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Review

Energy Harvesting Opportunities in Geoenvironmental Engineering

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Abstract: Geoenvironmental engineering involves defining solutions for complex problems, such as containment systems management, contaminant transport control, wastewater management, remediation of contaminated sites and valorization of geomaterials and wastes. In the last years, energy harvesting (EH) - or energy scavenging - methods and technologies have been developed to reduce the dependence on traditional energy sources, namely fossil fuels, and nuclear power, also responding to the increase of energy demands for human activities and to fulfill sustainable development goals. EH in geoenvironmental works and surrounding soil and water environment include a set of processes for capturing and accumulating energy from several sources considered deemed wasted or unusable associated to soil dynamics, stress and strain of geomaterials, hydraulic, vibrations, biochemical, light, heating and wind sources can be potential EH systems. Therefore, this work presents a review of the literature and critical analysis on the main opportunities for EH capturing, accumulating and use in geoenvironmental works, among basic electric concepts and mechanisms, analyzing those works in complex conditions involving biological, chemical, mechanical, hydraulic, and thermal coupled actions, concluding with the main investigation and challenges within geoenvironmental aspects for EH purpose.

Keywords: environmental engineering; geotechnics and geoenvironmental energy; geoenergy; energy harvesting; environmental impact

1. Introduction

Energy demands and environmental concerns have been witnessing a significant paradigm shift towards sustainable practices. At the same time, the increasing urbanization and world population have been demanding more energy to attend the societies´ higher demand. In order to do attend both, a change in the political paradigm is necessary towards to help develop new green technologies and turn them into feasible energy-production activities [1]. For instance, energy harvesting (EH) is one innovative conjunction of techniques and applications [2] where the inherent energies from the geoenvironment are tapped to generate power while promoting eco-friendly solutions, also within the scope of Sustainable Goals Development Agenda for 2030 [3]. Cao *et al.* [4] defined EH as primordial in the new era of the internet of things (IoT) and artificial intelligence (AI) for a smarter and sustainable world. Other digital systems, such as sensors, UAVs and robots can benefit from EH sources.

Furthermore, R. Perez and M. Perez [5] compared world's reserves in TW/year for renewable and finite energies, for finite ones with 900 TW, coal has the highest, followed by uranium, petroleum and natural gas representing still a great amount when having attention to 16 TW/year world's utilization. In addition, although finite resources have high energy-production potential, they are also generally associated to industrial processes and economical activities, implying in carbon emissions and, thus, affecting the aimed sustainable goals for the future. Petroleum, for example, responds for the third-largest source of carbon emissions, due to the processes taken in the refineries, leading to the necessity of researching alternatives to the finite resources or mitigating their impacts through enhancing energy efficiency and optimizing equipment and parameters [6]. Renewable ones are the focus when dealing with EH, and according to this same study, only solar have the potential of 23,000 TW/year, followed with less exorbitant numbers exposed in Fig.1, based on [5], by wind, oceanic (OTEC), hydro, geothermal, gravitational (TIDES) and biomass, being the latter promoted as a carbon-neutral, transitionary source that could act to the diversification of energy sources [7,8]. In addition, renewable sources potential energy-production values could be higher in the following years, as the efficiency of each used methodology is increased through research and development.

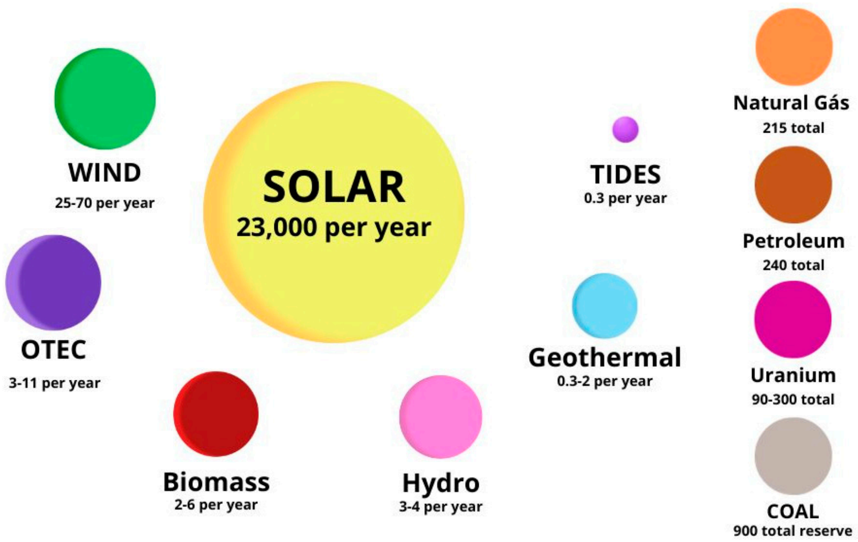

Figure 1. Renewable and finite energy reserves.

EH over geoenvironmental engineering needs attention in several types of works and potential processes. Summing up, it needs analysis on containment systems management when observing landfilling and other storage facilities for hazardous and non-hazardous wastes, structures with contaminant transport control which measure the pollutants looking to avoid soil, surface water and groundwater contamination, wastewaters management that involve safety transport, treatment and reuse processes, remediation of contaminated sites like brownfields, dumps, mines and ponds, and valorization of industrial wastes as geomaterials [9]. Across the globe, EH techniques have garnered immense attention for their potential to transform geoenvironmental engineering projects, the key factor emerges within the integration of renewable energy sources into conventional engineering practices [10]. Furthermore, Balakrishnan *et al.* [10] highlighted the fight against the unwillingness of the private sector regarding investments due to late return of capital, and the major role of the government to surpass this obstacle [11]. Solar photovoltaic systems, a prime example of EH, have gained substantial prominence in the past decades, according to the International Energy Agency (IEA), the global installed capacity of solar photovoltaic systems exceeded 700 GW by the end of 2022, illustrating the rapid uptake of this sustainable energy source [12,13]. Furthermore, piezoelectric systems have emerged as another noteworthy EH method which harnesses mechanical vibrations from traffic movement or groundwater flow and wind, converting them into electrical energy [14–17]. Alerting to its implementation in urban environments and demonstration of its potential to power remote sensors and monitoring systems. In addition, thermoelectric generators (TEGs), for instance, have gained prominence for their ability to convert temperature gradients into electricity,

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finding applications in geothermal areas, where subsurface temperature variations can be tapped producing a noteworthy power output [18,19].

Geoenvironmental engineering is also closely linked to the field of geotechnical engineering, where soil properties and movement play a pivotal role. Recent advancements have led to the integration of EH with geotechnical activities like self-powered sensing systems embedded within soil structures have been developed, enabling real-time monitoring without external power sources [2]. Moreover, microbial fuel cells (MFCs), enzyme-based fuel cells (EBFCs) and triboelectric nanogenerators (TENGs) have emerged as novelties EH technique that harnesses several industrial activities into opportunity to energy generation from biochemical mechanism. The energy generated through microbial processes offers a sustainable means to power geoenvironmental applications [20,21]. In addition, geothermal energy is another sector that provides high potential for EH, while being considered a renewable, clean source and with a relatively low-cost production addition, geothermal energy is considered a renewable, clean source and with a relatively low-cost production [22]. Its process consists of using the using the earth's deeply complex physical chemical for energy production through geothermal plants. Salazar *et al*. [23] analyzed this source for Colombia, stating that it not only has provided to be a good alternative for EH, but also that if used in its full potential, it could represent 20% of Colombia´s energy need, instead of the current 1.65%, other authors have studied similar topics around the world [24,25]. If applied on large a scale and for other countries, this sector could be responsible for largely contributing for mitigating the current energy crisis. Besides, Zhu *et al.* [26] alerted for a worldwide and current journey where the energy harvesting processes that are used are going to be transformed using TENG to nanoenergy and nanosystems, those challenges will be pointed out regarding geoenvironmental applications.

EH can also be obtained from environmental sanitation works such as biological wastewater treatment processes [27–29] (e.g. activated sludge, algae technology, constructed wetlands and lagoons) and solid waste composting [30–32]. Wastewater and water flow can also be harnessed to generate hydroelectric power [33,34] using micro-turbines and solar panels can be installed on the rooftops of water and wastewater treatment plants, as well as in solid waste management infrastructures, to generate electricity from sunlight. Methane produced in solid waste landfills [31] and anaerobic digestion reactors [35,36] can be captured and used for electricity generation or as a fuel source. The temperature difference between wastewater and organic solid waste and the environment can be used to generate thermal energy through heat exchangers and heat pumps [37,38]. Environmental sanitation facilities located in open areas in windy regions may be suitable for wind turbines [39,40]. Microbial fuel cells (MFC) can be used to capture electrons from organic matter in solid waste [41] or wastewater [42,43]. Thus, EH for geoenvironmental engineering holds immense promise for sustainable development [9]. The global impact of EH technologies underscore their potential to reshape conventional engineering practices. Such a scenario equally demands adequate politics framework to provide these sectors with the necessary regulation. This paper aims to review EH for geoenvironmental engineering techniques, exploring its global impact, and recent scientific advancements.

2. Literature Review Methodology

This research was done in 3 of the main databases for data analysis - Google Scholar, Scopus, and Web of Science -, the search was performed using Boolean and keywords truncated following schematic Figure 2a. The starting point was "energ* harvest*" AND "geoenvironment*", in addition to separated searches with AND "soil dynamic*", AND "hydraulic*", AND "solar*", AND "biochemic*", AND "magnetic*", AND "wind*", AND "vibration*". For each geoenvironmental application, were searched AND "characteristic*, AND "production*", AND "quantit*", looking to evaluate worldwide numbers. The selected papers are exposed in references.

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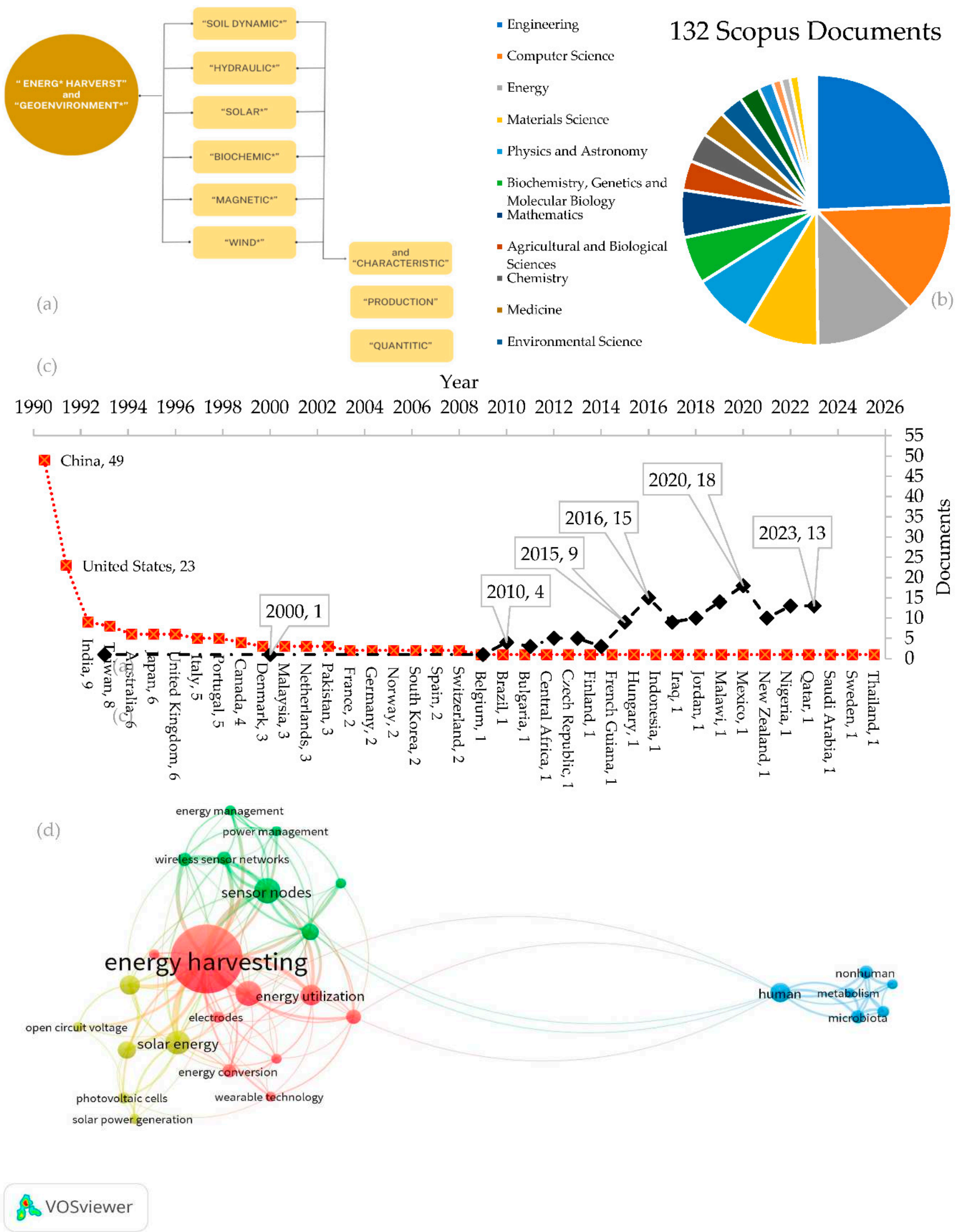

Figure 2. (**a**) Literature review methodology; (**b**) Bibliometric analysis according to subject area; (**c**) according to the number of published documents in each year and countries; (**d**) according to keywords cooccurrence with VOSviewer tool.

Besides, Scopus' key-word co-occurrence when searching for "energ* harvest*" AND "geoenvironment*", which resulted in 132 documents, in which the data was exported from Scopus website and organized by subject areas in pie chart (Figure 2b), and according to the number of published documents following the years of publication and the countries of the study (Figure 2c), besides, was developed in VOSviewer software, the keywords' co-occurrence map (Figure 2d).

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The software Canva online was used to illustrate EH different processes in Figure 3. And, in order not to infringe copyright and image rights, some images were generated to illustrate geoenvironmental applications using the artificial intelligence (AI) tool: Imagine AI and identified as AI generated (AIG) in Figure 4. Figure 2b exposes the main subjects when analyzing EH for geoenvironmental application and, as expected, engineering is first reaching almost 25% followed by what seems to be the general areas for EH: computer, energy, materials, physics, and biochemistry science. Besides, the path used in this work to determine what are the opportunities is to use mainly the least cited: environmental science, medicine, and agriculture. Figure 2c shows the increase of articles published during the past two decades with the black line, and the red line aligned the number of papers through countries highlighting the two biggest economies worldwide: China with 49 and United States of America with 23. Thus, Figure 2d keyword co-occurrence helps the understanding of EH, the strongest connections are around sensors, energy management and technology with the red and green dots, followed by the yellow with the main investments with solar energy and less connected with the emerged technologies over biological application.

3. Energy Harvesting Basics

Several authors [4,44,45] explicated the importance of basic physics', electrical', electronic', fluid and solid's mechanics', hydraulics', and soil mechanics' theories, which to analyze opportunities of EH in geoenvironmental engineering is a must to follow and understand some rules, theorems, law, and equations among:

- Newton's second law
- Maxwell's displacement current
- Joule's thermal conductivity
- Strouhal's number for frequency oscillation
- Euler-Lagrange theorem
- Bernoulli's fluid mechanics equation
- Navier-Strokes for incompressible Newtonian fluids
- Reynolds number for fluids
- Darcy's law of flow rate
- Among others, unfairly not cited.

It is important to refer to two major basic electric principles which will be less approached in this research due to less use for EH purpose: electromagnetic and electrostatic. Electromagnetic uses the induction of several materials to generate energy from movement, consisted of inductive material serially aligned surrounded by permanent magnets between two spiral strings, moreover, electrostatic using Coulomb's law parallel plate capacitors are not very popular for EH [27].

3.1. Piezoelectricity

First introduced by Pierre and Jaques Curie [46], a piezoelectric material forms dipole moments, called direct piezoelectric effect which generates energy due to force applied, this force can be from several sources [47]. When there is tension or compression in the material, an alternative current voltage will be the output, although when the material is polarized the converse piezoelectric effect occurs within extending or contracting due to the applied voltage (Figure 3a). Direct and converse piezoelectric effect are governed by constitutive equations according to electrical displacement, piezoelectric coefficient, stress, permittivity of the material, electric field, strain, and mechanical compliance [48]. Piezoelectric utilizes vibrating mass connected into a piezoelectric material and to a circuit with diodes, capacitor, and resistor, generating energy. The involved materials can be varied types, such as bio-based, organic, inorganic and composites, as ferroelectric ceramic, polyvinyde fluoride, macro-fiber composites, among others [48]. Besides, usually supported by flexible films or biofilms which are made of polymers as polyimide (PI), polyethylene terephthalate (PET) and encapsulated in biocompatible materials such as polydimethylsiloxane (PDMS) and polytetrafluoroethylene (PTFE) [47–49].

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Fuel cells (FCs) are based on a piezoelectric effect which have a cathode, an anode, a microorganism, and an oxidizing substrate, mainly composed of organic matter, in its structure inside a single or dual chamber. Basically, the microorganism decomposes the organic matter and electrons are generated, and flow through a cation exchange membrane developing a potential difference between electrodes (Figure 3b) [50]. EBFCs use similar mechanisms to MFCs, and are classified into in-vitro, plant, animal, or human powered, the last one being wearable as contact lens and patches [50].

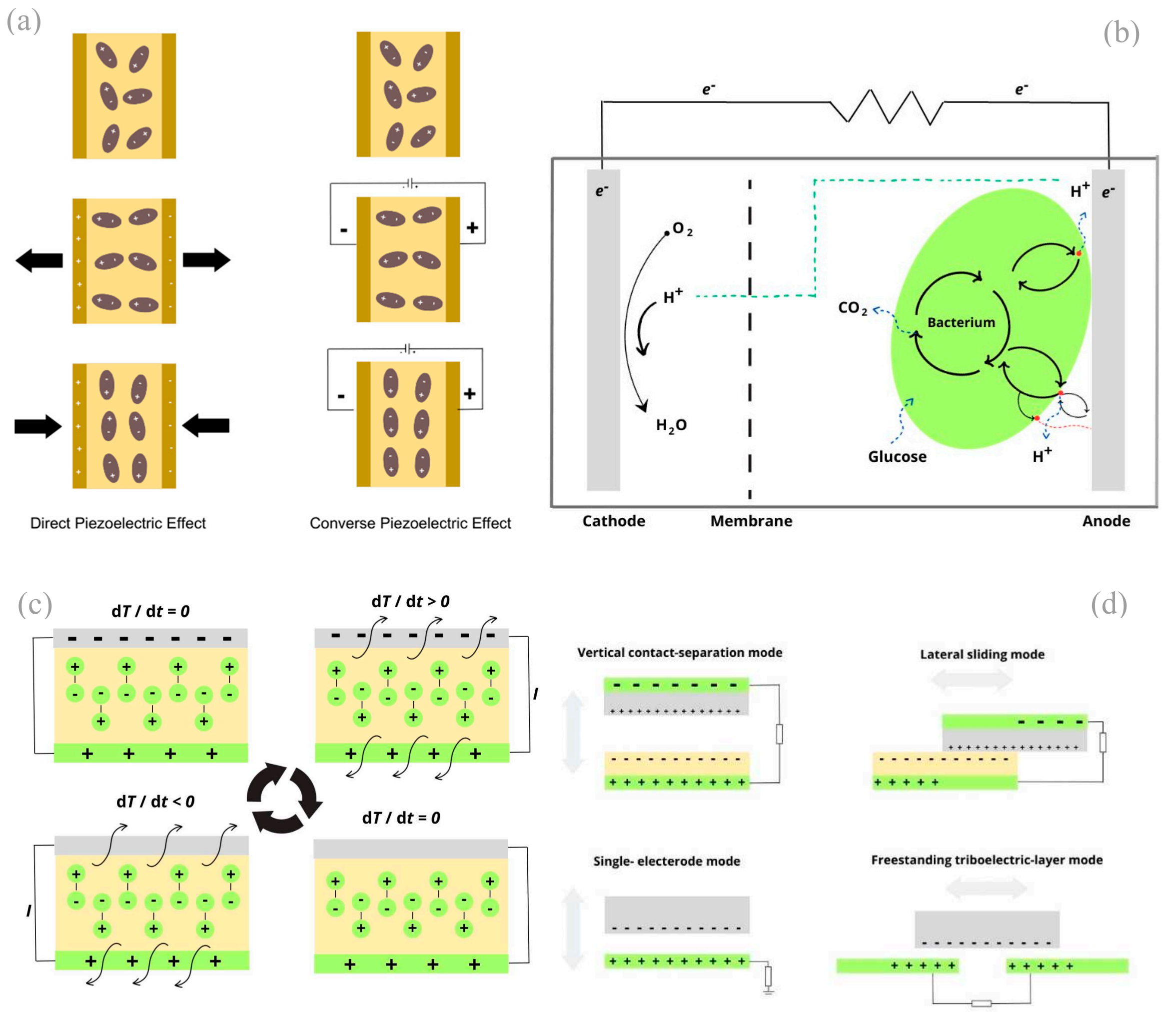

Figure 3. (**a**) Piezoelectric; (**b**) MFC; (**c**) Pyroelectric; (**d**) TENG principles.

3.2. Pyroelectricity

The pyroelectric effect can be explained as the spontaneous polarization of some crystalline structures when variation of temperature happens transforming the surface bound charge of the crystals (Figure 3c). Thermal activity uses this principle when heat occurs from any source like water or solar. Once the temperature rises, the intensity of spontaneous polarization will decrease, and the opposite also, as the crystalline structure is connected to an external circuit, the current pyroelectric is generated once atoms or ions move in response to increasing temperature, thus altering the balance of electrical charges in the material [49]. The effectiveness of thermoelectric materials is based on optimizing Seebeck coefficient, electrical and thermal conductivity, and stability [45,51].

Some devices have been developed using pyroelectricity, such as movement sensors. When a person moves in front of the sensor, the temperature variation is detected, and the sensor generates

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an electrical signal that can trigger systems. Alarm themes, as well as in small energy-generating devices, such as self-contained sensors, watches and even in smart clothes that take advantage of changes in body temperature to generate electricity. Detailed understanding of the molecular and atomic processes underlying pyroelectricity is still an ongoing area of research. Choosing the appropriate pyroelectric materials is crucial to the performance of the devices. Some pyroelectric materials are expensive or difficult to obtain in adequate quantities. Therefore, finding effective and economically viable materials is a challenge.

Another application of pyroelectricity is infrared spectroscopy, where pyroelectric crystals are used as detectors, to identify and analyze chemical substances based on their interaction, and when infrared radiation hits the crystal, it generates an electric current proportional to the intensity of the radiation. It can also be applied to detect gas leaks, as the presence of gas can be detected by pyroelectric sensors. The processing of pyroelectric materials to manufacture devices is a critical step. This includes manufacturing thin films, crystals, or other required formats. The manufacturing process must be scalable, efficient, and repeatable.

3.3. Triboelectricity

Triboelectric nano generators (TENGs) function on the principle of electric charge separation between the friction of particles generating electric charge layer throughout variation in capacitance within those systems. The simplified functioning of Wang's group invention, TENG is based in Maxwell's displacement current from a transient electric field and media dielectric polarization which convert mechanical into electrical energy [50]. TENGs can perform mainly in four modes (Figure 3d): the vertical contact-separated where two layers in contact are charge with the same amount of opposite charges; the lateral sliding with similar behavior than vertical contact-separated but one layer changes from contact and separation and the other layer to one pole sliding on the first one; the single-electrode where it is connected to an external circuit following single-electrode theory; and the freestanding layer optimizing the previous one using induced potential of both electrodes [49].

Triboelectric sensors can be used to measure pressure and force and have shown good application as a means of charging small batteries and portable devices, such as smart watches and health tracking bracelets, through body movements [52]. As for smart fabrics, these have been shown to have excellent performance, since the textile based TENG is qualified as having usability, low cost, flexibility, lightness, and the ability to collect energy and self-powered detection [53]. Furthermore, it is a power source that can operate for long periods of time without the need for frequent component replacement. Applications for accurately detecting displacement, direction, speed, and acceleration have also been developed [54]. Despite being recognized as a promising method for energy capture and self-powered devices, it is necessary to improve TENG production efficiency by changing the types of dielectric materials, which requires advanced technology and high implementation costs [55].

As it is an energy source, which can be considered recent, it is still necessary to investigate how electrons are transferred and how charges are separated during friction between materials. Although triboelectricity has shown promise on a small scale, it is still unclear what its potential is to generate energy at significant levels compared to other energy sources such as solar or wind. While triboelectricity shows potential in wearable technology, there are still challenges to be overcome, such as the size and flexibility of triboelectric generators in wearable devices.

4. Energy Harvesting in Geoenvironmental Engineering Sources

Table 1 summarizes the information dividing which industries can innovate and apply from EH techniques using known sources of energy and the energy mechanism attached to the technique according to the literature here analyzed and exposed.

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Table 1. Energy harvesting opportunities in geoenvironmental engineering.

Sources	EH Techniques	EH Basics	Recent Investigation	Geoenvironmental
Solar [12,13,45,56,57]	Photovoltaics Thermal Solar cells	Piezoelectricity TENG	AI compatibility Stable crystalline structure New materials Photo-reactors	Construction in general
Wind [58–63]	Wind Turbines	Piezoelectricity	Smart sensors AI compatibility	Offshore Platform Construction in general
Hydraulic [14,44,48]	Devices for Oceanic and River Flow	Piezoelectricity TENG	Smart sensors New materials Durability	Offshore Platforms Canals Water Distribution System
	Water Turbines	Piezoelectricity	Smart sensors AI compatibility Power storage	Water Storage Facility Waste Containment
Biochemical [7-9,20,21,28–31,35,41,43,50–54,64,65]	Microbial fuel cells Enzyme-based fuel cells	Piezoelectricity	Electrode configurations New materials Biosensors	Wastewater Treatment Bioremediation Solid Waste Processing Biosensing
	Biomechanisms	Piezoelectricity Pyroelectricity TENG	AI compatibility New materials Biosensors	Biosensing Agroindustry
Geothermal and Geomechanical [2,15–19,22,66,67]	Devices for Civil and Geotechnical structures	Piezoelectricity TENG	New materials Smart sensors Durability	Construction in general Earthworks in general Highway and Roads Railways Machinery in general

4.1. Solar

Heat and light sources, two usual elements in our daily lives, have emerged as a promising clean energy production and sources, mainly due to solar energy [13]. As the world seeks to transition into cleaner energy options, EH from these have a great potential towards reducing dependence on traditional fossil fuels and minimizing environmental impacts. Regarding industrial processes, IEA highlighted that lighting accounts for about 15% of global electricity consumption [68], moreover, numerous heating processes, from industrial operations to residential heating, release significant thermal energy, exposing their potential to convert to usable energy. According to [12], the global solar cell production was around 350 GW only in 2022 and is expected to grow up to 30% for 2023 led by China and United States, looking to harness solar energy potential. Figure 4d,e shows the main light and heat sources for EH.

When sun light and heat reach the semiconductor of a solar cell, free electrons are forced to flow crating electrical current [2]. To catalyze this latent energy, notably, thermoelectric generators (TEGs) are the key player in harvesting thermal energy, which can convert temperature gradients into electricity, enhancing energy conversion efficiency [45,69,70]. Organic, inorganic and hybrid thermoelectric materials have been developed within polymers, metals, or combining them, respectively, and should be used to replace batteries in near future [70].

A photo-voltaic device operation is, in a simplified way, the low bandgap from light results a shift of the electrons to the conduction band from valence band, these electrons diffuse in the transport layer and are collected in the cathode and anode [56]. Organometals halides are used as light harvesters in solar cells, which are composed by crystalline structures, oxides, carbides, nitrides, and hydrides, for example the most efficient is perovskite. Perovskite solar cells, a recent breakthrough in photovoltaic technology, offer enhanced efficiency and versatility [71] in addition to cost advantages [56,71], and seem to emerge and surpass older technologies like dye-sensitized solar cells, crystalline solar cells, cadmium telluride and copper indium gallium selenide.

Solar EH system can be hybrid, using photovoltaic and thermal to optimize light and heat, besides several models, algorithmic and simulation software can be used in that system to mitigate malfunctioning and energy loss [13–16]. Similarly, harvesting energy from light and heat sources has been growing exponentially worldwide. Another less discussed EH which uses heat is geothermal from earth's naturally stored energy source, like hot ground water or snow melting. [2] highlighted the utilization of geothermal EH technique within heat pumps combined with permeable pavement had the benefit of improving stormwater quality and heating systems in New York [57] based on hydronic radiant system and the heat source was from geothermal heat pumps. [44] performed simulations to develop low-enthalpy geothermal reservoir and found as challenge the fact that shale facies can improve reservoir's lifetime.

Light and heat sources still have high costs, although have high energy output potential and are renewable, needing cooperation among entities, companies, and government to reduce related costs. Thus, EH from solar sources stands at the intersection of practicality, sustainability, and technological innovation, confronting climate change and resource depletion issues, providing demands while minimizing environmental impacts.

4.2. Wind

Wind sources from kinetic energy of moving air to generate electricity stands as sustainable power for the past decades, thus, air masses produce clean energy [10,59]. Governments and industries seek to reduce fossil fuels consumption and mitigate climate change. Wind power has gained immense prominence, reduced greenhouse gas emissions, and achieved carbon neutrality. In 2021, global wind energy capacity reached over 700 GW, as reported by the Global Wind Energy Council [60], showing the capacity to provide for millions of households and industries powered by renewable energy, effectively reducing environmental impact. In Europe, UK and Germany lead with around 80% [62] remarking the influence of economic power. Although, during energetic transition, some business-like offshore platforms of oil extraction could explore wind power, and governments targets can help in achieving good results even for third world or in-development countries. On-shore and off-shore wind farm have improved economic and implementation aspects mostly due to advancements in turbines technologies and foundation structures [62]. Figure 4h shows the main wind sources for EH.

Remarkable advancements in the field are driven by innovations in wind turbine technology [59,61], materials science, and grid integration. The development of smart wind turbines that optimize energy capture by adjusting their operation based on real-time wind conditions within adaptive wind turbine control algorithm is an investigation line [10,59,61]. Furthermore, offshore wind energy have expanded the horizons of wind energy harvesting, while benefit from stronger and more consistent winds, enabling higher energy production, emphasizing its role in renewable energy target [62,63].

In the sense of meteorological field, TENGs have been used to convert mechanical energy into electricity from the wind speed and direction using wind cups and turbines, and flutter- and flag-type sensors [4]. Besides, attached to hydropower, TENG can be applied in meteoric stations due to rain sensoring using its vibration for EH. [4] highlighted 3 main fields that can collaborate and utilize TENG which are biological monitoring and learning, the industry in general using in aircrafts and unmanned aerial vehicle (UAV) and the academia applying in vortex and turbulence state. Future applications comprise micro to macro arrangement, self-powered, nanoscale, effectiveness, and less-costly material investigation.

EH from wind symbolizes the power of nature for the greater good, looking at the urgency of climate change issues and the need for cleaner energy options, wind energy offers a beacon of hope.

Mainly from kinetic energy, wind becomes a driving force in shaping a more sustainable and resilient future.

4.3. Hydraulic

EH from hydraulic sources, such as flowing water from water streams, rivers, or even ocean currents, has been explored since the past century. Water, in its various forms, holds huge potential as a renewable energy source due to kinetic energy of flowing rivers or ocean currents, hydraulic energy offers a continuous and abundant supply of energy that can be tapped for various applications. To illustrate the magnitude of this potential, as the International Energy Agency reported that hydropower accounted for approximately 16% of the world's total electricity generation in 2020 [72], underscoring the substantial contribution to global energy supply. [10] alerted that only in China, hydropower increased 50% between 2010 to 2015 reaching 300 000 MW of capacity. Moreover, advancements in EH techniques have paved the way for more efficient and environmentally friendly extraction of energy from hydraulic sources. EH from hydraulic sources still holds great potential for renewable energy transition while the world's energy security and climate change are issues. The global adoption of hydraulic energy technologies, macro to micro applications of hydropower captors from kinetic energy within every water source can reshape energy sustainability. Figure 4a–c show the main hydraulic sources for EH.

4.3.1. Dams and Reservoirs

Hydropower is the main source of power over the world [73], but very dependent on geographical aspects not being available for every country. However, due to the high amount of water in rivers hydropower plants are classified according to their capacity from below 5 kW to higher than 100 MW, showing the wide range of applicability within this technique. Environmental issues are still a thematic over dams and reservoirs, as the environmental impacts caused by them harms the population in its surroundings, while the ecosystem itself can suffer consequences, such as flooded areas or available land area reduced. In this sense, the need for investigation on how to mitigate those impacts emerges. Governments are exploring areas on improving technology for site investigation, development of water flood plans and sensoring water flow and aquatic biosystems attached to societal and rural electric perspective [73]. Still, [73] pointed out the main barriers for small hydropower EH which are installation and maintenance expenses, lack of control and technology, topographical aspects, and social acceptance and knowledge.

4.3.2. Fluid Dynamics

Besides dams and reservoirs, a prominent example is the development of underwater EH systems that harness the kinetic energy within rivers and oceans [14,48,67], moreover, [44] presents a comprehensive analysis of an underwater EH prototype, demonstrating its viability for providing power to remote offshore installations. In addition, oceanic EH offer a significant potential for energy generation using micro-hydropower systems that harness the energy from small- to large-scale water flows highlighted for energy generation [73].

Fluid dynamics sensing field have used TENGs technology over the past decades, from meteorologic, water wave, pipes fluid and bridges over water sensors, and [4] indicate a strong application within fluid fundamental local sensing. In this perspective, TENGs have been used for EH from water wave motion in the ocean to power offshore stations and structural vibration on bridges caused by hydrodynamics [4]. Moreover water currents, [48] summarized oceanic energy from wave motion according to their periodical classification and EH potential from capillary, ultra-gravity, gravity, infra-gravity, long-period, ordinary tidal, and trans-tidal wave type, besides EH from piezoelectric materials can be output from wave impact in structures. [44] used TENG to develop a flag-like EH device to explore ocean current energy under extremely low velocity

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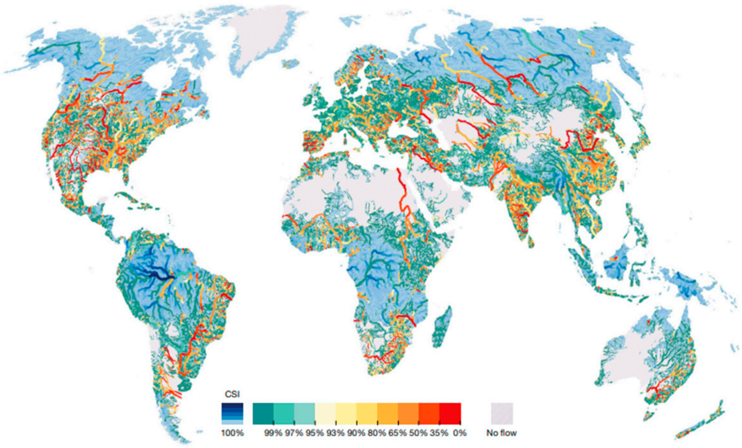
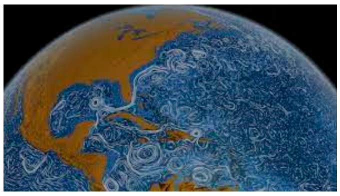
conditions and presented a cost-effective and accessible powering sensor which can be allied to AI and IoT.



(a) Connectivity status index (CSI) of world's river [74]

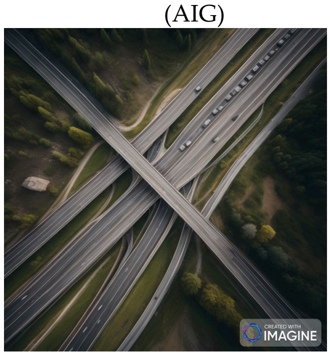


(b) Oceanic current flow [75]

(c) Water dam/reservoir (AIG)

(d) Solar power plant (AIG)

(e) Thermal power plant (AIG)



(f) Highway (AIG)

(g) Railway (AIG)

(h) Wind power plants (AIG)

(i) Smart houses (AIG)

(j) Dumpsite (AIG)

(k) Biochemical mechanisms (AIG)

(l) Biomechanisms **[76]**

Figure 4. EH opportunities in geoenvironmental engineering.

4.4. Geomechanical and Geothermal

The notable approach is the utilization of piezoelectric materials to convert mechanical vibrations from machinery into electricity [58,77,78], being able to use this potential for industries' machinery. Furthermore, advancements in TENGs have revolutionized the field by enabling EH from friction and mechanical contact, TENGs can be integrated into machinery components to capture energy from various mechanical interactions [79]. Thus, EH from machinery sources stands as a transformative solution at the intersection of energy demand, technological innovation, and environmental stewardship. Regarding the challenge of transitioning to sustainable energy systems. From harnessing kinetic, frictional, and mechanical energy with piezoelectric sensors and TENGs, machinery sources offer a pragmatic way to address nowadays and future energy needs. Figure 4f,g shows the main vibration sources for EH.

4.4.1. Soil Dynamics

Soil dynamics has emerged as an unexpected yet promising arena for energy harvesting regarding the possibility of usable energy from soil movements and vibrations. The vast potential that lies beneath the ground may seem novel, therefore, the world is witnessing a relentless pursuit of renewable energy sources to mitigate the impacts of climate change and dwindling fossil fuel reserves. EH from soil dynamics presents a unique opportunity to harness previously untapped energy resources while maintaining a sustainable balance with the environment, aligning with the global drive towards green energy. Soil dynamics can encompass a range of activities, from natural processes like wind-induced soil vibrations to man-constructed buildings and roads upon the soil. Inherent vibrations and movements generate stress through the soil and create energy that can potentially be converted into electricity. It seems to guarantee the potential when the perspective consider that worldwide construction activities alone can generate trillions of vibrations annually due to already constructed sites [9], challenging the investigation over converting these vibrations into usable energy.

EH within soil dynamics theme has witnessed significant strides, reflecting the interdisciplinary nature of sustainable technology, a pioneering avenue is the use of piezoelectric sensors embedded in the soil to capture vibrations and convert them into electrical energy [66,80]. Geotechnical engineering prospect are deep foundations because of the load needed for testing and installation, earthworks compaction procedures and excavations in general when machines can harvester their own energy from field work [15].

Furthermore, advancements in nanotechnology have unlocked new possibilities within energy harvesting from soil dynamics, nanogenerators are capable of converting mechanical energy at the nanoscale into electricity, hold immense promise for capturing subtle soil vibrations tailored for soil environments [4,81]. It's important to note that the energy output from soil dynamics can vary significantly depending on factors such as location, soil composition, and the specific energy harvesting technology employed. Research and development in this field are ongoing, and as technology advances, the potential for energy harvesting from soil dynamics may become more practical and efficient. The potential of EH due to soil dynamics is undeniable as the world grapples with the need for renewable energy sources, the convergence of recent scientific advancements with the global focus on sustainability aligns seamlessly with the goals of minimizing environmental impact and reducing carbon emissions. From piezoelectric sensors to nanogenerators, EH techniques can capitalize latent energy from soil vibrations, movements, and stress between particles.

Energy harvesting from soil dynamics is an emerging field that explores ways to harness energy from various soil-related processes and phenomena. While it's not as well-established as some other forms of EH, there are several possibilities and methods that researchers and engineers are exploring. Here are some potential avenues for energy harvesting from soil dynamics: Piezoelectric materials which can convert mechanical strain or vibrations into electrical energy, embedding piezoelectric sensors or materials in the ground, such as beneath roadways or near heavy machinery, can capture

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energy from the vibrations caused by vehicles or equipment passing over the soil. Besides, piezoelectric sensors placed in the soil can detect variations in soil pressure or compaction caused by natural processes or human activities. These sensors can be used for monitoring purposes and harvest energy from pressure fluctuations. Also, in regions with frequent seismic activity, systems can be designed to harness the energy generated during earthquakes or ground movements. This energy could potentially be used for emergency power or monitoring purposes.

4.4.2. Geothermal

Geothermal energy can be harvested by exploiting temperature differences between the soil, water, and the surface. In the ever-evolving quest for sustainable energy solutions, geothermal energy has risen as a significant contender when harnesses the Earth's natural heat to produce clean and renewable power.

Geothermal heat pumps can transfer heat between the ground and a building to provide heating and cooling, reducing the need for conventional HVAC systems [24]. The temperature gradient between the surface and subsurface of the soil can be utilized with thermoelectric generators to generate electricity. These devices convert heat differences into electrical energy and can be applied in geothermal systems, usually offering constant power generation without the variability inherent in solar and wind energy [25].

To put the global scale of geothermal energy into perspective, the worldwide installed geothermal power capacity reached 54 GW, as reported by [82]. The field of geothermal energy harvesting has witnessed remarkable advancements in recent years, driven by innovations in drilling technology, reservoir management, and enhanced geothermal systems. One significant avenue is the development of binary cycle geothermal power plants using low-temperature geothermal resources, previously considered unsuitable for power generation, and now highlighted by efficiency and adaptability [83]. Furthermore, advancements in enhanced geothermal systems have expanded the utilization of it in artificial reservoirs by stimulating deep geothermal resources emphasizing its role in regions with limited natural reservoirs [84].

Energy harvesting from geothermal sources represents a powerful and sustainable means of generating clean electricity. As the world confronts the escalating challenges of climate change and the need to transition to low-carbon energy sources, geothermal energy stands out as a dependable and environmentally friendly solution from binary cycle geothermal power plants expanding the resource base to enhanced geothermal systems unlocking deeper and hotter reservoirs, these advancements position geothermal energy as a cornerstone of the renewable energy transition.

4.4.3. Industry Machines

Machinery vibration’s EH sources have emerged as a promising avenue for generating clean energy while simultaneously reducing the environmental impact of industrial processes. Basically, due to kinetic and mechanical energy during industrial operations, this source offers a latent alternative to be captured and converted for several facilities. Global machinery is diverse within a great range of sectors such as manufacturing, transportation, and construction, representing a significant opportunity to fill the gap between energy demand and supply. IEA indicated that industrial sector accounts for around 37% of global final energy consumption [11], being a substantial energy demander, sustainable measurements are the potential with EH techniques. Moreover, forecast machine failure, issues and efficiency can help save time, money and even lives [58], self-powered sensors monitoring machinery behavior is a promising field for EH.

Palosaari *et al.* [58] created a prototype with piezoelectric ceramic and steel parts and clamped by a carbon-fiber nylon to harvester energy from rotation frequency motor in laboratorial-scale and concluded that many factors can impact EH process like the piezoelectrical material, ratios of its thickness, length, and width, besides mass, and the highest results was around 580 μW for 7.4 Hz. That paves the path through a more sustainable and self-sufficient machine industry where companies should develop machines for geoenvironmental engineering or any purpose to adapt and

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use the energy from vibration. Agricultural machinery and equipment create vibrations in the soil. Energy harvesting systems can be designed to capture these vibrations and convert them into electrical energy, which can be used to power sensors, monitors, or small-scale applications on farms. Kinetic energy from soil particles' movement due to factors like wind or water flow can be captured using kinetic energy harvesting mechanisms, such as piezoelectric generators or electromagnetic devices.

4.4.4. Transportation

Highways and railways are the most common geotechnical structures for transportation of people and cargo, those infrastructures have been increasing its importance to attend global exchange and globalization demands [16]. Because of automobiles and trains heavy impacts, a great amount of vibration is absorbed by roads and railways, providing a potential to harvester this into energy, self-powering themselves or converting into electrical power [80]. The reapplication of harvested energy in transportation industry is discussed within powering traffic lights, monitoring roads and ferric ways health, besides building's health of the stations [47].

A simulation was conducted [80] using piezoelectric EH for railway track vibrations verifying load resistance, pre-stress, and load frequency impacts, it was applied EH beam to absorb train's vibration and concluded that for frequency lower than 6 Hz, there is no efficiency in energy capture, but for higher frequency the results have great performance, besides, pre-stress had no significant impact on EH but the best values was 4.5 kN, providing a path to actually apply on the environment. Other study [66] designed EH system for vehicle wheels due to centrifugal force in rotational motion and concluded that can be used to stablish a wireless self-sufficient and intelligent vehicle wheel.

4.4.5. Smart Homes

Other investigation field is the utilization of vibration from buildings for EH, not one the building itself due to wind or soil movements but daily sources like kitchen machines, blenders, clothes dryer, microwave, vents, the floor due to foot traffic, washing machine, refrigerator, among others [9]. Smart homes (Figure 4i) seem to have a good perspective of EH when devices based on heat, ventilation, and air conditioning (HVAC) mechanisms can power electronic devices [47]. At the nexus of physics and engineering, EH from electromagnetic sources has garnered significant attention for its potential to transform ambient electromagnetic radiation. Electromagnetic radiation along with radio waves, microwaves, and light waves, permeates our environment and can be captured and converted into electrical power. To underscore the significance of electromagnetic sources, it is estimated that global data traffic is projected to reach around 175 zettabytes per year by 2025 [85], and with the proliferation of wireless communication technologies, there is an ever-increasing source that can be transformed into energy.

Materials science, nanotechnology, and electromagnetic wave manipulation have been investigated as energy sources, like the utilization of metamaterials to capture and manipulate electromagnetic radiation from radio frequency electromagnetic sources [86,87]. Furthermore, the abovementioned nanogenerators have propelled the field by enabling the direct conversion of mechanical vibrations, including the induced by electromagnetic waves. Besides, nanogenerators can be integrated into devices such as wireless sensors and communication devices, developing their potential for powering autonomous electronics [49,64]. Electromagnetic sources hold transformative potential as a clean and growing demand for energy solution, tapping into the ambient electromagnetic radiation. It has the potential to become a practical, and almost autonomous, pathway to meet energy needs while aligning with sustainability goals using communication technologies as supplier.

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4.5. Biochemical

EH from biochemical sources is still an unconventional but relatively new and promising field which has garnered attention for its potential to extract renewable energy from biological and chemical processes. Biologically, from microbial activities to biochemical reactions occurring within living organisms and ecosystems, and chemically when expected reactions occur in industries [50]. These natural processes offer an innovative pathway to meet energy demands while reducing the carbon footprint, pushing toward sustainable opportunity while the World Bank reported that around 2 billion tons of organic waste are generated globally each [68]. This vast organic waste can generate energy through biochemical EH technologies. Figure 4k,l shows the main biochemical mechanisms sources for EH.

4.5.1. Microbiological

Significant advancements have been observed, one noteworthy is the use of microbial fuel cells (MFCs) to convert organic matter into electricity through microbial metabolism of organic subtracts, showcasing waste reduction and energy generation [88,89]. Furthermore, studies in biomechanical systems have unveiled new dimensions in biochemical EH, which systems enable the direct conversion of energy from biological processes into electrical power [50,90], using living animals and humans daily activities and convert them into electrical energy. Besides, a new popular field of investigation is over enzyme-based fuel cells (EBFCs), where synthetic enzymes are immobilized on the electrode and generate energy through glucose oxidation [50].

Afroz *et al.* [50] classified MFCs as lab or in-site scale, differencing the in-situ as aquatics for docked in open or close water, or floating ones, and the terrestrial MFCs, besides structurally they can be in a single chamber or double-chambered, up-flow, stacked, tubular, and forced-flow [88]. They have been studied several microorganisms as Proteobacteria, microalgae, yeast, and fungi species [50]. The main materials for anodes are carbon or metal-based anodes, can be basic, natural, or synthetic, or composite within graphene or graphite, in addition to the modified with conductive polymer coating or surface treatment. Cathodes can be submerged with or without treatment, air cathodes or bio-cathodes when using plants or algae. Electrodes are an issue over efficiency and economic viability [50] for anodes and cathodes. Prathiba *et al.* [91] outlined as on-going issues of MFC needing investigation the type of organic substrate, electron transference between anode's chamber to surface, scale-up for micro and nano applications, oxygen supplier and penetrability of proton membranes.

J. Wang *et al.* [89] outlined low power generation efficiency and operational stability as the main issues of MFC, limiting scale-up and economical viabilization, resulting in growth research over enhancing the production within engineered techniques using low-cost substrates. Besides, soil MFCs can use the metabolic processes of soil microbes to generate electricity. These devices harness the potential difference between an anode buried in the soil and a cathode exposed to air. Organic matter in the soil serves as a fuel source for microbial activity, producing electricity in the process. In addition to plant roots EH which can generate small electric potentials due to ion transport processes, creating the potential for plant-based energy harvesting. Research is ongoing to develop technologies that can tap into this potential, although the energy output is currently relatively low.

4.5.2. Biomechanics

Biomechanical EH mechanism are biocompatible energy sources using wearable electronics into human [49], plants, or animals, mainly composed of piezoelectric, electromagnetic, electrostatic, and triboelectric mechanism. Investigation over compatibility of those micro-components within human body, animal, and plants application, like flapping wings, human joint movement, heart motion, aquatic animals' flipper, among others [50]. [47] highlighted [65] study where sensor tags were incorporated internally and externally in fishes to monitor and self-power it from fishes' migration patterns and movements. Furthermore, this energy seems to be the future for health monitoring for biomedical issues like cardiac sensors, blood pressure measurements, pulse anomalies, brain stimulation, and tissue engineered wearable devices [47].

Therefore, biochemical sources represent an innovative approach that converges sustainability with the inherent capabilities of biological systems. This approach aligns with global efforts to reduce waste, minimize environmental impact, and ensure a reliable energy supply. From microbial fuel cells, enzyme-based fuel cells, or biomechanical systems, these advancements illustrate the breadth and depth of innovation within the field.

5. Conclusions

In this review, several research topics were analyzed for energy harvesting through the scope of geoenvironmental engineering. The solutions for energy crisis can be related to research & development (R&D) opportunities within each industrial activities sector, based on basic principles of physics, fluid and solid mechanics, soil mechanics, electrical and electronic engineering, and biochemical mechanisms. In addition, it is known that the demand for energy is increasing as urbanization and growth of global population occur. Analyzing the evolution of each sector, new technologies and opportunities appear the most when the sector is in the imminence of crisis. Considering the demands for a greener are further that is forcing the industry to be restructured, it is expected to see further development in a rapid manner, based on the established values for R&D. Sensors, nanogenerators, methodologies and other approaches tend to become cheaper the more they are used and the more they are developed. The political framework should equally follow these evolutions to provide the regulatory framework for providing the right environment to develop new technologies that can arrive on the market.

Thus, new technologies begin as an experiment until they become more accessible. Geoenvironmental engineering is a part of the energy harvest strand, attracting more attention due to its potential. Recent technologies could enhance their development even further and respond to the emergency crisis the world is passing through, attending the demands for a more sustainable future through cleaner energy-production.

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References

1. Ekonomou, G.; Menegaki, A. China in the Renewable Energy Era: What has Been Done and What Remains to be Done. **Energies 2023**, *vol. 16*, p. 6696. https://doi.org/10.3390/en16186696.
2. Wang, H.; Jasim, A.; Chen, X. Energy harvesting technologies in roadway and bridge for different applications – A comprehensive review. **Applied Energy 2018**, *vol. 212*, pp. 1083-1094. https://doi.org/10.1016/j.apenergy.2017.12.125.
3. United Nations Parliament and Council. The 2030 Agenda for Sustainable Development. **2020**.
4. Cao, L.N.; Xu, Z.; Wang, Z. Application of Triboelectric Nanogenerator in Fluid Dynamics Sensing: Past and Future. **Nanomaterials 2022**, *vol. 12*, *no. 19*, p. 3261. https://doi.org/10.3390/nano12193261.
5. Perez, R.; Perez, M. A fundamental look at energy reserves for the planet. **IEA SHS Solar Update 2009**.

6. Da, H.; Xu, D.; Li, J.; Tang, Z.; Li, J.; Wang, C.; Luan, H.; Zhang, F.; Zeng, Y. Influencing Factors of Carbon Emission from Typical Refining Units: Identification, Analysis, and Mitigation Potential. **Energies 2023**, *vol. 16*, p. 6527. https://doi.org/10.3390/en16186527.
7. Maggiotti, G.; Colangelo, G.; Milanese, M.; Risi, A. Thermochemical Technologies for the Optimization of Olive Wood Biomass Energy Exploitation: A Review. **Energies 2023**, *vol. 16*, p. 6772. https://doi.org/10.3390/en16196772
8. Kozuch, A.; Cywicka, D.; Adamowicz, K.; Wieruszewski, M.; Wysocka-Fijorek, E.; Kielbasa, P. The Use of Forest Biomass for Energy Purposes in Selected European Countries. **Energies 2023**, *vol. 16*, p. 5776. https://doi.org/10.3390/en16155776.
9. Mo, C.; Davidson, J. Energy harvesting technologies for structural health monitoring applications. In Proceedings of 2013 IEEE Conference on Technologies for Sustainability (Sustech), Portland, Oregon, USA, 2013. https://doi.org/10.1177/1687814017696210.
10. Balakrishnan, P.; Shabbir, M.; Siddiqi, A.; Wang, X. Current status and future prospects of renewable energy: A case study. **Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 2020,** *vol. 42, no. 21*, pp. 2698-2703. https://doi.org/10.1080/15567036.2019.1618983.
11. Nurunnabi, M.; Esquer, J.; Munguia, N.; Zepeda, D.; Perez, R.; Velazquez, L. Reaching the sustainable development goals 2030: energy efficiency as an approach to corporate social responsibility (CSR). **GeoJournal 2020**, *vol. 85*, pp. 363-374. https://doi.org/10.1007/s10708-018-09965-x.
12. Jäger-Waldau, A. Snapshot of Photovoltaics - May 2023. **EPJ Photovoltaics 2023,** *vol. 14*, *no. 23*. https://doi.org/10.1051/epjpv/2023016.
13. Kazem, H.; Chaichan, M.; Ali, H.; Al-Waeli; Gholami, A. A systematic review of solar photovoltaic energy systems design modelling algorithms and software. **Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 2022**. *vol. 44, no. 3*, pp. 6709-6736. https://doi.org/10.1080/15567036.2022.2100517.
14. Mohamed, M.; Wu, W.; Moniri, M. Power harvesting for smart sensor networks in monitoring water distribution system. In Proceedings of 2011 International Conference on Networking, Sensing and Control, Delft, the Netherlands, 2011. https://doi.org/10.1109/ICNSC.2011.5874897.
15. Trivedi, A.; Shukla, S. Testing and Technology for Load Carrying Capacity of Deep Foundations. In Proceedings of 2019 International Symposium, Delhi, India, 2019.
16. Newston, C.; Halter, S.; Hassan, M. Tran-SET 2020. In Proceedings of Tran-SET Conference 2020, Albuquerque, New Mexico, USA, 2020.
17. Zheng, X.; He, L.; Wang, S.; Liu, X.; Liu, R. A review of piezoelectric energy harvesters for harvesting wind energy. **Sensors and Actuators: A. Physical 2023**. *vol. 352*, p. 114190. https://doi.org/10.1016/j.sna.2023.114190.
18. Chandrasekharam, D.; Bundschuh, J. Low Enthalpy Geothermal Resources for Power Generation. Bombay, India: CRC Press, 2008.
19. Wang,Y.; Voskov, D.; Khait, M.; Saeid, S.; Bruhn, D. Influential factors on the development of a low-enthalpy geothermal reservoir: A sensitivity study of a realistic field. **Renewable Energy 2021.** *vol. 179*, pp. 641-651. https://doi.org/10.1016/j.renene.2021.07.017.
20. Singh, P.; Hussain, C.; Sillanpaa, M. Innovative Bio-based Technologies for Environmental Remediation, Boca Raton, Florida, USA: CRC Press, 2022. https://doi.org/10.1201/9781003004684.
21. Fouladi, A.; Arulrajah, A.; Chu, J.; Horpibulsuk, S. Application of Microbially Induced Calcite Precipitation (MICP) technology in construction materials: A comprehensive review of waste stream contributions." **Construction and Building Materials 2023.** *vol. 388*, p. 131546. https://doi.org/10.1016/j.conbuildmat.2023.131546
22. Islam, T.; Nabi, M.; Arefin, M.; Mostakim, K.; Rashid, F.; Hassan, N.; Rahman, S.; McIntosh, S.; Mullins, B.; Muyeen, S. Trends and prospects of geothermal energy as an alternative source of power: A comprehensive review. **Heliyon 2022**. *vol. 8*, p. e11836. https://doi.org/10.1016/j.heliyon.2022.e11836.
23. Salazar, S.; Muñoz, Y.; Ospino, A. Analysis of geothermal energy as an alternative source for electricity in Colombia. **Geothermal Energy 2017**. *vol. 5, no. 27*, pp. 1-12. https://doi.org/10.1186/s40517-017-0084-x.
24. Trota, A.; Ferreira, P.; Ferreira-Gomes, L.; Cabral, J.; Kallberg, P. Power Production Estimates from Geothermal Resources by Means of Small-Size Compact Climeon Heat Power Converters: Case Studies from Portugal (Sete Cidades, Azores and Longroiva Spa, Mainland). **Energies 2019**. *vol. 12*, p. 2838. https://doi.org/10.3390/en12142838
25. Vieira, A.; Andrés, B.; Ferreira-Gomes, L.; Kallberg, P. Contribuição para a utilização de energia geotérmica no Brasil. In Engenharia de Construção Civil e Urbana, Ponta Grossa, PR, Atena Editora, 2019, pp. 149-165.
26. Zhu, J.; Zhu, M.; Shi, Q.; Wen, F.; Liu, L.; Dong, B.; Haroun, A.; Yang, Y.; Vachon, P.; Guo, X.; He, T.; Lee, C. Progress in TENG technology - A journey from energy harvesting to nanoenergy and

nanosystem. **EcoMat - Functional Materials for Green Energy and Environment 2020**. *vol. 2, no. e12058*, pp. 1-45. https://doi.org/10.1002/eom2.12058.

27. Mei, X.; Lu, B.; Yan, C.; Gu, J.; Ren, N.; Ren, Z.; Xing, D. The interplay of active energy harvesting and wastewater organic loading regulates fermentation products and microbiomes in microbial fuel cells. **Resources, Conservation and Recycling 2022**. *vol. 183*, p. 106366. https://doi.org/10.1016/j.resconrec.2022.106366
28. Stilwell, A.; Hoppock, D.; Webber, M. Energy Recovery from Wastewater Treatment Plants in the United States: A Case Study of the Energy-Water Nexus. **Sustainability 2010.** *vol. 2, no. 4*, pp. 945-962. https://doi.org/10.3390/su2040945
29. Santos, E.; Albuquerque, A.; Lisboa, I.; Murray, P.; Ermis, H. Economic Assessment of Energy Consumption in Wastewater Treatment Plants: Applicability of Alternative Nature-Based Technologies in Portugal. **Water 2022**. *vol. 14, no. 13*, p. 2042. https://doi.org/10.3390/w14132042.
30. Fan, S.; Li, A.; ter Heijne, A.; Buisman, C.; Chen, W.-S. Heat potential, generation, recovery and utilization from composting: A review. **Resources, Conservation and Recycling 2021**. *vol. 175*, p. 105850. https://doi.org/10.1016/j.resconrec.2021.105850.
31. Azizul Moqsud, M. Bioelectricity from Organic Solid Waste. Strategies of Sustainable Solid Waste Management. In Strategies of Sustainable Solid Waste Management, London, UK, IntechOpen, 2021.
32. Hanson, J.; Onnen, M.; Yeşiller, N.; Kopp, K. Heat energy potential of municipal solid waste landfills: Review of heat generation and assessment of vertical extraction systems. **Renewable and Sustainable Energy Reviews 2021**. *vol. 167, p. 112835*. https://doi.org/10.1016/j.rser.2022.112835.
33. Llácer-Iglesias, R.; López-Jiménez, P.; Pérez-Sánchez, M. Hydropower Technology for Sustainable Energy Generation in Wastewater Systems: Learning from the Experience. **Water 2021**. *vol. 13, no. 22,* p. 3259. https://doi.org/10.3390/w13223259.
34. Sarkar, P.; Sharma, B.; Malik, U. Energy generation from grey water in high raised buildings: The case of India. **Renewable Energy 2014.** *vol. 69,* pp. 284-289. https://doi.org/10.1016/j.renene.2014.03.046
35. Wang, S.; Liu, Q.; Li, J.; Wang, Z. Methane in wastewater treatment plants: status, characteristics, and bioconversion feasibility by methane oxidizing bacteria for high value-added chemicals production and wastewater treatment. **Water Research 2021**. *vol. 198*, p. 117122. https://doi.org/10.1016/j.watres.2021.117122.
36. Song, C.; Zhu, J.-J.; Willis, J.; Moore, D.; Zondlo, M.; Ren, Z. Methane Emissions from Municipal Wastewater Collection and Treatment Systems. **Environmental Science & Technology 2023.** *vol. 57, no. 6*, pp. 2248-2261. https://doi.org/10.1021/acs.est.2c04388.
37. Đurđević, D.; Balić, D.; Franković, B. Wastewater heat utilization through heat pumps: The case study of City of Rijeka. **Journal of Cleaner Production 2019.** *vol. 231*, pp. 207-213. https://doi.org/10.1016/j.jclepro.2019.05.235
38. Nagpal, H.; Spriet, J.; Murali, M.; McNabola, A. Heat Recovery from Wastewater—A Review of Available Resource. **Water 2021**. *vol. 13, no. 9,* p. 1274. https://doi.org/10.3390/w13091274
39. Zahmatkesh, S.; Amesho, K.; Sillanpaa, M.; Wang, C. Integration of renewable energy in wastewater treatment during COVID-19 pandemic: Challenges, opportunities, and progressive research trends. **Cleaner Chemical Engineering 2022**. *vol. 3*, p. 100036. https://doi.org/10.1016/j.clce.2022.100036.
40. Maktabifard, M.; Zaborowska, E.; Makinia, J. Achieving energy neutrality in wastewater treatment plants through energy savings and enhancing renewable energy production. **Reviews in Environmental Science and Bio/Technology 2018**. *vol. 17*, pp. 655-689. https://doi.org/10.1007/s11157-018-9478-x.
41. Kumar, S.; Yasasve, M.; Karthigadevi, G.; Aashabharathi, M.; Subbaiya, R.; Karmegam, K.; Govarthanan, M. Efficiency of microbial fuel cells in the treatment and energy recovery from food wastes: Trends and applications - A review. Chemosphere 2022. *vol. 287, no. Part 4*, p. 132439. https://doi.org/10.1016/j.chemosphere.2021.132439.
42. Serra, P.; Espírito-Santo, A.; Albuquerque, A. An experimental setup for energy efficiency evaluation of microbial fuel cells. In Proceedings of 2015 IEEE International Conference on Industrial Technology (ICIT), 2015. https://doi.org/10.1109/ICIT.2015.7125212.
43. Koffi, N.; Okabe, S. High electrical energy harvesting performance of an integrated microbial fuel cell and low voltage booster-rectifier system treating domestic wastewater. **Bioresource Technology 2022.** *vol. 359*, p. 127455. https://doi.org/10.1016/j.biortech.2022.127455.
44. Wang, Y.; Liu, X.; Chen, T.; Wang, H.; Zhu, C.; Yu, H.; Song, L.; Pan, X.; Mi, J.; Lee, C.; Xu, M. An underwater flag-like triboelectric nanogenerator for harvesting ocean current energy under extremely low velocity condition. **Nano Energy 2021**. *vol. 90*, p. 106503,. https://doi.org/10.1016/j.nanoen.2021.106503.
45. Yao, C.-J.; Zhang, H.-L., Zhang, Q. Recent Progress in Thermoelectric Materials Based on Conjugated Polymers. **Polymers 2019**. *vol. 11, no. 1*, p. 107. https://doi.org/10.3390/polym11010107.

46. Curie, J.; P. Curie, P. Développement par compression de l'électricité polaire dans les cristaux hémièdres à faces inclinées. **Bulletin de Minéralogie 1880**, *Vols. 3-4, pp. 90-93*.
47. Sezer, N.; Koç, M. A comprehensive review on the state-of-the-art of piezoelectric energy harvesting. **Nano Energy 2021**. *vol. 80*, p. 105567. https://doi.org/10.1016/j.nanoen.2020.105567.
48. Kargar, S.; Hao, G. An Atlas of Piezoelectric Energy Harvesters in Oceanic Applications. **Sensors 2022**. *vol. 22, no. 5*, p. 1949. https://doi.org/10.3390/s22051949.
49. Li, Z.; Zheng, Q.; Wang, Z.; Li, Z.; Nanogenerator-Based Self-Powered Sensors for Wearable and Implantable Electronics. **AAAS Research 2020**. p. 25, 2020. https://doi.org/10.34133/2020/8710686.
50. Afroz, A.; Romano, D.; Inglese, F.; Stefanini, C. Towards Bio-Hybrid Energy Harvesting in the Real-World: Pushing the Boundaries of Technologies and Strategies Using Bio-Electrochemical and Bio-Mechanical Processes. **Applied Science 2021.** *vol. 11, no. 5*, p. 2220, 2021. https://doi.org/10.3390/app11052220.
51. Junior, O.; Calderon, N.; Souza, S. Characterization of a thermoelectric generator (TEG) system for waste heat recovery. **Energies 2018.** *vol. 11, no. 6*, p. 1555. https://doi.org/10.3390/en11061555.
52. Chung, C.-K.; Huang, Y.-J.; Wang, T.; Lo, Y.-L. Fiber-Based Triboelectric Nanogenerator for Mechanical Energy Harvesting and Its Application to a Human–Machine Interface. **Sensors 2022.** *vol. 22, no. 24*, p. 9632. https://doi.org/10.3390/s22249632.
53. Chen, L.; Zhao, Y.; Shen, Y.; Wang, K.; Ma, P.; Wang, F.; Chen, C. 3D Stitching Double Weave Fabric-Based Elastic Triboelectric Nanogenerator for Energy Harvesting and Self- Powered Sensing. **Energies 2023**. *vol. 16*, p. 2284. https://doi.org/10.3390/en16052284.
54. Shi, S.; Jiang, Y.; Xu, Q.; Zhang, Y.; Zhang, J.; Li, J.; Xie, Y.; Cao, Z.-P. A self-powered triboelectric multi-information motion monitoring sensor and its application in wireless real-time control. **Nano Energy 2022.** *vol. 97*, p. 107150. https://doi.org/10.1016/j.nanoen.2022.107150.
55. Kahn, N.T.H. The Effect of Magnetic Field on Soli-Liquid Contact Electrification for Streaming Flow Energy Harvesting. **Energies 2023.** *vol. 16*, p. 4779. https://doi.org/10.3390/en16124779.
56. M. Aldamasy, I. Z.; Li, G.; Pascual, J.; Alharthi, F.; Abate, A.; Li, M. Challenges in tin perovskite solar cells. **Physical Chemistry Chemical Physics 2021**. *vol. 23*, pp. 23413-23427. https://doi.org/10.1039/D1CP02596A.
57. Ziegler, W. Radiant heating of airport aprons. Airport Operations and Maintenance Challenge, New York, USA, 2009.
58. Palosaari, J.; Juuti, J.; Jantunen, H. Piezoelectric Energy Harvesting from Rotational Motion to Power Industrial Maintenance Sensors. **Sensors 2022**. *vol. 22, no. 19*, p. 7449. https://doi.org/10.3390/s22197449.
59. Njiri, J.; Soffker, D. State-of-the-art in wind turbine control: Trends and challenges. **Renewable and Sustainable Energy Reviews 2016**. *vol. 60*, pp. 377-393. https://doi.org/10.1016/j.rser.2016.01.110.
60. GWEC. Global Wind Report 2018. GWEC, Brussels, Belgium, 2019.
61. Menezes, E.; Araújo, A. Bouchonneau da Silva, N. A review on wind turbine control and its associated methods. **Journal of Cleaner Production 2018.** *vol. 174*, pp. 945-953. https://doi.org/10.1016/j.jclepro.2017.10.297.
62. Soares-Ramos, E.; Oliveira-Assis, L.; Sarrias-Mena, R.; Fernández Ramírez, L. Current status and future trends of offshore wind power in Europe. **Energy 2020**. *vol. 202*, p. 117787. https://doi.org/10.1016/j.energy.2020.117787.
63. Lakc, J.; Pao, L.; Wright, A. Control of Wind Turbines: Past, Present, and Future. In Proceedings of 2009 American Control Conference, St. Louis, MO, USA, 2009. https://doi.org/10.1109/ACC.2009.5160590.
64. Kwak, S.; Yoon, H.-J.; Kim, S.-W. Textile-Based Triboelectric Nanogenerators for Self-Powered Wearable Electronics. **Advanced Functional Materials 2018**. *vol. 29, no. 2*, p. 1804533. https://doi.org/10.1002/adfm.201804533.
65. Cha, Y.; Chae, H.; Kim, H.; Walcott, H.; Peterson, S.; Porfiri, M. Energy harvesting from a piezoelectric biomimetic fish tail. **Renewable Energy 2016.** *vol. 86*, pp. 449-458. https://doi.org/10.1016/j.renene.2015.07.077.
66. Ri, X.; Zeng, Z.; Zhag, Y.; Li, Y.; Feng, H.; Huang, X.; Sha, Z. Design and experimental investigation of a self-tuning piezoelectric energy harvesting system for intelligent vehicle wheels. **IEEE: Transactions on Vehicular Technology 2020**. *vol. 69, no. 2*, pp. 1440-1451. https://doi.org/10.1109/TVT.2019.2959616.
67. Zhu, H.; Tang, T.; Yang, H.; Wang, J.; Song, J.; Peng, G. The State-of-the-Art Brief Review on Piezoelectric Energy Harvesting from Flow-Induced Vibration. **Hindawi Shock and Vibration 2021.** p. 19. https://doi.org/10.1155/2021/8861821.
68. Kasa, S.; Yao, L.; Bhada-Tata, P.; Van Woerden, F. What a waste 2.0: A global snapshot of solid waste management to 2050. pp. 1-295, 2018.

69. Lee, S.; Kim, S.; Pathak, A.; Tripathi, A.; Qiao, T.; Lee, Y.; Lee, H.; Woo, H Recent Progress in Organic Thermoelectric Materials and Devices. **Macromolecular Research 2020**. *vol. 28*, pp. 531-552. https://doi.org/10.1007/s13233-020-8116-y.
70. Toshima, N. Recent progress of organic and hybrid thermoelectric materials. **Synthetic Metals 2017**. *vol. 225*, pp. 3-21. https://doi.org/10.1016/j.synthmet.2016.12.017.
71. Fang, R.; Zhang, W.; Zhang, S.; Chen, W. The rising star in photovoltaics-perovskite solar cells: The past, present and future. **Science China Technological Series 2016.** *vol. 59*, pp. 989-1006. https://doi.org/10.1007/s11431-016-6056-8.
72. Ibrahim, I.; Otvos, T.; Gilmanova, A.; Tocca, E.; Ghanem, C.; Wanat, M. Intergovernmental Organizations. In International Energy Agency, The Netherlands: Kluwer Law International B. V., 2021.
73. Sen, S.; Al Nafi Khan, A.; Dutta, S.; Mortuza, A.; Sumaiya, U. Hydropower potentials in Bangladesh in context of current exploitation of energy sources: a comprehensive review. **International Journal of Energy and Water Resources 2022**. *vol. 6*, pp. 413-435. https://doi.org/10.1007/s42108-021-00176-8.
74. Erturk, A.; Inman, D. Piezoelectric Energy Harvesting, Chichester, UK: John Wiley & Sons, 2011.
75. Wu, N.; Bao, B.; Wang, Q. Review on engineering structural designs for efficient piezoelectric energy harvesting to obtain high power output. **Engineering Structures 2021**. *vol. 235*, p. 112068. https://doi.org/10.1016/j.engstruct.2021.112068.
76. T. Chen, T.; Song, W.-Z.; Zhang, M.; Sun, D.-J.; Zhan, D.-S.; Li, C.-L.; Cui, W.-Y.; Fan, T.-T.; Ramakrishna, S.; Long, Y.-Z. Acid and alkali-resistant fabric-based triboelectric nanogenerator for self-powered intelligent monitoring of protective clothing in highly corrosive environments. **RSC Advances 2023.** *vol. 13*, pp. 11697-11705. https://doi.org/10.1039/D3RA00212H.
77. Min, Z.; Hou, C.; Sui, G.; Shan, X.; Xie, T. Simulation and Experimental Study of a Piezoelectric Stack Energy Harvester for Railway Track Vibrations. **Micromachines 2023.** *vol. 14*, *no. 4*, p. 892. https://doi.org/10.3390/mi14040892.
78. Guo, H.; Li, T.; Cao, X.; Xiong, J.; Jie, Y.; Willander, M.; Cao, X.; Wang, N.; Wang, Z. Self-Sterilized Flexible Single-Electrode Triboelectric Nanogenerator for Energy Harvesting and Dynamic Force Sensing. **ACS Nano 2011.** *vol. 11*, *no.1*, pp. 856-864. https://doi.org/10.1021/acsnano.6b07389.
79. Laldjebaev, M.; Isaev, R.; Saukhimov, A. Renewable energy in Central Asia: An overview of potentials, deployment, outlook, and barriers. **Energy Reports 2021**. *vol. 7*, pp. 3125-3136. https://doi.org/10.1016/j.egyr.2021.05.014.
80. Lund, J.; Freeston, D.; Boyd, T. Direct utilization of geothermal energy 2010 worldwide review. **Geothermics 2011.** *vol. 40*, pp. 159-180. https://doi.org/10.1016/j.geothermics.2011.07.004.
81. Chandrasekharam, D.; Ranjith Pathegama, G. CO2 emissions from renewables: solar pv, hydrothermal and EGS sources. **Geomechanics and Geophysics for Geo-Energy and Geo-Resources 2021.** *vol. 6*, *no. 13*. https://doi.org/10.1007/s40948-019-00135-y.
82. Grill, G.; Lehner, B.; Thieme, M.; Geenen, B.; Tickner, D.; Antonelli, F.; Babu, S.; Borrelli, P.; Cheng, L.; Crochetiere, H.; Ehalt Macedo, H.; Filgueiras, R.; Goichot, M.; Higgins, J.; Hogan, Z.; Lip, B.; McClain, M.; Meng, J.; Mulligan, M. Mapping the world's free-flowing rivers. **Nature 2019.** *vol. 569*, pp. 217-239. https://doi.org/10.1038/s41586-019-1111-9.
83. NASA. NASA Scientific Visualization Studio. NASA, 3 May 2023. [Online]. Available: https://svs.gsfc.nasa.gov/3827. [Accessed 30 May 2023].
84. Rodrigues, J.; Segundo, D.; Junqueira, H.; Sabino, M.; Prince, R.; Al-Muhtadi, J.; Albuquerque, V. Enabling Technologies for the Internet of Health Things. **IEEE Access 2018**. *vol. 1*, *no. 1*, p. 99. https://doi.org/10.1109/ACCESS.2017.2789329.
85. Cisco. Cisco Annual Internet Report (2018–2023). Cisco, San José, California, USA, 25p., 2020.
86. Kim, M. Beyond-materials for sustainable power generation. In Proceedings of IEEE 34th International Conference on Micro Electromechanical Systems (MEMS), Virtual, 2021. https://doi.org/10.1109/MEMS51782.2021.9375418.
87. Abdugapbar, K.; Dautov, K.; Hashmi, M.; Nauryzbayev, G. Design of Performance Enhanced Metamaterial-Enabled Absorber for Low-Power IoT Networks. In Proceedings of International Conference on Internet of Things as a Service, 2022. https://doi.org/10.1007/978-3-031-37139-4_4.
88. Ramya, M.; Senthil Kumar, P. A review on recent advancements in bioenergy production using microbial fuel cells. **Chemosphere 2022.** *vol. 288*, p. 132512. https://doi.org/10.1016/j.chemosphere.2021.132512.
89. Wang, J.; Ren, X.; Zhu, Y.; Huang, J.; Liu, S. A Review of Recent Advances in Microbial Fuel Cells: Preparation, Operation, and Application. **BioTech 2022.** *vol. 11*, *no. 4*, p. 44. https://doi.org/10.3390/biotech11040044.
90. Rabaey, K.; Angenent, L.; Schroder, U.; Keller, J. Bioelectrochemical Systems, London, UK: IWA Publishing, 2010.

 doi:10.20944/preprints202311.0885.v1

91. Prathiba, S.; Kumar, P.; Vo, D.-V. Recent advancements in microbial fuel cells: A review on its electron transfer mechanisms, microbial community, types of substrates and design for bio-electrochemical treatment. **Chemosphere 2022.** *vol. 286,* p. 131856. https://doi.org/10.1016/j.chemosphere.2021.131856.