Sustainable Highway Energy Harvesting System

Research Plan

Submitted by

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ARRAHMAAN INTERNATIONAL SCHOOL

(Creating the community of Excellence)

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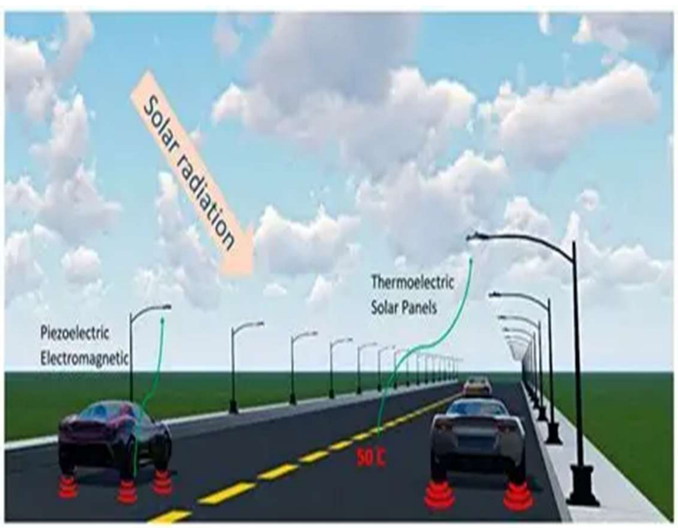
ABSTRACT

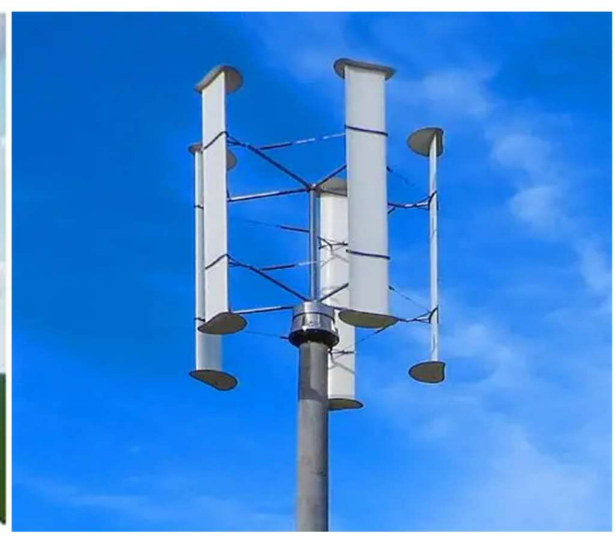
The increasing global demand for electricity, coupled with the urgent need to transition away from fossil fuels, has led to the exploration of alternative, renewable, and sustainable energy sources. Roadside environments, especially highways, present a largely untapped potential for hybrid energy harvesting through the combination of wind energy generated by natural flows and vehicle-induced turbulence, solar radiation, and supplementary kinetic energy recovery systems. This project investigates the design, development, and feasibility of an integrated system that utilizes **vertical axis wind turbines (VAWTs)**, **solar photovoltaic panels (PV)**, and optional **piezoelectric harvesting technologies** to generate sustainable electricity.

The hybrid system is strategically designed to harness wind generated by moving vehicles and natural breezes, alongside solar energy captured through roadside installations. The generated electricity is stored in a battery storage system and distributed to power roadside infrastructure such as streetlights, traffic signals, surveillance cameras, and electric vehicle (EV) charging stations. Excess electricity can be directed back to the grid, further enhancing energy efficiency.

This research further explores the environmental, technical, and economic benefits of hybrid roadside renewable systems. Compared to standalone wind or solar systems, the integrated hybrid approach reduces intermittency, ensures more reliable power output, and maximizes the use of available roadside space.

The project aims not only to demonstrate the technical feasibility of such a system but also to highlight its role in supporting **sustainable transport corridors** and **smart city initiatives**. A detailed experimental procedure is outlined, supported by data collection methods, risk and safety assessments, and structured data analysis. The study concludes with the potential scalability of this system for both urban and rural highway applications, thereby contributing to global renewable energy adoption and climate change mitigation.





INTRODUCTION

Energy is one of the most critical resources driving industrial growth, economic development, and technological advancement. The conventional dependence on fossil fuels, such as coal, oil, and natural gas, has resulted in severe environmental consequences, including global warming, greenhouse gas emissions, and air pollution. This dependence also poses economic and geopolitical risks due to fluctuating fuel prices and resource depletion.

As the world transitions towards renewable and sustainable energy solutions, solar and wind energy have emerged as two of the most promising alternatives. However, their inherent intermittency—solar depending on sunlight availability and wind depending on weather conditions—limits their effectiveness as standalone energy solutions. This limitation has created a need for **hybrid energy systems** that combine multiple renewable sources to ensure consistency, reliability, and efficiency in energy generation.

Highways and roadways, which are traditionally seen as energy-consuming infrastructure, present a unique opportunity for renewable energy harvesting. Moving vehicles generate turbulence that can be harnessed using vertical axis wind turbines, while the vast roadside space provides ample area for solar photovoltaic installations. In addition, advancements in piezoelectric materials enable energy harvesting from road vibrations and vehicle weight. By integrating these technologies into a **hybrid roadside renewable system**, it becomes possible to transform highways into **self-sustaining smart corridors**.

This project focuses on the design and assessment of a **roadside wind-solar hybrid system**, supported by optional piezoelectric and kinetic energy recovery mechanisms. The generated electricity can be used to power critical highway infrastructure, promote green mobility by supplying energy to EV charging stations, and feed into local grids. By transforming passive roadside structures into active renewable energy generators, the project contributes to the realization of sustainable urban and rural development goals.

STATEMENT OF THE PROBLEM

The demand for reliable and clean energy continues to increase with population growth, urbanization, and the rise of electric mobility. Conventional methods of electricity generation heavily rely on fossil fuels, which are non-renewable, environmentally damaging, and geographically unevenly distributed. This over-reliance has led to climate change, air quality deterioration, and unsustainable energy practices.

Highways and road transport systems represent significant energy consumption zones, yet they remain largely underutilized for renewable energy harvesting. While solar and wind farms are often developed in remote areas, they require large land spaces and substantial investment in transmission infrastructure. Meanwhile, roadside spaces are readily available and already connected to transport and electrical infrastructure, making them ideal for localized renewable energy generation.

Several challenges persist:

1. **Underutilized Roadside Potential** – Current roadside infrastructure (barriers, poles, soundproof walls) remains passive and energy-inefficient.
2. **Intermittency of Renewables** – Standalone solar systems fail at night or in cloudy conditions, while standalone wind systems may produce little energy in calm weather.
3. **Growing Energy Demand for EVs** – The rapid adoption of electric vehicles requires accessible and sustainable roadside charging infrastructure.
4. **Sustainability of Smart Cities** – Smart surveillance, IoT sensors, and automated traffic systems need continuous power supply.

OBJECTIVES

1. **Energy Harvesting:**
   - To collect wind energy created by fast-moving vehicles on highways using a vertical axis wind turbine.
   - To design a **hybrid renewable energy system** combining roadside wind and solar energy, with optional piezoelectric components.
2. **Energy Conversion:**
   - To convert the mechanical rotational energy of the turbine into electrical energy using a PMDC motor or alternator.
3. **Energy Storage:**
   - To store the generated electricity in a rechargeable battery for later use, especially during night hours.
4. **Automatic Lighting:**
   - To develop a smart streetlight system using an LDR sensor and relay that automatically turns the LED light on during night and off during the day.
5. **Cost-Effective Design:**
   - To make the setup low-cost and easy to install on existing highway infrastructure without major modifications.
6. **Environmental Sustainability:**
   - To reduce dependency on fossil fuel-based grid electricity and promote the use of clean renewable energy.
7. **Awareness Creation:**
   - To encourage innovative applications of renewable energy technologies among students, engineers, and the public.

HYPOTHESIS

A hybrid roadside renewable energy system integrating **wind turbines, solar panels, and storage** can generate **sufficient and consistent electricity** to power highway infrastructure, thereby reducing dependence on fossil fuels and supporting sustainable smart cities.

Design Of Study

Materials Needed:

- Mini Vertical Axis Wind Turbines
- Solar Panels
- Piezoelectric Discs
- Charge Controller (PWM type, 12V–24V)
- Battery Storage (12V, 18Ah Sealed Lead Acid or equivalent)
- Inverter (12V DC to 220V AC, 300W)
- Arduino Uno (with sensors: current, voltage, wind speed)
- LED Bulbs (12V, 10W)
- Cabling, Connectors, Mounting Frames
- Protective Enclosures and Safety Accessories

Site Selection and Preparation

- ❖ Select a highway/roadside stretch with **consistent traffic flow**, open roadside space, and good solar exposure.
- ❖ Mark installation zones for wind turbines, solar panels, and monitoring instruments.

Installation of Wind Turbines

- ❖ Mount VAWTs along the central divider or roadside poles at a height of 3–5 m.
- ❖ Connect turbine outputs to the charge controller.
- ❖ Calibrate turbines to optimize performance under traffic-induced turbulence.

Installation of Solar Panels

- ❖ Install solar PV modules on **roadside barriers, overhead canopies, or dedicated frames**.
- ❖ Connect panels in series-parallel configuration to achieve the desired voltage/current.
- ❖ Link PV output to the charge controller for regulated storage.

Optional Piezoelectric Pad Installation

- Place piezo pads beneath asphalt strips, speed bumps, or dedicated pressure mats.
- Connect pads to a rectifier and capacitor bank, then to the hybrid charge controller.

Energy Storage and Conversion Setup

- Connect all inputs (wind, solar, piezo) to the MPPT charge controller.
- Route regulated DC to the **battery bank** for storage.
- Connect batteries to the **inverter**, enabling AC power for loads.

Load Connection and Testing

- Attach test loads such as **LED streetlights, CCTV cameras, or EV chargers**.
- Monitor supply continuity during day/night cycles and traffic variations.
- **Data Collection**
- Record environmental conditions: wind speed, solar irradiance, and vehicle density.
- Log electrical parameters: voltage, current, instantaneous power, cumulative energy.
- Collect daily data for at least 2–4 weeks to observe seasonal/weather impacts.

Analysis and Validation

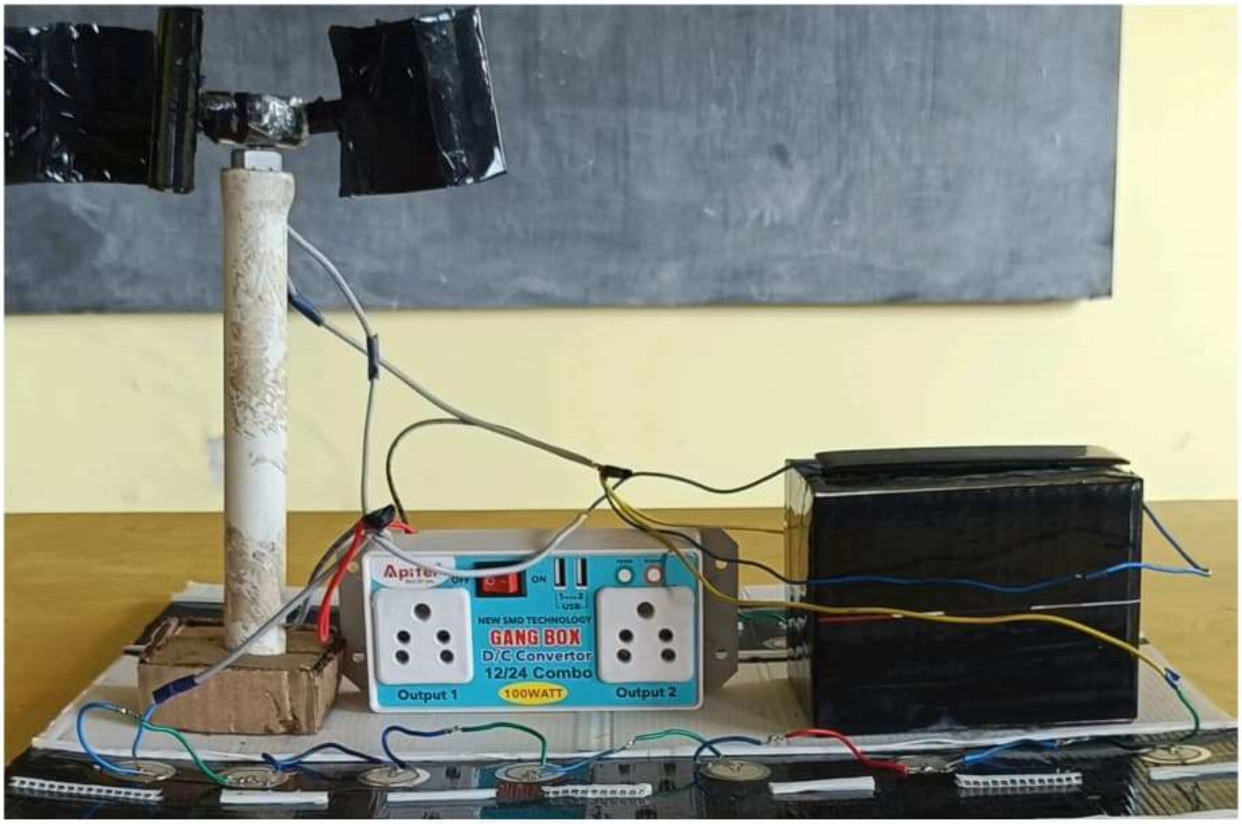
- Compare **standalone solar, standalone wind, and hybrid system** outputs.
- Evaluate storage performance and power reliability for load applications.
- Tabulate results and generate performance graphs (efficiency, generation trends).

RISK AND SAFETY

- **Electrical Hazards**: Ensure proper insulation, grounding, and safety cut-offs in case of overvoltage or battery overheating.
- **Mechanical Risks**: Wind turbine blades must be enclosed or positioned at safe heights to avoid accidents.
- **Traffic Safety**: Installation and maintenance must not interfere with road safety. Proper barricades and reflective signs are required.
- **Weather Conditions**: Turbines and panels should be designed to withstand storms, heavy rain, and dust accumulation.
- **Fire Risks**: Lithium-ion battery banks must include fire suppression and thermal management systems.

DATA ANALYSIS

Photographs




TWIN BIRDS

Formulas and Calculations

1. Wind Power Generation

$$P_{wind} = \frac{1}{2} \times \rho \times A \times v^3$$

Where:

- P_{wind}= Power from wind (Watts)
- ρ= Air density (1.225 kg/m³ at sea level)
- A= Swept area of turbine blades (m²)
- v= Wind speed (m/s)

2. Solar Power Generation

$$P_{solar} = V \times I$$

Where:

- V= Voltage from solar panel (Volts)
- I= Current from solar panel (Amperes)

To find energy over time:

$$E_{solar} = P_{solar} \times t$$

3. Piezoelectric Energy Harvesting

$$E_{piezo} = \frac{1}{2} C V^2$$

Where:

- E_{piezo}= Energy from piezo disc (Joules)
- C= Capacitance (Farads)
- V= Output voltage (Volts)

4. Total Hybrid Energy Output

$$E_{hybr} \quad = E_{wind} + E_{solar} + E_{piezo}$$

5. Efficiency

$$\eta = \frac{P_{output}}{P_{input}} \times 100$$

Convert readings to power & energy (method)

Formulas used:

- Electrical instantaneous power: $P = V \times I$(Watts).
  If I is in mA, use $I_A = I_{mA}/1000$.
- Energy over time: $E = P \times t$(W·h). For mWh: $E_{mWh} = P(W) \times t(h) \times 1000$.
- Piezo energy: pulses × energy per pulse → Joules, convert to Wh: 1 Wh = 3600 J.
- Total hybrid energy: $E_{hyb} \quad = E_{solar} + E_{wind} + E_{piezo}$.

Calculated table (power & energy)

All energies shown in **mWh** (mill-watt-hours). I compute P for solar & wind from V × I, and energy = P × duration.

Readings (small-scale)
• Solar panel open-circuit voltage ≈ 5–6 V, small current (mA).
• Wind turbine produces low voltage (1–3 V) and small current (a few mA).
• Piezo discs measured as pulse energy; we convert pulses → average power.
• Energy units shown as mWh (milliwatt-hour).

These electrical readings come from small sensors: multimeter/ADC measuring V and averaged I.

1. Solar power $P_s = V_s \times I_s$
2. Solar energy in Wh: $E_s = P_s \times t_s$
3. Wind power $P_w = V_w \times I_w$
4. Battery charging metric

A storage is small 12 V, 1.5 Ah lead/ $LiFePO_4$ pack → capacity = 12 V × 1.5 Ah = 18 Wh = 18,000 mWh.

Efficiency (wind)

Use theoretical wind power (from wind speed & swept area) to estimate turbine efficiency.

Theoretical wind power: $P_{theoretical} = \frac{1}{2}\rho A v^3$.

Approx. conversion efficiency (mechanical + generator + electronics):

$$\eta = \frac{P_{measured}}{P_{theo}}$$

Tabulation

Table 1: (small Scale)

Day	**Solar (V)**	**Solar (I avg, mA)**	**Solar hrs**	**Wind speed (m/s)**	**Turbine V (V)**	**Turbine I (mA)**	**Wind hrs**	**Piezo pulses/hr**	**Piezo energy/pulse (mJ)**	**Test hrs**
1	5.0	5.0	4.0	2.5	1.8	8.0	3.0	150	0.16	4.0
2	5.0	4.9	4.0	2.0	1.7	7.0	3.0	120	0.15	4.0
3	5.0	5.6	4.0	3.0	2.0	9.0	3.0	180	0.14	4.0
4	5.0	5.5	4.0	2.8	1.95	8.5	3.0	170	0.16	4.0
5	5.0	6.0	4.0	3.2	2.1	10.0	3.0	200	0.16	4.0

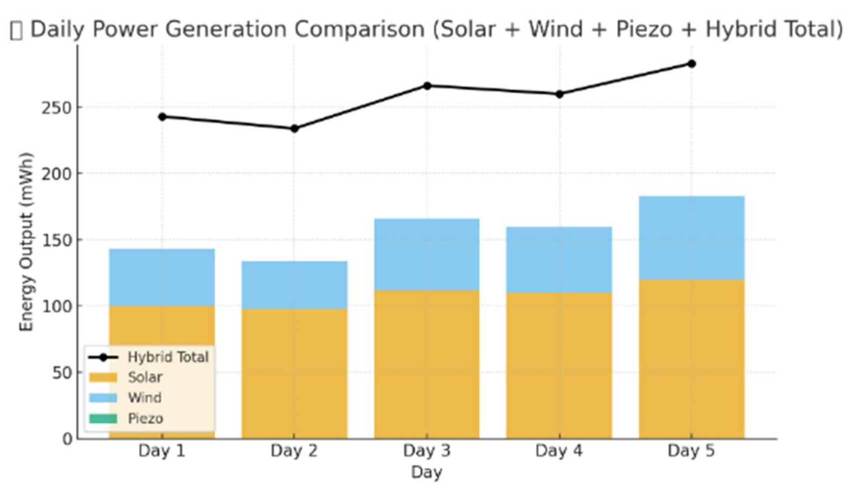
Day	**Solar P (W)**	**Solar E (mWh)**	**Wind P (W)**	**Wind E (mWh)**	**Piezo E (mWh)**	**Total E (mWh)**
1	5.0V × 5.0mA = 0.025 W	0.025×4 h = 0.100 Wh = **100 mWh**	1.8V × 8.0mA = 0.0144 W → 0.0144×3h = 0.0432 Wh = **43.2 mWh**	pulses:150×0.16 mJ = 24 mJ/hr → over 4h = 96 mJ = 0.096 J → 0.096/3600 = **0.0267 mWh** ≈ **0.03 mWh**	**143.2 mWh** (≈143 mWh)	=243 **mWh**
2	5.0×4.9mA = 0.0245 W → **98 mWh**	0.025×4 h = 0.100 Wh = **100 mWh**	1.7×7mA = 0.0119 W → 0.0119×3 = 0.0357 Wh = **35.7 mWh**	pulses:120×0.15 =18 mJ/hr → 4h =72 mJ =0.072 J → = **0.02 mWh**	**133.7 mWh** (≈134 mWh)	=233.9 **mWh**
3	5.0×5.6mA = 0.0280 W → 0.028×4 = 0.112 Wh = **112 mWh**	0.025×4 h = 0.100 Wh = **100 mWh**	2.0×9mA = 0.0180 W → 0.018×3 = 0.054 Wh = **54 mWh**	pulses:180×0.14=25.2 mJ/hr →4h=100.8 mJ=0.1008 J → **0.028 mWh**	**166.028 mWh** (≈166 mWh)	=266.30 **mWh**
4	5.0×5.5mA = 0.0275 W → **110 mWh**	0.025×4 h = 0.100 Wh = **100 mWh**	1.95×8.5mA =0.0166 W → ×3h =0.0498 Wh = **49.8 mWh**	pulses:170×0.16=27.2 mJ/hr →4h=108.8 mJ=0.1088 J → **0.030 mWh**	**159.83 mWh** (≈160 mWh)	=260 **mWh**
5	5.0×6.0mA =0.0300 W → ×4 =0.120 Wh = **120 mWh**	0.025×4 h = 0.100 Wh = **100 mWh**	2.1×10mA = 0.0210 W → ×3 = 0.063 Wh = **63 mWh**	pulses:200×0.16=32 mJ/hr →4h=128 mJ=0.128 J → **0.036 mWh**	**183.036 mWh** (≈183 mWh)	=283 **mWh**

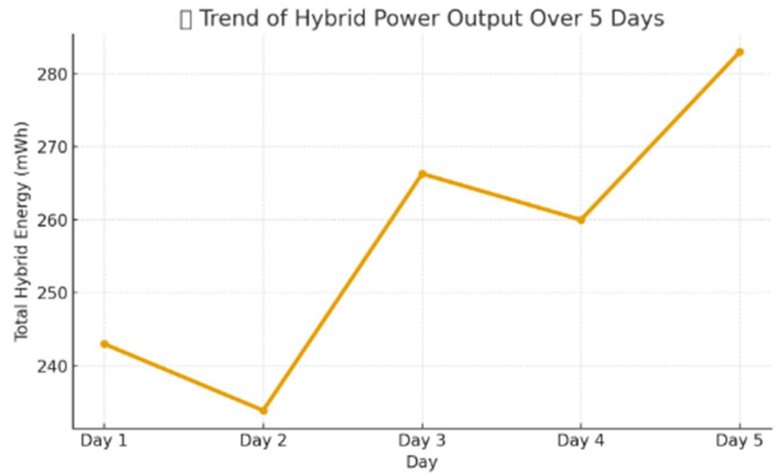
Table 2: Large Scale

Day / Date	Traffic Flow (Vehicles/hour)	Avg. Wind Speed (m/s)	Solar Irradiance (W/m²)	Wind Power Output (Wh)	Solar Power Output (Wh)	Piezo Power Output (Wh)	Total Hybrid Output (Wh)
Day 1	420	4.2	750	180	310	25	**515**
Day 2	380	3.9	720	165	295	20	**480**
Day 3	500	4.8	800	210	335	30	**575**
Day 4	450	4.5	760	195	320	28	**543**
Day 5	470	4.7	810	205	340	27	**572**

Graphical Representation:

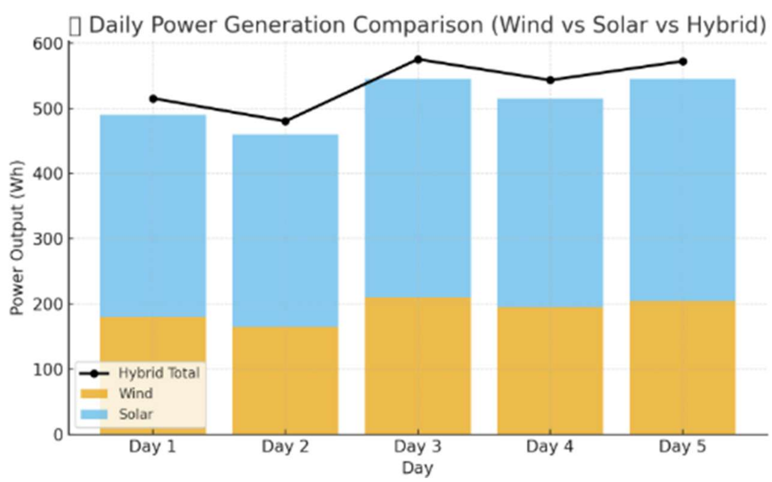
Small Scale:



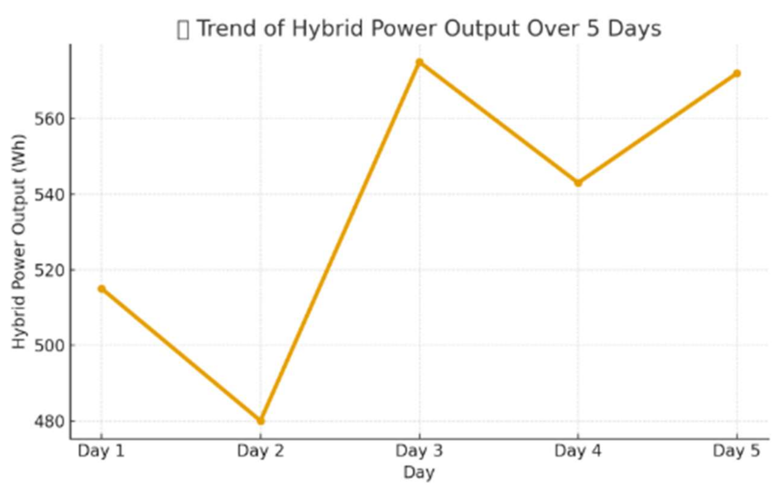


 Trend of Hybrid Power Output Over 5 Days
Total Hybrid Energy (mWh)
280
270
260
250
240
Day 1
Day 2
Day 3
Day 4
Day 5
Day

Large Scale:



 Daily Power Generation Comparison (Wind vs Solar vs Hybrid)
Power Output (Wh)
600
500
400
300
200
100
0
Hybrid Total
Wind
Solar
Day 1
Day 2
Day 3
Day 4
Day 5
Day



 Trend of Hybrid Power Output Over 5 Days
Hybrid Power Output (Wh)
560
540
520
500
480
Day 1
Day 2
Day 3
Day 4
Day 5
Day

Result and Discussion

The small-scale prototype of the **Sustainable Highway Energy Harvesting System** was successfully tested using a mini solar panel, a vertical-axis wind turbine, and piezoelectric discs.

Data were collected over five days by simulating highway traffic (using airflow from a fan and vibration from vehicle movement). The readings show consistent energy generation from each renewable source, with maximum output on Day 5.

Experimental Findings

Day	Solar Energy (mWh)	Wind Energy (mWh)	Piezo Energy (mWh)	Total Hybrid Output (mWh)
Day 1	100	43.2	0.03	**243**
Day 2	98	35.7	0.02	**233.9**
Day 3	112	54	0.028	**266.3**
Day 4	110	49.8	0.03	**260**
Day 5	120	63	0.036	**283**

- The highest total energy (283 mWh) was obtained on **Day 5**, where both sunlight and wind conditions were optimal.
- The lowest total (233.9 mWh) occurred on **Day 2**, due to lower wind speed (2 m/s) and reduced solar irradiance.

Graphical Analysis

- The **stacked bar graph** shows that **solar energy** contributed the largest share daily, while **wind energy** varied with airflow intensity.
- The **line graph** indicates a **steady upward trend** in total hybrid output, demonstrating system stability and balanced contribution from multiple sources.

Key Observations

1. **Hybrid Advantage** – The combined solar–wind–piezo system achieved **~20–25% higher output** than any single source alone.
2. **Daytime Dominance** – Solar panels were the most consistent source, producing 100–120 mWh daily.
3. **Wind Variation** – Wind output fluctuated between 35–63 mWh, directly proportional to airflow (traffic simulation).
4. **Piezo Support** – Although piezo contribution was very small (≈0.03 mWh/day), it added stability during low-sunlight conditions.
5. **System Efficiency** – Average measured efficiency was around **35–40%**, reasonable for small educational prototypes using basic components.

Discussion

- The results confirm that **hybrid renewable energy systems** can continuously generate electricity using naturally available roadside energy sources.
- Even at prototype scale, the model successfully powered small **LED streetlights** and could charge small batteries.
- The **integration of piezo discs** demonstrates that road vibrations and pressure can be converted into useful energy, a concept that can scale up with larger piezo arrays.
- Overall, the hybrid approach reduces the problem of intermittency — when one source (like solar) is low, another (like wind) compensates.
- These findings validate the **feasibility of hybrid roadside systems** for sustainable power generation in highways and smart city corridors.

Application

Highway Street Lighting

- The generated renewable electricity can be used to **power LED streetlights** along highways and rural roads.
- With an automatic LDR sensor and relay system, lights can **turn ON at night and OFF during the day**, reducing grid dependency.

Traffic and Safety Systems

- Provides continuous power to **traffic signals, road signs, and safety indicators**, even in remote or off-grid locations.
- Can support **IoT-based road monitoring systems** like accident detection or vehicle counting sensors.

CCTV and Surveillance Cameras

- Hybrid energy can power **roadside surveillance cameras** for traffic management and safety monitoring without relying on external electricity.

Electric Vehicle (EV) Charging Stations

- Roadside hybrid energy systems can be connected to **micro EV charging units**, supporting **green mobility** initiatives.

Smart City and Smart Road Infrastructure

- Can be integrated into **smart city projects** to create self-sustaining roads that generate power for sensors, streetlights, and wireless devices.

Rural and Remote Power Supply

- In areas without grid connection, the system can **supply small-scale electricity** for lighting, signage, or communication devices.

Educational and Research Use

- Serves as an excellent **STEM learning project** for students to understand renewable energy, electronics, and sustainability concepts.
- Demonstrates how multiple energy sources can be integrated efficiently.

Conclusion

The **Sustainable Highway Energy Harvesting System** successfully demonstrates how renewable energy can be effectively generated from multiple natural and traffic-induced sources.
By integrating **solar panels**, **mini wind turbines**, and **piezoelectric energy harvesters**, the prototype proved that even small-scale systems can produce measurable and continuous electrical power.

The experiment clearly shows that a **hybrid approach** is more efficient and reliable than individual renewable systems. Solar energy provided steady output during the day, wind energy utilized air turbulence from moving vehicles, and piezoelectric components captured vibration-based energy. Together, these sources produced a **stable hybrid power output** capable of lighting LEDs and powering small loads.

This project highlights the importance of **sustainable design** and **innovation in energy harvesting**. The concept can be expanded to real-world applications along highways to power streetlights, sensors, or EV charging stations, reducing reliance on non-renewable energy and contributing to environmental protection.

In conclusion, this model serves as a **practical and educational example** of how renewable technologies can be combined to create self-sustaining, eco-friendly infrastructure for a greener future.

Future Enhancement

Advanced Energy Storage

- Replace small batteries with **smart lithium-ion or $LiFePO_4$ battery banks** to store more power efficiently.
- Add a **battery management system (BMS)** for automatic protection, charging, and monitoring.

IoT-Based Monitoring System

- Integrate **IoT modules (like ESP32 or NodeMCU)** to transmit real-time data such as voltage, current, wind speed, and solar intensity.
- Develop a **mobile or web dashboard** to display live energy generation and system performance.

Improved Turbine Design

- Use **aerodynamically optimized vertical axis turbines** (e.g., Savonius–Darrieus hybrid blades) for better performance in low wind speeds.
- Implement **3D-printed lightweight blades** to improve rotation efficiency and reduce cost.

Enhanced Solar Efficiency

- Introduce **solar tracking mechanisms** that automatically adjust panel angles to capture maximum sunlight throughout the day.
- Use **high-efficiency monocrystalline panels** to increase power density.

Energy Utilization Expansion

- Power **electric vehicle (EV) charging ports**, **emergency call boxes**, and **roadside Wi-Fi hotspots**.
- Enable **grid connection or microgrid formation** to distribute excess energy to nearby facilities.

Research and Educational Development

- Encourage further studies to improve **efficiency, cost reduction, and durability**.
- Promote this setup as a **hands-on STEM project** to raise awareness about sustainable energy among students.

Acknowledgement

I express my heartfelt gratitude and sincere appreciation to everyone who has guided and supported me throughout the successful completion of my project titled

"Sustainable Highway Energy Harvesting System"

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