Chapter

Self-Powering Wireless Sensor Networks in the Oil and Gas Industry

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Abstract

The total revenue from the oil and gas industry in 2019 was 3 trillion dollars with nearly 350,000 businesses working in this field. For more efficiency, all machinery and equipment, including thousands of kilometers of transporting pipelines, need to be monitored continuously and in real time. Hundreds or even thousands of sensing and control nodes are needed for the oil and gas industry. WSNs approach has allowed the company to reduce the number of antenna towers and masts at remote sites, which accounts for 40–60% of the infrastructure cost of building a wireless digital oilfield network. A conventional solution to power these nodes is the use of electrochemical batteries. However, problems can occur using batteries due to their finite lifespan. The need for constant replacement in remote locations can become a very expensive or even impossible task. Over the last years, ambient energy harvesters have received great attention, including vibration-to-electric energy conversion. The aim of this chapter is to present the usefulness of implementing IoT and self-powered WSNs in the oil and gas sector, as well as challenges and issues related to adopting such a system.

Keywords: energy scavenging, wireless networks, sensors, MEMS, mechanical vibration, microsystems, ambient energy

1. Introduction

In the oil and gas industry, bulky wired cabling is not a good choice to monitor processes and communicate the information within the whole system. The energy industry is currently looking toward embracing IoT technology in almost all its operations, from monitoring well production to predicting when its gear will need maintenance. A recent report, produced by McKinsey Global Institute, estimates that $11.1 trillion a year in economic value by 2025 can be generated by moving from the physical world to the digital one [1]. The M2M (machine to machine) direct communication, between sensors and actuators through computing systems, can be achieved through the Internet of Things (IoT) and wireless sensor networks (WSNs). Today, many companies are developing wireless networks for various industrial applications, such as gas and oil industry. EE publishers produced a recent article in 2019 titled "Wireless monitoring to modernise the oil and gas industry" where it stressed industry 4.0 trends in the oil and gas industry through IoT and

WSNs and how these wireless technology can significantly affect the industry [2]. Wireless sensing technology is ideal for the oil and gas industry for many reasons, such as condition monitoring, production optimization, improving safety, and reducing the cost of wired devices [3]. In wireless sensing scenarios, hundreds or even thousands of sensors are deployed in a remote area, that is, production monitoring of an oil field, integrity monitoring of a long oil/gas pipeline infrastructure, or condition monitoring of a huge plant. There are many challenges faced while using conventional batteries to provide operating power to wireless sensing/control nodes [3]:

1. Limited lifetime of the batteries

2. Need to continuously replace batteries at thousands of points.

3. Batteries replacement could be a very time-consuming task and even uneconomical and unmanageable. In some applications, replacing batteries is not practical.

4. Huge maintenance effort would be required to replace or recharge the batteries of these sensors.

5. Sensors' battery replacement for pipelines buried in soil or water, or in a hazardous environment that could require the shutdown of a plant and operation.

6. In addition, in remote and difficult-to-access locations such as subsea oil fields, battery replacement or recharging could be very expensive.

7. The performance and reliability of conventional batteries (primary/rechargeable) drastically degrade in harsh environments, which are very common in the oil and gas industry.

8. Relatively big size of battery compared to other devices in the node (e.g. sensors and actuators)

Self-powering devices can resolve all the previously mentioned issues completely.

The pipeline infrastructure of thousands of kilometers also possesses a very small magnitude of vibrations at the pipeline surface. The pipeline carrying liquid (oil and water), gas, or a multiphase flow can exhibit vibrations. The nature of flow-induced vibration in a pipe conveying fluid is a broadband frequency vibration [4]. The turbulence-induced vibration generates random pressure fluctuations around the inner surface of the pipe forcing it to vibrate. In the case of plants and refineries, line-powered machinery is an excellent vibration source to harvest from. They have a repeatable frequency component of 50 or 60 Hz (typical line power frequency). Mechanical energy harvesting techniques can be used to convert mechanical vibrations to electrical energy. One example is a piezoelectric- or electromagnetic-based energy harvester, tuned at the structural vibration frequency of pipeline or process equipment. The harvester should have sufficient bandwidth and be able to operate at a range of frequencies. The power generated by the harvester can be utilized for many sensing applications including equipment condition monitoring, pipeline integrity monitoring, and production monitoring. **Figure 1** shows pressure, flow, temperature,

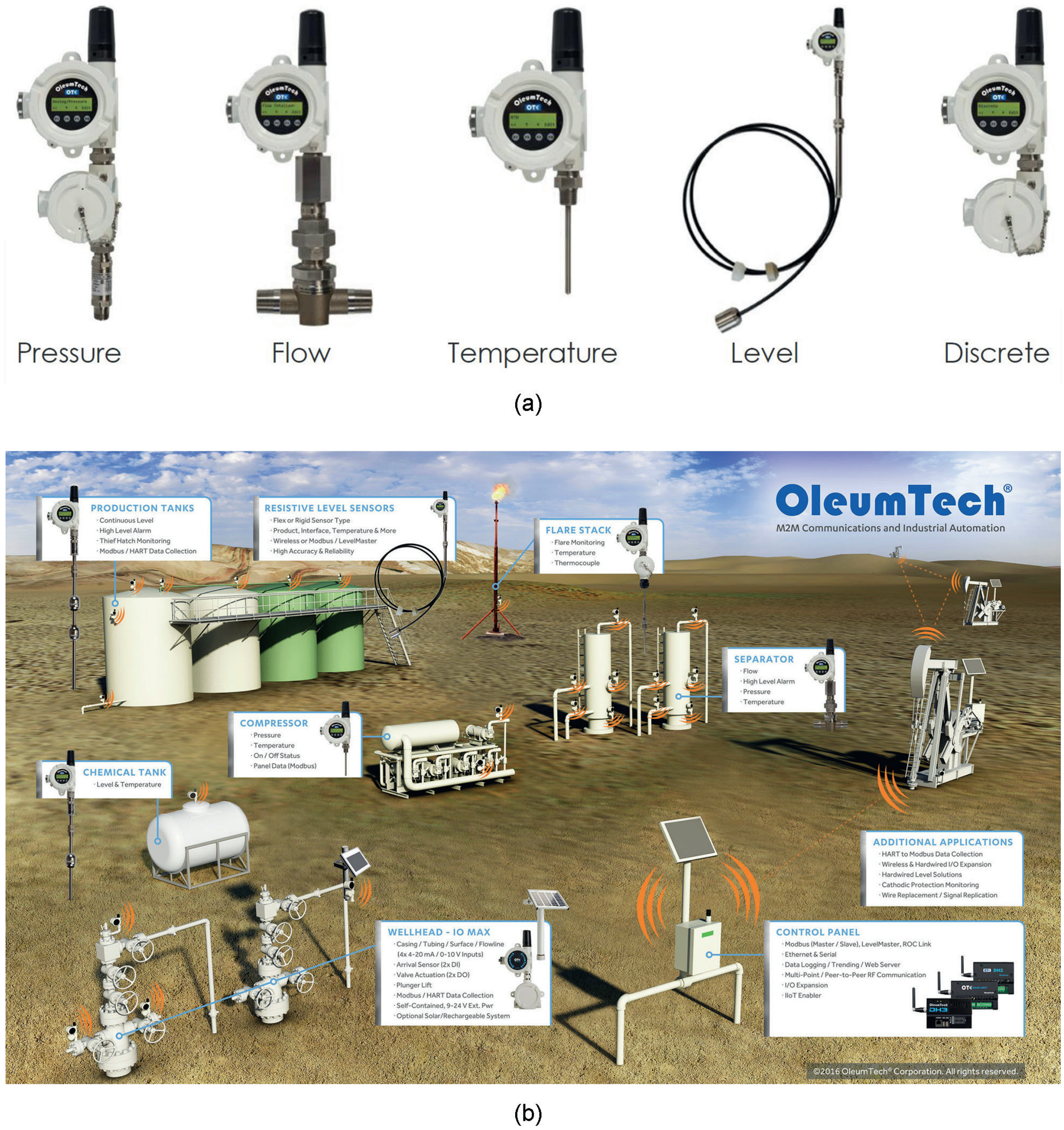

Figure 1.
(a) Example of sensor nodes used in oilfields (b) and their location in oil and gas field [4].

and level sensors that gather important industrial data and their location within the oil and gas industry [4].

2. Self-powered systems and sensors

Nowadays, there is a global need for sustainable energy generation, storage, and distribution of infrastructure to face challenges in developing energy technologies that will provide the amount of energy needed on a sufficient scale and timeframe with minimal impact on the environment and have limited economic and societal disruption during implementation [5]. There have been continuous efforts and tremendous interest to harvest ambient mechanical energy. Therefore, with the increasing demand for electrical energy, energy conversion from renewable energy resources has received huge attention in the last few decades. For low-power electronic devices (e.g. wireless network sensors), continuous replacement of these portable electronic batteries can be problematic and time consuming. Current average global primary power consumption sits at approximately 14 terawatts (TW, 14 × 1012 Jouless−1), with more than 80% of this energy coming from the carbon-dioxide emitting fossil fuel trio of oil, coal, and natural gas, and less than 1% coming from carbon-free renewable power, such as geothermal, wind, solar power, and biofuels [5].

The conversion of waste heat to electrical power arguably represents the greatest opportunity for energy conservation [5]. One promising approach to improve energy efficiency is to employ solid-state thermoelectric (TE) devices to recover part of this waste heat and convert it directly into electricity by utilizing the Seebeck effect [5]. Triboelectric nanogenerators (TENGs) facilitate an excellent opportunity to power wireless sensors and systems that requires few milliwatts of power which can be built into these sensors and devices. The working principle of TENGs is based on contact electrification and electrostatic induction to harvest waste mechanical energy. Therefore, there are plenty of ambient sources, such as wind energy, water wave energy, and vehicle and human body motion, that can be used to extract the energy using TENGs principle. There are successful attempts to extract biomechanical energy using TENGs and implement the harvested energy to power devices, such as touch pads, health monitoring systems, security application systems, exoskeletons, gloves, and many other portable and wearable electronics. The suitability of TENGs was further emphasized by their high adaptability, simple design, ease of fabrication, and cost-effectiveness. Nevertheless, improving power generation remains the main focus of the current research. For example, Dudem reported TENG energy-harvesting unit, that generates a maximum electrical output current of 3.5 μA and power of 0.61 mW, under an applied pushing frequency and force of 4 Hz and 25 N [6].

Piezoelectric nanogenerators (PNGs) are one of the promising technologies for energy harvesting. PNGs utilize piezoelectric materials that are capable of converting mechanical energies into electricity. When piezoelectric materials are stressed, electric charges accumulate at the surface, where they produce electricity that can be used to power portable electronic devices. The piezoelectric effect is also reversible, so that when electric load is applied, the piezoelectric material deforms. Piezoelectric nanogenerators can generate power density that is comparable with the power density of solar cells. For a large piezoelectric effect, the material needs to be initially polarized by applying high voltages across the piezoelectric material. The piezoelectric effect can be generally observed in inorganic materials, such as quartz, lead zirconium titanate (PZT; Pb(Zr,Ti)O3), zinc oxide (ZnO), and barium titanate (BTO, BaTiO3).

Under a very small dynamic force (less than 0.06 N), the output power of 1.5 mW was obtained with an 8.5 mm drum harvester across a load resistance of 17.8 kΩ at a frequency of 173 Hz [7]. TENGs were also combined with other energy-harvesting technologies, such as solar cells and electromagnetic generators, yielding hybrid nanogenerators that are able to operate in broader operating frequency ranges. Besides, the piezoelectric materials were also used in combination with the triboelectric polymers as active layers to form hybrid devices with enhanced output performances [8].

3. IoT for oil and gas industry

The Internet of Things (IoT) is a set of physical objects or devices that are capable of exchanging data over a communication network where sensors play an essential role in reading physical information. IoT facilitates continuous interaction between objects and devices (things). There are many interesting applications in many different areas, such as scientific, commercial, civil, and military domains, for continuous event detection and monitoring. Examples of this application are building management (smart homes/offices), smart manufacturing healthcare monitoring, smart cities, environment monitoring, tracking, security, and surveillance. **Figure 2** shows the function cycle of the Internet of Things [9]. A typical WSN-based IoT setup is formed by a number of distributed and autonomous sensing devices or nodes. These sensing networks need power to operate and that necessitate continuous replacement of batteries. Self-powering systems will be an ideal solution for wireless sensor networks [10].

Energy can be extracted from external sources through the process of energy harvesting or power harvesting, to be used for any viable purposes. External sources include solar power, thermal energy, wind energy, and kinetic energy, also known as ambient energy. The universal energy crisis and the global trend to use renewable energy have boosted research in the area of energy harvesting. One of the newly emerging areas is harvesting power for wireless autonomous devices. Nowadays, with the increase in power consumption, we continuously see electronic devices getting smaller in this era Internet of Things (IoT). According to a report published by Statista Research Department in November 2019, the total installed base of Internet of Things (IoT) connected devices is projected to be 75.44 billion worldwide by 2025 [11]. All these IoT devices face a real battery life problem where batteries need to be continuously charged or replaced. Energy harvesters provide a solution to the IoT battery problem. IoT is just an example of factors that have driven the energy harvesting market to grow at a large scale. According to a press release published in August 2019 by Market Watch (which is a leader in providing the latest financial news and market data), the major driving factor for the need for energy harvesting is the growing adoption of energy harvesting systems in wireless sensor networks (**Figure 3**) [12].

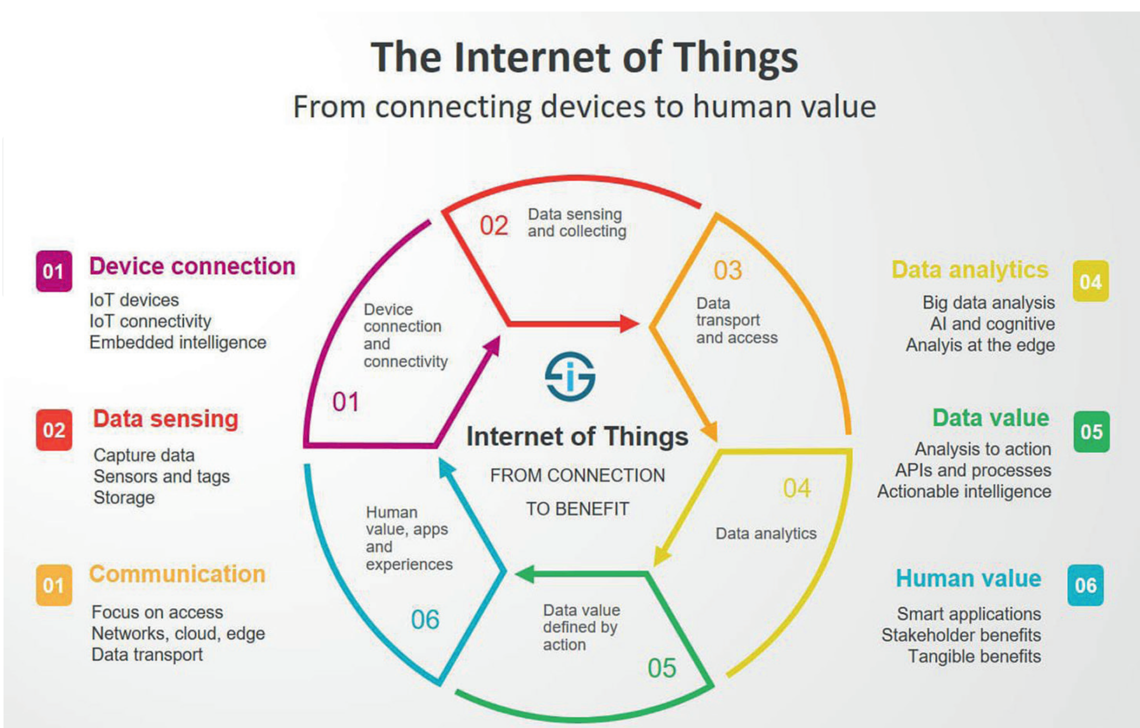

Figure 2.
Internet of things: Function cycle [9].

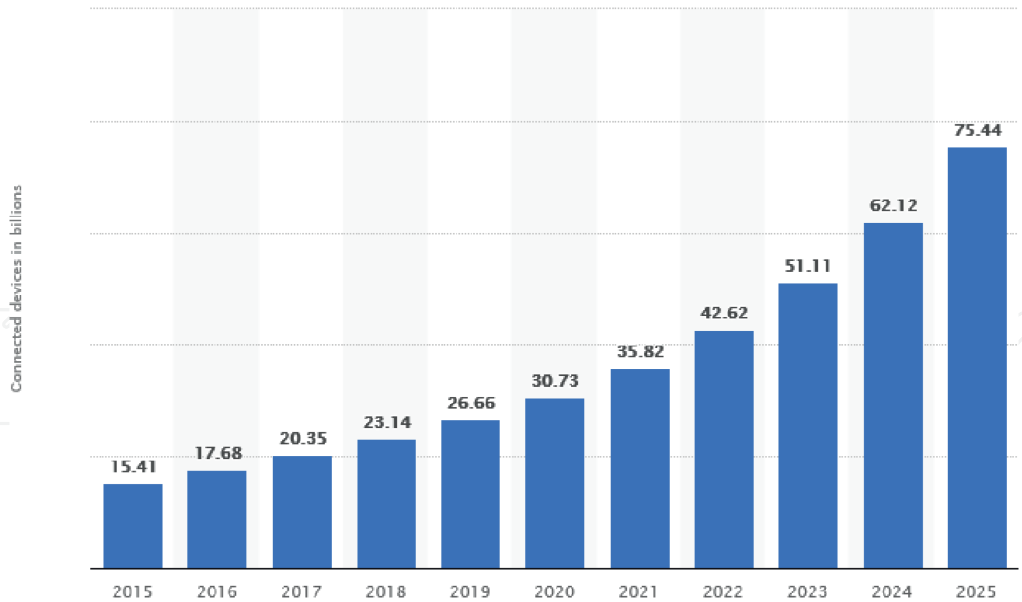

Figure 3.
Internet of things (IoT) connected devices from 2015 to 2025 (in billions) [11].

The energy harvesting chip market is expected to approach $3.4 bn by 2022 [13]. The gas and oil industry takes place in remote areas that need to be monitored continuously, besides, it requires remote monitoring of pipelines, gas and oil leaks, carrion, and equipment conditions all through upstream, midstream, and downstream. Wired technology is expensive, difficult to maintain, and less capable of working in a harsh environment. Wireless technology proved to be the ultimate solution to monitor and control oil and gas industries. Failures in pipelines have led to an annual loss of up to 10 billion USD in the United States, environmental disasters, and fatal incidents [14]. A Market Dynamics Report produced by ON World shows that oil and gas wireless sensor network is one of the key technologies that are transforming the oil and gas industry. According to their survey of 110 leading firms in the oil and gas industry, the majority of these firms are moving toward WSN solutions [4]. Some of these firms have already deployed more than 1000 nodes in their oil and gas industry. Millions of WSN devices will be deployed worldwide for well automation, pipeline operation, and exploration of new and existing oilfields. Oil and gas companies are adopting wireless sensor instruments that provide up to 80% infrastructure savings compared with wired options [11]. According to the market research report, the wireless sensor network (WSN) market was valued at USD 29.06 billion in 2016 and is expected to reach USD 93.86 billion by 2023 [15]. In 2023, global WSN revenues for oil and gas exploration, production, and pipeline operation will reach $2.2 billion. Oil and gas companies are adopting wireless sensor instruments that provide up to 80% infrastructure savings compared with wired options [16]. ON World's Q2 2018 survey found that two in five of the oil and gas respondents have installed over 1000 WSN nodes across all locations. Twenty percent (20%) have deployed networks with at least 3000 nodes compared with 6% in our previous survey in Q4 2016. ON World's survey found that the fastest-growing oil and gas WSN applications are asset tracking and locating, process control, environmental/safety, and asset/machine health monitoring [17].

There is a continuous growth of research for self-powered WSNs that can be used to monitor machines, processes via sensing different parameters (such as temperature, vibration, strain, rotating speed, displacement, pressure, voltage, current, and acoustics) [18]. Besides monitoring machines in the oil and gas industry, WSNs can also be used to monitor pipelines condition [19–22].

4. MEMS energy harvesters for oil and gas: options and challenges

There is continuous progress in reducing the power needed for wireless electronics for wireless sensors, which is now in the range of milliwatts. The milliwatts that need to power wireless sensing and control still pose an issue since they have to be supplied by batteries that need continuous replacement. Hundreds of thousands of network sensing batteries are to be placed along the pipeline and all over the huge oil and gas plants. Replacement or charging is costly and time-consuming, and it gets more complicated for sensing networks that are buried in soil, underwater, or exist in a hazardous environment. On the other hand, the disposal of these huge number of batteries is another environmental issue. An ideal solution to the aforementioned issues, (related to cost, safety, and environment) is to use self-powered devices that can extract free and renewable energy from the surrounding environment. With the advancement in microelectromenchal systems technology (MEMS), the energy harvester devices can be miniaturized to a very small scale and produce power in the range of microwatts. The energy can be harvested from ambient vibration that exists in oil and gas equipment, machines, and pipelines. The most common principles of harvesting vibration energy are electromagnetic, electrostatic [23], and piezoelectric [24–26]; while the latter has many advantages over other principles, since it does not need a voltage source like in the case of electrostatic harvesters and at the same time can be downscaled in size easily as opposed to the electromagnetic harvesters. Piezoelectric micro harvesters have proved to have the capability of producing large voltage output compared to others [27]. Although piezoelectric MEMS have proved to be good candidates for micro energy harvesting, they still face some challenges (e.g. small current output and depolarization), and research is being carried out to resolve these issues.

One of the first attempts to harvest energy from athletic shoes was carried out in 1998 [28]. The shoe contains piezoelectric material to convert dynamic force to electricity as an example of wearable power-generating systems. Although the whole system was bulky, this research has imitated more research to be carried out to improve circuit design as well as to miniaturize the system further. With the currently advancing MEMS technologies, research is now focusing a lot on MEMS-based energy harvesters. One issue, which was discussed earlier, is the electromechanical coupling factor for piezoelectric materials and its contribution to the produced power.

Typical modes of vibration discussed in the literature are mode31 and mode33, which mainly depend on the direction in which we are applying the force to the piezoelectric structure (vibration force being applied perpendicular to the polling direction in the case of mode31 or applied horizontally in the mode33). It was found that the mode33 produces larger electromechanical coupling which indicates higher generated power. Since power generated from piezoelectric materials depend on both the coupling factor and the amplitude of the applied mechanical stress, it was found that the mode31 produces larger mechanical stresses which imply larger electric power. Since the advantage of high mechanical stress overcomes the advantage of high coupling effect [29], mode31 is more preferred and hence adopted in the literature. The simplest structure that can produce high mechanical stresses is the beam-like structure (cantilevers and bridges) with cantilevers being simpler and they suffer less

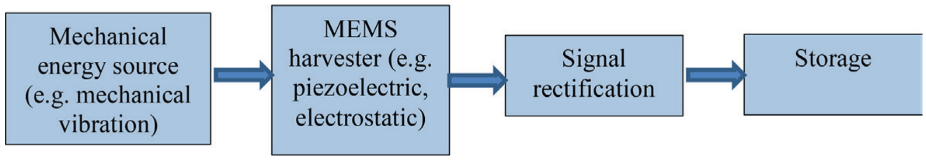

Figure 4.
Schematic diagram of typical MEMS harvesting system.

from other issues, such as residual stresses, developed in the structure. Therefore, the cantilever-like structure is more utilized for piezoelectric energy harvesting. Since there are many types of piezoelectric materials which can be used to harvest energy, a lot of research was made to investigate the advantages and disadvantages of piezoelectric materials that can be used to harvest mechanical energy. The most common piezoelectric thin films used for energy harvesting are PZT, PMN-PT, KNN, BiFeO3, BT, ZnO, AlN, and PVDF. Research indicates that PZT overcomes other candidates in terms of the piezoelectric coefficient [19], but PZT suffers from the issue of brittleness. It is well known that the highest extracted power from these harvesters can be achieved at the resonance frequency of the structure. Different structure layouts will result in different resonance frequencies. Another issue related to the level of power harvested is tuning the energy harvester device to the ambient vibration frequency. This issue was dealt with at two levels; lowering the resonance frequency of the device to match the ambient vibration and the other level reshaping the architecture and dimensions of the device to match the most common ambient vibration frequency. Shape, architecture, and sizing of the harvester device have been investigated intensively in the literature [30–35]. Among the top issues considered in recent research is lowering the resonant frequency of these MEMS micro harvesters to match the ambient vibration and conditions (e.g. acceleration, level of vibration, and frequency range) in the oil and gas industry [7, 36]. Another challenge is widening the bandwidth of these micro harvesters [37–42]. Different MEMS designs and solutions were proposed to overcome these challenges while maximizing the output power of these micro harvesters [43–54]. There is still more to do to overcome challenges related to the optimization of power harvested through MEMS devices, and how to increase the broadband capability of the MEMS harvesters while optimizing the power generated from the device. The piezoelectric harvesters and electrostatic harvesters are more feasible than electromagnetic harvesters to their down-scalability and possibility of fabricating MEMS energy harvesters, with the preference for piezoelectric harvesters due to their higher power intensity over electrostatic harvesters. **Figure 4** represents a typical MEMS harvesting system.

5. Recent trends in applying IoT & energy harvesting in oil and gas industry

The operations of the oil and gas industries present a huge amount of data. In the midstream sector alone, every 150,000 miles of pipeline produces up to 10 terabytes of data [55, 56]. More recent approaches to monitor pipeline networks are based on wireless sensor networks (WSN) and Internet of Things (IoT) for the three sectors of the oil and gas industry [14]. Today, there are several companies, such as Ambyint (previously PumpWell) and WellAware, that provide IoT solutions for wellhead and pump jack monitoring and other gas and oil monitoring needs, that are implemented.

According to WellAware, its production management solutions help companies reduce lease-operating expenses, minimize unplanned downtime, and ensure safety and regulatory compliance [57]. The diagram below describes some of the common threats, to good performance, which can be overcome by implementing IoT (**Figure 5)** [57]. BehrTech, a provider of wireless IoT connectivity for industrial and commercial networks, identified five areas of applications of IoT for the oil and gas industry, 1) asset maintenance, 2) hazard management and worker safety, 3) facility management, 4) regulatory compliance, and 5) security and access control [58]. Brian Ray, the founder and CTO of Link Labs, identified four areas, where connected wireless technology is helping the oil and gas industries to 1) optimize for efficient pumping activities, 2) maintain the pipes and wells, 3) monitor equipment failures and gas leaks, and 4) monitor pipe thickness, temperatures, and erosion in a refinery [57]. ON World Research, leading industry experts reported that oil and gas companies are adopting wireless sensor instruments that provide up to 80% infrastructure savings compared with wired options. They also report that, as oil prices continue to rise and

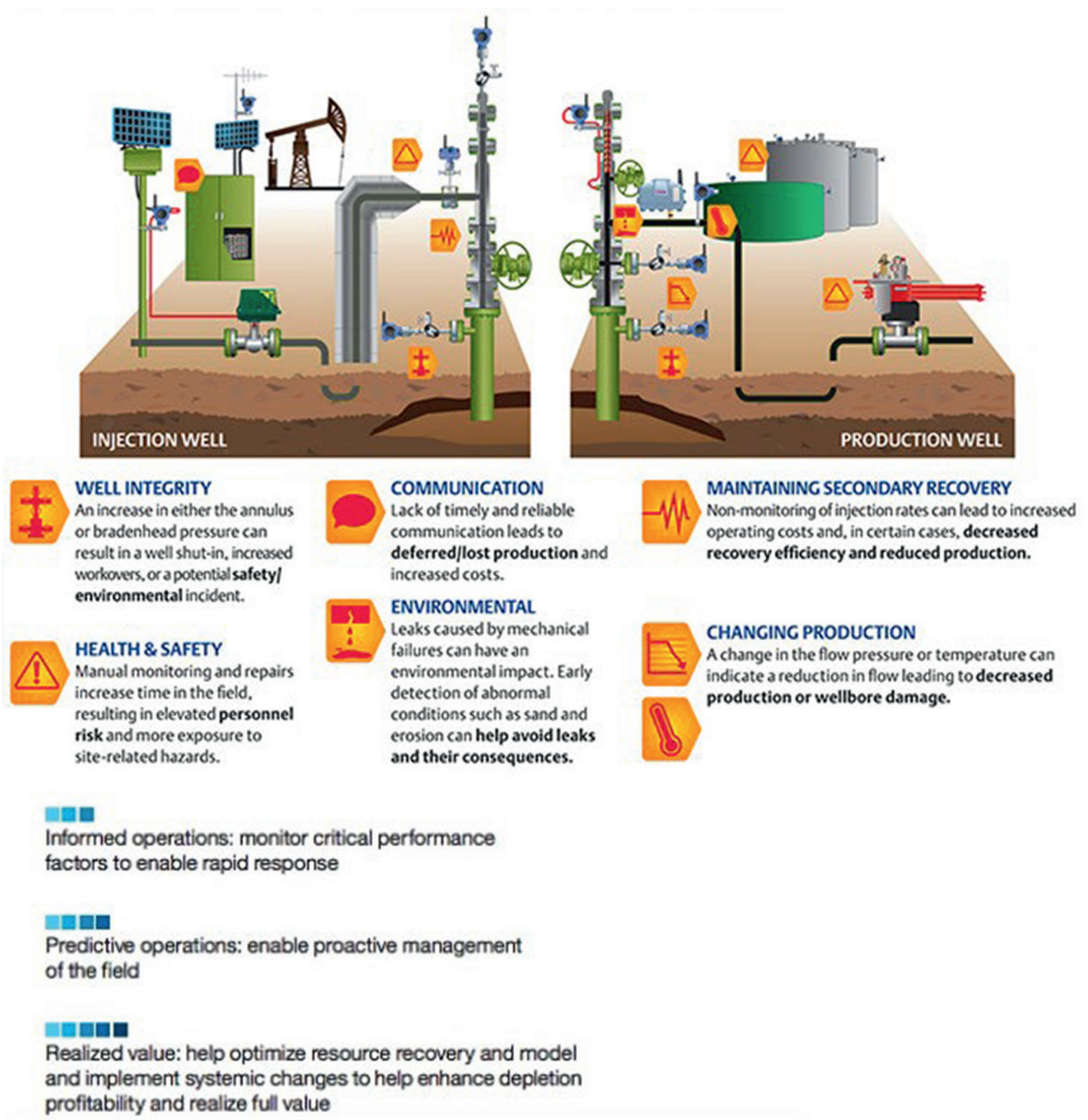

Figure 5.
Common threats to onshore well performance which can be overcome by implementing IoT [57].

exploration activity increases, WSN adoption is steadily growing for core applications, such as wellhead automation and pipeline compressor/pump station monitoring as well as growing innovations for asset management, worker safety, and environmental monitoring. They are expecting that in 2023, global WSN revenues for oil and gas exploration, production, and pipeline operation will reach $2.2 billion up from $480 million in 2017 [16]. BP (British Petroleum), which is one of the leading names in this space, has teamed up with GE (General Electric) to connect its oil rigs to the internet. The collected information can be analyzed in real time and uploaded to the cloud, where trained engineers can make further analyses [59]. Hill Corp, a famous energy company in the USA, uses sensors throughout the pumping system which are then fed into the Microsoft Azure Cloud, from where data is pushed to engineers working on digital dashboards who can monitor the pump's health and performance. The estimates are that a failure of its pumps could cost the company up to $300,000 a day in lost production [14]. Petroleum Development Oman (PDO) oil field covers an area of 72,520 sqkm (28,000 square miles) of desert, rugged, resilient, and reliable equipment is critical. In Oman, over 2000 of the 5000 oil wells in their Oman location are now connected wirelessly using redline equipment to a centralized site, where they are monitored and managed remotely in real time, eliminating the need to have workers drive from well-to-well to collect critical operating information and make changes to optimize the system. PDO is now expanding wireless coverage to all wells. SCADA systems, RTUS, video surveillance cameras, and Wi-fi hotspots are all connected over the wide-area Redline network. This WSNs approach has allowed the company to reduce the number of antenna towers and masts at remote sites, which account for 40–60% of the infrastructure cost of building a wireless digital oilfield network [60].

Having introduced the importance of IoT applications in the oil and gas industry, which can only be achieved by the installation of wireless networks, the challenge now is how to power these WNs in the oil and gas remote areas. Energy harvesters provide a solution to the IoT battery problem. Changing batteries for thousands of remotely deployed wireless sensor nodes could become an expensive logistical headache. ON World Research, leading industry experts reported that, energy harvesting was identified as the most needed innovation for wireless sensor networks. However, it is difficult to power wireless sensor nodes directly from solar panels since supply voltage depends on the time-varying load impedance [16]. A promising alternative to solar panels is mechanical vibration energy harvesting. Ahmad Talha and his colleagues at ARAMCO Saudi, in their conference paper titled "Energy harvesting, powered wireless monitoring and control in oil and gas," have demonstrated the great potentials and promising opportunities of harvesting energy to power wireless networks in the oil and gas industry [61]. They point out that energy can be harvested from this excessive flow energy and can be used for a variety of applications since the fluid flow is present almost everywhere inside pipelines carrying fluid (oil, gas, or multiphase) from well sites to refineries and then to seaports. There were successful attempts to generate the required energy to power WNs devices for IoT. Honeywell, diversified technology and manufacturing company, has developed wireless industrial transmitters (e.g. XYR6000) powered with thermoelectric energy harvesters, and this solution has addressed a key customer objection about batteries and expanded the environments where wireless is the best choice [62]. Perpetuum, a global leading company in wireless sensing technology, produced vibration energy harvesters to powered wireless sensor nodes used to monitor valuable equipment and processes within the oil and gas industry. They claim that the self-powered industrial wireless sensor nodes (WSN) can work over 10 years without changing batteries [14]. ReVibe Energy, a company founded to power the industrial Internet of Things, has developed three vibration energy harvesting products, to provide wireless power for sensor systems in the industry such as process manufacturing, oil and gas, railways, mining, and aerospace [63, 64]. The products vary in terms of the range of frequency of operation, acceleration range, and expected range of produced power.

6. Conclusions and recommendations

Implementing wireless technology and IoT can result in a huge reduction in the cost of monitoring and controlling the gas and oil industry (e.g. failures in the oil and gas industry and hence reduce the shut-down time). It also provides a real time managing system as opposed to traditional walk-through systems. At this stage, it is clear that there are many issues needed to be tackled to enable fully autonomous and maintenance-free wireless sensors for various applications in the oil and gas industry, as well as to provide the oil and gas industry with a continuous source of energy. Energy harvesting from ambient vibration existing in the oil and gas industry can result in further reduction in cost, inconvenience, and efforts, to replace batteries that power the wireless sensor networks (WSNs) and eliminate the use of chemical batteries and their negative environmental impact after disposal. To optimize the vibrational energy harvesting in the gas and oil industry, one must consider the level and frequency of vibration that exist in the fields. More investigation of the ambient mechanical vibration of equipment and pipelines in the oil and gas industry (e.g. level and frequency of vibration and the broadband range) is required. Implementing MEMS solution for power harvesting has another advantage massive production and subsequent cost reduction. Finally, despite the current efforts, more research is needed to design and implement a self-powered wireless system to monitor and control the oil and gas industry.

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