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Review

On Search for Unconventional Energy Sources for Harvesting

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Abstract: Energy transformation requires replacing power plants based on fossil raw materials with renewable energy. Energy harvesting plays an important, although not fully appreciated, role here. Distributed, local power supply systems for small receivers, based on various sources which previously dissipated energy, may contribute to changing the current energy paradigm. This article presents an overview of energy harvesting technologies and various energy sources used in this process. Particular attention was paid to sources of a less conventional nature. The aim of this article is to encourage and direct scientists with the potential to explore this topic to look for new, previously unexploited energy sources and innovative and effective methods of obtaining useful energy in the harvesting process.

Keywords: energy harvesting; local energy sources; energy conversion; smart technologies; systems; renewable energy

1. Introduction

Energy harvesting is a broad and not fully defined concept. It is standardly assumed that it is the acquisition of small amounts of energy from the environment, which would naturally be dissipated, intended for the local powering of electronic devices with low power consumption [1]. However, it seems that the concept of energy harvesting defined in this way does not reflect all of the important features of this technology. Limiting the amount of energy, its form, and its method of use clearly does not reflect all the important values of this concept. Intuitively, the boundary between a power plant and a harvester exists, but it is fluid and difficult to define. For example, a wind farm is a completely different project than a small turbine powering lighting or pedestrian crossing signals on the road. However, what size and number of turbines constitutes the limit remains an open question [2]. Therefore, it would be necessary to add other characteristics of this technology to the definition of energy harvesting, in particular those related to current requirements in the field of energy.

In my opinion, in order to clarify the concept of energy harvesting, it is important to additionally define the contemporary requirements for this technology. Therefore, attention should be paid primarily to obtaining energy in an ecologically friendly way—friendly to both people and the environment. It is about searching for and using sources of energy that without harvesting become dispersed, useless, and irretrievably lost in the abyss of entropy growth. One of the essences of energy harvesting is intelligent energy acquisition without excessive interference in the environment, i.e., the world of people, animals, vegetation, landscape, climate, soil, water resources, and everything that constitutes a priceless treasure for us and future generations.

The search for diverse energy sources for harvesting is a constant challenge for the scientific community [3]. Several dozen years ago, as a shortwave ham radio operator, I observed during a thunderstorm small sparks jumping between the plates of the capacitor that tuned the tube transmitter to the antenna. However, how surprised I was when similar discharges occurred during heavy snowfall! In those days, no one even thought about energy saving or renewable sources, let alone energy harvesting. Nowadays, the

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triboelectric phenomenon, responsible also for the induction of charges during snowfall, is one of the main topics of investigation for many groups of researchers.

This article, after this slightly unusual introduction, presents in the Section 2 the structure of the energy conversion chain in the harvesting process and an overview of the energy conversion methods used. Section 3 provides an overview of the variety of energy sources for harvesters. The Section 4 discuss the problems, challenges, and prospects of energy harvesting.

2. Energy Conversion Chain in the Harvesting Process

The conventional energy harvesting process involves converting forms of energy from source energy to usable energy. Energy sources and forms of source energy are very diverse; the search for possible sources is a constant challenge. The useful energy in the harvesting process is most often electricity, which is the most desirable form of energy in many applications. Electricity allows for relatively easy and effective transmission, storage, and use in end devices [4]. There are also harvesters in which the final energy is, for example, heat used to heat buildings [5]. The elements of typical energy conversion chains in the harvesting process are listed in Table 1.

Table 1. Energy conversion chains in the conventional harvesting processes.

Source Energy	Form of Energy	Conversion Method	Energy Storage
mechanical energy	directed motion wave motion vibrations pressure wave	electrodynamic piezoelectric triboelectric	supercapacitors batteries flywheel compressed air pumped hydro hydrogen production
thermal energy	temperature difference	thermoelectric heat engine + electrodynamic	
	temperature change	pyroelectric	
electromagnetic energy	light	photovoltaic thermoelectric	
	radio frequency	electric electronics	
chemical energy	energy of chemical bonds	electrochemical cell fuel cell heat engine + electrodynamic	
nuclear energy	radioisotope energy	nuclear battery	

Source energy is most often mechanical, thermal, or electromagnetic energy. Chemical and nuclear energy can also be analyzed as source energy, although this is rarely encountered in publications on energy harvesting [6]. The mechanical energy of the source can take various forms, which implies various technical solutions of harvesters. Directed movement is utilized in, for example, vehicles, water, or air. Another form of energy is derived from wave movement, especially of seas and oceans. Mechanical vibrations, for example of technical objects such as bridges and viaducts, may also be processed. The harvesting process also considers the use of pressure waves, for example noise generated by vehicle traffic. To convert mechanical energy into electric current, one of three method types is most often used: electrodynamic, piezoelectric, or, recently, more and more often, triboelectric.

Figure 1 shows a schematic diagram of example structures of harvesters that convert mechanical energy into electrical current.

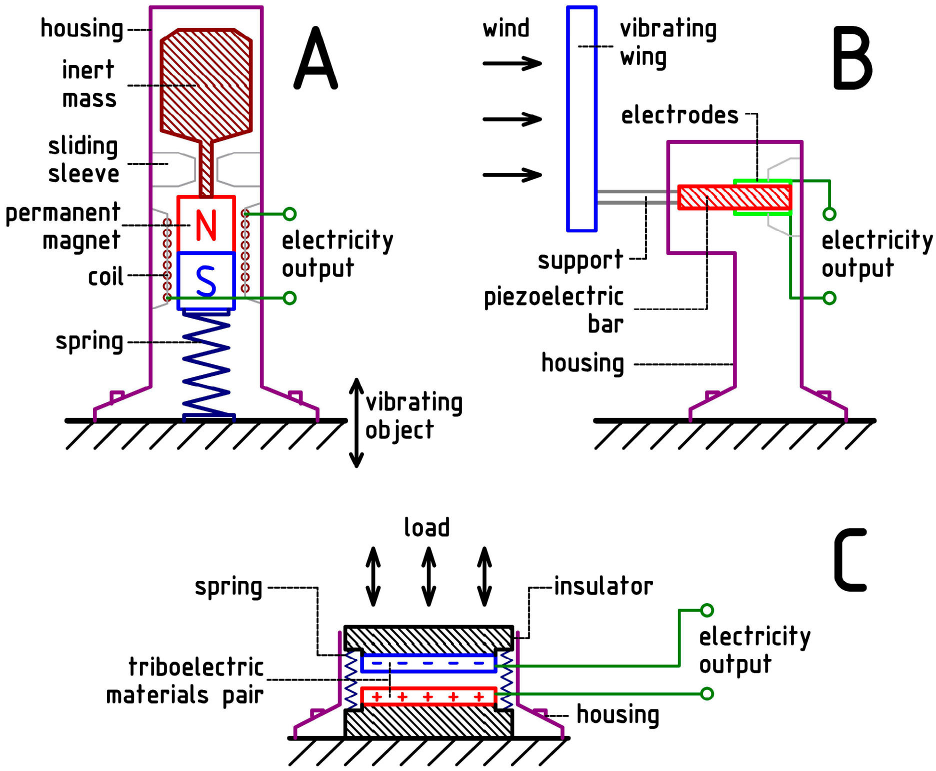

Figure 1. Example structures of harvesters that convert mechanical energy into electrical current. (**A**) Vibration converting harvester, (**B**) wind turbulence converting harvester, and (**C**) load converting harvester.

Electrodynamic (electromechanical) processing uses the phenomenon of electromagnetic induction, which involves the creation of an electromotive force in a conductor interacting with a variable magnetic flux [7]. This is the main method of converting mechanical energy into electrical energy, commonly used in power plants and vehicles. Progress in this technology resulting from the production of strong permanent magnets was one of the factors that enabled the development of electric vehicles, in which the electrodynamic transducer is used both to drive the vehicle and to recover electrical energy from motion during braking [8]. The example harvester shown in Figure 1A converts the mechanical energy of the object's vibrations into electric current. The vibrating object may be a vehicle, a viaduct, or a railway track. A spring is attached to the object, with a permanent magnet connected to an inert mass. The vibrations of the object are transferred to the back and forth movement of the magnet in the coil, which generates electricity.

Piezoelectric processing uses the phenomenon of the formation of electric charges on the surface of certain materials subjected to mechanical stress [9]. Piezoelectric properties are exhibited by some single crystals and polycrystals, ceramics, and synthetic polymers. Electrical voltages induced in piezoelectric materials can reach significant values, but the power generated per unit volume is small. An example of a harvester that converts the mechanical energy of turbulent wind flow into electric current is shown in Figure 1B. The wind causes vibrations of the aerodynamic wing connected with a piezoelectric material by the support. Mechanical deformations of the piezoelectric material cause the generation of electric charges on the electrodes placed on the piezoelectric material, and the creation of an electromotive force as the output of the harvester.

Triboelectric processing uses the phenomenon of generating electric charges in appropriately selected materials interacting with each other through contact, friction, or proximity movement [10]. The materials are selected in pairs so that they are significantly distant in the triboelectric series. An example of such a pair is Teflon and aluminum. Triboelectric processing technologies and the structures of triboelectric nanogenerators are currently being intensively developed and implemented both in industrial systems and in everyday devices. An example design of a triboelectric harvester converting the mechanical energy of load into electrical energy is shown in Figure 1C. The load on the harvester may be caused, for example, by a vehicle wheel or a human foot. The harvester is made of a lower insulator placed on the ground, covered with triboelectric material and a complementary triboelectric layer on the top insulator. The insulators are placed within a short distance of each other by means of springs. Load on the upper insulator brings the triboelectric layers together and generates electric charges. Releasing the pressure causes the layers to move apart, forced by the springs, generating a complementary charge. The generation of charges creates an electromotive force as the harvester output. One of the significant problems in converting mechanical energy into electrical current is the significant internal resistance of many typical transducers. This results in energetic matching only for receivers with high resistance, which require low currents to power them. Receivers with higher energy requirements can be powered periodically, and the required energy must be collected and stored.

Figure 2 shows a schematic diagram of example structures of harvesters that convert thermal energy and light into electrical current.

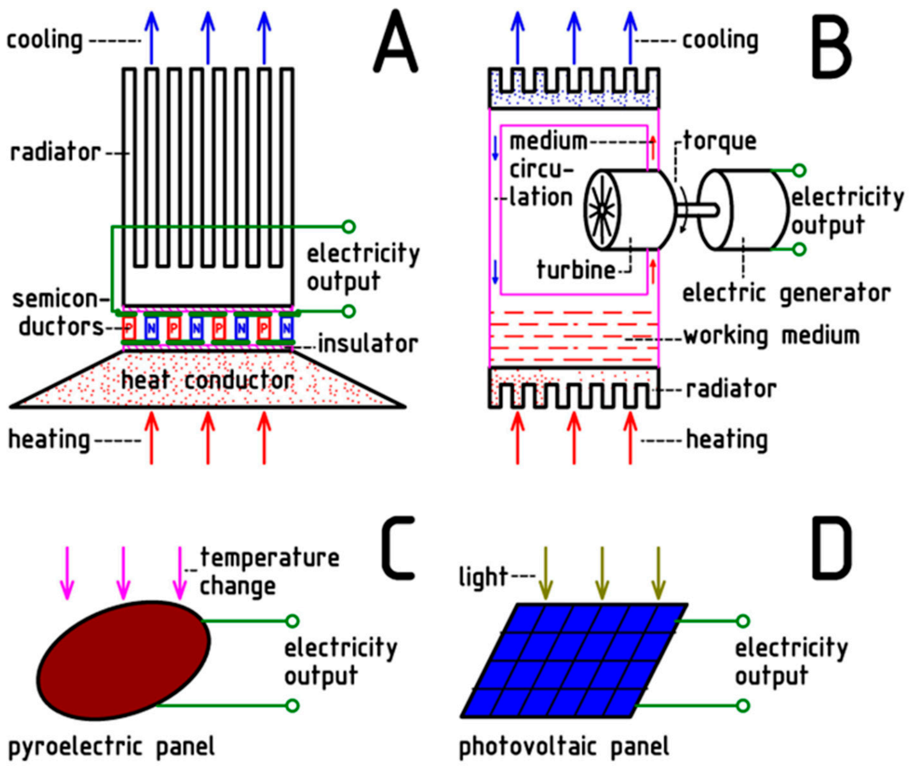

Figure 2. Example structures of harvesters that convert thermal energy and light into electrical current. (**A**) Thermoelectric harvester, (**B**) electrodynamic generator with heat engine harvester, (**C**) pyroelectric harvester, and (**D**) photovoltaic harvester.

Thermal energy can be used directly, for example to heat buildings or melt snow and ice [11]. This requires the use of heat exchangers and heat pipes. Efficient heat pumps are also increasingly used here. Converting thermal energy into electricity usually requires two sources with significantly different temperatures. For harvesters, thermoelectric processing is often used, based on the Seebeck effect [12]. It involves the generation of an electromotive force in a circuit containing junctions of different metals or semiconductors at different temperatures. Peltier modules are now commercially available and can be used in thermal harvesters to generate electricity [13]. An example construction of a harvester converting thermal energy into electrical energy is shown in Figure 2A. The heat conductor, which constitutes the base of the harvester, is placed on an object that is a source of high temperature. It may be a natural object, for example a geothermal source, or an anthropogenic object, for example related to an industrial process. A Peltier cell or set of cells is placed on the base. Such a cell consists of two planar electrical insulators and alternating P and N semiconductor elements placed between them, connected electrically in series. Above the Peltier cell there is an air-cooled heat sink thermally connected to the cell. The temperature difference generates an electromotive force in the Peltier cell.

If energy source conditions permit, a conventional system of a mechanical heat engine and an electrodynamic generator can be used for processing. An example of such an energy harvester is shown in Figure 2B. A high-temperature energy source, such as a geothermal source, heats the working medium (fluid) of the heat engine. The heated working medium drives a turbine, which transmits torque to an electric generator that produces electricity. After passing through the turbine, the working medium is cooled and returns to the closed circuit. Like a heat engine, an open-circuit piston engine or a Stirling engine can also be used. However, this type of harvester requires efficient sources with a large temperature difference.

It is also possible to generate electricity from one thermal source, the temperature of which changes over time. The pyroelectric effect is used here, which involves the generation of an electromotive force in some crystals due to a change in temperature. Some piezoelectric materials also have pyroelectric properties [14]. The structure of a pyroelectric harvester is schematically shown in Figure 2C. One of the significant problems in the use of thermal energy for harvesting purposes is the significant thermal resistance between the source and the harvester that occurs in typical applications. This problem is subject to constant research, and progress may be brought by the development of material technology and innovative designs of heat exchangers and conductors.

Ubiquitous electromagnetic energy is an important source used in harvesters. The basic form of energy here is light converted into electric current in photovoltaic cells [15]. The photovoltaic phenomenon, which involves the excitation of electrons in solids by light, is currently used on a large scale in photovoltaic panels to produce electricity. Photovoltaic cells and panels, which are an effective source of electricity, are obviously also used in harvesters. Schematically, such a harvester is shown in Figure 2D.

The increase in object temperature due to the absorption of electromagnetic energy, for example infrared, also enables the use of thermoelectric processing in harvesters.

Moreover, it is also possible to use radio frequencies from the wide spectrum of electromagnetic energy for processing [16]. An appropriate antenna with a rectifier and filter system may allow powering of low-power receivers in suitable locations. In a similar way, it is possible to obtain energy from lightning discharges.

Chemical energy contained in the chemical bonds of substances can also be a source for harvesters. For example, methane from biological processes, hydrogen, or another type of fuel can be used [17]. Conversion into electricity can take place conventionally in a heat engine system with an electrodynamic generator or in electrochemical and fuel cells [18]. Potentially, nuclear energy can also be used as a source energy for harvesters. Isotopes that emit beta radiation during decay are used in nuclear batteries to generate electricity [19]. The isotope constitutes the positive electrode, and beta radiation is captured by the second electrode, which gains a negative potential.

Regardless of the energy source, the last element of the processing chain in the harvesting process before its use is storage. If electricity in the harvester is generated continuously and in sufficient quantity to power the final receiver, energy storage systems are not required. However, most often, electricity in harvesters is generated irregularly and its storage is necessary. The basic solution here is the use of capacitors, supercapacitors, and batteries [20]. Here, electricity is stored directly and immediately available. Solutions are also used to convert electrical energy into another form of energy, for example into kinetic energy in flywheel storages [21], potential energy in pumped hydro storages [22], or pressure energy in compressed air tanks [23]. An important solution with increasingly wider applications is the production of hydrogen [24].

3. Review of the Diversity of Energy Sources for Harvesters

The previous section presented the structure of the energy conversion chain in the harvesting process. The beginning and end of a chain require an anchor point. The utility device whose powering is the target for the harvester is at the end of the chain. However, the beginning of the chain requires a primary energy source. The type and parameters of the source are key elements influencing the structure and effectiveness of the entire system. Harvesters use energy from the environment, both natural and anthropogenic. Without the use of a harvester, this energy is irrevocably dissipated. The energy source should be close to the load and provide the required efficiency. There must also be appropriate technical conditions to obtain and effectively process energy from the source. Conventional sources here are primarily sunlight processed in photovoltaic panels, and wind driving turbines. In many cases, these solutions allow for efficient and effective power supply of devices such as lighting, signaling, control, and monitoring devices, terminals, sensors and actuators, and data transmission devices.

However, there is a constant search for less conventional sources whose properties can be used in response to various issues and as a part of detailed processes which require a local power source. This section presents an overview of this type of source, along with a brief description of the harvester used and the type of end devices associated.

3.1. Water Waves

An example of a harvester converting the energy of ocean waves into electricity is presented in the article [25]. Processing using the piezoelectric effect was utilized here. The authors considered a system consisting of two blocks with significant inertia and different masses, connected by piezoelectric beams. Modeling this system for a variable value of the ratio of both masses allowed for optimization of energy efficiency for given excitations. Comparison of the modeling results with the experiment positively verified the adopted concept. This energy harvesting system was intended to power an aerologic ocean buoy that monitors the state of the ocean and weather. The presented system allowed for obtaining an average electrical power of approximately 5 mW, which, combined with the energy storage and management system, was sufficient to power the monitoring system.

The use of sea wave energy to power sea bridge monitoring systems was presented in the article [26]. Energy harvesters were mounted on the bridge pillars. They were composed of a buoy placed on the sea surface, performing a back and forth movement forced by the sea waves. This movement was then converted into unidirectional rotation in a mechanical gear system with one-way clutches. The last element of this energy harvester was a rotary electromagnetic generator that produced electricity. This energy was stored in supercapacitors and used to power the sea bridge's monitoring systems. The authors conducted simulation tests of the proposed system and tested a laboratory prototype. Depending on the amplitude and frequency of the waves, the obtained powers ranged from 0.12 W for amplitude of 2 mm and a frequency of 1 Hz, to 2.36 W for amplitude of 6 mm and a frequency of 2 Hz.

The article [27] proposed the use of triboelectric processing to obtain electrical energy from wave motion. The purpose of the system was to power sea state monitoring. The transducer consisted of a vertical pendulum with a fin attached at the lower end. The fin was placed in the sea, forcing the pendulum to move. This movement was converted into rotational motion through gears and transmitted to two triboelectric generators. In order to increase the efficiency of the system, two generators were used, optimized for two wave amplitudes: small and large. The generators were made in the form of two coaxial drums, stationary and rotating. The rotating drum had flexible polymer blades that rubbed against the copper electrodes of the stationary drum. The prototype model achieved a power of 0.7 mW with wave amplitude of 120 mm and a frequency of 1 Hz.

A sea wave energy harvester also using triboelectric processing, but with a different structure, was presented in the article [28]. This transducer took the form of a ball of insulating material floating on the sea surface. Inside the sphere, there were semicircular surfaces on a common axis that could move closer and further apart. The surfaces were covered with electrodes and acrylic insulating material. Thanks to the triboelectric effect, the mutual movement of semicircular surfaces generated electricity. Four symmetrical sections were placed in the optimized prototype, obtaining a maximum current power of 16.6 mW. The authors foresee a wide application area for this energy harvesting technology, from the presented application in a wireless digital thermometer to the concept of the maritime Internet of Things.

The article [29] proposed the use of water movements in deeper layers to power underwater devices. Electromagnetic processing was used here, with a linear transducer placed in a waterproof housing. The transducer had coils wound on a section of pipe in which the permanent magnet could move under the influence of inertia forces. The shape of the housing was designed to execute the moves caused by water movement. Changes in the speed and direction of movement of the housing caused the magnet to move inertly in the coil and generate a current. In the tested prototype, depending on the wave frequency, power from 1.31 mW at 0.1 Hz to 7.73 mW at 0.4 Hz was obtained. The planned application was to power water turbidity sensors.

3.2. Air Turbulence

Unconventional use of wind energy was proposed in the article [30]. The proposed harvester used chaotic, turbulent wind gusts in the low frequency range. Triboelectric processing was used here, using natural leaves as the triboelectric material. The experimental harvester was composed of a leaf with an electrode connected and a polymer layer placed close to the leaf surface. As the leaf vibrated in the wind, it approached and moved away from the polymer surface, inducing charges and current flow through the electrode to the receiver. The second contact of the receiver was grounded. The authors experimented with different species of leaves, obtaining voltages in the order of 100 V and currents in the range of single microamperes. The authors reported achieving a maximum power density of 45 mW/m^2. The proposed application was to power LED lighting or illuminate advertisements.

A further development of this concept was shown in the creation of a triboelectric harvester made of pressed powder from dried leaves modified with organic polymers layers, which vibrated in the wind [31]. Copper layer electrodes were also used here. Compared to a transducer made of a natural leaf, the current and voltage obtained were doubled, and therefore the power was quadrupled. This technology is also characterized by greater repeatability and durability of the transducer.

Also inspired by the fluttering of leaves in the wind, the authors of the article [32] proposed the use of piezoelectric processing. They proposed a harvester made of a piezoelectric beam, attached on one side, with an aerodynamic flap, stimulated by the wind, attached on the other side. The authors considered various shapes for the flap, with the best results obtained with an oval shape, inspired by a leaf. Based on the measurement data from the article, it can be estimated that the maximum power density obtained at a wind speed of 20 m/s reached 1.5 W/m^2.

3.3. Rainfall

The article [33] presented the results of research on an energy harvester using the kinetic energy of raindrops. The authors proposed the use of piezoelectric transducers that converted vibrations caused by the impact of raindrops into electricity. Three transducer models were proposed for testing: a vibrating beam supported on one side, a beam supported on both sides, and a radial system of beams with a common, central, circular vibrating element. Prototype laboratory transducers with sizes ranging from a few to a dozen or so centimeters were made and subjected to experimental tests. The obtained results are difficult to evaluate because the authors mainly presented graphs of the voltage obtained at the output of the transducers under the influence of water drops falling from a height of 0.5 to 2 m. Due to the lack of many experimental parameters, it can only be estimated that the average power obtained from the transducer was no more than 1 mW. The research presented was preliminary, and is very far from moving to the application phase.

A slightly more extensive technology for obtaining energy from rainfall was proposed by the authors of [34]. Piezoelectric processing was also used here, but the prototype harvester was more complex. Rainfall was collected by a large funnel and fed to a tank mounted on a rotating axis. The tank was designed in such a way that when a certain water level was reached, it empties and the water stream hits the plate mounted on the piezoelectric transducer beam. Therefore, there was a cyclical production of energy portions. The authors conducted a theoretical and model analysis of this process and presented the results of a laboratory experiment. Unfortunately, this work also presented mainly the voltage waveforms obtained from the transducer. It can be estimated that in the prototype system the authors obtained a peak electrical power of 180 microwatts in a single cycle, so the average power is at the level of single microwatts.

Another method of converting rainfall energy into electricity is described in the article [35]. Processing using a triboelectric nanogenerator was used here. Raindrops may have an electrostatic charge and have kinetic energy. By hitting the surface of the triboelectric nanogenerator, they transfer this energy, part of which is converted into useful electrical energy. The authors of the proposed harvester developed a special mesh structure of the transducer for this purpose which prevented the mutual impact and accumulation of raindrops. The article reported the maximum power density obtained at the level of 110 mW/m^2. It is over two hundred times higher than in transducers with a conventional gridless structure. A significant extension of the rainfall intensity range, enabling effective work, was also achieved. The authors believe that the proposed solution will contribute to the development of this technology on a significant scale.

3.4. *Snowfall*

In the article [36], the authors proposed the use of snowfall to obtain electricity. According to the authors, the purpose of this harvester was to power weather stations. The authors also pointed to the possibility of hybridization with photovoltaic panels. This harvester can also be used to power monitoring systems for athletes in winter sports. In the proposed solution to obtain energy, the authors used the triboelectric effect caused by the impact and friction of snow on the harvester surface. It was made using 3D printing technology in the form of a flexible silicone foil hardened with UV rays. PPS polymers were used as electrodes. 3D printing technology allowed the harvester to be made, depending on its purpose, in any required shape. In prototype tests, the authors obtained a momentary power density of 0.2 mW/m^2.

3.5. *Lightning*

Lightning is a potentially powerful source of energy for harvesters. The energy of a single discharge is estimated at billions of joules. However, in this case, problems related to controlling the effective and safe absorption of discharges remain at the initial stages of analysis, conceptualization, and research. The article [37] collected information on potential methods of obtaining energy from lightning discharges. One of the methods proposed was to connect many appropriately adapted lightning protection installations in parallel, use rectifiers, and collect the acquired electricity in capacitor banks. It was also proposed to use the Tesla coil inversely, as a transformer reducing the voltage induced in the lightning protection system. Another concept discussed was the indirect method, i.e., the use of energy accompanying the discharge, i.e., light, thermal, or mechanical energy. These forms of energy could be converted using conventional methods and stored in capacitor banks for further use. The use of discharge energy for water electrolysis and hydrogen production is also being considered. Attempts have been made to control the discharge of lightning by creating a discharge path with a laser. However, there is still a lack of publications and reports on effective applications of this type of energy source.

3.6. Volcanic Energy

The use of thermoelectric processing to obtain energy to power a volcano monitoring station was proposed in the article [38]. Geothermal energy is often used for heating, but there are relatively few applications for electricity production. The reason for this is in the low efficiency of such a system. In the presented harvester, the authors placed thermoelectric transducers based on the Seebeck effect between high-efficiency heat exchangers based on thermal pipes with phase change of the medium and heat sinks. The system extracted heat from volcanic fumaroles and released the heat to the air. The prototype was installed at the Teide volcano in the Canary Islands, and with a temperature difference of 51.5 °C, it generated a power of 0.49 W, which was completely sufficient to power the data acquisition and transmission station. The advantages of this power supply system include maintenance-free operation, durability, reliability, compactness, and environmental neutrality.

A similar system, intended to power the year-round monitoring system of the Erebus volcano, Ross Island, was presented in the article [39]. The construction of the harvester was analogous to the one previously described; a thermoelectric transducer and heat exchangers with thermal conductors were used. The system was installed in hot ground at a depth of 0.5 m, where the temperature was approximately 80 °C. At an air temperature of −20 °C, the temperature difference reached 100 °C. In this study, an average power of 270 mW was achieved.

3.7. Living Organisms

The conceptualization, construction, and test results of a wireless animal tracking module with an energy harvester are discussed in [40]. The miniature module was mounted on the monitored animal and consisted of a GPS receiver, a set of sensors, a microcontroller, a radio transmitter, and an energy harvester. A photovoltaic micro-panel with a supercapacitor was used to store electricity. The energy management system allowed charging of the warehouse when solar radiation was available, and the temporary consumption of significant power to power the GPS receiver and the data transmitter when required. In the sleep state, the power consumed was 0.054 mW, the GPS receiver required 89.1 mW, and the transmitter was powered by 1254 mW. The prototype system was used to track and monitor iguanas in the Galapagos Islands.

A different solution for powering animal or human monitoring modules is presented in the article [41]. In this solution, the energy of vibrations caused by the movement of an individual was used to generate electricity. Electromagnetic processing was utilized here. The energy harvester was composed of a rotor disk containing permanent magnets and a stator with built-in coils. The rotor was constructed in such a way that its center of mass is shifted relative to the rotation axis. The inertial forces caused by movement induced vibrations and rotation of the rotor, and thus the generation of electrical energy in the stator coils. The system was complemented by an energy management and storage system. The authors presented the results of model and laboratory tests of the developed harvester for various vibration excitations and mounting locations on the body. The prototype obtained a maximum power of 25.8 mW while running at 15 km/h.

The difficult task of constructing an energy harvester to power a fish monitoring module was undertaken by the authors of work [42]. The harvester was built in the form of a triboelectric nanogenerator isolated from the external environment by an air bag and mounted on the side surface of the fish's tail. The mechanical energy of the fish tail's swinging motion was converted into useful electrical energy. The transducer was made of flexible PTFE polymer with aluminum foil electrodes. It was placed in an air bag to isolate it from the external underwater environment. The authors presented the results of laboratory tests on a fish model. Peak voltages of 150 V and peak power of 0.74 mW were obtained from the transducer prototype.

The authors of the article [43] used the biomechanical energy of movement of living organisms, including humans, in their harvester concept. A mechanical linear-rotary converter was proposed here, converting the swinging motion of body elements, e.g., limbs into rotational motion. The rotational movement was used to generate electricity in a hybrid electromagnetic and triboelectric transducer. The system was composed of a linear, screw shape stator with a large pitch thread. There was a rotor placed on it, which moved under the influence of inertia forces, making a rotational movement. The rotor was placed in the outer ring. The rotor and ring had triboelectric interacting layers, as well as built-in electromagnetically interacting magnets and coils, which enabled hybrid conversion of biomechanical energy into electricity. According to the authors, this system allowed for effective operation in the single hertz frequency range of movement. In laboratory conditions, the conceptual harvester allowed the authors to obtain a maximum power of 0.6 mW. The authors propose the use of this power source, for example, in continuous bio-monitoring systems for remote measurement of body temperature and humidity.

3.8. Body Heat

The use of thermal energy produced by living organisms to generate electricity is presented in the article [44]. The authors developed manufacturing technology and presented the research results of a harvester using the thermoelectric effect. It worked based on the difference between body and ambient temperatures. The authors developed a technology for producing threads from conductive polymers and then producing a fabric constituting a thermoelectric generator. The difficult problem in this case was the significant values of thermal resistance between the fabric and external sources, and the high internal resistance of the textile thermocouple. A prototype fabric sample with an area of 25 cm^2 allowed the authors to obtain electrical power of 0.2 microwatts at a temperature difference of 30 °C, and 1.2 microwatts at a difference of 65 °C. This gives a power density of 80 microwatts/m^2 and 480 microwatts/m^2, respectively.

Temperature changes over time can be used to produce electricity thanks to the use of pyroelectric generators. An example of such a harvester is presented in the article [45]. The authors considered the processing of waste heat generated in industrial processes, when heating liquids, or heat produced by organisms. The research used a commercial piezoelectric transducer, which also had pyroelectric properties. It was made of piezoelectric foil covered with electrodes on both sides. The transducer area was approximately 20 cm^2. With temperature changes of 30 °C, a maximum power density of 0.34 mW/m^2 was obtained. Potential applications indicated in the article include temperature sensors with their own power supply. The authors also tested the transducer's response to proximity and finger touch, obtaining voltage changes at the level of tenths of a volt. This allows the module to be used as a proximity and touch sensor, as well as, for example, a breathing monitor.

New materials used as pyroelectric transducers are constantly being developed [46]. The authors of this work presented the current status and development prospects of energy harvesters based on new materials. Materials with a perovskite structure, single crystals, and graphene play an important role here. In their review, the authors discuss, among others, polymer-graphene pyroelectric and piezoelectric materials, which were used to build a self-powered pressure and temperature sensor worn on human skin. A power density of 6.2 mW/m^2 was achieved. However, many problems remain to be solved in the search for high energy density pyroelectric materials. Work is being carried out on combining various materials, using doping and using polymers and organic materials. Another problem is achieving long-term stability of materials and extending the life cycle of transducers.

3.9. Railway

The use of rail vibration energy during train passage is presented in [47]. The authors proposed a system for converting the mechanical energy of rail vibrations into useful electrical energy. Its purpose was to power track condition monitoring. The energy conversion path and system structure were conventional. Under the rail, on the railway sleeper, a beam on springs was mounted, which was set in vibrating motion when the train passed. This movement was converted into bidirectional rotation in a screw system. The bidirectional rotation was then converted into unidirectional rotation in a mechanical gear system with one-way clutches. The last element of this energy harvester was a rotary electromagnetic generator that made useful electrical energy during the train's passage. The article presented a prototype and model, and simulation and laboratory tests were carried out. The final experiment was to install the system in real conditions on tracks. During the passage of the train, an average power of 0.27 W was obtained at a train speed of 20 km/h, and 1.12 W at a speed of 30 km/h. The issues of vibration processing in energy harvesters in the field of non-linear forces were analyzed in the works [48,49]. The authors developed a device for adapting non-linear forces occurring in many processes for the purposes of energy harvesting. It was composed of a pre-compressed spring, a miniature bearing, and a raceway that are designed to respond to non-linear forces. The non-linear force adopting device allowed designers to obtain desired non-linear forces for vibrating energy harvesting devices.

A system using the energy of air movement in the vicinity of railway tracks was presented in the article [50]. The system was intended to power the automation and monitoring of railway turnouts. The system for converting air movement into electrical energy consisted of a vertical axial wind turbine, a three-phase electromagnetic generator with a rectifier, and a supercapacitor for energy storage. The design of the wind turbine had a self-adaptive structure that changed the angle of the blades depending on the rotational speed. The entire system was basically a conventional solution without any significant innovative features. An interesting aspect of this system was its use in converting the energy of air movement caused by the passage of a train. The presented system is in the laboratory testing phase. Measurements in the wind tunnel achieved an average power of 1.08 W for an air speed of 13 m/s. The application of the system in real conditions was not presented.

3.10. Bridges and Viaducts

Road and railway bridges are objects that require energy sources for lighting, signaling and control, and condition monitoring. The use of energy harvesters is also proposed here. In the article [51], the authors considered a hybrid system using bridge vibrations and wind to obtain useful energy. Electromagnetic and piezoelectric processing was used here. The system was composed of two beams placed one above the other and attached to the object on one side. An electromagnetic transducer winding was mounted on the lower beam. Above it, on the upper beam, a permanent magnet, an aerodynamic wing, and a piezoelectric transducer were mounted. Bridge vibrations and wind stimulated the system to oscillate in the low frequency range, up to 45 Hz. The prototype of this hybrid transducer was subjected to laboratory tests on a station generating mechanical vibrations and air flow. For accelerations up to 6 m/s^2 and air speeds up to 6 m/s, the power generated by the harvester was a maximum of 2.2 mW.

In article [52], a system for obtaining useful energy from the transformation of railway bridge vibrations was proposed. The authors investigated a conventional piezoelectric transducer mounted on a single-sided spring beam attached to a bridge, with a mass placed at the other end. The results of system modeling and experimental tests were presented. The fundamental vibration frequency of the bridge was estimated at approximately 7.8 Hz, and the acceleration was approximately 1 m/s^2. The proposed system generated maximum voltages of 0.1 V in such conditions. Unfortunately, the authors did not provide the harvester load conditions or the obtained powers. The proposed application was the detection of trains passing, and power supply for bridge monitoring.

3.11. Tunnels

A system that converts the energy of air movement in railway tunnels into electricity was presented in article [53]. The potential purpose was to power monitoring systems. The authors' intention was to use two types of air movement in the tunnel: natural flow, and flow forced by the piston effect during the passage of a train. Therefore, a wind turbine consisting of two types of vertical rotors mounted on a common axis was developed. The shape of the impellers was optimized for both types of flows. The path for converting rotational motion into electricity consisted of a three-phase electromagnetic generator with a rotating permanent magnet and stationary coils, a rectifier, and an energy storage system in the form of a supercapacitor bank. The authors conducted model and simulation tests as well as experimental tests of the prototype in a wind tunnel. For a wind speed of 11 m/s, an average power of 108 mW and a turbine efficiency of 23.2% were obtained. The research results were presented only for the laboratory phase.

Another system of energy harvesters intended for use in road tunnels is discussed in the article [54]. The system was built into the road and drew energy from vehicle traffic. The basic element was a flat friction plate, which moved backwards under the influence of the vehicle's tires, and when released returned forwards thanks to springs. The reciprocating motion was converted into rotational motion in a gear system. Electricity was generated by a three-phase generator, the current from which was rectified, and the energy was stored in a supercapacitor. The system was intended to power the control, signaling, and monitoring systems of a road tunnel. Thanks to this solution, the authors envisaged achieving a near-zero energy system. In a single prototype, with a plate travel of 10 mm and a travel frequency of 1.5 Hz, an average output power of 5.135 W and an energy efficiency of 64.4% were obtained. The system was intended for use in tunnels, but it can practically be used anywhere on the road.

The processing of acoustic energy generated in underground metro tunnels was proposed in article [55]. The purpose of the system, made of surface acoustic barriers, was to power monitoring and illuminate tunnels. The system was modular and included a sound wave acquisition input module, a Helmholtz resonator optimization module, a resonant frequency tuning module, and an electrical energy generation module. Acoustic energy was converted into useful electrical energy in piezoelectric transducers. The authors presented the process of modeling and optimizing the construction of the harvester. In laboratory tests of the prototype of a single harvester cell, an electrical power of 100.8 microwatts was obtained from an area of 16 cm^2 at a sound pressure level of 100 dB. In the proposed system, the acoustic barrier should be constructed as a matrix wall composed of such cells, ensuring the required power multiplication. The energy density of acoustic waves emitted by transport-related sources is relatively low. Therefore, to obtain significant output powers, energy harvesters must occupy large areas. This is a serious problem due to the large expenditure required in relation to the effect achieved. Nevertheless, there is constant progress in systems harvesting energy from acoustic waves. Progress concerns both processing methods and materials used in this technology [56–60].

3.12. Mars

The literature [61] also considers sources of energy for the inevitably approaching manned mission to Mars. Photovoltaic panels and nuclear energy are planned as the primary power sources. However, wind energy harvesters are proposed as additional sources, replacing panels at night or during a sandstorm. Potential wind conditions, locations, and effective technical solutions are analyzed from the available data. The issue is difficult to solve, because the density of Mars' atmosphere is approximately 1% of the density of Earth's atmosphere, so the power of a wind turbine on Mars will be reduced by 99% relative to Earth. Additionally, Martian wind speeds in the near-surface zone are much lower than on Earth. This constitutes a serious challenge for the designers of future Martian wind turbines, which should be large enough to overcome these low wind speeds. The use of technologies such as those used in the construction of airships, i.e., a light frame structure covered with a thin, durable material, is expected. This article is a study of the possibilities of using wind energy in a Mars mission. Potential locations ensuring appropriate wind conditions are indicated and the effectiveness of this solution is analyzed. The authors' conclusions regarding the possibility of using this power source are optimistic, but of course a lot of problems remain to be solved, and many problems are probably not even known yet.

4. Conclusions

The topic of this article is to present various energy sources used in the harvesting process, with particular attention given to less conventional sources. This is intended to encourage and direct scientists exploring this topic to look for new, previously unexploited energy sources and innovative and effective methods for obtaining useful energy. I also invite you to share the results of your original research in the field of energy harvesting in the special issue of Energies: "Development of Energy Harvesting Systems and Methods from Uncommon Sources" [3].

This article discusses the principles of energy conversion in the harvesting process and presents an overview of various sources used in this technology. The aim of the article is primarily to familiarize teams of researchers from the broadly understood field of technical sciences with the issues of energy harvesting. In particular, to spark interest in this technology among scientists who have not yet dealt directly with this field, and whose scientific potential may contribute to the search for innovative solutions.

Table 2 lists the unconventional energy sources presented in the article and indicates their basic positive and negative application properties. Based on the analyzed articles, the maximum power values obtained from the developed harvesters are given for the discussed energy sources and processing methods. The information presented in Table 2 allows for a comparative analysis of the discussed unconventional energy sources and the harvesters used in them. It should be noted, however, that such a comparison is very general, because both the sources and the harvesters used and their parameters are extremely diverse in terms of source energy, location, physical phenomena used, applications, and other important features.

Table 2. Comparative summary of the application properties of unconventional energy sources, current challenges, and the maximum power obtained from the harvesters used.

Energy Sources	Basic Source Properties		Current Challenges	Harvesters Comparative	
	Positive	Negative		Conversion Method	Maximum Power
water waves	huge energy resources, global world access, possibility of using various types of transducers	technological problems, aggressive environment, difficult service and operational activities	development and implementation of effective, mass technology	piezoelectric	5 mW [25]
				electrodynamic	2.26 W [26]
				triboelectric	16.6 mW [28]
air turbulence	global availability, good working conditions for harvester	difficulties in energy conversion, low efficiency	utilize turbulence generated by road traffic	piezoelectric	1.5 W/m^2 [32]
				triboelectric	45 mW/m^2 [30]
rainfall	possibility of hybridization with other sources, complementing other sources, wide localization	limited energy density, periodic availability, random occurrence time and parameters	hybridization with other sources	piezoelectric	1 mW [33]
				triboelectric	110 mW/m^2 [35]
snowfall	possibility of hybridization with other sources, complementing other sources	periodic availability, limited location, low energy density	hybridization with other sources	triboelectric	0.2 mW/m^2 [36]

Table 2. *Cont.*

Energy Sources	Basic Source Properties		Current Challenges	Harvesters Comparative	
	Positive	Negative		Conversion Method	Maximum Power
lightning	gigantic energy density, electrical form of energy	lack of effective technology, randomness of time and location	mastering effective technology	electric	no data [37]
volcanic energy	large energy resources, high energy density	cooling difficulties, aggressive environment, local availability	effective use, development of materials and technologies	thermoelectric	0.49 W [38]
living organisms	powering devices on organisms, moving the source with the object, continuous availability	limited power of the source, burden on the body, difficulties in operation	development and implementation of commonly used various systems	photovoltaic	1.25 W [40]
				electrodynamic	25.8 mW [41]
				triboelectric	0.74 mW [42]
body heat	powering devices on the body, mobility with the device, constant availability	small temperature differences, low energy density, body load	development of personal communication, monitoring and telemetry systems	thermoelectric	0.48 mW/m^2 [44]
				pyroelectric	6.2 mW/m^2 [46]
railway	source availability along the route, use in control and monitoring	quantized energy portions, limited energy density	wide commercial implementation of developed systems	electrodynamic	1.12 W [47]
bridges and viaducts	convenient harvesters location, power supply for local devices, various types of energy	lack of continuity of energy availability, difficulties in servicing	wide commercial implementation of developed systems	piezoelectric + electrodynamic	2.2 mW [51]
tunnels	convenient sources for local power supply for signaling, control, monitoring and lighting	limited location of harvesters, lack of access to solar energy, difficult operating and service conditions	wide commercial implementation of developed systems	piezoelectric	0.1 W [53]
				electrodynamic	5.14 W [54]
Mars	possibility of using solar and nuclear energy, possibility of choosing the location on the surface	transport and technological difficulties, strongly limited harvester weight, low wind energy density	taking the first step on Mars	photovoltaic + nuclear cell + electrodynamic	no data [61]

The analysis of the current state of knowledge regarding the problems, challenges, and prospects in energy harvesting prompts the author of the article to define the following statements and conclusions:

- In the process of energy transformation, energy harvesting should play a significant and constantly increasing role. Small, local generators of useful energy, using various natural and anthropogenic sources of previously dissipated energy, can in many cases replace energy from power supply networks.
- The search for new sources and effective processing methods for energy harvesting is a constant challenge for teams of scientists and engineers. The directions for exploration are of course open, but it is worth considering, for example, the use of post-industrial and post-mining infrastructure, waste storages, air and water turbulence, or biological potential [62–70].
- The number of publications on the issue of energy harvesting is huge. However, they are not always associated with progress and development. For many years, many publications have presented and researched only laboratory prototypes, not taking into account real application problems. There has been a lack of movement to the phase of application and testing of the harvesters during long-term real operation.
- Many authors present only the idea and selectively selected parameters of their prototype systems. There is no reliable description of the research stand and measurement conditions, equipment, or uncertainty analysis. This makes it impossible to comprehensively and objectively assess the proposed solutions and their potential suitability for real applications.

- Research and publications rarely provide a comprehensive analysis of the system taking into account the economic and operational factors as well as the scientific aspects involved. There is no analysis of the ratio of expenditure to potential effects, nor the issues of reliability, safety, maintenance, and service possibilities, or the resource of the system. This is a serious drawback of many scientific works and publications, because a system operating on a laboratory scale may not be applicable in real implementations. Only a few works devote attention to this issue [71–73].
- Some publications present solutions of a purely technical nature, without any innovation or significant consideration on a scientific level. Theoretical considerations concern the analysis of known issues, such as the dynamics of simple mechanical systems or current generation in an electrodynamic transducer. This allows for the introduction of equations and their transformations into the publication, but does not expand general scientific cognitive knowledge, nor innovative concepts and solutions that influence the development of science.
- An interesting direction in the development of energy harvesting systems is their hybridization. Hybridization may concern both the diversity of energy sources, energy forms, and methods of processing and storage. This allows energy systems to complement each other, equalize the level of energy supplied over time, reduce failure rates, extend operation, and often even achieve a synergistic effect. New concepts, research, and publications in this area are appearing more and more often [74–76].
- It seems that in striving for originality in their articles, some authors use technologies that are currently "in fashion" without justification. For example, rotational motion is converted to electrical energy in a triboelectric system, although a conventional electrodynamic system appears to be more efficient. This does not mean that the applications of new technologies should be limited, but their use should always be analyzed and justified by efficiency and other relevant factors [77–79].
- This article omitted an important energy source for the harvesting process: roads, their surroundings, and infrastructure. The author discussed this issue in detail in a separate publication [80]. The number of publications in this field is huge. New sources and methods of energy processing and storage are constantly being sought in energy generation technologies for road infrastructure facilities. The energy sources in the road area are primarily vehicles, solar radiation, and air movement. Additionally, they are also, although to a lesser extent, geothermal energy and electromagnetic radiation from sources other than the sun. Specific to roads is of course vehicle traffic, which is a distinguishing source of energy for roads. Vehicles have kinetic energy, causing turbulent air movement. They produce heat transferred to environment. Other electromagnetic radiation is produced too, but to a small extent. Solar radiation, air movement, and geothermal energy are energy sources specific to roads only when the characteristic features of these areas are used to obtain energy [81–85].
- It is also worth noting that relatively few concepts of energy harvesters presented in a huge number of publications find mass, commercial application and are implemented as final products. A historical example of such a wide application of an energy harvester is the self-winding mechanical watch, developed by Abraham-Louis Perrelet [86] in 1777, and successfully used to this day by prestigious manufacturers. Contemporary examples include self-powered sensors commercially available from several companies [87–91]. Unfortunately, it seems that the technology is currently not often implemented in commercial products.

The above comments are subjective observations and thoughts of the author of the article regarding the issues discussed. They are based on many years of experience and a comprehensive review of the latest literature in this field, of which only a small, but representative, part is presented in this article. The intention is to invite researchers to polemics and to express their own views and assessments, and above all, to search for new sources, innovative methods, and original energy harvesting systems. However, it should be remembered that the continuous increase in the generation and use of energy cannot be an end in itself. Rational energy management, and even striving to reduce consumption where it is not necessary, seems to be the responsibility of conscious inhabitants of our planet.

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