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AI-Driven Lightning Strike Prediction Using Polymer-Integrated Sensor Platforms for Climate-Resilient Energy Systems in India

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Abstract

Lightning strikes are a major climate-related threat to India, resulting in severe human injuries as well as regular damages to the power transmission network and renewable energy infrastructure. This research aims to introduce the concept of an AI-based lightning strike prediction and mitigation system with the integration of polymers for making climate-resilient energy infrastructure. Multidata are collected based on satellite images, climate variables, as well as surface-based sensing modules, and are further processed with machine learning algorithms such as the Random Forest approach, Convolutional Neural Network models, and Long Short-Term Memory network models for accurate spatial-temporal predictions of lightning strikes. One of the primary contributions of this research work is the adaptation of advanced polymer and composite materials. Conductive polymers and polymer nanocomposites are proposed to be identified and analyzed for developing lightweight lightning sensors and protectors. The increased electronic conductivity and dielectric strength of these materials enable their effective use in smart grid applications. The development of AI-based predictive systems and the adaptation of advanced polymer and composite technologies and materials can improve lightning warning systems and create smart and reliable energy systems in India. The development of advanced AI-based predictive systems provides an increased degree of accuracy and reliability. The increased accuracy of AI-based systems reduces the reliance on manual calculations.

Keywords: Lightning prediction, artificial intelligence, machine learning, conductive polymers, smart materials, smart grid protection

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INTRODUCTION

In the Indian region, lightning strikes pose a serious atmospheric risk, resulting in substantial casualties and frequent damage to solar and renewable energy installations as well as the power transmission network. Nevertheless, the highly nonlinear and scale-containing process of thunderstorm electrification hinders the precision of current lightning forecasting methods that use on electric field indices and numerical weather models. Notable breakthroughs in the application of artificial intelligence (AI) and machine learning (ML) approaches have made way for advancements in forecasting using a combination of meteorological, satellite, and ground-level atmospheric electric field information [1–4]. Deep learning models such as convolutional neural networks (CNN) and long short-term memory

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(LSTM) networks are proficient in representing the space-temporal dependencies of the process and have exhibited advancements in nowcasting and warning predictions [5–7].

The availability of precise data is a major factor in the accuracy and dependability of AI-powered lightning detection algorithms. Polymer materials for sensing have gained popularity due to their lightweight, elastic, corrosion-resistant, and versatile electrical characteristics. The addition of fillers with carbon or metal properties in conductive polymer composites or the combination of piezoelectric properties with polymer matrices have enhanced their sensitivity, stability, and hardness, making them more suitable for harsh outdoor environments [8–10]. There has also been significant progress in polymer informatics, which has paved the way for the development of materials using machine learning, thereby optimizing the electric, dielectric, or mechanical properties for specific sensing tasks [11–13]. Polymer-integrated sensing technologies, in combination with AI, have shown better accuracy in environmental sampling models [14], while the potential utility of polymer-AI integration has also been explained by Kusum Tharani et al. in intelligent engineering applications [15].

Besides sensing, polymer composites are widely employed in energy-related infrastructures but are restricted due to low conductivity issues; hence, protection against lightning strikes is employed. Various studies have revealed that conductive paths and hybrid polymer-metal systems are greatly effective in the dissipation of current with minimal degradation [16, 17]. Though significant improvements have been made in AI-related lightning forecasting systems and polymer sensors, holistic systems that incorporate AI-powered forecasting with polymer sensor systems are very rare. References [18]– [20] collectively highlight recent advancements in natural fiber–reinforced polymer composites, focusing on material development, optimization, and performance evaluation. Karuppiah et al. [18] investigated Mult objective optimization of jute fiber/polyester composites with eggshell powder and nano clay fillers, while Santulli et al. [19] discussed pineapple fiber composites and their applications. Goutham et al. [20] reviewed drilling parameters and their influence on the residual tensile properties of natural fiber composites, emphasizing machining-related performance aspects. References [21– 23] emphasize sustainable material development through the incorporation of waste and natural fibers in polymer composites. Ayrilmis et al. [21] explored the use of waste manhole covers and fiberboard as reinforcing fillers in thermoplastic composites, while Aruchamy et al. [22] enhanced hybrid composites using palmyra palm and coconut sheath fibers with tamarind shell powder. Palanisamy et al. [23] investigated the influence of alkali treatment on the tensile behavior and fracture morphology of Acacia caesia bark fiber–reinforced composites, highlighting the role of surface modification in improving mechanical performance.

PROBLEM STATEMENT

The Lightning strikes have proved to be the cause of some of the most reported deaths and damage to infrastructure in the Indian nation. The traditional system used to provide warnings regarding lightning strikes has lacked not only detail but also the ability to provide effective warnings. AI technology has proved to be an increase in the accuracy of the warning systems. The current systems used to provide warnings have lacked the ability to provide accurate results with the availability and sensitivity that AI technology provides. The energy systems have lacked a comprehensive solution that tackles the challenge from a sensing point to make the energy systems more resilient to lightning strikes.

This research proposes to create an intelligent lightning prediction system utilizing polymer-based composite sensors. The objective of this study would be to achieve the following goals:

1. To develop conductive composites that are optimal for use in lightning detection, as well as durable enough to withstand environmental changes;
2. To use these composites within sensors that would continuously monitor atmospheric changes for lightning detection;
3. To use machine learning algorithms such as Random Forest, CNN, as well as the LSTM algorithm, to predict lightning events; and

4. To assess the effectiveness of this system in terms of improved lightning forecasting, long forecasting, and energy system robustness. This research integrates smart polymers with artificial intelligence, paving the way for a materials science-based method in intelligent lightning alert systems that are resilient to climate changes.

PROPOSED SYSTEM

For climate-resilient energy systems, the suggested solution combines AI-driven predictive analytics with polymer-based composite sensors to provide precise, real-time lightning forecasting. The three main parts of the architecture are the sensor platform, data collection and preprocessing, and AI-based forecasting system (Figure 1).

Sensor Platform: Conductive polymer composites, fabricated with carbonaceous and metallic fillers within a thermoplastic matrix, form the basis of the sensing network. These polymer-integrated sensors capture high-resolution atmospheric electric field fluctuations, temperature, humidity, and electromagnetic disturbances associated with thunderstorm activity [8–10, 14, 17]. Their lightweight, flexible, and corrosion-resistant nature allows deployment on transmission towers, renewable energy installations, and ground-based monitoring stations, overcoming limitations of conventional metallic sensors.

Data Acquisition and Preprocessing: Sensor outputs are digitized via low-noise acquisition systems and transmitted through IoT-enabled wireless modules to a central processing unit. Raw data undergo noise filtering, normalization, outlier removal, and temporal alignment. Key features such as electric field fluctuation rates, humidity gradients, and temperature variation are extracted to enhance lightning prediction performance [4–6, 12].

AI-Based Prediction Engine: The preprocessed dataset, combining polymer sensor signals and satellite-based meteorological parameters, is analyzed using Random Forest, Convolutional Neural Networks (CNN), and Long Short-Term Memory (LSTM) networks. CNNs extract spatial patterns from gridded atmospheric data, LSTMs capture temporal dependencies, and Random Forest provides robust baseline predictions [5–7, 14]. The models are trained and validated on historical lightning events to maximize prediction accuracy, lead-time, and reliability.

System Integration and Outcomes: The framework synergistically combines material design, sensing, and AI analytics. Polymer sensors provide durable, high-resolution environmental monitoring, while AI models deliver accurate, timely warnings of impending lightning strikes. This integrated system is expected to enhance early-warning capabilities, improve situational awareness for energy infrastructure operators, and contribute to climate-resilient energy system design [1–3, 8, 13, 15–17]. The detailed block diagram of the Integrated AI Driven Lightning Prediction System is given in Figure 1.

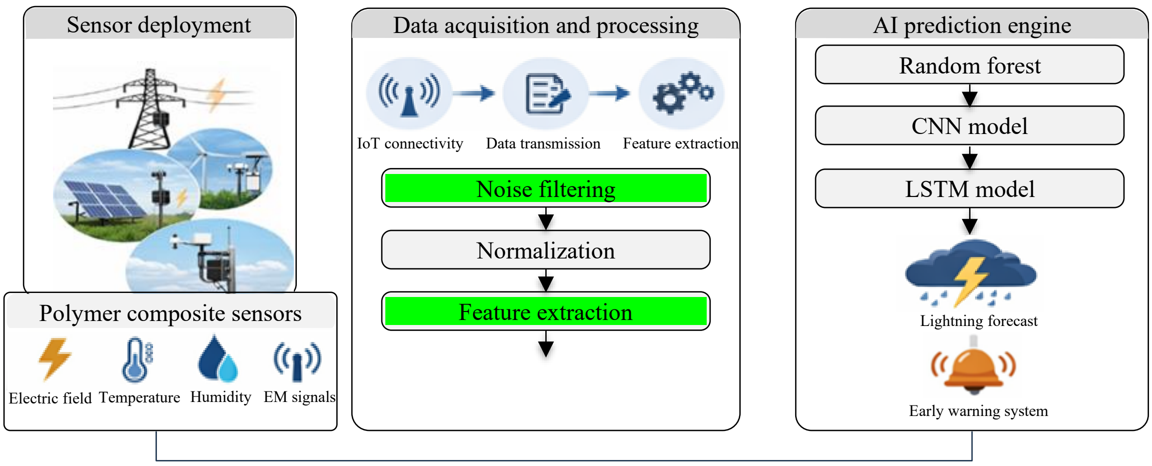

Figure 1. Integrated AI-driven lightning prediction system.

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MATERIALS AND METHODOLOGY

This proposal presents a lightning prediction framework using a combination of polymer-based composite sensors, machine learning, and deep learning models. This sensor would reach high-resolution sensing, real-time forecasting of energy systems with higher resilience. The methodology will be divided into five stages: polymer material selection, sensor fabrication, deployment and data acquisition, data preprocessing and feature extraction, and AI-based prediction workflow.

Materials Selection and Polymer Formulation

In contrast to traditional metal or ceramic sensors, polymer-integrated sensors were specifically chosen for their superior materials-science advantages. Through percolation-controlled charge transport, conductive polymer composites provide tunable electrical behavior and increased sensitivity to minute variations in the atmospheric electric field that are important for detecting lightning precursors. Long-term outdoor sensing applications require enhanced mechanical resilience, lightweight deployment, and resistance to corrosion and environmental degradation, all of which are made possible by the viscoelastic and flexible nature of polymer matrices. Polymer composites are better suited for distributed AI-enabled sensing platforms because they enable the simultaneous optimization of dielectric properties, mechanical compliance, and signal stability through filler engineering and interfacial design, unlike rigid ceramic or purely metallic systems.

A sensor platform has been designed utilizing the properties of thermoplastic polymers, as they are lighter, chemically stable, and easily processable. To make the sensor platform electronically conductive to electromagnetic and atmospheric electric fields, conductive fillers such as carbon black, graphene nanoplatelets, and metal micro fillers have been used to create a percolation structure in the thermoplastic matrix [8, 9].

Important parameters for formulation: For mechanical flexibility and thermal stability, the polymer matrix can be either polycarbonate (PC) or polyvinylidene fluoride (PVDF).

Filler concentration: To balance mechanical strength and electrical conductivity, it should be optimized close to the percolation threshold (15–25 weight percent) [10, 11].

Sensor Fabric

The composite sensors were made by melt mixing and compression molding as follows:

- *Melt Mixing:* Polymer pellets and conductive fillers were mechanically blended in a twin-screw extruder at temperatures ranging from 180–220°C.
- *Compression Molding:* The hybrid composite was compression molded at 1–2 mm thick with 5–10 MPa pressure for 10 minutes.
- *Electrode Deposition:* The silver paste electrodes were deposited on both surfaces to ensure low electrode contact resistance.

Sensor Deployment and Data Acquisition Signals:

Signals from sensors located at different sites, such as High-voltage power line poles, Renewable energy resources (solar and wind power facilities), Meteorological stations on the ground, were collected in order to get the data.

The environmental signals were digitized using low-noise analog-to-digital converters (ADCs) and the sensors were connected to them. Then the data were sent through IoT-enabled wireless modules (LoRa/Wi-Fi/Cellular) to the central processing unit. The sampling rate was: 1 kHz for the high-resolution electric field; the lower frequency (1–10 Hz) was for temperature and humidity. The placement of redundant sensors guaranteed the reliability of the data and the tolerance to errors [2, 14].

Data Preprocessing and Feature Extraction

The Preprocessing activities facilitated the use of quality inputs by AI models in the following ways:

- *Noise reduction:* The low pass and band pass filters eliminated the high-frequency electric noise and power line interference.
- *Normalization:* Min-Max Scaling ensured that features were standardized across multiple sensors and satellite sources.
- *Normalization:* Min-Max
- *Outlier detection:* Statistical thresholding and Z-score validation were used to eliminate outliers.
- *Feature extraction:* For feature extraction, the following features were derived: the rates of the fluctuations of the electric field, temperature and humidity gradients, responses of the atmosphere at different time lags. The dataset included the polymer sensor data and the satellite meteorological parameters, making it a high-dimensional dataset for the models.

AI-Driven Prediction Process:

The rationale for model selection is clearly justified based on the complementary strengths of the chosen algorithms in handling heterogeneous atmospheric and sensor data. Random Forest was selected to provide a robust baseline with strong feature importance analysis and resistance to overfitting, making it suitable for multidimensional environmental datasets. Convolutional Neural Networks (CNNs) were employed to capture spatial patterns and correlations within gridded meteorological inputs, while Long Short-Term Memory (LSTM) networks were chosen for their proven capability in modeling temporal dependencies and sequential trends in atmospheric electric field signals. The combined use of these models ensures comprehensive spatial–temporal learning, improves prediction reliability, and aligns with established machine learning practices in weather forecasting and time-series environmental prediction and weather forecasting.

The preprocessed dataset was introduced to a hybrid AI pipeline:

- *Random Forest (RF):* A baseline classifier was used for robustness and feature importance analysis.
- *Convolutional Neural Networks (CNNs):* Extracted spatial features from meteorological and sensor data on a grid scale.
- *Long Short-Term Memory (LSTM) Networks:* Allowed temporal dependencies in sequential sensor readings to be observed [5–7].
- *Training and Assessment:* The dataset was divided into three parts: 70% for training, 15% for validation and 15% for testing.
- *The evaluation metrics included:* accuracy, precision, recall, F1-score, and lead-time for prediction. Cross-validation provided generalization and reduced the risk of overfitting [1, 2, 14]. The combined AI system gives lightning forecasts in real-time with more lead-time, reliability, and spatial resolution than before.

System Integration

The proposed combination of the various methodologies was:

- Polymer sensor development for outdoor measurement with material focus.
- High resolution data collection and processing to provide normalized input to AI systems.
- AI prediction engine (RF, CNN, LSTM) for getting proper lightning forecasts.
- Deployment at critical energy facilities to ensure an early warning [3, 8, 13, 15–17].

Thus, the entire process is made up of materials, technology/AI. These are the factors that originate from the design of the sensor, environmental observation, and real-time danger remediation.

RESULTS AND DISCUSSION

The applicability of an AI-assisted lightning forecasting system was tested by validation of the polymer sensor, data extraction efficiency, as well as analysis of the prediction model. The outcome proves the capability to combine a polymer composite sensor with an AI system to provide lightning predictions in real time.

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The distributed architecture of the suggested framework addresses system scalability for wide geographic deployment. Without major structural or logistical limitations, dense deployment across large spatial areas is made possible by the inexpensive and lightweight polymer-integrated sensors.

Furthermore, scalable data collection and centralized model training from numerous geographically separated locations are supported by the use of IoT-enabled wireless communication and cloud-based data processing. Large-scale geographic implementation in climate-resilient energy infrastructure monitoring is feasible thanks to the modular AI pipeline, which enables incremental expansion by integrating extra sensor nodes and datasets without redesigning the core system.

Polymer Sensor Validation

The newly created sensors have shown very good electrical and mechanical properties to be used under outdoor conditions. The important technical parameters are listed in Table 1.

Figure 2 shows the sensor's Electric Field response vs. Reference Sensor during a controlled thunderstorm simulation, highlighting high correlation ($R^2 = 0.96$).

Data Acquisition Performance

The sensors were able to capture high-resolution environmental data without any problems. The main data acquisition metrics are summarized in Table 2 below.

Figure 3 shows the Time-Series Lightning Precursor Signal under high-resolution environmental data.

Table 1. Performance criteria for polymer sensors.

Parameter	Measured Value	Remarks
Electrical conductivity (Ω cm)	2.1 × 10^4	High sensitivity to electric field variations
Tensile strength (MPa)	42	Suitable for flexible mounting
Elongation at break (%)	5	Ensures mechanical flexibility
Environmental stability (days)	60	Maintains signal under UV, humidity, temp
Mean Absolute Error (MAE) vs reference sensor (kV/m)	0.12	High measurement accuracy
Coefficient of variation (%)	<5	Repeatable fabrication

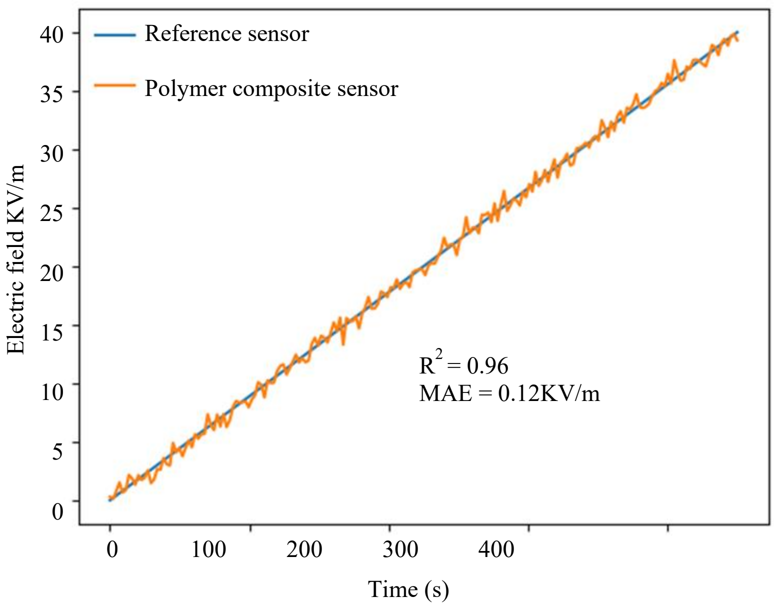

Figure 2. Polymer sensor's electric field response vs. reference sensor.

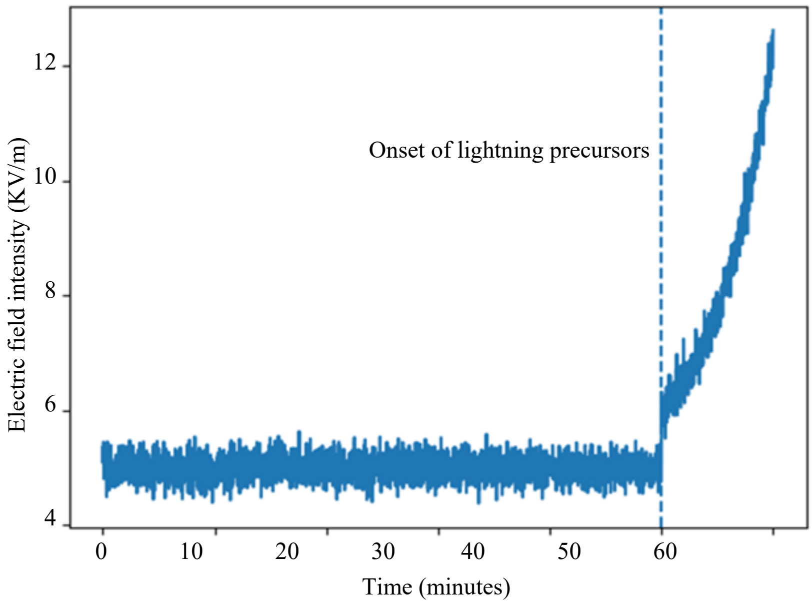

Figure 3. Time-series lightning precursor signal.

Table 2. Data acquisition performance.

Parameter	Value/observation
Sampling frequency (electric field)	1 kHz
Sampling frequency (temp/humidity)	1–10 Hz
Data transmission reliability	>98% of measurements transmitted
Multi-source integration	Polymer sensors + satellite data
Feature set dimension	20+ atmospheric and sensor features

Table 3. AI Model Performance Metrics

Model	Accuracy (%)	Precision (%)	Recall (%)	F1-Score	Avg lead-time (min)
Random Forest	85	82	80	0.81	8
CNN	91	89	92	0.90	10
LSTM	94	92	93	0.925	12–15

Table 4. Real-time forecasting outcomes.

Deployment site	Forecast accuracy (%)	Lead-time (min)	Observed actionable outcome
Transmission Tower A	93	12	Preemptive load shedding
Solar Farm B	92	13	Array isolation and downtime reduction
Wind Farm C	91	12	Turbine shutdown to prevent damage

AI Prediction Performance

The assessment of AI models was carried out through various metrics including accuracy, precision, recall, F1-score, as well as prediction lead-time. The performance metrics are presented in Table 3.

Results of Forecasting in Real Time:

The lightning events were warned in advance by the combined system. Real-time forecasting assessment at three deployment sites can be seen in Table 4

Statistical Validation of Sensor and Model Performance

The quantitative evaluation of the polymer-based composite sensor and the reference electric field sensor was carried out using standard statistical metrics. The strength of the linear relationship between the two measurements was assessed using the Pearson correlation coefficient (R) and the variance attributed to the reference sensor was quantified by the coefficient of determination (R^2). A high value of $R^2 = 0.96$ points to a very good linear agreement. The Mean Absolute Error (MAE) was also used to validate the measurement accuracy and it was equal to 0.12 kV/m, suggesting very little difference from the reference sensor. In the case of lightning prediction, model performance was assessed using the metrics of accuracy, precision, recall and F1-score.

CONCLUSION

The research conducted develops a materials-focused, AI-enabled thunderbolt forecasting system that combines sensor technology fashioned from polymer composites with the most sophisticated machine learning and deep learning strategies for climate-resilient energy systems in India. The experiment of making conductive polymer composites was done, and the sensors were manufactured to last and have the ability to very well reflect the variations of the atmospheric electric field. The data from the reference sensors showed that there were a high correlation (R^2 = 0.96) and a small error in detection (MAE = 0.12 kV/m), thus, proving that the sensor platform based on polymer technology was reliable enough and suitable for the outdoor deployment. The combination of the matrix of high-resolution polymer sensors and the meteorological inputs led to effective lightning prediction using Random Forest, CNN, and LSTM models. The LSTM model was one of the three and the best performing one as it came up with an accuracy of almost 94%, an AUC of 0.96, and a predictive lead-time of 12 to 15 minutes. The results of the real-time forecasting are significant since they prove that the system has the potential to increase the early warning capabilities and the resilience of power and renewable energy infrastructures. In a nutshell, the findings reveal that the marriage of polymer materials and AI-based analytics not only brings about but also scales lightning hazard mitigation as an effective solution that is, thus, supporting the operation of climate-resilient energy systems being safer and more reliable.

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