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Simulation Technology in Renewable Energy Generation: A Review

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***Abstract*— The escalating energy consumption rates and the alarming environmental impacts associated with fossil fuel usage have driven global attention towards alternative energy sources. While nuclear power has emerged as one such alternative, concerns about past reactor accidents and the health effects of radiation release have limited its widespread adoption. Renewable energy, on the other hand, offers a promising solution with minimal environmental harm compared to nuclear power. However, the intermittent nature of renewable energy sources and their inability to consistently supply power present significant challenges for nations aiming to harness these abundant resources. To address these challenges, the integration of simulation technology into energy generation processes has proven instrumental. By employing simulation tools, it becomes possible to identify, control, and even eliminate factors that may hinder energy generation and efficiency. Furthermore, simulation technology enables accurate predictions of the expected energy output from renewable sources. This paper presents a comprehensive review of the recent advancements and applications of simulation technology in renewable energy generation. It elucidates how simulation technology has been successfully integrated into renewable energy systems and discusses its potential to enhance the efficiency of renewable energy generation.**

Keywords*—Renewable energy generation; Simulation; Energy; Environment*

I. INTRODUCTION

A. *Simulation*

Simulation is performed through computer software by generating data via random sampling from known parameters [1], this serves as a powerful tool for creating virtual experiences that mirror real-world events [2]. It acts as a crucial link between theoretical conjectures and experimental investigations, enabling the analysis and confirmation of scientific theories. It can be categorized into physical simulation, which replicates systems governed by the laws of physics, and process or system simulation, which models processes influenced by human behavior and it offers valuable insights into various domains. Two commonly employed simulation methods are Agent-Based Simulation (ABS) and Discrete Event Simulation (DES)[3]. Simulation is widely utilized across scientific disciplines and it contributes to knowledge and skill acquisition [4,5], facilitates understanding of temporal atom movement [6], and provides insights into the evolution of quantum systems [7]. Furthermore, simulation finds applications in manufacturing and product development, enabling the exploration of complex systems without disrupting their actual operation [8].

B. *Examples of simulation technology*

Simulation technology encompasses a wide range of software tools, as highlighted in relevant studies. Kavadias et al. [9] discussed the utilization of simulation software in hybrid renewable energy systems, including notable examples such as INSPECTOR, DIgSILENT, PSCAD, DYMOLA, PSSIE, Thermolib, EMTP0RV, OPAL-RV, and Dspace [10]. Additionally, OMES, WINSYS, RETSCREEN, and HOMER were identified as simulation software commonly employed in hybrid renewable energy system analysis [11]. Notably, HOMER emerged as one of the most widely used simulation tools for integrating hybrid systems. In the context of energy generation simulation, other notable examples include pvlib python and EnergyPlus [12,13].

C. *Renewable energy generation*

Energy is of utmost importance for the socio-economic and industrial progress of nations [14,15,16], as well as for the overall development of the world. It serves as the fundamental framework of modern society [14], and the global energy consumption has reached staggering proportions [17]. Projections indicate that energy demand will double in less than 50 years (Figure 1). Presently, most of our energy comes from fossil fuels, with renewables accounting for only 22% (Figure 2). However, relying solely on fossil fuels is not sustainable due to their harmful by-products, which pose risks to human health, the environment, and the diverse ecosystems that inhabit the Earth [17]. These by-products contribute to pollution,

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global warming, and acid deposition, highlighting the urgent need for cleaner energy alternatives [14].

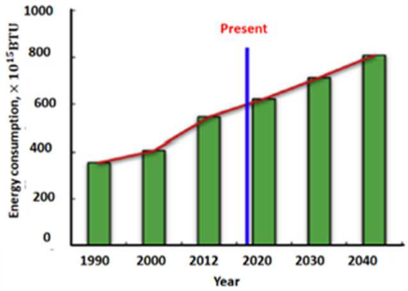

Figure 1: World energy consumption from 1990 to 2040[18].

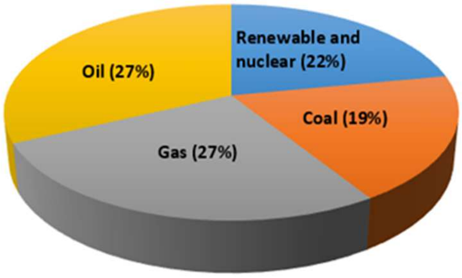

Figure 2: Energy sources used for power generation [18].

In response to the United Nations' call for adherence to the Sustainable Development Goals [19], the world has increasingly turned to renewable energy sources. These sources include solar power, wind energy, wave and tidal power, biomass, hydropower, and geothermal energy derived from the Earth's core [17,20,21]. Many countries are actively striving to reduce their carbon footprint by transitioning from high carbon-intensive power systems to those with lower carbon intensity [16]. Consequently, renewable energy has become an integral part of everyday life and is being integrated into all sectors of human activities [14]. By embracing renewable energy, nations can foster sustainable development, mitigate climate change, and create a cleaner and healthier environment for future generations.

II. APPLICATION OF SIMULATION IN ENERGY GENERATION

Simulating energy systems helps reduce cost of operation of the power systems. Simulating dynamic conditions is essential in improving the design and utilization of energy systems [22].

A. Solar energy

The utilization of solar energy harnessed from the abundant power of the sun offers numerous advantages, including its renewable nature, minimal maintenance requirements, and absence of pollution[20]. However, before implementing a solar power system, it is crucial to conduct simulations and analyze the photovoltaic (PV) generator's behavior under real-world weather conditions specific to the installation site [23].

This stage of simulation and analysis provides valuable insights into the performance of the solar power system.

Researchers like [23] have employed MATLAB and Simulink as essential tools for simulating and analyzing PV systems. Similarly, Gallardo-Saavedra et al, [24] utilized the same software to simulate the shading effect, as depicted in Figure 3. Shading is a major challenge in photovoltaic energy generation on the photovoltaic cells [25]. It occurs when certain portions of the PV cells receive reduced sunlight due to obstructions, thereby impacting the overall electricity production [25].

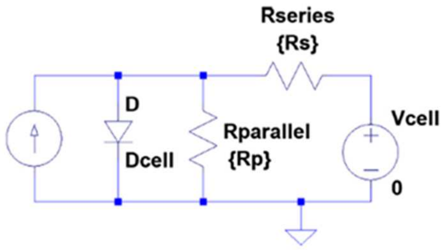

Figure 3: Picture of a solar cell simulated using LTSpice [24]

A photovoltaic (PV) panel functions by converting sunlight into electricity, with greater light intensity resulting in increased electricity generation [26]. However, shadows can disrupt the light reaching the photovoltaic cells, thus reducing electricity production [25]. Addressing the issue of partial shading is particularly important, considering that it is more prevalent than full shading and has a greater negative impact on PV system performance [27]. Non-uniform shading is especially problematic, as it significantly reduces efficiency compared to uniform shading [28]. Simulations and experiments are valuable tools for studying the impact of partial shading and devising strategies to mitigate its effects [27].

One effective approach to combat the shading effect and minimize its impact on PV panels is the installation of bypass diodes [27]. These diodes create alternative pathways for the electrical current to flow, bypassing shaded cells and preventing a reduction in power generation by cells adjacent to the shaded area. By implementing bypass diodes, the overall performance of the solar panel system can be improved, even under shading conditions.

B. Wind energy

Wind power is spread globally and renewable, producing no greenhouse gases[29] meaning there is no pollution. It is usually an unpredictable and sporadic source of energy[30]. Still, because of its green nature, it plays and will continue to play a big part in energy systems, now and in the future[31]. Sprague et al., [32] believes that to improve efficiency and flexibility of wind energy, one must understand and be able to predict the physics of the driving flow, how it interacts with the wind turbine and plants. Simulations of the wind in certain environments can be used to investigate the movement of wind around buildings which would help reduce the difference between the expected energy and the actual energy generated [33]. Exawind can used for wind turbine & plant simulation [32]. Reduction of the efficiency of wind energy can result from electrical inefficiencies, wake effects, mechanical degradation[29].

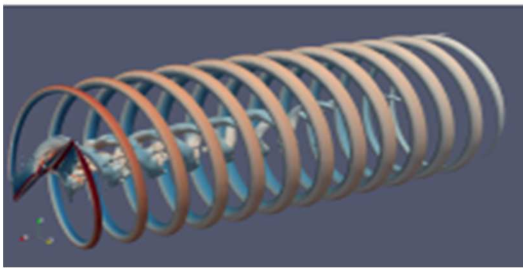

Figure 4: Simulation of flow field around a wind turbine[32].

C. *Wave energy*

Waves, both sea and ocean, are plentiful, not nearly exploited enough and available around the whole world[17]. When wave energy is predicted accurately, especially its parameters like the height and speed of the wave (Figure 5), it reduces the cost that goes into the energy generation and helps with its smooth maintenance and operation [34].

Saadatnia et al., [17] expressed that electromagnetic generations have usually been used to harness and harvest the energy from waves but setbacks such as inefficiency, large structures, high expenses, and its influence on its surroundings have stunted the advancement of this aspect of renewable energy generation. That is why in 2012 when the use of bioelectric nanogenerators to harness the mechanical energy of waves and convert it to electrical energy came up it was widely embraced[17]. The results of [17] research stated that triboelectric nanogenerator have proven to be more efficient as it runs on low cost, is not too heavy and its materials and structures impacts little on the environment.

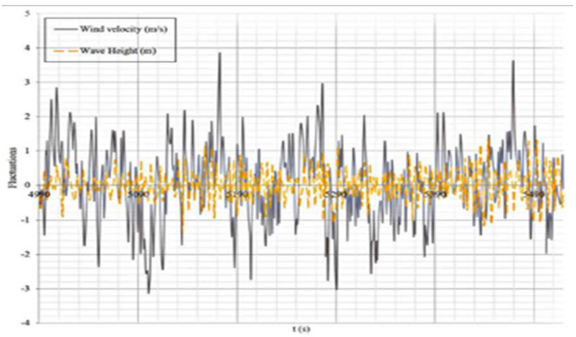

Figure 5: A simulation of the wind speed and height of waves using Flow-3D software [35]

D. *Tidal energy*

The impact of carbon on the environment is currently a major concern for the global community, prompting a shift towards alternative energy sources such as tides [36]. Thiébot et al., [36] added that there are additional renewable energy sources that, if harnessed, can be used to generate electricity. Ebakumo et al., [37] defines tidal energy as the energy harnessed from the timely change of the tides (curves of the ocean waves) as a result of the interaction between three things, the force of gravity of the sun on the earth, the force of gravity of the moon on the earth, and the centrifugal force due to the rotation of the moon and the earth about one another. This definition is consistent with [36]. who attributes the changes in tide to several factors acting across various time periods, the major ones being the sun and moon. The main advantage of tidal energy is its predictability [37,36]. It also has minimal effect on the landscape's aesthetics. According to Thiébot et al., [36] simulating the generation processes could provide solutions with tidal energy. Using LES, ANSYS Fluent, POLCOMS. Thiebot et al., [36] were able to simulate the tidal movement of the Aldeney Race (a strait in the English Channel) and obtain its hydrodynamic properties as well as identify the optimal location for turbine placement to maximise energy generation. The utilisation of simulation techniques employing models such as LANS and RANS facilitates the estimation of annual energy production, energy efficiency, and environmental impact resulting from the extraction of tidal energy from a large area. This is achieved by analysing the residual effects of the trails left behind after the devices interacts. In a recent study, Ebakumo [37] utilised MATLAB simulations to investigate the potential effects of tidal energy generation on the ecosystem at the site. The results suggest that the harvesting of tidal energy may have negative impacts on migrating species of organisms and lead to the accumulation of debris behind the deluge. To mitigate these issues, it is recommends that careful consideration be given to the design and construction of the barrage, as well as proper maintenance measures.

E. *Geothermal energy*

Eller et al., [38] Defines geothermal energy as a renewable energy source that has the potential to generate both heat and electricity while emitting low levels of carbon. In the extraction of heat for power generation, geothermal wells are most suitable due to their temperature [39]. He further states that to better extract heat for power generation from geothermal wells, a heat exchanger can be added along with a closed loop system to get the heat. In his paper Zeng et al., [40] used TOUGH2-EOS1 to simulate the heat generation process and how much electricity can be generated from a fractured granite reservoir in the Yangbajing geothermal field while in his work he was able to produce an electrical power of about 20MW.

DYMOLA was used to model a double-stage Organic Rankine Cycle (ORC) (geothermal plants was employ to convert the heating power of brine to electricity) based on an already existing thermal plant in Germany [38]. He further confirmed that the simulation model acted like the real ORC and proved from his results that more power can be generated by increased heat extraction from using parallel HHT. Liu et al., [18] Did a similar thing his paper on the exploitation of geothermal energy and natural gas hydrates from a geothermal heat exchange well. He simulates this process using the HydrateRes simulation software to obtain the parameters needed (Figure 6).

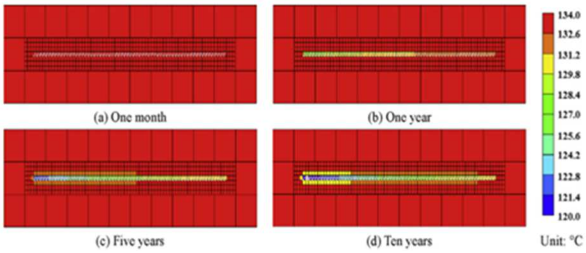

Figure 6: Heat distribution of a geothermal reservoir at different time periods using HydrateRes Sim. [18]

F. Bioenergy

Biomass is the first source of renewable energy that man harnessed [41]. It is the most efficient energy source for the generation of biofuel.[42]. It was defined by Adeleke et al., & Adegoke et al., [43,41] as a type of renewable energy gotten from plants and animal waste or organic matter. Energy resources like biomass are best used in situations where there is a need for storable fuel. Biofuels would always be an available and renewable source since they are constantly refilled[42]. Mazaheri et al., [44] pressed that simulation is required to improve the efficiency of the conversion of biomass to bioenergy. Karim et al., [45] used AVL Fire a CFD Simulation software to simulate the combustion of biomass in the presence of oxygen in a biomass grate furnace using wet wood as the biomass fuel, he simulated the burning in 4 different conditions of oxy-fuel ratios. In a bid to comply with the United Nation's Sustainable Development Goals, Martinez-Hernandez et al., [46] used TESARREC, IMPBio2Energy (The Mexican Petroleum Research Institute's in-house software), AspenPlus were used to simulate scenarios of bioenergy production with a forest-based system and it was discovered with the results that only about 0.23 cents per kWh was needed to produce 1 MWe fulfilling the SDG7 of making energy "affordable and clean" (SDG7). Forest-based energy systems were also seen to suppress greenhouse gas release by about 90% achieving the SDG6 of "clean water and sanitation for all" (SDG6) [46].
Akhtari & Sowlati, [47] used a Monte Carlo Simulation of a DES model to proffer a solution that converts the variations that occur when planning a biomass supply chain which would in turn maximise the profits a business owner would get from a bioenergy/biofuel project.

III. Conclusions

This paper has provided information into the part simulation plays in the advancement of energy generation. With the advent of simulation and its ability to replicate systems by modelling an already existing one. With this technology, it would be easy to identify, investigate whatever problem or risks is involved, help analyse the benefits and even proffer solutions to identified problems. This would enable governments, private individuals, businesses, etc looking to venture into the industry that is renewable energy generation. The use of simulation technology has been tested to be able to study, advance and upgrade different aspects of energy generation systems especially renewable energy generation. In conclusion, simulation technology has become very crucial in the field of energy generation allowing a deeper understanding of the process and giving one a powerful aid in decision making. It's unceasing advancement and application in energy generation will without doubt play a huge role in the world's transition to a greener and cleaner future.

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