

Review

# Capturing Flow Energy from Ocean and Wind

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**Abstract:** Flow-induced energy harvesting has attracted more and more attention among researchers in both fields of the wind and the fluid. Piezoelectric energy harvesters and triboelectric nanogenerators are exploited to obtain superior performance and sustainability, and the electromagnetic conversion has been continuously improved in the meantime. Aiming at different circumstances, researchers have designed, manufactured, and tested a variety of energy harvesters. In this paper, we analyze the state-of-the-art energy harvesting techniques and categorize them based on the working environment, application targets, and energy conversion mechanisms. The trend of research endeavors is analyzed, and the advantages, existing problems of energy harvesters, and corresponding solutions of energy harvesters are assessed.

**Keywords:** energy harvesting; flow induced; piezoelectric energy harvester; electromagnetic generator; triboelectric nanogenerator (TENG)

## 1. Introduction

Energy is a platitudinous topic, but plays a critical role in human society. The nonrenewable fossil fuels are being depleted, and the substantial pollutant emissions from their combustion process are poisoning us for decades [1,2]. The rapid development of the industrial sectors and growing population push the energy demand up to an unprecedented level. In the 2018 New Policies Scenario, World Energy Outlook forecasted that global energy needs will rise by over 25% to 2040 [3]. Thus, developing renewable, environmentally friendly, economical energy resources have become the focus of the current era. Nuclear, solar, wind, tidal, and osmotic energy are developed and utilized as emerging energy sources for years [4–8]. Among them, wind, tidal, water current, and other mechanical energy in flow form have remarkable advantages due to their environmental friendliness, abundance, and safety.

On a global scale, the total amount of flow energy is abundant. Soerensen et al. reported that flow energy in the ocean to be developed is around the order of  $10^{12}$  KWh per year [9], and renewable UK reported that during 1979 to 2010, the global wind flow energy averaged approximately  $1.50 \text{ MJ/m}^2$ , which means  $2 \times 10^{12}$  KWh per year [10]. At the end of the year 2015, 435 GW of wind power generation was in operation and occupy around 7% of total global power generation capacity. Besides, ocean energy generation reached 0.5 GW and still 1.7 GW generation capacity in the process [11]. The enormous magnitude of flow energy laid its position on renewable energies.

Meanwhile, the ubiquitous characteristic of flow makes sure it has good application prospects in micro-energy self-powered equipment field. Traditional portable devices and sensors use batteries for energy supply. However, batteries are dangerous and cause environmental and safety issues, even the small ones in cell phones [12]. The existing possibilities of chemical substance leakage and the explosion

pose a potential threat to human health. The environmental threat is more obvious for one-off batteries, which are not intended for replacement and recycling, resulting in appreciable pollution problems [13]. Harvesting energy from the environment instead of carrying a chemical battery around is safer, undoubtedly, for both humans and the nature. Safety and universality make environmental energy harvesting an attractive topic. Relatively speaking, energy harvesting has advantages, as follows: (a) Battery-less operations are feasible, (b) embedded systems are easy to wire, (c) the infrastructure is easy to retrofit, (d) labor is saved, or “fit and forget” [14], and (e) the equipment is lightweight. Some long-term monitor systems with low power consumption, such as sensors for building structure health detection, body information collection, and low-energy self-maintenance systems [15] usually need long-term stable energy supply. In practical applications, ocean climate detectors have an option to take advantage of the ocean by using tidal energy or wave energy, and bridge safety monitors can be recharged by wind flow to suit local conditions. Thus, ubiquitous flow energy provides a good energy harvesting option toward self-powered systems.

Energy harvesting from flow environments flourishes with the development of the energy industry along the general trend. Various forms of flow energy, such as wave, tidal, water current, wind flow have been exploited and utilized [16]. The mass level of large flow energy harvester can reach  $2 \times 10^5$  kg, where the energy harvesting magnitude can reach 18.2 KW [17]. Flow energy harvesters can also be minimized as small as a few centimeters and indicate energy harvesting density as 1–10 mW [18,19]. A variety of energy harvesters have been developed based on different energy conversion mechanisms. Among them, the large-scale electromagnetic energy harvester relies on large generators, suffering from complex structures [20]. The approach can produce energy in large magnitudes and can generate electricity feeding the grid for the industrial production process and daily life use. As for triboelectric nanogenerators (TENG) and piezoelectric energy harvesters (PEH), they usually have a relatively small size and simple structure [21]. Despite that, the energy harvested by them is generally small, it is still sufficient for low energy consumption devices such as intelligent sensors and equipment monitors.

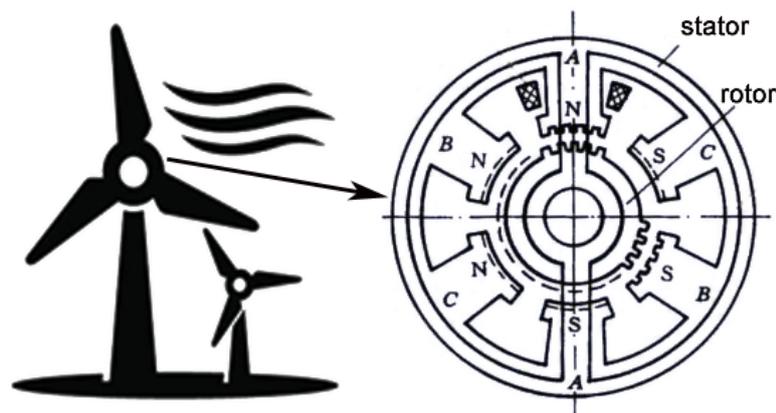
## 2. Mechanisms of Energy Harvesting in Flow Environment

To obtain superior performance and sustainability, researchers have tried many energy conversion methods to harvest flow energy. Among various conversion methods, energy harvesters based on electromagnetic, triboelectric, and piezoelectric mechanisms have been continuously developed, including single-mechanism energy harvesters and hybrid energy harvesters.

### 2.1. Electromagnetic Energy Harvesting

Electromagnetic is a traditional way of energy conversion. Electromagnetic is based on the principle of electromagnetic induction. The advantage of electromagnetic energy harvesting is high energy conversion rate and high output at high frequency and the disadvantage is that the mechanism is complex, which leads to a large volume and high maintenance frequency [22].

Electromagnetic energy conversion in flow energy harvesting usually converts flow energy into rotation through a mechanical structure, which drives the rotor of electromagnetic energy converter to rotate at a higher frequency. Relative motion between rotor and stator occurs during rotation. In the process of the relative motion, the coil moves along a plane perpendicular to the magnetic induction line, and the change of magnetic flux induces the electromotive force in the coil. The induced electromotive force is drawn through the connector and connected to the circuit, which generates the current. Depending on the structure of the generator, the output power of the energy harvester can be either direct current or alternating current. The efficiency of electromagnetic energy converters can reach 89–97% by data [23]. Figure 1 shows the schematic of the foundation wind power generation principle. The blades convert the flow movement into a rotation, and the generator rotor at the rotating axis will move accordingly. The stator consists of a stator core, a wire-wrapped winding, a frame, and other structural elements that fix these parts. The rotor is composed of a rotor pole, retaining ring, central ring, sliding ring, fan, and a rotating shaft.

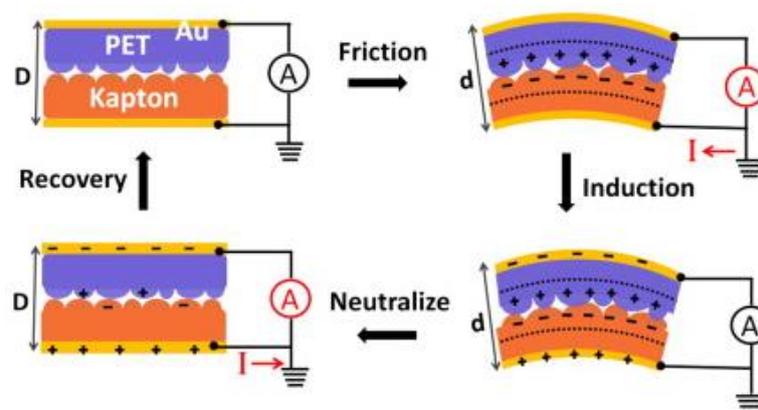


**Figure 1.** Schematic of common wind power generation principle.

Electromagnetic energy harvesting is widely used in wind power generation and large-scale liquid environment energy harvesting. Generally speaking, it is an efficient and reliable power generation technology.

### 2.2. Triboelectric Nanogenerators

Electrostatic is a state in which charges accumulate on a physical surface and do not flow. This usually occurs when the electric domains are oriented in an insulator or when the conductor does not form a loop. The electrostatic induction has been demonstrated for energy harvesting [24]. However, the static charge required in electrostatic energy harvesting usually demands additional polarization process. In 2012, triboelectric nanogenerators (TENG) were invented to generate surface static charge through triboelectrification, which is a common phenomenon in daily life [25,26]. Figure 2 shows the mechanism of triboelectric power generation, the triboelectric charge is essentially generated through a process of contact and separation, or sliding. Then it collects mechanical energy through electrostatic induction, and converts them into electricity, usually based on an all-polymer-based structures. The basic structure of this generator is usually two thin polymer membranes made of Kapton and polyester (PET) stacks that allow for charge generation, separation, and induction through mechanical motion or deformation of the polymer membrane [27].



**Figure 2.** Schematic diagram of triboelectric nanogenerators. (Reproduced with permission [27]. Copyright 2012, Elsevier).

### 2.3. Piezoelectric Energy Harvesting

In 1880, Curie Brothers discovered the piezoelectric effect through tourmaline [28]. Later in 1881, they validated the inverse piezoelectric effect by experiment [29]. Woldemar Voigt deduced the lattice characteristics that possess the piezoelectric effect [30].

As shown in Figure 3, when piezoelectric materials such as piezoelectric crystals and piezoelectric ceramics are electrified by an external force, the deformation caused by the external force results in the emergence of the bound charges with different polarity on the surface of both ends of piezoelectric materials. The induced charge density is proportional to the external mechanical force, which is called the positive piezoelectric effect. The inverse piezoelectric effect is the inverse process of the positive piezoelectric effect [31]. Piezoelectric material deformed by an external electric field and its deformation is proportional to external electric field strength. Piezoelectric phenomena are caused by the orderly arrangement of dipoles in materials.

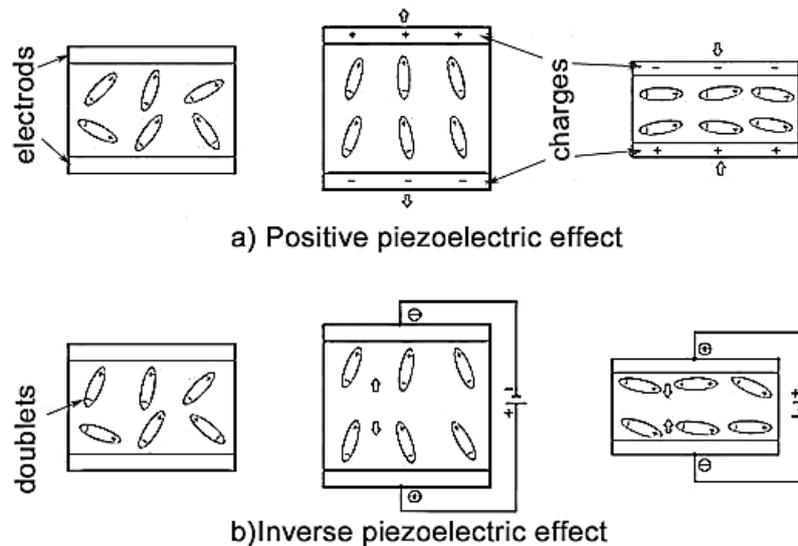


Figure 3. Schematic diagram of piezoelectric effect.

Direct piezoelectricity of certain materials, such as quartz, produces a potential difference of several thousand volts. However, the piezoelectric material generates a small current value, which makes it difficult to increase the power. Moreover, many piezoelectric materials have poor flexibility and are often damaged during power generation. At the same time, piezoelectric power generation has the advantage of good energy harvesting response in low-frequency and low-speed energy harvesting [32–35].

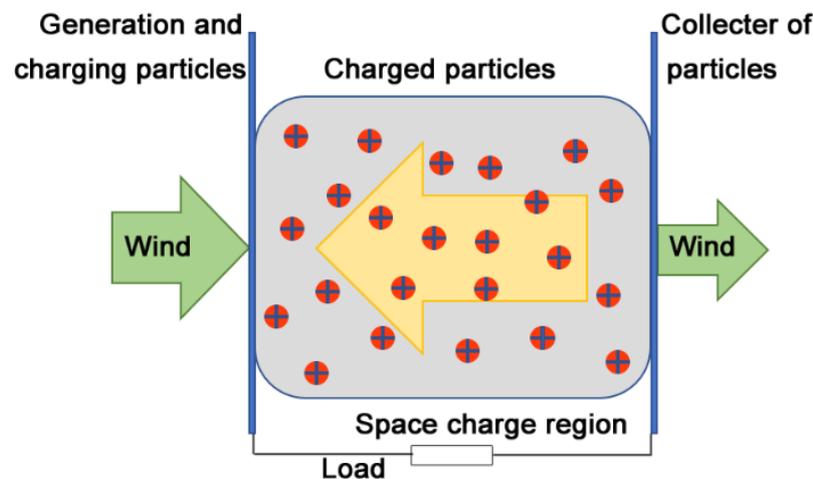
Piezoelectric energy conversion here is to convert flow energy into material deformation energy, which is further converted into electrical energy with the help of piezoelectric materials. Positive piezoelectric effect of piezoelectric materials is used in energy harvesters. Common piezoelectric materials include crystals, ceramics, organic materials, etc. [36].

#### 2.4. Other Energy Conversion Mechanisms

Other than the three basic energy conversion mechanisms, there is also other energy conversion mechanisms that can be used for fluid energy conversion, like the bladeless electrostatic wind energy converter in Figure 4. Bladeless electrostatic wind energy converter converts wind energy into potential energy of charged droplets, causing it to move in the direction of back potential [37]. When wind energy works, it will simultaneously increase the gravitational potential energy and electric potential energy of charged droplets. The particles lose their electrons at the blocked interface (dielectric barrier discharge) and form a loop with the external circuit, and then rely on gravity to fall back. The efficiency of this energy conversion mode is usually related to the radius of the liquid particles and the amount of charge.

In addition, the use of electrokinetic principles and membranes to collect fluid kinetic energy is another approach in development. In this mechanism, the chemical energy generated by kinetic energy will be converted into electrical energy. The adsorption of sodium ions in seawater by graphene

with a conjugated electron cloud maintains the chloride ions at the interface and generates a potential difference by the vibration of the water stream [38].



**Figure 4.** Bladeless electrostatic wind energy converter mechanism. (Reproduced with permission [37]. Copyright 2015, CI TASK).

### 3. Wind Energy Harvester

Wind energy is a renewable energy resource with properties of wide distribution, clean nature, environmental friendliness, and richness [39]. Besides, wind energy harvesting is relatively easy and simple compared to water flow since air is more insulated than water, thus, the wiring is easier. Traditional land wind power harvesting is cost effective and has been developed and utilized in some places where the wind resource is abundant [8,40]. Offshore wind energy harvesting can obtain more plentiful and steadier electric energy since ocean wind energy is more stable and abundant [41]. While the cost of construction and maintenance is relatively high, from the perspective of energy environment, data from GWEC show that during 2015 the increase of installed capacity reaches over 63 GW. They also predicted that the installed capacity of wind power will be 840 GW by the end of 2022 [42] and 4042 GW in the middle of this century [43]. At present, China is the leader of wind energy harvesting. In addition, the abundant and ubiquitous wind energy has no pollutant emissions during the energy harvesting process. From the perspective of energy harvesting of self-energizing devices, wind energy harvesting is an excellent choice for smart devices that need self-powering, as long as it is exposed to the air, for it is widely distributed, clean, and has abundant reserves as a flow energy source [44]. What is more, compared with the water flow energy harvesting, it has the advantage of simple wiring [45].

#### 3.1. Large-Scale Wind Energy Harvesters

As a mature technology, large-scale wind harvesting has already been connected to the power grid to benefit millions of households, especially land wind energy harvesting. As early as 2001, Eduard et al. [46] proposed efficient harvesting control techniques for different wind speeds. Large wind harvesters usually use electromagnetic energy harvesting principles, with the wind turbine is the protagonist.

Linni et al. [47] reported a new permanent magnet (PM) brushless motor for wind power generation in 2009. Their system consists of a turbo generator, bridge rectifier, converter, storage filter, and DC-AC inverter. They innovatively integrate high-speed permanent magnet brushless generators with coaxial magnetic gears. Quantitative results show that the proposed prototype has a smaller size, lighter weight, and lower cost than its counterpart. They predicted the model will attract attention in the field of wind power generation.

Compared with the mature onshore wind power grid, offshore wind power harvesting still faces some practical problems. The sea breeze is a more stable source of wind energy, but the construction and maintenance costs required for energy harvesting equipment in the ocean will be higher, and it will be more difficult to connect to the grid [48,49]. In 2016, Chen et al. [50] proposed replacing the doubly fed induction generator with a brushless doubly fed induction generator. The energy harvester without brushes and sliding rings will have higher stability, lower maintenance frequency, and lower cost. An improved vector control strategy based on the proportional-integral resonance controller in a single synchronous reference frame is developed. The validity of the control method is verified.

In general, research endeavors on large harvesters mainly employs the principle of electromagnetic induction. Land harvester technology is relatively mature for large-scale wind energy harvesting, and many countries have applied a large number of harvesters in suitable areas. Offshore wind energy is abundant, but for now, the application of offshore energy harvesters is not as extensive as land harvesters. Scholars are working to reduce the cost of construction and maintenance, such as designing brushless slip ring generators that require less maintenance.

### 3.2. Miniature Wind Energy Harvesters

Rasani et al. [51] proposed a basic piezoelectric cantilever model for harvesting flutter energy in 2012, which they believe could be used to provide additional power for satellite UAVs in the future. The simulation results show that the maximum energy of the flexible cantilever beam can reach is  $8 \times 10^{-8}$  J when the velocity changes from 3 m/s to 6 m/s. Their calculations are mainly in the high Reynolds number range and take air viscous into account.

Weinstein et al. [18] set up a piezoelectric energy harvesting device point at the air flow in the air outlet of the air conditioner, which provides energy for the monitor of the air conditioner. The basic configuration of the air conditioning energy harvesting mechanism includes an upstream cylindrical spoiler and a downstream vibrating cantilever beam. The given size of the energy harvester is less than 15 cm. When the wind speed is 2.5 m/s, 200  $\mu$ W energy can be harvested. When the wind speed is doubled (5 m/s), the energy of 3 mW can be harvested. Their work provides a good reference for the practical application of energy harvesting. Based on the spoiler-cantilever beam structure, Patel et al. [52] designed a nonlinear model for optimizing energy harvesting. The model includes material nonlinearities of the substrate and piezoelectric layers, as well as geometric nonlinearities incorporated by assuming non-scalability and accurately representing beam curvature. Their models need experiments to adjust the parameters to make accurate predictions for specific situations.

Gao et al. [19] made a piezoelectric energy harvester by placing the spoiler cylinder on one side of the cantilever beam. Their structure consists of a traditional cylindrical spoiler, a cantilever beam vibrating body, and a fixed end. At 5.2 m/s wind speed, his model obtained an output around 0.5 V for peak to peak value. The surface area of the piezoelectric material used is 380 mm<sup>2</sup>. The structure of spoiler cylinder plus cantilever beam is a common configuration of flow energy harvesting due to the strong spoiler ability and vibration sensitivity of cantilever beam. The asymmetric structure mentioned here increases the level of energy harvesting.

Wang et al. [53] proposed to use airflow for energy supply to power wireless sensor nodes through a flow-driven TENG. Figure 5a shows the composition of the energy harvester. Aiming at wireless sensors, PTFE and Kapton are used as triboelectric and electrostatic materials and constructed a device of  $22 \times 10 \times 67$  mm<sup>3</sup> size. At 7.6 m/s wind speed, about 400 V open-circuit voltage, 60 A short-circuit current, or 3.7 mW energy can be harvested with an external resistance of 3 M $\Omega$ . One year later, they reported another miniature wind flow energy harvester. In the new model, they replaced the aluminum electrode with the copper electrode. The maximum output power density of energy harvester is 9 kW/m<sup>3</sup> when the load resistance is 2.3 M $\Omega$  and the size of the air passage is  $125 \times 10 \times 1.6$  mm<sup>3</sup> [54]. Their continuous optimization of materials continues to increase the performance of the TENG energy harvester.

Jamshidi et al. [55] are more concerned about energy harvesting in high-speed turbulent flow environments. They numerically analyzed the energy capture performance of ionic polymer metal composites (IPMCs) in the limit cycle vibration of a cantilever beam in the velocity range of 50–60 m/s. They concluded that the material could reactivate 1.75 mW energy at 60 m/s with a square sheet with a side length of 38 mm, and that the limit cycle vibration of the cantilever beam had little effect on the vibration instability. Their research brings enlightenment to energy harvesting at high wind speeds.

In 2015, Hobeck et al. [56] confirmed the feasibility of using the lumped parameter method for simulation calculations. Figure 5b shows they constructed a structure consist of two similar adjacent cantilevers. The cantilevers are close to each other and are exposed to cross-flow, using piezoelectric devices for harvesting energy. The external forces they receive in the wind field would cause interaction between them. Hobeck called it dual cantilever flutter (DCF). They used the lumped parameter method to predict the dynamic characteristics of the DCF and verified by experiments. The team explored the effects of distance between the cantilevers and the flow velocity on energy capture parameters. They gave the influence formula of the separation distance and concluded that the output power can reach 22.5  $\mu$ W at a flow rate of around 11 m/s. The model in this study has a high requirement for the direction of flow velocity relative to the prototype.

In the same year, Wang et al. [57] put forward a micro wind energy harvester based on triboelectric-electromagnetic hybrid mechanism. The maximum feature size and weight of the compound energy harvester are 6.7 cm and 42.3 g respectively. Consisting of dual TENG and two electromagnetic generators (EMG), each TENG can provide a maximum output power of 3.5 mW (corresponding to 8.8 mW/g and 14.6 kW/m<sup>3</sup> per unit mass/volume) at an air flow rate of about 18 m/s, when the load resistance is 3 M $\Omega$ , while an EMG can provide 1.8 mW energy at the same time (corresponding to the power per unit mass/volume: 0.3 mW/g and 0.4 kW/m<sup>3</sup>). The goal of this energy harvester is to provide energy for a sustainable power temperature sensor.

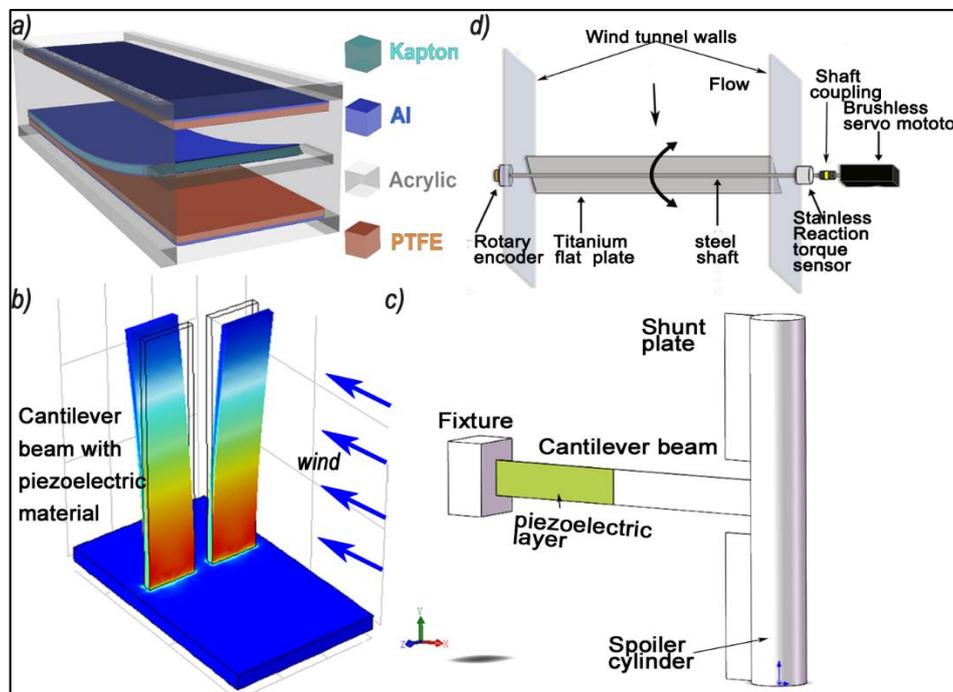
Song et al. [58] considered that the energy harvester could no longer withstand large-amplitude vibration when the wind speed was high. In order to expand the energy harvesting adaptability to high wind speed range, they added a shunt plate behind the spoiler cylinder. Figure 5c gives the conceptual map of whole structure. It is concluded that when the length of the shunt plate is 0.65 times the diameter of the cylinder, the effect is the best. Their spoiler cylinders are 4.8 cm in diameter and 24 cm in height. Their wind speed ranges from 0 to 7 m/s. Their maximum output voltage exceeds 12 V. The introduction of the shunt plate ensures the robustness of the structure in high-speed fluids at the expense of vibration amplitude.

K. Onoue [59] built a kind of vibrational model in 2015 that operates in air (immersed in an airstream) at high operational frequencies, in which, as shown in Figure 5d, a pitching plate was used as a spoiler and vibration source, connected to a stainless steel shaft. They proposed a feasible and novel electromagnetic energy harvesting structure for unidirectional flow. They estimated the velocity data by the pitch angle of the structure but did not give the parameters of energy harvesting ability accurately.

Another potential wind energy collection method, the bladeless wind generator, is also in the process of development. Djairam et al. [60] built two mechanical models with and without collectors. In order to obtain stable voltage output, they chose the model without collectors. Throughout the structure, the positive electrode is a container that ejects charged droplets, and the negative electrode is earth (model without a receiver), separated by an insulator. The wind drives the charged droplet movement to generate a flowing charge. The goal of this design is 1 kW of output power, but the result given during the test phase is 65 mW.

Compared with large harvesters, small wind energy harvesters have not been put into massive production. They are more in research and development. There are more researchers in small wind energy harvesters, and wind energy harvesting modes are more abundant. The research on small harvesters mainly includes the principle of piezoelectric power generation, the principle of friction generation, and the principle of brushless wind power generation. Researchers have studied

symmetrical and asymmetrical structures, and linear and nonlinear research methods. All studies are air immersed. Different studies involve flow rates ranging from a minimum of 2.5 m/s to a maximum of 60 m/s. Unit captive capacity is distributed from  $\mu\text{W}$  to mW. The focus of the research is to broaden the frequency band, increase the output, apply the custom range, and reduce the wear rate of components.



**Figure 5.** Schematic of miniature wind energy harvesters. (a) The composition of flow-driven triboelectric nanogenerators (TENG) (reproduced with permission [53]. Copyright 2015, Wiley on line). (b) Dual cantilever flutter (reproduced with permission [56]. Copyright 2015, The 10th International Symposium on Vibrations of Continuous System). (c) High wind speed energy harvester with shunt plate (reproduced with permission [58]. Copyright 2017, AIP). (d) Cyber-physical pitching plate energy converter (reproduced with permission [59]. Copyright 2015, Elsevier).

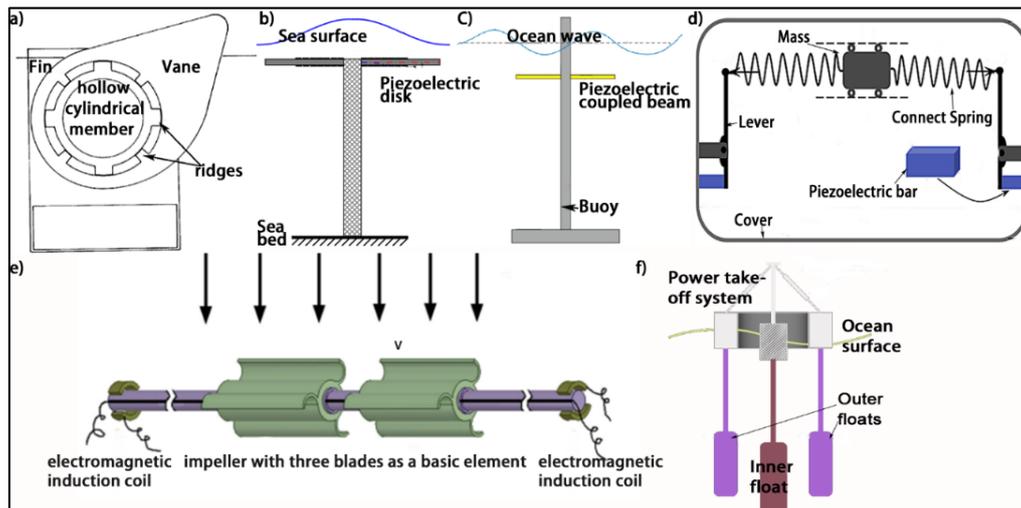
#### 4. Liquid Flow Energy Harvester

The earth's ocean area is about  $3.61 \times 10^8$  square kilometers [61], accounting for more than 70% of the earth's surface area. Wave energy is estimated to be  $8\text{--}80 \times 10^{12}$  kWh per year. If ocean energy can be effectively utilized, the world's energy problem will be alleviated. For all kinds of military, ecological, and environmental detectors, in ocean or river, charging or replacing batteries is far less economical and feasible than harvesting energy in the surrounding environment.

##### 4.1. Large- and Medium-Scale Energy Harvesters of Liquid Flow

Back in 1974, Salter [62] from the University of Edinburgh believed that rigid connections to the sea bed are impossible and rotating elements are most favorable, while both the optional movement of bouncing up and down and nonuniform motion array were eliminated. With those considerations, he came up with a mechanism consisting of vertical vane pivoted about a horizontal axis by means of spline pump, as shown in Figure 6a. The eccentric wheel drives the shaft to rotate reciprocally under the action of the wave. The reported prototype worked over a reasonable range of wavelength. The working efficiency was about 40% with 20% energy transmitted backward. With precise design when the wavelength is of a special value, the efficiency can be over 80%. This conceptual model should theoretically harvest wave and current energy successfully.

However, apparently, not all researchers agree with the elimination of bouncing movement, rigid connection, and motion array. In fact, in the later research works, the above three sports modes have been adopted by different energy harvesters based on geographical advantages. Frigaard et al. [17] manufactured low-head turbines wave power plant called Wave Dragon. The Wave Dragon was an offshore overtopping energy converter that weighs 237 ton with multi-turbines that rotate independently. The large-scale model could generate power by 18.2 kW and the full-scale one will get a captive ability of 4–11 MW. The wave dragon gathered ramp, multi-turbines elements in its design. This large-scale mechanism can harvest ocean wave energy effectively.



**Figure 6.** Medium-scale energy harvesters of liquid flow. (a) Rotating vane shape energy converter (reproduced with permission [62]. Copyright 1974, Nature Publishing Group). (b) Piezoelectric converter for deep ocean energy harvesting (reproduced with permission [63]. Copyright 2014, Elsevier). (c) Piezoelectric converter for buoy harvester (reproduced with permission [64]. Copyright 2015, Elsevier). (d) Mass-spring system for deep ocean energy harvesting (reproduced with permission [65]. Copyright 2016, Elsevier). (e) Three-blade impeller electromagnetic energy harvester (reproduced with permission [66]. Copyright 2017, Elsevier). (f) One-degree of freedom model with switched linear system (reproduced with permission [67]. Copyright 2010, Elsevier).

Vasquez et al. [68] reported their work on the analysis of a tensegrity mechanism for energy harvesting in the condition of an ocean wave in 2014. Two elastic ties and two linear generators are linked to the buoy by a cross tensegrity system. Elastic ties provide the structure with the force to return to equilibrium, and the generators ensure efficient harvesting of wave energy. They studied the ocean wave mechanism and build their analysis based on Snelson's X-frame and then came to the conclusion that the tensegrity mechanism can gain 10% more energy than heaving floats. Their design needs to be built on the seabed, thus limiting the scope of application in shallow waters.

In addition to wave energy collection on the ocean surface, deep-sea energy harvesting has also attracted attention. Xie et al. [63,64] proposed a concept to harvest the transverse wave motion from deep ocean current using a piezoelectric device. Furthermore, parameters like the influence of depth, location, length of the cantilevers, wave height, and the ratio of wavelength to ocean depth were explored [63]. The model is shown in Figure 6b. Later, the team manufactured a similar-appearing energy converter consisting of several piezoelectric coupled cantilevers, which were attached to a floating buoy structure, for harvesting wave energy on the sea surface, as shown in Figure 6c. It shows that the buoy converter with a 1 m cantilever and a 20 m buoy has a power capacity of 24 W [64]. Figure 6b,c show a rod-disk structure and the position of the disk changes when the captive environment changes from the seabed to the sea surface. Their model can collect wave energy and ocean current energy in any direction, but the structure size is relatively large. Similarly, Xie et al. [69] also proposed

a rod-shaped piezoelectric energy converter with a spherical mass at the top. When the wave depth is 3 m, the wave height is 2 m, and the wavelength is 15 m, the energy converter is estimated to have a 55 W power output.

Viet et al. [65] also focused on deep sea energy collection. The difference is that they used a mass-spring system instead of simple mass-cantilever to transfer the energy. Fluid energy is converted into mechanical energy by the internal relative motion of the system. They could harvest 103 W power with a 0.5 m thick cuboid whose bottom is a 1 m<sup>2</sup> square. The mass-spring system is shown in Figure 6d, where transverse movement of mass blocks promotes vibration and deformation of piezoelectric materials. In their design, the capture energy frequency bandwidth will be wide, suitable for wide flow range energy harvesting, but there is a certain direction restriction yet.

Gemme et al. [70] manufactured 1:4 prototypes of both direct-drive-system and resonant-drive-system to verify their “wave- to-wire” numerical model. They use a person’s high-sized floats, using hollow cylinders or balls as a source of welfare. They used the harvested wave energy for power supply for independent sensors and communication equipment in the ocean. The equipment is of medium size with harvesting capacity ranging from 1 to 10 W. The energy harvesting level is not a bright spot relative to the size of the harvester here. But this is one of the earliest models that have been tested in the sea and has its reference value.

In 2017, Zhu et al. [66] reported an electromagnetic harvesting mechanism consisting of a rotating impeller with three blades that collects flow current energy while suppressing pipe vibration and harvesting energy. Figure 6e gives the basic structure of the prototype. When harvesting energy, they also consider the effect of the device on the vibration of the pipeline and pay attention to the efficiency of energy conversion. The conclusion is that the linear energy density can reach 0.07 W/m~283.27 W/m in the range of water velocity from 0.1 m/s to 1.6 m/s. While working underwater, the structure of small and medium-sized electromagnetic energy harvesters is relatively complicated, which will increase the maintenance burden.

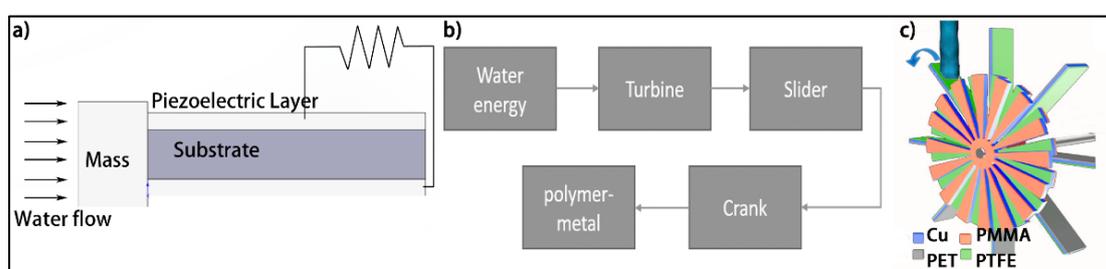
In 2009, Bastien et al. [71] presented the numerical simulation and experimental measurements of anchored linear generators which were driven by the heaving surface buoys. The results showed that the power would be in 1 to 10 W range and able to meet the demand of some ocean detective sensors. At the same year, Luan et al. [72] finished a permanent magnet (PM) linear generator for wave energy harvesting and reported their dynamic model and a control method based on the structure of mass spring system. This structure is closed and simple in structure, suitable for energy harvesting in complex sea areas. Orazov et al. [67] put forward an improvement method of the Wavebob by modulating the mass to get a resonant response with the help of the wave itself. The Wavebob converter is shown in Figure 6f. Energy conversion capability was improved from 25% to 65% and the damping was reduced. This structure is cleverly designed but may be blocked when there are obstacles. A similar but more complex structure appeared in the report of Nabavi et al. [73] in 2018. In this report, the float system longitudinally uses beam-column as the elastic system, and optimizes the model by adjusting the mass parameter ratio. Experimental and theoretical studies have shown that an energy harvester is sufficient to power aerologic sensors. This type of harvester is more suitable for high-frequency environments, and should have better robustness and in harsh environments.

Some large and medium-sized water environmental energy harvesters have been put into use, and others are still in experiments. Among them, large-scale institutions are in tonnage, and medium-sized institutions are mostly larger than an adult. The large-scale water harvester mainly uses the principle of electromagnetic power generation. The design principle of the medium-sized prototype covers the electromagnetic principle and the piezoelectric principle. Drawing structure, rotating element, slender rod, and mass spring system structure have been developed and applied. Research targets water speeds ranging from 0.1 m/s to 1.6 m/s. The medium-sized structure has data energy output from 1 W to 103 W, and the output of large structure has reached 18.2 kW. Most of the structure is semi-immersed in the water environment, and some are completely submerged.

#### 4.2. Miniature Energy Harvesters of Liquid Flow

For miniature energy harvesters, researchers have developed underwater small energy harvesters in a variety of energy harvesting forms in recent years. Akcabay and Young [74] investigated energy convert potential of flexible piezoelectric beam. They concluded that with regulation and control of Reynolds number and density ratio, energy converter with the piezoelectric beam is feasible. They gave a tentative model, as shown in Figure 7a. Their models determine the basic forms of mass blocks and cantilever beams. Many later studies of miniature energy harvestings in flow-induced field have similar models of cantilever beam and spoiler [21,75,76].

In 2013, Cellini et al. [77] conducted research on a polymer-metal bending-based energy harvesting. There was a turbine driven by water current and connected to a crank mechanism, which induces bending of the function material. This model changes the form of motion in the process of energy harvesting and transformation. Figure 7b shows the structure of the turbine-crank connected energy harvester. Its power attained was about 1 pW–1 nW. The experimental range of water velocity is 0.23~0.54 m/s. This model stays in the theoretical stage, and the energy harvesting performance analyzed was not ideal, but provides a reference for the conversion of the motion mode.



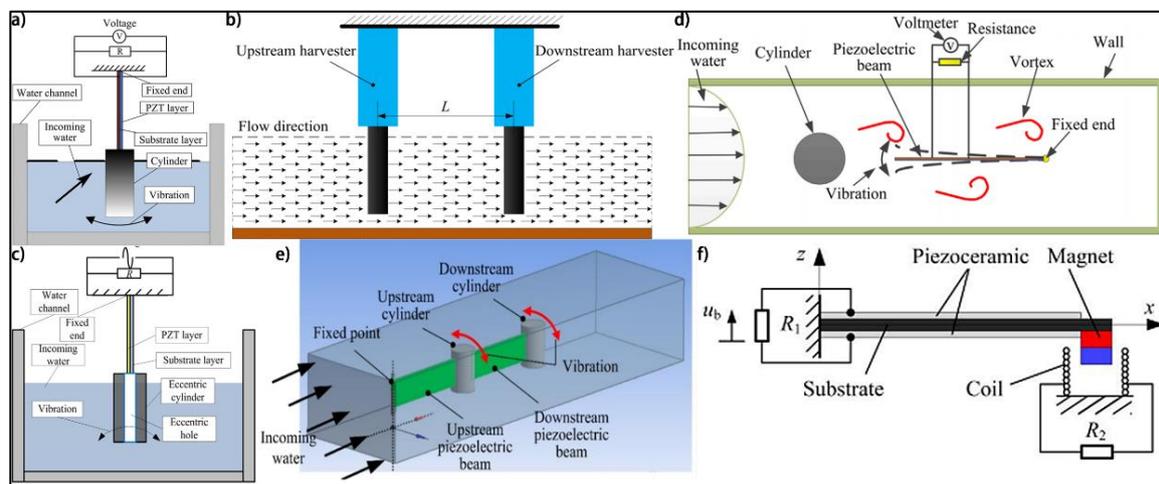
**Figure 7.** Underwater small energy harvester in various energy harvesting forms. (a) Flexible cantilever beam-mass structure piezoelectric harvester (reproduced with permission [74]. Copyright 2012, AIP). (b) Turbine-crank connected energy harvester. (c) Water TENGs and disk TENGs compound energy harvester (reproduced with permission [78]. Copyright 2014, ACS).

In 2014, Tang et al. [79] proposed to use water flow energy to break down water molecules. They used printed circuit technology to make grid discs, and use the flow energy to drive the disc stator and rotor to rotate relatively. The output current can reach 11 mA and the output voltage is around 17 V under 600 rpm driven by a motor, and the conversion efficiency is reported to be about 77.9%. However, in the experiment of hydraulic turbines, the efficiency of generating electricity is greatly reduced. Their experiments showed that about 3.8 mJ of energy can be generated in 65 min. Using the energy of water flow itself to decompose water molecules is critically important as it provides a new way to exploit hydrogen energy.

Cheng et al. [78] of the same group proposed a hybrid TENG that could harvest the electrostatic and flow energy of tap water simultaneously. Both water TENGs and disk TENGs are used in this device and the output open circuit voltages are 72 V and 102 V, and short circuit currents are 12.9  $\mu$ A and 3.8  $\mu$ A, respectively, under velocity of 54 mL/s. Figure 7c shows the three-dimensional structure of the compound energy harvester. This structure, similarly to a waterwheel, combines classical wisdom with modern technology and is very innovative.

For the cantilever beam-mass structure, more in-depth research is ongoing. Xie et al. have focused on vortex-induced vibration and designed many converter models to improve the performance of the harvesters. Based on piezoelectric effect, flexural and torsional vibration modes were investigated, and a class of interventions has been taken into consideration such as optimum load resistances, fluid velocity, characteristic size, etc. Prototypes mostly consisting of cylinders and cantilevers and many kinds of combinations have been tested. In 2015, Song et al. [80] reported a vertically fixed vortex-induced vibration (VIV) energy harvester using piezoelectric ceramics PZT as functional material on Ceramics

International with maximum output power is  $84.49 \mu\text{W}$  and energy density  $60.35 \text{ mW/m}^2$ . In 2016, Shan et al. [81] showed energy harvesting feature of two tandem cylinders. By adjusting the spacing ratio, the energy gained can be 29 times the single cylinder prototype at most. While in 2017, a kind of eccentric cylinder energy converter was developed and the output power was reported 1.99 times of the ordinary cylinder [82]. The vertically fixed cylinder converters are shown in Figure 8a–c. Besides, some other structures are also explored in Figure 8d–f. As can be seen in Figure 8d, in the upstream disturbance barrier, the cylinder was fixed, and the vortex induced by the barrier causes the oscillation of trapping oscillator downstream; this model refers to Weinstein’s model designed in air-conditioning equipment in 2012. Shan [83] reported in 2015 that the prototype can get a power density of  $1.1 \text{ mW/m}^2$ . Figure 8e shows a combinational horizontal transducer and results showed that the downstream cylinder was inspired by both vortex-induced vibration and wake-induced vibration [75]. Xu et al. [84] introduced a kind of hybrid converter using both piezoelectric effect and electromagnetic effect. It came to a result that the hybrid system works better than piezoelectric energy harvester or electromagnetic energy harvester alone. The hybrid system is shown in Figure 8f. All of their works is devoted to the study of vibrational energy harvesting in unidirectional fluid current environments with velocity arrange from  $0.2 \text{ m/s}$  to  $1 \text{ m/s}$ .



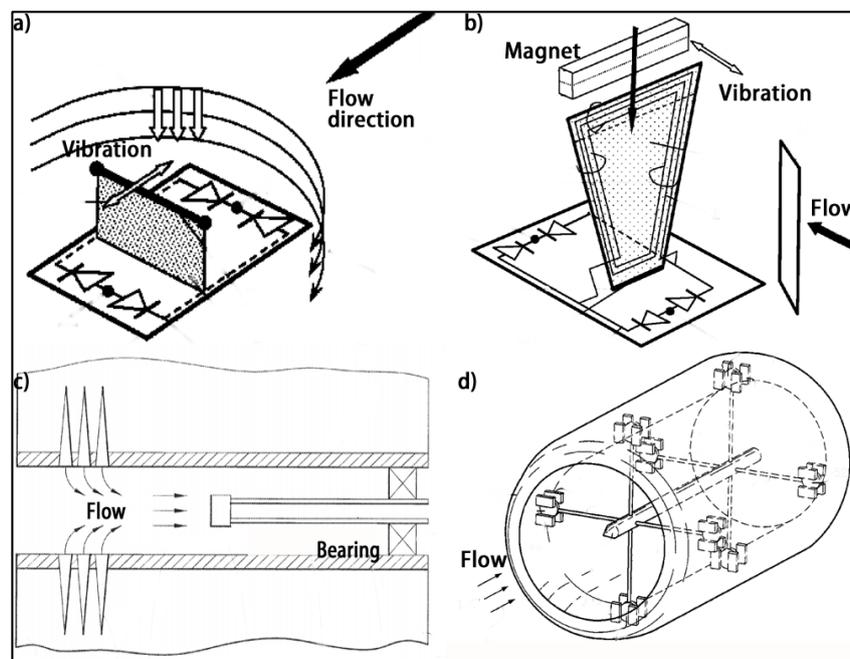
**Figure 8.** In-depth study of cantilever beam-mass structure energy harvesters. (a) Single cylindrical spoiler (reproduced with permission [80]. Copyright 2015, Elsevier). (b) Double cylindrical spoiler (reproduced with permission [81]. Copyright 2016, MDPI). (c) Eccentric cylindrical spoiler (reproduced with permission [82]. Copyright 2017, MDPI). (d) Split trapping device (reproduced with permission [83]. Copyright 2015, Elsevier). (e) Transverse double cylindrical trapping device (reproduced with permission [75]. Copyright 2015, MDPI). (f) Electromagnetic piezoelectric hybrid vibration energy harvester (reproduced with permission [84]. Copyright 2017, MDPI).

Different from the perpendicular disturbing oscillator, Ahsan and Akhtar [85] proposed an energy converter whose oscillator was installed horizontally. Output power can reach  $10^{-4}$ – $10^{-3} \text{ W}$  based on their numerical study. Their research focuses on voltage or power output in response to the fluid velocity. The energy harvester is turbulent by a horizontally placed long cylinder connected by a spring-damped system. Water flows from the side of the cylinder.

In the course of development of energy harvesting by the miniature prototypes in a unidirectional fluid, output power improved from  $1 \text{ pW}$ – $1 \text{ nW}$  to the level of  $\text{mW}$ . Xie et al. from Harbin Institute of technology and Ahsan and Akhtar from the Institute of Space Technology showed that the output power can be increased to  $\text{mW}$  level. They came up with many models and comparative analysis revealed vertical spoilers to have more captive potential than horizontal spoiler cylinder in energy converter.

As can be found in many patents, uniform fluid or unidirectional flow-induced energy harvesting were applied. Kaplan invented a power-trapping device based on electromagnetic effect [86]. Figure 9a

shows the trapping principle, basic captive device, and motion mode of the model. He gave another design [87] in 2013, which can be seen in Figure 9b. Pabon and Bettin [88] invented a structure for downhole energy harvesting in 2013 shown in Figure 9c, which shows a simplified trapper and the relative direction of the trapper and the fluid. Liu et al. [89] invented a pipeline trapping system in 2014. In the scheme shown in Figure 9d, the rotor structure of the trapping device is displayed from where the motion form of the captive is easily speculated. No testing reports of these patents have been found, but the emergence of these models at least provides some new ideas for people.



**Figure 9.** Unidirectional flow-induced energy harvesting examples in patents. (a) Square captive device by electromagnetic effect. (b) Trapezoid converter by electromagnetic effect. (c) Flow energy harvester of artificial environment. (d) Fluid EH of artificial pipeline.

Like small wind energy harvesters, most small water energy harvesters are still in the experimental development stage. Common research mechanisms include the piezoelectric principle, friction generation principle, and electromagnetic principle. In this type of research, the most common structure is the cantilever beam structure, in addition to the turbine crank structure, the waterwheel structure, the grid disk structure, and so on. The energy output is mostly in the pW to mW range, when the water speed is in the range of 0.1 m/s to 1 m/s. Most of the structures are completely submerged in the water, so they need to be tightly water resistant.

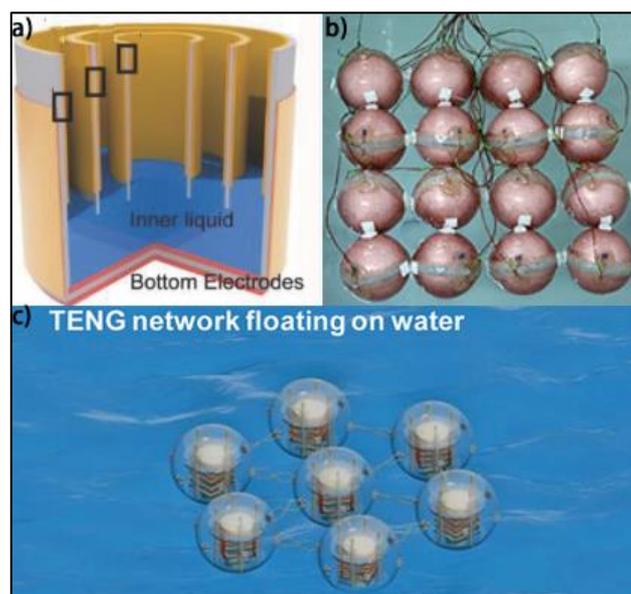
#### 4.3. Network-Based Large-Scale Blue Energy Harvesting

Targeting on abundant ocean energy, Wang puts forward a grand blueprint of large-scale blue energy harvesting network [90]. With the technology of energy harvesting based on ocean wave and current flourishing, still, rare commercial energy harvesters are reported. Material and technical challenges have always existed. In order to realize the blue dream and establish a viable energy harvesting network, material scientists, mechanical experts, and electrical experts are constantly exploring and developing new technologies [91].

Due to its light weight and environmental friendliness, the TENG is the preferred choice for building a marine energy harvesting network [90]. Wang et al. [92] later proposed a wave energy harvesting method for a liquid-solid contact electrified TENG. In this work, water acts as a side of the frictional movement, repeatedly contacting and separating from the polydimethylsiloxane (PDMS) film. The potential difference generated by the periodic contact causes the current of the

external circuit. The maximum short-circuit current obtained by the prototype is around  $10 \mu\text{A}$ . In addition, they also proposed closed solid-solid TENG models with nested spherical structures and duck structures. They believed that this opens the door to blue energy. They pointed out the value of the research and explored directions for future research.

Later in 2018, Li et al. [93] used higher-performance TENGs to achieve a growth of closed circuit current from  $10 \mu\text{A}$  to  $40 \mu\text{A}$  per unit. Figure 10a indicates that their model is a buoy with internal liquids and several polymer films. This structure produces an output signal when excited by different forms of motion. They have achieved commendable results in the optimization.



**Figure 10.** TENG harvester network explored. (a) Multi-motion conversion TENG with internal liquid (reproduced with permission [93]. Copyright 2018, Wiley). (b) TENG network with flexible connection (reproduced with permission [94]. Copyright 2018, ACS). (c) Hexagonal TENG network array (reproduced with permission [95]. Copyright 2019, Wiley).

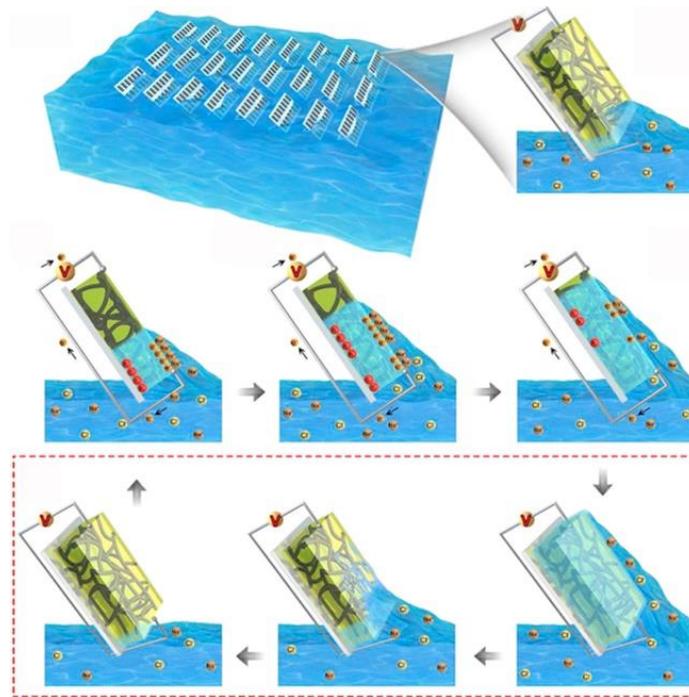
The same year, Xu et al. [94] brought the TENG model with nested spherical structure into reality. Figure 10b shows the structure of their network. They tried three different connections, confirming that the flexible connection is better than the rigid connection, and the coupled charge output can be more than 10 times that of the unit harvester. This work pushes forward the process of the blue energy dream.

Liang et al. [95] focused on the integration of power modules. Their work based on the model seen in Figure 10c. In order to realize the wide application of TENG network in collecting water wave energy, they implemented an efficient and autonomous power management module to manage the harvested electric energy. At 1.5 Hz, the sample output current and output voltage exhibit maximum values of  $78 \mu\text{A}$  and 253 V. This work completes the entire blue energy network system.

In addition to frictional power generation, some scholars have used membrane materials to convert chemical energy into electrical energy, and tried to build a blue energy network in the ocean. As shown in Figure 11, Tan et al. [96] gave a generator model made of carbon film. The carbon film contains a conjugated electron cloud that adsorbs positive ions (mainly sodium ions) in seawater and generates an electric potential with anions that accumulate at the boundary. As the moving potential of seawater changes, it will produce electricity. It has been verified that a  $15 \text{ cm}^2$  unit can produce outputs of more than 20 mV or  $10 \mu\text{A}$ .

Still, the establishment of the blue energy network faces some difficulties: (1) Durability of materials; (2) techniques for constructing captive networks, including large-scale wiring and waterproofing;

(3) energy transmission back to land; and (4) pollution control and reduction of the impact on marine life [90,91]. Researchers are still working tirelessly in their respective fields. We have reasons to believe that the dream of the blue energy network will be realized in the near future.



**Figure 11.** Membrane harvester network proposed (reproduced with permission [96]. Copyright 2018, Elsevier).

Some applications of water harvesters are completely immersed in water, while others are semi-immersed. The focus of the research is also to broaden the frequency bandwidth, increase the output, apply a custom range, reduce the wear rate of components, and also include equipment waterproofing and energy transfer.

## 5. Summary of the Current Situation and Problems

At present, in the field of wind flow and water flow energy harvesting, large-scale equipment and small-scale energy harvesters have been well developed and optimized. The efficiency and power output density are constantly increasing. The energy harvesting level of large equipment has increased from W to kW, and small equipment has gradually stabilized at the mW level. Advection wind energy, turbulent wind energy, liquid laminar current energy, wave energy, and other forms of energy have entered the scope of research [18,19,53–58,61,74,97–99]. Correspondingly, the kinetic energy and mechanical energy generated by flow motion have been effectively exploited and utilized. In terms of energy harvesting mechanism, different approaches such as electromagnetic, triboelectric, and piezoelectric methods have received sufficient attention and input. Among them, electromagnetic energy harvesting is mostly used in large- and medium-sized energy harvesters, while triboelectric and piezoelectric energy harvesting are mostly used in miniature energy harvesters. The specific data are shown in the statistical table in Tables 1 and 2. Facing the gratifying development situation, there are still many problems to be solved. The most urgent problems need to be solved for large and medium energy harvester include:

- (a) Unstable energy harvesting efficiency;
- (b) Huge offshore equipment, expensive manufacturing, transportation, and maintenance;
- (c) Difficulty of integrating into the power grid.

**Table 1.** Piezoelectric and electromagnetic energy harvesters.

	Author	Hobeck	Jamshidi	Gao	Weinstein	Song	Xie	Wu	Viet	Cellini	Song	Shan	
Piezoelectric	Year & Ref.	2015 [56]	2014 [55]	2013 [19]	2012 [18]	2017 [58]	2014 [63]	2015 [64]	2016 [65]	2013 [77]	2015 [80]	2016 [81]	
	Size		433.2 mm <sup>3</sup> #	48.26 mm <sup>3</sup> #	0.15 m	115.2 cm <sup>2</sup>	17.2 m 8.6 m	20 m	0.5 m <sup>2</sup> (block)			1600 mm <sup>2</sup> #	
	Proof mass (kg)		1.126 g #										
	Output power/voltage	22.5 uW*	1.75 mW	0.5 V *	3 mW	12 V	30 W	24 W	103 W	10 <sup>-12</sup> –10 <sup>-9</sup> W	84.49 μW	533 μW	
	Power density		1.2 W/m <sup>2</sup>								60.35 mW/m <sup>2</sup>		
	Flow velocity (m/s)	11 ^	60 ^	5.2 ^	5 ^	0–7					0.23–0.54 Fluid	0.2–1 Fluid	0.412 ^ Fluid
	Environment	Air	Subsonic air	Air/fluid	Air	Air		Ocean	Ocean	Ocean			
	Application target				Air conditioner	High speed	Deep sea current	wave	Deep ocean		Directional current	Directional current	Directional current
	Author	Salter	Frigaard	Vasquez	Gemme	Onoue	Zhu	Luan	Orazov	Ahsan	Shan	Shan	
	Year & Ref.	1974 [62]	2004 [17]	2014 [68]	2013 [70]	2015 [59]	2017 [66]	2009 [72]	2010 [67]	2015 [85]	2015 [83]	2017 [82]	
Electromagnetic	Size				Bigger than a person	1.22 m		2.5 m					
	Proof mass (kg)		2.37 × 10 <sup>5</sup>										
	Output Power/Density		18.2 kW		1–10 W		0.07–283.27 W/m	2.5 W	0.9849 W	10 <sup>-4</sup> –10 <sup>-3</sup> W		0.3978 mW	
	Power density										1.1 mW/m <sup>2</sup>		
	Flow velocity(m/s)						10–25	0.1–1.6				0.2–1	0.2–1
	Environment	Ocean	Ocean	Ocean	Ocean	Ocean	Air	Ocean	Ocean	Ocean	Fluid	Fluid	Fluid
	Application target	Wave	Wave	Wave	Wave	Wave	Directional current	Conduit	Wave	Wave	Directional current	Directional current	Directional current

\* estimated value by data schematic; # Data of effective material; ^ The Corresponding Value of Optimal Solution. Blue zone for piezoelectric energy harvester; yellow zone for electromagnetic energy harvester.

**Table 2.** Triboelectric nanogenerators (TENG) and the TENG network.

Author	Wang S.	Wang S.	Wang X.	Tang	Cheng	Li	Xu	Liang
Year & Ref.	2014 [53]	2015 [54]	2015 [57]	2014 [79]	2014 [78]	2018 [93]	2018 [94]	2019 [95]
Size	22 × 10 × 67 mm <sup>3#</sup>	125 × 10 × 1.6 mm <sup>3#</sup>	6.7 × 4.5 × 2 cm <sup>3</sup>			80 cm <sup>2</sup>	4 × 4 array 22.5 × 22.5 cm <sup>2</sup>	2 × 1 × 1 cm <sup>3#</sup>
Proof mass	42.3 g							
Main materials	PTFE and Kapton Al (electrode)	PTFE and Kapton Copper (electrode)	PTFE and Kapton Copper (electrode)	Kapton, Copper and Gold	PMMA, PTFE, Copper and PET	Water, PTFE and Acrylic	Polystyrene, Silicone rubber, POM particle, UV treated silicone rubber, Silver-Copper	Kapton, Copper, Acrylic and Spring
Output	400 V (open-circuit) 60 A (short-circuit) 3.7 mW		3.5 mW + 1.8 mW (TENG+EMG, hybrid)	3.8 mJ of energy can be used in 65 min 4.5 V	72 V + 102 V (open-circuit) 12.9 μA + 3.8 μA (short-circuit) (water TENGs + disk TENGs)	300 V (open-circuit) 290 μA (short-circuit),	1780 V (open-circuit) 1.8 μA (short-circuit)	253 V and 78 μA 4.31 mW
Resistance	3 MΩ	2.3 MΩ					52.88 MΩ	3.3 MΩ
Power density		9 kW/m <sup>3</sup> ^	8.8 mW/g + 0.3mW/g 14.6 kW/m <sup>3</sup> + 0.4 kW/m <sup>3</sup>				0.71 W/m <sup>3</sup>	3.33 W/m <sup>3</sup>
Velocity/Flux	7.6 m/s		18 m/s		54 mL/s (flux)			
Environment	Air flow	Air flow	Air flow	Water flow	Tap water flow	Ocean	Ocean	Ocean
Application target	Wireless sensor nodes		Temperature sensor	break down water molecules		Ocean network	Ocean network	Ocean network

\* estimated value by data schematic; # data of effective material; ^ the corresponding value of optimal solution.

For miniature equipment, the energy density still needs to be improved. The damage and durability problems of piezoelectric and triboelectric materials are to be addressed. Moreover, new devices need to be developed to collect flow energy in multi-directional ways. The network-based TENGs provide an alternative solution for large-scale blue energy harvesting, however, it still faces some other challenges in terms of durability, waterproof, energy transmission, and pollution controls.

## 6. Future Outlook

According to the previous development trend and the current enthusiasm of researchers, the problems raised in this paper are expected to be gradually solved. The instable power response problem of energy harvesters will be solved slowly through energy storage circuits; technology development will also reduce the cost for manufacturing, transportation, and maintenance of large-scale offshore equipment; through appropriate buffer circuit or storage equipment, the integration of large-scale energy harvesting equipment into power grid will also be realized eventually. The properties of triboelectric and piezoelectric materials required by miniature devices are constantly improved with the efforts of materials researchers, which will improve the lifetime and robustness of energy harvesters; the research of non-directional flow current has also been emphasized, and the research and development of adaptive mechanism will solve this problem; at the same time, people will continuously improve the efficiency of energy harvesting. The network-based energy harvesting technology will solve the technical problems of transportation energy and network construction with a small environmental cost.

Fluid energy including wave, tidal, as well as wind and water flow, is clean, renewable, ubiquitous and abundant throughout the world. Once it is fully developed and utilized, it will not only solve the current energy crisis, but also address the environmental challenges such as global warming and the pollution emission from fossil fuels.

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