Energy Harvesting Opportunities in Geoenvironmental Engineering

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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.

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, 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].

Furthermore, R. Perez and M. Perez [2] 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 [3].

The energy harvesting (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 [4]. 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 [5].

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 [6][7][8][9]. 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 [10][11].

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

[12]. 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 [13][14].

EH can also be obtained from environmental sanitation works such as biological wastewater treatment processes [15][16][17] (e.g., activated sludge, algae technology, constructed wetlands and lagoons) and solid waste composting [18][19][20]. Wastewater and water flow can also be harnessed to generate hydroelectric power [21][22] 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 [19] and anaerobic digestion reactors [23][24] 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 [25][26]. Environmental sanitation facilities located in open areas in windy regions may be suitable for wind turbines [27][28]. Microbial fuel cells (MFCs) can be used to capture electrons from organic matter in solid waste [29] or wastewater [30][31].

2. Energy Harvesting Basics

Several authors [32][33][34] 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 the 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 [15].

2.1. Piezoelectricity

First introduced by Pierre and Jaques Curie [35], 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 [36]. 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. 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 [37]. 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 [37].

2.2. 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. 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 [38]. The effectiveness of thermoelectric materials is based on optimizing the Seebeck coefficient, electrical and thermal conductivity, and stability [34][39]. 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.

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 [40]。

3. Opportunities for Energy Harvesting

3.1. 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 [41]. 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 [42]; moreover, numerous heating processes, from industrial operations to residential heating, release significant thermal energy, exposing their potential to be converted to usable energy.

When sunlight and heat reach the semiconductor of a solar cell, free electrons are forced to flow, creating electrical current [12]. 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 [34][43][44]. 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 [44].

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 [45]. 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 [46] in addition to cost advantages [45][46] 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 [6][7][8][41]. 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.

3.2. 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 [5][47]. 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 [48], 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% [49], 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 [49].

Remarkable advancements in the field are driven by innovations in wind turbine technology [47][50], 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 [5][47][50]. 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 [49][51]. 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 [32].

3.3. 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 [52], underscoring the substantial contribution to global energy supply.

Hydropower is the main source of power over the world [53], 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 [53].

Besides dams and reservoirs, a prominent example is the development of underwater EH systems that harness the kinetic energy from rivers and oceans [6][37][54]; moreover, ref. [33] 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 [53].

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. [32] 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 [32]. Along with water currents, [37] 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 [33] 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.

3.4. 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 [4], 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 [55][56][57][58][59][60], 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 [61]. Thus, EH from machinery on soil sources stands as a transformative solution at the intersection of energy demand, technological innovation and environmental stewardship.

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 [62][63]. 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 [7].

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.

3.5. 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 [64], 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 [55], self-powered sensors monitoring machinery behavior is a promising field for the area.

3.6. 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 [8]. 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 [63]. 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 [36]. A simulation was conducted by [63] 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.

3.7. 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 [4]. Smart homes seem to have a good perspective of EH when devices based on heat, ventilation and HVAC mechanisms can power electronic devices [36]. 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 [65], 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 [66][67].

3.8. 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 [40]. 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 [42]. This vast amount organic waste can be used to generate energy through biochemical EH technologies.

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 [68][69]. 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 [40][70], 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 [40].

4. 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 [71][72][73][74]. 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 [75]. 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.

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 [76]. The Roadmap for Carbon Neutrality 2050 (RNC 2050) [77] 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 [78][79][80].

References

1. Ekonomou, G.; Menegaki, A. China in the Renewable Energy Era: What has Been Done and What Remains to be Done. Energies 2023, 16, 6696.
2. Perez, R.; Perez, M. A fundamental look at energy reserves for the planet. IEA SHS Sol. Update 2009, 50, 2.
3. 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, 16, 6527.
4. Mo, C.; Davidson, J. Energy harvesting technologies for structural health monitoring applications. In Proceedings of 2013 IEEE Conference on Technologies for Sustainability (Sustech), Portland, OR, USA, 1–2 August 2013.

5. Balakrishnan, P.; Shabbir, M.; Siddiqi, A.; Wang, X. Current status and future prospects of renewable energy: A case study. Energy Sources Part A Recovery Util. Environ. Eff. 2019, 42, 2698–2703.
6. 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, 11–13 April 2011.
7. Trivedi, A.; Shukla, S. Testing and Technology for Load Carrying Capacity of Deep Foundations. In Proceedings of 2019 International Symposium, Delhi, India, 5–6 December 2019.
8. Newston, C.; Halter, S.; Hassan, M. Tran-SET 2020. In Proceedings of Tran-SET Conference 2020, Albuquerque, NM, USA, 1–2 September 2020.
9. Zheng, X.; He, L.; Wang, S.; Liu, X.; Liu, R. A review of piezoelectric energy harvesters for harvesting wind energy. Sens. Actuators A Phys. 2023, 352, 114190.
10. Chandrasekharam, D.; Bundschuh, J. Low Enthalpy Geothermal Resources for Power Generation; CRC Press: Bombay, India, 2008.
11. 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. Renew. Energy 2021, 179, 641–651.
12. Wang, H.; Jasim, A.; Chen, X. Energy harvesting technologies in roadway and bridge for different applications—A comprehensive review. Appl. Energy 2018, 212, 1083–1094.
13. Singh, P.; Hussain, C.; Sillanpaa, M. Innovative Bio-Based Technologies for Environmental Remediation; CRC Press: Boca Raton, FL, USA, 2022.
14. 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. Constr. Build. Mater. 2023, 388, 131546.
15. 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. Resour. Conserv. Recycl. 2022, 183, 106366.
16. 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, 2, 945–962.
17. 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, 14, 2042.
18. Fan, S.; Li, A.; ter Heijne, A.; Buisman, C.; Chen, W.-S. Heat potential, generation, recovery and utilization from composting: A review. Resour. Conserv. Recycl. 2021, 175, 105850.
19. Azizul Moqsud, M. Bioelectricity from Organic Solid Waste. Strategies of Sustainable Solid Waste Management. In Strategies of Sustainable Solid Waste Management; IntechOpen: London, UK, 2021.
20. 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. Renew. Sustain. Energy Rev. 2021, 167, 112835.
21. Llácer-Iglesias, R.; López-Jiménez, P.; Pérez-Sánchez, M. Hydropower Technology for Sustainable Energy Generation in Wastewater Systems: Learning from the Experience. Water 2021, 13, 3259.
22. Sarkar, P.; Sharma, B.; Malik, U. Energy generation from grey water in high raised buildings: The case of India. Renew. Energy 2014, 69, 284–289.
23. 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 Res. 2021, 198, 117122.
24. Song, C.; Zhu, J.-J.; Willis, J.; Moore, D.; Zondlo, M.; Ren, Z. Methane Emissions from Municipal Wastewater Collection and Treatment Systems. Environ. Sci. Technol. 2023, 57, 2248–2261.
25. Đurđević, D.; Balić, D.; Franković, B. Wastewater heat utilization through heat pumps: The case study of City of Rijeka. J. Clean. Prod. 2019, 231, 207–213.
26. Nagpal, H.; Spriet, J.; Murali, M.; McNabola, A. Heat Recovery from Wastewater—A Review of Available Resource. Water 2021, 13, 1274.
27. 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. Clean. Chem. Eng. 2022, 3, 100036.

28. Maktabifard, M.; Zaborowska, E.; Makinia, J. Achieving energy neutrality in wastewater treatment plants through energy savings and enhancing renewable energy production. Rev. Environ. Sci. Bio/Technol. 2018, 17, 655–689.

29. 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, 287, 132439.

30. 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), Seville, Spain, 17–19 March 2015.

31. Koffi, N.; Okabe, S. High electrical energy harvesting performance of an integrated microbial fuel cell and low voltage booster-rectifier system treating domestic wastewater. Bioresour. Technol. 2022, 359, 127455.

32. Cao, L.N.; Xu, Z.; Wang, Z. Application of Triboelectric Nanogenerator in Fluid Dynamics Sensing: Past and Future. Nanomaterials 2022, 12, 3261.

33. Wang, Y.; Liu, X.; Chen, T.; Wang, H.; Zhu, C.; Yu, H.; Song, L.; Pan, X.; Mi, J.; Lee, C.; et al. An underwater flag-like triboelectric nanogenerator for harvesting ocean current energy under extremely low velocity condition. Nano Energy 2021, 90, 106503.

34. Yao, C.-J.; Zhang, H.-L.; Zhang, Q. Recent Progress in Thermoelectric Materials Based on Conjugated Polymers. Polymers 2019, 11, 107.

35. Curie, J.; Curie, P.P. Développement par compression de l'électricité polaire dans les cristaux hémièdres à faces inclinées. Bull. Minéral. 1880, 3–4, 90–93.

36. Sezer, N.; Koç, M. A comprehensive review on the state-of-the-art of piezoelectric energy harvesting. Nano Energy 2021, 80, 105567.

37. Kargar, S.; Hao, G. An Atlas of Piezoelectric Energy Harvesters in Oceanic Applications. Sensors 2022, 22, 1949.

38. Li, Z.; Zheng, Q.; Wang, Z.; Li, Z. Nanogenerator-Based Self-Powered Sensors for Wearable and Implantable Electronics. AAAS Res. 2020, 2020, 8710686.

39. Junior, O.; Calderon, N.; Souza, S. Characterization of a thermoelectric generator (TEG) system for waste heat recovery. Energies 2018, 11, 1555.

40. 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. Appl. Sci. 2021, 11, 2220.

41. 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 Recover. Util. Environ. Eff. 2022, 44, 6709–6736.

42. Kasa, S.; Yao, L.; Bhada-Tata, P.; Van Woerden, F. What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050; World Bank Publications: Washington, DC, USA, 2018; pp. 1–295.

43. Lee, S.; Kim, S.; Pathak, A.; Tripathi, A.; Qiao, T.; Lee, Y.; Lee, H.; Woo, H. Recent Progress in Organic Thermoelectric Materials and Devices. Macromol. Res. 2020, 28, 531–552.

44. Toshima, N. Recent progress of organic and hybrid thermoelectric materials. Synth. Met. 2017, 225, 3–21.

45. Aldamasy, I.Z.M.; Li, G.; Pascual, J.; Alharthi, F.; Abate, A.; Li, M. Challenges in tin perovskite solar cells. Phys. Chem. Chem. Phys. 2021, 23, 23413–23427.

46. Fang, R.; Zhang, W.; Zhang, S.; Chen, W. The rising star in photovoltaics-perovskite solar cells: The past, present and future. Sci. China Technol. Ser. 2016, 59, 989–1006.

47. Njiri, J.; Soffker, D. State-of-the-art in wind turbine control: Trends and challenges. Renew. Sustain. Energy Rev. 2016, 60, 377–393.

48. GWEC. Global Wind Report 2018; GWEC: Brussels, Belgium, 2019.

49. 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, 202, 117787.

50. Menezes, E.; Araújo, A. Bouchonneau da Silva, N. A review on wind turbine control and its associated methods. J. Clean. Prod. 2018, 174, 945–953.

51. Lakc, J.; Pao, L.; Wright, A. Control of Wind Turbines: Past, Present, and Future. In Proceedings of the 2009 American Control Conference, St. Louis, MO, USA, 10–12 June 2009.

52. Ibrahim, I.; Otvos, T.; Gilmanova, A.; Tocca, E.; Ghanem, C.; Wanat, M. Intergovernmental Organizations. In International Energy Agency; Kluwer Law International B. V.: Alphen aan den Rijn, The Netherlands, 2021.

53. 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. Int. J. Energy Water Resour. 2022, 6, 413–435.

54. 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. Vib. 2021, 2021, 8861821.

55. Palosaari, J.; Juuti, J.; Jantunen, H. Piezoelectric Energy Harvesting from Rotational Motion to Power Industrial Maintenance Sensors. Sensors 2022, 22, 7449.

56. Erturk, A.; Inman, D. Piezoelectric Energy Harvesting; John Wiley & Sons: Chichester, UK, 2011.

57. Wu, N.; Bao, B.; Wang, Q. Review on engineering structural designs for efficient piezoelectric energy harvesting to obtain high power output. Eng. Struct. 2021, 235, 112068.

58. Chen, T.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 Adv. 2023, 13, 11697–11705.

59. 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, 14, 892.

60. 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, 11, 856–864.

61. Laldjebaev, M.; Isaev, R.; Saukhimov, A. Renewable energy in Central Asia: An overview of potentials, deployment, outlook, and barriers. Energy Rep. 2021, 7, 3125–3136.

62. 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 Trans. Veh. Technol. 2020, 69, 1440–1451.

63. Lund, J.; Freeston, D.; Boyd, T. Direct utilization of geothermal energy 2010 worldwide review. Geothermics 2011, 40, 159–180.

64. 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, 85, 363–374.

65. Cisco. Cisco Annual Internet Report (2018–2023); Cisco: San José, CA, USA, 2020; 25p.

66. Kim, M. Beyond-materials for sustainable power generation. In Proceedings of the IEEE 34th International Conference on Micro Electromechanical Systems (MEMS), Virtual, 25–29 January 2021.

67. Abdugapbar, K.; Dautov, K.; Hashmi, M.; Nauryzbayev, G. Design of Performance Enhanced Metamaterial-Enabled Absorber for Low-Power IoT Networks. In Proceedings of the International Conference on Internet of Things as a Service, Virtual, 17–18 November 2022.

68. Ramya, M.; Senthil Kumar, P. A review on recent advancements in bioenergy production using microbial fuel cells. Chemosphere 2022, 288, 132512.

69. 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, 11, 44.

70. Rabaey, K.; Angenent, L.; Schroder, U.; Keller, J. Bioelectrochemical Systems; IWA Publishing: London, UK, 2010.

71. Bizon, N.; Tabatabaei, N.M.; BLaabjerg, F.; Kurt, E. Energy Harvesting and Energy Efficiency-Technology, Methods, and Applications; Lecture Notes in Energy; Springer: Cham, Switzerland, 2017.

72. Fragaszy, R.J.; Santamarina, J.C.; Amekudzi, A.; Assimaki, D.; Bachus, R.; Burns, S.E.; Cha, M.; Cho, J.C.; Cortes, D.D.; Dai, S.; et al. Sustainable development and energy geotechnology—Potential roles for geotechnical engineering. KSCE J. Civ. Eng. 2011, 15, 611–621.

73. Bhowmik, D.; Chetri, S.; Enerijiofi, K.E.; Naha, A.; Kanungo, T.D.; Shah, M.P.; Nath, S. Multitudinous approaches, challenges, and opportunities of bioelectrochemical systems in conversion of waste to energy from wastewater treatment plants. Clean. Circ. Bioecon. 2023, 4, 100040.

74. Amorim, F.; Pina, A.; Gerbelová, H.; Pereira da Silva, P.; Vasconcelos, J.; Martins, V. Electricity decarbonisation pathways for 2050 in Portugal: A TIMES (The Integrated MARKAL-EFOM System) based approach in closed versus open systems modelling. Energy 2014, 69, 104–112.

75. Eurostat. Share of Energy from Renewable Sources, 2021 (% of Gross Final Energy Consumption). Statistics Explained 2021. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics&oldid=623919 (accessed on 1 December 2023).

76. European Parliament and Council. Directive 2009/28/CE on 23rd of April 2009 Related to the Promotion of Utilization of Energy from Renewable Sources. European Union Official Journal 2009. Available online: https://www.fao.org/faolex/results/details/en/c/LEX-FAOC088009/ (accessed on 9 December 2023).
77. APA. Roteiro Para a Neutralidade Carbónica 2050 (RNC2050)-Estratégia de Longo Prazo Para a Neutralidade Carbónica da Economia Portuguesa em 2050. Agência Portuguesa do Ambiente 2019. Available online: https://apambiente.pt/clima/roteiro-para-neutralidade-carbonica-2050 (accessed on 7 December 2023).
78. Lowitzsch, J.; Hoicka, C.E.; van Tulder, F.J. Renewable energy communities under the 2019 European Clean Energy Package-Governance model for the energy clusters of the future? Renew. Sustain. Energy Rev. 2020, 122, 109489.
79. República Portuguesa. PNEC 2030-Plano Nacional Energia-Clima. 2019. Available online: https://www.portugalenergia.pt/setor-energetico/bloco-3/ (accessed on 10 December 2023).
80. Verde, S.F.; Rossetto, N. The Future of Renewable Energy Communities in the EU-An Investigation at the Time of the Clean Energy Package; European University Institute: Fiesole, Italy, 2020.