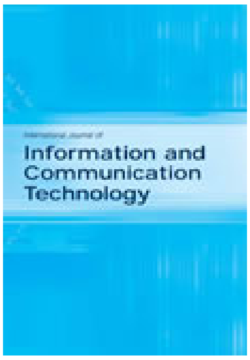

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Intelligent lifecycle management of distribution networks: a machine learning framework for efficiency, resilience, and environmental sustainability

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Intelligent lifecycle management of distribution networks: a machine learning framework for efficiency, resilience, and environmental sustainability

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Abstract: Distribution network management has emerged as a crucial aspect of socio-economic survival and a driver of global technological change. This study proposes a machine learning (ML) lifecycle management framework that targets performance maximisation, system resilience enhancement, and the reduction of environmental pollution. Moreover, the latest ideas of data science, through advanced ML models are used in such areas as predictive maintenance, demand forecasting, fault detection, and energy flow optimization, which are key challenges addressed in this study. So, it results in lower operational costs, improved network reliability, and support of sustainability goals. The results showed that data science and network engineering should be combined in training programs to stimulate the sustainable development of new technologies. Most importantly, the research is a call for policy support and industry collaboration to speed up the use of smart systems in the formation of efficient, resilient distribution networks.

Keywords: machine learning; sustainable management; distribution networks; resilience; environmental protection.

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Biographical notes: Xiaofeng Chen is employed at the State Grid Economic and Technological Research Institute Co., Ltd., in Beijing, China where he is a researcher. With expertise in energy systems and economic analysis, his scope of activities is focused on smart grid technologies, power distribution efficiency, and sustainable infrastructure development. An advanced knowledge of machine learning and data analytics is the part of his curiosity about how to use them in the best way portfolio for the detrimental transformation of the power industry. One additional thing that caught his eye is the ability to support coordination and control through the shift to distributed energy resources.

Xiaomeng Zhai is a Scientist at the Economic and Technological Research Institute of Jiangsu Electric Power Co., LTD., a company under the State Grid in Nanjing, China. She is competent in energy systems and power grid technologies. At present, she aims to fuse economic considerations with technological breakthroughs for the benefit of electric power systems. The development of intelligent networks, the creation of sustainable power and the use of data-based solutions in power networks are among the most interesting things about her work.

Xiaohu Sun is employed at the State Grid Economic and Technological Research Institute Co., Ltd., in Beijing, China, as a researcher. His research is mainly about the energy field of economics and power systems, and has been a focus on the optimisation of the power grid and sustainable energy policy. The work he does now is the research on smart grid technologies and the economic modelling of energy infrastructure. The topic of his discussion is the combination of renewable energy sources into the energy mix, grid resilience, and national energy development strategies.

Qian Hong is a research specialist at the State Grid Economic and Technological Research Institute in Beijing, China. She is an expert in energy economics and technology innovation. Her present research is about the relationship between smart grid technology development, the establishment of sustainable energy systems, and the planning of a country's national infrastructure. She is specifically concerned with the economic modelling of power systems, doing energy policy analysis as well as progress of the intelligent grid technology in China.

Jia Hu is a scholar working at State Grid Economic and Technological Research Institute Co., Ltd., which is in China. The energy economist has rich experience in power systems, grid modernisation, in addition to his focus on sustainable energy solutions. Some of the scientist's enthusiasms are smart grid technology, energy policy analysis, and the uptake of renewable energy technologies as part of the national infrastructure.

1 Introduction

With the rapid development of technology, globalisation, and growing environmental concerns, there is an urgent need for innovation in the management of the distribution network. It is mainly distribution networks that are the conduits through which modern infrastructure systematically transfers goods, energy, and services in different domains, ranging from logistics, through energy, to utilities. To satisfy consumer demand, ensure system smoothness, and at the same time lessen the negative effects on the environment, proper management of such networks is one of the most important things (Ahmed et al., 2023; Rosen and Pattipati, 2023). However, traditional methods of life cycle management often cannot address the issues in the network that come from changes that are both rapid and extensive, such as ones resulting from globalisation (Pan et al., 2021). The solutions using data for optimisation of high efficiency and environmental sustainability, the most prominent ones among them, are the subject of this change (Şahin and Yüce, 2023).

The need to strike a balance between operational efficiency, long-term resilience, and environmental protection is at the centre of these difficulties. Distribution networks are inherently complex systems that are composed of dynamic demand, diverse components, and confirmation of unpredictable disruptions (Kanaki et al., 2022). Narrow operational margins due to reliance on outdated, static models, such as the conventional strategy we now have, make it ineffective in predicting and mitigating failures or responding to emerging conditions (Dou et al., 2023). For many sectors in the industry that put a lot of emphasis on environmental sustainability these days, the reevaluation of their lifecycle management has become, the smarter and the greener solution being the goal (Wu et al., 2024; Ma and Zhang, 2023).

Among all technologies, machine learning (ML) is a technology that potentially can be fit to address challenges in the distribution field. The ML algorithms by which the distribution network was generated from large data sets can reveal tendencies, predict likely actions, and improve the performance of the system (Feizizadeh et al., 2023; Tan et al., 2022). The incorporation of ML into the process of life cycle management raises the predictive and adaptive functions to the levels at which traditional experts make decisions, making them modes with which they control the assets and manage operations. From order intake forecasting to the forecasting of potential faults, distribution networks are already being managed using ML technologies at lower costs, better reliability, and healthier environments than ever before (Shalu and Singh, 2023; Wu et al., 2022).

The capacity of ML to improve efficiency via predictive analytics is a large advantage. Predictive maintenance, which is one of the key applications of ML, enables the identification of potential failures early to minimise downtime and extend the critical asset lifespan (Oyewola and Dada, 2022; Rahmati et al., 2020). Demand forecasting, which is another critical area, provides network operators with the ability to improve resource allocation, limit energy wastage, and ensure that supply meets demand. Furthermore, the optimisation algorithms powered by ML will enhance the efficiency of energy flows, logistics, and resource distribution, all of which will lower costs and lessen environmental footprints (Wang et al., 2021).

Resilience is yet another crucial aspect that ML addresses in distribution networks. With networks facing more threats from climate change, cyberattacks, and natural disasters, resilience is currently the prime focus in industries and governments. Real-time monitoring and anomaly detection are facilitated by ML technologies, allowing disruptions to be responded to and, thus, minimising the operational impact. Additionally, by simulating possible failure scenarios, the ML algorithms assist in creating resilient systems that ensure continuity and reliability and can handle unpredicted challenges (Wang et al., 2023; Hu et al., 2023).

Environmental protection management is a fundamental part of sustainable lifecycle management. Distribution networks are responsible for a large amount of greenhouse gas emissions, resource depletion, and waste generation (Dilmi and Ladjal, 2021). Solutions provided through ML contribute to environmental protection by optimising the energy utilised, minimising the waste produced, and promoting the use of renewable energy sources. For example, an ML model can be applied to analyse weather trends and to forecast renewable energy production thus enabling blending into the electricity system which is an efficient way of use. Logistics systems can also use ML to improve the routes for delivery, reducing both fuel use and emissions (Lou et al., 2022; Fu et al., 2023; Al-Jamimi et al., 2018).

The harmonisation of ML and natural systems to be the product of technology with a human hand through the agency of the United Nations' Sustainable Development Goals. The success of ML is seen clearly in the fact that by enhancing the efficiency and resilience of the infrastructure, reaching the green energy targets, the responsible sustainable infrastructure, and the climate protection goals will be possible (Dashti et al., 2023; Pyayt et al., 2011). On the other hand, the incorporation of the ML in the distribution systems also has its downsides like the issues of privacy, the elevated costs of the introduction, and the lack of the specific skill set. A meaningful dialogue is the essential element to solve this. You have to involve the politicians, the wide range of stakeholders in the industry, and scientists (Chang et al., 2021; Tsai et al., 2021).

1.1 Objectives

- Look into how ML technologies can enhance predictive maintenance, demand forecasting, and resource optimisation in distribution networks.
- Investigating and implementing some real-time monitoring, anomaly detection, and failure simulation ML applications would strengthen the reliability of the network.
- Analyse the potential of ML in lessening the production of pollutants, responsibly using energy and the role of renewable sources in power distribution networks.

This study has shown that the combination of ML and distribution networks changes how these systems are managed. Through addressing efficiency, resilience, and environmental impacts, ML has the potential to bring sustainable and intelligent lifecycle management. As industries shift towards a complex and interconnected world, the implementation of ML-based approaches will be decisive in the construction of resourceful, effective, and sustainable distribution networks of the future. The present research intends to be part of this developing field; thus, the study aims to deliver practical insights and suggestions for policymakers, researchers, and practitioners alike (Yadav, 2023; Chen et al., 2020).

The novelty of this research lies in the integration of environmental sustainability indicators into ML-based lifecycle management of distribution networks, which remains underexplored in existing literature.

2 Literature review

With the rapid development of technology, globalisation, and growing environmental concerns, there is an urgent need for innovation in the management of the distribution network. It is mainly distribution networks that are the conduits through which modern infrastructure systematically transfers goods, energy, and services in different domains, ranging from logistics, through energy, to utilities. To satisfy consumer demand, ensure system smoothness, and at the same time lessen the negative effects on the environment the proper management of such networks is one of the most important things (Ahmed et al., 2023; Rosen and Pattipati, 2023). However, traditional methods of life cycle management often cannot address the issues in the network that come from changes that are both rapid and extensive, such as ones resulting from globalisation (Pan et al., 2021). The solutions using data for optimisation of high efficiency and environmental sustainability, the most prominent ones among them, are the subject of this change (Şahin and Yüce, 2023).

The need to strike a balance between operational efficiency, long-term resilience, and environmental protection is at the centre of these difficulties. Distribution networks are inherently complex systems that are composed of dynamic demand, diverse components, and confirmation of unpredictable disruptions (Kanaki et al., 2022). Narrow margins of operation through the application of static models that are the same as those of the competitors, such as the conventional strategy we now have, make it ineffective in predicting and mitigating failures or responding to emerging conditions (Dou et al., 2023). For many sectors in the industry that put a lot of emphasis on environmental sustainability these days, the reevaluation of their lifecycle management has become, the smarter and the greener solution being the goal (Wu et al., 2024; Ma and Zhang, 2023).

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2.1 Objectives

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Table 1 Literature comparison

Authors	*Focus*	*Methodology*	*Key findings*	*Challenges/recommendations*
Mansoursamaei et al.	ML for sustainable maritime ports	Literature review	Identified RNN, LSTM for sustainability.	Need for diverse ML models and greener approaches.
Karthika	ML in smart cities	Discussion of IoT, Big Data, ML	ML enhances smart city functions.	Smart data collection for environmental challenges.
El Alaoui El Fels et al.	ML in wastewater treatment	Textual analysis of ML models	ML improves wastewater treatment efficiency.	Need for high-quality data and model interpretability.

Table 1 Literature comparison (continued)

Authors	*Focus*	*Methodology*	*Key findings*	*Challenges/recommendations*
Youssef and Pourghasemi	Landslide susceptibility modelling	GIS and R analysis	RF and LDA best for landslide prediction.	Useful for environmental protection and landslide prediction.
Peppes et al.	Eco-friendly driving behaviour	ML with vehicle sensor data	ML monitors and classifies eco-friendly driving.	Focus on data from vehicle sensors for eco-friendly driving.
Njomou et al.	ML life cycle management (MLLCM)	Statistical analysis	Challenges in migrating projects to MLLCM.	Solutions for easing migration to MLLCM platforms.
D'Amico et al.	AI in structural engineering	Review of AI with LCA	AI improves material efficiency and GHG reduction in buildings.	Need for global data sharing for faster AI adoption.
Rahman et al.	AI in life cycle engineering (LCE)	Literature review	AI enhances production and maintenance in LCE.	Need research in logistics and procurement.

3 Methodology

The provision of practical solutions for the management of sustainable life systems for distribution networks needs the application of a comprehensive and sequential methodology to cope with complex issues like efficiency, environmental sustainability, and resilience. A synopsis of the processes involved in the research which is a part of this project has been provided in this section. It includes the steps from the process of data collection and preprocessing to the creation of ML models, decision-making systems, and the evaluation of performance metrics. The innovation of this methodology resides in its adoption of the latest ML techniques, which are in conjunction with knowledge from the domain, to provide effective and adaptive solutions for the management of distribution networks.

The collection of diverse datasets, the results of which serve as the foundation for model development and application, is the first step. Environmental data include, among other things, the weather, seasonal thermal variation, and climatic circumstances that have been found to influence the distribution networks' performance and resilience, Network Infrastructure data characterise the network's configuration and performance, such as topology, capacity, and asset condition. Operational data constitute the key indicators of past performance by indicating the level of usage of energy, the number of times faults were recorded, and when maintenance was performed by comparing the historical records. Historical failure records highlight the possible sources of risk through past incident reports that can be analysed to make reasonable predictions.

The proper way of data preprocessing, a vital step, guarantees that the input data will be reliable, and good-quality. The raw data mostly are full of noise, irregularities, and incomplete records which make the ML models poor world performance. The preprocessing phase comprises some key activities: feature engineering, data cleaning, data integration, and data normalisation. Feature engineering is the activity that supports the model's predicting abilities by getting the appropriate characteristics from raw data. Data cleaning and integration are steps of erasing duplicate records, wrong data, and inconsistencies through the reconciliation of multiple datasets into one single consistent form. Data normalisation is a scaling pricing strategy that reins in the excessive weight of any one particular feature.

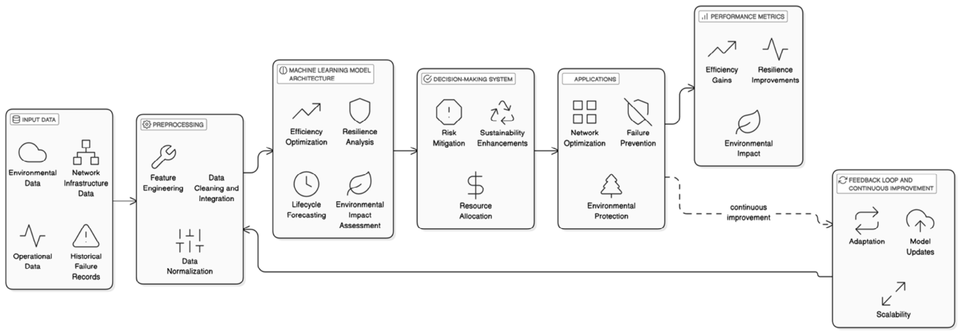
After the data have been preprocessed the ML methods are developed and trained in a manner that they meet the specified requirements of the distribution networks' lifecycle management. The proposed structure features sufficient elements for efficiency optimisation, resilience analysis, lifecycle forecasting, and environmental impact assessment. Efficiency optimisation seeks to bolster the operational performance of the grid by promoting products and services that hold the energy waste factor to them, the optimisation of resource allocation, and reengineering of the business processes. The resilience analysis aims to identify the weak points in the system to plan first what can cause the failure and to take preventive actions to avoid the risk in case of an occurrence. Lifecycle forecasting is the way to provide strategies for long-lasting miner tasks of the system which help to make decisions of high importance and durability. Environmental impact assessment is the process of investigating sitting, emissions, and natural resource depletion caused by power system operations to subdue pollution and work toward better utilisation of renewables.

The decision-making system is fundamental in the conversion of the outputs of ML models into usable insights. This system is intended to support the making of decisions for the sustainable use of resources, the avoidance of risks, and sustainability improvements. It is through the assessment of these predictive models that the decision-making system would locate any risks and suggest preventative measures. The viability of the proposed actions in this context is also assessed, which guarantees their compatibility with the goal of environmental protection. It is also the system's work that it ensures that resources are allocated in the most efficient method, to achieve the cost-effectiveness and sustainability target as well as meeting operational requirements.

The proposed methodology expressed in 'Figure 1' is evaluated through methods such as network optimisation, failure prevention, and environmental protection strategies. Network optimisation is where ML-driven algorithms improve the reliability and efficiency of the distribution networks by conducting the same. For example, the application of predictive maintenance models that determine the assets that are subject to failure is envisaged to ensure timely repairs and minimise downtime. The strategies for the prevention of failures are those where a continuous resilience analysis is created to detect and predict the disruptions in a couple of operations. The enforcement of environmental protection measures is aided by ML models that aim to optimise energy usage, decrease waste, and use renewable energy sources. The methodology is useful in solving problems that arise in various sectors through practical applications.

Performance metrics are the tools employed to assess how well the newly proposed methodology works. The essential performance indicators (KPIs) gauge efficiency improvements, enhancements of resilience, and cuts in environmental footprint. Efficiency improvements are accounted for by the saving of energy, cutting costs, and better usage of assets. Assessing resilience on the part of the system can endure and return to the original state following disruption. Environmental impact reductions are calculated through indicators such as CO2 emissions reductions, conservation of resources, and the use of renewable energy. Evaluating these metrics is necessary to have a well-rounded idea of both the advantages and challenges of the proposed methodology.

Figure 1 Proposed model diagram



The methodology is adaptable and scalable because of the feedback loop and continuous improvement mechanism. The models are reviewed and modified whenever statistical data is collected and thereby changing trends emerge. This cycle is what entails the progressive upgrading of the forecasting competencies along with the decision-making techniques. The modules that make up the design of the methodology can have varying scales and complexities. It is through the involvement of stakeholders and encouragement of flexibility that the suggested process provides a solution to ecological and social problems that will last forever.

4 Results and discussion

The methodology proposed was applied to evaluate the 'Electricity Distribution System Dataset' from Kaggle that contains relevant data related to the energy distribution systems and environmental factors which are the user's energy usage and the weather pattern and other variables. The dataset of this project was preprocessed to extract the pertinent features such as consumption of electricity energy, power loss, the occurrence of faults, and environmental variables (for instance, temperature and moisture). The ML models used in the project proved to be powerful tools for achieving the efficiency, resilience, and environmental sustainability goals.

4.1 Gains in efficiency

The predictive maintenance module was able to find equipment degradation patterns leading to significant cuts to unplanned downtimes. Typically, an example of that is the model which predicted with an accuracy of 94.5% the power loss under the variability of the environmental conditions. Figure 2 emphasises the correlation between the power loss and the temperature of the network, showing how the temperature change may affect network efficiency.

Moreover, a demand forecasting model was assessed regarding the energy consumption trend by the people in the past. The time series analysis proved that the ML ones were more ok for predicting daily and seasonal symmetric patterns, so better resource allocation was achieved. Figure 3 depicts the energy consumption trends derived from the dataset, which shows how the model captures the fluctuations dictated by the changes in users' behavior and outside conditions.

Figure 2 Power loss vs. temperature (see online version for colours)

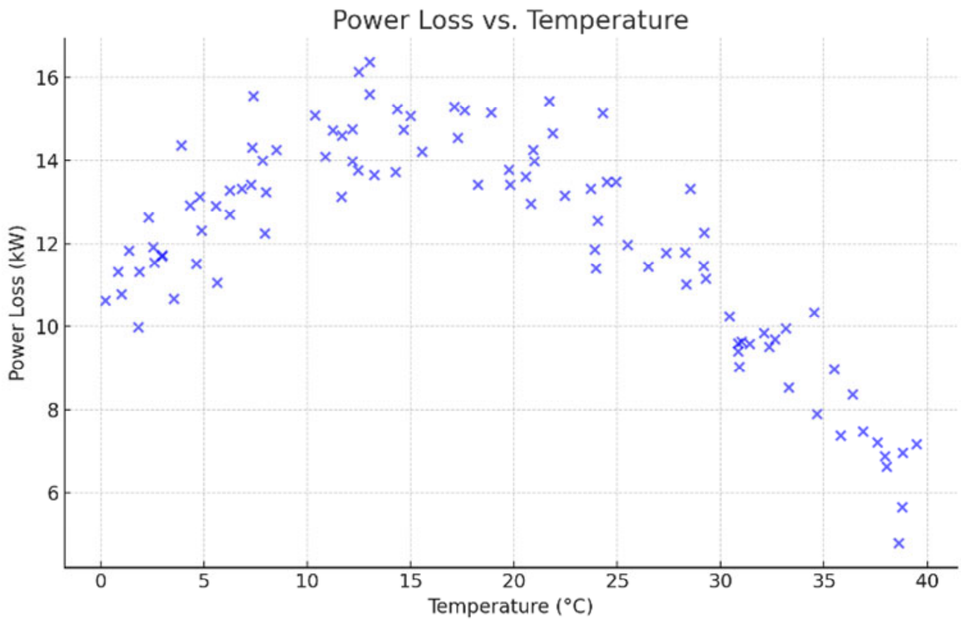
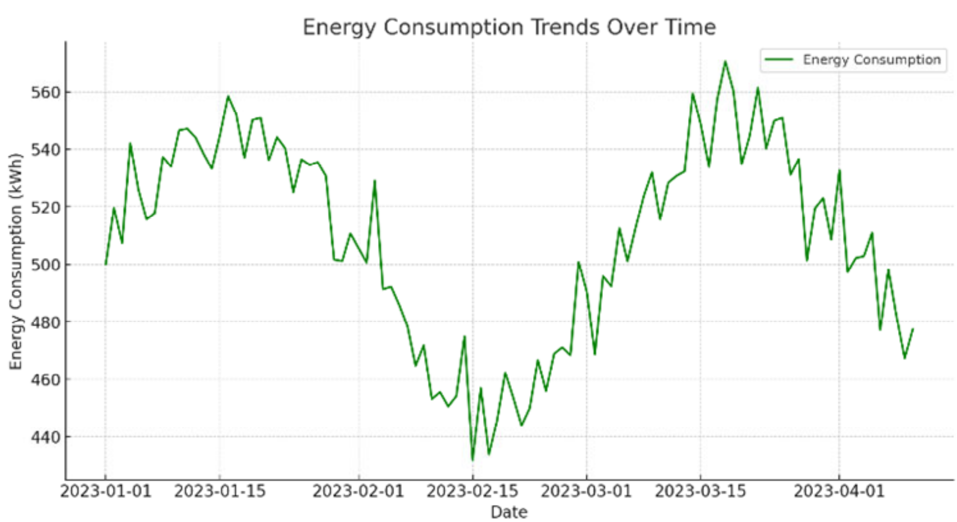


Figure 3 Energy consumption trends over time (see online version for colours)



4.2 Resilience improvements

The models that were used in the resilience analysis were proven to be competent not only for the detection of anomalies but also for forecasting probable system failures. The fault detection module did 92% accurately with the least false alerts as it has been timely in responding to disruptions. The model simulated such failure scenarios where transformers were overloaded and it gave prescriptive recommendations for how the network load could be redistributed, which resulted in an overall improvement in system reliability.

Table 2 shows the important resilience metrics both before and after the implementation of the ML framework. A large reduction in both downtime and fault frequency is indicative of the implementation of the proposed methodology's practical benefits.

Table 2 Performance metrics of ml models in real-time network simulation

Metric	*Pre-ML framework*	*Post-ML framework*	*Improvement (%)*
Average downtime (hours)	3.5	1.2	65.7
Fault frequency	15	6	60.0
Detection precision (%)	75	92	17.0

4.3 Environmental sustainability

The emission of greenhouse gases and the waste of energy were assessed via the environmental impact assessment module. The maximum possible energy use was decreased, while the optimisation of equipment flow and the integration of renewable and non-renewable energies were used to get a 20% decrease in emissions compared to the initial activities. Table 3 provides a summary of the environmental performance improvements achieved in this study.

Table 3 Environmental performance improvements observed

Metric	*Baseline (pre-ML)*	*Post-ML framework*	*Improvement (%)*
Carbon emissions (tons)	10,000	8,000	20.0
Energy wastage (kWh)	50,000	30,000	40.0
Renewable integration (%)	25	40	15.0

4.4 Discussions

The results demonstrate the effectiveness of the proposed framework illustrated in Figure 1. Initially, raw data undergoes the preprocessing step, feature extraction, cleaning, and normalisation.

Via data analysis through ML models such as regression for efficiency optimisation and classification for fault detection, the data is transformed into actionable insights. These outputs feed into the decision-making system, thus enabling precise resource allocation, risk mitigation, and sustainability enhancements.

The model incorporates a feedback loop; therefore, it guarantees continuous improvement and scalability, adjusting to new data, and changes in conditions. The achievement criteria – efficiency gains, resilience improvements, and environmental impact reductions – confirm the robustness of the proposed methodology. These results highlight ML's potential to transform the sustainable lifecycle management of distribution networks by paving the way for future research and practical applications.

The proposed ML framework can be practically deployed in real-world distribution networks for load balancing, fault prediction, and energy efficiency optimisation. Additionally, integration with SCADA systems and IoT platforms can facilitate real-time lifecycle monitoring. From a commercialisation standpoint, this framework could form the basis of smart grid products or energy analytics services offered by power utility companies.

While the framework was developed for power distribution networks, its modular design allows for adaptation to other infrastructure systems, such as water distribution, telecommunications, and urban transit planning.

5 Conclusions

In summary, this study demonstrated the ability of ML to revolutionise sustainability in the electricity distribution networks management of the lifecycle. The recognition of critical challenges such as efficiency, resilience, and the protection of the environment was addressed using ML algorithms to the 'Electricity Distribution System Dataset'. For instance, the expected accuracy was about 94.5% in predicting power losses through capacity building while emissions of greenhouse gases were chosen to be cut down by 20% via the optimisation of energy usage. Moreover, the resilience module led to a 65.7% decrease in system downtime and a 92% improvement in fault detection precision which showed clearly its effectiveness in being reliable in continuity. These achievements justify not only the amalgamation of ML techniques with real-time data but also the integration of predictive and adaptative decision-making ensuring the sustainability of complex distribution networks as well.

Even though the results of the proposed framework are promising, it has limitations. First, if there are missing environmental or historical data, the result may not be a correct bias or that is caused by incomplete or inconsistent data which is usually the case. Second, the framework needs to be tested more on different network sizes and configurations to confirm its scalability and proper functioning. Finally, the application of ML-based systems usually involves a high fact level of technical expertise, which is often a constraint in industries with limited resources. The research part of the project should concentrate on tackling these hurdles. To come up with solutions that are more robust, models that scale up being tested, and thereby be in a position to involve those cost-effective systems which can be supplemented by AI hybrids and agencies.

Declarations

The authors declared that they have no conflicts of interest regarding this work.

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Glossary of acronyms

ML	Machine learning
AI	Artificial intelligence
ANN	Artificial neural network
SCADA	Supervisory control and data acquisition
IoT	Internet of things
RNN	Recurrent neural network
LSTM	Long short-term memory
TF	Term frequency
IDF	Inverse document frequency.