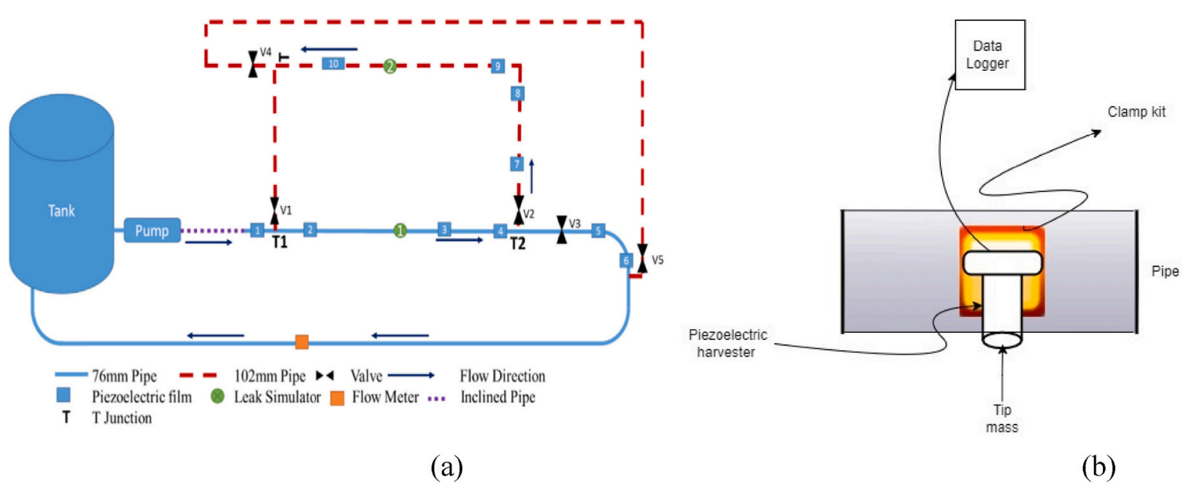

Fig. 11. (a) The layout of the experimental setup that is developed to measure vibrations in different pipe sections using Piezoelectric harvesters at 10 indicated locations, (b) Schematic of the PPA 1021 Piezo-film along with tip mass attached with the pipe with the help of clamp kit PPA 9001 [63].

4.2.3.2. Autonomous wireless sensor node with thermal energy harvesting for temperature monitoring of industrial devices [67]. This research focuses on designing and fabricating TEGs and energy conversion circuits to find the best solution that can generate maximum energy with the smallest sleep period. A complete system was designed for powering a commercial WSN (Jennic JN5139 supporting ZigBee standard). The system includes copper heat sinks, step-up converters, a super capacitor, a power manager IC and a linear regulator. Thermocouples are used as sensors. Two commercial Thermo-Electric Generator (TEG) units [TGM287-1.0-1.3 from Kryotherm] are used to convert thermal energy into electric energy (Fig. 15). The results demonstrate that the system can work autonomously at an active period of 0.9s and a sleep period of 16s, both of which result in a duty cycle of approximately 5.6%. A temperature difference of 14 °C between the two thermoelectric module was recorded, while the circuits' maximum percent energy-conversion rate was found to be 27%.

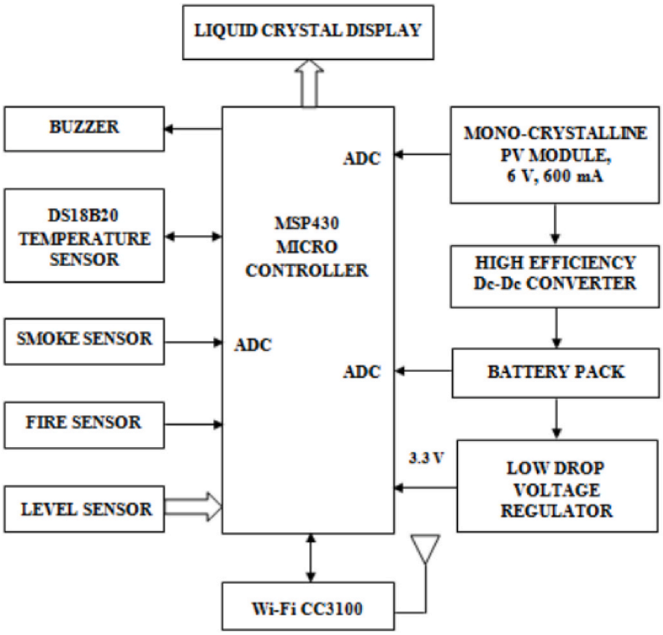

Fig. 12. System block diagram of monitoring and communication unit for inter integrated WSN for crude oil pipeline [64].

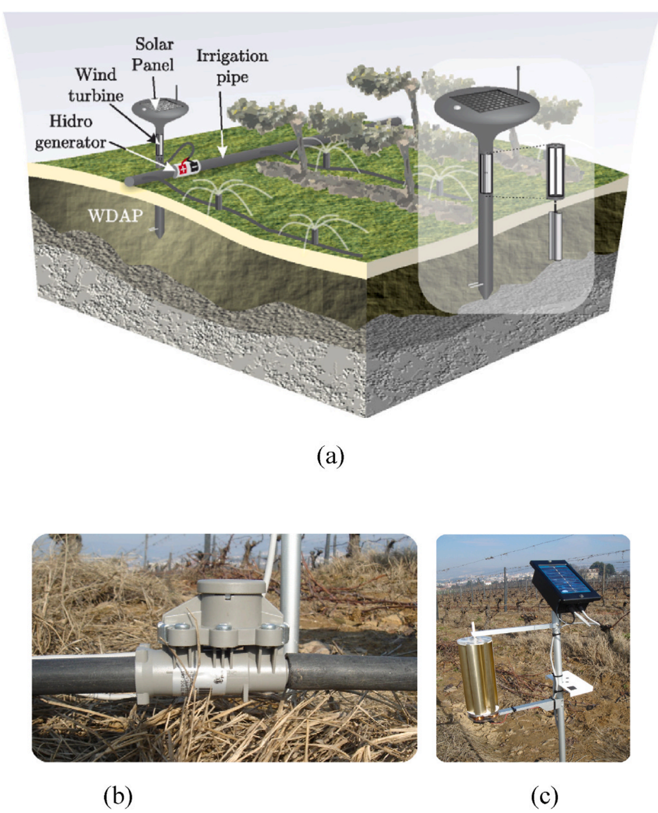

Fig. 13. (a) Pipelines, sensors and energy harvesting platforms in the irrigation area (b) VULCANO, a commercial Hydro generator used in irrigation pipelines; (c) A hybrid energy harvesting system consisting of small PV panel and vertical wind turbine [65].

4.2.3.3. Printed, metallic thermoelectric generators integrated with pipe insulation for powering wireless sensors [68]. Here, the focus was on designing TEGs and transmitting the temperature data of the stream pipe to nearby distances. The temperature of the heat pipes with an outer diameter equal to 8.9 cm and using TEGs was measured. Flexible thermo-electric generators were designed and manufactured from low-cost materials. These TEGs were integrated in the insulation of the heat pipes (Fig. 16). TEGs were applied on a 15 cm-radial section of the heat pipe with an 8.9 cm-outer diameter. From this EH, a power of 308 μW was generated at a temperature difference of about 147 °C. Through experiments, it was proved that such a power level is enough to power a complete circuit for 10 min with a transmitting time window of 30 s after each complete 4 h charging time. This circuit can sense temperature and can reliably transmit data over small ranges, thus being quite useful for Bluetooth-based applications. However, scaling and optimization is required to increase the efficiency and use the system on industrial scale for powering a wireless sensor network.

The electronic components that were powered in this study are as follows:

- DC. DC. Boost converter (20 mV)
- Microcontroller (1.9 V with current draw ratings of 4 μA for ultralow power mode, 12 mA for data transfer via low-energy Bluetooth and 0.5 mA for a standard output drive)
- Temperature probe (50 μA)
- Capacitors and super capacitors when continuous operation and power storage are required.

4.2.3.4. High-performance self-powered wireless sensor node driven by a flexible thermoelectric generator (2018) [69]. This research consisted of developing a large-area, optimized flexible Thermoelectric generator (f-TEG) with an area of 140 × 113mm^2. It was reported here that the developed f-TEG can harvest efficiently energy from heat pipes (Fig. 17). The pipe outer diameter is 140 mm. At a temperature of 70 °C, it can harvest an energy approximately equal to 272 mW. The energy requirement of the WSN used is as under:

- Power management module (PMIC + Buck converter) < = 1.4 μW
- Sensors (Thermal sensor for pipe + Thermal sensor for Ambient temperature + Humidity sensor + CO2 concentration sensor + Volatile Organic compounds concentration sensor) = 66.61 mW
- Microprocessor = 3.11 mW
- LoRa wireless transceiver = 43.1 mW.

One complete cycle that includes sensing and transmitting of data is found to be 7 s. The approximate energy required for the system is about 52 mW. The f-TEG EH is experimentally proven to be sufficient for powering WSN that can remotely monitor ambient temperature, surface temperature of the heat pipe, humidity, CO_2 level and volatile organic compound concentrations. It was also found useful for reliably transferring data within the range of 500 m which caters for the transmission needs of numerous industrial applications, thus enjoying a wide applicability.

4.2.4. Wireless energy sources

This field of energy harvesting is relatively new and is currently witnessing a vital research and development activity. It can also be further divided into two categories as explained next.

4.2.4.1. Dedicated RF energy source: optimizing the energy and throughput of a water-quality monitoring system (2018) [70] [71]. In this category, dedicated RF energy sources are used for supplying energy to the WSN-based PMS. Due to its relatively-recent introduction, this area still requires a lot of research work to be done in order to generate practical solutions that can be tested and implemented in industry. In order to illustrate how energy is harvested in this area, one selected research work done in an important practical area is reviewed below:

A Water Quality Monitoring System is examined in this research. The focus of the research is to study Multi-Network, Multi-Sensor, Multi-

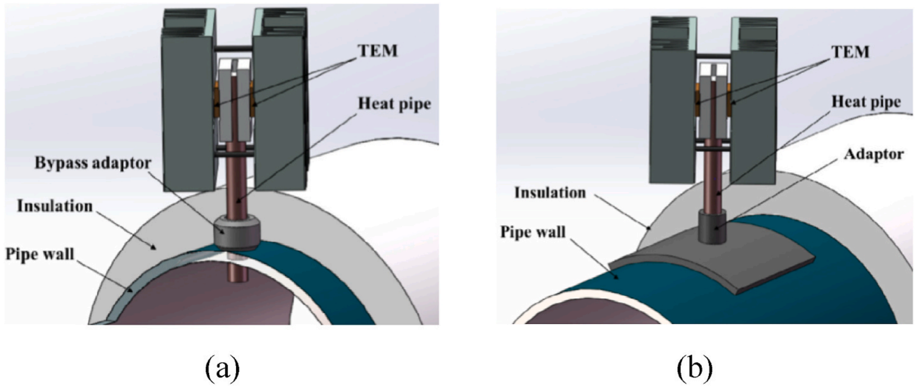

Fig. 14. (a) A thermal energy harvester that uses wicked copper-water heat pipe to pass heat from very high temperature fluid pipelines to TEG. (b) Another purposed TEG that uses finned heat sinks applied on the colder side of thermoelectric material in order to release heat to the surrounding environment [66].

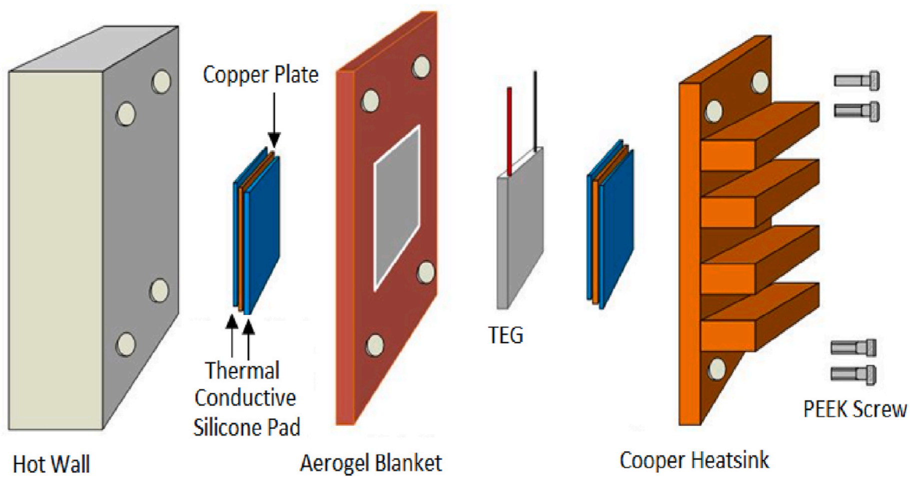

Fig. 15. A TEG mechanism that uses two TGM287-1.0–1.3 units to harvest energy from a hot pipe [66].

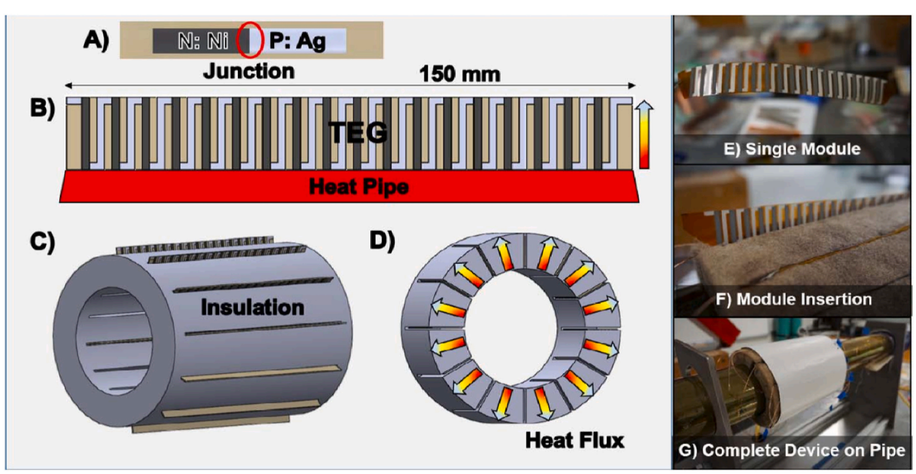

Fig. 16. Functioning of TEGs is explained in A) and B). While C) and D) shows that how TEGs can be placed inside the insulation of pipelines. E), F) and G) shows the actual images of the TEGs placed in the insulation of the pipeline [68].

Source Radio Frequency Energy Harvesters (RFEHs) for a WSN-based Water Quality Monitoring system. In this study, the Harvested Energy and Information Transfer rate was optimized by a sum-throughput optimization method. Although the research is carried out for water processing stations, it can also be applied to pipeline monitoring applications that deal with other types of fluids. In order to have maximum efficiency, the energy harvesting mechanism needs to include the following components: 1) Ultra-low power micro controller (MCU) module (TI-MSP430F1611); 2), Low-power RF transceiver module, such as (TI-CC2420); 3) dedicated RF sources, such as the Power Caster transmitter (TX91501); 4) RF energy harvester module, such as the Power Cast (P2110) and 5) an energy storage module (SAMXON super-

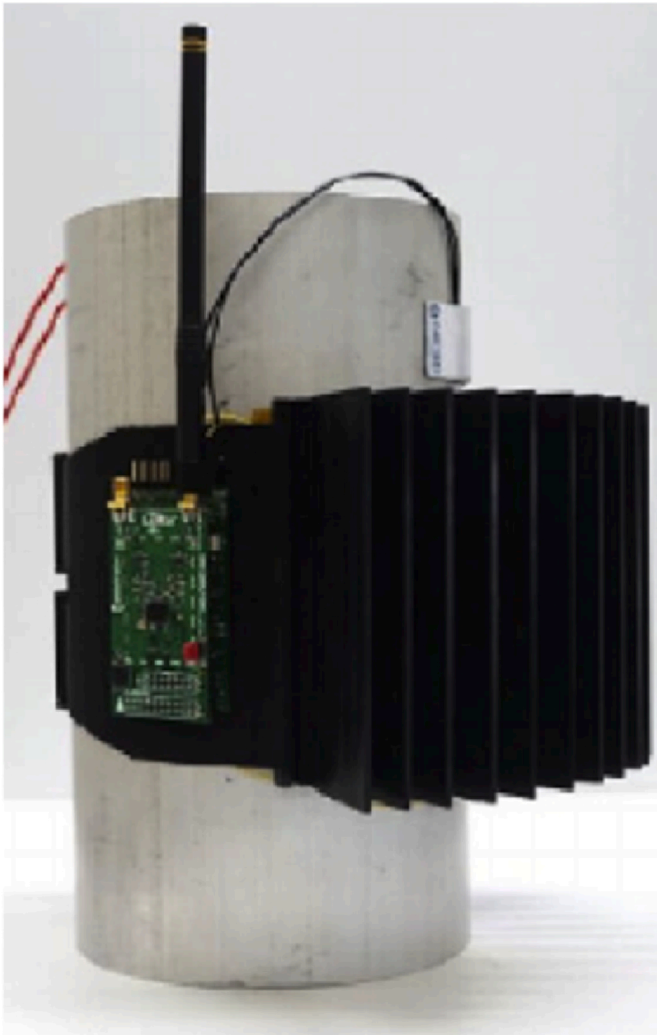

Fig. 17. Thermal energy harvester that can be used with 140 mm pipeline with temperature of 70 °C [69].

capacitor). A wireless information and power transfer (WIPT) method is considered by harvesting energy from dedicated radio frequency sources. Due to the doubly near–far condition that confronts WIPT systems, a new WIPT system is proposed to improve the fairness of resource utilization in the network which outperforms an existing state-of-the-art WIPT systems. A dedicated RF Energy Source with time switching RF receiver architecture was used. The energy requirement of the system amounts to 330 μA (Active State) + 1.1 μA (Standby State) + 0.2 μA (Idle State).

4.2.4.2. Wireless energy transfer: MISE-PIPE: magnetic induction-based wireless sensor networks for underground pipeline monitoring (2011) [39] [71]. This study bears some strong similarities with the previous one, but instead of using RF energy, an inductive coupling method was proposed to support the PMS used.

An energy harvesting strategy is proposed for underground pipeline monitoring sensors that monitor buried pipelines. Besides providing a new cost-effective and real-time method of leakage detection for underground pipelines using magnetic induction (termed here as MI-PIPE), this study also developed an energy harvesting mechanism that is specifically proposed to transfer energy to underground sensors through inductive coupling. This technique of inductive charging was first proposed in Ref. [72]. This study revealed an important weakness in the proposed method of [39], in that it had a node architecture which has a low-efficiency energy transfer, thus making it less practical and cost-ineffective. As such, it was not applied in this study as it required further improvement and was instead included in the list of future research challenges, which is the topic discussed next.

5. Summary of contributions and some suggested future research work

In this paper, we provided a comprehensive review of WSN-based energy harvesting (EH) technologies geared for pipeline monitoring systems in important applications pertaining mainly to the oil, water and gas industries. Clearly, the reviewed EH technologies can also be applied to other pipeline networks, and with the ever-increasing deployment of a large number of sensors across the industrial landscape, as has been ushered in by the advent of the Internet of Things (IoT) and its industrial version (Industrial Internet of Things (IIoT)), such a review, is viewed as timely with the aim of heightening the interest of the engineering community in the WSN-based PMS area, and invigorating the research interest and effort in this key area. This much-needed boost in research and development activity will undoubtedly lead to further improvements and maturation of the existing EH technologies, a rapid transfer of promising and emerging EH technologies from the research lab to the industrial application field, and naturally reaping the benefits of the consequent development of new more efficient, cost-effective and reliable PMSs for leak detection and localization. In its coverage, our review has struck a balance between comprehensiveness and a careful selection of EH technologies most commonly adopted in monitoring pipelines used to transport the 3 key products of water, oil and gas. In doing so, the aim was to build upon the previous work of other researchers in this area, and offer engineers working with PMS, a fresher look at the current research and development landscape in the pipeline monitoring arena, with a view to aiding them in making informed decisions in their choice of solutions for their particular pipeline monitoring problems. Our main contributions in this review may be summarized as follows:

- An introductory and informative discussion shining the light on the important role played by pipeline networks in the energy sector, especially those, listed in Table 1, that are spread far and wide over large geographical areas.
- The review argues that the importance of PMSs in the energy sector is equally matched by the importance of ensuring a continuous and reliable monitoring to achieve a timely detection of any leakages and an uninterrupted monitoring operation. If such a reliable monitoring is to be extended to PMSs covering large geographical areas, then it is argued that WSN-based systems are preferred over UAV-based ones because of the lesser requirements, by the former over the latter ones, for a successful deployment. The key issue connected to the extension of the operational lifetime of the battery-operated WSN-based PMSs so as to ensure a long and continuous monitoring of the PMSs is brought to the fore and the multi-faceted process of energy harvesting is introduced as a vital practical solution to the limited lifetime of the WSN-based PMSs. Table 2 describes a range of the WSN techniques used for energy harvesting.
- The importance of ensuring a long operational lifetime of the WSN-based PMSs if a continuous and reliable leakage monitoring is to be sustained, has warranted the provision of a separate section (Section 3) which emphasizes this key point and hopefully provide more impetus to more research in this area.
- Given the multitude of EHTs either already available or still in the research phase/under development, a helpful taxonomy (Fig. 1) and critical review of each of these techniques is given to offer the concerned engineer a brief but informative description of the mode of operation supported by schematic diagrams whenever appropriate, as well as the pros and cons, of these techniques so as to guide him/her to select the most appropriate technique for his/her application

and to design effective EH-(partially or fully) powered WSN-based pipeline leak detection and monitoring networked systems. Given the extensive use of PMS in transporting the life-sustaining liquid of water, a useful list of EHTs used in hydropower generation is provided in Table 3 for guidance to hydropower generation engineers.
- Last but not least, having experienced ample encouragement from this review of the state-of-the-art in the use of EHTs to alleviate the energy problem that plagues the much-desired implementation of long-life WSN-based PMS, this review ends with a list, by no means exhaustive, of some challenges, as listed below, that are hoped to play a catalytic role in furthering research and development in this vital area.

With a view to addressing some gaps and open issues in this area, the following suggestions, though by no means exhaustive, are made below:

- Study recently-developed energy harvesting techniques for WSNs like Microbial based EHTs [73,74] and ambient energy RF based EHTs [75,76] and propose practical solutions for WSN-based PMS.
- As discussed in previous sections, develop sensor nodes that are supported by flow-induced vibration-based energy harvesters which can be supported by wireless energy transfer.
- Focus more on using ultra power-saving modules for developing EHT, thus reducing the demand on the EH mechanism used, and improving the cost-effectiveness of the EH solution provided.
- Study further and exploit hybrid EH techniques (for example using wind-solar-thermal energies for outdoor harvesting and radiation-vibration for indoor harvesting, with both sets of combined energy sources working either in conjunction with, or independently of, the normally-used batteries) as these combined techniques tend to compensate for one another, thus increasing the likelihood of securing an uninterruptible energy source for the wireless sensor network.
- Exploit advances in electronics and materials science as these tend to spawn smart materials (enjoying energy efficiency, super light-weight, high durability and ruggedness, high reliability, etc.) leading to miniaturized sensors requiring less operational energy, thus freeing up some of the harvested energy for other network tasks, with their light weight and small size making them suitable for space- and weight-critical applications (such as indoor ones), and leveraging their high levels of ruggedness that makes them ideal for use in rough terrains and which empowers them to sustain the onslaught of extreme environment changes (such as in outdoor, underground and underwater applications).
- As the number of sensors keeps increasing, and as the new trend based on edge computing tends to shift computing to the sensor level, energy consumed by the added loads of computation and signal transmission may no longer be dismissed as negligible compared to the one consumed purely by the data acquisition and gathering activities of the sensor. Hence the energy needs for such added loads on sensors need to be factored into the overall EH task.

Finally, research carried out for this review has been an eye-opener to the authors in realizing and strongly appreciating the importance of the vital and multi-faceted area of EH, as well as the existence of the vast array of EHTs, collectively drawing on the strengths of various engineering fields to garner every drop of energy from the environment and the physical processes at hand so as to feed the energy-hungry PMS and enable them to fulfill the demands placed upon them, namely a continuous and reliable monitoring of pipeline networks that transport precious fluids whose availability to the life of its users, is synonymous to their very existence, in one form or another.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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