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# AI in Sustainable Energy: Applications and Innovations

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***Abstract: Incorporation of Artificial Intelligence (AI) into sustainable energy systems is a major achievement in maximizing efficient energy generation, distribution, and usage. This study examines the potential of AI to be a transformative technology, complements existing studies and attempts to pinpoint potential gaps that require further research while introducing a new model for adoption. The evaluation identifies specific AI and machine learning techniques that are technically viable, as well provides a multicriteria approach for ranking energy applications to be opportunities for AI and machine learning. Leading applications encompass solar and wind prediction, fault diagnostics, and grid stability, among others, although associated issues related to for instance intermittency and computational scalability continue as well.***

***The moral and environmental implications of using AI as it relates to more than just optimizing the technology itself are discussed. The idea of 'Sustainable AI' is proposed, in an effort to promote a conceptual frame that integrates environmental sustainability with considerations of social equity. A combination of LDA, BERT, and clustering on topic modeling is utilized to break down the literature into the eight main research themes, such as smart buildings, and renewable energy evaluation. The findings give rise to 14 recommendations for future research, which can provide a guide for policymakers and practitioners to synthesize theoretical knowledge with field practice. The use and potential of A.I . brings also new emerging risks as well as opportunities for progress in over 134 Sustainable Development Goal (SDG) targets . Challenges, such as the 'black box' problem of machine learning, privacy concerns, and the energy requirements of machine learning algorithms, require governance and to be puzzles over . It concludes by highlighting the need for interdisciplinarity, suggesting a form of STEAM ( STEM + Arts) approach to help advance innovation in an inclusive manner . Policy-based recommendations highlight support for mixed renewable systems, adaptable ML designs, and life-cycle- conscious AI research. The review thus also ultimately lays out a pathway for using AI to set in motion socio-technical carbon-neutral energy transitions.***

***Keywords: Artificial Intelligence, Sustainable Energy, Hybrid Energy Systems, Renewable Energy, Predictive Maintenance, Grid Management, Ethical AI, Federated, Learning, Edge AI, Climate Change***

## I. INTRODUCTION

The current urgency of transitioning to sustainable energy production has been exacerbated by both the rapid global rise in need for energy, and the growing concern about climate change, environmental destruction, and energy resource depletion. Key to this are clean renewable technologies, such as solar, wind, and hydropower, but due to their variability and “unpredictability” and the integration issues associated needing advanced electronics to be managed efficiently on the grid.

Artificial Intelligence (AI) has begun to be utilized as a revolutionary technique in optimizing the designs of renewable energy systems. Through machine learning and deep learning, AI systems make more accurate predictions, can provide real time analyses and monitoring, can predict when maintenance should be performed, and can improve operations to reduce costs and be more energy efficient. Nevertheless, AI poses a set of barriers in terms of data quality, computational requirements, ethical questions and social acceptability.

On top of that, there is an increasing awareness for the need to consider AI not only as a tool for achieving sustainability goals in energy, but also in enabling the development and deployment of AI technologies in a sustainable way so as to reduce their environmental footprint. These find an application in technological, policy, and ethics-related discussions, which require a cross-disciplinary effort to foster responsible AI governance [5].

The goal of this paper is to provide a systematic review of the literature on AI for sustainable energy that would highlight research trends, identify existing research gaps, and direct future research, spanning the years from 2021 to 2025. By employing sophisticated topic modeling and content analysis, this work provides a perspective to help policymakers, engineers, researchers, and others understand and work to shape the role of AI in a carbon-neutral and just energy future.

## II. LITERATURE REVIEW

Applications of Artificial Intelligence (AI) for the optimization and development of sustainable energy systems in general, and those including prediction, fault detection, energy management and control have been the subject of many studies . Machine learning (ML) and particularly deep learning (DL) among other AI, have had a large impact in several fronts of the energy value chain . [1,3]. Model-driven and data driven approaches are leading the way for the control, monitoring and optimization of energy systems. They have been used to address economic load dispatch, voltage stability and voltage regulation, fault location and restoration, planning and prediction, observability of the network, frequency regulation, storage, power control, Demand Side Management, and detection of electricity theft. Innovative AI methods such as ML blended models – for instance PI-LSTM, convolutional neural networks in the design prediction and Kalman filters for determining the life of machinery. Feature engineering has also been a large contributor towards increasing performance of models in materials science and in other fields. Some of this includes critiques of traditional bibliometric and LDA based topics modeling reviews and suggest hybrid methodology using bibliometric analysis, Latent Dirichlet Allocation (LDA), BERT-based contextual embeddings, and clustering to provide richer semantic analyses and to improve more coherent topic results . Of those 182 articles, limitations included a lack of integration between the various energy sectors (e.g., buildings, water, agriculture), a failure to explore cross-topic issues as well as insufficient semantic depth in earlier topic models.

Common themes divide the literature. As an example, basics papers on renewable energy systems include solar, wind, hydro, geothermal and also how to deal with the intermittency of these technologies using storage and smart grids [7]. AI is used for renewable energy optimization, including forecasting generation and demand, anomaly detection, resource allocation, and scheduling, with applications in practice via companies such as Siemens Gamesa and Google AI . [10, 9] . Also, software engineering paradigms like Agile and Model-Driven Engineering, simplify the integration with IoT in relation to predictive maintenance and real- time monitoring [9].

AI's influence is related to an estimated 128 targets across the SDGs, but could also have adverse effects on 58 targets, highlighting the "importance of ethical and governance frameworks to manage risks such as bias, privacy infringements, and inequality" [5]. Partial answers to this question might be found in studies considering the application of AI to the poultry industry, marine science, precision agriculture, digital twins and explainable AI [5,14] . Problems from STEM education challenges in the context of AI and energy include rigid siloing by discipline that acts as a barrier to creativity and excitement, particularly among underrepresented groups. A new STEAM (Science, Technology, Engineering, Arts, Mathematics) approach to education has been suggested to address this disparity by valuing interdisciplinary, creative, and inclusive learning [14] . The idea of Sustainable AI is a nascent concept that refers to two separate meanings: AI applications that target improved sustainability, such as those focused on clean energy or predicting the climate, and AI in terms of sustainability, e.g., reducing the carbon footprint of model training. Sustainable AI also provides the double perspective of both innovation and resource equity, and of both economic gain and intergenerational equity, supporting the environmental, social, and economic dimensions of sustainable development [15]. There is existing knowledge and broader applications of AI in wind-solar hybrids, smart cities, carbon capture and storage, scheduling operations and integration of markets. Nevertheless, there are few general reports about artificial intelligence in the context of its application for the integration of large-scale renewable energy systems and multi-energy systems [8,16] . Other reviews label AI techniques according to the learning type (supervised, unsupervised, reinforcement) as well as the application domain, which comprises load and generation forecasting, grid stability, smart metering, demand prediction, and energy storage management [4, 7]. Therefore, fundamental machine learning techniques and their progression in energy related studies remain as relevant research topics. Earlier reviews refer AI processes like Neural Networks, Support Vector Machines, Fuzzy Logic, Reinforcement learning, Hybrid Control Systems to predict Solar Irradiance, Wind Speed, Fault Detection, Demand Response or Microgrid optimization. These gaps include the integration of real-time data and more general AI models [2, 10] . In general, studies highlight AI's potential in leveraging energy efficiency, reducing operating costs and carbon footprints of buildings, but also shed light data availability, integration issues and lack of interdisciplinary research . [6, 11].

## III. RESEARCH METHODOLOGY

In this study, a systematic review of the literature is complemented with a multicriteria analysis, specifically looking at the use of AI on a broader scope concerning sustainable energy systems . Relevant studies were then filtered and classified according to their subject, contribution, and technically or strategically relevance. A dataset of 182 firstline peers reviewed between 2004 and 2022 was obtained via keyword-based search as well as manual review to both verify the quality of the corpus and capture recent publications.

The analysis consists of a mixed-method approach that combines advanced contextual topic modeling with qualitative analysis of the content in order to analyze trends in the topics and identify research gaps. More specifically, BERT embeddings were combined with Latent Dirichlet Allocation (LDA) and clustering algorithms such as KMeans and UMAP to account for both co-occurrence as well as semantic relationships in the literature. Text pre-processing used tokenization, stop-word removal and TF-IDF filtering and was done in Python using NLTK and Scikit-learn libraries. The Silhouette Score measurement confirmed the superior performance of the hybrid LDA- BERT model. Plus, an Analytic Hierarchy Process (AHP) based multi-criteria objective analysis was performed to assess and rank AI techniques and applications across their technical feasibility, environmental implications, economic feasibility, social desirability and regulatory implications. This structured process utilized a Common Metric for consistent assessment and normalization scores to rank order AI planning solutions. The methodology also leverages integration with case studies, developments in software engineering, and concrete applications in the real world, focusing on the context of AI in optimization, predictive maintenance, and smart grid management. Throughout an emphasis towards interdisciplinary lenses and finding possible future research directions based on empirical evidence and conceptual analyses was maintained.

## IV. RESULTS

Findings from the review are presented based on themes drawn from the literature that guide the complex role of Artificial Intelligence (AI) in the application of sustainable energy systems.

Applications in AI have also become significantly important in energy forecasting as well as automation and optimization to improve systems efficiency. In the case of solar, wind and smart grid, AI models improve the accuracy of forecasts and contribute to the efficiency of the operation [3, 9, 5]. These include applications to predict the incoming Solar Radiation and wind speed, improve the load demand and to automatize the control processes to increase the reliability of the grid [6, 10]. Through the Analytic Hierarchy Process (AHP), five options of incorporating AI and machine learning (ML) into energy systems are analized using the criteria of Technical Feasibility, Environmental Impact, Economic Viability, Social Acceptability, and Regulatory Compliance [3]. Among the four alternatives but, A4 is the most favoured solution with a normalized ranking of 0.3071 which means that provides the best trade-off to the criteria. Alternatives 1, 2, and 5 had similar lower scores than Alternative 3, which had the lowest at 0.1823. This type of scale can assist and support the use of A4 in policy/ planning issues, yet requires customization based on local context and local stakeholders [3]. Among the eighteen, word counts indicated eight prevalent themes:

*1)* Sustainable buildings and energy consumption (22.5% prevalence)
*2)* AI-based decision support systems (DSS) for urban water management (16.5%)
*3)* Climate Artificial Intelligence (14.8%)
*4)* Agriculture 4.0 and sustainable energy sources
*5)* IoT and AI convergence for smart cities
*6)* AI-based evaluation of renewable energy technologies
*7)* Smart campus and engineering education
*8)* AI for energy optimization

After 2018, there was a lot of interest in sustainable buildings and AI optimization. This was also the time when new cross-cutting themes started to appear, such as economic problems, real-time automation, and technology convergence, which includes blockchain and edge computing [12]. Combining results from different areas shows that AI makes it more accurate to predict solar irradiance, wind speeds, and load demand. Optimization algorithms also let resources be allocated dynamically, which makes the grid more cost-effective and resilient. Several case studies show real benefits, such as less downtime and a stronger system [9, 6].

AI helps with Sustainable Development Goals by predicting poverty, creating education models, and looking at climate change. But there are dangers, like Big Tech becoming too powerful and AI making inequality worse. So, we need to manage AI and make sure it's used ethically.

AI is also making renewable energy better by improving how we predict energy production, find problems, make solar panels work better, and manage hydrogen fuel cells. It uses models like CNN, LSTM, DNN, and reinforcement learning. In environmental health, AI can predict diseases and keep an eye on ecosystems using GeoAI.

Places like Stanford's MESMERIZE AI Hub and MIT have created tools and models that use data to predict things, which encourages teamwork between different fields. Community projects, like those in Nigeria and European Living Labs, focus on teaching people about AI and making sustainable technologies available to everyone.

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People are starting to worry about the carbon footprint of AI models. For example, Google's AlphaGo Zero produced 96 tonnes of CO2 in 40 days, and training big NLP models can create 600,000 lbs of CO2. Tools like CarbonTracker and ML Emissions Calculator have been created to keep track of these emissions and push for transparency and fair rules.

Important AI methods include Artificial Neural Networks (ANN) for making accurate models, fuzzy logic for dealing with uncertainty, and algorithms like Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO). Hybrid models that combine Genetic Algorithms with ANN or Support Vector Machines (SVM) are better at predicting things. These are used to predict generator-side system, find distribution-side faults, and manage energy demand.

Machine learning models like LSTM, CNN, and ensemble models are commonly used to forecast renewable energy production and load demand. Hybrid physics-informed ML models are being developed to improve power flow and energy efficiency. These methods help with grid management, battery use, and planning for the future when things are uncertain.

In general, AI greatly improves how well we can predict things, how well we can make energy systems work, and how much money we can save. Neural networks and SVMs are particularly good at predicting solar and wind energy, and studies show that AI-assisted systems are more efficient and stable.

Regional studies, like wind energy potential in Indonesia, show good average wind speeds and economic benefits from better turbine technology, highlighting the local use of AI in renewable energy planning. Hybrid renewable energy setups work well to cut costs and emissions, and they stay reliable. They get even better with the help of AI [16]. The study shows how much AI can change sustainable energy. It also points out some problems with data, how easy it is to understand, and rules. In the future, we should put these systems to use, make sure AI is used fairly, and work together across different fields to get the most out of AI in sustainable energy.

## V. DISCUSSION

This research shows how AI could really change things when it comes to meeting our sustainability goals in the energy industry. AI can help make energy use more efficient, bring in more renewable sources, and guide smarter policies.

But, there are some big problems we need to fix first. These include keeping data safe, dealing with the cost of computing power, working within policy limits, and getting experts from different fields like engineering, data science, and policy to work together [3, 12, 4]. The results show that using AI and ML in sustainable energy systems is becoming more doable and is really important.

Alternative 4 (A4) did best in our analysis, proving that a well-rounded strategy—one that balances technical, environmental, economic, social, and regulatory aspects—works best for making decisions and designing systems. By adding things like demand predictions, renewable energy integration, and ways to cut carbon emissions, we get a clearer picture of how complicated energy changes really are [2, 7, 10]. This way of looking at things proves that AI systems are key for making energy setups more efficient, tough, and able to predict what's coming.

Even with all this good news, how well AI works depends a lot on the situation. Things like how many local resources are available, what the policies are, and what people care about most mean that AI systems need to be custom-made and constantly improved to keep up with tech and data changes [8, 6]. Also, things like not having enough data, ML models that are too specific, complicated systems, and unclear rules can still get in the way. To deal with these issues, we need good management, teamwork across different sectors, and training programs to get the most out of AI while avoiding any unexpected bad results [16, 13]. AI is being used in more and more fields, though the research is a bit scattered. Saving energy in buildings is becoming more popular, but should focus more on how people act and building design [1]. In cities, AI helps manage water with smart pricing and maintenance. Also, AI is being used to predict climate changes and lower carbon output in a clear and reliable way [12, 5].

Farming 4.0 uses tech like IoT, robots, and renewable energy to create more intelligent agricultural methods. AI helps improve energy use through smart meters, predictions, and keeping the power grid stable. There's still room to explore using blockchain in these areas.

We still need more research, especially when it comes to using these technologies across different fields, making AI easier to understand, being responsible with new ideas, and teaching people how to use AI sustainably. When AI experts and software engineers work together, it can really make energy systems more responsive and greener. Even so, we have to keep working on things like data quality, privacy, and making sure algorithms are fair. For these technologies to succeed, they need to follow the rules and be designed in a way that's clear, open, and includes everyone.

When we add AI and Deep Learning to sustainability work, we have to focus on making sure people can understand how these models work, so they can trust them.

As AI teams up with new tech like 6G, IoT, and blockchain, we also need to think about things like fairness, data safety, and how these tools could be misused. It's important to put money into privacy methods, like federated learning and homomorphic encryption, and to research AI that uses less energy and works more like the human brain.

Education is also key. The usual science and math classes don't quite cover all the different things you need to know about sustainability. A STEAM approach, which adds creativity, empathy, and problem-solving, can attract a wider group of people and get them ready to deal with the technical, social, and political challenges of sustainability. AI can create personalized learning paths, but schools need to support mentoring and inclusion programs.

When it comes to how AI is used in sustainability, we should treat it like a test run for society and create policies that guide its use. Governments can set up groups to focus on sustainable AI, require companies to report emissions, fund low-energy and fair AI projects, and set guidelines for AI training. This would be similar to what's been done with environmental efforts like the European Green Deal and the Paris Agreement. In conclusion, AI has a real impact on energy systems. It helps make renewable energy more consistent, keeps power grids stable, and lowers costs. Yet, some problems slow things down, like not enough good data, old equipment, a shortage of AI experts, and money or rules getting in the way. Fixing these problems is important to get the most out of AI for moving to greener energy sources.

In conclusion, our talk shows that the multi-criteria framework works well for making sustainable energy plans based on solid facts, and it points out how crucial AI is. This study pushes for teamwork between different fields, smart new ideas that are responsible, and backing from people in charge, so we can get all the good stuff from AI while cutting down on the bad. To make sure AI helps sustainability in a way that includes everyone, is open, and makes a real difference, we need to keep researching and putting effort into using it in real situations. We also need to focus on making it easy to understand, fair, and teaching people about it.

## VI. CONCLUSION

AI is really important for moving to sustainable energy. It can really change how we predict, improve, and control renewable energy systems in real-time. This look at things uses a way to see how much better using data is than older ways, but it says we need to think about tech, money, the environment, society, and the rules about all this.

We're starting to see new research on making the most of energy that's spread out, using AI with new tech like 5G, blockchain, and edge computing, and making transportation more sustainable. Putting AI and good software practices together is key to making our energy stuff work better, be stronger, and adapt to changes, which helps us get to a carbon-neutral economy.

Even though AI can do a lot for Sustainable Development Goals and smarter, greener stuff, there are still some big problems. Training AI uses a lot of energy, it's not always clear how it works, there are ethical worries, and we need better data systems. To fix these, we need AI that is easier to understand, fair, and doesn't use much energy, and we need good rules and people from different fields to work together.

To teach people the skills they need for sustainable energy, we need to include science, tech, engineering, arts, and math in a complete way. Also, Sustainable AI should be more than just AI for Good. It needs to think about the environment, fair use of resources, and social justice when making AI.

For the future, it's important for those who make rules, researchers, businesses, and teachers to work together. We need to push forward with combined and physics-based machine learning, grow AI-run energy grids that are spread out, make energy storage better, and add electric cars to smart energy systems. In the end, this review shows how to use AI well and in a way that we're responsible for—getting all the good things about renewable energy while dealing with the tricky social, tech, and ethical parts of changing how we get energy.

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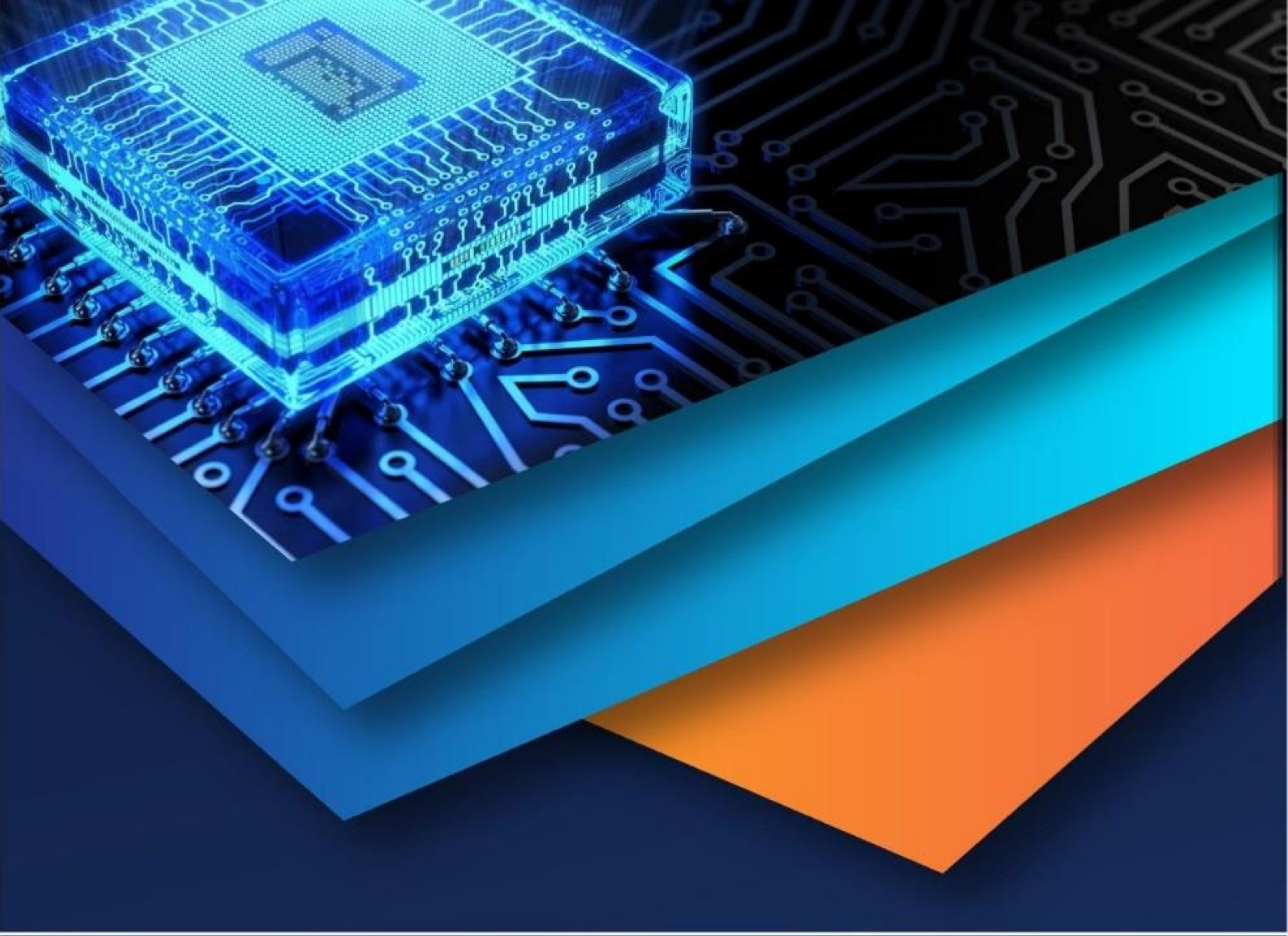


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