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A review of the renewable energy technologies and innovations in geotechnical engineering

Eman J. Bani ISMAEEL[1,a], Samer RABABAH[1,b],
Mohammad Ali KHASAWNEH[2,c], Nayeemuddin MOHAMMED[2,d*],
Danish AHMED [2,e]

[1] Civil Engineering Department, College of Engineering, Jordan University of Science &Technology, Irbid 22110, Jordan

[2] Department of Civil Engineering, Prince Mohammad Bin Fahd University, Al Khobar, Kingdom of Saudi Arabia

[a]egbaniissmaeel20@eng.just.edu.jo, [b]srrababah@just.edu.jo, [c]mkhasawneh@pmu.edu.sa, [d]mnayeemuddin@pmu.edu.sa, [e]dahmed@pmu.edu.sa

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Abstract. The recent trend in the energy sector is seeking eco-friendly and cost-effective solutions. In the last few years, the globe has given attention to renewable energy resources to overcome the depletion problems of fossil fuels and take advantage of abundant natural resources such as solar, wind, and natural gas. Renewable energy resources provide a long-term efficiency solution in different applications. This review paper comprehensively reviews recent advancements in renewable energy technologies and innovations, focusing on solar energy, wind energy development, smart grid technologies, and energy storage solutions for a cleaner and more sustainable future.

Introduction

Renewable energy sources have become increasingly important in recent years [1]. They offer a solution to combat the depletion of fuels and address environmental issues like global warming [2]. Generally, energy sources can be classified into two categories: fossil fuels and renewable energy [3]. The European Union has pledged to cut its emissions by 20% in the second phase of the Kyoto Protocol. The intermittent renewable energy sources solar and wind must be transmitted and stored as effectively as feasible in order to meet this objective. Renewable energy, known for its nature, includes clean energy options [4]. With the increasing global demand for energy consumption and environmental challenges such as climate change, carbon dioxide (CO_2) emissions, and greenhouse gas (GHG) emissions, authorities are increasingly encouraged to transition from conventional energy sources, particularly fossil fuels, to clean and secure renewable energy alternative [5]. Renewable energy resources offer energy security, environmental protection, economic advantages, and a pollution-free environment. Switching from relying on fuels for energy consumption to adopting a zero-carbon emission approach marks a shift in the energy sector. The transition to renewable energy will be facilitated through the integration of smart technologies, information technology, and the implementation of clean energy policy frameworks.

The adoption of renewable energy sources has prompted the development of numerous technologies and innovations that boost progress within the energy industry. These technologies provide environmentally friendly substitutes for energy derived from fossil fuels and establish the foundation for a future distinguished by carbon-neutral energy. Recent developments in renewable energy technologies and innovations, such as advancements in solar energy, energy storage solutions, wind energy development, and smart grid technologies, are examined in detail in this article. Moreover, this review will address the challenges and opportunities of transitioning to renewable energy.

Solar Energy Advancement

Solar energy is generated abundantly by the sun. Solar energy is considered a vital renewable resource, intercepting around 1.8×1014 kW on Earth. Its ubiquity, zero cost, and sustainability make it a promising solution to global energy demands. Solar energy is applicable across diverse sectors and is crucial for addressing the continuously increasing demand for energy resources. It is one of the renewable energy resources that has gained significant importance in the recent development of the energy sector [6]. Solar energy can be converted into different forms through photovoltaic (PV) systems. PV systems provide benefits such as minimal environmental impact, low maintenance expenses, and the lack of moving parts despite their typically 18-23% lower efficiency. However, numerous variables, including temperature fluctuations and solar insolation, influence the output of PV systems, resulting in power generation fluctuations. Various approaches, including maximum power point tracking (MPPT) methods and sun trackers, can increase the efficiency of a PV system [7].

The Integration of artificial intelligence (AI) into the utilization of solar energy resulted in the development of advanced solar panels optimized in structure, performance, and efficiency. [8] examined the AI can transform PV technology in the solar energy sector. According to the study, AI can potentially improve solar energy system efficiency, power grid integration, and the transition to sustainable energy. Researchers used machine learning models to accelerate the discovery of high-performance solar cell materials. These algorithms predict the material properties and searched large data sets quickly. [9] developed a solar energy tracking prototype to optimize solar energy collection using Arduino technology. The prototype could automatically adjust the position of the solar panel by utilizing servo motors and Light-Dependent Resistors (LDRs). An 18% increase in energy output compared to static panels indicates that these panels may be useful in various situations.

Advanced battery management algorithms and Neural Maximum Power Point Tracking (MPPT) control to optimize photovoltaic solar systems. This work optimized solar energy conversion to electricity by dynamically modifying the MPP and managing battery charging and discharging [10]. Thorough MATLAB/Simulink simulations showed that neural MPPT control outperforms other methods even in variable sunlight conditions. [11] investigated whether tiny machine learning (TinyML) could predict solar energy yield in real time for microcontrollers and other resource-constrained edge IoT devices. Four popular machine learning models: unidirectional long short-term memory (LSTM), bidirectional gated recurrent unit (BiGRU), bidirectional long short-term memory (BiLSTM), and simple bidirectional recurrent neural network (BiRNN) are extensively evaluated for predicting solar farm energy yield. This study adds to the body of knowledge on cost-effective IoT solutions and emphasizes edge device limitations in ML architecture selection. This makes the energy landscape more sustainable and efficient, benefiting residential and industrial sectors.

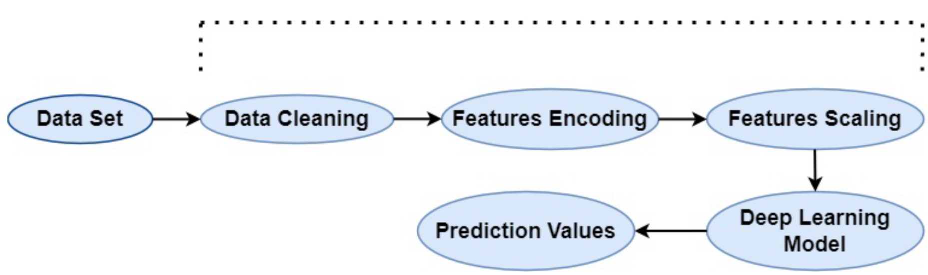

Fig. 1 shows the detail steps for ANN-ML modelling technique [11]

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Wind Energy Development

Renewable energy sources, such as wind energy, offer a promising way to reduce fossil fuel dependency while mitigating environmental impact. Wind, considered an indirect derivative of solar energy, is continually replenished by natural processes driven by the sun's energy [12]. Wind energy arises from the differential heating of the Earth's surface, considered an abundant and sustainable energy resource. Estimates suggest that more than 10 million MW of energy is continuously available in the Earth's wind, significantly contributing to global energy needs [13]. The advancement in wind turbines leads to stronger, lighter, and more efficient turbine blades, which means enhancements in annual energy output and reductions in turbine weight, emission, and noise over recent years [14]. Several measurements are considered to harness wind energy's potential further, such as establishing more wind monitoring stations, enhancing turbine maintenance techniques, carefully selecting wind farm sites, adapting high-capacity machines, and using advanced design techniques. These procedures lead to optimizing wind energy generation by maximizing the turbine's efficiency, increasing machine availability, and expanding operational capacity [15].

A recent study employs computational strategies for converting wind energy into hot water. This study optimized wind farm layout, modeling and simulation systems, energy management strategy, wind resource assessment, turbine design and size, power conversion control, and layout engineering [16]. An evaluation of the semicircular wind tower blasting and painting system's potential to revolutionize conventional wind tower coating methods was conducted by [17]. Contributing to advancing the wind energy industry toward a more sustainable future, the findings of this research demonstrated that the semicircular system presents notable benefits compared to robotic arms, including a substantial enhancement in efficiency, reduced costs, and an environmentally friendly solution. In a study conducted by [18], the objective was to investigate the feasibility of utilizing wind towers as natural ventilation and cooling systems in residential buildings. The primary focus of this research was the integration of wind towers with energy storage systems and renewable energy sources to maximize their efficiency and effectively reduce greenhouse gas emissions.

Smart Grid Technologies

In general, smart grids are advanced electricity networks engineered to utilize information and communication technologies to ensure improved dependability and productivity in power delivery [19]. Promoting energy conservation and sustainability, these technologies facilitate the seamless integration and administration of renewable energy sources. Storage solutions are crucial in mitigating fluctuations in energy output, especially when considering the decentralized nature of energy production facilitated by renewable resources. In order to prevent blackouts, smart grids attempt to maintain a balance between energy supply and demand by addressing a number of issues, such as rising pressures and peak consumption [20]. Smart Grids use cutting-edge technologies like intelligent control, communication, and self-healing to advance electricity networks. Demand side management (DSM) and demand response initiatives in these power grids give consumers more control over their energy use. Meters, microgeneration, and smart appliances enable this control. Smart grids use various generator and storage technologies, including distributed generation (DG) and renewable energy sources, to reduce the environmental impact of electricity provision. They optimize asset management and delivery independently, maximizing resource use. Smart grids also ensure reliable energy supply during disasters by strengthening resilience to physical and cyber threats. Smart Grids increase supply aggregation and transmission capacity to improve power supply and market access [21].

Recent developments in smart grid technologies have been instrumental in addressing the changing demands of the power distribution sector. These developments optimize grid operations, enhance resilience to cyber and physical threats, and facilitate the integration of renewable energy sources and energy storage solutions by utilizing cutting-edge innovations. In addition, the continuous advancement and enhancement of smart grid technologies possess tremendous potential to fortify and transform the distribution system, facilitating the transition to a future characterized by enhanced energy efficiency, dependability, and sustainability [22]. The smart grid technologies are driving significant progress toward enhancing modern power systems' reliability, sustainability, and efficiency. One notable area of advancement lies in the development of energy management systems, which play a crucial role in ensuring the seamless integration and coordination of various grid components from generation to consumption. Initiatives such as the Smart Grid Interoperability (SGIP) standards, initiated by the National Institute of Standards and Technology (NIST), have promoted interoperability among grid components and facilitated efficient planning and implementation [23].

Moreover, integrating Internet of Things (IoT) solutions has revolutionized grid communication and automation, marking an important advance in smart grid technology. IoT technologies provide greater connection and automation, allowing grid components to interact more efficiently and reliably. However, using IoT in smart grids introduces additional issues, notably regarding security and privacy. Researchers are currently addressing these problems by establishing strong security mechanisms and authentication methods to preserve the integrity and confidentiality of grid data [24]. Furthermore, big data analytics transforms smart grid operations by giving essential insights into grid efficiency and management. However, difficulties such as data storage, processing, integration, and security continue to be important emphasis areas for researchers looking to fully realize the potential of big data in smart grid technologies [25].

Energy Storage Solutions

Among the most recent developments in the renewable energy field, energy storage solutions are critical to assuring the reliability and scalability of renewable energy sources. Furthermore, this technology considerably increases energy consumption capacity. The increasing demand for sustainable and clean energy continues to rise, driving the development of new imperative solutions for energy storage [26]. This section aims to provide insights into the role of recent advancements in energy storage solutions in facilitating the transition towards a more sustainable energy landscape. The Energy PLAN modeling to find Finland's cheapest 100% renewable energy scenario by 2050. In the study, electricity and heat storage meet 15% of end-user demand, while thermal storage discharge meets 4%. High renewable energy integration requires electrical storage devices at 50% variable renewable energy penetration and seasonal storage devices at over 80% renewable energy (RE) penetration. Energy storage is crucial in Finland's 100% renewable energy system [27]. [28] analyzed the challenges during the remote Arctic region's transition from diesel and fossil fuels to renewable energy sources. Various energy storage options, including battery storage, underground solar power/storage, and hydrogen storage, are explored to achieve energy self-sufficiency at Flatey's. These energy storage options are summarized in Table 1.

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Table 1: The suggested energy storage options for remote areas [28]

Storage Solution	Description
Storing Solar Power in Battery Banks	- Utilizes battery storage in PV systems. - Flexible connection of batteries in series for larger facilities. - It requires less space than hydrogen storage.
Underground Solar Power Storage	- Utilizes borehole thermal energy storage (BTES). - Ground source heat exchangers (BHE). - Efficiency depends on geological factors.
Storing Power by Using Hydrogen	- Green hydrogen production through electrolysis - Challenges in storing hydrogen. - Can be stored under high pressure or in liquid form. - Utilized in fuel cells for high-efficiency electricity production. - Economic evaluation required.

Renewable Energy in geotechnical engineering applications

Geotechnical engineering is a crucial in providing good foundation and anchor systems for MRE devices. Marine renewable energy (MRE) systems on a commercial scale will consist of a variety of devices secured to the bottom by foundations or anchors [29]. The renewable energy is a substitute resource to address the high demand for conventional hydrocarbon energy, reduce the impact on the environment, and ensure sustainability for many years. The review of geotechnical engineering concerns and their connection to renewable energy engineering is intended to motivate geotechnical engineers to participate in the developing area of energy research [30]. Owing to the geo-dependent nature of renewable energy, geo technology can help optimize the effective use of renewable resources Environmental impact assessments and offshore wind turbine engineering designs both depend heavily on seabed characterization. The investigation into screw piles for the development of offshore renewable energy, significant upscaling of the currently in use onshore piles was necessary [31].

The main benefit is that it is a clean, renewable energy source with no adverse effects on the environment. In the past, Croatia's experience with geothermal energy extraction has mostly focused on the potential for deep geothermal resource extraction. "Investment Valuation Model for Renewable Energy Systems in Buildings" outlines the real options model that is being offered and identifies the special characteristics that set it apart from other valuation models [32]. The needs of a profession that will increasingly be involved in sustainable design, energy geo technology, waste management, underground utilization, enhanced/more efficient use of natural resources, and alternative/renewable energy sources must be addressed in the geotechnical engineering curriculum, from undergraduate education through continuing professional education [33]. Every technology was found to have a very wide range in terms of electricity costs, greenhouse gas emissions, and generation efficiency. This is mostly because each renewable energy source has a different geographical reliance and a different range of technological alternatives [34].

Table 2: The efficiency and cost aspect to renewable energy [35]

Aspect	Energy Production	Energy Storage	Energy Harvesting
Efficiency	-Solar Photovoltaics: 15-20% -Wind Turbines: >40%	-Lithium-ion Batteries: 80-90% -Lead-acid Batteries: 70-85%	-Photovoltaic Cells: >20% -Thermoelectric Generators: 5-10%
Cost	-Solar Photovoltaics: Decreasing, currently competitive -Wind Turbines: Decreasing.	-Lithium-ion Batteries: Decreasing,still significant cost -Lead-acid Batteries: Relatively low cost.	-Photovoltaic Cells: Decreasing, currently cost-competitive -Thermoelectric Generators: Costly,

Summary

Reviewing recent advancements in renewable energy technologies highlights the significant progress towards a sustainable energy landscape. Solar energy innovations, propelled by AI, promise enhanced efficiency and performance, while wind energy developments offer efficient and eco-friendly solutions for wind tower coatings and ventilation systems. Smart grid technologies facilitate seamless energy distribution and management, bolstering grid reliability and efficiency. Furthermore, energy storage solutions, such as thermal storage and PtG concepts, contribute to energy scalability and sustainability. These advancements underscore the critical role of renewable energy in mitigating environmental challenges and transitioning towards a greener future. Continued research and innovation in renewable energy technologies are essential to drive further progress and accelerate the global transition to clean and sustainable energy sources.

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