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Research Article

UTILIZING ARTIFICIAL INTELLIGENCE IN ENERGY MANAGEMENT SYSTEMS TO IMPROVE CARBON EMISSION REDUCTION AND SUSTAINABILITY

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Abstract
This article examines the revolutionary potential of artificial intelligence (AI) in improving energy management systems (EMS) to reduce carbon emissions and tackle pressing climate change issues. We conduct a comprehensive literature analysis to analyze AI-driven solutions for optimizing energy usage, minimizing carbon footprints, and promoting sustainability across diverse industries. Conventional EMS methodologies often depend on static and reactive strategies, limiting their efficacy in the face of increasing global energy needs and regulatory requirements. Conversely, AI-driven EMS provides sophisticated data analytics, predictive maintenance, and real-time optimization, markedly enhancing efficiency and emissions control. Our research includes case studies from both industrial and public sectors that illustrate the quantifiable effects of AI-integrated Energy Management Systems in reducing operating expenses, improving renewable energy integration, and fostering better energy practices. Significant hurdles, such as elevated implementation costs, data privacy issues, and regulatory compliance, are examined with prospective legislative frameworks to promote AI use. We underscore the significance of AI in delivering actionable insights, harmonizing energy practices with climate policy, and promoting a sustainable energy future. This study concludes that AI-driven Energy Management Systems are essential for significant emissions reductions and the development of resilient, eco-efficient energy systems, highlighting the necessity for strategic investment and supportive policies to optimize AI technology's societal and environmental advantages in energy management.

Keywords: Artificial Intelligence, Carbon Emissions Reduction, Energy Management Systems, Renewable Energy Integration, Sustainability.

INTRODUCTION

The urgent need to address climate change by reducing carbon emissions has attracted worldwide attention as industrialization and population expansion exacerbate environmental effects. As carbon dioxide (CO_2) is a primary greenhouse gas, reducing emissions has become crucial for ecological objectives and global policy initiatives. In this context, artificial intelligence (AI) has arisen as a potent instrument, providing novel strategies for optimizing energy use, improving efficiency, and diminishing CO_2 emissions across several industries. Energy management systems (EMS) are essential for accomplishing these goals via monitoring, analyzing, and optimizing energy use. However, conventional EMS methodologies sometimes neglect accommodating fluctuating energy requirements and intricate environmental restrictions. Traditional EMS often depend on manual data gathering, intermittent audits, and inflexible control mechanisms, which might impede real-time response and flexibility to changing energy requirements and sustainability standards. Incorporating AI technology into EMS signifies a significant transformation, enabling data-driven insights and predictive functionalities that enhance renewable energy efficiency, minimize energy waste, and bolster large-scale decarbonization initiatives.

This study comprehensively examines AI-driven EMS applications, emphasizing their capacity to mitigate carbon emissions while tackling technological, economic, and regulatory obstacles. We evaluate contemporary AI approaches, such as machine learning, predictive maintenance, and intelligent grid optimizations, via case studies and actual data from various industries. This research aims to elucidate the potential and constraints associated with AI integration, informing stakeholders about the practical and policy considerations essential for enhancing AI's involvement in sustainable energy management and climate resilience. Energy management is a multidisciplinary domain that optimizes energy use to enhance efficiency, cost-effectiveness, and sustainability (*Chapter 1 Introduction to Energy Management*, 2016)

It incorporates monitoring, evaluating, and executing energy conservation programs across several sectors. Effective energy management encompasses technical and strategic procedures, identifying opportunities for improvement, and implementing energy-efficient solutions. Standards like ISO 50001 provide universal goals for energy efficiency, offering systematic recommendations that encourage sustainable behaviors (Finnerty et al., 2017; Ningsih, 2024; Pangestu, 2024; Widodo, 2024). Energy management encompasses sustainable construction techniques, integrating renewable sources like solar power into energy networks to diminish dependence on non-renewable resources and mitigate environmental effects (Vigna et al., 2018; Apeadido et al., 2024; Fadhilah, 2024; Khoirunnisa et al., 2024). This methodology entails multidisciplinary collaboration, including engineering, environmental science, and economics, to facilitate strategic energy planning and enhance consumption patterns, promoting a lower-carbon future and decreasing operational expenses (Kharazishvili et al., 2021; Qodri, & Hassan, 2023; Tyas, & Suttiwan, 2023; Setiya Rini et al., 2024).

Conventional energy management systems (EMS) often depend on rigid rules and heuristics that are not adaptable to variable energy needs and changing supply situations. Although several Energy Management Systems use statistical techniques to discern consumption trends, these methods do not provide precise, anticipatory energy predictions (Alsamhi et al., 2018; Melisa et al., 2024; Rini et al., 2024). Moreover, conventional optimization tools, including Proportional-Integral-Derivative (PID) and Model Predictive Control (MPC) algorithms, are beneficial in particular contexts but encounter difficulties due to the complexity and variability of extensive energy networks (Chakraborty et al., 2020; Mohammadi-Ivatloo et al., 2020). Conventional EMS are significantly limited in their capacity to mitigate carbon emissions effectively. Their dependence on rigid timetables and fundamental optimization constrains energy conservation potential and obstructs carbon footprint mitigation (Alsamhi et al., 2018; Asmororini et al., 2024; Azis, & Clefoto, 2024; Naimah et al., 2023). These systems encounter considerable obstacles in assimilating renewable energy sources since they lack sophisticated predictive skills essential for effective and sustainable energy management (Flath et al., 2017; Mohammadi-Ivatloo et al., 2020; Mardiati et al., 2024; Setiyani et al., 2024).

Studies indicate that AI-driven Energy Management Systems markedly improve energy efficiency and diminish the carbon footprint of microgrids via continuous data analysis and operational adjustments (Wang et al., 2019; Fernande et al., 2024; Habibi et al., 2024). These developments illustrate AI's essential function in facilitating sustainability objectives and enhancing air quality via new energy management strategies. Artificial intelligence is essential for optimizing intelligent energy networks and demand response systems. Wang et al. (2021) performed a study using AI algorithms to forecast future energy requirements and modify supply appropriately. AI systems enhance energy distribution, minimize waste, and lessen reliance on fossil fuels by evaluating historical data, meteorological predictions, and sensor data. Dynamic pricing and incentives motivate consumers to adjust usage to off-peak times, enhancing resource management and reducing expenses.

Studies regularly demonstrate that AI improves grid sustainability by incorporating renewable energy sources and alleviating peak demand pressures. These skills promote environmental goals and aid in transitioning to a more resilient, low-carbon energy system. The report includes several case studies from the corporate and governmental sectors to illustrate the effectiveness of diverse solutions. Hilton Worldwide demonstrates accomplishment with ISO 50001 certification for energy management throughout its global properties. Using this technology, Hilton attained a 30% decrease in carbon intensity and a 20.6% reduction in energy intensity while achieving reductions in operating costs throughout its hotel portfolio. This illustrates the effectiveness of AI-driven energy management strategies in attaining sustainability and significant savings.

Artificial intelligence (AI) has become a revolutionary force, transforming sectors ranging from energy management to healthcare, economy, and commerce. AI provides novel solutions for intricate challenges, such as advanced analytics and network optimization in energy systems, contributing to sustainability improvements and reducing inefficiencies. In healthcare, AI techniques like Weighted Gene Co-expression Network Analysis (WGCNA) have revolutionized leukemia research by pinpointing essential gene modules and enhancing therapy approaches (Kapçiu et al., 2024). The amalgamation of IT technology with biological research illustrates AI's potential to analyze intricate networks and provide valuable insights across disciplines. The ability of AI to enhance complex systems and generate predictive insights extends beyond these domains. Economic modeling has advanced significantly with computational techniques, such as the logistic model—originally developed for biological systems—now used to predict inflation dynamics and evaluate financial stability (Kapçiu et al., 2024). These multidisciplinary applications demonstrate AI's capability to improve forecasting accuracy, reinforce systemic sustainability, and address global challenges.

Similarly, AI presents a compelling opportunity in shaping the future landscape of commerce. The findings (Tabaku et al., 2024) highlight the effectiveness of AI integration in e-commerce, emphasizing its role in enhancing customer satisfaction, expanding customer bases, and driving business growth. Moreover, modern AI-driven technologies facilitate detailed data analysis, allowing businesses to identify trends, forecast performance, and make strategic decisions more effectively (Tabaku et al., 2024; Syahputra, & Edwards, 2024). Beyond business growth, AI contributes to financial security. Advanced data security measures protect sensitive financial information, ensuring resilience against cyber threats and enabling secure access and regular backups. The ability of AI to connect disparate fields, from sustainable energy management to healthcare breakthroughs and economic modeling, reinforces its role as a transformative tool that fosters innovation, systemic change, and long-term sustainability across industries.

RESEARCH METHOD

This research utilizes secondary data from diverse scientific literature, including books, peer-reviewed journals, and electronic media. The data predominantly derives from esteemed sources such as the United Nations Framework Convention on Climate Change (UNFCCC), Statista, and the European Centre for Medium-Range Weather Forecasts (ECMWF), supplemented by literature acquired from research platforms like Google Scholar and ResearchGate. The dataset includes information on investments in innovative energy networks and carbon emissions throughout the European Union (EU) from 2010 to 2023, filling data gaps as required.

Owing to the restricted availability of Albania data, the research uses the EU as a case study. The EU countries provide a thorough and representative framework for comprehending developments pertinent to Albania, as they reflect the market structure and regulatory norms that Albania seeks to replicate. Between 1990 and 2021, greenhouse gas emissions in the EU dropped by 29%, primarily due to initiatives in nations such as Germany, Italy, France, Poland, and Spain. Emission reductions exhibited regional variability, with significant decreases in the Baltic states juxtaposed against rises in nations such as Ireland and Cyprus. In 2021, energy consumption was the predominant source of EU greenhouse gas emissions, with 76.7%.

This research analyses trends throughout the EU to provide insights relevant to Albania's energy management and emissions reduction goals. It situates the results within a wider European framework to tackle Albania's unique difficulties and ambitions.

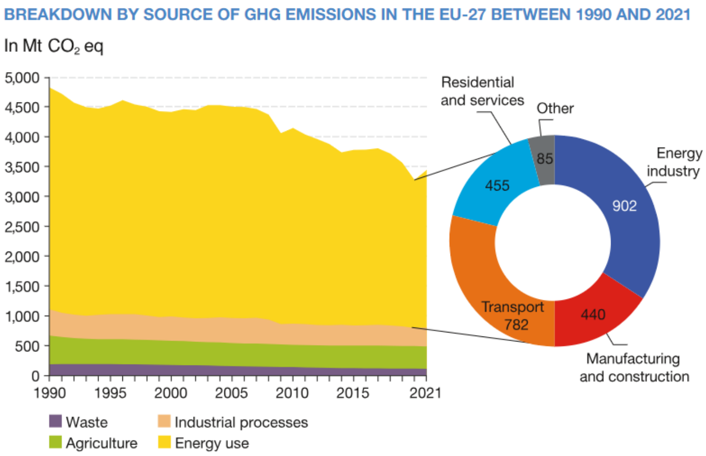

Figure 1. Greenhouse gas emissions from different industries (UNFCCC format - EEA, 2023)

This research examines the function of artificial intelligence (AI) in enhancing energy management systems and mitigating carbon emissions. In the European Union (EU), energy consumption constitutes around 76.7% of greenhouse gas emissions, with 33.9% directly attributable to the energy sector, mainly electricity production (UNFCCC, 2023). Given its substantial contribution, the research emphasizes power management as a pivotal domain for reducing emissions. The influence of AI on energy production and management includes several applications, yet this study focuses specifically on two key variables that significantly aid in emissions reduction.

The primary driver is an investment in AI-driven energy management systems, which provide several advantages, such as optimized energy usage, enhanced operational efficiency, predictive maintenance, and seamless integration of renewable resources. These systems offer adaptive modifications to energy use, improving operational sustainability. Evaluating the benefits of AI investments reveals their significant potential to mitigate carbon emissions, emphasizing the need for these investments for enduring sustainability in the energy industry.

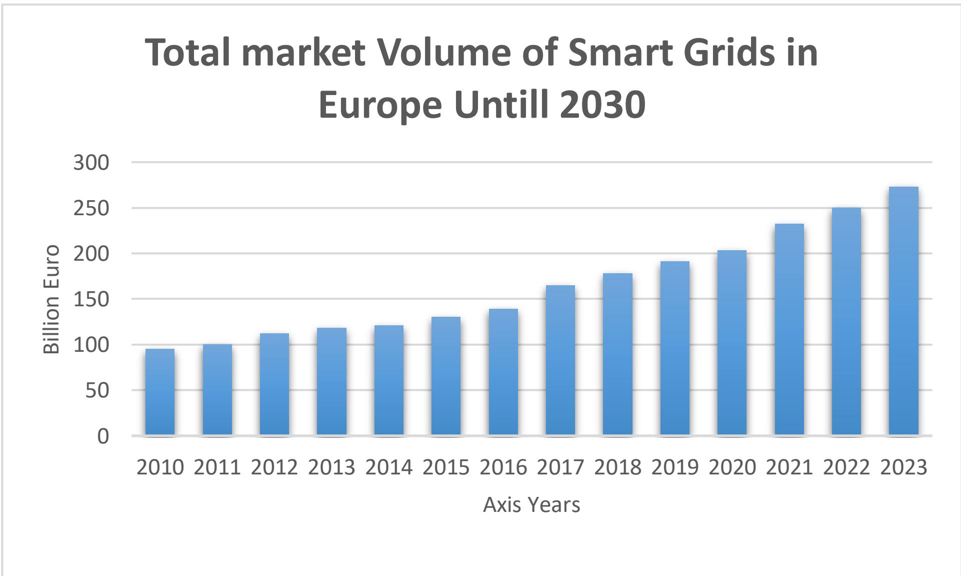

Figure 2. Cumulative Market Volume of Smart Grids in Europe Through 2030

Table 1. Investments in smart energy grids in the EU from 2010 to 2030 (expressed in billion euros)

Year	Investments in smart energy grids in the EU (in billion euros)
2010	95
2011	100
2012	112
2013	118
2014	121
2015	130
2016	139
2017	165
2018	178
2019	191
2020	203
2021	232
2022	250
2023	273

The second crucial component in mitigating carbon emissions is the enhanced precision of weather forecasting, attained by machine learning and artificial intelligence (AI) algorithms. Accurate weather forecasts are crucial for the efficient integration of renewable energy sources since dependable projections provide exact modifications in energy management to address fluctuations in solar and wind availability. Yang et al. (2022) argue that precise forecasts with a minimum lead time of 43 hours are essential for optimizing the efficiency of renewable energy integration. This research examines historical data on prediction accuracy for 3-day intervals throughout the European Union, evaluating the impact of AI-enhanced forecasting on optimizing renewable energy deployment and facilitating emissions reduction.

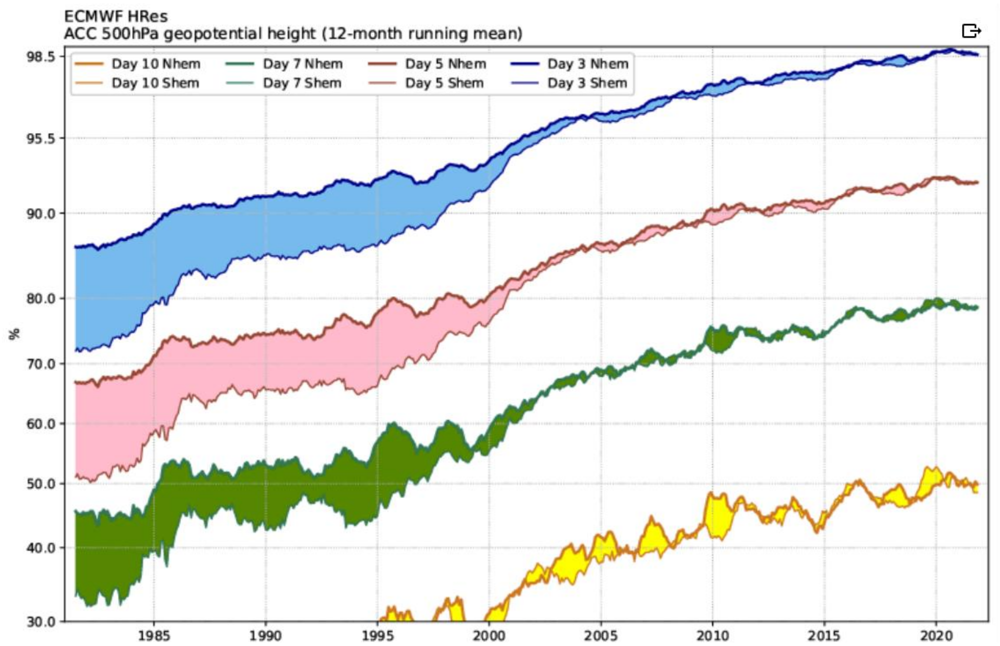

Figure 2. Weather forecast accuracy over the years (ECMWF, 2023)

Table 2. Accuracy of three-day weather predictions in the EU from 2010 to 2023 (given as a percentage)

Year	Accuracy of 3-day weather forecasts (in percent)
2010	96.3
2011	96.7
2012	97
2013	97.2
2014	97.3
2015	97.4
2016	97.8
2017	98.2
2018	98.3
2019	98.4
2020	98.6
2021	98.8
2022	98.5
2023	99.1

Precise weather forecasting is essential for improving the efficacy of power management systems, notably by facilitating the best use of renewable energy supplies. This research investigates the relationship between the accuracy of weather predictions, investments in AI-driven energy management systems (EMS), and atmospheric carbon dioxide (CO_2) emissions. By analyzing these correlations, we want to ascertain the influence of AI-enhanced forecasting and energy management on emissions reduction, therefore elucidating the significance of accurate data-driven tactics in fostering sustainable energy habits.

Table 3. Carbon Emissions Levels in the EU from 2010 to 2023 (measured in million tonnes)

Year	Carbon emissions in the EU (in million tonnes)
2010	3389.3
2011	3301.8
2012	3221.5
2013	3148.2
2014	2984.4
2015	3046
2016	3073.9
2017	3118.6
2018	3070
2019	2930.7
2020	2569
2021	2742.8
2022	2725.4
2023	2533.2

This research evaluates the hypothesis:

H1: Augmented investment in AI-driven intelligent power grids (energy management systems) and improved precision of meteorological predictions result in decreased atmospheric carbon emissions.

To substantiate this claim, we want to disprove the null hypothesis:

H0: Enhanced investment in intelligent power grids and augmented precision in weather forecasts do not facilitate a reduction in atmospheric carbon emissions.

A linear regression analysis is used to evaluate the influence of investments in new energy networks and the accuracy of weather predictions on carbon emissions within the European Union. Data are organized annually, including weather forecast accuracy (stated as a percentage), investment in sophisticated energy networks (quantified in billions of dollars), and carbon emission levels (measured in a million tonnes).

Table 4. Data presented in tabular form

Year	Investments in smart energy grids in the EU (in billion euros)	Accuracy of all 3-day weather (in percent)	Carbon emissions in the EU (in million tonnes)
2010	95	96.3	3389.3
2011	100	96.7	3301.8
2012	112	97	3221.5
2013	118	97.2	3148.2
2014	121	97.3	2984.4
2015	130	97.4	3046
2016	139	97.8	3073.9
2017	165	98.2	3118.6
2018	178	98.3	3070
2019	191	98.4	2930.7
2020	203	98.6	2569
2021	232	98.8	2742.8
2022	250	98.5	2725.4
2023	273	99.1	2533.2

RESULTS AND DISCUSSION

The factors examined in this research are as follows: Investment in Smart Energy Grids (billions of euros): This variable denotes the yearly investments in advanced energy networks within the European Union, quantified in billions of euros. Function in the Model: This is an independent variable (X_1) in the linear regression analysis. Accuracy of 3-Day Weather Forecasts (%): This variable denotes the precision of three-day weather forecasts, represented as a percentage. Function in the Model: This is the regression model's second independent variable (X_2). Carbon Emissions in the EU (million tonnes): This variable quantifies the total yearly carbon emissions in the European Union, expressed in million tonnes. Function in the Model: This represents the regression analysis's dependent variable (y).

The correlation analysis investigates the link between variables by computing the correlation coefficient and assessing the association's strength, direction, and type. The coefficient varies from -1 to +1, where

- +1 signifies a perfect positive linear correlation, indicating that an increase in one variable correlates proportionately to the rise in the other.
- -1 denotes a perfect negative linear correlation, indicating that a rise in one variable corresponds with a proportionate drop in the other.

Complete correlations of +1 or -1 are rare in most scientific and social sciences. Relationships are sometimes intricate, exhibiting varied levels of affinity rather than definitive correlations. A coefficient close to 0 indicates a negligible or nonexistent linear connection between the variables.

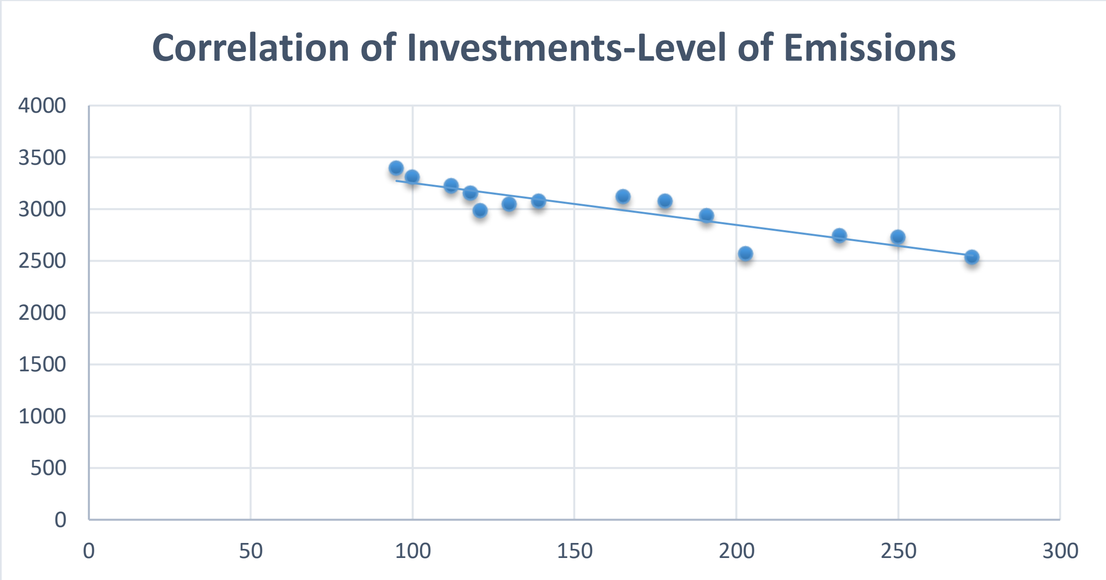

Figure 3. Correlation of Investments - Level of Carbon Emissions

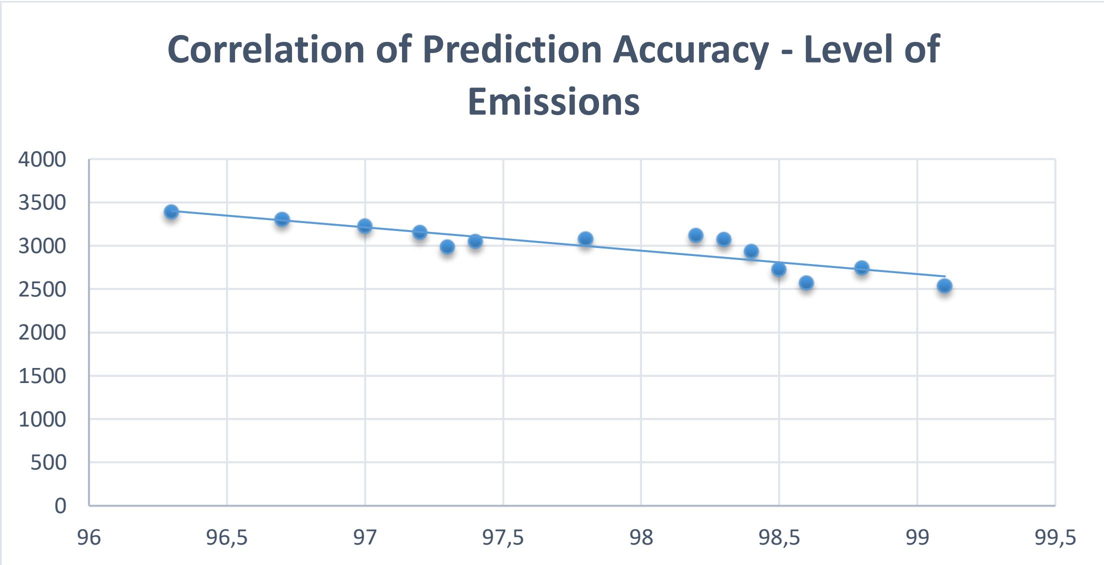

Figure 4. Correlation of Prediction Accuracy - Level of Emissions

Table 5. Correlation Summary

Korrelacioni	Investimet	Saktësia e Parashikimeve
Niveli i Emetimeve të Karbonit	-0.897090165	-0.8794136

The correlation study indicates a coefficient of -0.89 between investment in energy management systems and carbon emissions, indicating a robust negative relationship. This suggests that increased investment in energy management systems is directly associated with decreased CO_2 emissions. The correlation coefficient for prediction accuracy is -0.87, indicating a significant negative link; increased forecast accuracy correlates with reduced carbon dioxide emissions. These findings highlight the possibility of deliberate investments in energy infrastructure and enhanced predictive ability to reduce emissions substantially.

Table 6. Regression Analysis Results

Regression Statistics	
Multiple R	0.897090165
R Square	0.824770764
Adjusted R Square	0.788501661
Standard Error	120.2609178
Observations	14

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	715414.2883	715414.2883	49.4662037	1.36924E-05
Residual	12	173552.2603	14462.68836		
Total	13	888966.5486			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	3656.779911	100.1545209	36.51138138	1.14176E-13
X Variable 1	-4.048599376	0.575639402	-7.03322143	1.36924E-05
X Variable 2	-269.7446326	42.15308447	-6.39916713	3.40666E-05

The regression study produced a Multiple R-value of 0.897, indicating a robust association between the independent variables (investment in energy management systems and weather forecast accuracy) and the dependent variable (carbon emissions). The coefficient of determination, R^2, was determined to be 0.825, indicating that the model accounts for 82.5% of the variation in carbon emissions. The elevated R^2 value classifies the model as high-quality (ranging from 0.8 to 1.0) and substantiates its dependability in forecasting emissions based on the independent variables.

The ANOVA findings validate the model's statistical significance, presenting an F significance value of 1.37×10^{-5} ($p < 0.00001$), much lower than the 0.05 criterion, demonstrating that the model is resilient and adequately elucidates the link between the predictors and carbon emissions. The data indicate that at least one independent variable strongly influences the dependent variable, strengthening the model's validity. The research indicated that for every extra billion euros allocated to energy management systems (X_1), carbon emissions diminish by around 4.049 million tonnes, assuming other variables remain constant. A one-percentage-point enhancement in the accuracy of 3-day weather forecasts (X_2) correlates with a decrease in carbon emissions by around 269,745 tonnes, provided all other variables stay constant. The results highlight the significant influence of strategic investments in novel energy infrastructure and improved forecasting accuracy on decreasing carbon emissions.

CONCLUSION

This research reveals a statistically significant inverse relationship between investments in smart energy grids and carbon emissions, suggesting that heightened investment in these systems significantly decreases emissions. A negative link exists between the accuracy of weather predictions and carbon emissions, wherein enhanced forecast precision correlates with reduced emission levels. The regression analysis substantiates that investments in artificial intelligence (AI) technology are essential for mitigating greenhouse gas emissions. These results underscore the capability of AI-driven energy management systems to facilitate significant advancements in emissions reduction objectives and sustainable energy practices. To translate these findings into actionable measures, policymakers and stakeholders must prioritize investments in clean energy technologies and improved weather prediction systems. Policy actions should aggressively stimulate investments in renewable energy and energy efficiency, foster innovation, and implement sustainable technology. In the case of Albania, it is crucial to develop customized plans for reducing carbon emissions by leveraging regional best practices and adapting them to local conditions. Furthermore, future studies should explore emissions reduction strategies at the regional level within the EU to guide policy adaptations that address specific local requirements. The continuous assessment of policy outcomes is essential to ensure the effectiveness of adaptation measures and sustain progress toward achieving long-term sustainable development goals.

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AUTHOR CONTRIBUTIONS

All authors contributed equally to the conception and design of the study, data collection and analysis, and the preparation and revision of the manuscript. Specifically, Tabaku. E and Vyshka. E developed the research framework and performed the data analysis and interpretation; Kapciu. R and Shehi. A, coordinated data collection. All authors participated in drafting, critically revising, and approving the final version of the manuscript.

CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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