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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 in energy demands for human activities and to fulfill sustainable development goals. EH in geoenvironmental works and the surrounding soil and water environment includes a set of processes for capturing and accumulating energy from several sources considered wasted or unusable associated with soil dynamics; the 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 these 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 purposes.

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

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1. Introduction

Energy demands and environmental concerns have been witnessing a significant paradigm shift towards sustainable practices. At the same time, urbanization and world population growth have been demanding more energy to attend to society's necessities. In order to attend to both, a change in the political aspect is necessary 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 different sources are tapped to generate power while promoting eco-friendly solutions, also within the scope of the 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, unmanned aerial vehicles (UAVs) and robots can benefit from EH sources.

Furthermore, R. Perez and M. Perez [5] compared the world's reserves in TW/year for renewable and finite energies; for finite ones with 900 TW, coal has the highest quantities, followed by uranium, petroleum and natural gas representing still a great amount when paying attention to 16 TW/year world utilization. In addition, although finite resources have high energy-production potential, they are also generally associated with industrial processes and economical activities, implying carbon emissions and, thus, negatively affecting sustainability goals. Petroleum, for example, is the third-largest source of carbon emissions, due to the processes in the refineries, leading to the necessity of researching alternatives for finite resources or mitigating their impacts through enhancing energy efficiency and optimizing equipment and parameters [6]. Meanwhile, renewable energy sources are the focus when dealing with EH, and according to this same study [5], only solar has the potential of 23,000 TW/year, followed by the less exorbitant numbers associated in Figure 1 with wind, oceanic (OTEC), hydro, geothermal, gravitational (tides) and biomass sources, the last being promoted as a carbon-neutral and transitionary source diversifying energy sources [7,8]. In addition, renewables have the potential to increase in energy-production value in the following years, as their efficiency and methodology are improving through research and development.

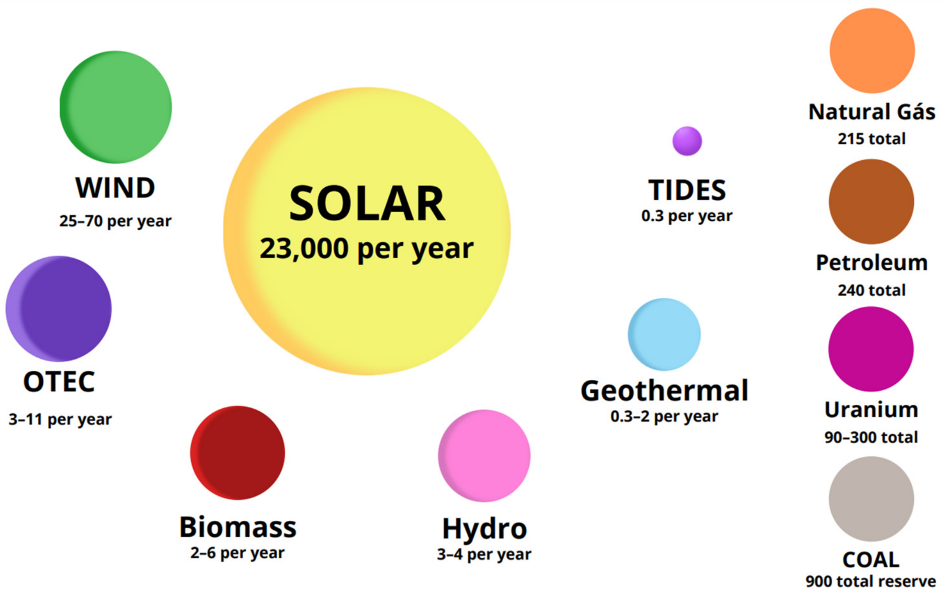

Figure 1. Renewable and finite energy reserves.

The EH of geoenvironmental engineering needs attention towards several types of works, infrastructures and potential processes. In summary, it needs analysis with regard to containment system management when observing landfilling and other storage facilities for hazardous and non-hazardous wastes; structures with contaminant transport control that measure the pollutants looking to avoid soil, surface and groundwater contamination, wastewater management that involves safe 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 factors emerge 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), when 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 that harnesses mechanical vibrations from traffic movement, groundwater flow or wind, converting them into electrical energy [14–17]. It is important to pay attention to its implementation in urban environments and demonstrate the potential of self-powered remote sensors and monitoring systems. In addition, thermoelectric generators (TEGs), for instance, have gained prominence for their ability to convert temperature gradients into electricity, finding applications in geothermal areas, where underground temperature variations can be tapped, producing 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, 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 novelty EH techniques that harness several industrial activities into opportunities for energy generation from biochemical mechanisms. 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 with relatively low-cost production [22]. Its process consists of using the using the earth's deeply complex physical and chemical processes for energy production through geothermal plants. Salazar et al. [23] analyzed this source for Colombia, stating that it not only provided a good alternative for EH, but also that if used to its full potential, it could represent 20% of Colombia's energy needs, instead of the current 1.65%; other authors have studied similar topics around the world [24,25], still needing further investigation. If applied on large a scale and for other countries, this sector could be responsible for largely contributing for mitigating the current energy crisis. In addition, Zhu et al. [26] called for a worldwide and current journey where EH processes that are used will be transformed using TENG towards nanoenergy and nanosystems; these 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 (MFCs) 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]. This work presents a critical review of the literature on harvesting energy from various earth and geoenvironmental works, which are the basis for infrastructures, discussing recent scientific advances, technical and economic aspects, sustainability of solutions and opportunities for use in cities, communities and territories.

2. Literature Review Methodology

A bibliometric analysis was carried out using the databases Google Scholar, Scopus, and Web of Science. The search was performed using Booleans 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, we searched AND "characteristic*, AND "production*", AND "quantit*", looking to evaluate worldwide numbers. The selected papers are listed in the references.

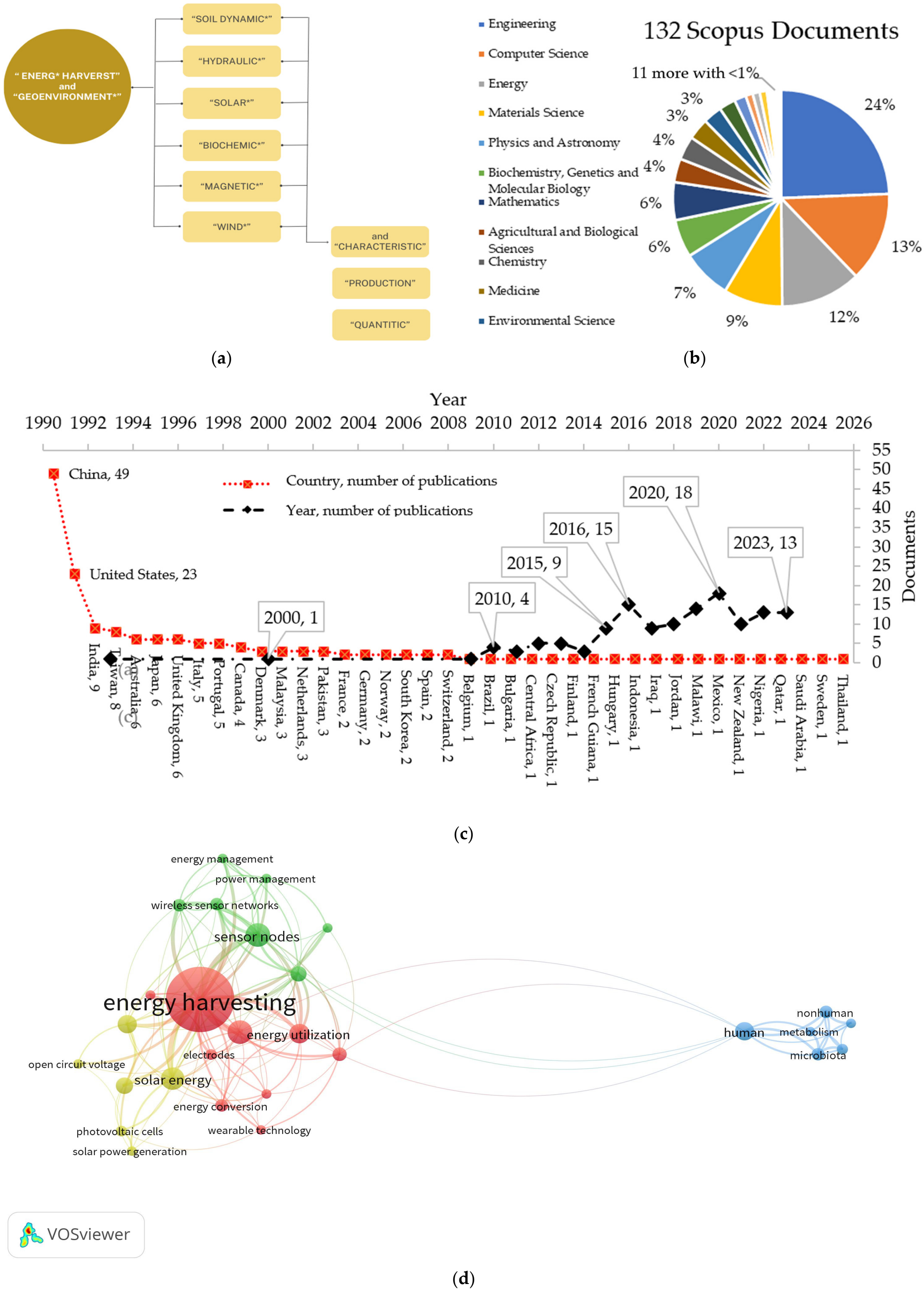

Figure 2. (**a**) Literature review methodology; (**b**) bibliometric analysis according to subject area; (**c**) according to the number of published documents in each year and countries; (**d**) according to keyword cooccurrence with VOSviewer tool.

Scopus' key-word co-occurrence when searching for "energ* harvest*" AND "geoenvironment*" resulted in 132 documents. The data were exported from the Scopus website and organized by subject areas in a pie chart (Figure 2b) according to the number of published documents following the years of publication and the countries of the studies (Figure 2c). VOSviewer software (online free software version 1.6.20) was used for generating a keyword co-occurrence map (Figure 2d).

The software Canva (online free resource accessed in https://www.canva.com/ (accessed on 25 December 2023)) was used to illustrate different EH processes as presented in Figure 3. In order not to infringe upon 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 shows the main subjects when analyzing EH from geoenvironmental works 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. The path used to determine EH sources included domains such as environmental science, engineering, medicine and agriculture. Figure 2c shows the increase in articles published during the past two decades with the black line, and the red line aligns 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's keyword co-occurrence helps in understanding EH: the strongest connections are around sensors, energy management and technology with red and green dots, followed by yellow with the main investments in solar energy. Less connected are the emerged technologies regarding biological applications.

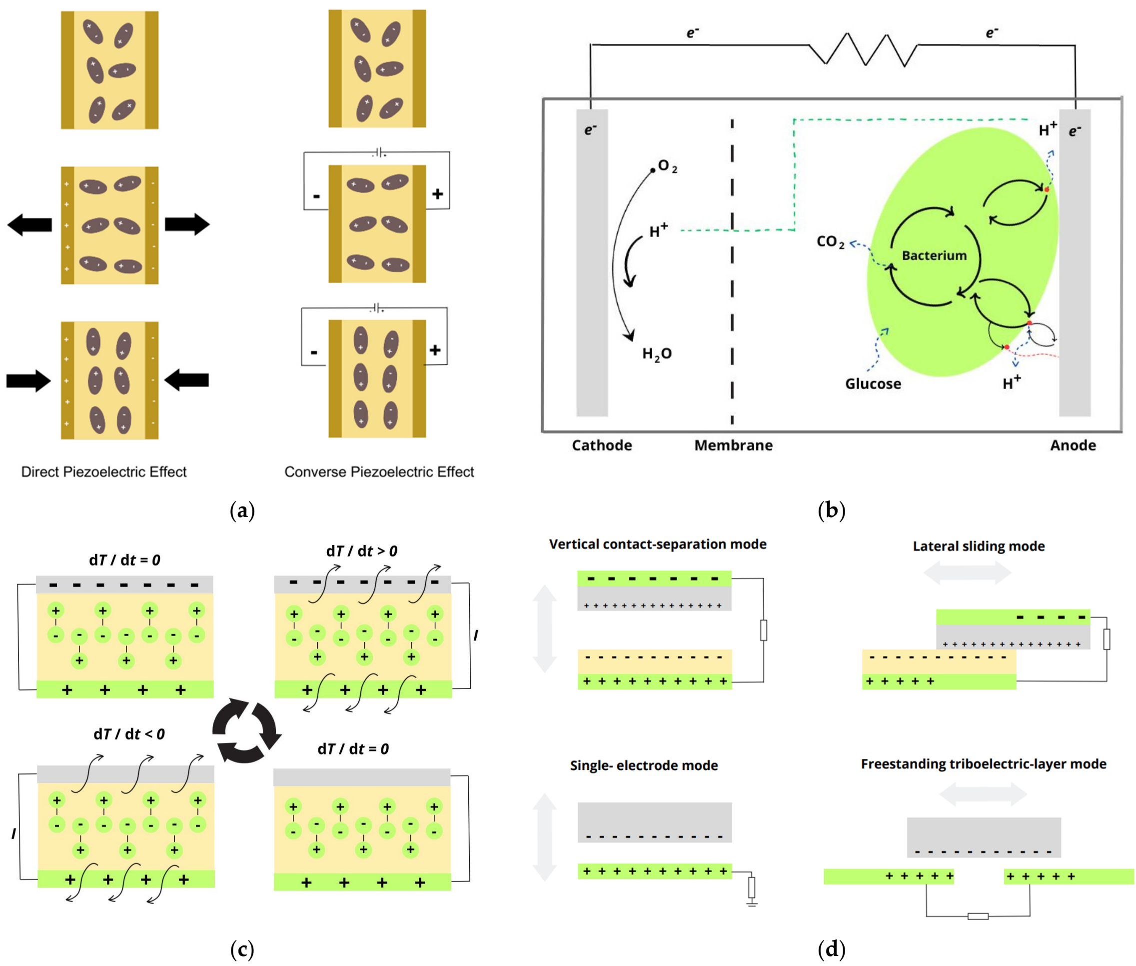

Figure 3. (**a**) Piezoelectric; (**b**) MFC; (**c**) Pyroelectric; (**d**) TENG principles.

Figure 4. EH opportunities in geoenvironmental engineering. (**a**) Connectivity status index (CSI) of world's river [44]. (**b**) Oceanic current flow [45]. (**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 [46].

3. Energy Harvesting Basics

Several authors [4,47,48] mentioned the importance of basic physics, electrical, electronic, fluid and solid mechanics, hydraulics, and soil mechanics theories to analyze opportunities of EH in geoenvironmental engineering, as well as understand some theorems, laws and equations such as:

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

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

3.1. Piezoelectricity

First introduced by Pierre and Jaques Curie [49], a piezoelectric material forms dipole moments, called the direct piezoelectric effect, which generates energy due to force applied; this force can be from several sources [50]. 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). The 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 [51]. The piezoelectric effect utilizes vibrating mass connected to a piezoelectric material and to a circuit with diodes, capacitors and resistors, generating energy. The involved materials can be varied types, such as bio-based, organic, inorganic and composites, such as ferroelectric ceramic, polyvinyde fluoride, macro-fiber composites, among others [51]. In addition, they are usually supported by flexible films or biofilms that are made of polymers such as polyimide (PI) or polyethylene terephthalate (PET) and are encapsulated in biocompatible materials such as polydimethylsiloxane (PDMS) and polytetrafluoroethylene (PTFE) [50–52]. Fuel cells (FCs) are based on a piezoelectric effect, having 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 organic matter and electrons are generated, and flow through a cation exchange membrane develops a potential difference between electrodes (Figure 3b) [53]. EBFCs use similar mechanisms to MFCs and are classified into in vitro, plant, animal or human-powered, the last one being wearable as contact lenses and patches [53].

3.2. Pyroelectricity

The pyroelectric effect can be explained as the spontaneous polarization of some crystalline structures when variation in 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 decreases; the opposite also follows, as the crystalline structure is connected to an external circuit, and the pyroelectric current is generated once atoms or ions move in response to increasing temperature, thus altering the balance of electrical charges in the material [52]. The effectiveness of thermoelectric materials is based on optimizing the Seebeck coefficient, electrical and thermal conductivity, and stability [48,54]. 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 an electrical signal that can trigger systems. Alarms are one potential application, as well as small energy-generating devices, such as self-contained sensors, watches and even 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 the 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 converts mechanical energy into electrical energy [53]. TENGs can perform mainly in four modes (Figure 3d): the vertical contact-separated mode, where two layers in contact are charged with the same amount of opposite charge; the lateral sliding mode, with similar behavior to the vertical contact-separated mode, but one layer changes from contact to separation, and the other layer becomes a pole sliding on the first one; the single-electrode mode, where it is connected to an external circuit following single-electrode theory; and the freestanding layer mode, optimizing the previous one using the induced potential of both electrodes [52]. 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 [55]. As for smart fabrics, these have been shown to have excellent performance, since textile-based TENG is qualified as having usability, low cost, flexibility, lightness and the ability to collect energy and self-powered detection [56]. 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 [57]. 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 [58].

As it is an energy source that 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 overcome, such as the size and flexibility of triboelectric generators in wearable devices.

4. Opportunities for Energy Harvesting

Table 1 summarizes the information on EH techniques and bases for application in several engineering applications found in the literature.

Table 1. Energy harvesting opportunities in geoenvironmental engineering.

Source	EH Techniques	EH Basics	Recent Investigation	Opportunities
Solar [12,13,48,59,60]	Photovoltaics Thermal Solar cells	Piezoelectricity TENG	AI compatibility Stable crystalline structure New materials Photo-reactors	Construction in general
Wind [61–66]	Wind turbines	Piezoelectricity	Smart sensors AI compatibility	Offshore platforms Construction in general
Hydraulic [14,47,51]	Devices for oceanic and river flow	Piezoelectricity TENG	Smart sensors New materials Durability	Offshore platforms Canals Water distribution systems
	Water turbines	Piezoelectricity	Smart sensors AI compatibility Power storage	Water storage facilities Waste containment
Biochemical [7–9,20,21,28–31,35,41,43,53–57,67,68]	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 [2,15–19,22,69,70]	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 promising clean energy production sources, mainly in the form of solar energy [13]. As the world seeks to transition into cleaner energy options, EH from the sun has a great potential for 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 [71]; moreover, numerous heating processes, from industrial operations to residential heating, release significant thermal energy, exposing their potential to be converted 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 the United States, looking to harness solar energy potential. Figure 4d,e illustrate the main light and heat sources for EH.

When sunlight and heat reach the semiconductor of a solar cell, free electrons are forced to flow, creating electrical current [2]. To catalyze this latent energy, notably, thermoelectric generators (TEGs) are the key player in harvesting thermal energy, as they can convert temperature gradients into electricity, enhancing energy conversion efficiency [48,72,73]. Organic, inorganic and hybrid thermoelectric materials have been developed with polymers, metals or combining them, respectively, and should be used to replace batteries in near future [73].

A photo-voltaic device operation can be explained in a simplified way as the low bandgap from light resulting in a shift of the electrons to the conduction band from the valence band; these electrons diffuse in the transport layer and are collected in the cathode and anode [59]. Organometal halides are used as light harvesters in solar cells, which are composed of 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 [74] in addition to cost advantages [59,74] and seem to emerge from and surpass older technologies like dye-sensitized solar cells, crystalline solar cells, cadmium telluride and copper indium gallium selenide.

The solar EH system can be hybrid, using photovoltaic and thermal means to optimize light and heat; in addition, several models, algorithmic and simulation software can be used in such a 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 that uses heat is geothermal, utilizing the Earth's naturally stored energy sources, like hot ground water or snow melting. The authors of [2] highlighted the utilization of geothermal EH techniques within heat pumps combined with permeable pavement, which had the benefit of improving stormwater quality and heating systems in New York [60] based on a hydronic radiant system; the heat source was from geothermal heat pumps. The authors of [47] performed simulations to develop low-enthalpy geothermal reservoirs and found as a challenge the fact that shale facies can improve a reservoir's lifetime.

Light and heat sources still have high costs, although they have high energy output potential and are renewable, as they require 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 for demands while minimizing environmental impacts.

4.2. Wind

Wind sources utilizing the kinetic energy of moving air to generate electricity have stood as a sustainable source of power for the past decades; thus, air masses produce clean energy [10,62]. Governments and industries seek to reduce fossil fuel consumption and mitigate climate change; thus, 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 [63], showing the capacity to provide for millions of households and industries powered by it, effectively reducing environmental impact. In Europe, UK and Germany lead with around 80% [65], indicating the influence of economic power. However, during energetic transition, some business-like offshore platforms of oil extraction could explore wind power, and government targets can help in achieving good results even for third-world or in-development countries. On-shore and off-shore wind farms have improved economic and implementation aspects mostly due to advancements in turbine technologies and foundation structures [65]. Figure 4h exposes the main wind sources for EH.

Remarkable advancements in the field are driven by innovations in wind turbine technology [62,64], 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 control algorithm is an investigation line [10,62,64]. Furthermore, offshore wind energy has expanded the horizons of wind energy harvesting, while benefiting from stronger and more consistent winds, enabling higher energy production, emphasizing its role in meeting renewable energy targets [65,66]. In the sense of meteorological fields, TENGs have been used to convert mechanical energy into electricity from wind speed and direction using wind cups and turbines, besides flutter- and flag-type sensors [4]. In addition, when attached to hydropower, TENG can be applied in meteoric stations due to rain sensoring using its vibration for EH. The author of [4] highlighted three main fields that can collaborate and utilize TENG, which are biological monitoring and learning, the general industry for aircraft and UAV, and academia in terms of vortex and turbulence state applications. Future applications comprise micro- to macro-arrangement, self-powered, nanoscale, effectiveness and less-costly material investigations.

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 its kinetic energy; wind becomes a driving force in shaping a more sustainable and resilient future.

4.3. Water

EH from hydraulic sources, such as the flowing of 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 the kinetic energy of flowing rivers or ocean currents, as well as hydraulic energy, which offers a continuous and abundant supply of energy that can be tapped for various applications. To illustrate the magnitude of this potential, the IEA reported that hydropower accounted for approximately 16% of the world's total electricity generation in 2020 [75], underscoring the substantial contribution to global energy supply. The authors of [10] called attention to the fact that only in China did hydropower increased by 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 and 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.

Hydropower is the main source of power over the world [76], but it is 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 theme regarding dams and reservoirs, as the environmental impacts caused by them harms the population in their 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 these impacts emerges. Governments are exploring areas in improving technology for site investigation, development of water flood plans and sensoring water flow and aquatic biosystems attached to societal and rural electric perspective [76]. Still, ref. [76] 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.

Besides dams and reservoirs, a prominent example is the development of underwater EH systems that harness the kinetic energy from rivers and oceans [14,51,70]; moreover, ref. [47] presents a comprehensive analysis of an underwater EH prototype, demonstrating its viability for providing power for remote offshore installations. In addition, oceanic EH offers a significant potential for energy generation using micro-hydropower systems that harness energy from small to large scales [76].

The fluid dynamics field has used TENGs technology over the past decades, from meteorological, water wave, pipe fluid and bridge over water sensor technologies, and ref. [4] indicates 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]. Along with water currents, [51] summarized oceanic energy from wave motion according to its periodical classification and EH potential as the capillary, ultra-gravity, gravity, infra-gravity, long-period, ordinary tidal and trans-tidal wave types, besides EH from piezoelectric materials, which can be output from wave impacts on structures placed in water. The authors of [47] used TENG to develop a flag-like EH device to explore ocean current energy under extremely low-velocity conditions and presented a cost-effective and accessible powering sensor that can be allied with AI and IoT.

4.4. Soil

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. This seems to guarantee potential, considering the perspective that worldwide construction activities alone can generate trillions of vibrations annually due to already constructed sites [9], challenging the investigation to convert these vibrations into usable energy.

Another notable approach is the utilization of piezoelectric materials to convert mechanical vibrations from machinery into electricity [61,77–81], being able to use this potential from machinery vibration. 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 [82]. Thus, EH from machinery on soil 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 todays and future energy needs. Figure 4f,g show the main vibration sources for EH.

The theme of EH within soil dynamics 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 [69,83]. Geotechnical engineering prospects are deep foundations because of the load needed for testing and installation, earthworks compaction procedures and excavations in general when machines can harvest their own energy from field work [15]. Furthermore, advancements in nanotechnology unlock new possibilities for EH from soil dynamics. Therefore, nanogenerators can convert mechanical energy at the nanoscale into electricity, holding immense promise for capturing subtle soil vibrations tailored for soil environments [4,84]. It is 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, and 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.

EH from soil dynamics is an emerging field that explores ways to harness energy from various soil-related processes and phenomena. While it is 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 that can convert mechanical strain or vibrations into electrical energy, embedding piezoelectric sensors or materials into the ground, such as beneath roadways or near heavy machinery, which can capture energy from the vibrations caused by vehicles or equipment passing over the soil. In addition, 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.

Geothermal energy can be harvested by exploiting temperature differences between the soil–water and underground–surface. In the ever-evolving quest for sustainable energy solutions, geothermal energy has risen as a significant contender that 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]. 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].

EH 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 their resource bases to enhanced geothermal systems unlocking deeper and hotter reservoirs; these advancements position geothermal energy as a cornerstone of the renewable energy transition.

4.5. Industry Machinery

The abovementioned machinery vibrations can be EH sources and 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 the industrial sector accounts for around 37% of global final energy consumption [11], being a substantial energy demander; these sustainable measurements indicate the potential of EH techniques. Moreover, as forecasts of machine failure, issues and efficiency can help save time, money and even lives [61], self-powered sensors monitoring machinery behavior is a promising field for the area. Palosaari et al. [61] created a prototype with piezoelectric ceramic and steel parts clamped by a carbon-fiber nylon to harvest energy from rotation frequency motors at the laboratorial scale. The authors of [61] concluded that many factors can impact EH processes like the piezoelectrical material and the ratios of its thickness, length and width, besides mass, and the highest results were around 580 µW for the 7.4 Hz frequency; this paves the path to a more sustainable and self-sufficient machine industry where companies should develop machines for geoenvironmental engineering or any purpose to adapt and use the energy from vibration. Agricultural machinery and equipment create vibrations in the soil; thus, EH 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 particle movement due to factors like wind or water flow can be captured due to new mechanisms, such as piezoelectric generators or electromagnetic devices.

4.6. Mobility and Transports

Highways and railways are the most common geotechnical structures for transportation of people and cargo; these infrastructures have been increasing in importance to attend global exchange and globalization demands [16]. Because of the heavy impacts of automobiles and trains, a great amount of vibration is absorbed by roads and railways, providing a potential to harvest this into energy, creating self-powering vehicles or converting the energy into electrical power [83]. The reapplication of harvested energy in transportation industry is discussed within powering traffic lights, monitoring roads' materials health, besides building's health of the stations [50]. A simulation was conducted by [83] using piezoelectric EH for railway track vibrations verifying load resistance, pre-stress and load frequency impacts; an EH beam was applied to absorb train vibration and concluded that for a lower frequency than 6 Hz, there is no efficiency in energy capture, but for higher frequency, the results have great performance; in addition, pre-stress had no significant impact, providing a path to actual environmental applications. Another study [69] designed an EH system for vehicle wheels due to centrifugal force in rotational motion and concluded that it can be used to establish a wireless self-sufficient and intelligent vehicle wheel.

4.7. Smart Homes

Another investigation field is the utilization of vibrations from buildings for EH: not the ones from the building itself due to wind or soil movements, but instead those from daily sources like kitchen machines, blenders, clothes dryers, microwaves, vents, floor vibrations due to foot traffic, washing machines and refrigerators, among others [9]. Smart homes (Figure 4i) seem to have a good perspective of EH when devices based on heat, ventilation and HVAC mechanisms can power electronic devices [50]. At the nexus of physics and engineering, electromagnetic sources have garnered significant attention for their 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 those induced by electromagnetic waves. In addition, nanogenerators can be integrated into devices such as wireless sensors and communication devices, developing their potential for powering autonomous electronics [52,67]. Electromagnetic sources hold transformative potential as a clean and growing demand for energy solution, tapping into the ambient electromagnetic radiation. This has the potential to become a practical, and almost autonomous, pathway to meet energy needs while aligning with sustainability goals using communication technologies as the supplier.

4.8. Biochemical and Biomechanics

EH from biochemical sources is still an unconventional, relatively new and promising field that has attracted attention for its potential to extract renewable energy from biological and chemical processes. Biologically, these sources span microbial activities to biochemical reactions occurring within living organisms and ecosystems, and when expected chemical reactions occur in industries [53]. These natural processes offer an innovative pathway to meet energy demands while reducing the carbon footprint, pushing toward sustainable opportunities, meanwhile the World Bank reported around 2 billion tons of organic waste generated globally each year [71]. This vast amount organic waste can be used to generate energy through biochemical EH technologies. Figure 4k,l show the main biochemical mechanisms sources for EH.

Significant advancements have been observed; one noteworthy one is the use of microbial fuel cells (MFCs) to convert organic matter into electricity through the 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, as these systems enable the direct conversion of energy from biological processes into electrical power [53,90], using living animals and human daily activities and convert them into electrical energy. Additionally, a new popular field of investigation is that of enzyme-based fuel cells (EBFCs), where synthetic enzymes are immobilized on the electrode and generate energy through glucose oxidation [53]. Afroz et al. [53] classified MFCs as lab or in situ scale, differing the in situ as consisting of docked aquatics in open or close waters, or floating ones. The terrestrial MFCs are structurally single-chambered or double-chambered, as well as up-flow, stacked, tubular and/or forced-flow [88]. Several microorganisms such as proteobacteria, microalgae, yeast and fungi species have been studied [53]. The main materials for anodes are carbon or metal-based anodes and can be basic, natural or synthetic or composite with graphene or graphite, in addition to those modified with conductive polymer coatings or surface treatment. Cathodes can be submerged with or without treatment, air cathodes or bio-cathodes when using plants or algae; however, electrodes are an issue over efficiency and economic viability [53] 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 the anode chamber to the surface, scaling up for micro and nano applications, oxygen suppliers and the 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 on enhancing production within engineered techniques using low-cost substrates. Additionally, 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, plant roots can generate small electric potentials due to ion transport processes, creating the potential for plant-based EH. Research is ongoing to develop technologies that can tap into this potential, although the energy output is currently relatively low. Biomechanical EH mechanisms are biocompatible energy sources using wearable electronics for humans [52], plants or animals, mainly composed of piezoelectric, electromagnetic, electrostatic and triboelectric mechanisms. Investigation of the compatibility of these micro-components with human body, animal and plant applications include flapping wings, human joint movement, heart motion, and aquatic animal flippers. Among others, refs. [50,53] highlighted a study [68] where sensor tags were incorporated internally and externally in fishes to monitor and be self-powered by the 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 [50].

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 for the field.

5. Integrated Use of Several Alternative Energy Sources in Portugal

Several countries in the south of Europe, such Portugal, still have a relevant percentage of green energy production from hydro, solar and wind sources, which are good examples of sustainable energy generation [92–95]. The favorable geography and environmental conditions of Portugal influence the types of HE opportunities that are most viable and relevant. For instance, solar and wind energy might be more emphasized in earthworks located in regions with suitable conditions where more investments could reach full decarbonization [96]. The EU has been increasing its investment in research and innovation for the further development of projects that could contribute to more sustainable earthworks infrastructures. For example, Portugal and Spain can join knowledge, innovation, energy plans and infrastructure for setting up EH plants throughout the Iberic Peninsula [95]. Therefore, there are also opportunities in interconnecting systems between countries that could be advantageous to lower costs and enhance the potential of these systems to produce energy for exportation.

In this context, Figure 5 illustrates the share of renewable energy incorporated in the European Union's electricity sector in 2021, according to Eurostat [96]. Portugal stands out as the fourth EU country with the highest contribution of renewable energy to electrical generation, reaching 58.4%. This performance is driven mainly by water and wind sources, which represent the largest proportion of this production (Figure 6). As for electricity generated from renewable energy sources (RESs), there was an increase in 2021, returning to the levels recorded in 2016, after the 54.9% drop in water production in 2017 due to the drought. Between 2016 and 2021, photovoltaic, biomass and wind technologies contributed to an increase of 9.2% in electrical generation through RESs.

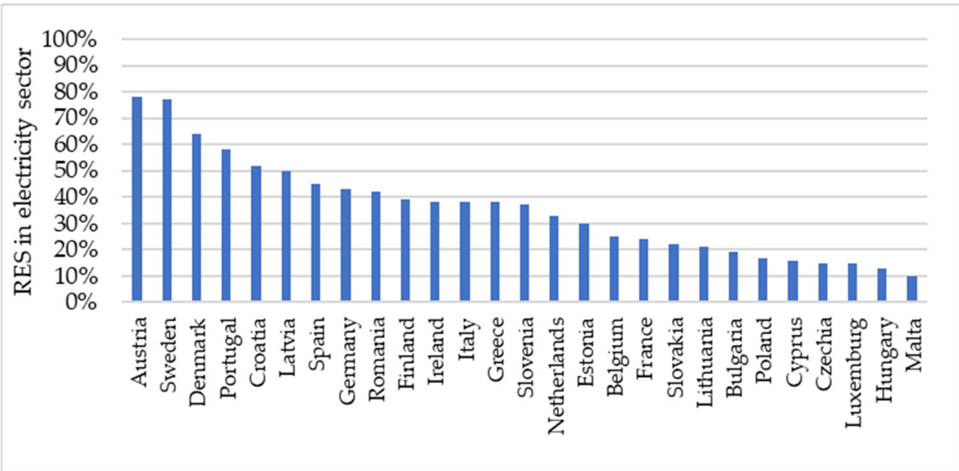

Figure 5. Percentage of incorporation of renewables in the electricity sector, in the EU 2021.

Portugal has actively participated in European initiatives, aligning itself with the EU's objectives to promote energy transition and achieve clean energy and SDGs. Its government has committed, since 2016, to achieving neutral emissions by 2050, in line with the Paris Agreement [97]. The Roadmap for Carbon Neutrality 2050 (RNC 2050) [98] outlines strategies to decarbonize the economy, reducing greenhouse gas emissions by 85% to 90% by 2050. This transition requires radical changes in electricity production and sources and changes in urban mobility, promoting circular models and boosting carbon sequestration capacity. By 2030, the aim is to reduce emissions by 45% to 55%, exceeding the previous target by 5 to 15 percentage points. These ambitious goals aim to align with the Paris Agreement and address climate challenges with the development of the National Energy and Climate Plan aligned with RNC 2050 [99–101].

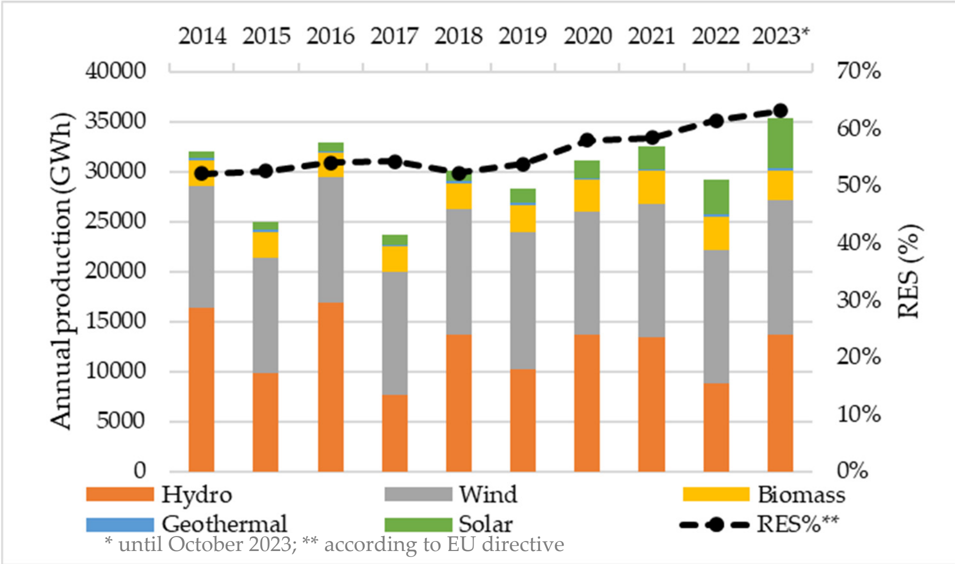

Figure 6. Annual production of electrical energy based on RESs, in Portugal.

In addition to comprehensive policies, individual choices towards the use of renewable energy play a crucial role in promoting global sustainability. On a personal level, conscious decisions and everyday practices have a positive impact on the environment and the promotion of clean energy. The adoption of energy efficiency measures at home, such as the preference for LED lamps, efficient electrical devices, adequate insulation, and the installation of solar panels, contributes to reducing electricity consumption, encouraging the use of sustainable sources. The Portuguese government complements these actions by offering tax incentives to both individuals and companies that invest in renewable energy systems, such as the installation of solar panels and heat pumps. These benefits include tax reductions and deductions, encouraging investments in clean technologies. Additionally, subsidized tariff programs for renewable energy production encourage decentralized generation, offering more advantageous tariffs to domestic producers who contribute surplus electricity to the electrical grid. These combined initiatives reflect a comprehensive approach to boosting the adoption of renewable energy in Portugal.

6. Final Analysis

This review analyzes and compares various EH options, highlighting emerging trends and technological developments in an accessible and informative manner, which can be obtained in earthworks infrastructures. This work explores the diversification of the energy matrix, placing emphasis on sources such as solar, wind, water, biochemical and hydroelectric power, showcasing the environmental and economic benefits of these alternatives.

Society growth impacts energy production in terms of supplying several activities in cities, communities and territories. The Agenda 2030 [3] emerges as a program to comply with for more sustainable, cleaner and efficient development. Based on the review of current EH methodologies, the need to invest in promising research and the urgency of ensuring the sustainability of geoenvironmental projects, these renewable energy sources can be complements to combat the energy crisis associated with classic carbon-based energy sources. It is therefore necessary to leverage innovation and invest in new technologies to generate energy in infrastructures that use land, which can additionally lead to reduced costs for the user and the mitigation of environmental impacts. This research also explores cost-effective methods for EH associated with geoenvironmental engineering infrastructures involving several sources such as water, wastewater, wastes, soils and vibrations. The opportunities identified can lead to the development of innovations and encourage researchers to invest in environmentally sustainable technologies and solutions, bringing together geotechnical, civil, environmental and energy engineering skills [92,93]. The added value of this review is also to show the possibility of increasing interdisciplinary collaborations for complex challenges. Practical applications and case studies were identified where EH was implemented to reduce dependence on fossil energy.

Geoenvironmental, geotechnical and sanitary engineering can produce negative environmental impacts, although they bring many social and economic gains. The integration of EH technologies in earthworks associated with roads, landfills, wastewater treatment or storage ponds, mining explorations and even buildings can contribute to minimizing impacts by reducing energy consumption based on carbon [94]. The main bibliometric databases show the multiplicity of opportunities with identifying source-specific work (e.g., use of MFC in wastewater treatment or to capture kinetic energy associated with transport movement or pavement vibration) or on the construction and optimization of energy measurement, capture and storage equipment. Some works focus on the economic aspects associated with the cost of this energy for the user, compared to the cost of classical energy sources. It is also necessary to optimize and streamline procedures. The microsystems and medium systems that involve obtaining solar, hydro or wind energy are already optimized and can represent competitive costs. However, energy originating from vibrations, biochemistry or biomechanics still needs research and innovation to be competitive. However, another great advantage of earthworks is the possibility of managing the obtaining of energy from diverse sources, according to the use of infrastructure and even climatological conditions that make obtaining energy in some infrastructures difficult and expensive.

Discussions around the challenges and barriers to widespread EH can be highlighted according to technical challenges, economic considerations, and the need for regulatory support. Energy and environmental, and from other fields, engineers, scientists, practitioners, industries, and politics should be involved for an interdisciplinary collaboration to develop governmental policies and regulations within education over the topic. The educational promotion and training programs to develop a skilled group play an important role; this can involve academic programs, workshops and professional involvement to address energy challenges. Supportive policies at the governmental and institutional levels that incentivize the development and adoption of EH technologies and cleaner production must be inserted in these plans, such as tax incentives, research grants and subsidies. Other measures should be public awareness at the individual and community levels using multimedia industry techniques and the establishing of innovation hubs and incubators that bring together researchers, entrepreneurs and industry experts impacting the scalability and affordability of development projects.

Thus, the innovative pathway to solve the EH crisis can be related to continuous research and development integrating countries and multidisciplinary teams. Moreover, emerging technologies such as AI and IoT can monitor in real time and predict behavior, increasing the efficiency of the current methods and/or associating different energy harvesting systems with mitigating environmental impacts when transitioning from non-renewable to renewable energy [102–104].

7. Conclusions

This review analyzed several topics associated with the production, capture, storage and application of EH within the scope of geo-environmental engineering works, leaving the feeling that there are alternative sources of energy that can be used, contributing to the sustainability of infrastructures and the reduction of environmental impacts. This work seeks to show alternative solutions to combat the energy crisis associated with fossil energy sources based on research and case studies published in three bibliometric databases. The technologies already developed to capture energy associated with wind, water, sun, vibrations, soil degradation and waste or wastewater are based on principles of physics, fluid and solid mechanics, soils, electrical and electronic engineering and biochemical mechanisms. Considering population growth, the demand for energy to develop activities in cities, communities and territories and the need to reduce carbon emissions, greater and faster development of methodologies and technologies (e.g., sensors or nanogenerators) is necessary to make these sources competitive in relation to classical energy sources. It is also necessary to increase investments and changes in legislation, opposing regulations that would delay the advancement of these alternative energy sources.

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