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Eco-AI: Artificial Intelligence Framework for Predicting and Reducing Carbon Emissions in Depok City

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ABSTRACT

Depok City faces increasing carbon emissions associated with rapid urbanization, a population exceeding 2.7 million, and more than 821,000 registered motor vehicles. However, the city lacks an integrated, data-driven framework for predicting greenhouse gas emissions and evaluating emission reduction strategies. This study aimed to develop Eco-AI, an artificial intelligence (AI)-based framework designed to predict greenhouse gas emissions and assess mitigation strategies in Depok City through the integration of multiple predictive and optimization models. A mixed-methods approach was employed, combining quantitative and qualitative analyses using Internet of Things (IoT) sensor measurements (MQ-135 and SDS011), Sentinel-5P satellite observations, and administrative data from relevant government agencies, including DLHK, Dishub, PLN, and BPS. Five AI models were incorporated: long short-term memory (LSTM) networks for time-series forecasting, random forest (RF) for identifying influential emission-related factors, extreme gradient boosting (XGBoost) for emission hotspot classification, graph neural networks (GNNs) for spatial analysis, and reinforcement learning using proximal policy optimization (PPO) for policy scenario optimization. The results indicated that Depok City's total greenhouse gas emissions reached 4,217,340 metric tons of carbon dioxide equivalent (tCO_2e) in 2024, with transportation accounting for 43.2% and residential energy consumption contributing 29.9%. The LSTM model achieved strong predictive performance (R^2 = 0.924; mean absolute percentage error [MAPE] = 4.97%), while the RF model identified the number of motor vehicles as the most influential predictor (feature importance = 0.234). Under the business-as-usual (BAU) scenario, annual emissions were projected to reach 5,891,200 tCO_2e by 2030. The combined mitigation scenario indicated a potential emissions reduction of 19.1% relative to the BAU projection, with an estimated investment requirement of IDR 1.24 trillion. These findings suggested that the Eco-AI framework could support data-driven emissions forecasting, identification of emission-related factors, spatial assessment, and evaluation of mitigation strategies. The framework may contribute to evidence-based urban climate planning and support Depok City's efforts toward Indonesia's national net-zero emissions target for 2060.

INTRODUCTION

Global climate change, driven primarily by increasing greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), represents one of the most pressing environmental challenges of the twenty-first century. Atmospheric CO_2 concentrations exceeded 420 parts per million (ppm) in 2023, highlighting the continued accumulation of greenhouse gases in the atmosphere and the urgency of climate change mitigation (Intergovernmental Panel on Climate Change [IPCC], 2023). Urban areas play a critical role in global mitigation efforts because urban activities account for a substantial proportion of energy-related CO_2 emissions worldwide, with estimates exceeding 70% depending on the accounting methodology and geographical boundaries applied (United Nations Environment Programme [UNEP], 2022).

Depok City, located in West Java Province and forming part of the Greater Jakarta metropolitan area, has experienced substantial urbanization pressures over the past two decades (Irawati, 2022). With a reported population exceeding 2.5 million and an estimated annual population growth rate of 2.8%, the city faces increasing challenges related to greenhouse gas emissions. The reported expansion of its motor vehicle fleet to more than 1.8 million units, increasing energy consumption in residential and commercial sectors, and limited green open space, estimated at approximately 10% of the urban area, have raised concerns regarding the environmental implications of urban development. These conditions highlight the need for reliable emissions inventories, integrated monitoring systems, and evidence-based mitigation strategies to support sustainable urban planning.

Advances in artificial intelligence (AI) have created opportunities to improve urban environmental monitoring, emissions forecasting, and climate-related decision-making. AI-based methods can analyze large and heterogeneous datasets, identify complex relationships among emission-related variables, and generate predictions to support policy development (Dong et al., 2024; Han et al., 2023; Zhang et al., 2024). Previous studies have highlighted the potential of AI applications to improve energy efficiency and facilitate data-driven environmental management, although the magnitude of these benefits depends on the technologies, implementation contexts, and evaluation methods employed (Ardabili et al., 2022; Tien et al., 2022; Wang et al., 2023). Integrating AI into urban emissions management may therefore strengthen the analytical capacity of local governments to evaluate mitigation alternatives and support progress toward national climate objectives.

Nevertheless, implementing AI-based greenhouse gas emissions management in rapidly urbanizing cities such as Depok presents several challenges, including fragmented environmental datasets, limited monitoring infrastructure, insufficient integration among administrative information systems, and constraints on technical expertise. These limitations can reduce the reliability of emissions estimates and complicate the development of coordinated mitigation policies (Hanami et al., 2025; Santoso et al., 2025). To address these challenges, this study developed the Eco-AI framework, an AI-based analytical system designed to integrate heterogeneous data sources, forecast greenhouse gas emissions, identify influential emission-related factors, and evaluate potential mitigation strategies for Depok City.

The research gap addressed in this study involved three interconnected areas. First, existing AI-based emissions research in Indonesia has frequently examined individual sectors

or employed separate modeling approaches, leaving opportunities for more comprehensive integration of urban emissions data and analytical methods (Al-Nefaie & Aldhyani, 2023; Li et al., 2024). Second, the integration of emissions forecasting with policy scenario optimization remains insufficiently explored in the context of local government decision-making, particularly in rapidly urbanizing municipalities with fragmented data systems. Third, the use of interpretable AI techniques to identify influential emission-related variables requires further investigation to improve the transparency and practical relevance of model outputs (Ding et al., 2024; Yan & Sun, 2025). Accordingly, this study developed an integrated Eco-AI framework incorporating five complementary approaches: long short-term memory (LSTM) networks, random forest (RF), extreme gradient boosting (XGBoost), graph neural networks (GNNs), and reinforcement learning (RL). These models were selected to address different analytical requirements within Depok City's urban emissions management context (Y. Chen et al., 2024; Z. Chen et al., 2024; Gong et al., 2024).

The urgency of this research was reflected in Depok City's projected greenhouse gas emissions trajectory and the need to identify feasible mitigation strategies. Under the business-as-usual (BAU) scenario, annual emissions were projected to reach approximately 5.89 million metric tons of carbon dioxide equivalent (tCO_2e) by 2030, representing an increase of approximately 39.7% compared with the estimated 2024 level. This projected growth highlighted the importance of strengthening local mitigation efforts in support of Indonesia's national net-zero emissions target for 2060 (Resosudarmo et al., 2023). The availability of Sentinel-5P satellite observations, Internet of Things (IoT) sensor measurements, and administrative records from relevant government agencies provided opportunities to develop an integrated analytical framework. However, differences in data coverage, measurement characteristics, and spatial and temporal resolution required careful consideration. Potential integration with Depok's smart city information systems could provide an institutional pathway for future implementation, subject to technical validation, stakeholder approval, and operational readiness.

The proposed novelty of this study lay in integrating predictive, diagnostic, spatial, and prescriptive analytical methods within a unified framework tailored to Depok City's emissions management requirements. The framework combined LSTM networks for time-series forecasting, RF for identifying influential predictors, XGBoost for classifying emission hotspots, GNNs for modeling spatial relationships, and RL for evaluating policy intervention scenarios (Wan & Liu, 2023). Feature importance analysis was incorporated to improve the interpretability of selected model outputs and support policy-oriented assessment (Anastasiadou et al., 2022). Additionally, the framework integrated administrative emissions-related records with satellite observations and IoT sensor measurements to support the analysis of urban environmental conditions (Islam et al., 2024). This approach provided a methodological basis for examining how heterogeneous datasets and complementary AI models could be combined to inform emissions management in municipalities facing data integration challenges.

This study aimed to design, develop, and evaluate the Eco-AI framework as a data-driven decision-support system for greenhouse gas emissions forecasting and mitigation planning in Depok City. Specifically, the study sought to characterize the city's emissions profile across major contributing sectors, develop and validate AI-based forecasting models,

identify influential socioeconomic and infrastructural variables, assess spatial patterns associated with emissions, and evaluate potential mitigation scenarios and their estimated investment requirements. The study also aimed to formulate policy recommendations aligned with local development priorities and institutional capacities. Through these objectives, the research examined the potential application of integrated AI methods to support evidence-based urban climate governance.

The anticipated contributions of this research encompassed methodological and practical dimensions. Methodologically, the study examined the integration of complementary AI models for urban greenhouse gas emissions analysis in a municipality characterized by heterogeneous data sources and institutional constraints. The framework provided an analytical approach that could inform similar investigations in other Indonesian cities, although its transferability would require further evaluation. Practically, the scenario analysis considered potential mitigation measures, including electric bus deployment along the Margonda Corridor, low-emission zones in areas identified as emission hotspots, and expanded rooftop solar photovoltaic installations. These interventions were evaluated as potential policy options rather than established solutions, with their feasibility depending on local infrastructure, investment requirements, regulatory conditions, and implementation capacity. Future integration of Eco-AI into Depok's smart city systems could support the translation of analytical findings into municipal planning processes, provided that the framework underwent appropriate technical and institutional validation.

The central objective of this study was to develop and evaluate an integrated AI framework capable of forecasting greenhouse gas emissions in Depok City through 2030, identifying influential emission-related factors, and estimating the potential emissions reductions and investment requirements associated with alternative mitigation scenarios. The study also sought to prioritize policy recommendations according to their projected environmental benefits and implementation considerations. By combining forecasting, factor analysis, spatial modeling, and scenario optimization, the framework was intended to provide a structured approach to AI-assisted urban emissions management. Its applicability to other municipalities would depend on the availability, quality, and comparability of local data and the capacity of relevant institutions to implement and maintain the analytical system.

The potential benefits of this research extended to local government, academic researchers, and civil society. For local government, the Eco-AI framework could support decision-making by integrating fragmented datasets, generating emissions forecasts, and comparing the projected outcomes of alternative mitigation strategies. For the academic community, the study provided an example of complementary AI model integration in an urban emissions management context, offering opportunities for further methodological development and independent validation. For civil society and environmental stakeholders, interpretable model outputs and transparent scenario assessments could facilitate informed discussion and participation in local climate governance. Nevertheless, the practical effectiveness of the framework would depend on data reliability, model validation, institutional adoption, and continuous performance monitoring. Overall, the study contributed to the development of data-driven approaches for urban climate planning and supported ongoing efforts toward Indonesia's net-zero emissions target for 2060.

METHOD

This study employed a mixed-methods approach integrating quantitative and qualitative analyses within an applied research framework using an exploratory and predictive design. The research was conducted in Depok City, West Java, Indonesia, covering the city's administrative districts.

Variables and Data Sources

Dependent variables are the carbon emission level (equivalent tons of CO_2/year) per sector and per sub-district. Independent variables include: number of motor vehicles and traffic density, electricity consumption per village, number of industries and production volume, area of RTH and vegetation cover, microclimate data (temperature, humidity, wind, rainfall), as well as population density and GDP.

Primary data was obtained through field surveys with IoT sensors (MQ-135 and SDS011) in 12 sub-districts, in-depth interviews with DLHK, Bappeda, and the Transportation Office, FGD with the environmental community, and community behavior questionnaires. Secondary data included GHG inventory from DLHK, Sentinel-5P satellite data, Dishub traffic data and Google Maps Traffic API, PLN electricity consumption data, BIG satellite imagery, BMKG data, and BPS Depok City data.

AI Predictive Modeling

The ECO-AI framework combines five AI models: (1) LSTM for emission time series prediction; (2) Random Forest for the identification of dominant factors; (3) XGBoost for hotspot zone classification; (4) Graph Neural Network (GNN) for spatial network analysis; and (5) Reinforcement Learning (PPO) for policy scenario optimization. Data sharing uses 80% training and 20% testing with K-Fold Cross Validation (K=10). Hyperparameter optimization is carried out through Bayesian Optimization and Grid Search.

The evaluation metrics include MAE, RMSE, R^2, MAPE, and F1-Score. The prediction accuracy targets are MAPE < 10% and $R^2 > 0.85$. The simulation of emission reduction scenarios includes four scenarios: S1 (Green Transportation), S2 (Renewable Energy), S3 (RTH Expansion), and S4 (Integrated Combined).

RESULTS AND DISCUSSION

Overview of Carbon Emissions of Depok City

Depok City's total estimated carbon emissions in 2024 will reach 4,217,340 tons of CO_2 equivalent per year, an increase of 23.4% compared to the 2019 estimate of 3,417,200 tons of CO_2eq/year, with an average growth rate of 4.3% per year. The distribution of emissions is dominated by the transportation sector (43.2%) and residential & building energy (29.9%), which together account for more than 73% of total emissions.

Table 1. Distribution of Carbon Emissions per Sector in Depok City in 2024

Sektor	Emisi (ton CO_2 eq/th)	Persentase	Tren 2019–2024
Transportasi	1.823.450	43,2%	↑ +31,2%
Permukiman & Energi	1.264.780	29,9%	↑ +18,7%
Industri & UMKM	612.340	14,5%	↑ +12,4%
Pengelolaan Limbah	389.210	9,2%	↑ +8,9%
Pertanian & Lahan	127.560	3,0%	↓ -5,3%
RTH (serapan)	-89.000	(-2,1%)	↓ -11,8%
TOTAL NETO	**4.128.340**	**100%**	**↑ +23,4%**

Spatial analysis showed that Cimanggis, Sukmajaya, and Pancoran Mas Districts were identified as the highest emission zones (hotspots), while Sawangan and Bojongsari Districts recorded relatively lower emissions due to the presence of agricultural land and wider vegetation cover.

AI Modeling Results – Identification of Dominant Factors

The Random Forest model was trained using 14 input features reaching $R^2 = 0.91$ and MAE = 18,340 tons CO_2 eq/year. The feature importance analysis showed the number of motor vehicles per sub-district (importance: 0.234) and daily fuel consumption (0.198) as the two most dominant factors, followed by population density (0.167) and road network length (0.142). The XGBoost model for emission zone classification achieved F1-Score = 0.87, Precision = 0.89, and Recall = 0.85.

LSTM Modeling Results – Emission Prediction 2025–2030

The LSTM model with a 2-layer architecture (128 units and 64 units) reached $R^2 = 0.924$ and MAPE = 4.97% in the testing data. Based on the Business-as-Usual (BAU) scenario, Depok City's carbon emissions are projected to reach 5,891,200 tons of CO_2 eq/year by 2030, an increase of 39.7% from 2024 conditions.

Table 2. Depok City Carbon Emission Projections 2025–2030 (BAU Scenario)

Tahun	Proyeksi Emisi (ton CO_2 eq/th)	Pertumbuhan YoY	Interval Kepercayaan 95%
2024 (Aktual)	4.217.340	–	–
2025	4.483.120	+6,3%	[4.312.450 – 4.653.790]
2026	4.741.680	+5,8%	[4.521.340 – 4.962.020]
2027	4.989.210	+5,2%	[4.718.640 – 5.259.780]
2028	5.234.870	+4,9%	[4.912.450 – 5.557.290]
2029	5.563.410	+4,7%	[5.187.230 – 5.939.590]
2030	5.891.200	+5,9%	[5.432.180 – 6.350.220]

Simulation of Emission Reduction Scenarios

The Reinforcement Learning (PPO) model simulates four intervention scenarios. The S1 (Green Transportation) scenario projects a reduction of 434,680 tons of CO_2 eq/year

(10.3%) with an investment of IDR 248.1 billion. The S2 (Renewable Energy) scenario reduces 320,350 tons (7.6%) with an investment of IDR 613 billion. The S3 scenario (RTH expansion) absorbs 252,240 tons (6.0%). The combined S4 scenario is able to reduce emissions by 1,128,140 tons of CO_2 eq/year or 19.1% of the BAU 2030 projection, with a total investment of IDR 1.24 trillion over six years.

Table 3. Summary of the Performance of All AI Models in the ECO-AI Framework

Model AI	Tugas	Metrik Utama	Nilai	Status
LSTM	Prediksi deret waktu	R^2 / MAPE	0,924 / 4,97%	Sangat Baik
Random Forest	Faktor dominan	R^2 / MAE	0,910 / 18.340	Sangat Baik
XGBoost	Klasifikasi hotspot	F1-Score	0,870	Baik
GNN	Jaringan spasial	R^2	0,890	Baik
RL (PPO)	Optimasi skenario	Konvergensi	94,2%	Baik

Validation and Qualitative Analysis

Model validation with measurement data from 24 IoT sensors showed an average deviation of 5.3% from the actual measurement, still within the tolerance limit of ±10%. Triangulation with DLHK, Sentinel-5P, and PLN data confirmed the consistency of the estimates (< difference of 8%). Interviews with 18 key informants and FGDs with 67 participants revealed that public awareness is still low (only 34% understand the relationship between behavior and carbon emissions), but all government stakeholders support the integration of the ECO-AI dashboard into the Smart City Depok platform.

Policy Recommendations

Based on the integration of the analysis results, the study formulated priority recommendations: (1) the development of 50 units of electric buses in the Margonda Corridor; (2) the establishment of Low Emission Zone Regional Regulations in three hotspot districts; (3) the mass rooftop solar power plant program in 2,340 public facilities; (4) the construction of 120 km of integrated bicycle paths; (5) the planting of 1.2 million trees towards the 20% RTH target; and (6) the integration of the ECO-AI dashboard into the Smart City Depok platform.

CONCLUSION

This study developed the Eco-AI framework by integrating five artificial intelligence (AI) approaches: long short-term memory (LSTM) networks, random forest (RF), extreme gradient boosting (XGBoost), graph neural networks (GNNs), and reinforcement learning (RL) for comprehensive urban greenhouse gas emissions analysis. Depok City's total greenhouse gas emissions were estimated at 4,217,340 metric tons of carbon dioxide equivalent (tCO_2e) in 2024, with the transportation sector accounting for the largest share (43.2%). The LSTM model demonstrated strong predictive performance ($R^2 = 0.924$; mean absolute percentage error [MAPE] = 4.97%), while the RF model identified the number of motor vehicles as the most influential predictor of emissions.

Under the business-as-usual (BAU) scenario, annual greenhouse gas emissions were projected to reach 5,891,200 tCO_2e by 2030. The combined mitigation scenario indicated a

potential emissions reduction of 19.1% relative to the BAU projection, with an estimated investment requirement of IDR 1.24 trillion. These findings demonstrated the potential of the Eco-AI framework to support data-driven emissions forecasting, identification of influential emission-related factors, and evaluation of urban mitigation strategies. However, its operational reliability and effectiveness in real-world decision-making would require further validation. Based on the findings, the study recommended prioritizing low-emission zones, electric bus deployment, and the expansion of green open spaces (ruang terbuka hijau, RTH), alongside the proposed integration of Eco-AI into Depok's smart city platform. Future research should explore transformer-based architectures for long-term emissions forecasting and conduct comparative evaluations across municipalities in the Greater Jakarta metropolitan area to assess the framework's generalizability. These efforts could strengthen evidence-based urban climate governance and support Indonesia's national net-zero emissions target for 2060.

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CONFLICT OF INTEREST

The author states that this research was conducted without any commercial or financial relationship that can be interpreted as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

The author fully contributes to the formulation of the main idea, the collection of library data, the analysis and interpretation of the primary text of the character, and the preparation of the manuscript. All authors have agreed on the final version of the manuscript

GENERATIVE AI STATEMENT

The author states that generative artificial intelligence (AI) was used in the preparation of this manuscript. The author acknowledges the use of generative AI to help improve language clarity and improve the grammatical structure of the manuscript. The use is done in compliance with the applicable ethical guidelines regarding the use and disclosure of generative AI in scientific research. Each author has made substantial intellectual contributions to this work. The entire manuscript content has been carefully reviewed to ensure its accuracy, and the author is solely responsible for the integrity and final content of the manuscript.

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