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 SURVEY

Energy Harvesting in Underwater Acoustic Wireless Sensor Networks: Design, Taxonomy, Applications, Challenges and Future Directions

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ABSTRACT In underwater acoustic wireless sensor networks (UAWSNs), energy harvesting either enhances the lifetime of a network by increasing the battery power of sensor nodes or ensures battery-less operation of nodes. This, in effect, results in sustainable and reliable operation of the network deployed for various underwater applications. This work provides a survey of the energy harvesting techniques for UAWSNs. Our work is unique than the existing work on underwater energy harvesting in that it includes state-of-the-art techniques designed in the last decade. It analyzes every harvesting scheme in terms of its main idea, merits, demerits and the extent of the harvested power (energy). The description of the merits results in selection of the suitable scheme for the suitable underwater applications. The demerits of the addressed schemes provide an insight to their future enhancement and improvement. Moreover, the harvested techniques are classified into various categories depending upon the involved energy harvesting mechanism and compared based on the maximum and minimum amount of harvested power, which helps in selection of the suitable category keeping in view the power budget of an underwater network before deployment. The challenges in energy harvesting and in UAWSNs are described to provide an insight to them and to address them for further enhancement in the harvested extent. Finally, research directions are specified for future investigation.

INDEX TERMS Energy harvesting, underwater communications, underwater acoustic wireless sensor networks, UAWSNs.

I. INTRODUCTION

The underwater acoustic wireless sensor networks (UAWSNs) is one of the emerging fields of research in academia and industry due to its potential applications: detection of

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underwater mines, minerals, compounds and elements [1], underwater monitoring for military and civilian purposes [2], water quality evaluation [3], forecasting underwater earthquake and obtaining seismic data [4], studying marine life [5], oil leakage and finding debris of planes crashed into water [6], to mention a few. However, exploring the underwater medium requires to cope with a number of challenges

accompanied with it. These challenges are long propagation delay by using acoustic waves instead of radio waves, as radio waves are absorbed in water [7]. Optical waves require fine alignment between transmitter and receiver, which is also challenging in water [8], [9]. Other challenges include narrow available bandwidth for communications [10], highly unpredictable nature of underwater channel [11] and limited lifetime of batteries of sensor nodes [12].

Sensor nodes in UAWSNs have limited battery life and it is infeasible and expensive to replace nodes' batteries [13]. Therefore, harvesting energy for sensor nodes provides a number of advantages [14], [15], [16], [17]. Firstly, it prolongs the network life time by making sensor nodes capable of operating for a long time. This is usually accomplished either by adding harvested energy to the batteries of the sensor nodes or by devising strategies to ensure battery-less operation of sensor nodes [18]. This, in effect, extends the network lifetime, which ensures that underwater applications are not affected or halted by the usually short battery life [19]. It also eliminates the need for recharging or replacement of batteries in the underwater environment. Secondly, with harvested energy, the network throughput is enhanced as nodes are able to process high amount of data [20]. Thirdly, with high amount of harvested energy, sensor nodes that bear the maximum data traffic in the network do not early deplete their batteries [21]. As a result, these nodes do not die quickly that provides stability to the network by enhancing the lifetime of these nodes [22]. The stability of the network further enhances the throughput of the network in that active nodes are available persistently for data processing [23], which is further effective in data sensitive military and emergency applications [24], [25].

In this article, a survey of the energy harvesting techniques developed for UAWSNs is addressed. Our work is unique compared to the existing underwater energy harvesting, such as in [18], in several aspects. The proposed work considers the state-of-the-art energy harvesting schemes developed in the last decade. It analyzes the energy harvesting scheme in terms of their main idea, merits, demerits and extent of the harvested power. The description of the merits of the key idea eases the selection of harvesting schemes for specific underwater applications. The demerits of these schemes help in their improvement in future investigation. Moreover, the energy harvesting techniques are classified into various categories and compared based on the maximum and minimum amount of harvested power, which is helpful in selection of the suitable category keeping in view the power budget requirement before deploying an underwater network. Finally, future research directions are given. To summarize, the contribution of this paper is three-fold as below:

- State-of-the-art energy harvesting schemes designed in the last decade for UAWSNs are described. These schemes are analyzed based on their main idea, merits, demerits and the extent of the harvested power (energy). Such a description is helpful in identifying the underwater applications in which the addressed schemes can

be utilized. Moreover, the description of the demerits of the energy harvesting schemes is effective in their future improvement and enhancement.

- The addressed schemes are classified into various categories, depending upon the mechanism by which they harvest energy and compared based on the minimum and the maximum amount of harvested power. This helps in choosing the right category for the required power budget while designing an underwater network.
- Research directions are given for future enhancement.

The rest of this paper is organized as follows: Section 2 describes the major characteristics of the underwater channel. A general energy harvesting model for UAWSNs is addressed in Section 3 and the need for energy harvesting is described. Classification of underwater energy harvesting is addressed in Section 4. A comparison of the power harvesting capability of the classified categories is made in Section 5. Challenges in UAWSNs and energy harvesting are addressed in Section 6. Finally, Section 7 concludes the work and specifies future research directions.

II. ORGANIZATION OF THE MANUSCRIPT

The Figure 1 shows the flow chart of the organization of the manuscript. The limitations of the existing literature on energy harvesting in UAWSNs are addressed in the Introduction section of the manuscript followed by contributions of the proposed survey. Then underwater channel model is described by channel noise and the attenuation that a signal suffers while passing through the channel. The next section only discusses the algorithms that harvests energy for UAWSNs, which are categorized into the eight categories: temperature, piezoelectric, solar, AUV motion, marine life, turbine ultrasonic, hybrid and optimization. Finally, the harvesting techniques with maximum and minimum generated power are identified, the challenges in UAWSNs and the corresponding energy harvesting techniques are described and conclusion is drawn with future research strategies.

A. THE UNDERWATER CHANNEL MODEL

The underwater channel possesses unique characteristics that affect the signals passing thorough this medium. Channel noise and attenuation are among the major properties that affect underwater communications and are, therefore, described here.

B. CHANNEL NOISE

The underwater ambient noise is generated by shipping activities in the sea, waves, turbulence and thermal noise. The power spectral density of each noise type is given by [26]

$$\begin{aligned}
 N_s &= 40 + 20(s - 0.5) + 26\log f - 60\log f + 0.03 \\
 N_w &= 50 + 7.5w^{0.5} + 20\log f - 40\log f + 0.4 \\
 N_t &= 27 - 30\log f \\
 N_{th} &= -25 + 20\log f,
 \end{aligned} \tag{1}$$

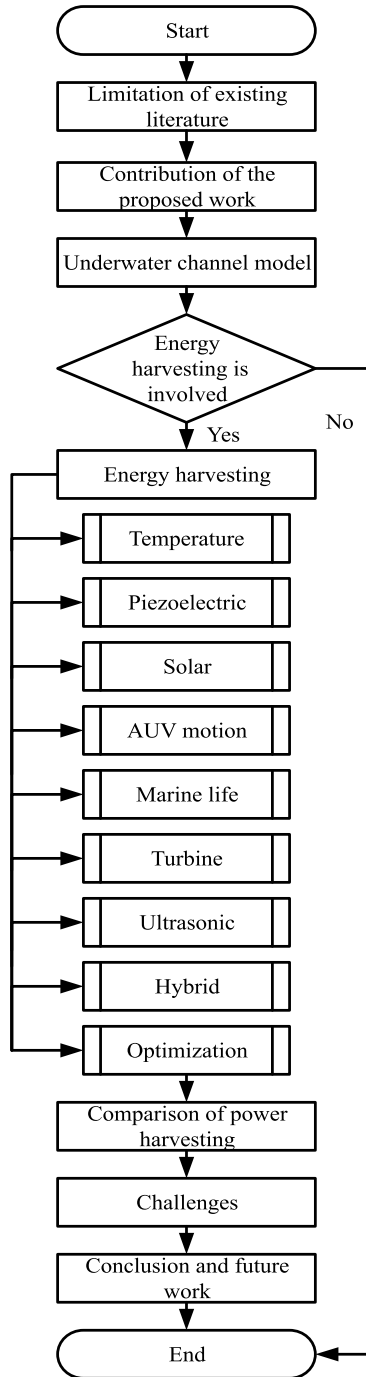


FIGURE 1. Flow chart of manuscript's organization.

where, N_s , N_w , N_t , and N_{th} are the power spectral densities of the shipping, wave, turbulence and thermal noise, in a respective fashion. The parameter s measures the extent of shipping in the sea, w is the wind speed and f is the frequency in kHz. Shipping noise is dominant in the 20 Hz to 200 Hz range. Wind noise prevails in the 200 Hz to 200 kHz spectrum. Turbulence noise is present below 20 Hz while thermal noise is prevalent above 200 kHz.

C. CHANNEL ATTENUATION

Thorp modeled that an underwater signal suffers attenuation A measured in $dB re \mu Pa$, which at a specific frequency f in kHz and at a distance d in km from the source, is mathematically characterized by [27]

$$10 \log A(d, f) = k 10 \log (d) + d 10 \log (\alpha(f)), \quad (2)$$

where, the first term in the above equation represents the spreading loss and the second term characterizes absorption loss. The spreading factor k determines whether an underwater signal is spreading spherically or cylindrically as it travels and its value varies between 1 and 2. The absorption loss, $\alpha(f)$, is measured in dB/km and is modeled as

$$10 \log \alpha(f) = \begin{cases} \frac{0.11 f^2}{1 + f^2} + \frac{44 f^2}{4100 + f} + 2.75 \times 104 f^2 & f \geq 0.4 \\ 0.002 + 0.11 \frac{f}{1 + f} + 0.011 f & f < 0.4 \end{cases} \quad (3)$$

Energy is also lost when an acoustic signal is reflected from the sea surface. If an acoustic signal is incident at water surface at an horizontal incident angle θ , then the reflection loss due to surface, RL_s , is modeled by the Beckmann-Spizzichino model as

$$RL_s = 10 \log \left[\frac{1 + \left(\frac{f}{f_1}\right)}{1 + \left(\frac{f}{f_2}\right)} \right] - \left(1 + \frac{90 - w}{60} \right) \left(\frac{\theta}{30} \right)^2, \quad (4)$$

where, $f_1 = \sqrt{10} f_2$ and $f_2 = 378/w^2$ and w is wind speed in m/s. When an acoustic wave bounces from the sea bottom, the resulting loss due to reflection, RL_b , is modeled by [28]

$$RL_b = 10 \log \left[\frac{(m \sin \theta_1 - (n^2 - \cos^2 \theta_1)^{1/2})^2}{(m \sin \theta_1 + (n^2 - \cos^2 \theta_1)^{1/2})^2} \right], \quad (5)$$

where, ρ_1 is the density of water in which an acoustic wave travels with a speed c_1 until it bounces from the bottom having sediment with density ρ_2 and in which the acoustic speed changes to c_2 . The relationship among the various parameters is governed by $m = \frac{\rho_1}{\rho_2}$, $n = \frac{c_1}{c_2}$ and θ_1 is known as the grazing angle.

III. THE NEED FOR ENERGY HARVESTING AND ITS GENERAL MODEL

Since underwater nodes are generally battery powered, energy harvesting has a vital role as it directly enhances the battery life time and can even power the sensor nodes without batteries [29]. To harvest energy on the surface of water or within a water body, a number of techniques have been utilized by the researchers. They are, for instance, energy harvesting from turbine [30], temperature variations in water [31], piezoelectric materials [32], solar radiations [33], ultrasonic radiations [34], marine life [35] and the kinetic energy of water [36] and/or the motion of an autonomous

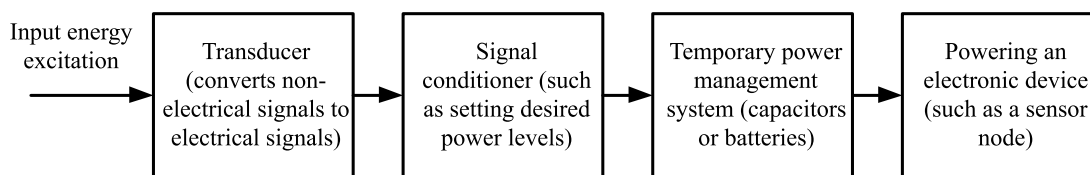


FIGURE 2. General architecture of an underwater energy harvester.

underwater vehicle (AUV). The Figure 2 shows the architecture of an energy harvester. The input energy excitation originates from an external source of energy. For instance, input energy excitation may arise from temperature variations, pressure on a piezoelectric material, kinetic energy of waves to drive a turbine or chemical reactions from microorganisms present in water, among the many. The input excitation is converted into electrical signals by a transducer. The signal conditioner performs a number of tasks. For instance, it defines a certain threshold for the generated power and its calculation, converts analog signals to digital signals in case the harvester uses digital circuitry and computation and conversion from alternating to direct current, to mention a few.

IV. TAXONOMY OF UNDERWATER ENERGY HARVESTING

This section classifies the energy harvesting methods for UAWSNs into various categories. They include energy harvesting based on temperature gradient, piezoelectric materials, solar radiations, AUV motion or kinetic energy, marine life, turbine, ultrasonic radiations, hybrid sources and parameters optimization.

A. ENERGY HARVESTING USING A TEMPERATURE GRADIENT

The authors in [37] utilize the thermal energy of the ocean to power underwater sensors and vehicles. The developed system directly converts the thermal energy of the ocean using a certain threshold temperature difference. The floating device consists of ten canisters directly exposed to water pressure. Every canister is filled with hydraulic oil and its middle part contains flexible tubes that are filled with a phase change material. As soon as a temperature change with a threshold of 12°C is detected, the phase change material melts and it expands the flexible tubes that further pressurize the hydraulic oil to push a piston. Following this, oil at a high pressure flows into a hydraulic motor, which is rotated with an almost four-fold speed using a special gearbox arrangement and power generation is accomplished in an attached generator. A power extent of 200 Watt is generated in 30 seconds. This amount is over 110% of the required amount for powering the complete unit. A thermal engine is used to harvest energy for a glider from the temperature variations in sea water [38]. When the engine undergoes a temperature gradient from a lower temperature to a higher temperature, the phase-change wax in the engine expands that puts pressure on the hydraulic oil in the engine. The potential

energy associated with the oil is captured in a high pressure accumulator, which is then discharged to propel the glider. When the oil is discharged from the high pressure accumulator, it is brought into the low pressure accumulator from where it is input back to the engine.

It is argued in [39] that the volume of a phase change material is one of the key parameters in energy harvesting by a glider from a temperature gradient. Therefore, the effect of pressure on the volume of the phase change material in liquid, solid and in the transition phase is studied. This includes modifying the conventional thermal engines with a closed hydraulic valve and a tank from which oil is retrieved. In addition, two check valves are used to prevent oil flow into the tank or from the accumulator. It is argued in [40] that electrical energy is generated by sea water having different salinity levels by passing the water through a certain membrane so that certain ions could be passed and electrical current is produced. However, the generated energy is not significant in amount and that the membrane could only pass certain kind of ions. Therefore, a temperature gradient is introduced to the salinity difference through a tube in which water moves along a tube due to gravity. Water with low salinity is kept at a higher temperature while high saline water is kept at a lower temperature. The temperature and salinity difference alters the frictional drag of water that enhances the kinetic power of the water, which is then harvested with the help of a generator.

The hydrodynamic study of the position of heat exchangers for an AUV is investigated to measure the effect of stability and energy harvesting capability [41]. The heat exchangers were mounted above, below and to the sides of the main body of the AUV. It was found that the best position of the exchangers in terms of static stability and energy harvesting efficiency of the AUV was mounting them below the main frame of the AUV.

B. PIEZOELECTRIC-BASED HARVESTING

The authors in [42] argue that the conventional piezoelectric materials generate energy that is dependent on the resonant frequency of the materials. Therefore, such materials require a significant magnitude of vibration to be detected and converted to a significant amount of harvested energy. However, in sea bed, the vibrations have very low frequency (up to few Hertz) that mismatches with the resonant frequency of the piezoelectric materials. Therefore, a module is designed to detect even the low vibrations at sea bed and

enable the piezoelectric materials to harvest energy from them, independent of the resonant frequency. The module consists of a pluck-driven piezoelectric material that generates a beam of high resonant frequency. This beam is interacted with another short beam. This interaction excites the system first at the specified frequency of the system and then at the high resonant frequency to produce power. Sea waves affect a cylinder and drive it into an oscillatory motion that excites the piezoelectric material. The generated energy lies in the range 0.3-0.6 mJ when an energy harvesting system is used with the designed module. A micro-bubble is trapped between two piezo-cantilevers over a silicon surface in [43]. When light falls on the micro-bubble in an aqueous medium, it expands due to the opto-thermal effect. A reduction in the intensity of light shrinks the micro-bubble. Thus pulsating behavior of the micro-bubble causes vibrations in the piezo-cantilevers that, in turn, generates electrical power. An analytical study of electromagnetic and piezoelectric energy harvesting schemes is performed in [44] for underwater pipelines. Parameters such as total power requirements of the sensors in the pipelines, distribution of nodes and size of the harvester using the properties and the parameters upon which it depends are considered. The analysis concluded that a 2-20 W power generation required a piezoelectric harvesting system with almost double area than a corresponding electromagnetic harvester. The design of the mechanical structure of a piezoelectric generator is addressed in [45] so as to harvest energy in the underwater environment for sensors and other electronic devices. The structure consists of two cylinders. The first fixed cylinder is subjected to water pressure that causes oscillations in the second cylinder. These oscillations lead to generation of electrical energy by an energy harvesting circuit. Based on computational analysis, the best distance between the two cylinders is four to five times the combined diameter of the two cylinders. The shapes of the two cylinders are chosen in such a manner that the maximum interaction is achieved between the water and the cylinders for optimal performance. The authors in [46] argue that piezoelectric harvesters having a single degree of freedom have a high response frequency that reduces the generated power. To address it, three types of piezoelectric harvesters having double degree of freedom are considered. They are called U-shape, H-shape and folded piezoelectric harvesters. It was found that the H-harvester harvests the maximum amount of energy of extent 3.32×10^{-7} J than the rest of the harvesters. It is due to the reason that the top and bottom beams of an H-harvester are equivalent to a cantilever beam having double degree of freedom with harvesting capability comprising of linear combinations of the two cantilevers.

To power sensor nodes in an underwater pipeline, a piezoelectric material based power generation scheme is developed in [47], after analyzing power requirements by a sensor node in various modes. The unsteady water flow enters into a piezoelectric module. The water flow is hindered by a certain D-shape structure that produces a periodic stress

(Von Karman's vortex), which exerts pressure on a cantilever beam and deflects it that; in turn, produces electrical energy. Energy is harvested by two relay nodes between a transmitter-receiver pair that involves cooperative communications [48]. The relay nodes are special nodes with special circuitry to harvest the energy and are deployed at three different depth levels so as to avoid data loss and ensure enhanced network lifetime by avoiding death of relay nodes. In [49], a piezoelectric beam is implanted within the body of a fish. As the fish swims, it activates the piezoelectric beam and energy is harvested. The beam does not involve a battery arrangement rather directly uses the harvested energy to transmit acoustic signals. This helps in tracking underwater animals and monitoring their migration. A system devised in [50] consists of a propeller that rotates with water flow and it causes a stick to hit a piezoelectric module to generate energy. The bending of the piezoelectric module is controlled such that it produces the maximum amount of power at a specific frequency. A hybrid piezoelectric beam is submerged in water partially or fully in [51].

A mass-spring system devised in [52] transforms the kinetic energy present in ocean waves into mechanical vibrations, which are further input to piezoelectric levers to harvest electrical energy. It is found that the extent of harvested power increases with an increase in mass and size of the mass-spring system, amplitude of the waves, Young's modulus of the lever and a decrease in the time period of the waves. A varying length of the beam is allowed to vibrate. It is shown that an increase in the wet length of the beam reduces the resonant frequency and quality factor of the vibrations. In addition, the extent of the generated power decreases with an increase in the wet length. An intelligent selection of a relay node for routing and harvesting is presented in [53]. The relay node is selected by a source node within a certain transmission range that is adaptive subject to certain conditions. In addition, various levels of energy harvesting are defined that are involved in relay selection. Based on a vitality criterion, relay nodes are selected in [54] that harvest energy using piezoelectric materials, in addition to the energy obtained from battery. This enhances the lifetime of the sensor nodes. To provide power to a mini AUV, a circuit is designed in [55]. It harvests energy from water pressure and the harvested power is enhanced by a boost converter. Furthermore, the maximum power transfer is achieved by using a matching circuit between the rectifier and the converter resistances.

C. ENERGY HARVESTING FROM SOLAR RADIATIONS

The authors in [56] harvest power using amorphous silicon solar cells for autonomous jellyfish vehicles. The solar radiations incident on the silicon surface by considering a specific incident angle as well as at some tilt. Three different kind of the vehicles were studied considering their shapes in the form of a fitness ratio of height to the bell (hood) of the jellyfish. The harvested power amounts to be 55 W, 85 W and 125 W for the three different types of vehicles used. The energy harvesting performance of the solar cells made up of

TABLE 1. Energy harvesting using temperature gradient [37], [38], [39], [40], [41] and piezoelectric materials [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55]. The symbol x is used to represent the unspecified value of a metric.

Reference	Operational Mechanism	Harvested Energy/Power	Achievement	Limitations	Tested Depth (m)	Year
[37]	A certain threshold temperature difference is made to expand a phase change material that pushes hydraulic oil into a piston to move. The piston is further subjected to high pressure and a valve lets the high pressure oil to rotate a motor with four-fold more speed using a special gearing mechanism and power is generated in a generator linked with the motor	6000/1.7	Power can be generated even below the surface of water up to a depth of 500 meters	A specific temperature difference threshold should exist prior to power generation	500	2016
[38]	A thermal engine uses the temperature gradient to affect the volume of phase-change wax material that further changes the volume of hydraulic oil to create a pressure difference and provide the harvested energy	220-800 W	Harvested energy enough to operate a glider for many years in the sea	Optimization of flight and energy storage is required	1200	2015
[39]	A heat engine is modified by having a tank with two check valves to control the flow of the oil and accumulator. The effect of pressure on the phase change material in liquid, solid and transition phase is studied to optimize the generated power	220 W	Devised a way to increase the efficiency of a heat engine for thermal glider, particularly when temperatures are not constant, which can be further optimized	Diminished increase in the efficiency of the heat engine	x	2016
[40]	Combines temperature gradient with saline content difference to make water movable due to gravity and harvest energy	261 W	Enhances harvested power output due to salinity difference with the help of a temperature gradient	Maintaining temperature and salinity difference at the same time in sea is challenging	1.5	2016
[41]	Performs an analysis of heat exchangers for thermal gliders at various positions	x	Persistent operation of the glider	Requires further experimental validation	x	2014
[42]	A module is designed to reduce the higher resonant frequency of a piezoelectric material to a lower frequency usually available in the sea bed. Sea waves oscillate a piezoelectric material that generates a high frequency beam that is interacted with a short beam to lower down the resonant frequency of the system	0.3-0.6 mJ	The generally higher resonant frequency of a piezoelectric material is lowered down so it could be made resonant at a lower frequency available at sea bed	Only small frequencies can be detected associated with slow motion of sea waves	20	2006
[43]	A micro-bubble on a silicon surface in water is subjected to light with variations in intensity that vibrates two cantilevers to generate electrical energy	10 μ W	Variations in intensity of light generate electrical power	Diminished extent of generated power	x	2018
[44]	Analytical analysis of energy harvesting is made for underwater pipelines keeping in view the total power requirements, nodes' distribution, harvester size, properties and its other related parameters	2-20 W	A prototype model with computed parameters for harvesting energy using piezoelectric and electromagnetic techniques is given	Costly arrangement due to the use of a turbine in electromagnetic harvesting	x	2015
[45]	A prototype mechanical structure of a piezoelectric generator is designed that makes use of a fixed cylinder causing vibrations in a second cylinder. These vibrations are transformed into harvested energy by an energy harvesting circuit	x	Experimental results matching closely to those obtained through computational fluid dynamics	The designed prototype has not computed the generated power	x	2013
[46]	The high response frequency of a piezoelectric harvester with a single degree of freedom is reduced by using three piezoelectric harvesters each with a double degree of freedom. This enhances the efficiency of the harvester and makes it a linear combination of the harvesters with double degree of freedom	3.32×10^{-7} J, 2.99×10^{-8} J and 1.68×10^{-7} J	The higher response frequency of the harvester is reduced to a lower response frequency that enhances the generated power	Lacks evidence for sufficiency of the generated energy to drive a sensor node	x	2018
[47]	A piezoelectric module is designed that is installed in an underwater pipe. Turbulent water flow enters into the pipe and is hindered by a D-shape structure to produce periodic stress on a piezoelectric beam and deflects it that produces electrical energy	0.029-0.82mW	Sensor nodes charging without a battery in an underwater pipe	Generated power is low compared to the required computed power so further improvement is required	x	2017
[48]	Two specially designed relay nodes at various depth levels harvest energy	x	Prolonged network lifetime	Determining optimal depth levels for energy harvesting is challenging	x	2019
[49]	An implanted tiny battery-less piezoelectric beam is activated by a fish motion to harvest energy and transmit signals	4.7-24 μ W	Can be used to locate underwater animals' positions and monitor their locomotion	Low power output makes the communications less effective for long distance and depth	100	2016
[50]	A propeller rotates due to water flow and causes a stick to actuate a piezoelectric module for power generation	17 mW	The bending length of the piezoelectric module can easily be controlled to match a specific frequency for the maximum power generation	Propeller does not work in stationary water and cannot generate power	x	2020
[51]	A composite piezoelectric beam with varying wet length is excited with varying base amplitudes and frequencies to compute the generated power	$10^2 \mu$ W	Varying wet length of the beam can produce desired power levels	Resonance frequency and quality factor decrease with an increase in the submerged length of the piezoelectric material	x	2013
[52]	A mass-spring system converts the kinetic energy of ocean waves into mechanical vibrations that are utilized by piezoelectric levers to harvest energy	103 W	Simple and easy to implement design	The harvested power requires specific characteristics of the ocean waves, such as an amplitude of two meters of the waves and a time period of six seconds	x	2016
[53]	A relay node harvesting various energy levels is selected for data routing	9 J	Dynamic degree of freedom of relay selection with multiple energy harvesting levels	Source-destination cannot communicate unless relay has harvested sufficient energy	x	2020
[54]	A relay node harvesting energy is chosen in addition to sender-receiver pair	x	Data transfer reliability due to relay involvement and extra harvested energy	Relay involvement increases delay	x	2022
[55]	Energy is harvested for a mini AUV using a boost converter with a matched circuit	14.4 mW	Sufficient power for a mini AUV	Limited range of operational frequencies	x	2021

amorphous and mono-crystalline silicon is studied in [57] at various depth levels, incident angles and salinity in water. It was observed that as the solar cell is submerged in water, the cooling effect increases its efficiency unless a certain depth threshold is met after which the fading effect dominates and the efficiency decreases. Moreover, solar cells made up of mono-crystalline silicon exhibited the best performance at various depth levels and types of water. It is due to the fact that ions in sea water make these solar cells to conduct electricity in a better way than pure water. To harvest energy from solar radiations by a solar cell at and below the surface of sea water, the involved parameters are discussed and analyzed in [58]. These parameters include the various angles of incidence of solar radiations, the position of the cell, light scattering at water-air interface and within water, depth level and quality of water. This helps in computation of harvested power in anticipation provided some parameters are already known.

To monitor aquatic environment, several poly-crystalline solar cells are used in [59] by ensuring that every cell tracks the maximum point for power extraction even when the lightening conditions are not ideal. Two major electronic circuits are used: one for managing the radio signals and the other for dealing with harvested energy and its storage. The storage consists of two batteries that are charged and discharged at separate instances of time so as to avoid the conventional partial charging and discharging of the batteries. Therefore, when one battery powers the system (discharges), the other battery is being charged. When the later is discharged, the former starts charging. This switching is performed by a special circuit. It controls the particle charging and discharging of the batteries due to day night cycle. For persistent operation at water surface and in the air for speedy monitoring and tasks accomplishment, a hybrid device is designed in [60] that is capable to sail at water surface, go underwater as well as fly at the surface of water for rapid position change. It involves aircraft control mechanism, data sensing, processing, command and control strategies. Solar panels involving silicon mono-crystalline solar cells are used in the vehicle for powering at day time so that it could sustain its operation. This device, however, has so many challenges. First, defining the trajectory of the device within the water and the above the surface of the water is challenging because the geographical position of the path has to be known, which is difficult to compute compared to the terrestrial path. Secondly, the motion of the aircraft consumes a significant amount of energy.

D. ENERGY HARVESTING FROM AN AUV MOTION OR KINETIC ENERGY

A flywheel mounted in an AUV in [61] is affected by the rotational motion of the AUV due to sea waves. This causes a gyroscopic motion in the flywheel that generates torque. The generated torque is converted into energy by the system. The gyroscopic motion can be further utilized for sea journey monitoring and developing storage system for the generated electrical energy. The developed system is a further enhancement of the prototype developed in [62], which is further

analyzed for resonant and other frequencies that increase in a nonlinear fashion [63]. The concept of a rotating sphere of mass on a circular track within or outside an underwater buoy is described in [64]. When waves in water hit a buoy, the circular track tilts that causes the sphere to rotate on the circular track due to gravity. This rotation is sped up with the help of a gear and is input to a generator to produce electrical energy. However, the authors in [65] argue that increasing the mass of the rotating sphere, although increases the harvested power output, it damages the buoy. Therefore, the rotating sphere is replaced with a circular half disk while still keeping the whole system stable. When sea waves are incident on the buoy, the disk rotates and applies torque on the buoy that increases the tilting angles of the buoy by interacting with its natural mode and, consequently, power generation is enhanced. Other parameters that affect the harvested power include damping effect of sea water on the buoy and on the generator and ratio of rotor mass to overall mass of the buoy.

An ocean kinetic energy harvester designed in [66] is attached with a glider to harvest energy from the ocean waves. The harvester is composed of a pendulum that is attached with a permanent magnet generator made up of a rare-earth element. The generator is kept fixed with the glider while the pendulum is attached with the rotor of the generator. Ocean waves hit the pendulum and cause it to oscillate around its axis that correspondingly oscillates the generator rotor and a varying magnetic field is produced that produces induced electricity in the coil of the generator stator. An AUV with flapping wings and controlled by a remote controller, in combination with an electronic controller, is designed in [67]. The remote control helps in governing the journey of the AUV. The control electronics consists of an Arduino board and a Raspberry Pi board that help in managing battery power as well as harvested power. They also communicate with the offshore remote control device to steer the AUV and govern speed, control and thrust. The flapping wings of the AUV are rotated by sea water that further drive a generator to produce electricity with the help of a gearbox. The trajectory of an underwater kite is optimized in [68]. It harvests energy from ocean currents when it moves away from the base station and consumes it when comes back. The path optimization problem is considered as a single joint problem and solved analytically rather than splitting it into two sub-problems in the conventional manner. The dynamics of the kite are linearized by considering a reference level equilibrium trajectory in spherical coordinates. A similar kind of underwater kite with simultaneous optimization of spooling motion and cross-current trajectories is designed in [69]. This is in contrast to the usual approach where a single parameter is optimized for energy harvesting. A linear electromagnetic generator designed in [70] uses frequencies in the 0.1-0.4 Hz range and powers six sensor nodes. When sensors are in the sleeping mode, it can provide power to charge the batteries of the sensor nodes. The authors in [71] consider the currents, tides and the kinetic energy associated with underwater waves to harvest energy by triboelectric nano-generators (TENGs).

TABLE 2. Energy harvesting using solar cells [56], [57], [58], [59], [60], AUV motion or kinetic energy [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77] and marine life [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89]. The symbol x indicates unspecified metric value.

Reference	Operational Mechanism	Harvested Energy/Power	Achievement	Limitations	Tested Depth (m)	Year
[56]	Amorphous silicon solar cell applied on the top surface of a jellyfish autonomous vehicle generates power directly from solar radiations	55 W, 85 W and 125 W	Easily available solar radiations are used to generate power to fully operate an autonomous underwater vehicle	Not effective as the depth increases beyond few meters	2	2011
[57]	Amorphous and mono-crystalline silicon solar cells were analyzed at various depth levels, incident angles of solar radiations and various water types. Mono-crystalline solar cells proved to have the best efficiency in sea water due to the presence of ions in the water that make it a good conductor	22% power efficiency	Selection of the best solar cell for a particular application based on the tested results	Reduced efficiency at high depth levels when solar intensity starts to fade	0.17-98.50	2019
[58]	The effect of solar radiations incidence at various angles, scattering in water and water-air interface, depth, salinity and position of the cells is analyzed and harvested power is computed	210 J/cm ² /day	The presented model can be used to predict the harvested power in an underwater environment knowing the required parameters in advance	Some parameters related to solar cell and water quality have to be known in advance	200-1200	2019
[59]	Uses a number of poly-crystalline solar cells to harvest energy at the maximum power point tracking even in bad light conditions with two batteries arrangement designed to be charged and discharged at different instances of time to avoid partial charging and discharging of the batteries due to day-night cycle	5 W	Energy harvesting with charging and discharging of batteries at different instances of time to avoid partial charging/discharging	Uses radio signals which are severely attenuated in water	x	2011
[60]	A hybrid vehicle is designed that can sail at water surface, go underwater and fly in air and is powered by solar cells	50 W	Power sufficient hybrid device for accomplishing underwater tasks and in air	Complex design and requires further refinement	x	2016
[61]	A flywheel housed within an AUV detects the gyroscopic motion of the AUV due to sea waves and produces torque to harvest energy	2.86-3.58 W	Built-in power generation within the AUV to avoid environmental hazards, capability of gyroscopic motion to storage power and monitor ocean journey	Less effective as the depth increases and the gyroscopic motion of the AUV with sea waves diminishes	x	2016
[65]	A half circular disk installed in a buoy is allowed to rotate on circular path due to tilting angle of the buoy with incident water waves. The rotating disk further exerts torque on the buoy and increases its tilting angle by interacting with its natural angle. This enhances the rotation of the disk and drives a generator with a gear to generate power	1-9 kW	Alters the natural tilting angle of the buoy for more power harvesting with the help of a half circular disk rather than using a spherical mass	Ocean waves are necessary for producing tilt in the buoy	x	2019
[66]	An ocean kinetic energy harvester is designed that consists of a pendulum and a rare-earth permanent magnet generator. The pendulum is oscillated by the ocean kinetic energy that causes oscillations in the rotor of the generator to produce a varying magnetic field that induces electrical energy in a coil	150 mW	Miniaturized harvesting system design with enough power to drive ocean gliders without any gearing mechanism	Sensitivity of the output power to the damping effect of the sea medium	x	2015
[67]	Flapping wings are installed on an AUV that rotate with water waves to drive a generator for the production of electrical energy	x	Continuous power generation	Remote control requires WiFi	x	2018
[68]	A kite running on a spherical reference path harvests energy from ocean kinetic energy	x	Computational efficiency in trajectory definition	Requires reference spherical coordinates	x	2021
[69]	A kite harvests energy from the ocean kinetic energy	x	Optimizes more than one parameters	Computational complexity due to various parameters optimization	x	2021
[70]	A micro underwater generator is presented	x	Can power six underwater sensor nodes	Has a narrow band of operating frequencies	x	2022
[71]	An arrangement of four triboelectric nano-generators is used to harvest energy from ocean tides, currents and waves inside water rather than at surface	200 mW	Low cost fabrication with high throughput	The probability of existence of tides and currents below the sea surface is low	x	2022
[72]	Designs a linear electromagnetic generator capable of harvesting 7.77 mJ energy per second from ocean low frequency waves	Can power several submerged sensors with less complex manufacturing	Ocean waves existence varies with water depth	x	x	2022
[73]	A device with five vibrational modes harvests energy from vibrations caused by ocean waves in combination with a liquid metal	1.25 mW	Can power 36 light emitting diodes in series	The structure is complex	x	2022
[74]	Uses an underwater triboelectric generator with oil, water and solid interface in combination with a double layer capacitance. The squeezing and releasing of oil droplets cause movement of charges due to the discrepancy of the capacitance in the oil, water and solid interface	X	Ease of combination of materials to produce energy	High cost due to combination of various materials	x	2022
[75]	Devices a hybrid TENG with double Halbach array and double-slided fluff for optimum weight and the maximum harvesting	x	Low weight and maximum harvesting at ultra-low frequencies of the ocean waves	Complex design as hybrid techniques are involved	x	2022
[76]	Triboelectric nano-generators coupled with thin, flexible layer and a rigid coupling mechanism are designed to harvest energy even at high water depth	x	Can withstand high water pressure and produce energy at a large spectrum up to 75 Hz of the ocean waves	High cost of manufacturing due to extra mechanisms to withstand high water pressure	x	2022
[77]	A single drop of water is allowed to fall from an elastomeric pipe and is passed through an electrode to generate open circuit for power generation	57.6 μW	Can generate electrical power from drops of water	Diminished harvested extent	x	2022
[78]	A sedimentary MFC harvests energy based on MPPT	80 μW	Up to 75% efficiency of the fuel cell	Output power varies with oxygen in water	x	2017
[79]	The generated energy of an MFC is enhanced by a super-capacitor and boosting process	153 mW/m ²	Up to 75% efficiency of the fuel cell	Harvested energy affected by oxygen	x	2013
[80]	Uses an MFC to generate low voltages first stored in small and then large capacitors	4.2 kJ	Can power a sensor node for 1-2 months	The generated voltage is low	x	2012
[81]	Several MFCs with uninterrupted circuitry are used to provide a continuous threshold voltage	10.89 mW	Self-sustainability and uninterrupted operation	Complex circuitry	x	2020
[82]	Four MFCs are connected in a series-parallel configuration to harvest energy for a sensor node that detects an envelope due to enhanced sensitivity	62 μW	Self-sustained operation of the sensor node	Expensive due to multiple cells usage	x	2019
[83]	MFCs with boost converter and voltage multiplier circuits are used to produce high output voltage	240 μW	Low magnetic storage requirement	Several circuit components consume extra power	x	2020
[84]	A linear cable anode rather than carpet-like benthic MFCs with binder removal and fraying for enhanced power are designed	1-2 mW/m	Deployment convenience	Requires extra processes by the anodes	x	2016

TABLE 2. (Continued.) Energy harvesting using solar cells [56], [57], [58], [59], [60], AUV motion or kinetic energy [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77] and marine life [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89]. The symbol x indicates unspecified metric value.

[85]	Two benthic MFCs at extreme underwater conditions generate enough power to drive sensor nodes and acoustic modems	< 10 mW	Sufficient power generation at given conditions	Requires cabled control from sea surface	890	2013
[86]	An MFC is utilized with integrated micro-sensors and energy management circuitries to produce perpetual electric power	190 mW/m ²	Persistent and perpetual operation of micro-sensors	Requirement of specific micro-sensors nodes	x	2014
[87]	A Hall-effect sensor is used to monitor the opening and closing of the valve of a sea shell to evaluate nitrogen concentration as a measure of sea water quality. Sea water with dissolved salts is used to act as an electrolyte and make a Galvanic cell	26.6 μ W	Water quality monitoring based on nitrogen concentration	Metal electrodes replacement with time due to corrosion	x	2012
[88]	A device attached with a fish body harvests energy from the fish motion. It can monitor the swing and frequency of the swing of the body of the fish	0.74mW	Can power sensors and monitor the locomotion of the fish	Fish locomotion beyond the communication range halts the system performance	x	2022
[89]	A relay node harvests energy from marine environment to empower the communication between a source and a destination	x	Readily available energy harvesting from marine environment	Adds communication delay due to harvesting when relay battery power is exhausted	x	2022

Four such generators are connected in a parallel arrangement and work together to harvest energy. The harvested extent spans to 200 mW and is used for powering pH and turbidity sensors for monitoring the ocean environment. This generated power is the highest by the available generators in this category with low fabrication cost and high throughput. The authors in [72] design a linear electromagnetic generator that uses low frequencies of ocean waves. It combines two coils for harvesting an amount of energy enough to charge several sensors with an energy generation rate of 7.77 mJ per second. The authors in [73] design a device that is capable of harvesting energy from ocean waves from various directions rather than a single direction by using a liquid metal. It has five vibrational modes with a low frequency range less than 22 Hz. An underwater water-solid interface is used in [74] to harvest energy by a TENG. It introduces oil to the water-solid interface using a double layer capacitor. The oil droplets are squeezed and released on the surface of an underwater dielectric. This causes the movement of charges in the electrode of the device due to the sweeping of the ions by the oil near the solid interface due to discrepancy of the double layer capacitor. The authors in [75] design a hybrid device that combines triboelectric and electromagnetic nanogenerators to convert ocean mechanical energy to electrical energy.

This approach enhances the power generation capability of the device at the optimum weight. The authors in [76] design a sophisticated paired TENGs system integrated with a thin layer having flexibility as a triboelectric surface and coupled through a rigid yet flexible mechanism. This ensures that it can withstand the high water pressure at a high depth. It can harvest energy from ocean waves with a maximum frequency of 75 Hz. A TENG is designed in [77] to harvest electrical energy from the kinetic energy of water. A drop of water falls from an elastomeric pipe and passes through an electrode that generates an open circuit voltage for energy harvesting.

E. ENERGY HARVESTING FROM MARINE LIFE

To provide unlimited energy supply and enhance the efficiency of a sedimentary microbial fuel cell (MFC), an electrical interface is designed in [78] between a harvester and

an underwater sensor. The interface reduces the electrodes surface area to avoid the losses associated with large size and extracts the generated voltage at the maximum power point. The fuel cell developed utilizes the bacteria in the sediment of sea water. These bacteria catalyze the oxidation process of the organic materials present in water sediment at the anode terminal. At the same time, reduction reaction of oxygen takes place at the cathode terminal. This oxidation-reduction processes release electrons that generates energy. The anode is inserted within the sediment while the cathode floats over water surface. The authors in [79] argue that the voltage generated by a microbial fuel cell is very low by default and is not sufficient to operate an underwater sensor. Therefore, an electric circuit is made that operates in two phases. First, the energy generated by the fuel cell is accumulated in a super-capacitor. In the second phase, the energy stored in the super-capacitor is transferred to a load when it is above a certain monitored value.

To harvest energy, a microbial fuel cell in which the anode is inserted in the sediment and the cathode is placed in the salty ocean water is proposed in [80]. At first, the magnitude of the generated energy is small so it is stored in a capacitor with low capacitance. The stored energy is then transferred to a capacitor with high capacitance so as to produce voltages that are required for operation of underwater sensor nodes. The generated voltages are enough to power an underwater sensor node for one to two months and has a computed life span of three years with a varying degree of duty cycles. The authors in [81] claim that energy combiner circuit is usually used to enhance the power output of a microbial fuel cell and make it reliable and robust against power failure. However, the existing schemes do not consider self-sustainability of the cells and coping with external living agents that perturb the operation of these cells. Therefore, an energy combiner circuit is proposed that consists of two cells and a specially designed circuit. The circuit consists of a charge pump, a super-capacitor and a transistor that work together to maintain a specific threshold voltage at the output of the cells. Moreover, the cells are connected in a manner that if any of the two cells is made to malfunction by the external living agents, the other cell still operates and

works independently. An acoustic sensor is developed in [82] that extends the sensitivity of an existing sensor and makes it respond upon detection of an envelope characterizing an event. Four MFCs are connected in a series-parallel configuration with an energy harvesting circuit for a persistent and sustained operation of the sensor. It is argued in [83] that the ordinary approaches used to increase the output voltage of an MFC either have complex circuitries, require high magnetic memories or the output voltage is only a function of the duty cycle and is not scalable. All these factors affect the structure and performance of the energy harvesting system associated with an MFC. Therefore, a boost converter circuit is used in combination with a voltage multiplier circuit so as to achieve a high voltage, reduce magnetic storage requirement of the energy and achieve high voltage and current values. The generated output power is enough to power underwater sensor nodes.

Ocean monitoring by powering sensor nodes with benthic MFCs is becoming one of the feasible ways due to advances in the structure and function of these cells [84]. Such cells are previously used for powering underwater sensor nodes in carpet like anodes that are difficult to deploy underwater. Therefore, linear cable anodes are designed that are wound around an insulated underwater cable and treated as hydrophone arrays. Moreover, passing these anodes through the stages of binder removal and fraying enhances the power production of these cells. Two benthic MFCs were deployed in a deep water observatory in [85] and a power management circuit was used to measure the harvested power. The cabled acoustic communications with the energy harvesting module led to monitoring of the harvested amount of energy. It was observed that the harvested power at the extreme conditions was enough to drive the communication unit with sufficient self-power. Aquatic monitoring parameters such as dissolved oxygen, pH, conductivity and temperature usually require long term and persistent monitoring that becomes difficult with the ordinary sensor nodes due to their limited battery power. Therefore, an energy harvesting based approach is adopted in [86] to harvest energy and ensure perpetual monitoring of the aquatic environment. The designed system consists of integrated micro-sensors that require sufficiently low power to operate. The energy harvested by an MFC is processed by power management circuits so as to amplify it to a level to power the sensors.

To investigate the content of nitrogen in sea water as a measure of the quality of water, a mechanism is proposed in [87]. The mussel present in sea water is used as a sensing animal that shortens or widens the gap between its two valves in response to the nitrogen concentration present in water. In addition to a backpack module that contains a micro-controller and a radio, a Hall-effect sensor is glued at one end of the outer shell of the animal and a magnet made up of a rare-earth element at the other end. When the valve in the shell of the animal opens or closes in response to nitrogen concentration, this movement is detected by the Hall-effect sensor that further triggers a micro-computer from the sleeping

mode, which records the reading and informs its near nodes at regular intervals. The sea water is used as an electrolyte and this, in combination with the different metal strips glued on the shell, makes a galvanic/electrochemical cell for energy generation. The generated output power using an energy harvesting module with the Galvanic cell is $26.6 \mu\text{W}$ while the power required to drive the module fixed on the mussel shell is $26 \mu\text{W}$. Variations of the experiment also showed that power required to drive a sensor node could be generated with different electrodes. The authors in [88] use a wearable device with the body of a fish. The device harvests energy from the swing and body motion of the fish and monitors the swing angle and the overall body motion of the fish. It can be used for powering sensor nodes and monitoring the locomotion of the fish. The authors in [89] enables a relay node to harvest energy from the marine environment when source-destination nodes communicate via the relay node. This enhances the operational lifetime of the battery of the relay node and, therefore, the overall throughput of the network is enhanced.

F. ENERGY HARVESTING FROM TURBINES

The authors in [90] propose a wave energy converter that converts the up and down motion of waves in water into electrical energy. The converter consists of two parts: an upper part that floats over the surface of water and a lower part that is submerged in water and acts as a turbine with flap type blades. The two parts are connected using an elastic wire. The turbine consists of two rotors with every rotor having flap type blades to produce circular motion in response to the incident water waves. The turbine operates in two modes. In the vertical mode, the

upper part moves up and down due to an incident wave that produces tension in the wire due to which the lower part also starts the same motion. In the horizontal mode, a drag force acts on the turbine frame and its blades that produces a lift force that is converted into a torque to rotate the rotor. A generator is then used to convert the rotational mechanical energy into electrical energy. Moreover, the effect of blades' geometry, incident wave conditions, rotor design, geometry of the floating body and power storage system were also analyzed to determine their effect on the harvested energy. To monitor water quality for an extended period of time, an energy harvesting device based on a turbine is designed in [91]. The device first analyzes the water velocity in a fish farm and the obtained results are used to design blades and propellers of the turbine. The turbine was then analyzed for various values of the stress and torque at different speed values of the water flow and to achieve the maximum torque by a generator that induces voltage, which is stored in a Lithium battery. An electronic circuit is designed to govern the operation and energy generating capabilities of the turbine, which consists of a micro-controller, a real time clock and electronic components involved in power generation and communications with the sensors and other related devices. Energy is harvested by turbines from weak ocean currents

TABLE 3. Energy harvesting by turbines [90], [91], [92] ultrasonic radiations [93], [94], hybrid sources [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105] and parameters optimization [101], [102], [103], [104]. Unspecified value is x.

Reference	Operational Mechanism	Harvested Energy/Power	Achievement	Limitations	Tested Depth (m)	Year
[90]	Incident sea waves drive a turbine's blades into rotation that further drive a rotor to produce some torque, which is converted into electrical energy	x	The unique rotary system reduces torque loss. Also, the system bypasses the requirement of a gearing mechanism	Harvester power is compromised, especially at a higher depth when sea waves have almost no movements	x	2017
[91]	Uses the best possible design of a turbine's blades and propellers based on pre-design measurements of water flow and achieves the maximum torque generation at various flow speed values to produce the maximum energy from the kinetic energy of ocean with the help of an electronic circuit to govern the turbine movements and energy storage	4-40 W	Extended monitoring time of an underwater wireless sensor network with the harvested energy	Requires the use of a separable acoustic modem for its full functioning	45	2017
[92]	A turbine uses weak ocean currents at sea bed to harvest energy for an AUV	2.8 W	Energy is harvested even from weak ocean currents	Energy cannot be harvested beyond a certain limit from the weak ocean currents	x	2021
[93]	Ultrasonic waves are incident on a power platform that uses a transducer to convert these waves into electrical signals. Super-capacitors in various arrangements are used to retain the energy to a certain level, which is then input to a storage element after passing through an electronic circuitry with rectifier and matching circuit for maximum power harvesting. The power platform is linked with a communication platform to send the sensed information back to the source of ultrasonic waves	1.6 W	Energy harvesting with communication capabilities over distances significantly longer than power generated by inductive or magnetic technologies	High attenuation of the ultrasonic radiations affects the generated output. Time consuming element of the storage element rather than being quick	x	2018
[94]	Proposes an energy harvesting architecture from ultrasonic radiations	32.5 mW	Can work even in long distance communications	Not efficient for high data rates, which require high harvested power	x	2022
[95]	Uses wind-solar combination as a hybrid model of energy harvesting to power ocean surface vehicles and robots	35-80 W/m ²	Can power ocean surface vehicles and robots even with spatio-temporal variations in the sources for energy generation	Requires more sophisticated mechanical and electronic devices as compared to a single source of energy	x	2017
[96]	Combines piezoelectric and microbial fuel cells based harvesting	0.14 J	Long time powering of sensor nodes due to two different harvesting mechanisms	Requires continuous sensing of harvesting conditions to decide about the appropriate mechanism of harvester selection	x	2015
[97]	Harvests energy using three mechanisms: turbine, piezoelectric material and sound waves in combination with power management policies to enhance lifetime of sensor nodes	0.03-8.57-64.41 mW	Can power sensor nodes up to 2000 days	High computational complexity due to combining multiple strategies	40	2019
[99]	Combines wave, wind and solar mechanisms to harvest energy	x	Optimizes energy for powering sensor nodes at their own locations	Determination of nodes' positions and energy level	x	2019
[100]	The solar radiations, wind waves and the the kinetic energy present in sea water are combined to harvest energy	x	Optimized and likely to be uninterrupted supply of energy, as it is unlikely that none of the three sources is unavailable to generate energy. So, can provide persistent and continuous operation of sensor nodes	Uses additional circuitry to combine and optimize the energy harvested from three different sources, as the generated power by each of the sources has varied extent and characteristics. Moreover, this method may not be suitable at the sea bottom where the three addressed sources of energy have diminished extent	x	2019
[101]	Optimizes a linear electromagnetic generator with size and geometry of the magnet and coils by inducing voltage in each coil due to tilting of a movable magnetic core and using external resistors equal to the internal resistances of the coils. This matching resistance mechanism ensures to generate and deliver the maximum power	25-100 mW	Since no moving parts are involved, there is no biofouling of the generator, reduced size and significant amount of harvested power	Reducing distance between coils concentrates energy over a short time span that requires specific electronic devices to store the generated power	x	2019
[102]	Optimizes the positions of a number of AUVs in response to the water flow variations with the help of a radar and computational circuitries	86.11 kW	The best positions of the AUVs are computed to generate the maximum energy and the positions with the minimum output power are specified	Constant computation of the flow rate of water that usually varies with the depth of water	x	2019
[103]	A magnetic coil is placed near a high voltage current carrying cable to induce magnetic field and generate energy from it	Tens of milli-watts	Can power sensor nodes without built-in battery requirement	It is rare to have a high voltage alternating current cable in water. Moreover, some sensor nodes may not operate with the diminished value of the generated output power	x	2011
[104]	Energy harvesting from Longuet-Higgins pressure waves is analyzed. These waves extend to the ocean bottom and are very low frequency pressure variations generated by the interaction between opposing waves and have been validated by the observatories for underwater applications	x	Numerical analysis is performed to determine energy harvesting capability of pressure waves	Requires further experimental validation based on the computed numerical values	x	2021

for powering the AUV at ocean floor [92]. The turbines convert the kinetic energy of ocean into rotational mechanical energy that is further passed to a permanent magnet generator

for conversion into electrical energy. For achieving energy efficiency, various harvesting parameters are optimized by simulations and tested experimentally.

G. ENERGY HARVESTING FROM ULTRASONIC RADIATIONS

A battery-less platform for underwater Internet-of-Thing is developed in [93]. It consists of a communication unit and a power unit. The communication unit acts as a sensing and communication platform and contains a sensor node as one of the major elements in addition to a special electric board to govern the communication and sensing operations. The power unit harvests energy from ultrasonic waves that are sent either from the source elements at water surface or submerged in water using a transducer. The transducer is connected with a full wave rectifier using a matching circuit for enhanced harvesting. Several super-capacitors are used during the charging and powering phase. The rectifier output is sent to the storage element for storing the energy and powering the designed platform. The designed platform communicates back with the source elements and shares the processed information detected within the water. This work is further extended in [94] that presents the architecture of the underwater ultrasonic harvester and is capable of performing a sensing operation and harvesting enough power to operate the modem for communications. The overall energy efficiency of the system is also evaluated.

H. ENERGY HARVESTING FROM HYBRID SOURCES

It is argued in [95] that spatial and temporal variations in the sources of energy harvesting for underwater environment directly affect the production of harvested energy. At times, the variations may be such that the generated output energy may not be sufficient to drive the required devices. Therefore, the concept of a hybrid way of harvesting energy is proposed that combines solar and wind energy as a hybrid way of better driving devices than propulsion power, especially devices such as surface vehicles and robots. The authors in [96] propose a hybrid system for energy harvesting for continuous powering of the sensor nodes. It combines piezoelectric based harvesting with a microbial fuel cell, depending upon the suitability of the conditions. These two system harvest the energy and initially store it in a super-capacitor, which is then used to charge a battery for powering sensor nodes. Three different mechanisms of energy harvesting are combined in [97], which is an underwater version of the harvesting mechanism presented in [98]. They are turbine, piezoelectric and hydrophone harvesters. The turbine harvester produces energy from the water flow. The Piezoelectric harvester transforms the mechanical stress due to water pressure on a piezoelectric material to electrical energy. The hydrophone harvester utilizes the sound waves coming from ships and other objects present in water to harvest energy. To further enhance the operational lifetime of sensor nodes, power of sensor nodes is managed based on a scheduled utilization or event based utilization. The former mechanism uses power of sensor nodes according to the scheduled activities while the later uses it when a certain event is detected. An underwater buoy is developed in [99] that harvests energy from wind, solar and energy present in the waves of an ocean. The combined energy is optimized and stored in a battery.

The buoy locates the sensor nodes and charges their batteries. Energy from solar radiations, wind and ocean waves is harvested in [100]. The harvested energy is optimized using power management circuit that delivers the energy to a gateway sensor node or recharges its battery.

I. ENERGY HARVESTING FROM PARAMETERS OPTIMIZATION

The authors in [101] argue that the existing energy harvesters in underwater communications are oversized, subjected to disturbance by living organisms in water due to moving parts or do not harvest enough power to drive sensor nodes. To overcome these challenges, a linear electromagnetic generator is optimized that consists of a movable magnetic core inside a hollow cylindrical acrylic tube. Two coils are wrapped around the tube. Water movements cause the magnetic core to tilt and it passes through the coils and each coil generates an induced voltage, which is maximized by using an external resistor equal to the internal resistance of the coil. Optimization of the size and geometry of the magnets and position of the coils led to power generation from 25 mW to 100 mW, enough to drive sensor nodes. The authors in [102] optimize the positions of a group of AUVs to locate them at the best positions in terms of energy harvesting from the flow of water using the built-in turbines. An estimator based on Kalman filter is used to compute water flow in the stream for the AUVs and is monitored by signals from a high frequency radar to optimize the positions in response to the flow speed. The uncertainty in water flow is computed by the Gaussian process. The generated energy is stored and used by the AUVs when required. Energy is harvested from a high voltage alternating current carried by a cable in [103]. A magnetic coil is placed near the cable that induces a magnetic field in the coil that is converted into electrical energy. The generated energy is optimized to tens of milli-watts using appropriate number of turns, impedance and position of the coil. The authors in [104] describe the pressure waves discovered in 1950 by Longuet-Higgins in 1950 that extend from surface to sea bed. The mechanism by which these waves are generated and their energy harvesting capability are analyzed numerically.

The Figure 3 shows the number of articles published in each of the energy harvesting category classified above from 2012 to 2022. The publication trends shows that the latest techniques focus on harvesting energy from the AUV/kinetic energy of water or hybrid techniques that further combine two or more methods of energy harvesting to obtain the optimal energy harvesting values. Some of the values are normalized, such as energy harvested by temperature variations, solar radiations, marine life and hybrid sources in 2014, along with others for better overall depiction.

V. COMPARISON OF THE POWER HARVESTING CAPABILITY

The Figure 4 shows the maximum power harvesting capability of the compared techniques. It shows that optimization of parameters results in the highest amount of harvested power,

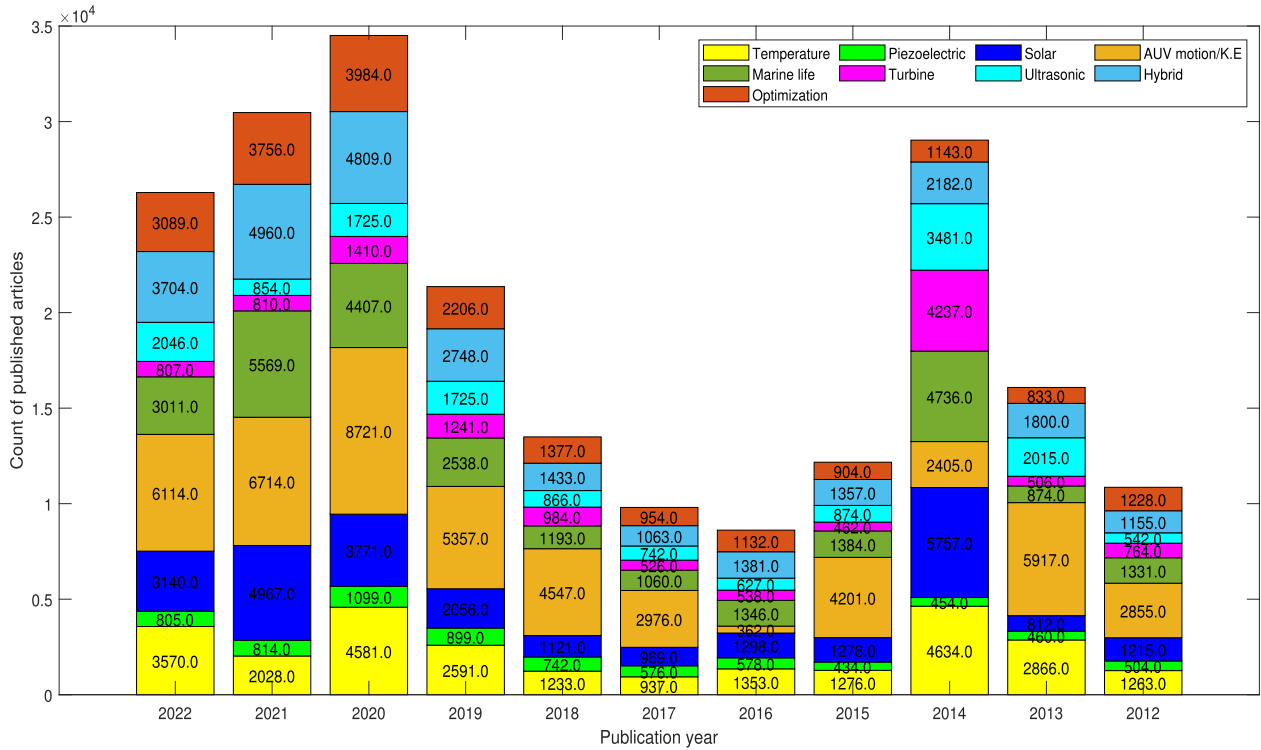


FIGURE 3. Number of articles published per year from 2012 to 2022 on various energy harvesting techniques for underwater acoustic wireless sensor networks, data taken from: <https://app.dimensions.ai>. The latest techniques mainly harvest energy from AUV motion or kinetic energy of water, combining hybrid techniques and marine life.

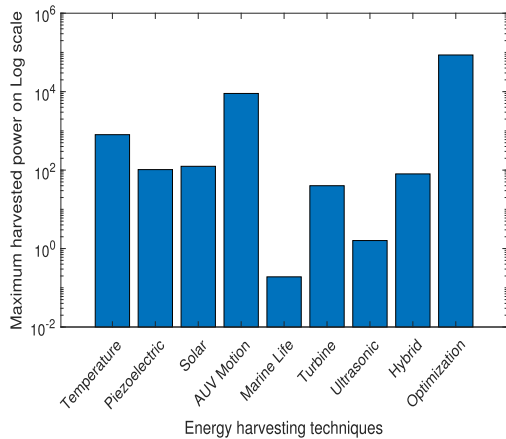


FIGURE 4. Maximum power harvesting capability of the compared techniques on the Logarithmic scale. The Logarithmic scale is used for better overall presentation of the harvested values. The category of optimization harvests the maximum power. The kinetic energy from water is ubiquitous, and, therefore, is conveniently utilized.

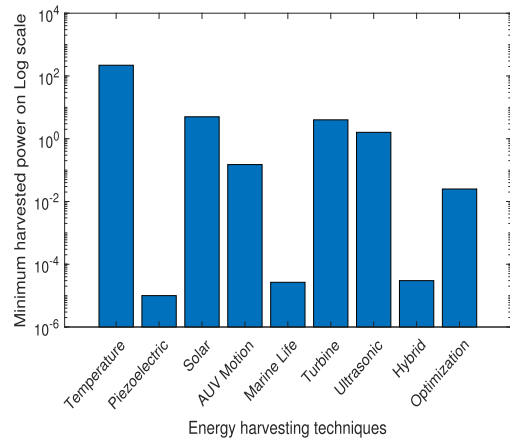


FIGURE 5. Minimum power harvesting capability of the compared techniques on the Logarithmic scale. The Logarithmic scale is used for better overall presentation of the harvested values. The piezoelectric technique harvests the minimum power.

which is 86.11 kW (equivalent to 11.36 on the Logarithmic scale). Next, the the AUV motion, which harvests energy directly from the kinetic energy of water, harvests the second maximum possible amount of power, which is 9000 Watt (equivalent to 3.954 on Logarithmic scale).

The third highest amount of power is harvested by the temperature variations in water, which is 800 Watt (equivalent to 2.903 on Logarithmic scale), followed by solar harvested power of 125 Watt (equivalent to 2.097 on

Logarithmic scale). The power values harvested by piezoelectric, hybrid techniques, turbine, ultrasonic radiations and marine life are 103 Watt, 80 Watt, 40 Watt, 1.6 Watt and 0.190 Watt (correspondingly equivalent to 2.013, 1.903, 1.602, 0.204 and -0.721 on Logarithmic scale), respectively. The Figure 5 shows the minimum amount of harvested power in Watt, converted to Logarithmic scale, by each of the compared energy harvesting techniques. The minimum amount of power is harvested by the piezoelectric technique.

VI. CHALLENGES IN UAWSNs AND ENERGY HARVESTING

The major challenges that the UAWSNs face include short life span of nodes' batteries, high delay in data communication on account of the use of acoustic waves since radio waves are absorbed in water, narrow bandwidth of acoustic waves and the harsh and unpredictable underwater environment [24]. Specifically, the challenges associated with energy harvesting in UAWSNs include:

- The battery-less operation of nodes is still challenging as not all the harvesting schemes produce enough power to permanently operate the nodes.
- Piezoelectric materials bear pressure up to a certain extent. Deep underwater applications, therefore, require sophisticated materials to withstand in such type of environment.
- The generated power fluctuates and varies proportionally in response to the input parameter designed for harvesting. Therefore, these fluctuations require sophisticated electronic treatment (signal conditioning) before being applied to the sensor devices.
- Underwater energy harvesting is dependent on the environment to a significant extent. For instance, energy harvesting from solar radiations will be challenging if the nodes operate at a depth where the penetration of sunlight is low. Similarly, energy harvesting from the kinetic energy of the ocean waves becomes challenging in the scenario where tides are not present. In a similar fashion, energy harvesting from marine life requires the presence of specific living organisms (such as bacteria) to initiate the chemical reaction for energy production.
- Sophisticated materials are required to fabricate the underwater energy harvesting devices (or modules) so as to withstand in the harsh and unpredictable underwater conditions.
- The precise location of nodes and defining the traveling trajectory of an AUV is challenging in underwater as the conventional methods of locating the position of devices are not effective inside the water.

VII. CONCLUSION AND FUTURE WORK

The energy harvesting techniques designed for UAWSNs are addressed in terms of their operational mechanism, harvested power (energy), achieved goals and limitations. They include state-of-the-art schemes designed in the last decade. Starting from the architecture of an underwater power harvester, power harvesting schemes are classified into various categories, namely, temperature, piezoelectric, solar, AUV motion, marine life, turbine, ultrasonic, hybrid and parameters optimization techniques. The extent of the generated power (energy) for every category is described and the maximum and minimum harvested power of all the classified categories is plotted. The maximum theoretical power of 86.11 kW is generated by the parameters optimization. On the other hand, the minimum power harvested by the piezoelectric method is 10 μ W. The description of the extent of the harvested power eases the selection of the specific power

harvesting category for the specific applications depending upon the power usage requirement. The limitations of the power harvesting schemes provide further research directions towards improvement.

Since most of the harvesting techniques have limited amount of practically harvested power, they do not usually ensure battery-less operation of the sensor nodes in UAWSNs. Therefore, future techniques require to combine two or more methods for the sustainable and continuous operation of the devices. In addition, a thorough analysis of the power required to operate different sensor nodes will provide an insight to the selection of the suitable power harvesting techniques for underwater applications in which these nodes are used.

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