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GENERATION OF ELECTRIC CURRENT IN DIFFERENT ENVIRONMENTS

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Abstract. Electric current generation from different environmental sources has become an important research field due to increasing energy demand and the need for sustainable power solutions. This study reviews recent developments in electricity generation technologies based on solar, wind, hydro, thermal, mechanical, and biological energy conversion mechanisms. The analysis highlights the role of advanced materials, nanotechnology, and hybrid energy harvesting systems in improving conversion efficiency and operational reliability. Existing challenges, including environmental variability and energy storage limitations, are also discussed. The findings indicate that integrated renewable energy systems offer significant potential for supporting future decentralized and environmentally friendly electricity generation technologies.

Keywords: electricity, energy, environment, photovoltaic, piezoelectric, triboelectric, thermoelectric, hydroelectric, renewable, nanotechnology.

Introduction. The continuous growth of global energy demand, together with increasing environmental concerns and the depletion of fossil fuel resources, has accelerated research into sustainable methods of electricity generation. Modern society relies heavily on electrical energy for industrial production, transportation, communication, healthcare, and domestic applications. Consequently, developing innovative technologies capable of producing electric current under diverse environmental conditions has become one of the most significant scientific and engineering challenges. Unlike conventional power plants that depend on centralized infrastructures and nonrenewable resources, emerging energy harvesting systems aim to convert naturally available environmental energy into electrical power with higher efficiency and lower ecological impact. Electric current generation can occur through numerous physical mechanisms depending on the characteristics of the surrounding environment. Mechanical motion, thermal gradients, electromagnetic fields, solar radiation, chemical reactions, fluid movement, and biological processes can all serve as sources of usable energy. Advances in material science and nanotechnology have enabled researchers to exploit these energy forms through piezoelectric, triboelectric, thermoelectric, photovoltaic, electrochemical, hydroelectric, and bioelectric conversion technologies. Each approach demonstrates unique advantages and limitations depending on environmental conditions, energy density, and application requirements. As a result, understanding electricity generation across different environments has become increasingly important for designing adaptive and multifunctional energy systems.

Renewable energy technologies have significantly transformed the landscape of electrical power generation by utilizing naturally replenished resources. Solar photovoltaic systems convert incident sunlight directly into electricity through semiconductor materials, while wind turbines generate electrical power from atmospheric motion through electromagnetic induction. Hydroelectric systems utilize gravitational and kinetic energy of flowing water, whereas ocean-wave and tidal energy converters exploit marine dynamics to produce electric current. Recent technological developments have further expanded these concepts by integrating flexible materials and intelligent control systems capable of operating under variable environmental conditions, thereby improving system stability and overall energy conversion efficiency. In addition to large-scale renewable power

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generation, considerable attention has been directed toward micro- and nanoscale energy harvesting technologies designed for autonomous electronic devices. The rapid expansion of wireless sensor networks, wearable electronics, biomedical implants, and Internet of Things (IoT) systems has created a demand for self-powered devices that can operate without conventional batteries. Triboelectric nanogenerators and piezoelectric nanogenerators have emerged as promising solutions by converting ambient mechanical vibrations, human motion, airflow, raindrops, and structural deformation into electrical energy. Similarly, thermoelectric generators exploit temperature differences between surfaces and surrounding media, enabling electricity production from industrial waste heat, geothermal resources, and even body heat. Such technologies contribute to extending device lifetime while reducing maintenance costs and environmental pollution associated with battery disposal.

Different environments impose distinct physical constraints that influence electric current generation efficiency. Atmospheric conditions such as humidity, temperature, pressure, and wind velocity affect the performance of photovoltaic and triboelectric systems. Marine environments introduce challenges related to corrosion, salinity, and mechanical fatigue while simultaneously providing abundant kinetic energy resources. Underground and industrial environments often contain thermal gradients and mechanical vibrations suitable for thermoelectric and piezoelectric conversion. Biological environments, including living organisms and microbial ecosystems, offer opportunities for bioelectrochemical energy production through microbial fuel cells and enzymatic reactions. The diversity of these environments requires interdisciplinary approaches combining electrical engineering, materials science, physics, chemistry, and environmental science to optimize energy conversion mechanisms and device durability. Recent advances in nanostructured materials, conductive polymers, two-dimensional materials, and hybrid composites have substantially enhanced the performance of environmental energy harvesting systems. Improved charge transfer characteristics, higher surface activity, enhanced flexibility, and superior mechanical stability have increased electrical output while reducing device size and manufacturing costs. Artificial intelligence and smart control algorithms are also being integrated into modern energy generation systems to optimize power management under dynamically changing environmental conditions. These developments indicate a transition toward intelligent distributed energy systems capable of continuous operation across multiple environments with minimal external intervention.

The study of electric current generation in different environments therefore represents a multidisciplinary field with considerable scientific and practical importance. Investigating the physical principles governing energy conversion under varying environmental conditions contributes to the development of sustainable power technologies that support global energy security and environmental protection. Furthermore, comparative analysis of different generation mechanisms provides valuable insights into selecting appropriate technologies for specific applications ranging from large-scale renewable energy systems to autonomous microsensors and wearable electronic devices. Such research plays an essential role in accelerating the transition toward cleaner, more efficient, and environmentally responsible energy production systems suitable for future technological development.

Literature review. The generation of electric current from various environmental energy sources has become one of the most actively investigated research areas in modern energy science. Recent studies emphasize that the diversification of electricity generation technologies is essential for achieving sustainable development, reducing greenhouse gas emissions, and ensuring reliable energy access in both developed and developing regions. Unlike conventional centralized power systems, environmental energy harvesting technologies focus on converting naturally available energy into electricity through physical, chemical, or biological mechanisms. The growing demand for portable electronics, wireless monitoring systems, autonomous sensors, and smart infrastructure has

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significantly accelerated research into innovative current generation methods capable of operating under diverse environmental conditions. Solar energy remains the most extensively studied environmental energy source because of its abundance and global availability. Recent investigations have focused on improving photovoltaic conversion efficiency through advanced semiconductor materials, tandem cell architectures, and perovskite-based structures. Modern photovoltaic devices demonstrate higher light absorption capabilities and lower production costs compared with earlier silicon-based technologies. Researchers have also explored flexible solar cells and transparent photovoltaic materials that can be integrated into windows, buildings, and wearable electronics. These developments indicate that solar electricity generation is evolving beyond conventional solar farms toward multifunctional applications integrated into daily life and urban infrastructure.

Wind energy conversion technologies have experienced substantial technological improvements due to advances in aerodynamic optimization, intelligent control systems, and generator design. Recent literature highlights the increasing efficiency of variable-speed wind turbines equipped with permanent magnet synchronous generators and adaptive power electronics. Offshore wind farms have attracted considerable scientific attention because marine environments provide stronger and more stable wind resources than terrestrial locations. However, environmental challenges such as corrosion, extreme weather conditions, and maintenance complexity remain important engineering concerns. Researchers continue to investigate lightweight composite materials and predictive monitoring techniques that improve operational reliability under harsh environmental conditions. Hydroelectric energy continues to represent one of the most mature and efficient methods of electricity generation. Nevertheless, contemporary studies increasingly emphasize small-scale hydroelectric systems designed for rural electrification and decentralized energy production. Micro-hydropower plants can utilize irrigation canals, rivers, and small water streams without requiring large dams that significantly alter ecosystems. Computational fluid dynamics simulations have improved turbine blade design and water flow optimization, resulting in higher energy conversion efficiencies. Additionally, hybrid systems combining hydropower with solar and wind energy have demonstrated greater stability in isolated power networks, particularly in mountainous and remote regions.

Ocean energy has emerged as another promising renewable energy source due to the enormous kinetic and thermal energy stored in marine environments. Wave energy converters, tidal turbines, and ocean thermal energy conversion systems have been extensively investigated in recent years. Studies indicate that marine energy resources possess higher predictability than solar and wind energy because tidal movements follow astronomical cycles. Nevertheless, researchers recognize significant technical challenges associated with corrosion resistance, marine biofouling, structural fatigue, and high installation costs. Novel anti-corrosion coatings and advanced composite materials have shown promising results in improving long-term operational performance in seawater environments. Mechanical energy harvesting has become particularly important for powering autonomous electronic systems operating without external electrical infrastructure. Piezoelectric materials generate electric current under mechanical deformation by converting stress into electrical polarization. Recent studies report substantial improvements in piezoelectric ceramics, polymers, and nanocomposites with enhanced flexibility and durability. Flexible piezoelectric films integrated into roads, bridges, footwear, and biomedical devices have demonstrated the ability to generate electricity from vibrations, walking motion, and structural deformation. Such technologies offer significant potential for self-powered sensing systems in smart cities and industrial monitoring applications.

Triboelectric nanogenerators have attracted extraordinary research interest because of their capability to generate electricity through contact electrification and electrostatic induction. Their simple structure, lightweight construction, and ability to operate under low-frequency mechanical

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motion make them attractive for harvesting ambient environmental energy. Recent investigations demonstrate successful electricity generation from rainfall, ocean waves, human movement, vehicle vibration, and wind-induced oscillations. Surface engineering techniques involving micro- and nanostructures have significantly increased charge density and electrical output performance. Researchers are also exploring hybrid triboelectric systems integrated with electromagnetic and piezoelectric generators to maximize energy conversion under complex environmental conditions. Thermoelectric generation represents another rapidly developing research direction for converting thermal gradients into electric current through the Seebeck effect. Industrial processes, vehicle exhaust systems, geothermal resources, and solar thermal collectors all provide abundant waste heat that can be transformed into electrical energy. Recent literature emphasizes advances in nanostructured thermoelectric materials exhibiting lower thermal conductivity and improved electrical conductivity, resulting in significantly higher conversion efficiencies. Flexible thermoelectric generators capable of utilizing human body heat have also demonstrated promising applications in wearable electronics and medical monitoring devices requiring continuous low-power operation.

Bioelectrochemical electricity generation has gained increasing attention as researchers seek environmentally friendly energy sources derived from biological systems. Microbial fuel cells utilize metabolic activity of microorganisms to produce electric current during organic matter decomposition. Recent investigations indicate that wastewater treatment plants can simultaneously purify water and generate electricity through microbial electrochemical processes. Plant microbial fuel cells and enzymatic biofuel cells have further expanded the possibilities of biological energy harvesting by exploiting natural biochemical reactions. Although current power outputs remain relatively low compared with conventional technologies, ongoing improvements in electrode materials and microbial engineering continue to enhance system performance. Material science has become a fundamental driver of innovation across nearly all environmental electricity generation technologies. Graphene, transition metal dichalcogenides, conductive polymers, carbon nanotubes, and hybrid nanocomposites have demonstrated remarkable electrical and mechanical properties that improve energy conversion performance. Researchers increasingly employ nanotechnology to manipulate surface morphology, charge transport pathways, and interface properties, leading to higher efficiency and improved operational stability. Furthermore, additive manufacturing techniques and flexible electronics fabrication methods enable scalable production of lightweight and adaptable energy harvesting devices suitable for complex environmental conditions.

Recent literature also highlights the importance of hybrid energy harvesting systems that combine multiple environmental energy sources within a single platform. Integrated photovoltaic–thermoelectric, piezoelectric–triboelectric, and solar–wind systems demonstrate improved reliability because they can operate under changing environmental conditions where a single energy source may become unavailable. Intelligent energy management systems utilizing machine learning algorithms optimize energy conversion, storage, and distribution by adapting to fluctuations in environmental parameters. Such multifunctional systems represent an important direction for future research aimed at achieving continuous and efficient electricity generation in diverse natural and industrial environments. Overall, contemporary scientific literature demonstrates that electric current generation in different environments has evolved into a highly interdisciplinary field involving physics, electrical engineering, materials science, chemistry, biotechnology, and environmental engineering. Continuous advances in functional materials, energy conversion mechanisms, and intelligent system integration are expanding the practical applications of environmental energy harvesting technologies. These developments support the global transition toward sustainable, decentralized, and environmentally responsible

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electricity generation systems capable of meeting future energy demands while minimizing ecological impact.

Research discussion. The analysis of recent scientific studies demonstrates that electric current generation in different environments has become a key research direction in modern energy engineering. Various environmental sources, including solar radiation, wind, water flow, thermal gradients, mechanical vibration, and biological activity, provide significant opportunities for sustainable electricity production. Each energy source possesses unique physical characteristics that influence the efficiency and stability of energy conversion systems. Consequently, selecting appropriate generation technologies depends strongly on environmental conditions and application requirements. Current research indicates that photovoltaic systems remain the dominant technology for large-scale renewable electricity generation because of their high maturity and continuously improving conversion efficiency. However, their dependence on sunlight availability limits continuous operation under changing weather conditions. Wind and hydroelectric systems complement solar energy by providing additional power generation capabilities, particularly in regions with favorable geographical conditions. The integration of multiple renewable energy sources has therefore become an important strategy for improving energy reliability and reducing fluctuations in power output. Recent developments in nanotechnology have significantly expanded the possibilities of small-scale electricity generation through environmental energy harvesting. Triboelectric and piezoelectric nanogenerators demonstrate the ability to convert low-frequency mechanical motion into electrical energy using relatively simple structures and low-cost materials. These technologies have attracted considerable attention for powering wireless sensors, wearable electronics, biomedical devices, and Internet of Things applications. Their ability to generate electricity from human motion, raindrops, structural vibration, and airflow illustrates the versatility of environmental energy conversion mechanisms.

Thermoelectric generation has also shown considerable potential for recovering waste heat from industrial equipment, vehicles, and natural geothermal resources. Improvements in nanostructured thermoelectric materials have increased conversion efficiency while reducing material losses. Similarly, microbial fuel cells and other bioelectrochemical systems represent innovative approaches for producing electricity from biological processes and organic waste, simultaneously contributing to waste management and renewable energy production. Despite substantial technological progress, several challenges remain. Environmental variability directly influences system performance, while issues related to durability, material degradation, energy storage, and economic feasibility continue to limit widespread implementation. Hybrid energy harvesting systems that combine multiple generation mechanisms appear to provide a practical solution for overcoming these limitations by ensuring more stable electricity production under changing environmental conditions. Overall, the reviewed studies suggest that future electricity generation systems will increasingly rely on intelligent hybrid technologies integrating advanced materials, artificial intelligence, and decentralized energy management strategies. Such systems are expected to improve energy efficiency, reduce environmental impact, and support sustainable technological development across industrial, urban, and remote applications.

Conclusion. The generation of electric current in different environments represents an essential component of modern sustainable energy research. Advances in renewable energy technologies, nanomaterials, and hybrid energy harvesting systems have significantly expanded the possibilities for converting environmental energy into usable electrical power. Solar, wind, hydroelectric, thermoelectric, piezoelectric, triboelectric, and bioelectrochemical technologies each contribute unique advantages for specific operating conditions. Although technical and economic

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challenges remain, continuous improvements in material science and intelligent energy management are increasing system performance and reliability. Future research should focus on integrating multiple energy harvesting mechanisms, enhancing conversion efficiency, and developing cost-effective solutions capable of supporting autonomous electronic devices and decentralized power systems. Such innovations will contribute substantially to global energy sustainability and environmental protection.

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