World Journal of Advanced Research and Reviews

eISSN: 2581-9615 CODEN (USA): WJARAI

Cross Ref DOI: 10.30574/wjarr

Journal homepage: https://wjarr.com/

(Review Article)

Artificial Intelligence in Climate Change Mitigation: A Review of Predictive Modeling and Data-Driven Solutions for Reducing Greenhouse Gas Emissions

Adedolapo Olujuwon Adegbite [1], Ibrahim Barrie [2, *], Saheed Femi Osholake [3], Tunde Alesinloye [4] and Anuoluwapo Blessing Bello [5]

[1] D&I Geosolutions, Schlumberger Oilfield Services, Port Harcourt, Nigeria.
[2] Electrical and Computer Engineering, Southern Illinois University Edwardsville, USA.
[3] Information Science, Ball State University, Muncie Indiana.
[4] Mathematics, University of North Dakota, USA.
[5] Project Management, Saint Louis University, Missouri, USA.

World Journal of Advanced Research and Reviews, 2024, 24(01), 408–414

Publication history: Received on 25 August 2024; revised on 02 October 2024; accepted on 04 October 2024

Article DOI: https://doi.org/10.30574/wjarr.2024.24.1.3043

Abstract

Artificial Intelligence (AI) is increasingly recognized as a powerful tool for addressing the challenges of climate change. Its ability to process vast amounts of data and generate advanced predictive models positions AI as a key player in efforts to reduce greenhouse gas (GHG) emissions and develop sustainable solutions. This review delves into the multifaceted role of AI in climate change mitigation, highlighting its potential in several critical areas. Firstly, AI is revolutionizing predictive climate modeling by providing more accurate forecasts and simulations, enabling better-informed policy and decision-making. Secondly, it is optimizing energy systems through smart grid management, demand forecasting, and the integration of renewable energy sources, thereby enhancing energy efficiency and reducing reliance on fossil fuels. Furthermore, AI is advancing carbon capture and storage technologies by improving the identification of optimal sites and enhancing process efficiency. In environmental monitoring, AI-driven solutions are enabling real-time detection and analysis of environmental data, contributing to more effective conservation efforts. This review also presents case studies and data that demonstrate the tangible impact of AI applications in driving progress towards global emission reduction targets. However, the adoption of AI in this domain is not without challenges. Issues such as data privacy, algorithmic transparency, and the ethical implications of AI deployment need to be carefully addressed. The paper concludes by outlining future research directions and emphasizing the need for interdisciplinary collaboration to fully harness the potential of AI in combating climate change.

Keywords: Artificial Intelligence; Greenhouse gas (GHG) emissions; Environmental Sustainability; Global Emission Reduction; and Renewable Energy

1. Introduction

The rate at which the earth is change is unprecedented. Climate change represents one of the most pressing global challenges of the 21st century, with greenhouse gas (GHG) emissions being the primary driver. [1] As efforts intensify to limit global warming, Artificial Intelligence (AI) has become a key enabler in reducing emissions and facilitating sustainable solutions [2]. AI technologies, particularly through predictive modeling and big data analysis, offer innovative pathways for improving the efficiency of energy systems, optimizing industrial processes, and enhancing environmental management practices [3].

* Corresponding author: Ibrahim Barrie

This paper reviews the role of AI in climate change mitigation, examining how predictive modeling and data-driven solutions are being applied to reduce GHG emissions. We focus on AI's ability to forecast climate impacts, optimize renewable energy systems, enhance carbon capture, and facilitate data-driven policies aimed at emission reduction.

Figure 1 An overview of the framework for recording data to data storage, analysis, modelling and finally results communication to the appropriate authorities [4]

2. AI-Powered Predictive Climate Modeling

2.1. Machine Learning in Climate Predictions

Machine learning (ML) has revolutionized climate modeling by allowing the analysis of vast datasets, enabling more accurate predictions of future climate scenarios [5]. Traditional climate models rely on physics-based simulations that require intensive computational resources and often suffer from uncertainties due to the complexity of atmospheric and oceanic systems. AI, especially ML, offers a complementary approach by learning patterns from historical climate data, improving the accuracy and precision of predictions [6].

For instance, convolutional neural networks (CNNs) and recurrent neural networks (RNNs) have been used to predict extreme weather events like hurricanes and floods, providing better early-warning systems for communities and governments. Such predictive capabilities help policymakers plan mitigation strategies and resource allocation [7, 8].

2.2. AI Models for Long-Term Climate Projections

Long-term climate projections are essential for understanding the potential impacts of GHG emissions on global temperatures, sea level rise, and ecosystem shifts [9]. AI-driven models have been used to improve the granularity and reliability of such projections by integrating data from multiple sources, including satellite imagery, ocean buoys, and historical climate records [4, 10, 11].

- **Case Study**: In a 2022 study, a deep learning-based climate model outperformed traditional models in predicting temperature anomalies across North America over a 50-year horizon. The AI model reduced the uncertainty margin by 20%, which is crucial for making informed policy decisions on emission reductions [12].

3. AI in Optimizing Energy Systems

3.1. Renewable Energy Optimization

Renewable energy sources like solar, wind, and hydropower play a critical role in reducing GHG emissions. However, the intermittent nature of these energy sources poses challenges for consistent supply [13]. AI can optimize energy production and distribution by forecasting energy demand and supply, thereby improving the efficiency of renewable energy grids [14].

Machine learning algorithms are employed to predict wind speeds, solar radiation, and energy demand patterns, enabling more efficient integration of renewable energy into the grid. Additionally, AI-driven energy management systems can dynamically adjust energy storage and distribution to minimize waste and reduce reliance on fossil fuel backups [15].

- **Survey Data**: In a survey conducted with 100 energy system operators in Europe, 85% reported significant improvements in grid stability and reduced reliance on fossil fuels after integrating AI-based energy management systems [16].

3.2. Reducing Energy Consumption in Industrial Processes

Industries account for a significant portion of global GHG emissions, particularly in energy-intensive sectors such as manufacturing, mining, and transportation. [17] AI technologies can be employed to optimize industrial processes by reducing energy consumption and improving efficiency. AI-powered systems can monitor real-time energy usage, identify inefficiencies, and suggest process adjustments that lower energy demand and emissions.

- **Example**: Siemens has implemented an AI-driven energy management system that reduced energy consumption in its factories by 10%, resulting in a corresponding reduction in carbon emissions [18].

4. AI-Enhanced Carbon Capture and Sequestration (CCS)

4.1. AI for Carbon Capture Technologies

Carbon Capture and Sequestration (CCS) is a crucial technology in mitigating climate change by capturing CO_2 emissions from industrial processes and power plants before they reach the atmosphere [19-20]. AI is being used to improve the efficiency of CCS technologies by optimizing the capture process, reducing energy consumption, and identifying optimal geological storage sites for long-term CO_2 sequestration.

AI algorithms analyze real-time data from carbon capture facilities, predicting equipment maintenance needs and optimizing chemical processes to enhance capture efficiency [21]. These algorithms also identify cost-effective methods for retrofitting existing power plants with CCS technology.

- **Case Study**: A 2021 study demonstrated that AI-powered CCS systems could capture up to 95% of CO_2 emissions from coal-fired power plants, significantly reducing the carbon footprint of these plants [22].

4.2. Monitoring and Verification of CO_2 Sequestration

Once CO_2 is captured and stored underground, monitoring its behavior is critical to ensure it remains safely sequestered [23]. AI-driven monitoring systems use data from sensors and seismic imaging to track CO_2 movement in storage reservoirs, ensuring the gas does not leak back into the atmosphere. AI's ability to process vast amounts of data enables real-time monitoring, improving the safety and reliability of long-term carbon storage [24].

5. Data-Driven Solutions for Emission Reduction

5.1. AI for Emission Tracking and Reporting

One of the critical challenges in global climate agreements, such as the Paris Agreement, is tracking and reporting emissions across different sectors and regions [25]. AI is playing an essential role in automating emission tracking systems by processing large datasets from various industries and national governments. AI-driven tools can aggregate data from sensors, satellite imagery, and industrial reports to provide accurate and real-time emissions data, enabling governments to monitor their progress in meeting climate targets [26].

For instance, AI systems used by the Carbon Monitor initiative are capable of tracking CO_2 emissions in near real-time across major economic sectors, providing crucial data for global emission reduction efforts [27].

5.2. Optimizing Transportation for Reduced Emissions

Transportation accounts for nearly 25% of global CO_2 emissions, and AI is being used to mitigate this through smarter logistics, vehicle route optimization, and the promotion of electric vehicles (EVs) [28]. AI algorithms help optimize traffic flow, reduce congestion, and decrease fuel consumption by analyzing real-time traffic data and providing optimal route suggestions. Moreover, AI is helping accelerate the transition to EVs by improving battery efficiency, predicting energy consumption, and optimizing EV charging infrastructure.

- **Data**: A study showed that AI-based traffic optimization systems implemented in major European cities reduced vehicle emissions by 12% and decreased average travel times by 15% [29].

6. Results and Discussion

6.1. Data from AI Applications in Climate Change Mitigation

The data gathered from various studies and real-world implementations of AI systems in climate change mitigation present promising results. AI-driven climate models have shown a 20% improvement in predicting long-term climate anomalies, providing a more reliable foundation for policymaking [30] Additionally, AI-optimized renewable energy systems have demonstrated significant improvements in grid stability and energy efficiency, with grid operators reporting up to a 15% reduction in energy waste due to AI interventions [16].

The application of AI in carbon capture technologies has been particularly impactful, with AI-powered systems achieving a CO_2 capture rate of up to 95% from fossil fuel power plants [22]. This efficiency is a substantial improvement over traditional CCS systems, which typically capture only 85–90% of emissions. These advancements make AI an indispensable tool in reducing GHG emissions from energy-intensive sectors.

6.2. Limitations and Challenges

Despite its potential, the integration of AI into climate change mitigation strategies faces several challenges. One of the primary concerns is the energy consumption of AI systems themselves. Training large AI models requires significant computational power, which can lead to increased energy demand. While AI contributes to reducing emissions in various sectors, it is essential to ensure that AI technologies are developed and deployed in an energy-efficient manner.

Another limitation is the availability and quality of data. For AI systems to function effectively, they require vast amounts of accurate and high-resolution data. In many regions, especially in developing countries, such data is either scarce or unavailable, limiting the applicability of AI solutions for emission reduction.

Finally, ethical concerns surrounding AI decision-making must be addressed, particularly in the context of environmental justice. AI systems, if not designed with care, could exacerbate inequalities, with the benefits of AI-driven climate solutions disproportionately favoring wealthier nations or industries while leaving vulnerable populations at risk.

7. Challenges and Future Directions

To fully harness the power of AI in climate change mitigation, several challenges need to be addressed:

- **Data Availability**: Increasing the accessibility of high-quality environmental and industrial data is essential for the success of AI systems in tracking and reducing emissions.
- **Energy Efficiency of AI**: AI development needs to focus on minimizing its own carbon footprint. This can be achieved by exploring more energy-efficient algorithms and investing in renewable energy sources for AI computation.
- **Ethical AI Development**: AI solutions must be designed with fairness and inclusivity in mind to ensure that all communities benefit from climate change mitigation efforts.
- **Policy Support**: Governments need to develop clear regulatory frameworks to support the integration of AI in climate change strategies, ensuring transparency, accountability, and data security.

7.1. Future Research Directions

- Exploring the potential of quantum computing in enhancing AI's ability to model complex climate systems and reduce computational energy consumption.
- Investigating the use of AI in nature-based climate solutions, such as reforestation and sustainable land use practices, to further reduce GHG emissions.
- Developing AI systems that are adaptive to low-data environments, making them more applicable in regions with limited data availability

8. Conclusion

Artificial Intelligence is playing an increasingly critical role in global efforts to mitigate climate change by offering predictive modeling, optimizing energy systems, enhancing carbon capture technologies, and facilitating data-driven policy decisions. The application of AI has already demonstrated tangible benefits in reducing GHG emissions across various sectors, from renewable energy to industrial processes and transportation.

However, to maximize AI's potential in combating climate change, addressing challenges related to data availability, energy efficiency, and ethical deployment will be key. With continued investment in AI research and development, along with supportive policies and international collaboration, AI can become a cornerstone technology in achieving a sustainable and low-carbon future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Ledley, T.S., et al., Climate change and greenhouse gases. Eos, Transactions American Geophysical Union, 1999. 80(39): p. 453-458.

[2] Vellingiri, A., et al., Harnessing GPS, Sensors, and Drones to Minimize Environmental Impact: Precision Agriculture, in Designing Sustainable Internet of Things Solutions for Smart Industries. 2025, IGI Global. p. 77-108.

[3] Chaudhary, G., Environmental Sustainability: Can Artificial Intelligence be an Enabler for SDGs? Nature Environment & Pollution Technology, 2023. 22(3).

[4] Montillet, J.-P., et al., How big data can help to monitor the environment and to mitigate risks due to climate change: a review. IEEE Geoscience and Remote Sensing Magazine, 2024.

[5] Huntingford, C., et al., Machine learning and artificial intelligence to aid climate change research and preparedness. Environmental Research Letters, 2019. 14(12): p. 124007.

[6] Zennaro, F., et al., Exploring machine learning potential for climate change risk assessment. Earth-Science Reviews, 2021. 220: p. 103752.

[7] Oluwadare, S.A., M.A. Alakuro, and O.A. Sarumi. Early Warning System for Flood Disaster Risk Reduction Using Predictive Analytics. in International Conference on Intelligent Systems Design and Applications. 2023. Springer.

[8] Linardos, V., et al., Machine learning in disaster management: recent developments in methods and applications. Machine Learning and Knowledge Extraction, 2022. 4(2).

[9] Ghahfarokhi, M.F., S.H. Sonbolestan, and M. Zamanizadeh, A Comparative Study of Convolutional and Recurrent Neural Networks for Storm Surge Prediction in Tampa Bay. arXiv preprint arXiv:2408.05797, 2024.

[10] Khallaf, A.N., Using Ai to Help Reduce the Effect of Global Warming. Power System Technology, 2024. 48(1): p. 1927-1947.

[11] Curry, A., et al., Intelligent Infrastructure Futures: The Scenarios--Towards 2055. 2006: Foresight Directorate, Office of Science and Technology.

[12] Johnson, R., et al. (2022). Improving Long-Term Climate Predictions Using AI-Based Models. Climate Science Journal, 38(4), 112-130.

[13] Amponsah, N. Y., Troldborg, M., Kington, B., Aalders, I., & Hough, R. L. (2014). Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations. Renewable and Sustainable Energy Reviews, 39, 461-475.

[14] AI can optimize energy production and distribution by forecasting energy demand and supply, thereby improving the efficiency of renewable energy grids.

[15] Muniandi, B., Maurya, P. K., Bhavani, C. H., Kulkarni, S., Yellu, R. R., & Chauhan, N. (2024). AI-Driven Energy Management Systems for Smart Buildings. Power System Technology, 48(1), 322-337.

[16] Smith, A., & Harris, D. (2023). Survey on AI-Based Energy Management Systems in European Grids. Journal of Renewable Energy, 29(1), 80-98.

[17] Kucukvar, M., Cansev, B., Egilmez, G., Onat, N. C., & Samadi, H. (2016). Energy-climate-manufacturing nexus: New insights from the regional and global supply chains of manufacturing industries. Applied energy, 184, 889-904.

[18] Siemens Energy. (2021). AI-Powered Energy Management in Industrial Processes.

[19] Hammed, V. (2023). Solubility of CO2 in Paramagnetic Ionic Liquids (Master's thesis, North Carolina Agricultural and Technical State University).

[20] Hammed, Victor O., Taiwo Oluwanisola Omoloja, Yohannes T. Ogbandrias, Coolin-Campbell M. Zor, Daniel Edet Eyo, and Olasupo Baiyewunmi. "HARNESSING CARBON DIOXIDE (CO2): A CRUCIAL FACTOR IN ATTAINING ZERO EMISSIONS AND ENVIRONMENTAL SUSTAINABILITY IN THE 21ST CENTURY."

[21] Al-Sakkari, E. G., Ragab, A., Dagdougui, H., Boffito, D. C., & Amazouz, M. (2024). Carbon capture, utilization and sequestration systems design and operation optimization: Assessment and perspectives of artificial intelligence opportunities. Science of The Total Environment, 170085.

[22] Li, H., Zhang, Y., & Wang, J. (2021). AI-Driven Carbon Capture Technologies: Maximizing Efficiency in Coal-Fired Power Plants. Energy Systems Journal, 45(2), 210-225.

[23] Chadwick, R. A. (2010). Measurement and monitoring technologies for verification of carbon dioxide (CO2) storage in underground reservoirs. In Developments and Innovation in Carbon Dioxide (CO2) Capture and Storage Technology (pp. 203-239). Woodhead Publishing.

[24] Ahmad, T., Zhang, D., Huang, C., Zhang, H., Dai, N., Song, Y., & Chen, H. (2021). Artificial intelligence in sustainable energy industry: Status Quo, challenges and opportunities. Journal of Cleaner Production, 289, 125834.

[25] Falkner, R. (2016). The Paris Agreement and the new logic of international climate politics. International Affairs, 92(5), 1107-1125.

[26] Bachmann, N., Tripathi, S., Brunner, M., & Jodlbauer, H. (2022). The contribution of data-driven technologies in achieving the sustainable development goals. Sustainability, 14(5), 2497.

[27] Carbon Monitor. (2020). Real-Time Global CO_2 Emissions Data.

[28] Mandala, V., Surabhi, S. N. R. D., Kommisetty, P. D. N. K., Kuppala, B. M. S. R., & Ingole, R. (2024). Towards Carbon-Free Automotive Futures: Leveraging AI And ML For Sustainable Transformation. Educational Administration: Theory and Practice, 30(5), 3485-3497.

[29] Muller, A., et al. (2022). AI for Optimizing Transportation Systems: Reducing CO_2 Emissions in European Cities. Journal of Transportation Research, 18(6), 170-185.

[30] Amiri, Z., Heidari, A., & Navimipour, N. J. (2024). Comprehensive Survey of Artificial Intelligence Techniques and Strategies for Climate Change Mitigation. Energy, 132827