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Harvesting Energy from Roadways for Smart and Sustainable Cities

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ABSTRACT

Industry, modernization, and urbanization started in the 21st century. At present, we live lavishly with everything automated and machine-driven. Cars and expensive vehicles use more gas. A.C. and other features are energy intensive. Road cars waste energy by vibration, heat, etc. There are various ways to harness waste and renewable energy. In this work, harvesting energy through solar energy, geothermal energy, piezoelectric technology, thermoelectric generators and wind energy installation on the roadside and their cost comparison analysis have been analysed. Furthermore, the air density, wind velocity and power output from wind turbines are analyzed in major cities of India (Like Chennai, Erode, Coimbatore, Bangalore, Mumbai and Delhi). For analysis, a 200 W wind turbine is considered, and it develops a maximum power output of 3.47 W in Bangalore and Coimbatore cities and a low power output of 3 W in Mumbai when the cross-sectional area of the turbine is 1 m^2. The results indicate huge potential for developing harvesting energy on the roadside through different energy sources.

1. INTRODUCTION

The Indian Road network has 58,97,671 km, including 1,32,500 km of national highways/expressways, 1,56,694 km of state highways, and 56,08,477 km of other roads. National, state, and urban roads comprise 2%, 3%, and 10%. India produces 26 million automobiles. As traffic increases, energy-harvesting devices should be used to extract energy with suitable technology [1]. Urbanization and population growth make cities economic and residential hubs. Urbanization increases transportation demand, generating traffic, lengthier commutes, and environmental damage. Cities need sustainable transport infrastructure to maintain productivity and quality of life. Conventional travel causes air pollution and climate change owing to car emissions. Sustainable transport infrastructure reduces carbon footprints, uses renewable energy, and encourages eco-friendly conduct. Protecting the world and its inhabitants requires addressing these environmental concerns. Traditional transport systems waste energy and materials. Sustainable transport infrastructure saves energy with nanotechnology and energy harvesting. These gadgets recycle solar and automobile energy to conserve resources and encourage a circular economy.

In India, street lighting accounts for 18–20% of the energy bill, thus it needs attention. Piezoelectricity from road cars generates electricity. More people drive during the day than at night. Roads with piezoelectric generators convert car pressure into power. The majority of cars travel asphalt commercial routes. Based on assumptions, cars, bikes, and other vehicles create more electricity. It can resist heavy vehicle loads, which generates more electricity. Batteries power roadside lights and advertisements [2, 3]. The pavement-buried piezoelectric energy harvester generates city power and mountainous traffic safety early warning. Power generation and long-term performance depend on how well the energy harvester fits the pavement structure. Thus, the energy harvester is studied for its suitability to various transportation applications. Power pavement technology uses energy harvesters buried in pavement to convert road mechanical vibration energy to electricity. It has better controllability, easier construction, and less road surface cracking than the special power device application.

Pavement energy harvester output voltage and power grow linearly with load. The actual implementation gave heavy load portions additional power. Energy harvester for pavement power production depends on road construction integrity, ruts, and other parameters. Pavement energy harvesters' voltage and power increased with heat. Energy harvester for pavement works well at low and high temperatures, thus it may be used in intermediate temps. The findings will boost road engineering piezoelectric energy harvesters [4]. This study discusses Indian city road pavement power-generating energy harvesting devices, analysis of wind turbine energy and power in Chennai, Erode, Coimbatore, Bangalore, Mumbai, and Delhi.

2. ENERGY HARVESTING

Road pavement energy harvesting research has focused on the following:

1. Piezoelectric technology
2. Photovoltaic technology
3. Thermoelectric technology
4. Geothermal energy
5. Wind energy

2.1 Piezoelectric technology

Piezoelectric pavement materials can convert tyre-road mechanical energy into electricity. Piezoelectric crystals generate electricity when squeezed or vibrated. Voltage causes extraordinary stress. Heated, stressed, or illuminated solid-state piezoelectric materials generate electricity. Both thermoelectric and photovoltaic materials generate electricity from heat and light. The stress in piezoelectric materials generates electricity. These semiconductors are Silicon (Si) or Germanium (Ge) plus other elements, like traditional electronics. Piezoelectrics are crucial because they capture vibration energy from people, industry, and autos. The energy of movement is everywhere, so simply capturing it can boost efficiency and clean energy.

2.2 Photovoltaic technology

Solar panels can power paved roadways instead of asphalt and concrete. Solar energy scavenging is old. Modern solar energy harvesting uses PV panels. Aviation, transportation, and others use PV panels. PV panels generate power cost-effectively when space is available, supplying some of the grid's electricity. PV panel adaptation to driving conditions is difficult and requires extensive research when pavement is the only installation space.

N- and P-type semiconductors are used in PV cells. P-type semiconductors are positively charged by solar radiation, while N-type semiconductors are negatively charged. PV panel driving surfaces need to be carefully designed and chosen in terms of material. Polycrystalline silicon, dye-sensitized, thin-film, organic thin-film, and monocrystalline silicon cells are examples of common PV materials. Energy production was highest in monocrystalline silicon cells. They should not shade PV surfaces due to their internal structure and arrangement, as cell shadowing lowers performance.

Additionally, transparent PV panels' support and structure matter. PV cell surfaces need vehicle-resistant frames. Limited structural materials include steel, aluminium, and FRP. Automotive braking demands coarse PV panel surfaces, which reduces transparency. Polycarbonate, tempered glass, and acrylic can be textured for the clear surface layer if they remain transparent. Despite having higher compressive strength than concrete, these materials may not be strong enough to withstand traffic and environmental strain. Traffic tensile loads also attack panel support system strength. Think about waterproofness and flexibility under different foundations. In order to keep drivers from hydroplaning, there should be enough cross-slope to quickly remove water from driving surfaces.

PV systems and roadways with solar panels are depicted in Figure 1. Figure 1(a) shows solar roadways products. Colas built a "solar road" near Tourouvre, France, to demonstrate solar roads' power generation potential (Figure 1(b)). Multiple solar PV panels are connected in series or parallel for voltage or current. PV pavement was 11–15°C cooler than asphalt, researchers found [5].

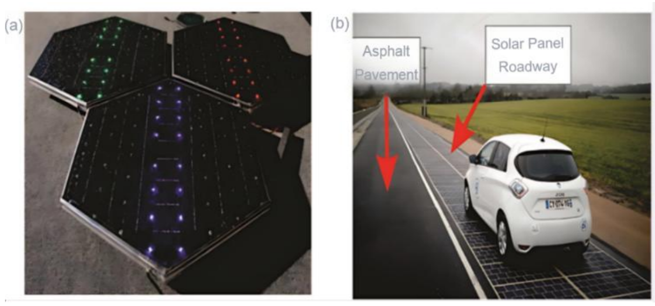

Figure 1. (a) Nussbaum highway solar panel with LEDs in the daytime, (b) France's first solar-powered road [5]

2.3 Geothermal energy

Geothermal heat pumps (GSHPs) and subsurface thermal energy storage devices can generate power and deice from pavement geothermal energy. GSHPs heat or cool the ground using low-temperature energy, making them an energy-efficient and clean pavement heating solution [6].

2.4 Wind energy

The optimal energy supply always rises with transport demand. Conservatism predicts wind energy will offset transport power costs. Non-fossil transporters can use aerodynamic losses as a sustainable energy source. Energy loss from machine efficiency should improve transport system balance [7]. Effects include wind turbines' massive size, high cost, and large inclined blade rotating radius. Most nations capture wind energy from hills and oceans. Today's wind turbine designers are innovative. Vehicles that move quickly were researched. Peak air velocity. Airspeed that generates power. Currently, wind turbines cannot totally control vehicle airflow. Air velocity is maximized. Design has special features. Any velocity with curved blades increases capturing.

Self-powered tunnel WSN node system. Figure 2 shows tunnel WSN nodes self-powered system concepts. The electromagnetic, piezoelectric, and power producing energy storage modules make up the self-powered system. Energy comes from natural wind and piston-effect wind in the tunnel. Subway tunnels have slower natural airflow when no subway passes through. When a tube travels through the tunnel, the piston effect increases wind speed. S-type rotor wind wheels may absorb wind energy from numerous directions and transform it into kinetic energy for the motor and cam via the gearbox shaft [8, 9].

- **Ultra-high-performance concrete overlays**

Concrete overlays can be laid using standard concrete pavement methods to enhance and extend pavement life. Ultra-high-performance concrete (UHPC) or UHPFRC has a fiber-reinforced dense granular matrix (DSP). Ultra-high compressive strength, impermeability, drying shrinkage, post-cracking tensile capacity, and early strength make UHPC a durable and mechanically strong material that can shorten traffic closure time.

- **Smart and multifunctional pavement**

The Internet of Things (IoT), which refers to "embedded devices (things) with Internet connectivity, allowing them to interact with each other, services, and people on a global scale," is one of the cutting-edge computing technologies that many nations are investigating as a way to enhance conventional pavement systems [10].

- **Reflective coating**

The functional coating substance that is applied to the surface of asphalt pavement is referred to as "reflecting coating." It can reflect solar radiation in the near-infrared (0.7–2.5 µm) and visible (0.4–0.7 µm) bands. Long waves (2–15 µm) are then reflected to the outside from the absorbed heat energy, lowering the pavement's temperature and preventing the coating surface temperature from rising.

- **Regional climate**

The pavement surface temperature is often greater than the bottom layer during the day in a hot region, while the opposite is true in a cold climate. Numerous applications employ this temperature gradient to generate power or for other reasons, such as deicing. When the road surface has the capacity to cool, the urban heat island (UHI) impact can be lessened, which is another benefit of heat harvesting from the pavement in hot climates. In addition, lowering the asphalt surface's operating temperature can enhance its resistance to rutting and cracking. Rutting on pavement can happen in hot climates because bitumen softens in warmer weather, which causes the aggregate on the pavement to migrate a little.

On cloudy days, it was lowered to 4,738 Wh, while on wet days, it was able to reach 2,419 Wh. The average daily global radiation during the dry season (January–July) was also found to be higher than during the rainy season (August–December), based on Malaysia's climate. Malaysia is among the nations that experience a wet climate. The relatively high humidity and temperature in Malaysia are characteristics of its climate [11, 12].

- **Traffic load**

The impact of field-simulated factors on electric power generation, including traffic load and speed. Their findings demonstrate that the location and magnitude of the piezoelectric sensor alter the stresses applied, resulting in changes in the output power generated. Roadside power supply facilities, for instance, can be utilized for traffic information sensing systems, power supplies that don't require cable installation, power supplies for cars, and power supplies for road conditions. Additionally, the road may sustain less damage if the piezoelectric conversion device is able to transform a portion of the vibration energy into electrical energy.

In order to examine the road's dynamic behavior under traffic loads, a number of laboratory tests were also carried out. The connection between experimental findings and numerical computation was then explained. Additionally, the impact of excitation load, excitation frequency, and asphalt layer thickness on the dynamic response of the elastic double-layer plate lying on the road base was examined. It encompasses piezoelectric energy harvesting, the road base's peak acceleration, and the displacement of the elastic double-layer plate [13]. The technology, advantage and drawbacks of different energy harvesting system comparison is shown in Table 1 [14].

2.5 Thermoelectric technology

Road surface thermal energy can be transformed into power by thermoelectric generators (TEGs) inside or outside pavement. Pavement energy collecting systems are not widely used due to technical issues [8]. This was used to design a unique road thermoelectric generator system (RTEGS) that generates energy when road surface and ambient air temperatures vary.

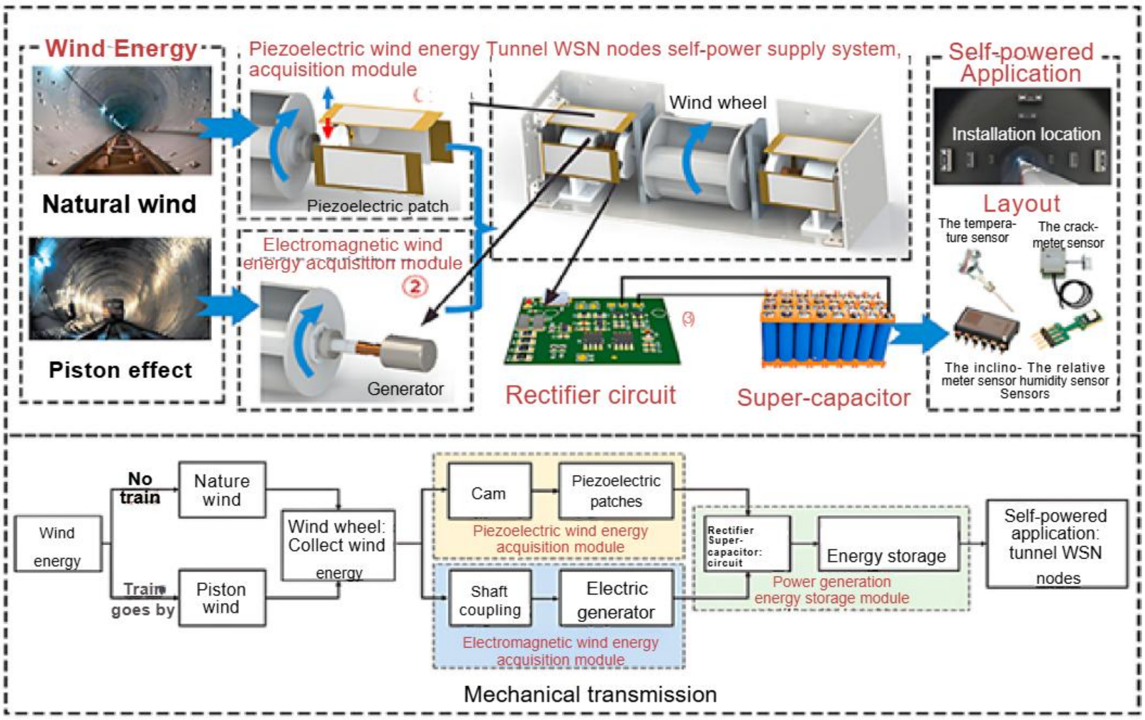

Figure 2. Self-powered tunnel WSN nodes [9]

Table 1. Comparative analysis of different energy harvesting methods [11-14]

Methods	Techniques	Advantages	Limitations
Solar energy	Sunlight is converted into electricity via PV panels or solar mirrors.	Effective, widely used, and capable of producing significant amounts of electricity.	It is less useful in low-light or nighttime areas.
Wind energy	Wind rotates blades, running a generator and generating clean electricity.	The most stable nonconventional energy sources, with 40% efficiency notably.	Compared to less efficient and socially costly onshore windmills, installation and maintenance are expensive.
Thermal energy	A system's temperature is controlled by thermal energy.	Low-power applications benefit from thermal energy collecting from industry or humans.	Low conversion efficiency (5–8%).
Piezoelectric energy	Piezoelectric materials convert mechanical strain and vibration into electricity.	Piezoelectric generators with 2.2% efficiency scavenge small-scale energy from vibrations and mechanical stresses.	Material development is improving durability and efficacy.

3. METHODOLOGY

People move on roads and other civic infrastructure. Traditionally, roads load traffic. Mechanical vibration and temperature differences in roadway and bridge pavement layers are caused by vehicle loads and solar radiation. Electromagnetic or piezoelectric materials convert mechanical energy into electricity using magnetic or strain fields. Solar energy is harvested by photovoltaics, heat flux, and thermoelectric fields. Roadways waste energy that can be reused. Figure 3 shows all roadside energy harvestings.

The energy harvesting system includes a generator, circuit, and storage device. Once ambient energy becomes electrical energy, a circuit raises and regulates voltage. Supercapacitors or rechargeable batteries store energy. The harvesting technique considerably affects energy generation. Some energy can heat road surfaces or bridge decks for anti-icing, illumination, or traffic devices.

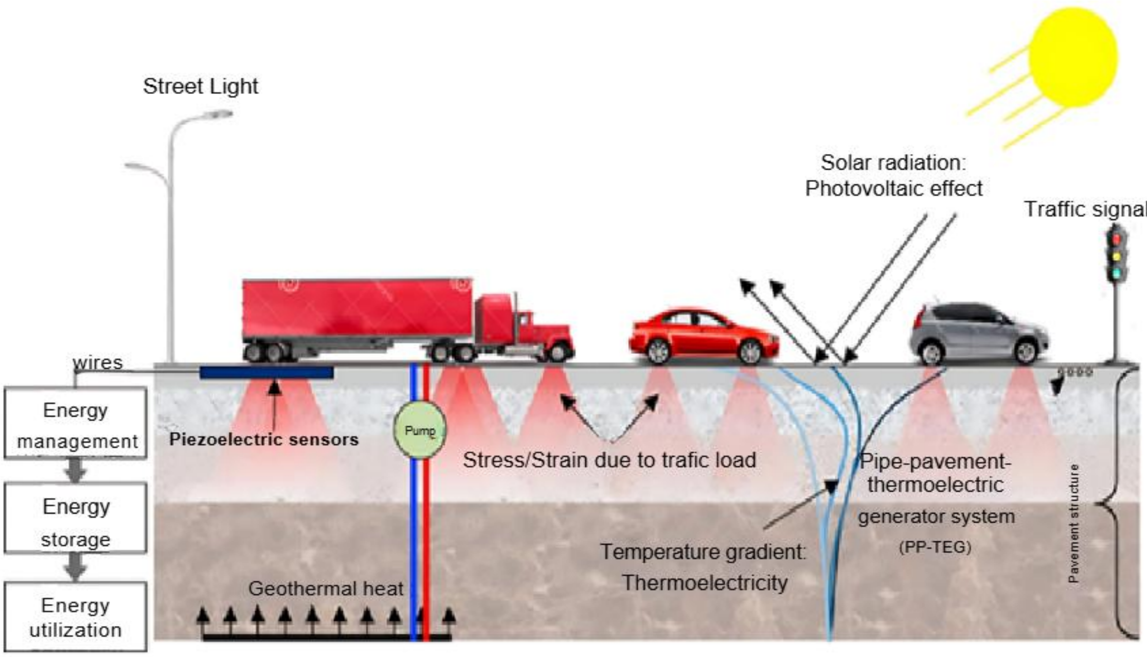

Figure 3. Roadway energy harvesters [15]

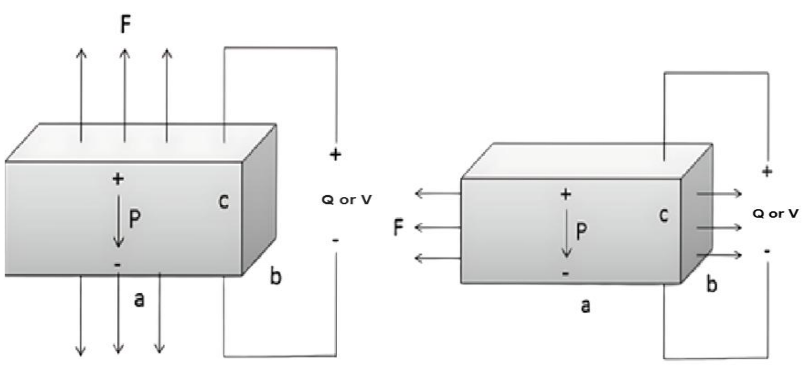

Figure 4. The piezoelectric energy harvesting [16]

Modern society relies on cars for convenience and flexibility. Cars lose millions of joules of mechanical energy. Road and highway traffic is much higher during the day than at night. Using piezoelectric generators in highways to generate power from car pressure. Even heavy cars can be converted into electric power. Roadside streetlights and advertising boards use batteries.

Electro mechanical coupling coefficient = $K^2 = \frac{Stored\ electrical\ energy}{Input\ mechanical\ energy}$

From electrical input to mechanical output:

$$K2 = \frac{Stored\ mechanical\ energy}{Input\ electrical\ energy} \tag{1}$$

In terms of material properties [17],

$$\text{Coupling coefficient} = K_{ij}^2 = \frac{d_{ij}^2}{\epsilon_{ii}^X S_{jj}^E} \tag{2}$$

d_{ij} = Piezoelectric strain coefficient
ϵ_{ii}^X = Permittivity at constant stress
S_{jj}^E = Mechanical compliance of the material

$$\text{Energy harvesting Figure of Merit } (FOM) = FOM_{ij}^X = \frac{d_{ij}^2}{\epsilon_{ii}^X} \tag{3}$$

Input mechanical energy = $U_{mech,in} = \frac{1}{2}xX$, where, x= Strain, X = stress.

$$\text{Output mechanical energy} = U_{elec,stored} = K^2 U_{mech,in} \tag{4}$$

$$U_{mech,stored} = (1 - K^2)U_{mech,in}$$

- **Energy stored in capacitor**

$$U_{elec,stored} = \frac{1}{2}CV^2$$

Formulate piezoelectric device voltage under mechanical load. By integrating the piezo-electric elements' theoretical values and inserting them in the equation's variables, we predicted a 15.422 V terminal potential difference for 60 kg elements. The piezoelectric's distortion maximises reading. The performance of 11.5–13.9 Volt elements depends on several parameters [17-20].

Table 2. Vehicle device loads [21]

Vehicle Type	Vehicle Load
Motor bike	87 kg–170 kg
Public car	1000 kg–2500 kg
Mobil bus	3500 kg–15000 kg
Truck	12000 kg–40000 kg
Bicycles	5 kg–20 kg
Rickshaw	100 kg–120 kg
Special vehicle	100 kg–40000 kg

The vehicle device loads have been analyzed with the parameters provided in Table 2. Statistics and polynomial average road load character of passing cars calculate the load trend. The average car goes 18,728 km and uses 2514 L. Regular petrol has 3.478 107 J/L. At 15% tyre energy loss, US cars waste 3:478 107 J=L 2514 L 253; 639; 386 15% 2:218 1016 kJ the energy collecting environment will benefit from a new energy technology. Application-specific piezoelectric materials are used [22]. Many energy harvesters use piezoceramic lead zirconate titanate (PZT). Low strain endurance and limited application characterize this delicate material. Flexible PVDF can tolerate significant strains. Several piezoelectric energy harvesters with different conversion techniques have been shown. The 170 lm 260 lm beam-shaped energy harvester produces 1 lW.

To enhance production, the carrier vibrates at resonance. Stress along the material's polarization under 33-mode increases the harvester's energy productivity linearly. Anton and Sodano's 31- and 33-mode methods are shown in Figure 4. A piezoelectric energy harvester (PEH) was created to capture the massive energy lost by public roadway vehicles. Moving automobiles strain pavement, which the PEH turns into electricity. Parallel piezoceramic discs have the same voltage.

3.1 Energy harvested by the wind turbine

Empirically derived exponent depends on atmospheric stability. A common wind resource assessment coefficient is 1/7 or 0.143. Wind power varies with speed and location. The following equation estimates wind power,

$$P = \frac{1}{2} C_p \rho A V_w^3 \tag{5}$$

C_p = Betz limit = 0.593
ρ = Wind density (kg/m^3)
A = Cross sectional area of the turbine (m^2)
A_w = Wind velocity (m/s)

where, P is the power extracted from wind in Watts, The ratio of power output to wind power. Wind turbines can only convert 59.3% of kinetic energy to mechanical energy to turn a rotor. The theoretical maximum power coefficient for a wind turbine is Betz limit. It's 35%–45% for a good turbine [23, 24]. Wind velocity in the given surface area can be calculated by using the equation [25].

$$\text{Wind velocity } V_w = \sqrt{\frac{2F}{\rho A}} \tag{6}$$

where,
F = Force
ρ = Air density
A = Cross sectional area

- **Energy harvesting by piezoelectric technology**

A hybrid piezoelectric energy harvester with stacked and cantilevered beams was designed by China's Ministry of Transportation and Communications' Highway Research Institute. It was then examined whether it could be buried on the forming road or embedded in the road construction process.

Pavement deformation and vibration waste energy raises the risk of pavement damage. It is possible to gather this wasted energy through piezoelectric energy harvesting. Piezoelectric action is directly used in piezoelectric energy harvesting (Figure 5) [26].

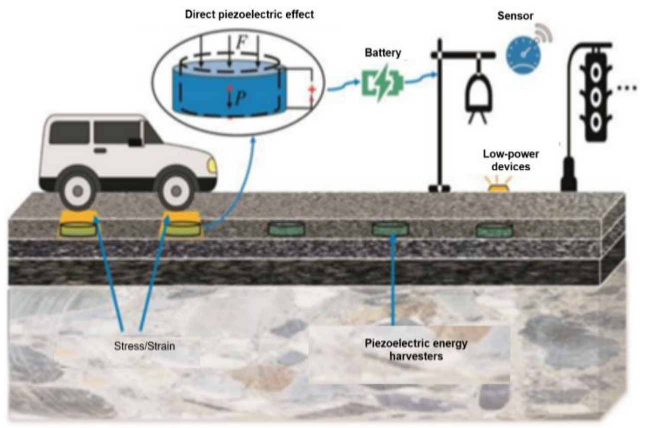

Figure 5. Pavement-mounted piezoelectric energy harvesting device [26]

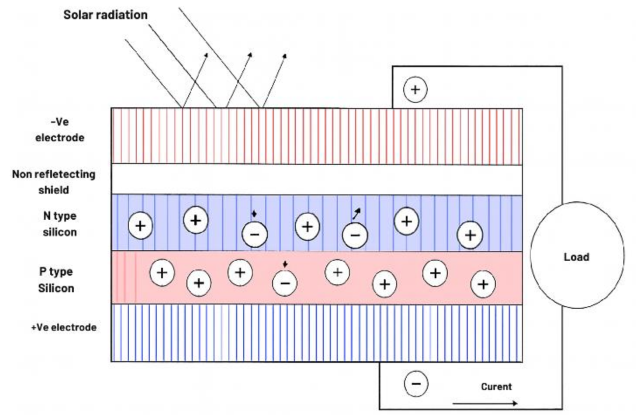

Figure 6. Principle of PV cell [27]

- **Energy harvesting by photovoltaic technology**

PV cells directly convert solar energy into electricity. Each cell contains N- and P-type semiconductor layers. Solar radiation forces free electrons in PV cell semiconducting material layers to flow directionally. Thus, positive electrons will travel toward the P-type semiconductor and negative electrons toward the N-type semiconductor. When coupled to a load, free electrons generate electricity. Figure 6 shows PV cell operation.

PV panels can harvest 100% road-exposed solar energy by theory. Road auxiliary facilities such as the central reserve and noise barriers, tunnel roofs, pavement, road slope, and management and service zones along road lines can all be utilized to harvest solar energy due to their application feasibility and energy production efficiency. The ability of PV cells on an existing road to continuously generate electricity using built-up land resources has drawn the attention of researchers and businesses from all over the world. Field installation of PV cells is challenging. PV cell construction for pavements should consider weatherability, durability, and load-bearing capacity [27].

- **Energy harvesting by Thermoelectric technology**

The voltage output of TEG fluctuates in response to the temperature differential between its hot and cold sides due to the Seebeck effect. Charge carriers allow electrons in N-type materials and holes in P-type materials to move freely through semiconductors and metals. As the diffusion potential and electrostatic repulsion potential get closer to equilibrium, charge carriers move from hot to cold along a temperature gradient, building up as shown in Figure 7. In thermoelectric devices, P and N-type semiconductors alternately become electrically coupled in series and thermally coupled in parallel. As a result, electricity can be produced by the opposite flow of holes and electrons.

The difference in temperature impacts TEG power generating efficiency. Energy increases with temperature gradient. Pavements of varying depths show temperature differences. The pavement's slight temperature gradient limits this discrepancy [28].

- **Energy harvesting by geothermal energy**

In hydronic pavements, a fluid passes through pipes positioned in the top layer to collect heat energy. Heat energy is transferred from the pavement surface to the lower pavement layers by conduction in geothermal pavements using flowing fluids via embedded pipes (Figure 8).

The strength and durability properties of pavement may be negatively impacted by pipe embedding. They should therefore be specifically constructed so as not to negatively impact the structural performance. Traditional pavement maintenance methods, including milling, overlaying, and trenching, may degrade energy harvesting system structural and thermal efficiency. Due to compaction issues, gaps between pipes and pavement construction may limit system efficiency. The energy needed for fluid circulation is another issue [29].

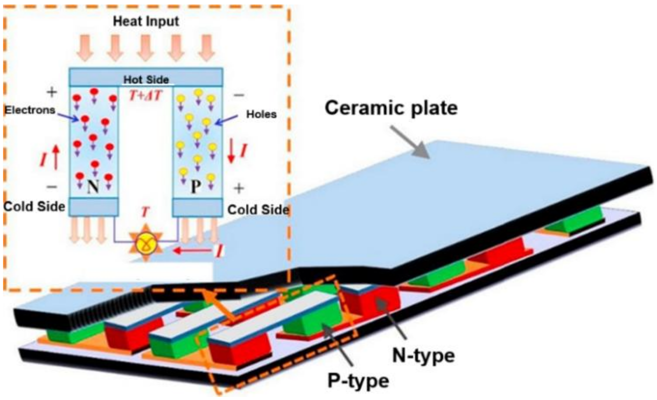

Figure 7. Configuring TEG module [28]

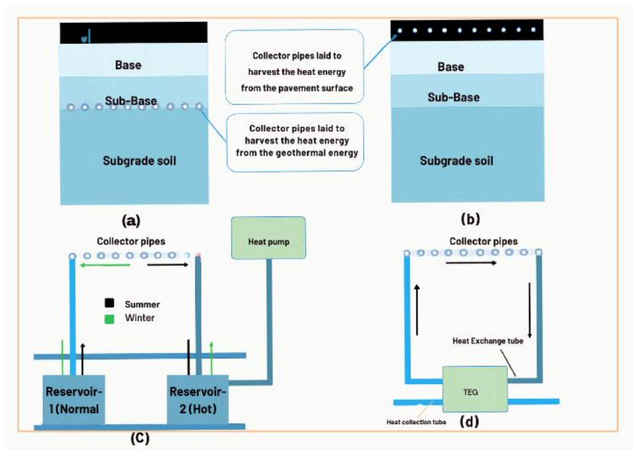

Figure 8. (a) Geothermal pavements, (b) Hydronic pavements, (c) Utilizing the pavements' thermal energy for winter heating, and (d) Utilizing a TEG to convert thermal energy into electrical energy [29]

4. RESULTS AND DISCUSSION

National highways carry fast cars. Aerodynamics increase side and top airspeed. So, we must maximize wind speed with minimal upkeep and expenditure. Horizontal windmill blades angle. Blade angles collect air well in bends. Vessel and blades rotate one way with air velocity. Fits rooftops, bridges, and national highways. The six blades are connected to the main shaft and horizontal axis shaft to the direct current generator. Generation uses electromagnetic induction to transform mechanical energy to electricity. Inverters convert DC to AC. Batteries shop DC. Batteries store road turbine output [30].

Air density in India is seen in Figure 9. Coimbatore and Bangalore have 1.04 and 1.04 kg/m^3 air densities, respectively. Pressurized air densifies. Pressure-induced air molecule collisions increase mass/volume. Increasing height lessens pressure. Mountain climbers breathe less oxygen due to reduced air density. Temperature also affects air density. Heat accelerates up air molecules and spreads them on impact. Heavy air pulls things. On hot summer days, golf balls fly farther than on cold days. High heights have decreased air density due to higher temperatures and pressure. Air density depends on humidity. Humidity lowers air density.

Figure 10 shows Indian city winds. It shows Bangalore and Coimbatore had the strongest winds that day. When wind power, surface area, and air density are constant, Mumbai has reduced wind speed. Each place's wind speed changes naturally and owing to industrial growth. Extreme value dispersion of structural part and system load and strength parameters is necessary for reliable component and structure design analysis. All regions should have gust wind speed data for structure design using severe wind speeds for several years. Wind load evaluation on wind sensitive buildings requires regional design foundation wind speed with a return interval [30].

Figure 11 shows the Indian city wind velocity and turbine power output. Coimbatore and Bangalore generate the most power that day. Under steady conditions, Mumbai produces less power. Naturally, wind speed differs everywhere. Initial energy generation maps reveal site potential. Power density maps only use wind speed to estimate wind potential. Energy generating maps with advanced technologies offer possibilities in some locations, but no potential density maps. In both circumstances, potential density generates energy. No energy generation maps exist for wind turbine capacity and hub height, although there are wind power density maps at various heights. The initial investment, maintenance and life span and scalability of various energy harvesting sources are mentioned in Table 3 [26].

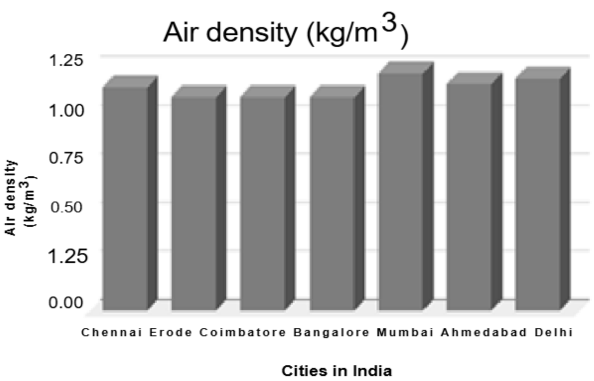

Figure 9. Air density values for different cities in India

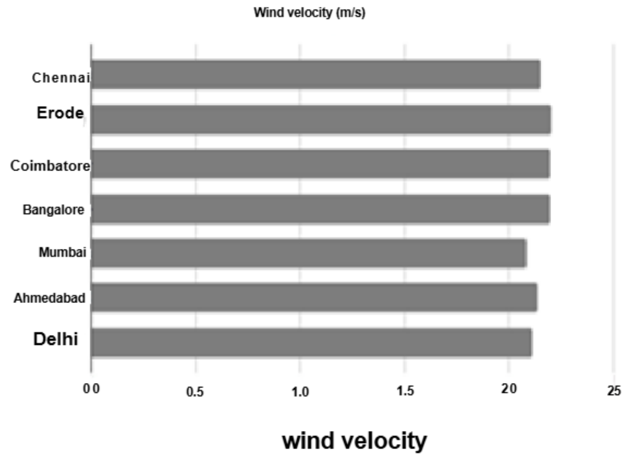

Figure 10. Wind velocity values for different cities in India

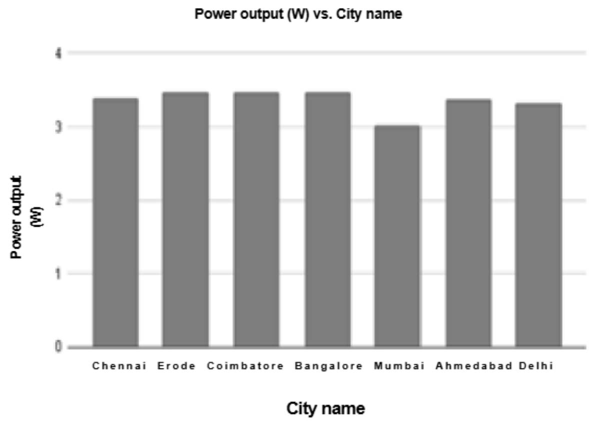

Figure 11. Power output from wind turbine for different cities in India

Table 3. Cost benefit analysis [26]

Technique	Initial Investment	Maintenance and Lifespan	Scalability
Solar Energy	High	Low (20–30 years)	High
Piezoelectric	Moderate to High	Moderate (5–10 years)	Moderate
Wind Energy	Moderate to High	Moderate (15–25 years)	Moderate to High
Thermal (Heat) Energy	Moderate	Low to Moderate (20+ years)	Moderate
Geothermal Energy	Very High	Moderate (30+ years)	Low

5. CONCLUSION

This study reviews different types of road energy-harvesting systems and power output from wind turbine. This work covers piezoelectric, thermoelectric, solar, and wind turbine energy harvesting. The outcome of this analysis as follows:

(1) Energy harvesting technique can guarantee energy security for modern energy problems.

(2) For energy resource issues, wind energy was explored and power output was theoretically evaluated in Chennai, Erode, Coimbatore, Bangalore, Mumbai, and Delhi. Other cities generate less wind energy than Bengaluru and

Coimbatore.

(3) For analysis, a 200 W wind turbine produces 3.47 W in Bangalore and Coimbatore and 3 W in Mumbai when its cross-sectional area is 1 m^2.

In the future, research should increase mechanical efficiency and maintenance to construct more sustainable infrastructures. Energy storage is a big challenge for lower devices and their energy conversions.

AUTHOR CONTRIBUTIONS

Shantamallappa Kadaganchi proposed the core idea, guided the study design, and supervised the research. Paresh Nasikkar contributed to the literature review, supported methodology development, and assisted in drafting. Uma Maheswari Viswanadhula led the experimental and data analysis components and supported technical interpretation. Sailaja Vemuri carried out simulations, modeling, and performance evaluation. Sai Prashanth Mallellu coordinated manuscript preparation, integrated author inputs, and finalized editing and formatting.

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