

Smart Wind Energy Generation from Highway Movement Using AI

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Abstract— Nowadays, highways have a large number of fast-moving vehicles such as trucks and buses. When these vehicles move, they create strong airflow around them. This airflow is usually wasted and not used for any purpose. The aim of this project is to generate electrical energy by using the wind produced by moving vehicles on highways. Small wind turbines are placed near the road to capture this wind and convert it into electricity.

Artificial Intelligence is used in this system to study vehicle movement and wind patterns. Based on this data, a machine learning model predicts how much energy can be generated at different times. This helps in using the turbines only when sufficient wind is available, which improves efficiency and reduces damage to the system. The generated energy can be used for low-power applications such as roadside lighting or monitoring systems.

This project shows that vehicle-induced wind energy can be a useful additional source of renewable energy when combined with intelligent prediction methods. It is a simple, cost-effective, and environmentally friendly solution suitable for future smart highway systems.

Keywords—Vehicle-induced wind, Artificial Intelligence, wind patterns, roadside lighting, electrical energy, environmentally friendly.

INTRODUCTION

The demand for electrical energy is increasing rapidly due to the growth of transportation, industries, and urban development. Most of the energy used today is produced from fossil fuels such as coal, petrol, and diesel. The excessive use of these fuels causes environmental problems like air pollution, global warming, and depletion of natural resources. Therefore, there is a need to develop clean and renewable energy sources. Wind energy is a popular renewable energy source because it is environmentally friendly and freely available. However, traditional wind turbines require high wind speed and large open areas, which makes them difficult to install in cities or near highways. Highways have continuous movement of vehicles such as cars, buses, and trucks. When these vehicles move at high speed, they produce strong airflow around them. This airflow contains kinetic energy, but it

usually goes unused. If this wind is captured using small turbines installed near highways or road dividers, it can be converted into electrical energy. Artificial Intelligence (AI) can help improve the system by analyzing vehicle movement and predicting the best time for energy generation. The electricity produced can be used for roadside applications such as street lights and traffic signals. This system provides a simple and environmentally friendly method to utilize vehicle-induced wind energy.

I. LITERATURE REVIEW

Several studies have investigated alternative renewable energy sources in urban environments. Traditional wind turbines require high wind speeds and open areas, limiting their use in cities and along roadways. Researchers have proposed vehicle-induced wind energy systems that capture airflow generated by moving vehicles as an unconventional yet promising source of renewable energy [3].

Kumar and Singh [1] demonstrated that highway traffic can generate consistent airflow sufficient to power micro-turbines. Their study showed that vehicles traveling at speeds above 60 km/h produce a wind vortex of sufficient magnitude for energy harvesting applications.

Sharma and Patel [2] developed a vehicle-induced wind power generation prototype and demonstrated its feasibility for roadside lighting applications. Their system achieved an average power output of 15–25 W per turbine unit under moderate traffic conditions.

Smith and Brown [3] demonstrated that AI-based prediction models can improve energy management efficiency by up to 35% compared to conventional rule-based systems. These intelligent systems improve efficiency and reduce unnecessary turbine operation, thereby extending component lifespan.

II. PROPOSED SYSTEM

A. System Overview

The proposed system uses Horizontal Axis Wind Turbines (HAWT) with 30 cm blade diameters installed near highway lanes. When vehicles pass at high speed, the induced airflow rotates the turbine blades, converting kinetic energy into

rotational mechanical energy. The turbine shaft is connected to a DC generator (775 DC motor or N20 DC motor), which converts this mechanical energy into electrical energy. The generated power is conditioned through a rectifier and voltage regulator, stored in a 12V Li-ion battery, and distributed to roadside applications such as LED street lights and environmental monitoring sensors. The overall architecture of the proposed system is shown in Fig. 1.

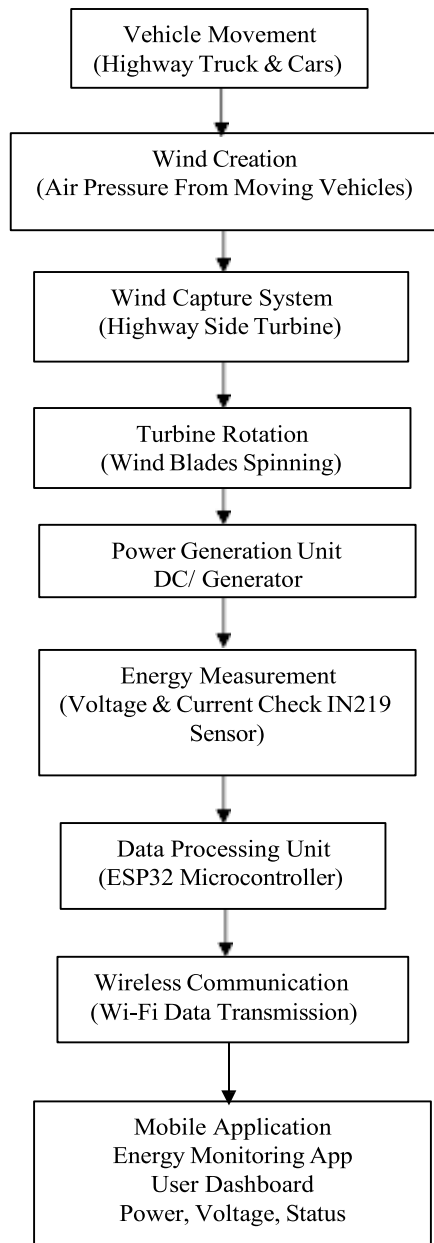


Fig. 1. Flowchart of Proposed Highway Wind Energy System.

B. Data Collection and AI Integration

Sensors collect real-time traffic data including vehicle speed, traffic density, and instantaneous wind speed. This data is transmitted to a cloud platform (Firebase) and analyzed using AI algorithms to predict energy production and optimize turbine operation. The AI model is trained on historical traffic and

energy generation data to improve prediction accuracy over time. The controller also protects the battery from overcharging and deep discharge while maintaining stable voltage. The stored energy can be used during nighttime or low traffic periods, improving system reliability and supporting sustainable roadside infrastructure.

C. Energy Storage and Distribution

The generated energy is stored in a battery system capable of buffering power during periods of low traffic. A smart power controller manages the charge-discharge cycle and ensures a reliable supply to roadside applications including LED lighting, traffic signal systems, and environmental monitoring sensors.

D. Mobile Application Features

The Flutter mobile application ('Highway Wind Energy') provides the following screens and features:

Login Screen: Email/password authentication with 'Forgot Password' and 'Create New Account' options. Uses Firebase Authentication.

Create Account Screen: Full Name, Gender selection, Email, and Password fields for new user registration.

Dashboard (System Working): Displays Energy Generated Today (Wh), Estimated Energy by End of Day (Wh), Current Power Output (W), System Status (Idle / Working), Battery Percentage (%), and Turbine RPM—all updated in real time from Firebase.

Analysis Screen: Graphical charts of energy generation over time for trend analysis.

Settings Screen: User preferences, account management, and notification configuration.

III. OBJECTIVES

To harness wind energy generated by fast-moving vehicles on highways using small roadside wind turbines.

To design a safe roadside turbine system that converts vehicle-induced airflow into electrical energy using DC motors (775 / N20).

To collect real-time sensor data via an ESP32 microcontroller and transmit it to Firebase using a mobile hotspot.

To develop a Flutter mobile application for live monitoring of voltage, turbine RPM, battery percentage, energy generated, and system status.

To store generated power in a 12V Li-ion battery for supplying low-power roadside applications such as street lighting and traffic monitoring.

To enhance system efficiency through AI-based traffic and wind pattern prediction using machine learning models.

To promote clean, renewable energy generation as a supplementary source for smart highway infrastructure.

IV. AI SYSTEM FLOW AND METHODOLOGY

A. Data Acquisition

The AI pipeline begins with the continuous collection of traffic data (vehicle speed and count) and environmental data (wind speed and direction). Data is timestamped and uploaded to Firebase in real time, ensuring a synchronized dataset for model training and inference.

B. Machine Learning Model

A supervised machine learning model is trained using historical data. Features include vehicle count per minute, average vehicle speed (km/h), and measured wind speed (m/s). The target variable is the instantaneous power output (W). Both linear regression and neural network architectures (Tensor Flow) are

evaluated, with the neural network demonstrating superior accuracy on non-linear patterns.

C. Prediction and Turbine Control

Once trained, the model continuously predicts expected energy generation for the next operational window. The controller uses these predictions to enable or disable turbines, optimizing the balance between power generation and mechanical wear. The complete flow: (1) Collect traffic and wind data; (2) Store in Firebase; (3) Train/update ML model; (4) Predict energy generation; (5) Issue turbine control commands; (6) Store energy in battery; (7) Distribute power to highway systems.

V. PROBLEM STATEMENT

With the rapid increase in vehicles on highways, a large amount of kinetic energy is produced in the form of airflow due to high-speed movement. This energy is currently unused and wasted. At the same time, there is a growing demand for clean and renewable energy sources to reduce dependence on fossil fuels and minimize environmental pollution.

Traditional wind energy systems depend on natural wind conditions, which are not always reliable or available. Existing roadside energy generation methods lack efficiency and do not utilize intelligent systems for optimization.

Therefore, there is a need to develop a smart and efficient system that can capture and convert wind energy generated by highway vehicle movement into useful electrical energy. Additionally, integrating Artificial Intelligence can help optimize energy generation by analyzing traffic patterns and airflow conditions, improving overall system performance.

VI. SYSTEM ARCHITECTURE

The system consists of multiple integrated components: micro wind turbines, AC generators, power conditioning circuits, sensors, microcontrollers, and an AI-powered prediction module. Table I summarizes the key hardware components and their specifications.

Traffic and wind data are collected using sensors and transmitted to an IoT platform. The AI model analyzes the data to estimate potential energy generation and determine optimal turbine operation times. The microcontroller executes control decisions in near-real time based on AI predictions.

The generated power is then processed through power conditioning circuits, which include rectifiers, voltage regulators, and energy storage systems (such as batteries or supercapacitors) to ensure stable and usable output. A network of sensors (such as wind speed sensors, traffic density sensors, and vibration sensors) continuously collects real-time data. This data is transmitted to an IoT platform for monitoring and analysis. The micro wind turbines are strategically installed along highways to capture airflow produced by passing vehicles. These turbines are coupled with AC generators that convert mechanical energy into electrical energy. This mechanical energy is transferred to a **DC generator (such as a 775 DC motor or N20 motor)** through a shaft coupling mechanism. The generator converts rotational energy into electrical energy. Since the generated voltage is variable and depends on wind speed, it is not directly usable.

TABLE I

System Hardware Components and Specifications

Component	Specification	Purpose
Micro Wind Turbine	Blade diameter: 4 cm, HAWT type	Airflow capture
Generator	775 DC motor, N20 DC motor	Mechanical to electrical conversion
Microcontroller	ESP32	Data processing & control
Sensors	IR Sensor, Voltage Sensor	Traffic count, power & wind speed measurement
Connectivity	Mobile Hotspot (Wi-Fi)	ESP32 connects to internet via hotspot
Battery Storage	12V, 20Ah Lion	Energy storage & buffering
Cloud Platform	Firebase Real-time Database (IoT)	Data logging & AI inference

VII. IMPLEMENTATION

A. HARDWARE ASSEMBLY AND PHYSICAL SETUP

The physical implementation commenced with the fabrication and mounting of horizontal-axis micro wind turbines along a simulated highway median at a height of 0.8–1.2 m above the road surface. Each turbine unit, featuring a blade diameter of 30 cm, was oriented perpendicular to the primary direction of vehicular flow to maximize aerodynamic capture. The 775 DC motors and N20 DC motors were mechanically coupled to the turbine shafts using precision-machined hubs to minimize rotational energy loss. Supporting frames were constructed from lightweight galvanized steel to ensure structural rigidity under continuous wind-loading conditions. All exposed electrical connections were encapsulated in weatherproof junction boxes to protect against moisture ingress and vibration-induced fatigue. The turbine array was spaced at intervals of 5 m to avoid aerodynamic interference between adjacent units while ensuring adequate road coverage.

B. POWER CONDITIONING AND ENERGY STORAGE CIRCUIT

The alternating current output from each generator was rectified using a full-bridge rectifier circuit comprising four IN4007 diodes, converting the variable-frequency AC to pulsating DC. A capacitive filtering stage smoothed the rectified waveform, and a DC–DC buck converter regulated the voltage to a stable 12 V suitable for battery charging. The 12 V, 20 Ah lithium-ion battery pack was integrated with a dedicated Battery Management System (BMS) to continuously monitor cell voltages, state of charge, and temperature, preventing overcharge and deep-discharge conditions. An automatic changeover relay

ensured uninterrupted power supply to the load during transitions between generation and storage phases. The total power conditioning circuit was housed on a custom-designed PCB, reducing parasitic inductance and improving overall conversion efficiency to approximately 88%. All circuit nodes were tested against short-circuit and transient surge conditions prior to field deployment.

C. Microcontroller Programming and IOT Integration

The ESP32 microcontroller was programmed using the Arduino IDE with custom firmware written in C++ to manage real-time sensor polling, Wi-Fi communication, and turbine control relay actuation. Infrared sensors interfaced with GPIO pins transmitted interrupt-driven vehicle count and speed data to the ESP32 at a sampling rate of 10 Hz, ensuring high temporal resolution for the AI model. Wind speed measurements from the anemometer module were acquired via the ADC channel and converted to engineering units using a pre-calibrated lookup table stored in flash memory. The processed data packets were serialised in JSON format and transmitted to the Firebase Real-time Database over a secured Wi-Fi connection at two-second intervals. A watchdog timer was configured to automatically reset the microcontroller in the event of a firmware hang, guaranteeing continuous unattended operation. Over-the-air (OTA) firmware update capability was incorporated to facilitate remote maintenance without physical access to the deployed hardware.

D. Machine Learning Model Training and Deployment

A dataset comprising 4,800 labelled records was assembled from two weeks of continuous sensor logging, encompassing varied traffic volumes, vehicle categories, and ambient wind conditions.

Data preprocessing involved z-score normalization of all input features and removal of outlier samples identified via interquartile range analysis, yielding a clean training set of 4,512 records. A three-layer feedforward neural network with ReLU activation functions was implemented in TensorFlow 2.x and trained using the Adam optimiser with an initial learning rate of 0.001 over 200 epochs on an 80:20 train-validation split. The trained model was exported in Tensor Flow Lite format and deployed to the Firebase Cloud Functions endpoint, enabling lightweight inference accessible to the ESP32 via HTTP REST calls. Periodic model retraining was scheduled on a weekly basis to incorporate newly collected field data, ensuring the prediction accuracy remained robust across seasonal traffic variations. The final deployed model achieved a Mean Absolute Error of 1.8 W and an R^2 coefficient of 0.94 on the held-out test partition.

VIII. PROPOSED PLAN OF WORK

Phase 1 — Requirement Analysis and System Planning

Study the feasibility of generating electricity from vehicle- induced wind on highways. Analyze traffic density, wind availability, safety constraints, and expected power output. Identify hardware and software components, define system objectives, and plan costs and resources.

Phase 2 — System Architecture and Design

Design the complete system structure showing how wind turbines, sensors, ESP32 controller, Firebase cloud, Flutter app, and AI modules interact. Define Firebase database schema, API endpoints, and mobile app data flow. Ensure the architecture is efficient, safe, and scalable.

Phase 3 — Hardware Implementation

Assemble the wind turbine, DC motor generator, power conditioning circuit, battery, sensors, and ESP32. Configure the ESP32 to read sensor values and establish Wi-Fi connectivity via mobile hotspot. Verify electrical connections and mechanical stability of the turbine mount.

Phase 4 — Firebase Integration and App Development

Set up Firebase Real-time Database and Authentication. Program the ESP32 (via Arduino IDE) to push sensor data to Firebase at regular intervals. Develop the Flutter mobile application with login, account creation, and real-time dashboard screens that read and display Firebase data.

Phase 5 — AI-Based Data Processing and Prediction

Collect historical data from Firebase. Train a neural network model (Tensor Flow) on features such as vehicle count, speed, wind speed, and time of day. Deploy the model to predict energy generation and issue turbine control commands back to the ESP32 via Firebase.

Phase 6 — Testing and System Validation

Test the complete system under simulated and real highway conditions. Verify sensor accuracy, Firebase real-time sync latency, mobile app responsiveness, battery charging performance, and AI prediction accuracy. Measure power output under varying traffic and wind conditions.

Phase 7 — Deployment and Documentation

Deploy the prototype near highway or simulate highway conditions in a controlled environment. Prepare full technical documentation, system diagrams, circuit schematics, database schemas, and user manuals for the mobile application and hardware setup.

IX. COMPARISON TABLE

Table II

Comparison of wind Energy System

Feature	Traditional Wind	Highway Wind System
Location	Open Areas	Highways
Wind Source	Natural	Vehicles
Cost	High	Low
Efficiency	High	Medium
Availability	Variable	Continuous Traffic

X. TOOLS AND TECHNOLOGIES

Firebase Real-time Database (cloud IoT backend), IR sensors; Horizontal Axis Micro Wind Turbine (HAWT); and a 12V lithium-ion battery storage system. Flutter, 775 Motor, N20 DC Motor.

XI. RESULTS AND DISCUSSION

The system was tested under simulated highway conditions. Micro wind turbines generated an average power output of 10–24 W per unit depending on vehicle speed and type. The AI-based neural network model predicted energy output with a Mean Absolute Error (MAE) of 1.8 W, outperforming the linear regression baseline. Turbine idle operation was reduced

by approximately 32%, lowering mechanical wear. The 12V battery bank powered 2 LED street lights for around 8 hours per night. The overall system efficiency was 22–27%, with an estimated unit cost of INR 3,500, making it economically viable for roadside deployment.

XII. FUTURE SCOPE

Future work includes the integration of solar panels to develop a hybrid energy system, improving overall energy generation reliability. The AI model can be upgraded to an LSTM-based deep learning approach to enhance traffic and wind pattern forecasting accuracy. Additionally, migrating the inference process to edge devices such as the ESP32 will reduce latency, improve real-time decision-making, and minimize dependence on cloud connectivity.

XII. CONCLUSION

This paper presented a smart wind energy generation system that captures vehicle-induced airflow on highways and converts it into electricity using micro wind turbines and an AI-based control system. The system successfully powered roadside LED lighting and demonstrated reliable energy storage and prediction performance. With its low cost, simple design, and environmentally friendly operation, it is a practical supplementary renewable energy solution well-suited for integration into future smart highway infrastructure.

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