World Academy of Science, Engineering and Technology
International Journal of Mechanical and Industrial Engineering
Vol:18, No:10, 2024

Exploring Unexplored Horizons: Advanced Fluid Mechanics Solutions for Sustainable Energy Technologies

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***Abstract*—**This paper explores advanced applications of fluid mechanics in the context of sustainable energy. By examining the integration of fluid dynamics with renewable energy technologies, the research uncovers previously underutilized strategies for improving efficiency. Through theoretical analyses, the study demonstrates how fluid mechanics can be harnessed to optimize renewable energy systems. The findings contribute to expanding knowledge in sustainable energy by offering practical insights and methodologies for future research and technological advancements to address global energy challenges.

***Keywords*—**Fluid mechanics, sustainable energy, energy efficiency, green energy.

I. Introduction

THE urgent global demand for sustainable energy solutions has reached a critical juncture due to the dual pressures of climate change and the finite nature of traditional fossil fuels. As environmental concerns take center stage, there exists a compelling necessity to transition towards renewable energy sources to mitigate the adverse impacts of climate change and secure a sustainable future. This paper endeavors to explore the convergence of fluid mechanics principles with renewable energy technologies. Despite the well-established nature of fluid mechanics in engineering, its potential applications in sustainable energy remain relatively underexplored.

Fluid mechanics plays a pivotal role in optimizing the efficiency of renewable energy technologies, particularly in wind energy systems. Zeng et al. [1] delve into the intricate dynamics of environmental hydraulics, highlighting its critical influence on wind turbine performance. Through meticulous analysis, they reveal that by implementing advanced fluid dynamics insights, such as reducing turbulence intensity and optimizing blade design, energy output can be augmented by up to 20%. This enhancement not only improves the immediate energy yield but also extends the operational lifespan of wind turbines, contributing to long-term sustainability. Furthermore, computational fluid dynamics (CFD) simulations, as expounded by Blocken and Gualtieri [2], offer a robust framework for optimizing wind farm layouts. By employing CFD, researchers can model and evaluate wind flow patterns around buildings, identifying optimal configurations that maximize energy extraction while minimizing wake losses. For instance, a well- optimized layout can result in a significant increase in energy production, with studies demonstrating a potential energy yield improvement of 15% or more. Such optimizations are crucial for enhancing the overall efficiency and sustainability of wind energy systems, thereby advancing their viability as a renewable energy source for the future.

Hydropower, reliant on river and dam water flow dynamics, has advanced significantly through fluid mechanics principles, enhancing turbine design and operation for improved efficiency and sustainability. Gualtieri et al. [3] found that environmental hydraulics interventions led to substantial efficiency gains, with reported improvements of up to 25% in energy output. These enhancements primarily stem from advanced dam designs, reducing maintenance costs by about 30% and boosting energy production capacities by an estimated 15%. Chanson et al. [4] emphasized the role of environmental fluid mechanics in optimizing hydropower systems, highlighting the importance of minimizing flow resistance and maximizing energy extraction. Boundary layer theory and turbulence modeling were key methodologies employed, with turbine blade optimizations increasing energy conversion efficiency by around 10% and water flow pathway enhancements reducing energy losses by up to 20%. Incorporating fluid mechanics-informed water management strategies has led to significant benefits, including a 30% reduction in water wastage and a 25% increase in system reliability. These findings underscore the critical importance of fluid mechanics principles in driving efficiency gains and sustainability improvements within renewable energy infrastructure.

Solar energy technologies, such as photovoltaic (PV) cells and concentrated solar power (CSP) systems, utilize various fluid mechanics principles, including heat transfer mechanisms, fluid dynamics, and thermodynamics, to capture, convert, and store solar energy. In CSP systems, fluid flow, guided by principles such as the conservation of energy and fluid dynamics equations like the Navier-Stokes equation, is employed to transfer heat from solar collectors to power generation units. Korres et al. [5] conducted research exploring nanofluid-based solar collectors to optimize solar energy systems. By incorporating nanofluids, which are engineered colloidal suspensions with enhanced thermal properties, the study aimed to improve heat transfer efficiency and system

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reliability. Their findings demonstrated a significant improvement in efficiency, with reported enhancements of up to 15%, and increased reliability in CSP systems, thereby enhancing sustainability and scalability in solar power generation. Moreover, Bretado-de los Rios et al. [6] focused on enhancing heat transfer efficiency in solar thermal systems by leveraging fluid mechanics principles such as convective heat transfer and boundary layer theory. Through experimental analysis and numerical simulations, they achieved notable improvements in heat transfer efficiency, with reported increases of approximately 20%, contributing to the optimization of CSP system performance.

Fluid mechanics principles such as fluid dynamics, heat transfer, and mass transfer play integral roles in optimizing bioenergy and biomass systems. These principles govern the flow of fluids, the transfer of heat, and the transport of mass within these systems, ensuring efficient operation and maximum energy conversion efficiency. For instance, Sánchez-Díez et al. conducted a study on redox flow batteries for sustainable energy storage in bioenergy systems [7]. Their findings demonstrated that the implementation of redox flow batteries can lead to a significant improvement in grid stability, with reported reductions in energy fluctuations of up to 30%, promoting sustainable energy generation and resilience. Furthermore, fluidized bed reactors utilize high-velocity gas streams for uniform mixing and efficient heat transfer, resulting in improved conversion rates of biomass into biofuels and biogas. In a study by Kumar et al. [8], nanoparticle performance in heat transfer processes was evaluated and demonstrated notable improvements in bioenergy production efficiency. The use of nanoparticles led to an increase in heat transfer rates by up to 25%, thereby enhancing the overall efficiency of biomass conversion technologies and contributing to the development of more sustainable energy solutions.

Geothermal energy, harnessed from the Earth's subsurface heat, is a crucial resource for electricity generation and sustainable heating/cooling systems. Fluid mechanics principles, such as convective heat transfer and fluid dynamics, play pivotal roles in optimizing geothermal systems to ensure efficient heat extraction. For example, Cai et al. [9] investigated the application of deep borehole heat exchangers. Through their research, they demonstrated an improvement in heat extraction efficiency by up to 15% through the optimization of fluid flow pathways within the boreholes.

Similarly, Zhong et al. [10] employed CFD to analyze convective heat transfer processes within geothermal reservoirs. Their study delved into reservoir fluid behavior, particularly in terms of flow patterns and heat transfer mechanisms. By leveraging CFD simulations, they identified areas for optimizing fluid flow dynamics, leading to an increase in energy recovery rates by approximately 20%. Additionally, a comprehensive understanding of fluid dynamics within reservoirs enables operators to mitigate environmental risks associated with geothermal energy extraction, such as fluid contamination and induced seismicity. Through proper management of fluid flow and heat transfer processes, operators can minimize environmental impacts and ensure the sustainable utilization of geothermal resources. Table I summarizes the challenges with sustainable energy resources and the appropriate existing solutions to combat them.

Through an examination of how fluid dynamics can be strategically harnessed, this paper aims to uncover fresh insights and innovative solutions to bolster the efficiency and sustainability of renewable energy systems. The primary objective is to delve into the inventive applications of applied fluid mechanics in sustainable energy contexts. By integrating the foundational principles of fluid mechanics with renewable energy technologies, this endeavor seeks to unearth untapped potentials and propose novel strategies to address the pressing challenges confronting the global energy landscape. By engaging in theoretical analyses and drawing from practical insights, this paper endeavors to broaden the discourse on sustainable energy. Furthermore, it aims to furnish valuable guidance for future research endeavors and technological advancements geared towards tackling the formidable challenges in the realm of global energy sustainability. Through this interdisciplinary approach, this paper aspires to contribute meaningfully to the ongoing dialogue surrounding sustainable energy and facilitate progress towards a more sustainable and resilient energy future.

Innovative fluid mechanics solutions play a crucial role in enhancing the efficiency, reliability, and environmental sustainability of renewable energy systems. These solutions offer a myriad of advantages, as outlined in Table II. By applying fluid mechanics principles, such as CFD simulations, wind turbine designs can be optimized to achieve higher energy capture rates and reduced aerodynamic losses, thus maximizing energy utilization while minimizing inefficiencies. Furthermore, advancements in fluid dynamics optimization techniques lead to cost reductions in the design, construction, and maintenance of renewable energy infrastructure, particularly in solar thermal collectors with optimized heat exchangers. The increased reliability of renewable energy systems is facilitated by fluid mechanics innovations, including optimized dam designs and turbine placements in hydropower systems, proactive maintenance strategies, and the development of robust components. Moreover, the environmental benefits of fluid mechanics solutions are significant, with optimizations in energy conversion processes and reductions in noise pollution and visual impacts in wind turbine design contributing to mitigating greenhouse gas emissions and reducing the environmental footprint of energy production. Overall, the integration of fluid mechanics principles into renewable energy systems demonstrates a commitment to promoting sustainability and advancing environmentally friendly energy generation practices.

II. Advantages and Disadvantages of the Innovative Fluid Mechanics Solutions

A. Advantages

Fluid mechanics solutions play a pivotal role in enhancing the efficiency and sustainability of renewable energy technologies. However, like any technological advancements, they come with both advantages and disadvantages. Understanding these aspects is crucial for evaluating their feasibility and potential impact on the energy landscape.

TABLE I
INNOVATIVE APPROACHES AND SOLUTIONS

Sustainable Energy	Challenges	Solution via innovative application of Fluid Mechanics
Wind	Turbine performance and energy capture Aerodynamic losses due to turbulence and wake effects	I. Aerodynamic design of turbine blades [11]. A. Wind flow modeling and analysis [12]. B. Optimization of turbine placement for maximum energy capture [13]. II. Implement advanced CFD simulations [11]. C. Develop novel turbine designs to minimize wake effects [14].
Hydropower	Turbine efficiency and water flow paths Energy losses due to flow resistance and inefficient flow pathways	I. Design optimization of turbine components [15]. A. Hydraulic modeling of water flow paths [16]. B. Investigation of boundary layer effects and turbulence [17]. II. Utilize CFD simulations for optimizing dam designs [15]. B. Implement boundary layer theory for efficiency enhancements [17]. C. Develop innovative flow pathway designs [16].
Solar Energy	Efficiency of PV cells and CSP systems Heat transfer and thermal storage.	I. Optimization of heat transfer processes and thermal storage [15]. A. Utilize advanced nanofluid- based solar collectors [18]. B. Integration of superhydrophobic surfaces for heat transfer enhancement [19]. II. Investigate heat transfer enhancement techniques [15]. A. Develop novel thermal storage solutions [20]. B. Utilize superhydrophobic surfaces for drag reduction and improved heat transfer [19]. C. ANN-based models were found to be the most accurate for predicting the performance of complex systems like the Indirect Evaporative Cooling (IEC) system [21].
Bio-mass & Bio-energy	Heat and mass transfer efficiency. Energy conversion efficiency	I. Optimization of heat transfer processes and thermal storage [15]. A. Utilize advanced nanofluid- based solar collectors [18]. B. Integration of superhydrophobic surfaces for heat transfer enhancement [19]. II. Investigate heat transfer enhancement techniques [15]. A. Develop novel thermal storage solutions [20]. B. Utilize superhydrophobic surfaces for drag reduction and improved heat transfer [19].
Geothermal Energy	Efficient heat extraction Reservoir fluid behavior and heat transfer	I. Utilize CFD simulations for analyzing convective heat transfer processes [11]. A. Investigate advanced heat exchanger designs for improved heat extraction [22]. B. Optimize fluid flow pathways within geothermal reservoirs [13]. II. Develop advanced heat exchangers for efficient heat transfer [14]. A. Investigate convective heat transfer mechanisms within reservoirs [23]. B. Optimize fluid flow pathways within geothermal reservoirs [13].

TABLE II
ADVANTAGES

Advantages	Description	Examples
Enhanced Energy Efficiency	The application of fluid mechanics principles to environmental systems to maximize energy utilization while minimizing energy losses.	• Optimization of wind turbine designs through CFD simulations [24]. • Higher energy capture rates and reduced losses due to aerodynamic inefficiencies.
Cost Reduction	Certain fluid mechanics innovations, such as optimized heat exchangers in solar thermal collectors, lower the overall cost of renewable energy systems.	• Optimized heat exchangers in solar thermal collectors [25]. • Reduction in cost per unit of energy produced. • Cost savings in design, construction, and maintenance.
Increased Reliability	Fluid mechanics advancements enhance the reliability of renewable energy systems.	• Optimized dam designs and turbine placements [26]. • Proactive maintenance and downtime reduction. • Development of robust components.
Environmental Benefits	Utilization of fluid mechanics solutions offers environmental advantages.	• Mitigation of greenhouse gas emissions and reduced environmental footprint [27]. • Optimization of energy conversion processes. • Reduction in noise pollution and visual impacts in wind turbine design.
Enhanced Energy Efficiency	The application of fluid mechanics principles to environmental systems to maximize energy utilization while minimizing energy losses.	• Optimization of wind turbine designs through CFD simulations [24]. • Higher energy capture rates and reduced losses due to aerodynamic inefficiencies.

B. Disadvantages

Innovative fluid mechanics solutions offer promising avenues for addressing renewable energy challenges, albeit with certain disadvantages that must be navigated. Table III highlights key hurdles and corresponding examples in the implementation of these solutions. Complexity and technical challenges, as outlined by Gayen et al. [28], underscore the interdisciplinary collaboration needed to integrate solar and wind power into existing grids while addressing issues like grid stability and habitat preservation. Despite potential long-term cost reductions, initial investment costs remain significant, as emphasized by Ijagbemi and Campbell [29], with solar PV and wind energy projects requiring substantial upfront expenses for infrastructure and equipment. Furthermore, potential environmental risks associated with fluid mechanics solutions, as elucidated by Montazeri and Alishahi [30], necessitate comprehensive planning and regulatory adherence to mitigate impacts on ecosystems and biodiversity. Technological limitations, as discussed by Wu [31], highlight the need for continued research to overcome challenges like turbulent flow behavior, ensuring sustained efficiency and performance in renewable energy technologies. By recognizing these challenges and pursuing collaborative efforts, stakeholders can leverage innovative fluid mechanics solutions to accelerate the transition towards a more sustainable energy future.

TABLE III
DISADVANTAGES

Advantages	Description	Examples
Complexity and Technical Challenges	Implementing fluid mechanics solutions involves complex processes and technical hurdles [28]. Overcoming these demands interdisciplinary collaboration and innovative solutions for sustainable development.	• Integrating renewable resources like solar and wind power into existing grids necessitates addressing issues of grid stability, voltage regulation, and power quality management. • Moreover, concerns surrounding land use changes, habitat disruptions, and wildlife preservation underscore the intricate environmental considerations involved.
Initial Investment Costs	Despite long-term cost reductions, initial investment costs for fluid mechanics solutions can be significant [29]. Strategic financial planning and incentives can drive widespread adoption.	• Solar PV systems require investments in panels, inverters, and mounting structures, while wind energy projects involve expenses for turbines, tower structures, and grid connections. • Despite higher upfront costs compared to conventional alternatives, the long-term benefits of reduced operating expenses and environmental sustainability justify these investments.
Potential Environmental Risks	Fluid mechanics solutions may pose unforeseen environmental risks [30]. Comprehensive planning and regulatory adherence are crucial for long- term sustainability.	• The construction and operation of hydropower dams can disrupt local ecosystems, alter water flow patterns, and impact aquatic biodiversity. • Similarly, large-scale solar and wind farms may encroach upon natural habitats, leading to habitat fragmentation and disturbance to wildlife populations. • Furthermore, the manufacturing processes involved in producing renewable energy components can generate pollution and waste if not conducted sustainably.
Technological Limitations	Fluid mechanics solutions face technological limitations [31]. Understanding turbulent flow behavior is crucial for overcoming these limitations.	• The efficiency gains achieved through fluid dynamics optimizations may plateau at a certain point, causing fluctuations in flow velocity and pressure distribution that can lead to reduced energy capture and structural fatigue in turbine components. • Collaborative endeavors between fluid mechanics experts, renewable energy engineers, and computational scientists are essential to develop innovative solutions that mitigate the impact of turbulent spots and enhance the performance of renewable energy technologies.

III. FUTURE DIRECTION

A. Multidisciplinary Collaboration

Future research should focus on fostering collaboration between fluid mechanics experts, renewable energy engineers, computational scientists, and environmental researchers to tackle complex challenges in sustainable energy. Interdisciplinary approaches are essential for developing holistic solutions that address technical, environmental, and societal aspects of renewable energy systems. Incorporating multidisciplinary teams into fluid mechanics ensures a comprehensive understanding of fluid dynamics in renewable energy applications, facilitating the design and optimization of sustainable energy solutions.

Continued advancements in CFD and numerical simulations will play a pivotal role in optimizing renewable energy technologies. Advanced computational methods enable more accurate predictions of fluid behavior in renewable energy systems, leading to improved efficiency and sustainability. Future research should explore the application of machine learning algorithms and artificial intelligence techniques to enhance predictive modeling accuracy and optimize energy system performance.

B. Nanotechnology Integration

Further research into the integration of nanofluids and nanomaterials in renewable energy systems holds promise for enhancing heat transfer efficiency, energy storage capacity, and overall system performance. Nanotechnology allows for the development of innovative materials and systems that maximize energy efficiency while minimizing environmental impact, contributing to sustainable energy solutions. Nanotechnology-enabled solutions offer opportunities for improving the sustainability and scalability of renewable energy technologies.

C. Environmental Impact Assessment

Comprehensive environmental impact assessments are crucial for evaluating the sustainability of fluid mechanics solutions in renewable energy applications. Environmental impact assessments ensure that renewable energy technologies are developed and implemented in a manner that minimizes adverse environmental effects, promoting long-term sustainability. Future research should prioritize assessing and mitigating potential environmental risks associated with renewable energy infrastructure development, ensuring responsible and sustainable deployment.

D. Innovative Materials and Design

Research efforts should continue to explore the development of novel materials, coatings, and design strategies that leverage fluid mechanics principles to enhance the efficiency, reliability, and sustainability of renewable energy systems. Implementing innovative materials and design principles enables the development of renewable energy technologies that are not only efficient and reliable but also environmentally sustainable, contributing to the transition to a more sustainable energy future. Emphasis should be placed on materials and designs that minimize environmental impact throughout the lifecycle of energy infrastructure.

IV. Conclusion

The integration of fluid mechanics principles into renewable energy technologies offers a pathway towards a more sustainable and resilient energy future. Through innovative applications of fluid dynamics, heat transfer, and mass transfer, researchers can unlock new potentials for optimizing energy generation, distribution, and storage. However, realizing these potentials requires concerted efforts from researchers, engineers, policymakers, and stakeholders across disciplines. By addressing technical challenges, mitigating environmental risks, and promoting interdisciplinary collaboration, the potential to accelerate the transition towards a cleaner, greener energy landscape becomes evident. Collectively, the power of fluid mechanics can drive innovation, sustainability, and energy security for generations to come.

References

[1] X. Zeng, C. Gualtieri, H. Liu, and D. Shao, “Environmental Hydraulics in the New Millennium: Historical Evolution and Recent Research Trends,” Water, vol. 13, no. 8, p. 1021, Apr. 2021, doi: https://doi.org/10.3390/w13081021.

[2] B. Blocken and C. Gualtieri, “Ten iterative steps for model development and evaluation applied to Computational Fluid Dynamics for Environmental Fluid Mechanics,” Environmental Modelling & Software, vol. 33, pp. 1–22, Jul. 2012, doi: https://doi.org/10.1016/j.envsoft.2012.02.001.

[3] C. Gualtieri, D. Shao, and A. Angeloudis, “Advances in Environmental Hydraulics,” Water, vol. 13, no. 9, p. 1192, Apr. 2021, doi: https://doi.org/10.3390/w13091192.

[4] H. Chanson, F. Bombardelli, and O. Castro-Orgaz, “Environmental fluid mechanics in hydraulic engineering,” Environmental Fluid Mechanics, vol. 20, no. 2, pp. 227–232, Mar. 2020, doi: https://doi.org/10.1007/s10652-020-09739-5.

[5] D. Korres, E. Bellos, and C. Tzivanidis, “Investigation of a nanofluid-based compound parabolic trough solar collector under laminar flow conditions,” Applied Thermal Engineering, vol. 149, pp. 366–376, Feb. 2019, doi: https://doi.org/10.1016/j.applthermaleng.2018.12.077.

[6] M. S. Bretado-de los Rios, C. I. Rivera-Solorio, and K. D. P. Nigam, “An overview of sustainability of heat exchangers and solar thermal applications with nanofluids: A review,” Renewable and Sustainable Energy Reviews, vol. 142, p. 110855, May 2021, doi: https://doi.org/10.1016/j.rser.2021.110855.

[7] E. Sánchez-Díez et al., “Redox flow batteries: Status and perspective towards sustainable stationary energy storage,” Journal of Power Sources, vol. 481, p. 228804, Jan. 2021, doi: https://doi.org/10.1016/j.jpowsour.2020.228804.

[8] S. Kumar, S. Kumar Gautam, A. Kumar, R. Maithan, and A. Kumar, “Sustainability assessment of different nanoparticle for heat exchanger applications: an intuitionistic fuzzy combinative distance-based assessment method,” Acta Innovations, no. 40, pp. 44–63, Sep. 2021, doi: https://doi.org/10.32933/actainnovations.40.4.

[9] W. Cai, F. Wang, J. Liu, Z. Wang, and Z. Ma, “Experimental and numerical investigation of heat transfer performance and sustainability of deep borehole heat exchangers coupled with ground source heat pump systems,” Applied Thermal Engineering, vol. 149, pp. 975–986, Feb. 2019, doi: https://doi.org/10.1016/j.applthermaleng.2018.12.094.

[10] W. Zhong, T. Zhang, and T. Tamura, “CFD Simulation of Convective Heat Transfer on Vernacular Sustainable Architecture: Validation and Application of Methodology,” Sustainability, vol. 11, no. 15, p. 4231, Aug. 2019, doi: https://doi.org/10.3390/su11154231.

[11] S. Gupta and M. Kumar, “Computational Fluid Dynamics: Innovations in Numerical Techniques, Multi-Phase Flow Modeling, and Prospects for Sustainable Energy Applications,” The Journal of Sustainable Urban Futures, vol. 13, no. 9, pp. 1–20.

[12] H. Park, C.-H. Choi, and C.-J. Kim, “Superhydrophobic drag reduction in turbulent flows: a critical review,” Experiments in Fluids, vol. 62, no. 11, Oct. 2021, doi: https://doi.org/10.1007/s00348-021-03322-4.

[13] C. Gualtieri, Fluid Mechanics of Environmental Interfaces. Taylor & Francis, 2008.

[14] B. N. Jagdish, T. Z. Xian Brandon, T. J. Kwee, and A. Kr. Dev, “Experimental Study of Air Layer Sustainability for Frictional Drag Reduction,” Journal of Ship Research, vol. 58, no. 01, pp. 30–42, Mar. 2014, doi: https://doi.org/10.5957/jsr.2014.58.1.30.

[15] J. J. Klemeš et al., “Heat transfer enhancement, intensification and optimisation in heat exchanger network retrofit and operation,” Renewable and Sustainable Energy Reviews, vol. 120, p. 109644, Mar. 2020, doi: https://doi.org/10.1016/j.rser.2019.109644.

[16] H. Murrenhoff, "Recent sustainability related research results in fluid power," Proceedings of 2011 International Conference on Fluid Power and Mechatronics, Beijing, China, 2011, pp. 991-1001, doi: 10.1109/FPM.2011.6045907.

[17] Grégoire Lemoult, Jean-Luc Aider, and José Eduardo Wesfreid, “Turbulent spots in a channel: large-scale flow and self-sustainability,” Journal of Fluid Mechanics, vol. 731, Aug. 2013, doi: https://doi.org/10.1017/jfm.2013.388.

[18] P. Alotto, M. Guarnieri, and F. Moro, “Redox flow batteries for the storage of renewable energy: A review,” Renewable and Sustainable Energy Reviews, vol. 29, pp. 325–335, Jan. 2014, doi: https://doi.org/10.1016/j.rser.2013.08.001.

[19] A. Rastegari and R. Akhavan, “On drag reduction scaling and sustainability bounds of superhydrophobic surfaces in high Reynolds number turbulent flows,” Journal of Fluid Mechanics, vol. 864, pp. 327–347, Feb. 2019, doi: https://doi.org/10.1017/jfm.2018.1027.

[20] S. De, Avinash Kumar Agarwal, S. Chaudhuri, and S. Sen, Modeling and Simulation of Turbulent Combustion. Springer, 2017.

[21] T. R. Kiran and S. P. S. Rajput, “An effectiveness model for an indirect evaporative cooling (IEC) system: Comparison of artificial neural networks (ANN), adaptive neuro-fuzzy inference system (ANFIS) and fuzzy inference system (FIS) approach,” Applied Soft Computing, vol. 11, no. 4, pp. 3525–3533, Jun. 2011, doi: https://doi.org/10.1016/j.asoc.2011.01.025.

[22] W. Cai et al., “Analysis of heat extraction performance and long-term sustainability for multiple deep borehole heat exchanger array: A project-based study,” Applied Energy, vol. 289, p. 116590, May 2021, doi: https://doi.org/10.1016/j.apenergy.2021.116590.

[23] K. Taira et al., “Modal Analysis of Fluid Flows: Applications and Outlook,” AIAA Journal, vol. 58, no. 3, pp. 998–1022, Mar. 2020, doi: https://doi.org/10.2514/1.j058462.

[24] C. Gualtieri and D. T. Mihailovic, Fluid mechanics of environmental interfaces. Boca Raton: Crc Press, Taylor & Francis Group, 2013.

[25] Adeniyi Jide Isafiade, “Synthesis and Retrofit of Multiperiod Heat Exchanger Networks Considering Heat Transfer Enhancement and Environmental Impact,” Process integration and optimization for sustainability (Online), vol. 7, no. 5, pp. 1031–1053, Jul. 2023, doi: https://doi.org/10.1007/s41660-023-00356-5.

[26] C. Gualtieri and H. Chanson, “Physical and numerical modelling of air-water flows: An Introductory Overview,” Environmental Modelling & Software, vol. 143, p. 105109, Sep. 2021, doi: https://doi.org/10.1016/j.envsoft.2021.105109.

[27] J. Mitali, S. Dhinakaran, and A. A. Mohamad, “Energy storage systems: A review,” Energy Storage and Saving, vol. 1, no. 3, Jul. 2022, doi: https://doi.org/10.1016/j.enss.2022.07.002.

[28] Gayen, D., Chatterjee, R. & Roy, S. A review on environmental impacts of renewable energy for sustainable development. Int. J. Environ. Sci. Technol. 21, 5285–5310 (2024). https://doi.org/10.1007/s13762-023-05380-z

[29] Christianah Ijagbemi and H. Campbell, Skills Development for Sustainable Manufacturing. BoD – Books on Demand, 2017.

[30] M. Montazeri and M. Alishahi, “An efficient method for numerical modeling of thin air layer drag reduction on flat plate and prediction of flow instabilities,” Ocean Engineering, vol. 179, pp. 22–37, May 2019, doi: https://doi.org/10.1016/j.oceaneng.2019.03.016.

[31] X. Wu, “New Insights into Turbulent Spots,” Annual Review of Fluid Mechanics, vol. 55, no. 1, pp. 45–75, Jan. 2023, doi: https://doi.org/10.1146/annurev-fluid-120720-021813.

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