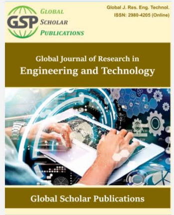
Global Journal of Research in
Engineering and Technology
Journal homepage: https://gsjournals.com/gjret/
ISSN: 2980-4205 (Online)



(Review Article)

Sustainability-driven electrical engineering optimizing energy efficiency through ai and developing eco-friendly electronics

Adeola Ona-Olapo Esho [1, *], Adeoye Taofik Aderamo [2] and Henry Chukwuemeka Olisakwe [3]

[1] *Independent Researcher, Osun State, Nigeria.*
[2] *Independent Researcher; Lagos Nigeria.*
[3] *Department of Mechanical Engineering, Nnamdi Azikiwe University, Awka, Nigeria.*

Global Journal of Research in Engineering and Technology, 2024, 02(02), 039–048

Publication history: Received on 21 August 2024; revis.ed on 01 October 2024; accepted on 04 October 2024

Article DOI: https://doi.org/10.58175/gjret.2024.2.2.0031

Abstract

This paper explores the transformative potential of AI-driven solutions in optimizing energy efficiency and the development of eco-friendly materials for electronics. As global energy consumption and electronic waste continue to rise, innovative technologies are essential to mitigate their environmental impact. AI models have shown significant promise in enhancing the performance of smart grids and residential and industrial energy systems by predicting and adjusting energy usage in real time. Additionally, the research and development of sustainable materials for semiconductors and electronic components offer an important pathway to reducing the environmental footprint of electronics manufacturing. By aligning these advancements with national sustainability and climate goals, this paper highlights the critical role of AI and sustainable materials in creating a more energy-efficient and environmentally responsible future. The paper concludes by suggesting areas for future research, emphasizing the long-term impact of these technologies on the electrical engineering field and their contribution to sustainability.

Keywords: AI-driven energy efficiency; Smart grids; Sustainable electronics materials; Energy optimization; Renewable energy integration

1 Introduction

1.1 Overview of Energy Challenges

The global energy demand has risen steadily over the past few decades, driven by population growth, urbanization, and increased industrial activity (Avtar, Tripathi, Aggarwal, & Kumar, 2019). This rise in demand has placed immense pressure on both natural resources and energy systems, leading to significant environmental concerns. The U.S., one of the world's largest energy consumers, faces similar challenges, particularly in reducing greenhouse gas emissions and managing energy consumption efficiently (Arent et al., 2022). Despite advancements in energy technologies, inefficiencies in electrical systems and energy distribution remain prevalent. These inefficiencies contribute to excessive energy waste, higher costs, and increased emissions, creating a pressing need for more effective solutions (J. Wang & Azam, 2024).

A major area of concern is the transmission and distribution of electricity. In the U.S., electrical grids are aging and often fail to meet modern efficiency standards. The reliance on fossil fuels for power generation further exacerbates environmental issues, as these energy sources contribute heavily to carbon emissions (Kartal, 2022). At the global level, efforts to transition to renewable energy sources such as solar and wind are underway, but they come with their own

* Corresponding author: Adeola Ona-Olapo Esho

challenges, particularly in terms of managing energy variability and grid stability. Balancing energy demand with sustainable generation and storage solutions remains a critical challenge in achieving global climate goals (Hanif, 2018).

Beyond inefficiencies in energy consumption, electronic waste (e-waste) is another significant environmental issue. The rapid advancement of technology and the increasing consumption of electronic devices have led to a surge in e-waste. According to a report by the United Nations, global e-waste amounted to 53.6 million metric tons in 2019, and this figure is expected to continue growing (Castro et al., 2023). Disposal of these devices is often mishandled, releasing hazardous substances like mercury, lead, and cadmium into the environment. This creates a dual challenge: how to address the growing demand for electronics while minimizing their environmental impact (Forti, Baldé, Kuehr, & Bel, 2020).

The current state of energy inefficiency and e-waste poses a significant threat to both economic and environmental sustainability. Governments and industries worldwide are seeking innovative solutions to mitigate these issues, and it is in this context that new technologies, particularly those driven by artificial intelligence (AI) and the development of eco-friendly materials, have emerged as potential game-changers (Linkov, Trump, Poinsatte-Jones, & Florin, 2018).

1.2 Role of AI and Eco-Friendly Materials

Artificial intelligence has begun to play a transformative role in addressing energy inefficiencies, particularly optimizing energy consumption across various sectors. AI-driven systems have the potential to analyze vast amounts of data from energy grids and electronic devices, identifying patterns and inefficiencies that may otherwise go unnoticed (Chen, Hu, Karuppiah, & Kumar, 2021). These systems can adjust energy usage in real time, leading to more efficient power distribution, reduced energy waste, and cost savings. For example, AI models can predict energy consumption patterns in smart grids, allowing operators to optimize energy generation and storage based on demand forecasts. This real-time decision-making capability is critical for enhancing the performance of renewable energy systems, where energy production is often variable (Ahmad et al., 2021).

Moreover, AI can potentially transform the residential and industrial sectors by automating energy management systems. AI can optimize home heating, ventilation, and air conditioning (HVAC) systems, ensuring energy is used efficiently without compromising comfort (Merabet et al., 2021). AI can monitor machinery and production processes in industrial settings, reducing energy consumption by identifying inefficiencies in real time. AI is emerging as a critical tool in the transition towards more sustainable energy systems through these applications (Ahmad et al., 2022).

Simultaneously, the development of eco-friendly materials for electronic devices offers a promising avenue for reducing the environmental impact of e-waste. Traditional electronic components are often made from non-renewable resources and contain toxic substances that are harmful to the environment (Cenci et al., 2022). Developing sustainable materials that are both biodegradable and energy-efficient can significantly reduce the environmental footprint of electronic devices. For example, researchers are exploring the use of organic semiconductors and materials derived from renewable resources to replace conventional silicon-based components. These sustainable materials reduce the reliance on finite resources and open up new possibilities for creating electronics that can be recycled or biodegraded at the end of their life cycle (Lee et al., 2024).

The integration of AI-driven energy optimization and the development of eco-friendly materials has the potential to revolutionize the way energy systems and electronics are designed and operated. Together, these innovations can address both the inefficiencies in energy consumption and the growing problem of e-waste, offering a comprehensive solution to two of our most pressing environmental challenges.

1.3 Purpose of the Paper

This paper aims to explore the intersection of AI-driven energy efficiency and the development of eco-friendly materials for electronic devices. Specifically, it will investigate how AI models can be leveraged to optimize energy consumption in electrical systems, focusing on applications in smart grids, residential energy management, and industrial operations. By analyzing energy usage patterns and providing real-time solutions, AI systems can significantly enhance energy efficiency, contributing to the broader goal of reducing carbon emissions.

Additionally, the paper will delve into the development of sustainable materials for electronic components, examining the potential of these materials to reduce the environmental impact of e-waste. This research will contribute to the broader efforts to create a more sustainable electronics industry by proposing new materials and manufacturing processes. Ultimately, the paper seeks to highlight the role of AI and eco-friendly materials as key enablers in addressing the global challenges of energy consumption and electronic waste, aligning with the U.S. national interest in sustainability and climate action.

2 AI-Driven Energy Efficiency in Electrical Systems

2.1 AI in Smart Grids

A smart grid is an intelligent electrical grid that uses digital communications technology to monitor, manage, and optimize electricity generation, transmission, and distribution. AI is pivotal in smart grids by providing advanced analytics and automation capabilities that help grid operators manage energy distribution more efficiently (Kabalci & Kabalci, 2019). Traditional power grids are often plagued by inefficiencies, such as energy loss during transmission and an inability to effectively balance supply and demand. Smart grids equipped with AI address these challenges by utilizing machine learning algorithms to analyze real-time data from the grid, allowing operators to make informed decisions about energy distribution (Faheem et al., 2018).

One key application of AI in smart grids is load forecasting. AI models can predict electricity demand based on historical data, weather patterns, and consumption trends. By accurately forecasting energy demand, smart grids can optimize the generation and distribution of electricity, ensuring that the right amount of energy is produced and transmitted to meet demand without excessive waste (Ahmad & Zhang, 2021). This is particularly important in integrating renewable energy sources, such as solar and wind, which are often variable and difficult to predict. AI algorithms can analyze renewable energy generation patterns and adjust the grid's operations to ensure efficient use of these resources, thereby reducing reliance on fossil fuels (Shaukat et al., 2018).

Another important application of AI in smart grids is fault detection and prevention. Electrical grids are complex systems that can experience a range of issues, such as equipment failures or power outages (Rivas & Abrao, 2020). AI-powered systems can monitor the health of the grid infrastructure in real-time, identifying potential faults before they escalate into more serious problems. For example, machine learning models can detect anomalies in energy flow that may indicate an impending equipment failure. By proactively addressing these issues, grid operators can prevent energy loss, reduce downtime, and improve overall grid reliability (Shi et al., 2020).

Moreover, AI enables the development of automated demand response systems, which allow the grid to adjust energy consumption in real-time based on current demand levels. This optimizes energy use and reduces the need for energy storage or backup power, both of which can be costly and resource-intensive. As AI continues to evolve, its integration into smart grids will play a central role in transforming electricity distribution, reducing energy waste, and enhancing grid efficiency (Khan, Saleh, Waseem, & Sajjad, 2022).

2.2 Residential and Industrial Applications

AI's potential to improve energy efficiency extends beyond smart grids into residential and industrial settings. AI-driven energy management systems are becoming increasingly popular in homes and commercial buildings as consumers and businesses seek to reduce their energy bills and carbon footprints (Stecuła, Wolniak, & Grebski, 2023). These systems use AI algorithms to optimize energy consumption by learning user behavior and predicting energy needs. For instance, AI can regulate heating, ventilation, and air conditioning (HVAC) systems by adjusting temperatures based on occupancy patterns, weather conditions, and user preferences. This reduces unnecessary energy consumption, leading to significant cost savings and improved energy efficiency (Yayla et al., 2022).

One notable application of AI in residential settings is the use of smart thermostats. Devices like Google's Nest or Ecobee employ AI to learn a homeowner's routine, adjusting temperature settings to maximize comfort while minimizing energy usage. Over time, these systems become more adept at predicting when to heat or cool a home, reducing energy consumption during periods of low occupancy. This reduces electricity costs and lowers overall energy demand, particularly during peak usage times, which can strain the electrical grid (Ghahramani et al., 2020).

AI's impact on energy efficiency is even more pronounced in industrial settings. Manufacturing facilities, which often operate around the clock, are major consumers of electricity. AI-powered energy management systems in these environments use machine learning models to analyze production processes and identify inefficiencies in energy usage. For example, AI can detect when machines are operating inefficiently or when energy consumption spikes unnecessarily during specific production cycles. By identifying these inefficiencies, manufacturers can adjust their processes to optimize energy use, reduce waste, and lower costs (Ahmad et al., 2021).

Another industrial application of AI is predictive maintenance. In large industrial plants, equipment failure can lead to significant energy waste and costly downtime. AI models can monitor the condition of machinery in real-time, identifying signs of wear and tear or inefficiencies that might lead to equipment failure (Meng, Yang, Chung, Lee, & Shao, 2018). By predicting these issues before they occur, companies can perform maintenance proactively, reducing the likelihood of unexpected breakdowns and the associated energy waste. AI's ability to enhance energy efficiency in residential and industrial settings rapidly transforms how energy is consumed and managed, leading to more sustainable practices and significant cost savings (Farzaneh et al., 2021).

2.3 Case Studies

The effectiveness of AI-driven energy efficiency solutions can be demonstrated through several case studies. One notable example is the implementation of AI in New York City's energy grid. Consolidated Edison (Con Edison), one of the largest energy companies in the U.S., uses AI-powered systems to optimize energy distribution across its grid (Veeraiah et al., 2024). By analyzing data from smart meters, AI algorithms can predict energy demand in different parts of the city and adjust power distribution accordingly. This has allowed Con Edison to reduce energy waste and improve the overall efficiency of the grid, particularly during peak demand periods such as heatwaves (Burman, Kimbrel, Pridemore, Thanos, & Zitelman, 2020).

Another compelling case study comes from Google, which uses AI to optimize energy usage in its data centers. Data centers are notorious for their high energy consumption, as they require significant power to cool servers and maintain operations (Isaev, Kornilov, & Grigor'ev, 2023). Google has implemented AI algorithms developed by its subsidiary DeepMind to manage the cooling systems in its data centers. These AI systems monitor real-time data from thousands of sensors and adjust cooling processes to minimize energy use. As a result, Google has reduced the energy required for cooling by 40%, significantly lowering its overall carbon footprint (Kelechi et al., 2020).

General Motors (GM) provides a prime example of how AI can improve manufacturing energy efficiency in the industrial sector. GM has integrated AI-powered energy management systems into its factories, using machine learning models to optimize energy consumption across its production lines. These systems monitor the energy use of individual machines and processes, identifying inefficiencies and suggesting improvements. By implementing these AI-driven solutions, GM has reduced its energy consumption by 15%, resulting in substantial cost savings and a lower environmental impact (Chimeudeonwo, 2023).

These case studies highlight the transformative potential of AI in enhancing energy efficiency across various sectors. From smart grids and residential energy management to large-scale industrial applications, AI is driving significant energy consumption and management improvements, contributing to a more sustainable future.

3 Development of Eco-Friendly Electronics Materials

3.1 Sustainable Materials for Semiconductors

Semiconductors are the building blocks of modern electronics, from smartphones to computers and even renewable energy technologies. The traditional semiconductor materials, such as silicon, gallium arsenide, and other rare earth elements, pose various environmental concerns. The extraction of these materials is resource-intensive and often involves environmentally damaging processes such as mining, which contributes to land degradation, water pollution, and the emission of harmful chemicals (Das & Mao, 2020).

Research into sustainable alternatives for semiconductor materials is gaining momentum, with a focus on developing materials that are both environmentally friendly and efficient in terms of performance. One promising area of research is the use of organic semiconductors, which are composed of carbon-based materials that are more abundant and biodegradable compared to traditional inorganic materials like silicon (Dhoble, Nande, Kalyani, Tiwari, & Arof, 2022). Organic semiconductors can be used in flexible electronics, solar cells, and light-emitting devices (OLEDs). They offer several advantages, including lower energy consumption during production and the possibility of creating lightweight, flexible, and more sustainable devices (Dey, Singh, Das, & Iyer, 2015).

Another significant development is in the field of perovskite materials, which have gained attention for their potential use in solar cells. Perovskites are a group of materials that have shown high efficiency in converting sunlight into electricity, making them a viable alternative to traditional silicon-based solar cells. The production of perovskite solar cells involves less energy and fewer hazardous materials than silicon cells, making them a more eco-friendly option. While challenges remain, such as the stability and long-term performance of perovskite materials, ongoing research is addressing these issues with the goal of creating more sustainable semiconductors for the electronics industry (Porlles, Tomomewo, Uzuegbu, & Alamooti, 2023; Ugwu & Adewusi, 2024).

In addition to organic semiconductors and perovskites, researchers are exploring the use of biodegradable and recyclable materials in the production of electronics. For instance, bio-based polymers and natural materials like cellulose are being investigated as alternatives to traditional plastics used in electronic components. These materials could significantly reduce the amount of non-biodegradable waste the electronics industry generates. While these innovations are still in the early stages, they represent a promising step toward a more sustainable future for semiconductor technology (Li et al., 2020).

3.2 Environmental Impact of Electronics

The environmental impact of traditional electronic components extends beyond the materials used in semiconductors. The manufacturing, usage, and disposal of electronic devices all contribute to significant environmental challenge (Castro et al., 2023) s. One of the most pressing issues is electronic waste, or e-waste, which includes discarded electronic devices such as smartphones, computers, and televisions. According to the Global E-Waste Monitor 2020, the world generated approximately 53.6 million metric tons of e-waste in 2019, and this figure is expected to grow in the coming years. E-waste often contains toxic materials such as lead, mercury, and cadmium, which can leach into the environment and pose serious health risks to both humans and wildlife (Forti et al., 2020).

Conventional electronics manufacturing also has a large carbon footprint. The production of electronic devices requires substantial energy, much of which comes from non-renewable sources, leading to greenhouse gas emissions. Additionally, mining rare earth elements and metals required for electronic components, such as lithium, cobalt, and nickel, is often associated with environmental degradation and human rights abuses in developing countries. The extraction processes can result in deforestation, water pollution, and the release of harmful chemicals into the environment (Martin & Iles, 2021).

The transition to eco-friendly materials in electronics could help mitigate these environmental challenges. For example, by replacing traditional plastics and metals with biodegradable or recyclable materials, manufacturers could reduce the amount of e-waste generated and the environmental harm associated with disposal. Moreover, using sustainable materials that require less energy to produce, such as organic semiconductors and bio-based polymers, could help lower the carbon footprint of electronics manufacturing (D. R. E. Ewim, Abolarin, Scott, & Anyanwu, 2023; Olaleye, Oloye, Akinloye, & Akinwande, 2024).

Sustainable materials can also extend the lifespan of electronic devices, thereby reducing the overall demand for new products and the associated environmental costs. For instance, using durable, long-lasting materials in semiconductors and other electronic components could decrease the need for frequent replacements and upgrades, resulting in less waste and resource consumption. As the global demand for electronics continues to rise, developing sustainable and high-performing materials is crucial to reducing the industry's environmental impact (Li et al., 2020).

3.3 Integration into Manufacturing

While the development of eco-friendly materials is a critical step toward creating sustainable electronics, integrating these materials into the manufacturing process presents a unique set of challenges. The electronics industry is highly complex and globalized, with supply chains that span multiple countries and involve numerous stakeholders. To successfully integrate sustainable materials into electronics manufacturing, companies must consider factors such as cost, scalability, performance, and environmental benefits (O'Connor, Zimmerman, Anastas, & Plata, 2016).

One of the primary challenges in integrating sustainable materials is ensuring that they meet the high-performance standards required for electronic devices. Consumers expect electronics to be durable, reliable, and efficient, and any new materials must be able to deliver on these expectations. Organic semiconductors, for instance, have great potential for sustainable electronics, but their performance in terms of conductivity and stability is still being optimized. Similarly, while biodegradable materials may offer environmental benefits, they must be tested for long-term durability and functionality in electronic applications (H. Wang & Yu, 2019).

Despite these challenges, there are successful examples of companies integrating sustainable materials into their production processes. For example, Fairphone, a Dutch electronics company, has developed a modular smartphone designed to be easily repairable and upgradeable, reducing the need for frequent replacements. The company also uses responsibly sourced materials and recycled plastics in its products, demonstrating that it is possible to prioritize sustainability without sacrificing quality or performance (Peters, 2022).

The integration of eco-friendly materials into the broader electronics manufacturing industry will likely require collaboration between various stakeholders, including manufacturers, materials scientists, and policymakers.

Governments can play a key role by incentivizing the use of sustainable materials through regulations, subsidies, and tax incentives. In addition, consumer awareness and demand for sustainable products can drive companies to adopt more environmentally friendly practices (Lamoureux, Movassaghi, & Kasiri, 2019).

Another crucial aspect of integrating sustainable materials into electronics manufacturing is ensuring that supply chains are transparent and responsible. Many of the materials used in traditional electronics, such as rare earth elements, are sourced from regions with poor environmental and labor standards. By prioritizing the use of ethically sourced and sustainable materials, companies can reduce the social and environmental harm associated with their supply chains (S. A. Khan et al., 2022).

4 AI and Sustainability for National Climate Goals

4.1 Contribution to U.S. Climate Goals

One of the major contributors to greenhouse gas emissions in the U.S. is the energy sector, particularly the use of fossil fuels for electricity generation. As the U.S. transitions to a low-carbon economy, optimizing renewable energy sources and improving energy consumption efficiency are essential steps. AI is pivotal in this transformation by enabling more efficient energy distribution, storage, and usage (Arumugham et al., 2023). For instance, AI-powered energy management systems can monitor and predict energy consumption in real time, allowing for more efficient use of energy in residential, commercial, and industrial settings. By analyzing energy usage patterns, AI can help identify areas of inefficiency and recommend adjustments to reduce energy waste. This is particularly important in smart grids, where AI can balance supply and demand, optimize the use of renewable energy sources like wind and solar, and reduce the reliance on fossil fuels during peak demand periods (Ahmad et al., 2021).

In addition to improving energy efficiency, AI can also support the integration of renewable energy into the grid. Renewable energy sources, such as solar and wind, are inherently variable, making it difficult to predict their availability and integrate them into the energy system (Sweeney, Bessa, Browell, & Pinson, 2020). AI algorithms can analyze weather patterns, energy consumption trends, and other factors to predict fluctuations in renewable energy generation and adjust the grid accordingly. This helps maximize the use of renewable energy, reduce the need for backup power from fossil fuels, and ultimately lower carbon emissions (Inman, Pedro, & Coimbra, 2013).

Furthermore, AI can contribute to reducing energy consumption in transportation, another significant source of greenhouse gas emissions. By optimizing traffic flow, improving vehicle efficiency, and supporting the development of autonomous electric vehicles, AI technologies can help reduce the environmental impact of transportation. In particular, AI-powered autonomous electric vehicles can reduce fuel consumption and emissions through optimized driving patterns, reduced idling, and more efficient route planning (Rinchi, Alsharoa, Shatnawi, & Arora, 2024).

The impact of AI-driven energy efficiency solutions aligns directly with the U.S. climate goals by reducing overall energy demand, promoting the use of renewable energy, and minimizing emissions in key sectors. By improving energy efficiency and enabling the shift to cleaner energy sources, AI helps drive progress toward achieving the net-zero emissions target, making it a critical component of the nation’s sustainability strategy (Bonire & Gbenga-Ilori, 2021).

4.2 Implications for Policy and Industry

The implementation of AI-driven energy efficiency solutions presents several important implications for policy and industry. As these technologies become more prevalent, policymakers must adapt regulations and incentives to encourage widespread adoption and ensure they contribute effectively to sustainability goals. One of the key policy implications is the need for incentives that promote the development and deployment of AI-based technologies for energy efficiency (Zamponi & Barbierato, 2022). Governments can play a crucial role by providing financial support for research and development, offering tax incentives for companies that implement AI-driven energy solutions, and funding pilot projects to demonstrate the potential of these technologies. For instance, tax credits for businesses that adopt AI-powered energy management systems or invest in renewable energy projects can help accelerate the transition to a more sustainable energy system (Ukoba, Olatunji, Adeoye, Jen, & Madyira, 2024).

In addition to financial incentives, policymakers will need to update regulatory frameworks to support the integration of AI technologies into the energy sector. This includes establishing data collection and sharing standards, ensuring that AI systems are transparent and accountable, and developing cybersecurity measures to protect against potential vulnerabilities in AI-powered energy infrastructure. As AI systems become more deeply integrated into critical infrastructure such as the power grid, ensuring their reliability, security, and resilience to external threats will be essential (D. R. Ewim, Olatubosun, & Abolarin, 2024; Ikemba et al., 2024).

For the industry, the adoption of AI-driven energy efficiency solutions presents both opportunities and challenges. Companies investing in AI technologies can save significantly by reducing energy consumption, improving operational efficiency, and lower carbon footprint (Hasan et al., 2024) s. This can enhance their competitiveness in the long run, particularly as consumers and investors increasingly prioritize sustainability. The development of AI-powered energy systems also opens up new business opportunities for technology companies, startups, and research institutions, particularly in the fields of renewable energy, smart grid technology, and sustainable manufacturing (Franki, Majnarić, & Višković, 2023).

However, the integration of AI into industry also requires a significant investment in infrastructure, training, and workforce development. Companies will need to invest in advanced data analytics platforms, develop new skills among employees, and ensure that their systems can handle the complexity of AI-powered energy management. In some cases, this may require collaboration between industry and government to provide the necessary support for businesses to transition to more sustainable practices (Orikpete, Ikemba, & Ewim, 2023).

Moreover, the use of AI in energy efficiency has broader implications for corporate social responsibility and environmental, social, and governance (ESG) criteria. As sustainability becomes an increasingly important consideration for consumers, investors, and regulators, companies that adopt AI-driven energy efficiency solutions can enhance their ESG performance and improve their reputation in the marketplace (Rane, Choudhary, & Rane, 2024).

5 Conclusion

AI technologies offer transformative opportunities to enhance energy efficiency across various sectors. In smart grids, AI models enable more accurate energy distribution, balancing supply and demand while minimizing energy loss. AI's real-time monitoring and predictive capabilities in residential and industrial applications allow for better management of energy consumption, adjusting usage to optimize efficiency. These systems reduce energy waste and enhance the integration of renewable energy sources like solar and wind, making energy systems more sustainable.

In parallel, developing eco-friendly materials for electronics, particularly semiconductors, presents an opportunity to reduce the carbon footprint of electronic manufacturing significantly. Conventional electronic components are resource-intensive and contribute to pollution and electronic waste. Sustainable alternatives, such as biodegradable or recyclable materials, offer solutions to mitigate these environmental impacts. When integrated into the manufacturing process, these materials can help reduce the energy required for production and the waste generated by electronic devices at the end of their life cycles.

5.1 Future Research

While promising, the advancements discussed in this paper highlight the need for continued research to unlock their full potential. In the realm of AI-driven energy systems, future research should focus on improving the accuracy and scalability of predictive models for energy consumption. As AI systems become more integrated into national energy infrastructure, it will be crucial to ensure their security, resilience, and adaptability to fluctuating conditions. Another area for exploration is the development of decentralized AI-driven energy solutions, where localized, AI-powered systems can manage energy at the community level, further optimizing resource use and supporting the transition to renewable energy.

Additionally, the research and development of eco-friendly electronic materials must continue. Innovations in biodegradable and recyclable semiconductors and other electronic components can significantly reduce environmental damage. Further studies are needed to explore these materials' lifecycle, durability, and ability to meet industry standards for performance and longevity. Collaborations between materials scientists, engineers, and policymakers will be essential to ensure that sustainable materials can be effectively integrated into mass production and adopted by the industry on a large scale.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Ahmad, T., & Zhang, D. (2021). Using the internet of things in smart energy systems and networks. *Sustainable Cities and Society, 68*, 102783.

[2] 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.

[3] Ahmad, T., Zhu, H., Zhang, D., Tariq, R., Bassam, A., Ullah, F., . . . Alshamrani, S. S. (2022). Energetics Systems and artificial intelligence: Applications of industry 4.0. *Energy Reports, 8*, 334-361.

[4] Arent, D. J., Green, P., Abdullah, Z., Barnes, T., Bauer, S., Bernstein, A., . . . Carpenter, B. (2022). Challenges and opportunities in decarbonizing the US energy system. *Renewable and Sustainable Energy Reviews, 169*, 112939.

[5] Arumugham, V., Ghanimi, H. M., Pustokhin, D. A., Pustokhina, I. V., Ponnam, V. S., Alharbi, M., . . . Sengan, S. (2023). An artificial-intelligence-based renewable energy prediction program for demand-side management in smart grids. *Sustainability, 15*(6), 5453.

[6] Avtar, R., Tripathi, S., Aggarwal, A. K., & Kumar, P. (2019). Population–urbanization–energy nexus: a review. *Resources, 8*(3), 136.

[7] Bonire, G., & Gbenga-Ilori, A. (2021). Towards artificial intelligence-based reduction of greenhouse gas emissions in the telecommunications industry. *Scientific African, 12*, e00823.

[8] Burman, D., Kimbrel, E., Pridemore, T., Thanos, A., & Zitelman, K. (2020). *Artificial Intelligence for Natural Gas Utilities: A Primer*. Retrieved from

[9] Castro, F. D., Júnior, A. B. B., Bassin, J. P., Tenório, J., Cutaia, L., Vaccari, M., & Espinosa, D. (2023). E-waste policies and implementation: a global perspective. In *Waste management and resource recycling in the developing world* (pp. 271-307): Elsevier.

[10] Cenci, M. P., Scarazzato, T., Munchen, D. D., Dartora, P. C., Veit, H. M., Bernardes, A. M., & Dias, P. R. (2022). Eco-friendly electronics—a comprehensive review. *Advanced Materials Technologies, 7*(2), 2001263.

[11] Chen, C., Hu, Y., Karuppiah, M., & Kumar, P. M. (2021). Artificial intelligence on economic evaluation of energy efficiency and renewable energy technologies. *Sustainable Energy Technologies and Assessments, 47*, 101358.

[12] Chimeudeonwo, N. B. (2023). *Review on the AI technologies used in the manufacturing of electric cars.* Technische Hochschule Ingolstadt,

[13] Das, S., & Mao, E. (2020). The global energy footprint of information and communication technology electronics in connected Internet-of-Things devices. *Sustainable Energy, Grids and Networks, 24*, 100408.

[14] Dey, A., Singh, A., Das, D., & Iyer, P. K. (2015). Organic semiconductors: a new future of nanodevices and applications. *Thin Film Structures in Energy Applications*, 97-128.

[15] Dhoble, S. J., Nande, A., Kalyani, N. T., Tiwari, A., & Arof, A. K. (2022). *Functional Materials from Carbon, Inorganic, and Organic Sources: Methods and Advances*: Woodhead Publishing.

[16] Ewim, D. R., Olatubosun, S. A., & Abolarin, S. M. (2024). 14 Energy Alternatives and Efficiency Options for Sustainable Development. *Localized Energy Transition in the 4th Industrial Revolution*, 225.

[17] Ewim, D. R. E., Abolarin, S. M., Scott, T. O., & Anyanwu, C. S. (2023). A survey on the understanding and viewpoints of renewable energy among South African school students. *The Journal of Engineering and Exact Sciences, 9*(2), 15375-15301e.

[18] Faheem, M., Shah, S. B. H., Butt, R. A., Raza, B., Anwar, M., Ashraf, M. W., . . . Gungor, V. C. (2018). Smart grid communication and information technologies in the perspective of Industry 4.0: Opportunities and challenges. *Computer Science Review, 30*, 1-30.

[19] Farzaneh, H., Malehmirchegini, L., Bejan, A., Afolabi, T., Mulumba, A., & Daka, P. P. (2021). Artificial intelligence evolution in smart buildings for energy efficiency. *Applied Sciences, 11*(2), 763.

[20] Forti, V., Baldé, C. P., Kuehr, R., & Bel, G. (2020). The global e-waste monitor 2020. *United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam, 120*.

[21] Franki, V., Majnarić, D., & Višković, A. (2023). A comprehensive review of Artificial Intelligence (AI) companies in the power sector. *Energies, 16*(3), 1077.

[22] Ghahramani, A., Galicia, P., Lehrer, D., Varghese, Z., Wang, Z., & Pandit, Y. (2020). Artificial intelligence for efficient thermal comfort systems: Requirements, current applications and future directions. *Frontiers in built environment, 6*, 49.

[23] Hanif, I. (2018). Impact of fossil fuels energy consumption, energy policies, and urban sprawl on carbon emissions in East Asia and the Pacific: A panel investigation. *Energy strategy reviews, 21*, 16-24.

[24] Hasan, M. R., Islam, M. Z., Sumon, M. F. I., Osiujjaman, M., Debnath, P., & Pant, L. (2024). Integrating Artificial Intelligence and Predictive Analytics in Supply Chain Management to Minimize Carbon Footprint and Enhance Business Growth in the USA. *Journal of Business and Management Studies, 6*(4), 195-212.

[25] Ikemba, S., Song-hyun, K., Scott, T. O., Ewim, D. R., Abolarin, S. M., & Fawole, A. A. (2024). Analysis of solar energy potentials of five selected south-east cities in nigeria using deep learning algorithms. *Sustainable Energy Research, 11*(1), 2.

[26] Inman, R. H., Pedro, H. T., & Coimbra, C. F. (2013). Solar forecasting methods for renewable energy integration. *Progress in energy and combustion science, 39*(6), 535-576.

[27] Isaev, E. A. e., Kornilov, V. V., & Grigor'ev, A. A. (2023). Data center efficiency model: A new approach and the role of Artificial Intelligence. *Математическая биология и биоинформатика, 18*(1), 215-227.

[28] Kabalci, E., & Kabalci, Y. (2019). *Smart grids and their communication systems*: Springer.

[29] Kartal, M. T. (2022). The role of consumption of energy, fossil sources, nuclear energy, and renewable energy on environmental degradation in top-five carbon producing countries. *Renewable Energy, 184*, 871-880.

[30] Kelechi, A. H., Alsharif, M. H., Bameyi, O. J., Ezra, P. J., Joseph, I. K., Atayero, A.-A., . . . Hong, J. (2020). Artificial intelligence: An energy efficiency tool for enhanced high performance computing. *Symmetry, 12*(6), 1029.

[31] Khan, M. A., Saleh, A. M., Waseem, M., & Sajjad, I. A. (2022). Artificial intelligence enabled demand response: Prospects and challenges in smart grid environment. *Ieee Access, 11*, 1477-1505.

[32] Khan, S. A., Mubarik, M. S., Kusi-Sarpong, S., Gupta, H., Zaman, S. I., & Mubarik, M. (2022). Blockchain technologies as enablers of supply chain mapping for sustainable supply chains. *Business strategy and the environment, 31*(8), 3742-3756.

[33] Lamoureux, S. M., Movassaghi, H., & Kasiri, N. (2019). The role of government support in SMEs' adoption of sustainability. *IEEE Engineering Management Review, 47*(1), 110-114.

[34] Lee, S., Huang, M., Lee, J., Choi, H., Jo, I. Y., Na, H., . . . Shim, B. S. (2024). Eco‐Friendly Materials for a Zero E‐Waste Society: Challenges and Opportunities in Engineering Plastics. *Advanced Sustainable Systems*, 2300428.

[35] Li, W., Liu, Q., Zhang, Y., Li, C. a., He, Z., Choy, W. C., . . . Kyaw, A. K. K. (2020). Biodegradable materials and green processing for green electronics. *Advanced materials, 32*(33), 2001591.

[36] Linkov, I., Trump, B. D., Poinsatte-Jones, K., & Florin, M.-V. (2018). Governance strategies for a sustainable digital world. *Sustainability, 10*(2), 440.

[37] Martin, A., & Iles, A. (2021). The ethics of rare earth elements over time and space. In *Ethics of chemistry: from poison gas to climate engineering* (pp. 317-346): World Scientific.

[38] Meng, Y., Yang, Y., Chung, H., Lee, P.-H., & Shao, C. (2018). Enhancing sustainability and energy efficiency in smart factories: A review. *Sustainability, 10*(12), 4779.

[39] Merabet, G. H., Essaaidi, M., Haddou, M. B., Qolomany, B., Qadir, J., Anan, M., . . . Benhaddou, D. (2021). Intelligent building control systems for thermal comfort and energy-efficiency: A systematic review of artificial intelligence-assisted techniques. *Renewable and Sustainable Energy Reviews, 144*, 110969.

[40] O'Connor, M. P., Zimmerman, J. B., Anastas, P. T., & Plata, D. L. (2016). A strategy for material supply chain sustainability: enabling a circular economy in the electronics industry through green engineering. In: ACS Publications.

[41] Olaleye, D. S., Oloye, A. C., Akinloye, A. O., & Akinwande, O. T. (2024). Advancing green communications: the role of radio frequency engineering in sustainable infrastructure design. *International Journal of Latest Technology in Engineering, Management & Applied Science(IJLTEMAS), 13*(5), 113.

[42] Orikpete, O. F., Ikemba, S., & Ewim, D. R. E. (2023). Integration of renewable energy technologies in smart building design for enhanced energy efficiency and self-sufficiency. *The Journal of Engineering and Exact Sciences, 9*(9), 16423-16401e.

[43] Peters, J. (2022). *The economic and ecological impact of shifting to a modular smartphone design.* University of Twente,

[44] Porlles, J., Tomomewo, O., Uzuegbu, E., & Alamooti, M. (2023). *Comparison and Analysis of Multiple Scenarios for Enhanced Geothermal Systems Designing Hydraulic Fracturing.* Paper presented at the 48 Th Workshop on Geothermal Reservoir Engineering.

[45] Rane, N., Choudhary, S., & Rane, J. (2024). Artificial intelligence driven approaches to strengthening Environmental, Social, and Governance (ESG) criteria in sustainable business practices: a review. *Social, and Governance (ESG) criteria in sustainable business practices: a review (May 27, 2024)*.

[46] Rinchi, O., Alsharoa, A., Shatnawi, I., & Arora, A. (2024). The Role of Intelligent Transportation Systems and Artificial Intelligence in Energy Efficiency and Emission Reduction. *arXiv preprint arXiv:2401.14560*.

[47] Rivas, A. E. L., & Abrao, T. (2020). Faults in smart grid systems: Monitoring, detection and classification. *Electric Power Systems Research, 189*, 106602.

[48] Shaukat, N., Ali, S., Mehmood, C., Khan, B., Jawad, M., Farid, U., . . . Majid, M. (2018). A survey on consumers empowerment, communication technologies, and renewable generation penetration within Smart Grid. *Renewable and Sustainable Energy Reviews, 81*, 1453-1475.

[49] Shi, Z., Yao, W., Li, Z., Zeng, L., Zhao, Y., Zhang, R., . . . Wen, J. (2020). Artificial intelligence techniques for stability analysis and control in smart grids: Methodologies, applications, challenges and future directions. *Applied Energy, 278*, 115733.

[50] Stecuła, K., Wolniak, R., & Grebski, W. W. (2023). AI-Driven urban energy solutions—from individuals to society: a review. *Energies, 16*(24), 7988.

[51] Sweeney, C., Bessa, R. J., Browell, J., & Pinson, P. (2020). The future of forecasting for renewable energy. *Wiley Interdisciplinary Reviews: Energy and Environment, 9*(2), e365.

[52] Ugwu, M. C., & Adewusi, A. O. (2024). Impact of financial markets on clean energy investment: A comparative analysis of the United States and Nigeria.

[53] Ukoba, K., Olatunji, K. O., Adeoye, E., Jen, T.-C., & Madyira, D. M. (2024). Optimizing renewable energy systems through artificial intelligence: Review and future prospects. *Energy & Environment*, 0958305X241256293.

[54] Veeraiah, V., Karthiga, B., Akram, C. M., Koujalagi, A., Nanthakumar, S., Sharma, V., & Pandey, D. (2024). Role of Artificial Intelligence in Making Wearable Robotics Smarter. In *Robotics and Automation in Industry 4.0* (pp. 152-174): CRC Press.

[55] Wang, H., & Yu, C. (2019). Organic thermoelectrics: materials preparation, performance optimization, and device integration. *Joule, 3*(1), 53-80.

[56] Wang, J., & Azam, W. (2024). Natural resource scarcity, fossil fuel energy consumption, and total greenhouse gas emissions in top emitting countries. *Geoscience Frontiers, 15*(2), 101757.

[57] Yayla, A., Świerczewska, K. S., Kaya, M., Karaca, B., Arayici, Y., Ayözen, Y. E., & Tokdemir, O. B. (2022). Artificial intelligence (AI)-based occupant-centric heating ventilation and air conditioning (HVAC) control system for multi-zone commercial buildings. *Sustainability, 14*(23), 16107.

[58] Zamponi, M. E., & Barbierato, E. (2022). The dual role of artificial intelligence in developing smart cities. *Smart Cities, 5*(2), 728-755.