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International Journal of Advanced Electrical and Electronics Engineering

ISSN: 2278-8948
Volume 14 Issue 01, 2025

Advanced Electric Bicycles: Technologies and Innovations Overview

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Peer Review Information

Submission: 11 Sept 2025

Revision: 10 Oct 2025

Acceptance: 22 Oct 2025

Keywords

Multi-Charging, Regenerative Braking, Kinetic Energy Recovery System (KERS), Dynamo, BLDC Motor, Electric Bicycle, Sustainable Transport.

Abstract

The escalating demand for sustainable and economical personal transport necessitates innovative design in electric bicycles. This survey focuses on multi-charging hybrid electric bicycle systems that enhance range and efficiency by integrating multiple non-grid energy sources. The core charging methods explored include conventional AC wall charging, active regenerative braking to recover kinetic energy during deceleration, and the use of a dynamo or mechanical pedal power to generate supplemental charge. These systems utilize highly efficient Brushless DC (BLDC) motors and energy-dense Lithium-ion batteries for propulsion. The integration of mechanical energy recovery systems, such as flywheels for kinetic energy storage, significantly increases the vehicle's overall energy efficiency by minimizing wasted power. The primary goal of these designs is to reduce environmental impact and provide a practical, energy-independent transportation solution.

Introduction

The current global energy scenario is characterized by a peak demand for petroleum products, driven by the ever-increasing number of automobiles [1, 2]. As these fossil fuels are non-renewable sources, there is an urgent and critical need to transition to alternative energy sources to mitigate the danger of future exhaustion [1]. The rising cost of crude oil, as noted by Indhumathi and Mercy [2], further emphasizes the economic unsustainability of fossil fuel-dependent transportation. Concurrently, environmental concerns have pushed cleaner alternatives to the forefront of research and development globally [1, 5]. The usage of electric power for transportation has grown significantly, motivated by the desire for pollution-free commuting, which, in turn, reduces the reliance on conventional vehicles [2]. Electric bicycles (E-bikes) and hybrid electric bicycles (HEBs) represent an increasingly accessible and cost-effective solution for urban and regional travel [2]. A "hybrid" system, as conceptually defined by Kothari, Patel, and Panchal [1], implies the use of more than one energy source for a vehicle’s propulsion or charging. Modern designs go beyond simple battery-powered operation by integrating multiple charging modes, such as a conventional wall charger, a solar panel, and mechanical energy recovery mechanisms like regenerative braking or dynamos [1, 2]. This approach significantly addresses the primary challenge associated with battery electric vehicles: the lack of pervasive charging infrastructure and associated range anxiety [2]. For example, Pratama, Jamaaluddin, Sulistiyowati, and Anshory [3] focused on optimizing solar energy harvesting for battery charging, confirming that solar-powered charging is a viable, sustainable, and environmentally friendly alternative to traditional fossil fuel-based systems. Shanmuga Priya, Thangapandiyan, Shankarnarayanan, Siva, and Venkatesh [4] enhanced this concept by recovering kinetic energy during braking using a flywheel system to further increase the vehicle's efficiency. By combining human pedaling, solar energy, and regenerative kinetic energy recovery, these bicycles promote cleaner technology and lessen dependency on oil, a sentiment strongly supported by Ligil Vijayan et al. [5]. This paper provides a comprehensive survey of these systems, their core components, design methodologies, and the key challenges they currently face.

Historical and Technical Overview

The concept of a Hybrid Electric Vehicle (HEV) generally involves combining two propulsion systems, typically an electric motor/battery system with a combustion engine, to maximize fuel efficiency [6]. However, in the context of personal mobility, the term "hybrid bicycle" specifically refers to combining human power (pedaling) with electric assist, and crucially, incorporating multiple energy sources for battery charging [1, 2]. Electric bicycles are globally promoted as a means to decrease city emissions and encourage a healthier lifestyle for users [2].

Key technological components underpin these advanced designs. Most modern hybrid e-bicycles utilize a Brushless DC (BLDC) motor due to its inherent advantages in high torque, efficiency, and compact size [2, 4]. Power is stored in energy-dense batteries, with Lithium-ion batteries being the preferred choice over older lead-acid types due to their superior high energy density, lighter weight, and compactness [5]. A core feature distinguishing many of these hybrid designs is the utilization of regenerative braking, where the motor controller reverses the motor's operation during deceleration, allowing it to function as a generator that feeds electrical energy back into the battery [1,6]. Furthermore, integrating photovoltaic (solar) panels allows the bicycle to harness unlimited solar energy, converting it to electrical power through components like a DC-DC Boost Converter and a Solar Charge Controller (SCC) before storage [3, 5]. This model of multi-source energy recovery and supply elevates the hybrid electric bicycle beyond a conventional battery-only e-bike.

2. Methodology

The methodology for this survey paper involves a systematic review and qualitative synthesis of the conceptualization, design, and practical implementation of hybrid and solar-assisted electric bicycles as presented in the reference literature. The approach is comparative, focusing on extracting and synthesizing information regarding component choices and energy management techniques across various proposed prototypes. The selected papers were meticulously analyzed to extract key data points regarding (1) the specific charging modes employed (e.g., wall, solar, regenerative, dynamo), (2) the type of motor (e.g., BLDC, PMDC) and battery technology utilized, and (3) specialized energy recovery mechanisms, such as flywheel kinetic energy recovery systems [4]. Additionally, the control strategies, such as the use of PI controllers and Maximum Power Point Tracking (MPPT) algorithms mentioned by Indhumathi and Mercy [2], were examined. This detailed analysis allowed for the identification of common design trends, reported performance metrics (e.g., charging time, speed), and shared technical limitations faced by researchers in this field, thereby establishing a comprehensive overview of the current state of technology.

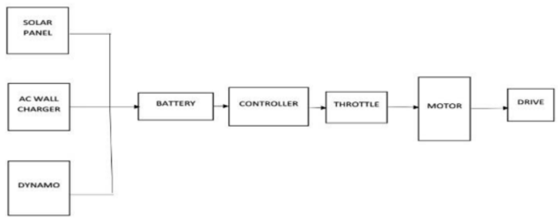

Fig.Block Diagram of E-Cycle[1].

Survey of Advancements

Integration of Solar Photovoltaics and Multi-Charging Systems:

The central innovation in hybrid electric bicycle designs is the robust utilization of solar energy to supplement conventional charging, effectively overcoming the challenge of relying solely on the power grid, which is a major infrastructure issue noted by Indhumathi and Mercy [2]. The Hybrid Bicycle developed by Kothari, Patel, and Panchal, for instance, incorporated three distinct charging methods: a standard AC wall outlet, photovoltaic solar power, and regenerative braking [1]. Similarly, Ligil Vijayan et al. presented an electric bicycle system that also integrates a dynamo, regenerative braking, and a solar panel to charge the lithium-ion battery, significantly enhancing its overall utility and range capability [5]. The study by Pratama et al. focused on optimizing the solar charging process using multiple parallel-connected 12V solar panels and a dedicated Solar Charge Controller (SCC) to efficiently store 36V in the battery, demonstrating a relatively quick full charging time of just 3 hours under ideal sunny conditions [3]. These comprehensive multi-mode approaches are designed to maximize the energy harvested from the immediate environment, directly promoting the goal of energy independence.

Kinetic Energy Recovery and Regenerative Braking Mechanisms:
Energy efficiency in electric bicycles is critically improved by mechanisms that recover energy typically lost as heat during deceleration. The widely implemented technique is regenerative braking, a process where the motor controller reverses the motor's operation during deceleration, causing it to function as a generator that feeds electrical energy back into the battery [6]. This essential feature is a core component in the hybrid systems designed by Kothari et al. [1] and Ligil Vijayan et al. [5]. Taking this concept further, the design proposed by Shanmuga Priya et al. incorporated a flywheel specifically to capture and reuse the kinetic energy otherwise dissipated when sudden braking is applied [4]. This stored mechanical energy in the flywheel is then automatically used to recharge the battery, working synergistically with the primary solar charging system and the BLDC motor [4]. The inclusion of energy recovery systems, particularly the specialized flywheel by Shanmuga Priya et al. [4], drastically extends the bicycle's effective range and efficiency.

Propulsion System and Controller Technology:
The selection of the propulsion motor heavily influences the efficiency, performance, and weight of the final e-bicycle product. Brushless DC (BLDC) motors are consistently favored across most modern designs due to their recognized high torque, superior efficiency, and compact size[2,4].For example, Indhumathi and Mercy's Simulation and Fabrication of Hybrid Electric Bicycle used a BLDC motor to increase performance, connecting the entire propulsion system with a Proportional-Integral (PI) controller [2]. This PI controller is crucial for calculating the precise speed and relevant voltage needed for the drive, thereby ensuring smooth and efficient operation [2]. Furthermore, the specific BLDC motor system used by Shanmuga Priya et al. was cited for increasing the bicycle's speed to an impressive 40-45 km/hr, demonstrating the performance benefits of this motor choice [4].The motor controller is an indispensable part of the overall energy management system, not only regulating speed but also acting as the central unit for receiving and managing regenerative energy input from solar or braking sources [5].

System Design, Simulation, and Hardware Implementation:
The development of advanced hybrid systems commonly adheres to a rigorous methodology involving detailed simulation prior to physical fabrication. Indhumathi and Mercy performed a comprehensive simulation of their proposed multi-charging hybrid system using MATLAB/Simulink software to thoroughly evaluate its performance and efficiency before moving to the physical fabrication stage [2]. In terms of hardware, Shanmuga Priya et al.'s design involved configuring two 12V, 7Ah Lead Acid Batteries to power the BLDC motor, alongside a solar controller and the specialized flywheel mechanism [4].The testing conducted byPratama, Jamaaluddin, Sulistiyowati, and Anshory [3] focused on real-world performance evaluation under differing light conditions (morning, afternoon, and night) to comprehensively assess the solar charging system's viability, confirming its effectiveness as a sustainable charging alternative[3].The crucial mechanical conversion of a standard bicycle to integrate these various electrical components, including the motor, controller, battery, and solar panel, requires careful attention to component weight and placement to ensure the final product remains both light and easily maneuverable [1, 5].

Challenges & Limitations
Despite the promising designs, several technical and practical challenges and limitations remain. One primary constraint is the physical size and overall efficiency of the solar panel, which must be small and lightweight enough to be mounted on a bicycle without compromising stability while still providing a meaningful charging current [1]. Ligil Vijayan et al. explicitly noted that their initial boost converter provided an extremely low current (3mA) from the solar panel, which would require an impractical 4000 hours for a full charge, highlighting a major barrier in practical solar power integration [5]. Furthermore, battery safety and longevity, particularly for the high-energy-density lithium-ion cells, require highly reliable management and protection systems [5]. While Kothari et al. aimed to design a system with a minimal amount of additional weight, the inevitable inclusion of multiple components—motor, battery, controller, solar panels, and possibly a flywheel—adds to the bicycle's overall weight and production cost, which may impact the system's long-term mass production feasibility in developing economies [1, 5].

Applications

- **Urban Commuting**

E-cycles are used for daily travel in cities, reducing traffic congestion and saving fuel. They provide an eco-friendly and convenient alternative to cars and motorcycles.

- **Last-Mile Delivery**

E-cycles are used by delivery companies for transporting goods over short distances. They help reduce delivery time and lower carbon emissions compared to conventional vehicles.

- **Healthcare & Rehabilitation**

Electric cycles assist elderly or physically challenged people to travel comfortably. They provide motor-assisted pedaling, making cycling easier and less tiring.

- **Tourism & Recreation**

E-cycles are used in parks, trails, and tourist areas for leisure rides. They allow riders to cover longer distances without excessive effort.

- **Logistics & Cargo Transport**

Small cargo e-cycles are used to transport goods in urban areas or campuses. They reduce dependence on fuel-based vehicles and improve efficiency for short-distance deliveries.

Comparative Analysis of Research on Advanced Electric Cycles

Feature	Kothari[1]	Indhumathi[2]	Pratama[3]	Shanmuga [4]	Ligil Vijiyan[5]
Primary Charging Modes	Wall Outlet,Regenerative , solar	Wall Outlet,solar,Pedal	Solar panel	Solar Panel,Flywheel,Pedal	Wall Outlet,Regenerative , solar
Motor Type	Electric Motor Hub	BLDC Motor	Electric Motor	BLDC Motor	Hub Motor
Energy Recovery	Regenerative Braking	Pedal	N/ A	Flywheel Kinetic Energy	Regenerative Braking
Battery Type	Lithuim-ion	Lead Acid	Lead Acid	Lead Acid	Lithium-ion
Special Feature	Integrated control system for efficiency	PI controller for speed and voltage management	Tested charging efficiency across day/night	Flywheel mechanism for energy recovery	DC-DC Boost converter for solar charging

Conclusion and Future Scope

Conclusion

The comprehensive review confirms that hybrid and solar-assisted electric bicycles are a crucial, multi-faceted solution to immediate global energy and pervasive environmental challenges. The integration of diverse power sources, such as solar power, regenerative braking, and conventional wall charging, significantly enhances the utility, range, and operational independence of these vehicles [1, 5]. The successful simulation and testing results reported by Indhumathi and Mercy [2], alongside the effective solar charging efficiency confirmed by Pratama, Jamaaluddin, Sulistiyowati, and Anshory [3], validate the essential feasibility of these composite designs. Moving forward, future research, as clearly suggested by Ligil Vijayan et al. [5], must decisively focus on substantially improving the current efficiency of solar energy harvesting and its associated boost converters to make the "free energy" claim truly practical for consistent daily use. Ultimately, as confirmed by Kothari, Patel, and Panchal [1], the hybrid bicycle represents a successful design for a cleaner, more efficient, and sustainable mode of personal transport that is ready for broader adoption.

Future Scope

The future of advanced electric cycles (e-cycles) holds significant promise in transforming sustainable mobility. With the development of next-generation battery technologies, such as solid-state and high-energy-density lithium-ion cells, e-cycles are expected to achieve longer ranges, faster charging, and improved safety. Integration of artificial intelligence and IoT-enabled smart controllers will optimize energy usage, adapt motor performance to terrain and rider behavior, and enable predictive maintenance, reducing downtime. Lightweight and eco-friendly materials will enhance efficiency while promoting sustainability. Additionally, smart charging infrastructure powered by renewable energy, regenerative braking systems, and AI-based safety features will make e-cycles more practical and safe for urban commuting, last-mile logistics, and rural transportation. Growing environmental awareness, supportive policies, and cost reductions are likely to drive wider adoption globally, positioning advanced e-cycles as a key component of future green mobility solutions.

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