STREET LIGHT GENERATION USING PIEZOELECTRIC SENSORS AND WIND TURBINES

A MINI PROJECT REPORT FOR THE COURSE

DESIGN THINKING

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ABSTRACT

In today's world, the demand for sustainable and renewable energy sources is increasing rapidly. Traditional methods of power generation are not only depleting finite resources but also contributing to environmental degradation. To address these challenges, this project presents a hybrid energy generation system that utilizes piezoelectric sensors and a wind turbine to harness mechanical and wind energy, respectively. Piezoelectric sensors convert pressure exerted by footsteps into electrical energy, while a small DC motor functioning as a turbine captures wind energy effectively even at low speeds. Both energy sources are combined and stored in capacitors to maximize efficiency and provide continuous power. An Arduino microcontroller is used to regulate and monitor the generated voltage, with real-time values displayed through an LCD screen. This system aims to provide an eco-friendly, cost-effective solution for powering small-scale applications like streetlights and smart pathways, promoting clean energy adoption and innovation in urban infrastructure. Furthermore, it highlights the potential for integrating multiple renewable sources to create smarter, more resilient energy systems for the future.

CHAPTER 1

1.INTRODUCTION

1.1 INTRODUCTION:

In an era where global energy demands are escalating at an unprecedented pace and conventional resources are being rapidly exhausted, the need for disruptive, sustainable solutions has never been more critical. This project introduces a bold step toward the future: a cutting-edge, **piezoelectric-based energy harvesting system** that redefines how we power urban infrastructure.

Titled *"Piezoelectric-Based Energy Harvesting for Intelligent Street Lighting Systems,"* this project leverages the untapped potential of mechanical pressure—generated daily by pedestrians and vehicles—to produce clean, renewable electricity. By integrating high-efficiency piezoelectric transducers into the urban landscape, the system captures mechanical vibrations and seamlessly converts them into electrical energy.

At its core, the system is powered by an intelligent Arduino-based microcontroller that regulates energy flow, stores it in capacitors, and powers energy-efficient LED streetlights. A real-time LCD module displays voltage levels for continuous monitoring and optimization. Taking innovation a step further, a **DC motor-driven wind turbine** supplements the setup, harnessing natural wind energy to ensure continuous power generation under varying environmental conditions.

This hybrid energy solution is more than a technical achievement—it is a **visionary blueprint for the cities of tomorrow**. Scalable, eco-friendly, and economically viable, the system exemplifies next-generation urban design. It aligns seamlessly with global sustainability goals, smart city frameworks, and clean energy commitments, making it a flagship initiative in the movement toward greener, smarter, and self-sustaining public infrastructure.

1.2 OBJECTIVES:

The overarching objective of this project is to pioneer a revolutionary advancement in sustainable urban infrastructure by harnessing the immense potential of **piezoelectric energy harvesting** to power intelligent street lighting systems. This project seeks not only to reduce dependency on conventional energy sources but to **redefine the future of smart city design** through innovation, efficiency, and environmental consciousness. The specific objectives include:

1. **To engineer a cutting-edge system** that captures the latent mechanical energy from pedestrian footsteps and vehicular movement—an energy source often overlooked—and convert it into valuable electrical power through advanced piezoelectric technology.
2. **To create a self-sustaining, intelligent street lighting model** that operates independently of the conventional power grid, thereby drastically reducing urban energy consumption and operational costs.
3. **To integrate a sophisticated embedded control unit (Arduino)** that monitors energy output, regulates power flow, and provides real-time data visualization through an interactive LCD interface, showcasing the seamless fusion of hardware and smart technology.
4. **To enhance energy generation capacity** by incorporating a hybrid approach, combining piezoelectric sensors with a micro wind energy system (turbine and DC motor), thus ensuring consistent power availability under varying conditions.
5. **To develop a robust and efficient energy storage framework** using high-capacitance components, ensuring uninterrupted operation of the street lighting system and paving the way for grid-independent infrastructure.
6. **To demonstrate a scalable, eco-friendly solution** that sets a precedent for sustainable urban development, contributing to national and global goals in green technology and smart city transformation.

1.3 MODULES:

The proposed system is composed of the following key functional modules, each contributing to the overall objective of efficient and sustainable street lighting through piezoelectric energy harvesting:

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1. **Piezoelectric Energy Harvesting Module**

- **Description:** This is the core module responsible for converting mechanical stress or vibrations—caused by foot traffic or vehicles—into electrical energy.
- **Components:** Piezoelectric sensors/transducers, pressure pads.
- **Function:** Generates AC voltage when mechanical pressure is applied; acts as the primary energy source.

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2. Power Conditioning and Rectification Module

- **Description:** Converts the raw AC output from piezoelectric sensors into stable DC voltage suitable for storage and usage.
- **Components:** Bridge rectifier, voltage regulators, smoothing capacitors.
- **Function:** Ensures a consistent and usable DC power output, protecting connected devices from voltage fluctuation.

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3. Energy Storage Module

- **Description:** Stores the harvested electrical energy for later use.
- **Components:** High-capacity capacitors or rechargeable batteries.
- **Function:** Acts as a buffer to supply power to the street lighting system during periods of low or no mechanical activity.

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4. Wind Energy Integration Module (Optional/Hybrid Enhancement)

- **Description:** Supplements piezoelectric energy with wind-generated power using a turbine connected to a DC motor.
- **Components:** Mini turbine, DC motor, rectifier circuit.
- **Function:** Enhances total energy output, improving reliability and performance under varying environmental conditions.

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5. Microcontroller and Control Unit

- **Description:** The brain of the system that monitors and controls the overall functionality.
- **Components:** Arduino Uno or equivalent microcontroller.
- **Function:** Reads input voltages, manages energy flow, and communicates with display/output modules. It ensures intelligent control and energy efficiency.

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6. Display and Monitoring Module

- **Description:** Provides real-time monitoring and visualization of system parameters such as voltage levels.
- **Components:** LCD display (16x2 or 20x4), interface wiring.
- **Function:** Informs users of the current energy generation status and system health.

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7. LED Street Lighting Module

- **Description:** The end-application module that utilizes the harvested and stored energy to power street lights.
- **Components:** Energy-efficient LED bulbs, connecting circuits.
- **Function:** Provides illumination using renewable energy, validating the feasibility and effectiveness of the overall system.

MATERIALS REQUIRED:

Component / Material	Specification / Description	Quantity
Piezoelectric Sensors	Piezo discs/transducers (e.g., PZT type) – for energy harvesting	4–8 units
Arduino Uno	Microcontroller board based on ATmega328P	1 unit
Capacitors	For smoothing and energy storage (e.g., 1000µF, 470µF)	2–4 units
Rechargeable Battery / Super Capacitor	Optional – for longer energy storage	1 unit
Mini Wind Turbine	Small-scale wind turbine for hybrid energy support	1 unit
DC Motor	Coupled with turbine to generate electricity	1 unit
LED Street Light / High-Power LED	Energy-efficient light source for demonstration	1–2 units
LCD Display (16x2)	To display voltage and status information	1 unit
Diodes (e.g., 1N4007)	For rectification and circuit protection	As needed
Resistors	Various values as per circuit design	As needed
Breadboard / PCB	For circuit prototyping or permanent assembly	1 unit
Jumper Wires / Hookup Wires	For circuit connections	As needed
Acrylic / Wooden Base Platform	For mounting piezo sensors (floor prototype)	1 unit
Multimeter	For testing voltage and continuity	1 unit
Soldering Kit	For permanent wiring (iron, solder, flux)	1 kit
Connecting Terminals / Connectors	For clean wiring and component connections	As needed

CHAPTER 2

2.EMPATHY PHASE

2.1 INTRODUCTION:

Modern cities face a dual challenge: meeting the rising demand for energy while transitioning to environmentally sustainable systems. Street lighting, an essential component of public infrastructure, consumes a significant portion of urban electricity and often relies on non-renewable power sources. In many regions, frequent power outages, high energy costs, and carbon emissions further exacerbate the problem—affecting not just efficiency, but also safety and quality of life.

Through the empathy phase of this project, we sought to understand these real-world issues from the perspective of everyday users—pedestrians, commuters, local authorities, and urban planners. We observed how bustling streets generate constant mechanical activity that currently goes to waste. This inspired a simple yet powerful question: *What if the very footsteps of people could help light the roads they walk on?*

We interacted with people who experience poor street lighting firsthand—residents concerned about safety after dark, students walking home from evening classes, and city workers burdened by high electricity bills. Their stories shaped our vision for a system that not only conserves energy but directly benefits the communities it serves.

By listening to these needs and identifying gaps in existing infrastructure, our project aims to create a sustainable solution that is practical, cost-effective, and environmentally conscious. More importantly, it reflects a human-centered approach to engineering—where innovation is driven by empathy, and technology serves the greater good.

2.2 EXISTING SYSTEMS:

Piezoelectric energy harvesting has gained significant attention in recent years due to its potential to convert mechanical vibrations, pressure, and motion into electrical energy. However, existing systems and applications of this technology have certain limitations that hinder their widespread implementation, particularly in urban settings.

Street lighting systems have been traditionally powered by the electricity grid, but with the growing emphasis on energy efficiency and sustainability, several alternative methods have been explored. Below are the key existing systems for street lighting generation:

1. **Grid-Powered Conventional Street Lighting**
   The most common system in use today is the conventional street lighting powered by the electricity grid. These systems use high-energy-consuming lights, such as sodium-vapor or halogen lamps, to illuminate streets. They typically operate on fixed timers or dusk-to-dawn sensors. While this system is reliable, it is also energy-intensive, resulting in high electricity consumption and carbon emissions. Additionally, it poses a financial burden on municipalities due to the high energy and maintenance costs.
2. **Solar-Powered Street Lighting**
   Solar-powered street lights are one of the most popular renewable energy alternatives for outdoor lighting. These systems incorporate solar panels to capture energy from the sun during the day, storing it in batteries for use during the night. Solar-powered lights are often used in remote areas or locations with high sun exposure. However, their efficiency is greatly impacted by factors such as weather conditions, availability of sunlight, and geographical location. In urban settings with less sunlight or high-rise buildings, their performance may be limited.
3. **Wind-Powered Street Lighting**
   Wind energy is another renewable energy source being explored for street lighting. Small-scale wind turbines are sometimes integrated with street light poles to generate electricity from the wind. While this system can provide energy during windy conditions, it is often unreliable in areas where wind speeds are inconsistent. Moreover, the integration of wind turbines into street lighting infrastructure raises challenges related to cost, space, and potential environmental impact (e.g., noise or wildlife concerns).

4. **Hybrid Solar-Wind Street Lighting**
   Some modern street lighting systems combine both solar and wind energy to generate electricity. These hybrid systems aim to address the limitations of each energy source by providing a backup when one is insufficient (e.g., solar energy during the day and wind energy during the night or in poor weather). These systems are more reliable but still face challenges in terms of cost, maintenance, and the need for suitable locations with consistent wind and sunlight.

5. **Smart Street Lighting**
   Smart street lighting systems integrate advanced technologies to optimize energy consumption. These systems use sensors and controllers to adjust light intensity based on real-time data, such as traffic density or time of day. In addition to reducing energy use, smart lighting systems can also detect faults and remotely monitor the status of each light. Some smart systems are also experimenting with integrating renewable energy sources like solar power, but they often still rely heavily on the grid as a primary energy source.

6. **Piezoelectric Energy Harvesting for Street Lighting (Emerging Concept)**
   A growing trend is the use of **piezoelectric energy harvesting** embedded within the street infrastructure to generate electricity from mechanical vibrations. This technology captures the kinetic energy produced by the movement of vehicles or pedestrians and converts it into electrical power. However, while this concept is innovative, its widespread application in street lighting is still in its infancy. The challenges include low power output, inconsistent energy generation, and difficulties in energy storage and regulation.

7. **Energy-Efficient LED Street Lighting**
   The transition to **LED street lighting** has been a significant improvement in reducing energy consumption and costs. LED lights consume less power and have a longer lifespan compared to traditional incandescent or sodium-vapor lights. Though energy-efficient, they still depend on conventional power sources and do not address the need for renewable energy integration or self-sustaining infrastructure.

2.3 ISSUES IN EXISTING SYSTEM:

Despite the efforts to incorporate renewable energy and optimize street lighting, several challenges remain in the existing systems. These challenges hinder their effectiveness and scalability, particularly when considering large-scale urban applications. Below are the key issues in the existing systems for street lighting generation:

1. **Conventional Grid-Powered Street Lighting**
   - **High Energy Consumption**: Conventional street lights, such as sodium vapor and halogen lamps, consume large amounts of energy, resulting in high electricity bills for municipalities. These lights are inefficient compared to modern technologies like LEDs, leading to unnecessary energy wastage and higher carbon footprints.
   - **Environmental Impact**: Grid-powered street lighting depends on electricity generated from fossil fuels, contributing to carbon emissions and exacerbating climate change. This reliance on non-renewable energy sources goes against global sustainability goals.
   - **Maintenance and Replacement Costs**: These lights require regular maintenance and replacement, increasing the operational costs for municipalities. The traditional lamps also have a shorter lifespan compared to newer technologies, leading to more frequent replacements.
2. **Solar-Powered Street Lighting**
   - **Inconsistent Energy Generation**: Solar-powered street lights are highly dependent on sunlight. In urban areas with many high-rise buildings or limited sun exposure, the efficiency of solar panels decreases, especially during cloudy days or winter months. This makes them less reliable for nighttime illumination.
   - **High Initial Costs**: While solar-powered systems reduce dependency on the grid, the initial installation cost for solar panels, batteries, and controllers can be quite high. This creates a barrier for widespread adoption, especially in cities with limited budgets for infrastructure improvements.
   - **Battery Life and Storage Issues**: Batteries used in solar systems degrade over time and require regular replacement. This increases maintenance costs and can lead to periods of insufficient energy

storage during poor weather conditions, leaving street lights without power.

3. **Wind-Powered Street Lighting**
    - **Inconsistent Energy Availability**: Wind-powered street lighting systems are only effective in areas with consistent wind speeds. In urban environments or regions with little wind, these systems fail to provide reliable power, making them unsuitable for widespread implementation.
    - **High Installation and Maintenance Costs**: The installation of wind turbines can be expensive and complex, requiring considerable space and structural support. Additionally, wind turbines have moving parts that are prone to wear and tear, leading to higher maintenance costs.
    - **Environmental and Aesthetic Concerns**: Wind turbines can create noise pollution, which may be disruptive to residential areas or sensitive environments. Moreover, large turbines may not fit aesthetically in urban landscapes, where space is often limited.
4. **Hybrid Solar-Wind Street Lighting**
    - **Complexity and Cost**: While hybrid systems attempt to combine the advantages of solar and wind power, they come with increased complexity in terms of installation, energy storage, and maintenance. The combination of both energy sources requires careful management of power flow and energy regulation, which can be difficult to achieve in practice.
    - **Reliability**: Hybrid systems are still susceptible to weather conditions. If both solar and wind energy sources are unavailable simultaneously (e.g., during cloudy and windless days), these systems may not provide sufficient energy to power the street lights.
    - **Space and Infrastructure Demands**: Hybrid systems require additional space for both solar panels and wind turbines, which can be difficult to implement in densely populated urban areas. This requirement for large infrastructure can make these systems unsuitable for certain locations.

5. **Smart Street Lighting**
   - **Dependency on the Grid**: Despite the advanced capabilities of smart street lights, such as dimming based on traffic flow or time of day, they still rely heavily on the electricity grid. This limits their potential for sustainability and increases operating costs.
   - **Limited Integration with Renewable Energy**: Many smart street lighting systems do not fully integrate renewable energy sources like solar or wind power, which means they are still vulnerable to the fluctuations of grid energy prices and supply.
   - **High Implementation Costs**: The installation of smart street lighting involves significant initial investment in sensors, controllers, and communication infrastructure. Additionally, the need for ongoing software and hardware updates can increase long-term maintenance costs.
6. **Piezoelectric Energy Harvesting for Street Lighting ^**
   - **Low Power Output**: One of the primary challenges with piezoelectric energy harvesting for street lighting is its relatively low power output. The mechanical energy generated by pedestrian or vehicular traffic may not be sufficient to power the street lights consistently, particularly in areas with low traffic volumes.
   - **Energy Storage and Regulation**: Piezoelectric systems often struggle with efficient energy storage and regulation. The energy produced is often intermittent and low in voltage, making it difficult to store and convert into usable power for street lights. Without effective energy storage solutions, piezoelectric systems are unreliable for continuous illumination.
   - **Scalability Issues**: While piezoelectric energy harvesting can work in small-scale applications (e.g., single poles), scaling up the system to power an entire street or neighborhood is challenging. The amount of kinetic energy produced by individual vehicles or pedestrians is insufficient to power large-scale lighting systems.
   - **Wear and Tear on Components**: Piezoelectric transducers can experience wear and degradation over time, especially in high-traffic areas. This reduces the efficiency of the system and necessitates

regular maintenance or replacement of components, increasing operational costs.

7. **Energy-Efficient LED Street Lighting**
    - **Dependency on Grid Power**: Although energy-efficient LEDs are a significant improvement over traditional lamps, they still rely on grid electricity for power. This continued dependence on the grid prevents them from being fully sustainable, especially in areas with unreliable or expensive grid power.
    - **Limited Use of Renewable Energy**: Most energy-efficient LED systems do not incorporate renewable energy sources like solar or wind. As a result, while they are more efficient, they do not contribute to the broader goal of reducing the environmental impact of street lighting.
    - **Integration with Smart Systems**: While LED lights are energy-efficient, they often do not include advanced features like dimming or adaptive lighting. Incorporating these features requires additional investments in smart technology and sensors, which further complicates the system.

CHAPTER 3

3. EXPERIMENT PHASE

3.1 INTRODUCTION:

The Experiment Phase of the project is a critical stage where theoretical concepts are put to the test through practical implementation. In this phase, the proposed system for Piezoelectric-Based Energy Harvesting for Intelligent Street Lighting Systems is physically constructed, and its performance is evaluated under real-world conditions. The objective of this phase is to validate the feasibility, efficiency, and sustainability of the energy harvesting mechanism, ensuring that it can meet the power requirements of street lighting systems.

During this phase, various components such as piezoelectric transducers, energy storage units (capacitors), microcontrollers (Arduino), LED lights, and additional energy-generating systems (such as a wind turbine) will be integrated and tested for optimal performance. Real-time data, such as voltage levels and power output, will be monitored to assess the system's ability to generate, store, and regulate energy effectively.

The Experiment Phase involves a series of steps, including:

- Component Integration: Assembling and connecting the piezoelectric transducers, storage devices, and microcontroller to form a functional energy harvesting and management system.
- Testing and Data Collection: Conducting experiments to measure energy generation under various conditions, including varying traffic loads (for pedestrian and vehicle movement), wind conditions (for turbine), and different times of day (for energy storage capacity).
- System Optimization: Fine-tuning system parameters, including energy storage, voltage regulation, and light intensity control, to ensure the system meets energy demands efficiently.
- Performance Evaluation: Comparing the actual performance with expected results to identify any discrepancies, troubleshoot issues, and assess the practicality of the system for urban street lighting applications.

The outcomes of this phase will provide crucial insights into the system's effectiveness, potential scalability, and reliability in powering street lighting infrastructure.

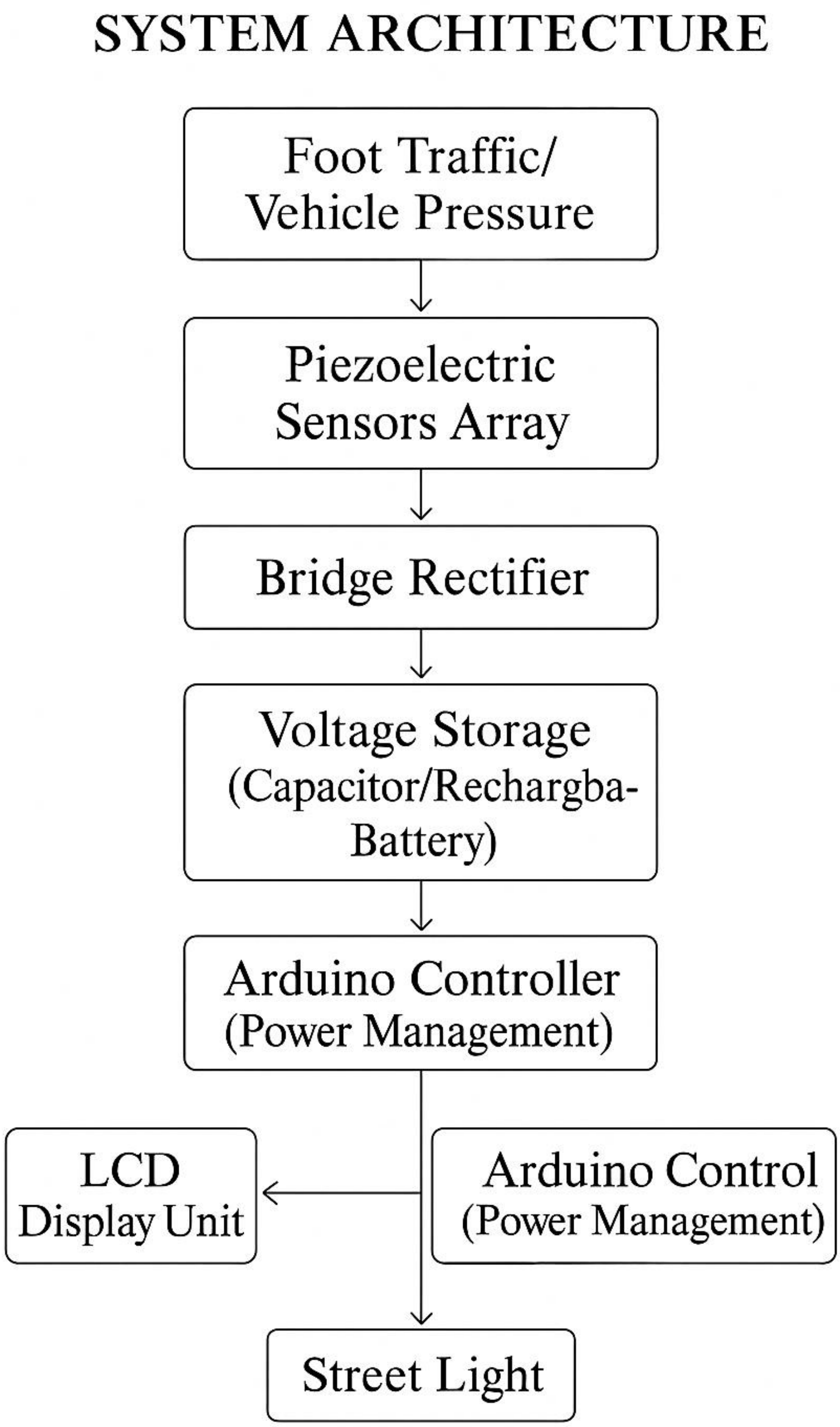
3.2 PROPOSED SYSTEM:

The proposed system is a hybrid energy harvesting setup designed to generate electrical power from mechanical pressure using **piezoelectric sensors** and supplement it with **wind energy** captured via a **turbine connected to a DC motor**. The system aims to power **streetlights** in urban areas by utilizing renewable sources from both **foot traffic and wind flow**.

In the experimental phase, the setup comprises the following components and their integration:

1. **Piezoelectric Sensors Array:**
    - Multiple piezoelectric discs are embedded under a platform to convert pressure (from footfalls or vehicles) into electrical energy.
    - The generated AC voltage is passed through a **bridge rectifier** and **voltage regulator** to store in a **capacitor** or charge a battery.
2. **Wind Turbine and DC Motor Setup:**
    - A small-scale horizontal axis turbine is connected to a **DC motor**, which acts as a generator to produce power when wind flows.
    - This energy is also stored in the same capacitor circuit, ensuring dual-mode energy input.
3. **Power Management and Control Unit (Arduino-based):**
    - An **Arduino microcontroller** is used to monitor voltage and current levels.
    - It controls the switching between piezo and turbine inputs, manages power storage, and activates the **LED streetlight** when the energy threshold is met.
4. **LCD Display Unit:**
    - Displays real-time voltage readings from both sources.
    - Used to monitor performance during testing and experimentation.
5. **Energy Storage:**
    - A **rechargeable battery** or **supercapacitor** stores harvested energy and ensures regulated supply to the streetlight.

3.3 SYSTEM ARCHITECTURE:



3.4 HARDWARE AND SOFTWARE REQUIREMENTS:

3.4.1 HARDWARE REQUIREMENTS:

➢ **Piezoelectric Sensors (Discs or Plates)**

- **Function:** Converts mechanical pressure (footsteps/vehicle weight) into electrical energy
- **Quantity:** Based on energy demand (usually an array of 10–20 for experiments)

➢ **Bridge Rectifier**

- **Function:** Converts AC output from piezo sensors into DC

➢ **Energy Storage Components**

- **Capacitor** or **Rechargeable Battery**
- Function: Stores the energy harvested

➢ **Arduino Uno / Nano / Mega**

- **Function:** Microcontroller for monitoring voltage, controlling output to lights, and displaying data

➢ **DC Wind Turbine**

- **Function**: Generates electricity from wind using a DC motor as generator
- Used to convert wind turbine rotation into electrical output

➢ **LCD Display Module (16x2 or I2C-based)**

- Function: Displays voltage, current, or status messages
- Optional but helpful for experimentation

➢ **LED Street Light Module or High-Power LEDs**

- Function: Final output to illuminate using stored energy
- Power: Based on available stored energy (3V–12V)

➢ **Resistors, Diodes, and Wires**

- For supporting circuitry, LED protection, and signal conditioning

➢ **Breadboard or PCB**

- For prototyping the circuit layout

➢ **Switches & Connectors**

- Manual control and safe connections between modules

➢ **Multimeter & CRO (for testing phase)**

- For voltage/current monitoring during experimentation

3.4.2 SOFTWARE REQUIREMENTS:

3.4.2.1 Arduino IDE

Purpose:
The **Arduino Integrated Development Environment (IDE)** is the primary software used to write, compile, and upload code to the Arduino microcontroller. It acts as the programming and debugging interface for the Arduino board, enabling direct interaction with hardware components like sensors, displays, and output modules.

Key Features Used in the Project:

- **Code Editor:** For writing embedded C/C++ code to manage sensor input, energy storage monitoring, and LED control.
- **Serial Monitor:** To read real-time voltage and sensor data from the Arduino for analysis and debugging during the experimental phase.
- **Serial Plotter:** Visualizes data (like voltage fluctuation from piezo sensors) in a graphical format, which helps in interpreting energy generation trends.
- **Library Manager:** To install and manage useful libraries such as:
    - LiquidCrystal.h – for interfacing with the LCD display.
    - Wire.h – if using I2C communication for modules.
- **Board Manager:** Allows selection and configuration of the connected Arduino model (e.g., Uno, Nano).

Version Recommendation:
Use the latest stable version (Arduino IDE 2.x series) for better performance and an improved user interface.

3.4.2.2. Embedded C / Arduino C++

Purpose:

The Arduino microcontroller is programmed using a simplified version of C/C++, often referred to as **Arduino C**. This language allows precise control over hardware components connected to the board, such as piezoelectric sensors, voltage regulators, LEDs, and LCDs.

Usage in the Project:

- **Sensor Reading:** Code handles analog/digital input from piezo sensors and DC motors.
- **Power Threshold Logic:** Implements logic to check if stored energy is sufficient to power the streetlight.
- **LCD Output:** Displays voltage readings and system status.
- **Control Flow:** Includes if-else, switch, and loops for automation, such as turning the streetlight ON when voltage exceeds a threshold.
- **Pin Configuration:** Digital and analog pins are defined and managed to ensure correct connections to hardware components.

CHAPTER 4

4. ENGAGE / EVOLVE PHASE

4.1 INTRODUCTION:

The **Engage/Evolve Phase** of the Piezoelectric Power Generation for Streetlights project focuses on transforming the conceptual prototype into a more robust and responsive system through real-time interaction and iterative enhancement. This phase is crucial in validating the system's performance in practical scenarios and addressing real-world constraints such as inconsistent pressure input, variable wind flow, and fluctuating voltage levels.

During this stage, the project engages actively with environmental stimuli—like footfalls, vehicle movement, and natural wind—to test the dual-source energy harvesting setup. The goal is to evaluate the efficiency of piezoelectric sensors and the wind turbine generator under experimental conditions and evolve the hardware-software interaction accordingly.

System behaviors such as voltage fluctuation, charging duration, power threshold activation for lighting, and storage efficiency are closely monitored. Data from these observations is used to adjust the Arduino logic, optimize energy storage regulation, and ensure a more stable output to the streetlight module. Additionally, LCD feedback and serial plot monitoring assist in visualizing system performance.

This phase plays a pivotal role in bridging theoretical design and practical deployment, ensuring the prototype evolves into a solution capable of sustainable, eco-friendly street lighting through renewable micro-energy harvesting.

4.2 PERFORMANCE ANALYSIS:

The performance of the piezoelectric-based power generation system was evaluated based on its ability to harvest energy under varying load conditions and its efficiency in powering a streetlight through regulated storage. Multiple test scenarios were conducted to analyze energy output, storage efficiency, and system responsiveness.

1. Energy Generation

- **Piezoelectric Sensors Output:** Each piezo sensor generated approximately 1.2V–3.5V under moderate mechanical pressure. An array of sensors connected in series and parallel configurations improved total voltage and current output.
- **Wind Turbine Generator Output:** Supplementary power from a DC motor-based wind turbine generated 2V–9V depending on wind intensity, enhancing the hybrid system's overall reliability.

2. Rectification and Regulation

- The **bridge rectifier** successfully converted the AC voltage from the piezo sensors into DC.
- The **voltage regulator** maintained a stable output (around 5V) to prevent damage to storage components and downstream circuitry.

3. Energy Storage and Utilization

- **Capacitor Charging Time:** With medium foot traffic, a 1000µF capacitor charged within 20–30 seconds.
- **Battery Storage:** Rechargeable batteries offered better capacity and longer retention, suitable for prolonged lighting.

- **Threshold Voltage Activation:** The Arduino-controlled system activated the streetlight only when stored voltage surpassed a set threshold (e.g., 4.5V), ensuring efficient energy use.

4. Output Performance

- **Streetlight Duration:** A fully charged system was able to power a low-watt LED streetlight for approximately 30 seconds to 2 minutes, depending on energy source and storage size.
- **LCD Display & Monitoring:** Real-time voltage updates and system status were clearly shown, allowing for quick diagnostics during testing.

5. Limitations Observed

- Energy generation from piezo sensors alone was not sufficient for continuous lighting without frequent mechanical input.
- Wind turbine efficiency was weather-dependent and required consistent airflow for optimal output.
- Storage capacity and sensor durability impacted long-term performance.

4.3 FEEDBACK FROM ENGAGE PHASE:

The Evolve Phase offered crucial insights into the practical implementation, reliability, and efficiency of the proposed system. Through multiple test iterations and environmental trials, several strengths and limitations were identified, helping to shape future improvements.

Key Feedback Highlights

1. **Improved System Understanding**
   Testing under real-world conditions revealed how piezoelectric sensors react to varying pressure levels. The hands-on approach enhanced understanding of voltage generation patterns and sensor alignment techniques.
2. **Hybrid Energy Approach Validated**
   The combination of piezoelectric and wind energy proved effective in stabilizing power output. In scenarios with minimal foot traffic, the wind turbine offered supplementary voltage, extending light uptime.
3. **Threshold-Based Lighting Logic Worked Well**
   The Arduino-controlled voltage threshold mechanism prevented premature energy drainage and ensured that the streetlight only turned on when sufficient charge was stored, enhancing energy efficiency.
4. **Need for Enhanced Energy Storage**
   Feedback from repeated trials emphasized the limitation of capacitors for sustained energy storage. Using higher-capacity rechargeable batteries significantly improved performance duration.
5. **Monitoring Tools Were Beneficial**
   Real-time voltage display via the LCD and serial plotter helped detect voltage dips and peaks. This allowed quick troubleshooting and adjustments to component placement and system logic.

6. **Durability Concerns**
   Piezo sensors showed signs of wear with continuous pressure over time, indicating a need for stronger encapsulation or material support to maintain long-term performance.
7. **Scalability Consideration**
   Feedback from mentors and peers suggested the system could be scaled with additional sensors, better turbine blades, and more efficient energy management modules for real-world deployment.

CHAPTER 5

5. CONCLUSION AND FUTURE WORK

5.1 CONCLUSION:

The **Piezoelectric Power Generation for Streetlights** project demonstrates the potential of harnessing renewable micro-energy sources—specifically mechanical pressure and wind—for low-power applications such as street lighting. Through the integration of piezoelectric sensors and a DC motor-based wind turbine, the system successfully harvested, stored, and utilized energy to illuminate a streetlight, validating the core objective of sustainable power generation.

The project journey involved critical phases such as system design, prototyping, and iterative testing under real-world conditions. The engage/evolve phase was especially insightful, as it revealed practical constraints like inconsistent input energy, storage limitations, and sensor durability. These insights were used to evolve the system by enhancing the Arduino-based control logic, incorporating voltage threshold mechanisms, and utilizing dual sources of energy for improved reliability.

Performance analysis confirmed that the system could generate sufficient voltage under moderate foot pressure and airflow, with real-time monitoring through LCD. While the current prototype is suitable for short-duration lighting, future scope includes scaling the design with more efficient sensors, advanced storage solutions, and optimized energy management circuits.

Overall, the project not only met its objectives but also highlighted the importance of hybrid renewable solutions in addressing energy needs in a sustainable and eco-friendly manner. It lays the groundwork for further innovation in smart urban infrastructure, particularly in areas where conventional power access is limited or expensive.

5.2 FUTURE WORK:

The success of this prototype opens the door to a range of promising developments that extend beyond basic street lighting. The core concept of harvesting energy from mechanical pressure and wind can be scaled and adapted to serve diverse public infrastructure needs. Future enhancements aim not only to optimize energy generation and storage but also to apply the system in **smart city environments**, promoting both sustainability and public comfort.

1. Smart Misting Systems for Bus Stands & Pedestrian Zones

- Integrate the piezoelectric system with **automated misting nozzles** at crowded bus stops or sidewalks to provide cooling during hot weather.
- Pressure from footfalls or traffic can trigger short bursts of mist, enhancing commuter comfort without relying on external power grids.

2. Self-Sustaining Pedestrian Pathways

- Expand the sensor array along **sidewalks and footbridges**, allowing energy harvested from human movement to power pathway lights, motion sensors, and small digital signboards.
- Energy can also support **emergency call buttons** or **ambient sound systems** for visually impaired pedestrians.

3. Canopy-Integrated Plant Irrigation in Parks

- Combine piezoelectric and solar energy systems to power **automated drip irrigation or misting systems** for green canopies in public parks.
- This supports **urban greening initiatives**, helping maintain plant health with minimal energy consumption.

4. Environmental Monitoring Stations

- Use excess energy to power **mini environmental sensors** (temperature, humidity, air quality) in smart poles or near bus shelters.
- Data collected can be sent via low-power IoT modules to municipal dashboards for smart city analytics.

5. Modular Energy Tiles for Public Installations

- Develop **modular piezo tiles** that can be embedded in high-footfall areas like metro stations, malls, and amusement parks to gather kinetic energy.
- The collected energy can be used to light up artistic installations, public announcements, or interactive maps.

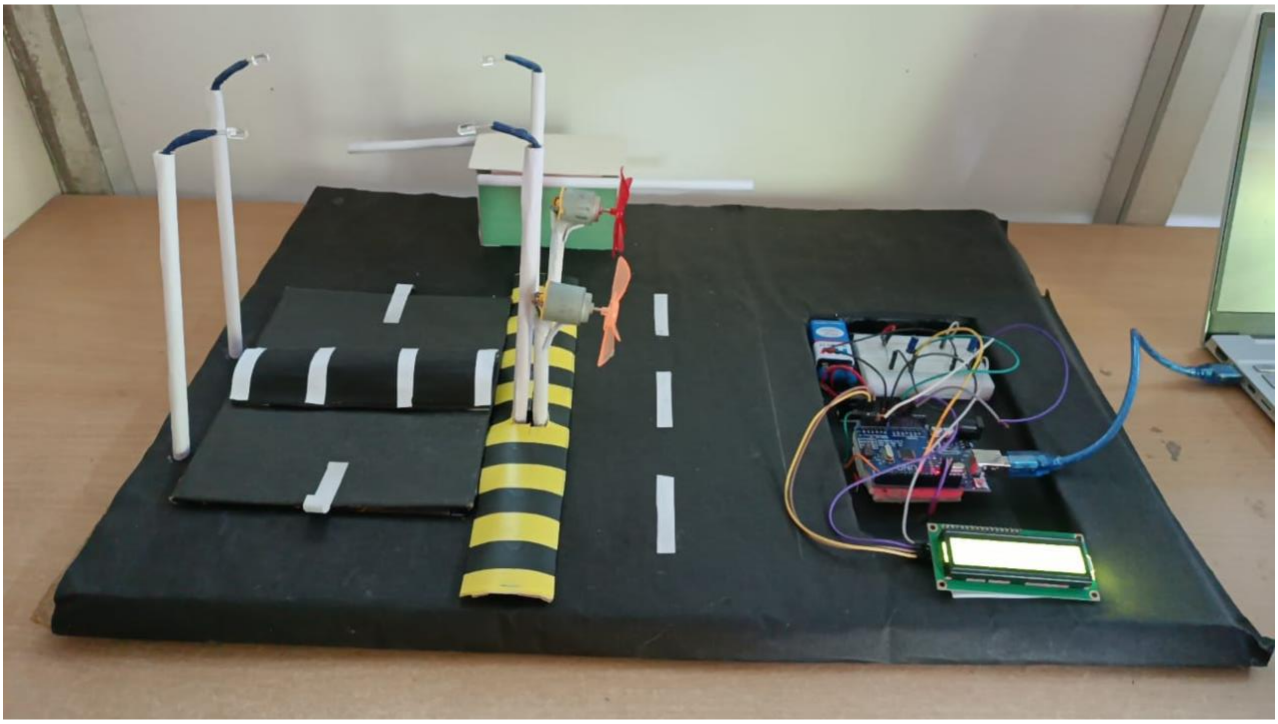
APPENDIX

PROGRAM CODE:

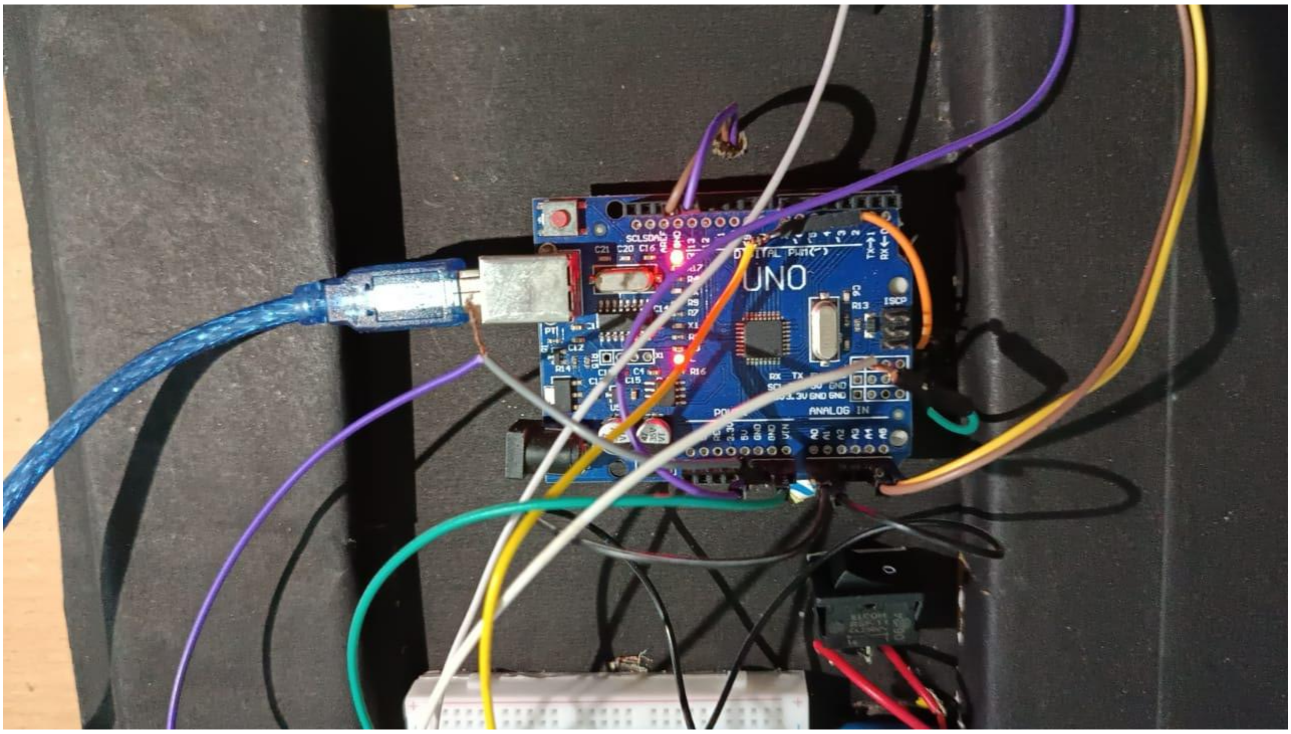
```
#include <Wire.h>
#include <LiquidCrystal_I2C.h>

// Pin definitions
const int piezoPin = A0;      // Analog pin for piezo
const int dcMotorPin = A1;    // Analog pin for DC motor
const int ledPin = 13;        // LED pin (optional)
const int threshold = 512;    // LED activation threshold

int piezoValue = 0;
int dcMotorValue = 0;

// Initialize LCD: address 0x27, 16 characters, 2 lines
LiquidCrystal_I2C lcd(0x27, 16, 2);

void setup() {
  pinMode(ledPin, OUTPUT);
  Serial.begin(9600);

  // LCD setup
  lcd.init();
  lcd.backlight();
  lcd.setCursor(0, 0);
  lcd.print("Dual Voltage");
  delay(1000);
  lcd.clear();
}

void loop() {
  // Read sensor values
  piezoValue = analogRead(piezoPin);
  dcMotorValue = analogRead(dcMotorPin);

  // Convert to voltage
  float piezoVoltage = piezoValue * (5.0 / 1023.0);
  float motorVoltage = dcMotorValue * (5.0 / 1023.0);

  // Debug output
  Serial.print("Piezo: ");
  Serial.print(piezoVoltage, 2);
  Serial.print(" V\tMotor: ");
```

```
  Serial.print(motorVoltage, 2);
  Serial.println(" V");

  // Display on LCD
  lcd.setCursor(0, 0);
  lcd.print("Piezo: ");
  lcd.print(piezoVoltage, 2);
  lcd.print("V  ");

  lcd.setCursor(0, 1);
  lcd.print("Motor: ");
  lcd.print(motorVoltage, 2);
  lcd.print("V  ");

  // Optional LED indicator
  if (piezoValue > threshold || dcMotorValue > threshold) {
    digitalWrite(ledPin, HIGH);
  } else {
    digitalWrite(ledPin, LOW);
  }

  delay(500);
}
```

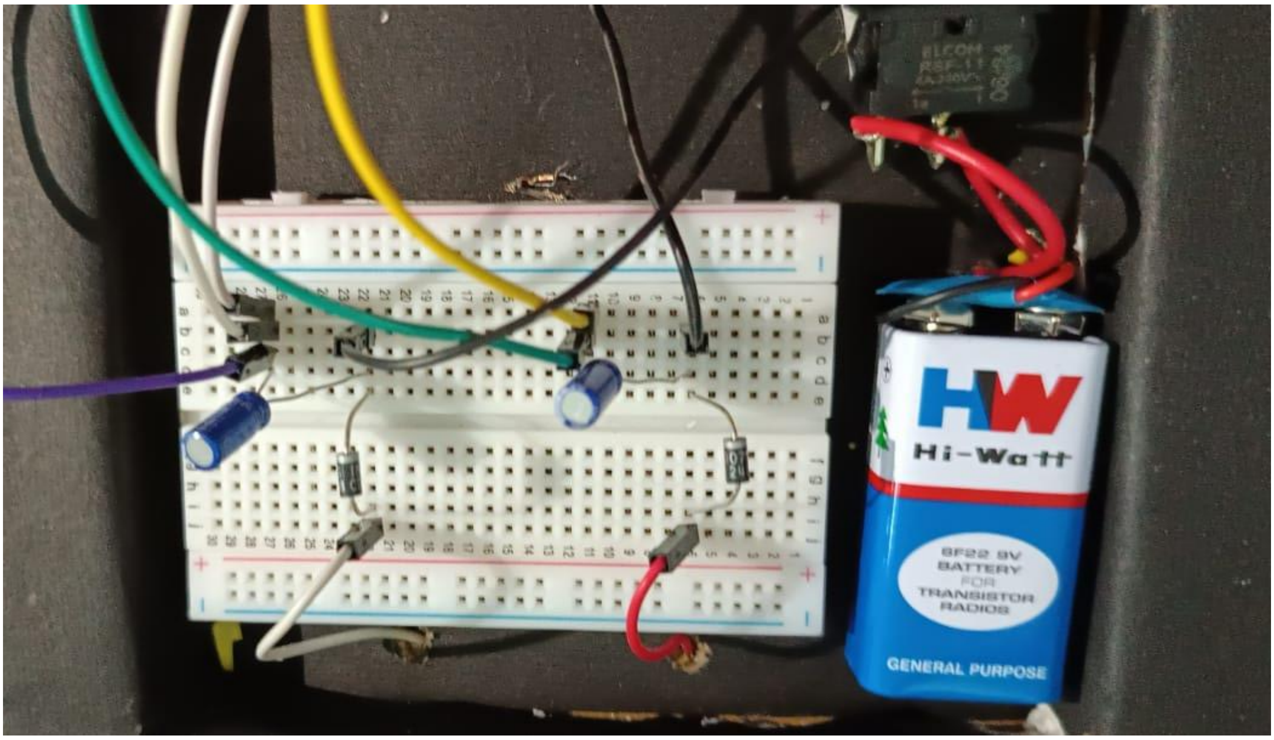
PROJECT KIT:



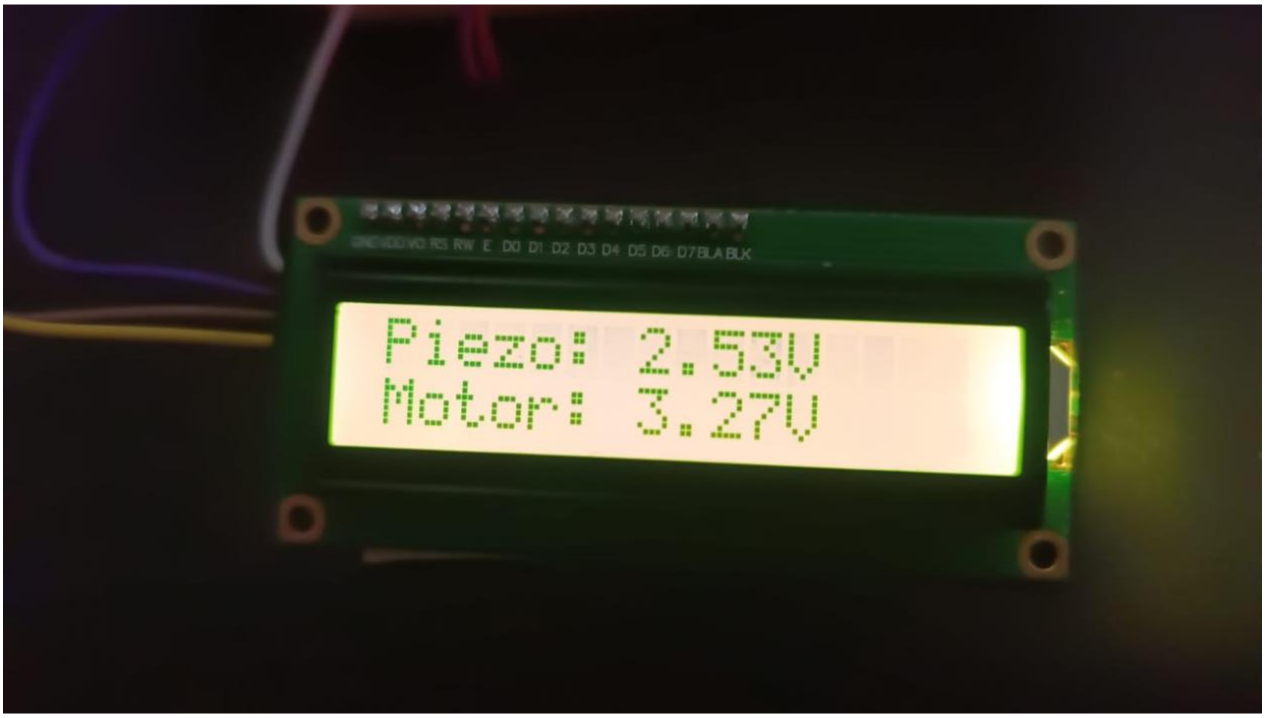
THE PIEZOELECTRIC AND WIND TURBINE STREET LIGHT GENERATION



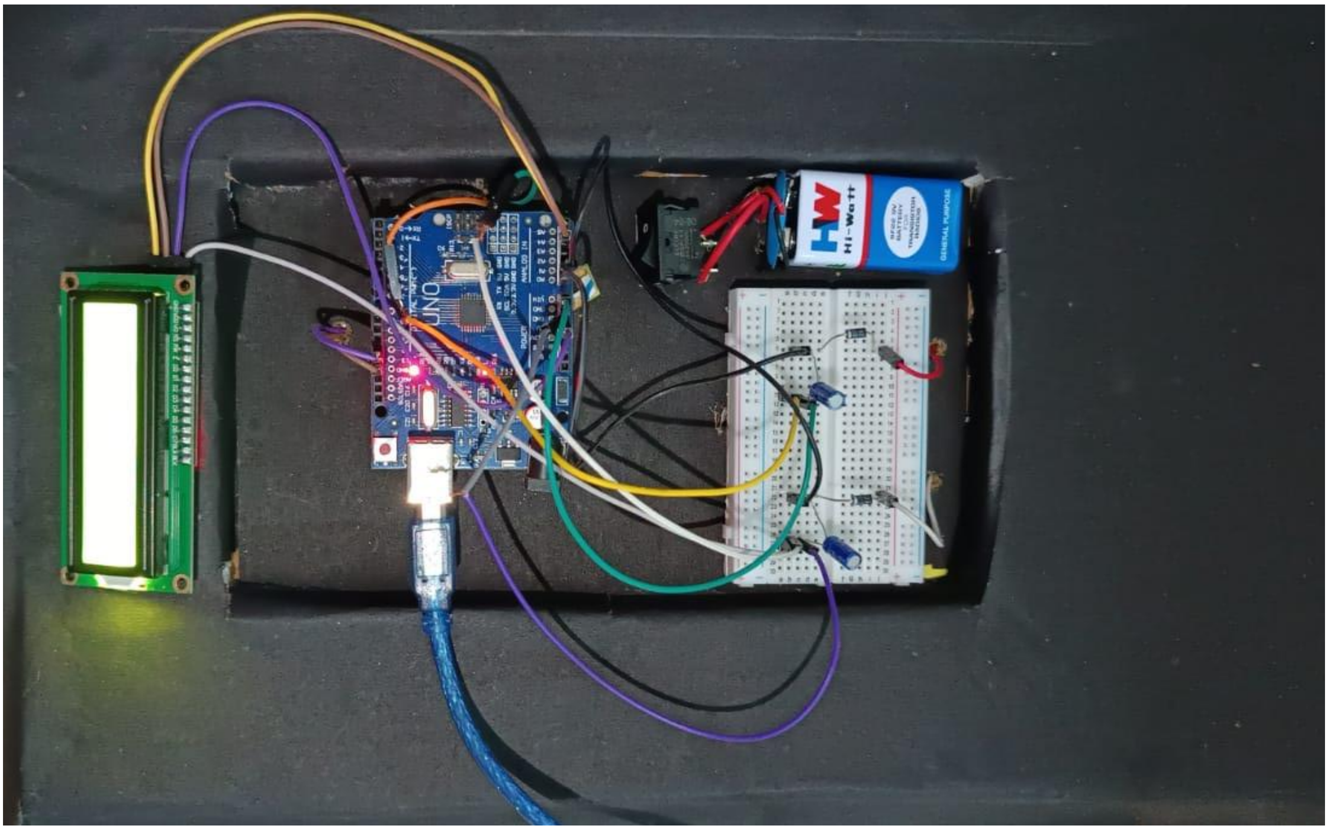
ARDUINO UNO BOARD AND ITS CONNECTIONS



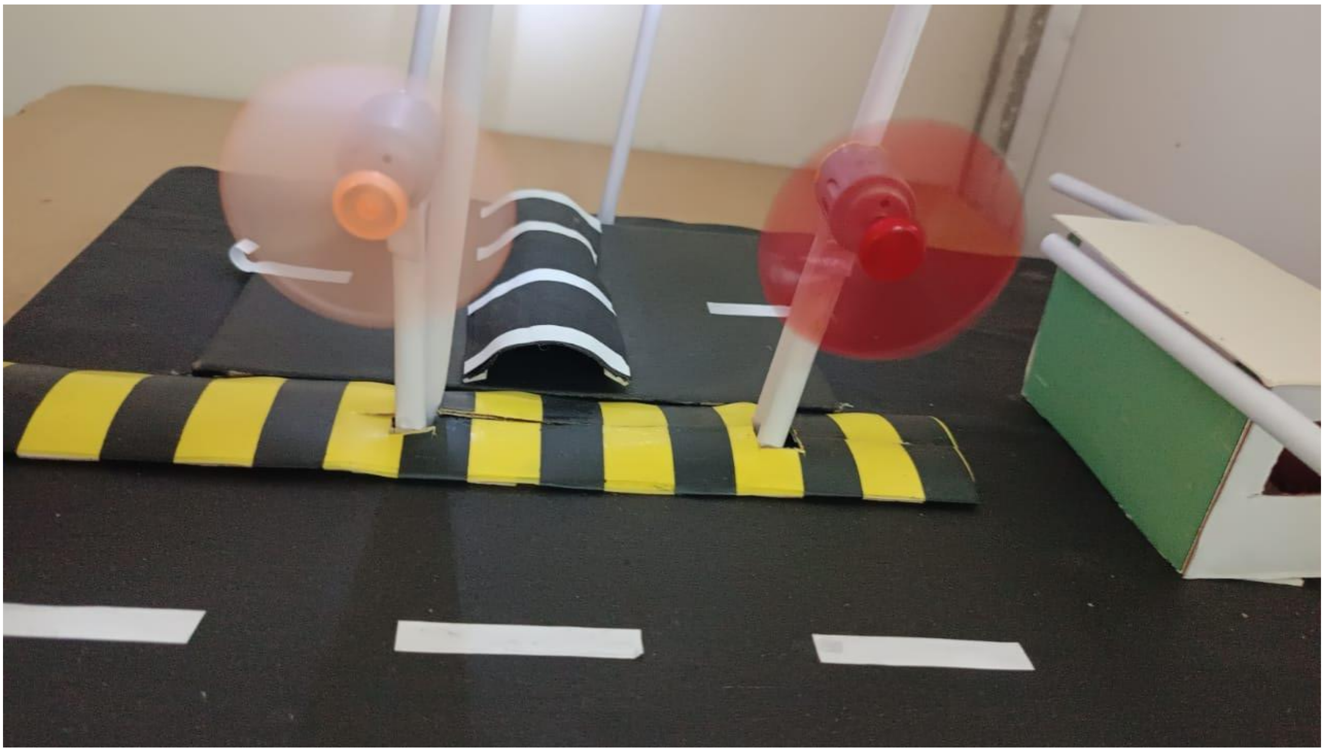
BREAD BOARD AND BATTERIES



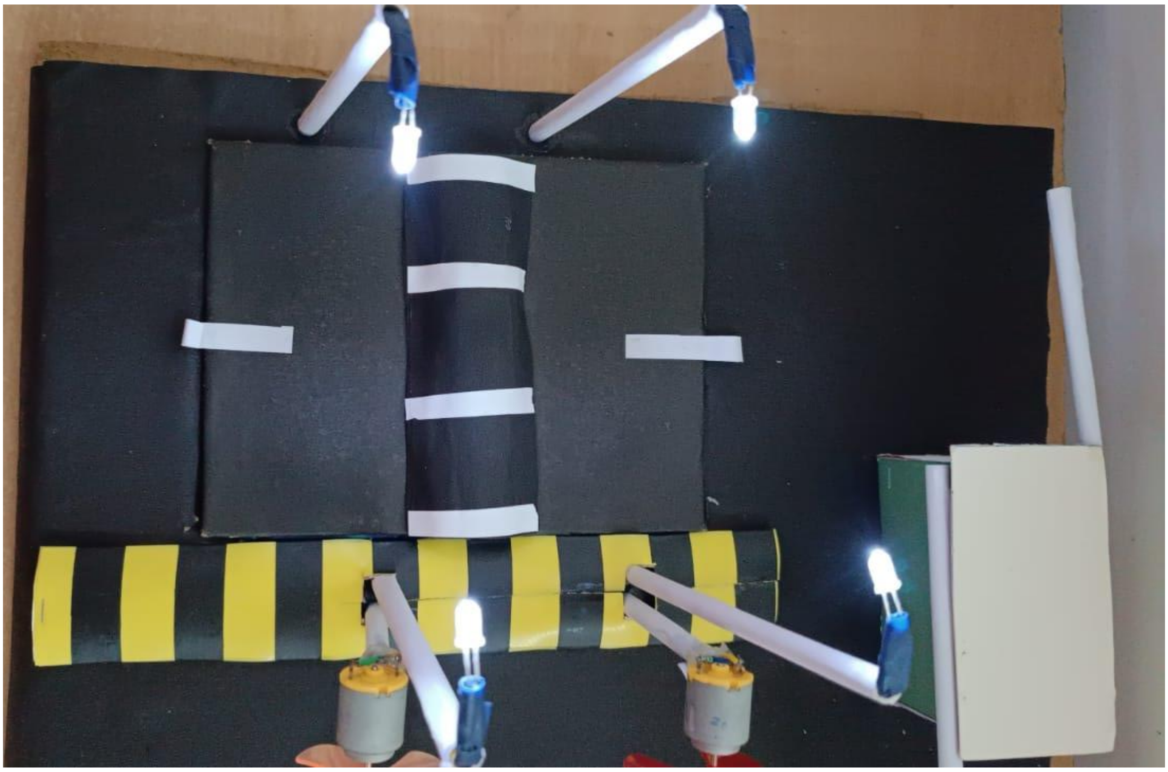
THE LCD DISPLAY WHICH SHOWS THE READING FROM PIEZO SENSORS AND WIND TURBINES



THE COMPLETE CONNECTION SETUP

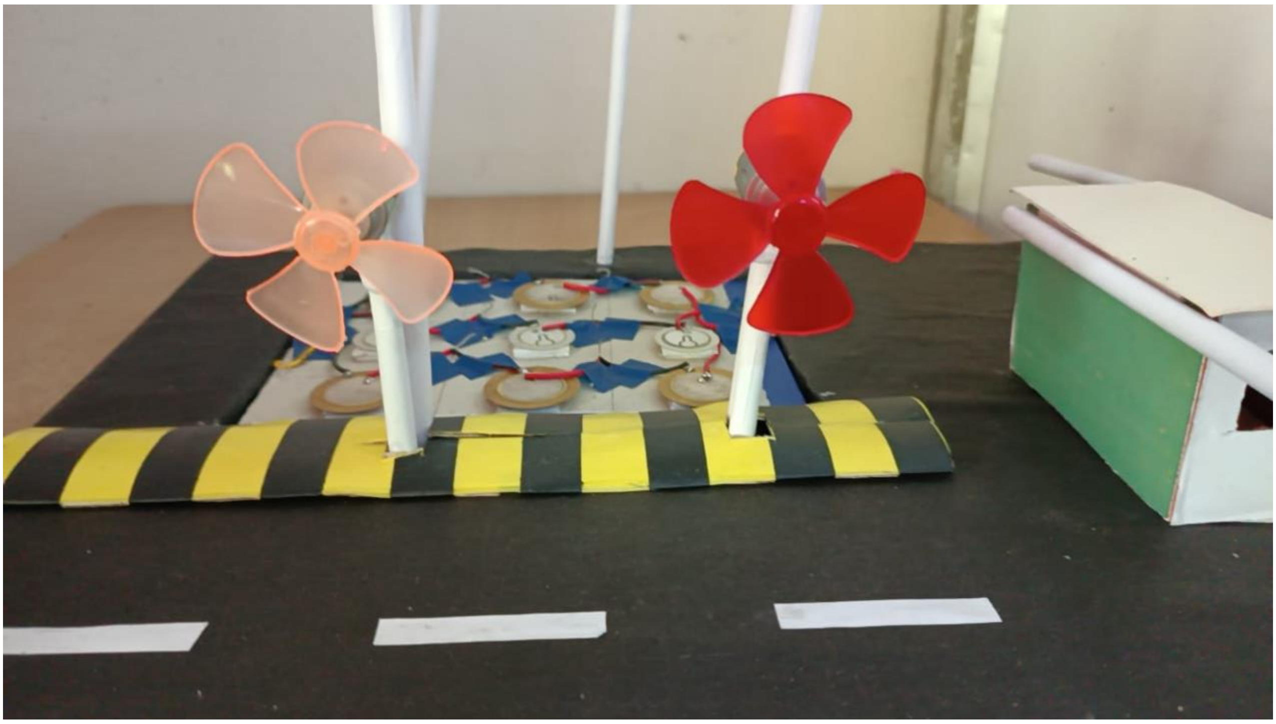


WIND TURBINES ATTACHED ON STREET LIGHTS IN ROAD

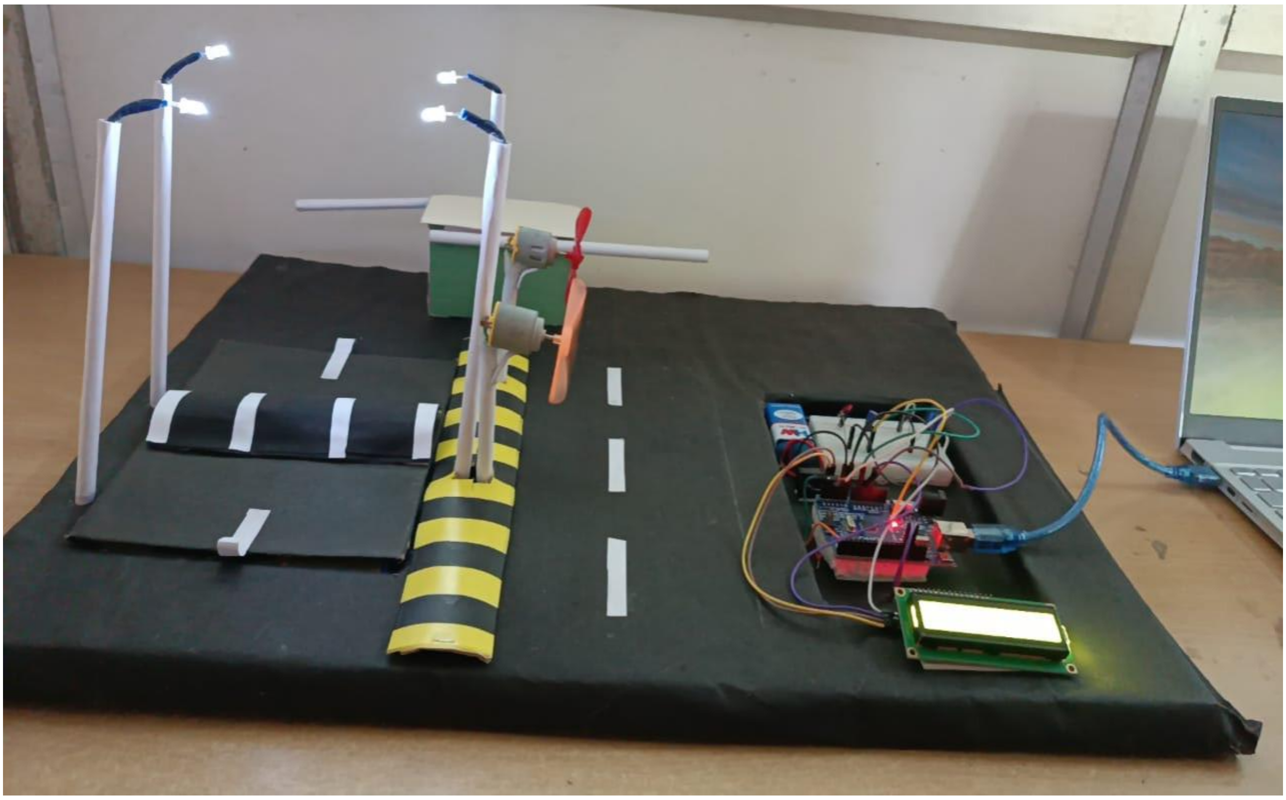


THE ROAD WITH STREET LIGHTS POWERED BY PIEZO SENSORS AND WIND TURBINES

PIEZO-ELECTRIC SENSORS INSIDE THE ROAD



WIND TURBINES



PROJECT KIT

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