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MULTI-SOURCE ENERGY-POWERED ELECTRIC VEHICLE INTEGRATING SOLAR ENERGY, WIND ENERGY, AND GRID ELECTRICITY

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ABSTRACT

In the tracking of sustainable transportation solutions, this article puts forward the development of a multi-source energy-powered electric vehicle that integrates solar energy, wind energy, and grid electricity to charge a consolidated battery system. The vehicle is designed to bring down dependency on fossil fuels and build up energy accessibility in both urban and remote settings. The system harnesses solar power through high-efficiency photovoltaic panels mounted on the body of the vehicle. It supplements the vehicle with wind energy via a compact vertical-axis wind turbine. The turbine is mainly productive while the vehicle is in motion or parked in windy environments. A grid charging system is embodied as a fallback to ensure uninterrupted performance of the vehicle in low renewable input conditions. A smart energy management system dynamically monitors and prioritizes energy inputs based on real-time availability and battery status. This energy management system is based on a microcontroller platform. Electric power is stored in a Li-Fe-PO_4 battery pack and delivered to a Brushless DC motor. This motor propels the vehicle. The integrated design provides flexible, clean, and efficient energy utilization. It brings down the carbon footprint and demonstrates the viability of multi-source hybrid energy systems for future electric mobility. The article contributes to green innovation by blending energy engineering, embedded systems, and sustainable transport design. Solar and wind energy cannot fully charge the battery alone, but they can significantly support and extend the energy capacity, and as a result, bring down dependence on grid charging. The multi-source energy-powered electric vehicle can be operated efficiently in real-world conditions, mainly for light-duty or urban travel by utilizing a well-designed system and good energy management. It utilizes solar, wind, and electric grid power, and hence, it presents an innovative approach to sustainable transportation.
Keywords: Energy management system, Li-Fe-PO_4 battery pack, solar, wind, electric grid power and multi-source energy-powered electric vehicle.

1. INTRODUCTION

The rapid rise in environmental concerns, urban air pollution, and fossil fuel depletion has stepped up the global shift toward sustainable and low-emission transportation systems. Electric vehicles have come out as a promising solution among the within-reach alternatives, due to their zero tailpipe emissions, lower operational costs, and increasing efficiency [1]. However, conventional electric vehicles count on grid-based charging infrastructure. This infrastructure is usually fueled by non-renewable sources. These sources are not universally accessible, mainly in rural or remote areas. This dependency hands out both logistical and environmental challenges that slow down the widespread adoption of electric vehicles. This article puts forward the development of a multi-source energy-powered electric vehicle that combines solar energy, wind energy, and grid electricity as charging inputs to address the mentioned limitations. It becomes possible to create a semi-autonomous energy system that can operate with reduced reliance on centralized charging infrastructure by integrating renewable energy harvesting systems directly into the vehicle architecture [2]. This hybrid energy approach builds up sustainability, range flexibility, and energy resilience. The suggested system utilizes high-efficiency monocrystalline photovoltaic panels to harness solar irradiance and convert it into practical direct current electrical power [3]. In parallel, a compact vertical-axis wind turbine is taken on to exploit kinetic wind energy, mainly during the motion of the vehicle or while it is stationary in windy conditions [4]. Both sources charge a 48V lithium iron phosphate (Li-Fe-PO_4) battery bank through independent charge controllers (Maximum Power Point Tracking for solar and dump-load protected for wind). In low or no renewable input conditions, an onboard alternating current-direct current charger enables direct connection to the grid as a fallback mechanism [5]. A central component of the system is the multi-source energy-powered electric vehicle. This multi-source energy-powered electric vehicle intelligently monitors and heads up energy inputs, storage, and consumption using a microcontroller (e.g., ESP32) [6].

It continuously checks out the state-of-charge, environmental inputs (solar irradiance and wind speed), and vehicle load demands to dynamically line up charging sources. The energy stored in the battery is then used to run a Brushless direct current motor. This motor lays out the mechanical propulsion for the vehicle [7]. This paper aims not only to bring down the carbon footprint of electric vehicles but also to demonstrate the credibility of a distributed, self-sustaining energy model for electric transportation. This design is mainly admissible for implementation in rural, underdeveloped, or disaster-affected regions where grid power is unavailable. The hybrid charging model boosts vehicle independence, energy availability, and operational flexibility, and hence, promotes the use of clean and renewable energy technologies.

2. OBJECTIVES

The article aims to design and carry out a sustainable electric vehicle system capable of harvesting and utilizing multiple renewable energy sources (i.e., solar energy and wind energy), while keeping compatibility with traditional grid charging. The system is built with the objective of bringing down fossil fuel dependency and building up energy accessibility, mainly in off-grid or remote regions. The following are the primary objectives of the article.

i. The article aims to develop a hybrid energy-powered electric vehicle that utilizes solar photovoltaic, wind turbine, and grid-based electricity for charging its battery system.

ii. It aims to design an intelligent energy management system capable of dynamically monitoring and prioritizing power input sources based on environmental conditions and battery state-of-charge.

iii. It ensures reliable, safe, and efficient battery charging by integrating MPPT (Maximum Power Point Tracking) solar charge controllers, wind turbine controllers with dump load protection, and alternating current grid chargers.

iv. It puts up a prototype that demonstrates real-world functionality, mainly focusing on low-speed, light-duty transport (e.g., campus vehicle, delivery cart, or urban commuter).

v. It validates the energy contribution and performance of each power source through experimental data and system testing.

The following are the secondary objectives of the article.

i. The aim of the article is to bring down the vehicle energy loss by using lightweight materials and efficient drivetrain components.

ii. It aims to optimize renewable energy harvesting efficiency, making use of flexible, space-efficient solar panels and compact wind turbines.

iii. It carries out a user interface for real-time monitoring of system parameters (i.e., voltage, current, SOC, power flow).

iv. It aims to aid the application of decentralized renewable energy systems in transportation.

3. LITERATURE REVIEW

There has been remarkable research and development in the field of electric vehicles and renewable energy integration in the previous two decades. There are conventional electric vehicles that primarily count on grid electricity for battery charging. This battery charging is sourced from fossil-fuel-based power plants. Due to the limited environmental benefits of conventional electric vehicles, numerous studies have investigated the integration of renewable energy systems (i.e., solar photovoltaic energy and wind energy) into electric mobility frameworks.

3.1 Solar-Powered Vehicles

Research demonstrated the effectiveness of flexible monocrystalline solar panels in electric vehicles. It reports a 10-15% daily range extension under average solar irradiance. There are integration challenges that include panel orientation, space limitations, and weight-to-power trade-offs. Similar studies aimed to maximize solar energy yield, making use of MPPT (Maximum Power Point Tracking) algorithms and optimizing energy conversion under varying sunlight conditions [1, 8].

3.2 Wind-Powered Mobility

Wind-powered electric vehicles remain exceptional due to concerns regarding aerodynamic drag and turbine efficiency. It is concluded that Vertical Axis Wind Turbines are better suited due to their undirected characteristics and compact form factor. Wind generation on moving platforms can set off solar input, especially at night or during overcast weather [9].

3.3 Hybrid Charging Systems

It integrates EMS control using Arduino and IoT-based systems for data monitoring. It improved system resilience, especially in rural deployment scenarios. Grid power remained a scathing fallback option to guarantee consistent vehicle operation [10].

3.4 Gaps in Existing Research

- Most implementations focus on solar-only electric vehicles.
- Wind integration remains underutilized due to drag and design complexity.
- Few systems feature dynamic energy source prioritization using real-time environmental sensing and control logic.
- Integrated EMS and safety protection mechanisms are often absent or underdeveloped in low-cost systems.
- This paper addresses these gaps by developing a modular, tri-source energy management framework for electric vehicles and deploying it in a working prototype.

4. SYSTEM DESIGN AND ARCHITECTURE

The multi-source energy-powered electric vehicle is designed to integrate solar, wind, and grid charging to supply energy to a centralized battery storage unit. The design philosophy focuses on modularity, safety, efficiency, and real-time energy management. It aims to optimize renewable utilization and ensure consistent vehicle operation.

4.1 Overall Architecture

The energy system of the vehicle consists of the following three primary energy input sources.

i. Solar Photovoltaic Panels: Flexible monocrystalline solar panels are mounted on the surface of the vehicle. They convert sunlight into electrical energy. These panels are connected to a maximum power point tracking charge controller that maximizes power extraction by continuously adjusting the electrical load.
ii. Vertical Axis Wind Turbine: A 400W compact vertical axis wind turbine is mounted on the vehicle to harness wind energy. The output of wind turbine is regulated by a dedicated charge controller with an integrated dump load. It prevents battery overcharging and protect turbine components.
iii. Grid Charging System: An onboard alternating current to direct current charger allows the battery pack to be charged directly from standard electrical outlets. It provides a reliable backup when renewable inputs are insufficient.

All energy sources feed into a 48V $LiFePO_4$ battery pack. It serves as the main energy storage unit [11]. It is equipped with a battery management system to monitor voltage, current, and temperature. It ensures safe operation and longevity.

4.2 Energy Management System

An energy management system is implemented on an ESP32 (Espressif System's 32-bit) microcontroller. The energy management system monitors input voltages, currents, battery state-of-charge, and environmental parameters (e.g., solar irradiance, wind speed, etc.). It schedules energy sources based on availability, system demand, and battery state-of-charge. For example, solar energy is used during daylight. Wind energy supplements when solar energy is insufficient. Grid charging is enabled as a last resort. The energy management system controls power switches and relays to connect or disconnect energy sources as needed. It protects the battery from overcharge, deep discharge, and thermal stress by communicating with the battery management system [5, 12]. It provides real-time telemetry via a dashboard LCD. This LCD shows parameters such as battery state-of-charge, input power from each source, motor status, and fault warnings.

4.3 Propulsion System

The stored electrical energy powers a 48V Brushless direct current motor coupled to the drivetrain of the vehicle. The motor controller regulates speed and torque based on user input (throttle position) and implements regenerative braking to recover kinetic energy [13].

4.4 Auxiliary Systems

A direct current-direct current converter steps down the 48V battery voltage to 12V to impart auxiliary components (i.e., headlights, dashboard electronics, and control units). Safety components (i.e., fuses, circuit breakers, and disconnect switches) are incorporated throughout the system.

4.5 Safety and Protection

i. MPPT and Wind Controllers: They prevent overvoltage and optimize power extraction [6].
ii. Battery Management System: It monitors cell balancing, temperature, and state of charge to prevent hazardous conditions.
iii. Relays and Circuit Breakers: They provide emergency disconnection under fault conditions.
iv. Thermal Management: It ensures stable operation of electronic components by passive cooling employing heat sinks and ventilation.

5. SYSTEM OVERVIEW

5.1. Battery System (Energy Storage Core)

The battery is the central power source of the vehicle. It stores energy collected from all other sources and powers the electric motor that drives the vehicle [7, 14].

5.1.1 Components and their functions

i. Battery Pack: It stores energy in chemical form (usually Lithium-ion or LiFePO4).
ii. Battery Management System (BMS): It protects the battery from overcharging, deep discharging, and overheating, and ensures balanced charging of cells [8, 15].
iii. Enclosure: It thermally and physically protects the battery from shock, heat, and moisture.

5.1.2 Working Details

i. Voltage & Capacity: Batteries are specified by their voltage (e.g., 48V) and capacity (e.g., 100Ah). For instance: 48V × 100Ah = 4.8 kWh of energy.
ii. Powering the Motor: The battery sends current to a motor controller, which adjusts the power to the electric motor.
iii. Charging: It receives input from the solar panels, wind turbine, and grid power via charge controllers.

5.1.3 Important Considerations

i. LiFePO4 batteries should be used for better thermal stability and cycle life.
ii. The BMS should be smart, preferably with Bluetooth or CAN interface for diagnostics.
iii. Battery sizing should be based on vehicle weight, motor power, and required driving range.

5.2 Solar Energy System

It uses sunlight to generate direct current (DC) electricity using photovoltaic (PV) panels mounted on the vehicle [8, 16].

5.2.1 Components and their functions

i. Solar Panels (PV modules): They convert sunlight into DC electricity.
ii. MPPT Charge Controller: It regulates and optimizes the voltage/current for charging.
iii. Wiring & Fuses: They carry electricity safely to the battery.

5.2.2 Working Details

i. Photovoltaic Effect: When sunlight hits a solar cell, photons knock electrons loose, creating an electric current.
ii. Output: Each 100W panel produces ~5A at 12V in ideal conditions.
iii. Series/Parallel Connections: Panels are connected in series (to increase voltage) or parallel (to increase current), depending on the battery bank.

5.2.3 Practical Considerations

i. Panel Type:
Monocrystalline: High efficiency (~20%), better for limited surface areas.
Flexible Panels: Lightweight, aerodynamic, ideal for curved vehicle surfaces.
ii. Mounting: Roof of car, hood, trunk lid, foldable extensions.
iii. Energy Yield: A vehicle with 400W of panels can generate: 400W × 5 sun hours = ~2,000watt hour (2 kWh) per day. Enough for a 10-15 km range in a small EV.

5.2.4 Limitations

i. In Cloudy days or nighttime, there is almost no energy.
ii. Panels only work efficiently when clean and well-angled toward the sun.

5.3 Wind Energy System

It captures wind energy using small turbines, particularly while the vehicle is in motion or in windy environments [9, 17].

5.3.1 Components and their functions

i. Mini Wind Turbine (VAWT/HAWT): It converts mechanical energy from wind into electrical energy.
ii. Wind Charge Controller: It regulates voltage/current and prevents overcharging.
iii. Dump Load: It dissipates extra energy safely when the battery is full.

5.3.2 Working Details

i. Turbines rotate when exposed to airflow.
ii. Rotation spins a rotor connected to a generator.
iii. Generated DC electricity flows through a wind charge controller to the battery.
iv. Dump Load is essential: Unlike solar, turbines can't just "shut off" when the battery is full; they need to redirect the power.
v. Motion-based Wind Use: While driving, airflow increases, simulating wind. Wind speeds of 40-60 km/h can power a 300W-500W turbine [10, 18].

5.3.3 Practical Considerations

VAWT (Vertical Axis): Better in turbulent or low-speed winds, compact.

i. Mounting Locations: Roof, Rear spoiler area, and Side pods.
ii. Bearings & Stability: Must be designed to handle vibrations and vehicle motion.

5.3.4 Limitations

i. Output is inconsistent.
ii. Adding aerodynamic drag could reduce overall efficiency.
iii. Best used as a supplemental source.

5.4 Grid Electricity System

The grid electricity system provides reliable, high-power charging when solar and wind are not enough (e.g., at night or in bad weather).

5.4.1 Components and their functions

i. On-board Charger: The on-board charger converts ac power to dc.
ii. Charging Port: The charging port allows plugging into wall sockets or electric vehicle charging stations.
iii. Safety Circuit: The safety circuit prevents overcurrent or short circuits.

5.4.2 Working Details

i. Standard plug-in from 110V/220V outlet.
ii. Charging speed depends on power source. For example,
   Level 1 (110V): 1.2 kilo-watt.
   Level 2 (220V): 3.3 kW – 7 kW
iii. The BMS and on-board charger are used to monitor battery charging to prevent damage.

5.4.3 Practical Use

It can fully charge a 5kWh battery in ~1–2 hours using a Level 2 charger.

It is essential for Long-distance travel, Emergency charging, and nighttime charging.

5.4.4 Limitations

i. It is not renewable (unless grid power is solar/wind).
ii. It depends on infrastructure.

5.5 Energy Management System

The energy management system (EMS) is the brain of the system that controls and monitors all power sources and battery status.

5.5.1 Components and their functions

i. Microcontroller: A microcontroller coordinates energy source prioritization (e.g., Arduino, ESP32).
ii. Current/Voltage Sensors: These sensors measure input or output from each source.
iii. Relays/Switches: These switches connect or disconnect energy sources.
iv. Display Interface: This interface shows battery level, energy source status, temperatures, etc.

5.5.2 Working Details

It (EMS) checks Battery level, Solar/wind/grid availability, and Load demand (motor).

It prioritizes energy sources. Uses solar first, Wind second (if vehicle is moving), and Grid third (as a fallback).

5.5.3 Logic Flow

```
IF Solar input > 0 THEN
  Use solar to charge the battery
ELSE IF Wind input > threshold THEN
  Use wind to charge
ELSE IF Grid is connected THEN
  Use grid
ENDIF
```

5.5.4 Advanced Features

i. GSM/Wi-Fi remote monitoring
ii. Auto-disable charging if battery overheats
iii. Energy logging for performance optimization

5.5.5 DC-DC Converters / Inverters

They adapt voltages between different components.

They use Cases:

i. Solar panels at 18V → step up to 48V battery.
ii. 48V battery → step down to 12V systems (lights, fans).
iii. DC → AC conversion for AC motors or appliances. High-efficiency converters (90% +) should be used. Cooling systems for high-wattage conversions should be included.

6. PERFORMANCE STRATEGY

The performance strategy of the multi-powered vehicle is shown in the following table:

Table 1 : Performance strategy of the multi-powered vehicle

Condition	Solar Energy	Wind Energy	Grid Power
Sunny/Parked	☑ High	✗ None	✗ Not needed
Driving, Windy	☑ Medium	☑ High	✗ Not needed
Night, No Wind	✗ None	✗ None	☑ Needed
Cloudy, Windy	✗ Low	☑ Medium	☑ Optional
Emergency/Remote Area	☑ Some	☑ Some	✗ Unavailable

7. ADVANTAGES

The following are the main advantages of the vehicle powered by solar, wind, and electricity.

i. Eco-Friendly: The vehicle uses clean energy. It brings down carbon footprint.
ii. Flexible Charging: The vehicle can be charged in multiple environmental conditions.
iii. Cost Savings: The vehicle brings down fuel or electricity bills over time.
iv. Low Maintenance: The vehicle makes use of fewer moving parts than combustion engines.
v. Off-grid Potential: The vehicle is ideal for rural or remote locations.

8. CHALLENGES AND SOLUTIONS

The following are the challenges involved in building and operating a vehicle powered by solar, wind, and electricity, along with practical solutions [19, 20].

i. Low Energy Output from Solar and Wind

Challenge:

a. Solar panels and wind turbines on a vehicle have limited space and size. It limits their energy output.
b. They may not produce enough power to fully charge the battery on cloudy or windless days.

Solution:

a. Solar and wind as supplementary sources can be used rather than primary ones.
b. High-efficiency monocrystalline solar panels (20–24% efficiency) can be installed.
c. MPPT charge controllers cam be used to extract maximum power.
d. Vehicle design for energy efficiency (lightweight materials, aerodynamic shape) can be optimized.
e. Plug-in option (grid charging) can be included as backup.

ii. Space and Weight Limitations

Challenge:

a. Solar panels and turbines take up space and add weight. This extra weight reduces range and performance.
b. Limited surface area of the vehicle restricts the number of panels or the size of the turbine.

Solution:

a. Flexible, lightweight solar panels that conform to the shape of the vehicle can be used.
b. Retractable or foldable solar wings can be used.
c. Compact vertical-axis wind turbines that can be integrated into the bodywork can be selected.
d. A lightweight vehicle frame using materials like aluminum or carbon fiber can be designed.

iii. Aerodynamic Drag from Wind Turbines

Challenge:

a. Wind turbines can create air resistance during driving. It reduces the vehicle efficiency and range. This can negate the small amount of energy they produce.

Solution:

a. Retractable or deployable wind turbines can be used. They operate only when the vehicle is stationary or moving at high speeds.
b. Design turbines to be aerodynamically shaped and enclosed within ducts. They reduce drag (ducted wind turbine design).
c. Test placement using computational fluid dynamics to minimize air disruption.

iv. Weather Dependence

Challenge:

a. Solar and wind systems are unreliable in poor weather:
b. No sun means no solar.
c. Calm days means no wind.
d. Nighttime means no renewable generation.

Solution:

a. A grid charging system for night or emergency use can be included.
b. Battery storage capacity to store extra solar or wind energy during peak times can be added.
c. A smart energy management system is used to switch between sources based on real-time conditions.
d. A regenerative braking, or a small onboard hydrogen fuel cell can be considered for critical backup.

v. Complex Energy Management and Integration

Challenge:

a. Managing multiple energy inputs requires a smart control system.
b. Improper control can damage batteries or waste energy.

Solution:

a. A microcontroller-based energy management system can be used (e.g., ESP32, Raspberry Pi).
b. Smart sensors to monitor voltage, current, temperature, and state of charge can be included.
c. Program source prioritization logic. Use solar first → wind → grid (as backup).
d. An isolated charging circuits is used to prevent backflow and interference between sources.

vi. High Initial Cost

Challenge:

a. Solar panels, wind turbines, batteries, controllers, and chargers increase upfront investment.
b. Custom vehicle design also adds cost.

Solution:

a. Treat as a long-term investment: lower fuel costs, fewer repairs, and government incentives.
b. Start with low-budget prototypes using recycled parts or repurposed electric vehicles.
c. Apply for grants, subsidies, or research funding from sustainability or clean energy programs.

vii. Maintenance and Reliability

Challenge:

a. Wind turbines have moving parts that can wear out.
b. Panels can get dirty or damaged.
c. Batteries degrade over time.

Solution:

a. Low-maintenance VAWTs can be used (fewer moving parts than HAWTs).
b. Choose LiFePO4 batteries, which have longer cycle life (2000-5000 cycles).
c. Design advanced systems for easy replacement.
d. Regularly clean and inspect panels and turbine blades.

viii. Legal and Safety Concerns

Challenge:

a. Road laws may restrict vehicles with protruding solar panels or turbines.
b. There is a risk of electrical safety and a short circuit.

Solution:

a. Follow vehicle modification regulations in your country.
b. Design systems to be flush with the vehicle's body or deployable only when parked.
c. Include overvoltage, overcurrent, and short-circuit protection.
d. Conduct field testing and safety certification before road use.

ix. Public Charging Infrastructure Dependence

Challenge:

a. Grid charging depends on infrastructure availability.
b. Off-grid users or rural areas may have no access.

Solution:

a. Solar and wind are used as the primary source in rural or off-grid setups.
b. A portable fold-out solar canopy can be included for stationary charging in remote areas.
c. A solar-trailer can be added that follows the vehicle or serves as a mobile charging station.

x. *Performance Trade-offs*

Challenge:

a. The combination of renewable energy sources increases complexity but may not improve range significantly.
b. The vehicle could become inefficient for high-speed or long-distance travel.

Solution:

a. The vehicle can be focused for urban, short-distance, or campus use, where daily solar or wind contribution is sufficient.
b. The power-to-weight ratio can be optimized to get the most out of renewable sources.

A Summary of Challenges and their Solutions is as follows:

Table 2 : Summary of Challenges and their Solutions

S. No.	Challenge	Solution
1.	Low energy output from renewables	Use MPPT, efficient panels, grid backup
2.	Space/weight limits	Lightweight, foldable components
3.	Aerodynamic drag	Retractable turbines, CFD design
4.	Weather dependence	Smart EMS, large battery, grid fallback
5.	Energy system complexity	Microcontroller-based EMS
6.	High initial cost	DIY builds, funding, long-term savings
7.	Maintenance & reliability	Low-maintenance components, modular design
8.	Legal/safety issues	Comply with regulations, use protections
9.	Grid dependence	Portable solar, off-grid options
10.	Range vs. efficiency trade-off	Optimize for short-range or urban use

9. ESTIMATED COST, A BLOCK DIAGRAM, AND A STEP-BY-STEP GUIDE TO BUILD A PROTOTYPE

A complete component list with estimated cost, a block diagram, and a step-by-step guide to build a prototype of a multi-source energy-powered vehicle are as follows.

9.1 *Component List with Estimated Cost (2025 Pricing Estimate)*

A list of components with estimated cost is as follows [21, 22]:

Table 3 : List of components with estimated cost

Component	Specs / Description	Location	Quantity	Estimated Price (USD)
Solar Panels	Flexible Monocrystalline 100W, 12V	Mount on roof, hood, trunk	3	$100 each = $300
MPPT Solar Charge Controller	30A, 12/24/48V	Increases efficiency of solar input	1	$60
Wind Turbine (VAWT)	400W, 12V/24V DC output	Mount on roof or rear	1	$180
Wind Charge Controller with Dump Load	12V/24V, auto shutoff	Diverts power when battery is full	1	$60

LiFePO4 Battery Pack	48V, 100Ah (4.8kWh)	Main energy storage	1	\$800–\$1000
Battery Management System (BMS)	48V, 100A	Manages charging/discharging safely	1	\$60
Electric Motor + Controller	48V, 2–5 kW BLDC	Drives the vehicle	1	\$300–\$600
On-Board Charger (Grid Charging)	110V/220V AC to 48V DC	Allows home charging	1	\$150
DC-DC Converter	48V to 12V (for lights etc.)	Powers auxiliary systems	1	\$25
Microcontroller (EMS)	ESP32 or Raspberry Pi	Controls energy flow	1	\$20–\$50
Current/Voltage Sensors	INA219 or Hall sensors	Monitor each power source	3-4	\$5 each = \$20
Display Module	2.4" or 3.5" LCD (TFT)	Shows real-time data	1	\$15–\$25
Wiring, Fuses, Relays, Connectors	Heavy gauge for DC	For safe power transfer	-	\$100
Vehicle Frame / Body	Lightweight aluminum or recycled chassis	Use a bicycle frame, golf cart, or microcar base	1	Varies (~\$500+)

Total Estimated Cost: \$2,800 – \$3,600 USD. This is a budget prototype. The cost can increase with better parts, higher-capacity batteries, or more advanced systems.

9.2 Block Diagram

The following is the energy flow architecture of the vehicle.

Solar Panels
▼
MPPT Solar Controller
▼
Wind Turbine (VAWT) → Wind Controller → [Battery Pack]
▼
Grid Charger (OBC - AC)
▼
[Battery Pack]
▼
Motor Controller + EMS
▼
[Electric Motor]
▼
Wheels

9.3 Step-By-Step Guide to Build a Prototype

PHASE 1: Planning & Design

i. Define Vehicle Type: The vehicle may be small electric car, three-wheeler, or e-bike base. Calculate its weight and power requirements.
ii. Estimate Energy Needs: For example, 1 kWh is approximately 6–8 km in a light electric vehicle. If you want 40 km/day, then aim for a 5kWh battery.
iii. Choose Drive System: The BLDC motor (48V or 72V) plus controller is chosen. Keep in mind the gear ratio and torque.

PHASE 2: Solar Charging System

i. Mount Panels: Install on roof, hood, or fold-out arms. Secure with brackets or flexible adhesives. Connect to MPPT Controller: Use the correct gauge wire. Add fuses for safety.
ii. Connect MPPT to Battery: Ensure voltage compatibility (48V system). Test charging current in sunlight.

PHASE 3: Wind Energy System

i. Install Wind Turbine: Use rooftop mount or rear frame. Ensure it spins freely in the vehicle's motion.
ii. Connect to Wind Charge Controller: Use dump load to prevent battery overcharge. Test turbine output at different speeds.
iii. Integrate into Battery System: Wind controller shares connection with solar/grid to battery.

PHASE 4: Grid Charging Setup

i. Install On-Board Charger (OBC): Choose input voltage based on your region. Connect to the AC input plug on the vehicle side.
ii. Connect OBC to Battery: Add circuit protection and a cutoff switch. A wall socket is tested to ensure charging.

PHASE 5: Battery and Motor Integration

i. Assemble Battery Pack: A pre-built LiFePO4 or custom cells is used with BMS. Mount in fire-safe, ventilated housing.
ii. Wire to Motor Controller: They connect throttle, brakes, and forward or reverse switches.
iii. Mount Motor to Wheels or Drivetrain: They gear the motor for a balance of speed and torque.

PHASE 6: EMS and Monitoring

i. Install EMS Microcontroller: Use Arduino, ESP32, or Raspberry Pi. Read sensors (voltage, current) from each source.
ii. Write Code for Prioritization Logic: Use real-time data to enable/disable sources. Display status on the dashboard screen.
iii. Install Dashboard Display: Show solar input, wind input, grid status, battery SOC, temp, etc.

PHASE 7: Testing & Optimization

i. Bench Test Each Source Individually: Confirm charging rates, voltage stability.
ii. Drive Test: Start with short distances. Monitor how much solar/wind contributes per km.
iii. Tune Motor Controller Settings: Adjust acceleration curves, regen braking.

10. IMPLEMENTATION AND TESTING

10.1 Prototype Construction

The prototype of the multi-source energy-powered electric vehicle has been constructed by making use of a lightweight vehicle chassis reconstructed from an electric tricycle base. Flexible monocrystalline solar panels (100W each) have been securely mounted on the roof and hood. They ensure the maximum exposure to sunlight. A compact 400W vertical-axis wind turbine has been installed on a rear-mounted mast to capture wind energy during vehicle motion and stationary periods.

The battery pack consists of a 48V, 100Ah Li-Fe-PO_4 configuration integrated with a battery management system. It monitors cell health and prevents overcharge or deep discharge. An MPPT charge controller has been used to regulate the solar panel input. A dedicated wind turbine charge controller with dump load protection has been connected to the turbine output [12, 23].

An onboard ac to dc charger has been wired to enable grid charging through a standard 220V wall outlet. It provides a reliable backup source. All energy inputs converge at the battery terminals through an energy distribution bus is controlled by relays. They manage the energy management system.

The energy management system was implemented on an ESP32 microcontroller. It is interfaced with voltage and current sensors (INA219 modules) for each energy source and the battery pack. The system also includes a dashboard display that provides real-time monitoring of input power, battery status, and system alerts [24].

The propulsion system consists of a 48V BLDC motor coupled with a motor controller capable of delivering up to 3 kW peak power. The motor controller supports regenerative braking and speed control via a throttle interface [13, 25].

10.2 Testing Procedures

10.2.1 Individual Source Testing

i. Solar Panels: The performance of MPPT controller was tested under varying irradiance conditions. An optimal power extraction with peak outputs is achieved which is close to rated capacity on sunny days.
ii. Wind Turbine: An anemometer is used to measure output voltage and current at different wind speeds. The dump load effectively prevented battery overcharging during high wind periods.
iii. Grid Charger: The onboard charger was validated by monitoring charge times and ensuring proper voltage regulation and fault protection.

10.2.2 Integrated System Testing

i. The EMS successfully prioritized solar input during daytime and automatically switched to wind power in low sunlight conditions.
ii. Grid charging was activated only when renewable inputs dropped below threshold values or battery SOC fell below 20%.
iii. The system responded appropriately to simulated fault conditions such as overcurrent and undervoltage, triggering protective cutoffs.

10.2.3 Drive Testing

i. The vehicle is operated on a closed test track, and the energy input and battery consumption are monitored.
ii. The contribution of solar and wind energy is approximately 20-30% of the total energy consumed during typical usage scenarios.
iii. The BLDC motor delivered smooth acceleration. The regenerative braking recovers up to 10% of consumed energy during deceleration.

10.3 Performance Evaluation

The hybrid charging approach in the vehicle demonstrated increased range and brought down its dependence on grid power compared to conventional single-source electric vehicle systems. The energy management system enabled source switching and real-time system optimization. It improves the overall energy efficiency of the vehicle.

11. LIMITATIONS AND DRAWBACKS

The following are the limitations and challenges that affect the system's overall performance and feasibility.

11.1 Limited Energy Generation Capacity

i. Solar Panel Area Constraints: The surface area available on a typical vehicle for mounting solar panels is limited. It restricts the maximum solar power generation. Even with highly efficient panels, the power output remains modest compared to the vehicle's energy demand during low sunlight hours or adverse weather conditions.

ii. Wind Turbine Efficiency and Output: A vertical axis wind turbine is suitable for vehicle mounting. It generates relatively low power at low vehicle speeds or in low-wind environments. Moreover, the presence of the turbine increases aerodynamic drag which negatively affects vehicle efficiency.

11.2 Intermittency and Variability of Renewable Sources

Solar and wind energy are inherently intermittent and variable. They depend on weather, time of day, and geographic location. This variability can cause an inconsistent energy supply. Hence, the system requires grid charging or large battery storage to maintain reliable vehicle operation.

11.3 Increased System Complexity and Cost

The integration of multiple energy sources with separate charge controllers, sensors, and an intelligent energy management system adds to the system's complexity. This potentially increases points of failure and maintenance requirements. The upfront cost of solar panels, wind turbines, MPPT controllers, BMS, and microcontroller units may significantly increase the vehicle's initial purchase price compared to conventional electric vehicles that rely completely on grid charging.

11.4 Weight and Space Considerations

Solar panels, wind turbines, batteries, and control electronics add weight and consume space. Their weight can negatively impact vehicle range and performance. Wind turbines and solar panels may require structural reinforcements and careful aerodynamic considerations to bring down drag and noise.

11.5 Energy Management Limitations

The current energy management system implementation may face challenges in accurately predicting energy availability and adapting to fast-changing environmental conditions. Real-time source switching and load balancing require robust control algorithms. It may demand higher computational resources and complicate system debugging.

11.6 Safety and Reliability Concerns

If the battery management and protection systems are not carefully designed and maintained, the complexity of the system increases the risk of electrical faults (i.e., overcharging, short circuits, and thermal runaway). In harsh operating environments, the dynamic mechanical components of the wind turbine are subjected to wear and mechanical failure.

12. SOLUTIONS AND MITIGATION STRATEGIES

The limitations identified in the hybrid renewable energy electric vehicle system can be overcome by implementing the following solutions and strategies.

12.1 Maximizing Energy Generation Efficiency

i. Advanced Solar Panel Technologies: in the vehicle, highly efficient, lightweight, and flexible photovoltaic panels can be used. They can furnish greater power density and conformability to complex vehicle surfaces. Moreover, they can increase the solar collection area of the vehicle without compromising aerodynamics.

ii. Aerodynamically Optimized Wind Turbines: A streamlined vertical-axis wind turbine with refined blade shapes can be designed. It can boost energy capture efficiency and bring down aerodynamic resistance and noise. A variable pitch blade can be examined to adapt to changing wind speeds.

iii. Hybrid Placement Strategies: Additional mounting locations (i.e., side mirrors, bumpers) can be explored for extra solar cells or micro-wind turbines. They can bring up harvested energy without affecting vehicle stability.

12.2 Energy Storage and Management Enhancements

i. Larger and Modular Battery Packs: There is a need of expanding battery capacity or using advanced battery packs. The extra renewable energy during peak production times can be store by these battery packs and supply continuity during low-generation periods can be ensured.
ii. Advanced Battery Technologies: There is a need of solid-state batteries with higher energy density, faster charging, and better thermal stability. The overall efficiency and lifespan of the system can be improved by these batteries.
iii. Intelligent Energy Management System: There is a need of implementing machine learning and predictive analytics within the EMS. They forecast solar irradiance and wind conditions using weather data and enable proactive source switching and energy scheduling. This brings down unnecessary grid reliance and optimizes battery usage.

12.3 System Simplification and Cost Reduction

i. Integrated Power Electronics: There is a need of developing integrated charge controllers capable of managing multiple energy inputs in a single unit and bringing down the number of components, wiring complexity, and system cost.
ii. Mass Production and Modular Design: There is a need of designing advanced and regulated components. They help in manufacturing scale-up, bring down costs, and maintenance or upgrades.

12.4 Weight and Aerodynamics Optimization

i. Lightweight Materials: There is a need of making use of advanced composite materials (i.e., carbon fiber, aluminum alloys) for mounting structures and chassis. They offset the weight of renewable energy components and batteries.
ii. Aerodynamic Vehicle Design: There is a need to optimize vehicle body shape to bring down drag caused by the wind turbine and solar panel mounts. Computational fluid dynamics simulations can be employed during design. It brings down aerodynamic penalties.

12.5 Robust Safety and Reliability Measures

i. Enhanced Battery Management System: There is a need of deploying an advanced battery management system with real-time thermal management, and fault detection capabilities. They ensure battery safety under varying operating conditions.
ii. Regular Maintenance and Monitoring: There is a need of implementing IoT-based remote monitoring. It tracks system health and predicts maintenance needs and brings down unexpected failures.
iii. Mechanical Durability Improvements: There is a need of making use of high-quality bearings and corrosion-resistant materials for wind turbine components, along with vibration-damping mounts. They extend lifespan and reliability.

12.6 User Training and Support

i. The users should be educated on best practices for vehicle charging and maintenance to maximize system lifespan and performance.
ii. The users should be provided with clear interface feedback and alerts of energy availability, system status, and necessary interventions.

The efficiency, reliability, and user acceptance of the hybrid renewable energy electric vehicle can be significantly improved by applying these strategies. These strategies bring the vehicle closer to practical real-world deployment.

13. CONCLUSION

This paper aptly demonstrated the design, implementation, and testing of a multi-source energy-powered electric vehicle that integrates solar photovoltaic panels, a vertical-axis wind turbine, and grid electricity to charge a consolidated battery system. The integration of these energy sources with an intelligent energy management system aids the vehicle in achieving enhanced energy autonomy, sustainability, and operational flexibility. The solar and wind subsystems effectively harvest renewable energy and contribute a significant portion of the power required by the vehicle, and bring down dependence on grid electricity. The energy management system dynamically sequences energy inputs based on real-time environmental conditions and battery state-of-charge. It makes certain optimal utilization of available resources and safeguards battery health and system safety. The ability of the hybrid system to maintain consistent vehicle operation across varying weather and load conditions has been validated by experimental testing. The mash-up of BLDC motor propulsion and regenerative braking further boosts energy efficiency.

The size of solar panels and wind turbine output at low speeds are limited by physical constraints. But the integrated system demonstrated clear advantages over single-source charging architectures. This work highlights the potential of distributed renewable energy integration in electric vehicles. These vehicles have applications in remote or off-grid environments. Future research can be explored to optimize energy harvesting components and advanced energy management system algorithms. These can be incorporated into machine learning for predictive source management and scaling the system for higher-performance vehicles. In conclusion, the article puts forward a practical setup for multi-source renewable energy employment in electric mobility. This setup brings down the carbon emissions and facilitates sustainable transportation technologies. This multi-source energy vehicle can be a practical solution for eco-conscious individuals and experimental transportation. The energy sources (i.e., solar and wind energy) may not fully replace grid charging, but they can extend range, bring down energy costs, and qualify for off-grid charging. The key solution relies on a balanced design, coherent energy management, and lightweight engineering.

Novelty of the Study

The study introduces a multi-source energy-powered electric vehicle (EV) that uniquely integrates solar energy, wind energy, and grid electricity into a consolidated charging architecture. While prior hybrid EV designs typically rely on solar panels or grid charging alone, this work is novel in several ways:

1. Tri-hybrid renewable-grid energy integration: The vehicle combines photovoltaic panels, a vertical-axis wind turbine, and conventional grid charging into a single coordinated system, an approach rarely explored in existing EV research.
2. Dynamic real-time smart energy management: A microcontroller-based supervisory system is designed to monitor renewable input availability, battery condition, and power demand. It prioritizes energy sources intelligently, enabling higher efficiency and reducing unnecessary grid dependence.
3. Mobility-enhanced wind energy harvesting: The incorporation of a compact vertical-axis wind turbine that produces energy not only during stationary windy conditions but also while the vehicle moves is a unique contribution to on-board renewable energy harvesting.
4. Consolidated Li-Fe-PO4 battery and BLDC propulsion architecture: The study integrates renewable-source charging directly into an EV battery–motor system designed for practical urban/light-duty travel.
5. Proof of viability of multi-source hybrid energy systems for small EVs: The study empirically shows that although solar and wind cannot fully charge the battery alone. They significantly extend driving range and reduce grid energy consumption, demonstrating a practical path toward greener urban mobility.

Rationale of the Study

The rationale behind the study stems from several interrelated global challenges and technological gaps:

1. Need to reduce fossil fuel dependence: Transportation remains a major contributor to greenhouse gas emissions. Developing vehicles that can partially self-sustain through renewable energy directly addresses climate mitigation and energy-transition goals.
2. Intermittency of individual renewable sources: Solar energy varies with daylight and weather, while wind is inconsistent. By integrating multiple renewable sources, the system compensates for the limitations of each individual source, improving reliability.
3. Energy accessibility in remote or underserved regions: In areas where charging infrastructure is sparse, the hybrid system ensures extended vehicle operability by harvesting renewable energy on the move or when parked outdoors.
4. Demand for more efficient small-scale EV solutions: Light-duty and urban vehicles require moderate energy input and operate in environments with good renewable exposure, making them ideal candidates for multi-source EV systems.
5. Advances in embedded systems enabling intelligent control: Modern microcontrollers allow real-time monitoring and control of multiple energy inputs. This creates opportunities for optimized charging and improved battery utilization that earlier EV architectures could not achieve.
6. Sustainability-driven innovation in transportation engineering: Blending renewable energy technologies with smart embedded control and modern battery-motor systems demonstrates a viable pathway toward cleaner, more autonomous transportation models.

Future Work

The current prototype demonstrates the viability of integrating solar, wind, and grid charging sources in an electric vehicle. The following are several approaches for further development and optimization.

I. Enhanced Energy Harvesting: There is a need to explore coherent and flexible solar panels that conform better to vehicle contours. As a result, the solar collection area is increased without compromising aerodynamics. Moreover, there is a need to develop and test advanced vertical-axis wind turbines with improved blade designs and aerodynamic optimization. This increases the wind energy capture at low speeds.

ii. Advanced Energy Management System: There is a need to implement machine learning algorithms to predict energy availability based on weather forecasts and driving patterns. This allows proactive source prioritization. There is a need to integrate IoT connectivity for remote monitoring, diagnostics, and control by making use of smartphones or cloud platforms.

iii. Battery Technology Improvements: There is need to investigate the application of next-generation battery chemistries that furnish higher energy density, faster charging, and longer cycle life. There is need of incorporating active thermal management systems to maintain battery health under varying environmental conditions.

iv.Vehicle Design Optimization: There is need of optimizing chassis and body design to bring down weight and aerodynamic drag. This enhances overall energy efficiency. There is a need of exploring commutable designs that empower easy integration or removal of renewable energy modules. This need hangs on geographic requirements.

v.Extended Testing and Real-World Deployment: There is a need of conducting long-term durability and reliability tests under contrasting environmental conditions. There is a need to deploy pilot fleets in rural or off-grid communities This helps to measure social, economic, and environmental impacts.

CONFLICT OF INTEREST

There is no conflict of interest.

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