

Powering an IoT-driven world: a survey of Energy Harvesting methods for the ZED concept

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6G technology relies largely on the mass penetration of IoT devices, which collect, do primary processing and transmit data in the respective networks, generating big data - something that is also known as massive IoT. Powering the expected huge number of such devices will present a real challenge from an energy point of view. This is also the reason why the concept of Zero-Energy Devices (ZEDs) was created, which use the energy available in various forms from the environment to power themselves autonomously. In the present survey the technologies for the so-called Energy Harvesting (EH) are considered, which are of primary interest at the moment, namely those that use radio frequency (RF), light, kinetic (based on piezoelectric and triboelectric effect), thermal and wind energy, as well as some typical scenarios for their application.

Keywords – (6G Technology, Internet of Things, massive IoT, Energy Harvesting, Zero-Energy Devices)

Захранване за свят, управляван от IoT: преглед на методите за събиране на енергия (Energy Harvesting) за ZED концепцията (Емил Е. Владков). 6G технологията разчита до голяма степен на масовото навлизане на IoT устройства, събиращи, обработващи първично и предаващи данни в съответните мрежи, генерирайки big data - нещо, което е познато и като massive IoT. Захранването на очаквания огромен брой подобни устройства ще представлява истинско предизвикателство от енергийна гледна точка. Това е и причината, поради която бе създадена концепцията за Zero-Energy Devices (ZEDs), които употребяват наличната в различни форми енергия от околната среда за да се захранват автономно. В настоящото проучване са разгледани технологиите за т.нар. Energy Harvesting (EH), представляващи основно интерес към момента, а именно тези, които използват радиочестотна (RF), светлинна, кинетична (на база пиезоелектричен и трибоеклектричен ефект), термична и вятърна енергия, както и някои типични сценарии за тяхното приложение.

The world is on the threshold of a new era that promises to merge communication technologies with solving problems of everyday life. Thanks to 6G, for the first time the standardization efforts of the scientific community and business are focused on more than just developing a new standard for high-speed, low-latency, high-reliability communications. 6G will not be just a continuation of the current mobile communication standards, but also will become a framework for the transformation of almost every sphere of life as we know it.

In this context of thought wireless sensor networks and the Internet of Things (IoT) will play a central role. At the same time (as of February 2024) there are already more than 17 billion connected IoT devices operating worldwide [1]. 6G is expected to give life to 10 trillion devices with IoT-functionality [2]. It is on them that great hopes are placed not only to realize the many goals of the new communication paradigm, such

as autonomous vehicles, telemedicine, patient health monitoring anytime and anywhere and the new experience of virtual and mixed reality with haptic feedback, but also to overcome the technological and economic backwardness in certain parts of the world and to contribute to the development of rural areas and the achievement of modern smart agriculture. All this implies the deployment of almost 1 million devices per square kilometer according to ITU estimates [3], which will collect, do primary processing and transmit vital data - something described as "massive IoT".

Justification of the “Massive IoT” concept

In fact, the concept of the trillions of connected devices and sensors providing information about the surrounding world in real time is not a human creation, but borrowed from nature. As an example, human skin can be considered, which has about 4 million tactile

receptors. At the same time, each such receptor gives relatively inaccurate information, but big data obtained from all the receptors in combination with the networks of neurons of the human body provide a fairly accurate picture of the surrounding world [4]. With massive IoT, scientists are practically mimicking this evolution-proven concept, with each IoT sensor node not even needing to provide high-resolution data. With the help of Machine Learning (ML) algorithms, the collection of big data can be correctly interpreted and ultimately achieve the extremely ambitious goals of ubiquitous accurate sensing set in 6G.

The power supply challenge

To achieve the goals of 6G networks the following requirements are set:

- The connected IoT devices must be deployed almost everywhere, including in hard-to-reach or inaccessible areas, as well as in hostile and even dangerous environments. This means that IoT-enabled sensor nodes cannot rely on conventional power supply, as it is simply not available in these areas. Using battery power in this case is not always an option, as it involves changing the batteries, which would shorten the life cycle of such devices and also requires human intervention.
- The IoT devices shall become smaller and smaller, which would allow them to be embedded in fabrics, clothing, surfaces and architectural elements, or even dispersed over large geographical areas in the form of smart dust on the order of 1 cubic millimeter in volume. Such miniature devices simply will not have the volume for battery power.

Ideally, massive IoT devices would be fully autonomous, providing their energy to function by harvesting it from the environment. Such a concept gave impetus to the development of an entirely new field of technological research known as Energy Harvesting (EH) [5,6,7]. In this context the efforts of scientists and developers are directed independently towards achieving technological progress in two areas: 1. finding new sources of energy and improving the efficiency of energy collection of already existing ones and 2. reducing the consumption of IoT devices by developing new, ultra-low-power integrated circuits and circuit solutions and the implementation of energy-efficient algorithms and communication protocols within the entire protocol stack of the OSI-model, as well as new energy-optimized network topologies and data transmission techniques.

All these development efforts that have been observed in recent years culminated in the emergence of another concept, that of Zero-Energy Devices

(ZED), that is, devices that need extremely little energy to function, obtaining this energy through new methods for its efficient harvesting and utilization from the environment, something that is also known as "ambient IoT" [8].

As a side effect the concept of ZED will lead to the achievement of the goals of the 2030 Agenda for Sustainable Development outlined by the United Nations [9]. This is because ZEDs rely entirely on energy harvested from the environment and thus do not contribute to the increase of the carbon footprint of 6G technology.

To successfully meet the challenge of providing power to the huge number of IoT devices, various Energy Harvesting methods have been proposed, most of them being under continuous research and development. These will be discussed individually in the survey.

A myriad of ambient energy sources

With global energy consumption on the order of 607 quintillion Joules per year [5] and the forecast of increasing energy consumption especially with the advent of hyper-connected communication technologies around 6G, humanity is facing another energy crisis. It is at this point that using energy from the environment through Energy Harvesting provides a reasonable solution. And such energy, which is currently literally wasted, is abundant.

Besides radio frequencies (RF), being also the most cited for EH because of the ubiquitous network connectivity and cellular communication technologies, there exists other forms of ambient energy too. Such energy sources are light, heat, and any form of mechanical energy, including wind energy, mechanical stress, pressure, vibration, and resonance. Until now, due to the large size of the the Energy Harvester, wind energy was not considered an option [10], but due to rapid technological development in the field, this is about to change. All these sources of ambient energy are summarized in Fig.1, where the structure of the Energy Harvester is also presented.

The latter consists of the transducer that converts the ambient energy of the respective source into electrical energy, an interface circuit that extracts the maximum possible amount of energy from the transducer by conditioning it for the specific application (for example, by rectification, filtering and regulation) and a load that represents the entire EH-powered IoT device, including energy storage in the form of super capacitors or batteries if provided. At the same time, thanks to its built-in intelligence, the interface circuit also takes care of the power management, considering the presence and quantity of ambient energy of any

kind at any moment and the battery state of charge.

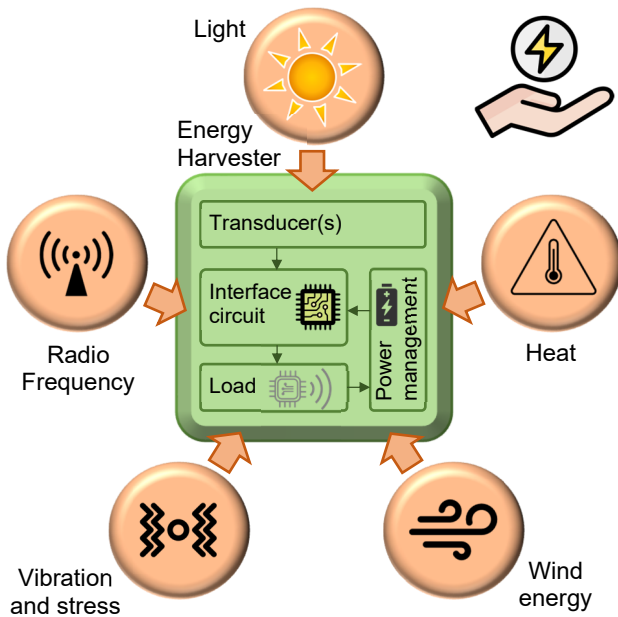


Fig.1. Sources of ambient energy and Energy Harvester

The particular energy sources EH designs follow.

RF Energy Harvesting

When talking about Energy Harvesting, usually the first thing that comes to mind is the use of radio frequency (RF) energy. The reasons for this are obvious. First, radio waves are practically everywhere, especially with the increasing number of mobile users and wireless connectivity covering every location. Second, radio waves can penetrate obstacles, thus realizing the possibility of powering IoT devices without the limitations of their placement.

The idea of transmitting energy via the so-called Wireless Power Transfer (WPT) and utilizing it with suitable RF circuits is not new at all [11]. As early as 1864 Maxwell formulated its theoretical foundations. Two centuries later the importance of this technology for humanity was recognized by Nikola Tesla, who dedicated his life to it. RF Energy Harvesting in its modern version appeared in the 1960s thanks to the work of William C. Brown, who also introduced the main concept associated with this technology, namely the rectenna (from rectifying antenna). His team's experimental work on microwave energy transfer in 1968 led to significant advances in WPT technology. Modern WPT technology is extremely promising for the realization of Ultra-Low-Power communications in combination with the transmission technique of Backscatter Communications, the various variants of which will be discussed shortly.

WPT exists in two main forms [10]:

- Non-radiative near-field WPT, where inductive coupling between two coils takes place within a few millimeters. The latter is widely used both as a technology for charging mobile devices and for powering wireless RF-tags and contactless payments options.
- Radiative far-field WPT, which uses the emission and reception of electromagnetic waves by means of dedicated antennas and is suitable for transmitting energy over long distances. It is the latter type that is suitable for RF Energy Harvesting for IoT devices.

A key element of any WPT system is of course the RF Energy Harvester itself. Fig.2 illustrates its general structure that consists of a receiving antenna to pick up as much RF energy from the environment as possible, an impedance matching network to ensure maximum utilization of the radio frequency power received by the antenna, a rectifier to ensure high power conversion efficiency and a power management circuit to optimize the whole process of Energy Harvesting [11]. An optional DC/DC converter may be included in the design after the rectifier stage to supply a higher voltage to the load or to adapt the voltage to a specific type of load. Usually simple boost and buck DC/DC converters are preferred for this task.

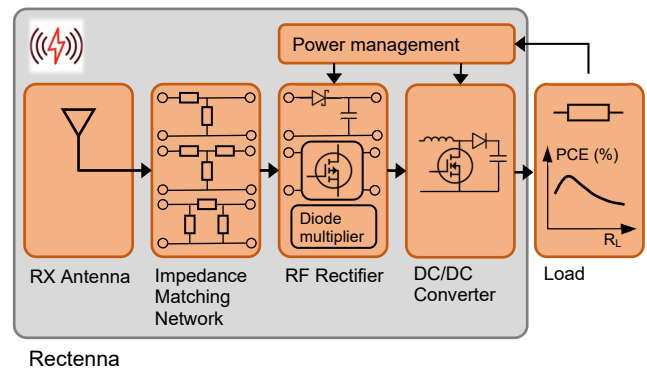


Fig.2. General block diagram of an RF Energy Harvester

Regarding the antenna, the choice depends on the required frequency band for Energy Harvesting, with both wideband and narrowband solutions available. Variants are bowtie, dipole and log-periodic dipole, monopole, loop, Yagi-Uda, planar inverted-F and dielectric resonator antennas. Given the small physical dimensions of typical IoT devices, microstrip designs are particularly interesting.

For impedance matching, L-, T- and π -networks of lumped or distributed elements implemented as stubs or microstrip lines are mainly used. With a completely resistive nature of the load, the combined impedance of the matching circuit and the rectifier stage should be

the complex conjugate of the source impedance, which will ensure minimum losses. The rectifier stage itself can be organized as a half-wave, full-wave or bridge rectifier implemented with Schottky diodes. The diode rectifier can be combined with a voltage multiplier (e.g. of the Villard or Dickson type [12,13]) to eliminate the need for a subsequent boosting DC/DC converter. To further reduce the loss-contributing voltage drop in the rectifying stage, the diodes can be replaced with MOSFETs in diode connection.

The design of the entire input circuit of the RF Energy Harvester (the Rectenna) must consider the nature of the load (resistive, capacitive, inductive) as well as the magnitude of its impedance to maximize the Power Conversion Efficiency (*PCE*) factor (1), with the latter having a pronounced maximum at the optimum load of the harvester R_L , as sketched in Fig.2 [11]. In the *PCE*-expression P_{in} is the input RF power, P_{out} is the power supplied to the load and V_{out} is the output voltage of the rectenna. So, every harvester circuit implementation should be tailored to the specific application and there is no universal solution up to this point.

$$(1) \quad PCE = \frac{P_{out}}{P_{in}} = \frac{V_{out}^2}{P_{in} \cdot R_L}$$

As for the wireless energy transfer, different options exist as depicted in Fig.3.

Perhaps the most straightforward option is the so-called **Wireless Powered Communication Network (WPCN)**, where RF Energy Harvesters receive their energy from dedicated transmitters called Power Beacons. For ultra-low-power mode data transmission is accomplished through Backscatter Communications in the bistatic mode with wireless power transmitter differing from the backscatter receiver and a configuration with three participants: the Power Beacon, the CN base station and the IoT-device [6,14].

In the presence of N identical Power Beacons, the Friis model can be applied to determine the power P_R harvested by the rectenna, as it is given by (2) [15].

$$(2) \quad P_R = P_T \cdot G_T \cdot G_R \cdot \left(\frac{c}{4\pi f}\right)^2 \cdot \left[\sum_{i=1}^N \frac{1}{d_i^2} + \sum_{i=1, i \neq j}^N \sum_{j=1}^N \frac{\cos(k(\Delta d_{ij}))}{d_i d_j} \right]$$

In it, P_T is the transmitted power from each of the identical power sources, G_T and G_R are the transmit and receive antenna gains respectively, c is the speed of light, f is the operating frequency of the WPCN, d_i is the distance between the Power Beacon transmitter and the ZED IoT device, and $\Delta d_{ij} = |d_i - d_j|$ represents the

absolute difference in distances to any two transmitters of RF energy. Using the coefficient k , an estimate of the phase difference between any two received signals is considered in the calculations, which allows modeling of constructive and destructive interference.

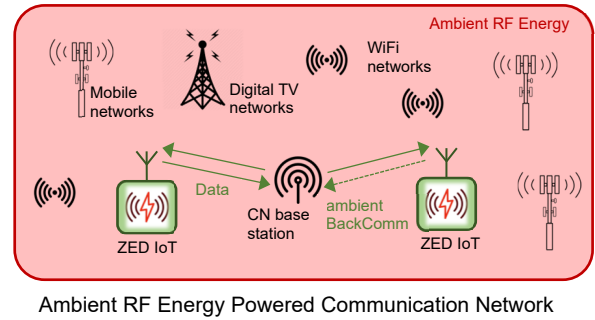
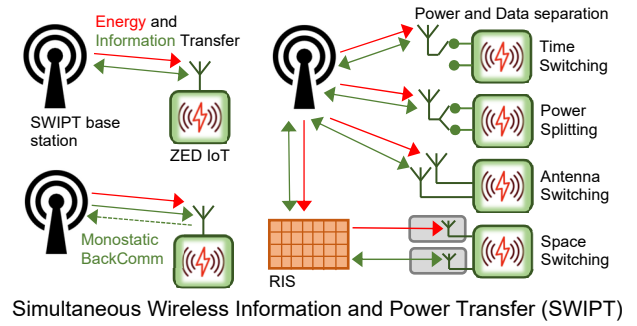
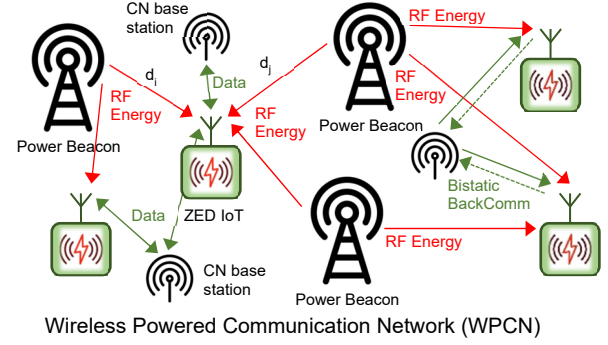


Fig.3. Wireless Information and Power Transfer topologies

Another option for a network of RF energy powered ZEDs that requires significantly more complicated implementation of the Energy Harvester itself is the **Simultaneous Wireless Information and Power Transfer (SWIPT)**. With it, the radiated radio frequency energy not only powers the IoT device but also carries data. A challenge is the separation and subsequent processing of power and data within the autonomous device itself. It can be implemented generally through four techniques [6]: **Time Switching**, in which the separation of signals occurs in the time domain, alternating between data mode and power harvesting mode, **Power Splitting**, in which the signal is split into two streams after the antenna that are processed simultaneously, that is, energy is harvested at the same time as data is received, **Antenna**

Switching, in which the antennas of the IoT device are divided into two separate groups for Energy Harvesting and data respectively, and **Spatial Switching**, in which the Multiple Input Multiple Output (MIMO) technique is used and the energy and data are carried by separate spatial streams. In the last technique beam steering using Reconfigurable Intelligent Surfaces (RIS) and MIMO-antenna design of the IoT device are successfully applied [16]. SWIPT is the ideal case for the monostatic Backscatter Communications scenario with the signal transmitted to the IoT device carrying both power and data and reverse channel accomplished through backscattering of the received RF signal [6,14].

In **Ambient RF Energy Powered Communication Network (AmRFPCN)** the energy for the operation of IoT devices is obtained from the ubiquitous ambient sources of RF energy, in particular from the mobile, wireless and digital TV networks. This energy is used to receive and transmit data in the IoT network between the RF-EH IoT devices and the corresponding base stations. This last option for a Wireless Information and Power Transfer system successfully applies the ambient Backscatter Communications (ambient BackComm) technique with their three parties: the ambient RF power source, the backscatter transmitter and the backscatter receiver [6,14].

In the Ambient RF EH variant the expected power yield is in the order of $1 \mu\text{W}/\text{cm}^2$, while in Dedicated RF it is about $10 \mu\text{W}/\text{cm}^2$ [10].

Light Energy Harvesting

Using light energy to power electronic devices is not a new idea and technology, but the very concept of IoT devices, which are small in size and can be placed practically anywhere, requires a new approach to it. Traditional solar cells using the photovoltaic effect in Si are bulky, expensive, not flexible, and not transparent, which severely limits their applications for ZEDs. In addition, they also have poor low-light performance, as seen in indoor applications [17].

This is also the reason why alternative solutions have been developed in recent years, such as solar cells based on perovskite, a mineral mainly composed of calcium titanate CaTiO_3 . "Perovskite" often refers to a whole class of materials with a crystal structure similar to that of the original mineral, often a combination of organic and inorganic compounds. What makes perovskite so attractive is exactly its crystal structure, allowing extremely good absorption of light and excellent mobility of charge-carriers [18]. A big advantage is also that the material can be "printed" on flexible and transparent substrates, exactly what silicon

based solar cells lack. At the same time, the voltages generated by the prototypes of a Perovskite Solar Cell (PSC) are of the order of 4.3V under one sun illumination, and the efficiency varies between 18.5% and 21.4%. So, 45 minutes of exposure to any light source has been found to be sufficient to power a typical IoT device for nearly 3 hours of operation [17].

As can be seen from the structure of a typical perovskite cell shown within the Light Energy Harvester block diagram in Fig.4, the perovskite layer, in which the absorption of light causes electrons to jump from lower to higher energy levels, is located in the middle of a "sandwich" of electron and hole transporting layers that separate the charge-carriers and bring them to the electrode and the transparent conductive electrode (TCE) on the substrate. A technological challenge is to fabricate the active layer with a minimal number of defects that would otherwise trap electrons and holes, reducing the efficiency of the perovskite cell [19, 20].

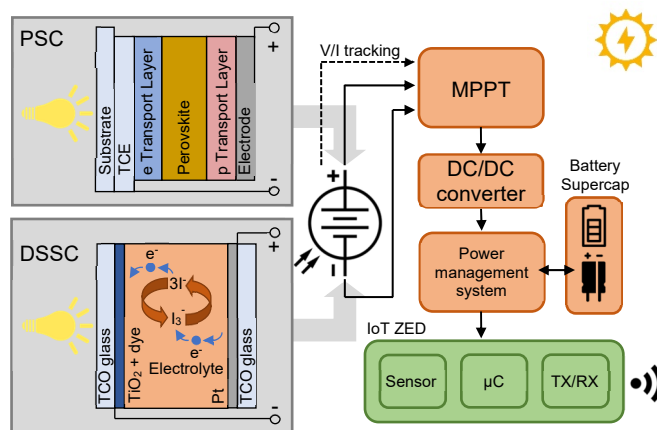


Fig.4. Solar cell-based Light EH block diagram

Another promising alternative to Si solar cells are the so-called dye-sensitized solar cells (DSSC), also shown as a structure in Fig.4. In them, a thin layer of TiO_2 is deposited on a transparent conductive oxide (TCO) cathode. The TiO_2 which has high porosity and surface area is impregnated with photosensitizer ink, which gets excited by incident light. A thin layer of Pt, which acts as a catalyst, is applied to the cathode. An iodide/triiodide solution acts as an electrolyte between the two electrodes, the whole representing a photoelectrochemical system for electron exchange [21,22].

Besides the PSC or the DSSC, the Solar Cell Energy Harvester consists of the following building blocks also shown in Fig.4: an Maximum Power Point Tracking Circuit (MPPT) to maximize the power transfer to the load with varying EH conditions (illumination level) and load doing so by varying the duty cycle of a boost

DC/DC converter as suggested in [23], a power management system which also regulates the charging of an optional battery or supercap, both supplying power in the absence of light, and the load itself, representing the circuitry of the IoT device (microcontroller, transceiver and sensor(s)).

The expected light EH technology power output is between $10 \mu\text{W}/\text{cm}^2$ and $100 \text{mW}/\text{cm}^2$ [10].

Kinetic Energy Harvesting (KEH)

Wherever there is some form of mechanical motion, be it mechanical stress, deformation, vibration or any other form, there is usually a certain amount of energy that, instead of being wasted, could be used for so-called Kinetic Energy Harvesting (KEH). KEH has different forms depending on the physical effects it uses in the corresponding EH devices, whereby most often piezoelectric, electromagnetic and triboelectric phenomena are utilized, allowing the conversion of kinetic energy into electrical energy [24].

As currently existing electromagnetic EHs are relatively large in size, Piezoelectric and Triboelectric Energy Harvesters are of major interest for application in ZED IoT devices.

Piezoelectric Energy Harvesting (PEH)

At the basis of this type of technology for obtaining energy from the environment is the well-known piezoelectric effect, first observed by the Curie brothers in 1880, in which the deformation of a material with inherent polarization of the crystal structure turns into an electric charge. Despite being an old technology, interesting for the needs of ZED IoT implementations are modern materials with piezoelectric characteristics, as well as special construction solutions allowing miniaturization.

Classical piezoelectric materials based on ceramics such as $\text{Pb}(\text{Zr,Ti})\text{O}_3$ (lead zirconates and titanates) and $(\text{K,Na})\text{NbO}_3$ (potassium and sodium niobates) are increasingly being replaced by flexible piezoelectric polymers. In terms of piezoelectric generator (PEG) structures, perhaps the most typical one used to harvest vibrational energy (VEH) is shown in Fig.5. Consisting of a cantilever with applied piezoelectric layers and an inertial mass, it lends itself perfectly to a MEMS (Microelectromechanical Systems) implementation [25]. Also depicted in the figure is the construction of a stretchable piezoelectric energy harvester (SPEH), which uses a kirigami structure on a polyvinylidene fluoride film [26]. To improve the efficiency of the EH the authors applied topological depolarization eliminating the opposite charge generation in the compression segments of the kirigami pattern, thus

favouring the tension segments, and optimization of the neutral axis to maximize the stress on the PE film. The resulting SPEH is well suited for wearable devices and soft electronics, embedded in clothing.

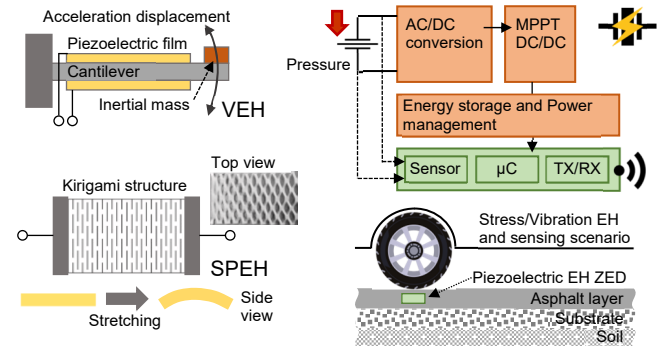


Fig.5. Piezoelectric EH construction variants and block diagram and application of a pressure sensing PEH ZED

Although applicable to some of the other EH technologies too, Piezoelectric EHs converting pressure into electricity represent a very convenient option for combining the functions of energy harvesting and sensing in one device as can be seen from the block diagram of such pressure sensing ZED in Fig.5. Such a IoT device can be embedded in the road pavement structure (realizing what can be called smart asphalt) and combined with other EHs (for example, thermoelectric and photovoltaic) and sensing technologies can collect traffic information, contributing to the goal of intelligent and green transportation [27]. Another convenient application is to place self-powered pressure sensors in car tires to measure tire pressure [5].

Vibration-based PEH is expected to deliver up to 30 mW of power [10].

Triboelectric Energy Harvesting (TEEH)

This is a relatively new method for Energy Harvesting, as it gained popularity with the demonstration in 2012 of the triboelectric nanogenerator (TENG), the work of the team of Zhong Lin Wang from the Georgia Institute of Technology [28]. The basis of such a device is the combination of triboelectric effect and electrostatic induction, and the principle of operation is illustrated in Fig.6. To generate a triboelectric charge, two materials with different electron affinity are needed, whereby their surface is electrically charged due to the transfer of electrons upon contact or friction. When the materials are separated, thanks to this triboelectric charge the electrodes attached to them are electrostatically charged. If the described process is repeated cyclically, conditions are created for generating current in an external circuit (e.g. that of an IoT ZED). To improve

efficiency, of course, the structure of the TENG is significantly more complex, including charge-trapping layers to prevent charge recombination [29].

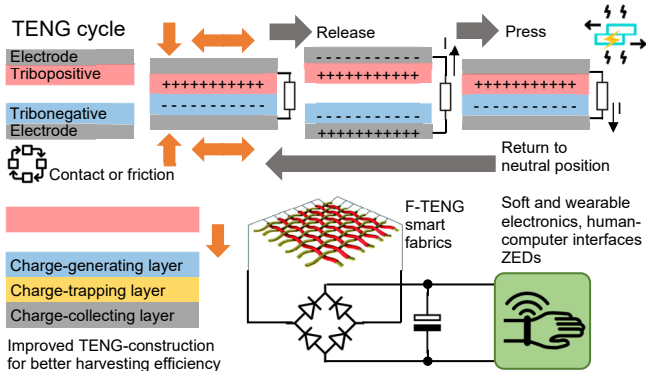


Fig.6. Principle of operation and applications of a TENG

Modern TENGs are based on a wide range of widely available materials such as aluminum and copper films, fluorinated ethylene propylene (FEP), polytetrafluoroethylene (PTFE), as well as cellulose-based materials [30]. It is this, as well as their high instantaneous output power, that makes TENGs so promising for their incorporation into smart fabrics (fabric TENG or F-TENG), which allows the creation of clothing with self-powered sensors and so-called wearable electronics. These particularly promising F-TENG IoT applications are discussed in detail in [31]. A characteristic of F-TENG-based EHs is the simplicity of the required electronics, consisting of a rectifier of the cyclically generated TE-voltage and a filter capacitor (also illustrated in Fig.6).

Thermal Energy Harvesting

In everyday life and in nature too there are numerous sources of heat, the energy of which is wasted. It is this energy that thermoelectric generators (TEGs) use. These devices are based on the Seebeck effect, where a temperature difference (gradient) at the junction between two different conductors or semiconductors generates a voltage difference. To improve efficiency, such a Thermal Energy Harvesting system is constructed from multiple thermocouples connected thermally in parallel and electrically in series, as shown in Fig.7 [5,32,33].

Apart from typical industrial applications, where there is most often a large amount of heat, TEGs can be used in smart agriculture to power data-gathering sensors for soil moisture, temperature, light or CO₂-content, as shown in the example application in the figure. Such EH systems use the natural temperature gradient between soil and air, which although extremely small (about 3 °C) is sufficient to power the ZED. Good thermal contact is provided by heatsinks

attached to the TEG [34].

Contemporary TEGs can deliver between 10 $\mu\text{W}/\text{cm}^2$ and 1 mW/cm^2 [10].

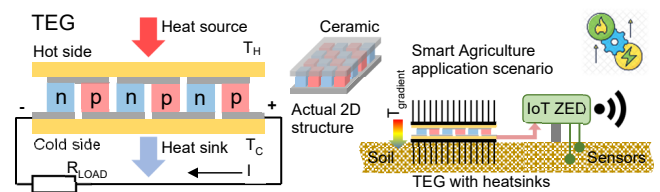


Fig.7. TEG construction, functioning and application

Wind Energy Harvesting

When talking about generating energy from the wind, perhaps the first thought is that of wind turbines. In the case of ZED, however, miniaturized solutions such as the one described in [35] and shown in Fig.8 are sought. In this case cylindrical structures are attached to piezotransducers in the form of MEMS. They are designed to cause turbulence in the air flow, which in turn turns into vibrations, which are converted by the PEH into electrical energy. By additionally placing the main cylinder in a formation of dummy cylindrical structures, the energy yield can be significantly increased. Although at the moment such solutions are mainly prototypes generating powers in the order of nW, this EH technology looks very promising for the purposes of massive IoT.

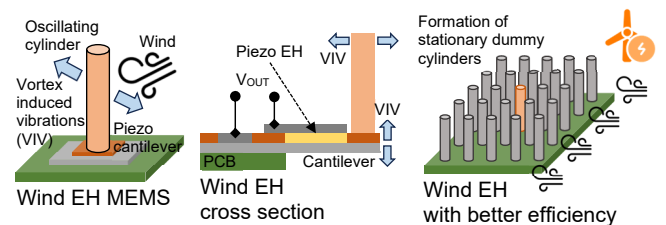


Fig.8. A Wind Energy Harvester prototype

Conclusion

The choice of a specific Energy Harvesting technology to power a ZED depends on various design considerations, but first and foremost on the availability of relevant energy sources at the devices' application site. In addition, the maturity of the relevant technology must be taken into account. While some EH concepts such as RF EH and photovoltaic EH are mature, others such as triboelectric technologies and wind EH are still in the phase of intensive research and development. Making this overview of the available solutions for powering massive IoT devices, the author came to the conclusion that the optimal and largely universal option is the combination of two or more EH systems in one ZED. In doing so, it is advisable to

combine an application-specific and site-available primary Energy Harvesting technology (e.g. Kinetic in smart fabric or Thermoelectric in smart agriculture) with a universal one using ubiquitous energy sources such as RF or light. This would ensure uninterrupted power supply to the respective ZED in the case the primary energy source fails.

REFERENCES

- [1] Shewale, R., How Many IoT Devices Are There. DemandSage Data and Statistical Analysis, February 2024.
- [2] 6G – “Connecting a cyber-physical world”, A research outlook toward 2030. Ericsson White Paper, February 2022.
- [3] Das, M. et al. Synergy of 6G technology and IoT networks for transformative applications. International Journal of Communication Systems, Vol. 37, Issue 14, September 2024.
- [4] Parkvall, S., J. Hansryd. Designing a sensor-driven world: the research take on zero-energy devices. The Ericsson Blog, May 2023.
- [5] Finanger, R. What is energy harvesting? OniO Energy Harvesting Solutions, 21 January 2020.
- [6] Mouapi, A. Radiofrequency Energy Harvesting Systems for Internet of Things Applications: A Comprehensive Overview of Design Issues. Sensors, 22, 8088, 2022.
- [7] Mohammadi, M., I Sohn. AI based energy harvesting security methods: A survey. ICT Express 9, June 2023, p. 1199.
- [8] Lopez, O. Zero-energy Devices for 6G: Technical Enablers at a Glance. Cornell University, February 2024.
- [9] Transforming Our World: The 2030 Agenda for Sustainable Development., A/RES/70/1, United Nations, 2015.
- [10] Naser, S. et al. Zero-Energy Devices Empowered 6G Networks: Opportunities, Key Technologies, and Challenges. IEEE Internet of Things Magazine, Vol. 3, issue 3, pp. 44-50.
- [11] Bougas, I.D. et al. State-of-the-Art Techniques in RF Energy Harvesting Circuits. Telecom 2021, Vol. 2, pp. 369-370.
- [12] Jabbar, H. et al. RF energy harvesting system and circuits for charging of mobile devices. IEEE Trans. Consum. Electron., 2010, 56, pp. 247-253.
- [13] Kasar, Ö. et al. Analysis of rectifier stage number and load resistance in an RF energy harvesting circuit. Microwave. Opt. Technol. Lett. 2019, 62, pp. 1542–1547.
- [14] Niu, Jin-Ping, Ye Li Geoffrey. An Overview on Backscatter Communications. Journal of Communications and Information Networks, Vol.4, No.2, Jun. 2019.
- [15] Naderi, M.Y. et al. Wireless sensor networks with RF energy harvesting: Energy models and analysis. In Proceedings of the 2015 IEEE Wireless Communications and Networking Conference, New Orleans, LA, USA, 2015, pp. 1494–1499.
- [16] Mishra, D., G.C. Alexandropoulos. Jointly optimal spatial channel assignment and power allocation for MIMO SWIPT systems. IEEE Wirel. Commun. Lett. 7, 2017, pp. 214–217.
- [17] R. Matheson. Photovoltaic-powered sensors for the Internet of Things. MIT News Office, September 2019.
- [18] Nexus solar energy. Perovskite Solar Cells: A Breakthrough in Renewable Energy Technology. July 2024.
- [19] Kosar, S. et al. Unraveling the varied nature and roles of defects in hybrid halide perovskites with time-resolved photoemission electron microscopy. Energy & Environmental Science, Issue 12, 2021.
- [20] Dickie, L. Zooming in on tiny defects. Okinawa Institute of Science and Technology, December 2021.
- [21] Pecunia, V. et al. Emerging Indoor Photovoltaic Technologies for Sustainable Internet of Things. Adv. Energy Mater. 11, 2021.
- [22] Gamry Instruments. DSSC: Dye Sensitized Solar Cells. Basic Principles and Measurements. App. Note, 2024.
- [23] Olzhabay, Y. et al. Perovskite PV Energy Harvesting System for Uninterrupted IoT Device Applications. Energies, Vol.14:7946, 2021.
- [24] Chen, Z. et al. Kinetic energy harvesting based sensing and IoT systems: A review. Front.Electron., Vol. 3, October 2022.
- [25] Sarker, M.R. et al. Review of piezoelectric energy harvesting system and application of optimization techniques to enhance the performance of the harvesting system. Sensors and Actuators A: Physical, Vol. 300, 111634, December 2019.
- [26] Kim, Y.G. et al. Improved performance of stretchable piezoelectric energy harvester based on stress rearrangement. Scientific Reports, Vol. 12:19149, 2022.
- [27] Cao, Y. et al. Energy output of piezoelectric transducers and pavements under simulated traffic load. Journal of Cleaner Production, Vol. 279:123508, January 2021.
- [28] Fan, F. R., Z.Q. Tian, Z. Lin Wang, Flexible triboelectric generator. Nano Energy, Vol. 1 (2), 2012, pp. 328–334.
- [29] Kim, D.W. et al. Material aspects of triboelectric energy generation and sensors. NPG Asia Materials, 12:6, 2020.
- [30] Alam, S.N. et al. An introduction to triboelectric nanogenerators. Nano-Structures&Nano-Objects, Vol. 34, 100980, April 2023.
- [31] Yi, J. et al. Fully Fabric-Based Triboelectric Nanogenerators as Self-Powered Human–Machine Interactive Keyboards. Nano-Micro Lett., Vol. 13:103, 2021.
- [32] Saima, S.S. et al. Equivalent Electrical Circuits of Thermoelectric Generators under Different Operating Conditions. Energies, Vol. 10, 2017, p. 386.
- [33] Faraj, A. et al. New Concept of Power Generation Using TEGs: Thermal Modeling, Parametric Analysis, and Case Study. Entropy, Vol. 22, 2020, p. 503.
- [34] Ouhmad, L., M. Abdessamad. Experimental Study and Simulation of a New Power Supply Method for Intelligent Agricultural Systems by a Thermoelectric System. Int. J. Renew. Energy Res., Vol.13, No.2, June 2023, pp. 561-562.
- [35] Lee, Y.J. et al. Vortex-induced vibration wind energy harvesting by piezoelectric MEMS device in formation. Scientific Reports, Vol. 9: 20404, 2019.

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