



e-ISSN: 2319-8753 | p-ISSN: 2347-6710

IJIRSET

International Journal of Innovative Research in
SCIENCE | ENGINEERING | TECHNOLOGY



INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

Volume 13, Issue 5, May 2024

ISSN INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA

Impact Factor: 8.423

9940 572 462

6381 907 438

ijirset@gmail.com

www.ijirset.com

Multi-Source Self-Charging Electric Bike: A Sustainable Urban Mobility Solution

Ateeb Baig H^[1], Asma Tabassum^[2], VidyaShree RS^[3], B Lingamurthy^[4], Mrs. Farzana Begum K^[5],

U.G. Students, Department of Electrical and Electronics Engineering, Ballari Institute of Technology and Management, Ballari, Karnataka, India^{[1],[2],[3],[4]}

Assistant Professor, Department of Electrical and Electronics Engineering, Ballari Institute of Technology and Management, Ballari, Karnataka, India^[5]

ABSTRACT: This paper presents the Multi-Source Self-Charging Electric Bike (MSSCEB), a novel electric vehicle that integrates dual-power generation through kinetic energy capture and solar photovoltaic panels. The MSSCEB operates on an electric motor, eliminating manual pedaling, and incorporates a regenerative braking system to harness kinetic energy during motion. Simultaneously, an embedded high-capacity solar panel converts sunlight into supplementary electrical charge. This multi-source approach enables continuous battery charging during operation, significantly extending the vehicle's range without external recharging. An advanced Electrical Control Unit (ECU) based on an Arduino microcontroller intelligently manages real-time battery switching and power flow, ensuring optimal utilization of the generated energy. The MSSCEB represents a paradigm shift in sustainable urban transportation, offering an eco-friendly, convenient, and extended-range mobility solution aligned with global efforts towards sustainable transportation.

KEYWORDS: Electric Bike, Solar Power, Regenerative Braking, Self-Charging, Sustainable Transportation.

I. INTRODUCTION

Modern societies face an urgent need to transition transportation systems towards sustainable energy sources [1]. The heavy reliance on fossil fuels for mobility has precipitated immense environmental challenges, including escalating greenhouse gas emissions contributing to climate change, deteriorating urban air quality from vehicular exhaust leading to public health concerns, and unsustainable depletion of non-renewable petroleum resources. Exploring alternative energy vehicles offers a promising pathway to address these pressing issues and create a greener, more sustainable transportation future.

Electric vehicles, in particular, have gained significant traction globally as a clean and eco-friendly personal mobility alternative compared to conventional gasoline-powered automobiles [1]. Electric bicycles (e-bikes) have emerged as a highly versatile urban transportation option, offering many benefits over both traditional pedal bicycles and full-sized electric cars [5]. E-bikes provide riders with electric pedal assistance that gives a smooth, low-effort riding experience, eliminating the physical exertion needed with standard bicycles. Several studies have highlighted the potential for e-bikes to reduce car dependence for short-range urban commuting and recreational trips [5].

However, some persistent barriers remain for e-bikes to fully transform urban transportation and displace private gasoline vehicles on a mass scale. Two significant limitations of current electric bike technology are the need for frequent external battery recharging and constrained per-charge riding range [3]. Self-charging electric vehicles that can actively replenish their own batteries while driving, by harvesting renewable energy from onboard sources, provide an enticing solution that could elevate e-bikes to the convenience level of gas-powered transport [2].

Electric bicycles, with their lightweight frames and significant rider exposure to sunlight, offer a suitable platform for effectively implementing solar-based self-charging concepts [1]. Beyond solar photovoltaics, a variety of approaches leveraging other ambient energy sources have been explored in research literature to realize self-charging capabilities in e-bikes, such as micro wind turbines, piezoelectric vibration harvesting, and regenerative braking [1, 5, 6]. Intelligent blending of multiple complementary energy harvesting and charging mechanisms is critical to enable continuous self-charging functionality across changing environmental factors [3, 4].

Moreover, self-charging electric bicycles open up the ability to feed stored electricity back to the main power grid when parked and idle, known as vehicle-to-grid (V2G) technology [1, 4]. Networks of self-charging e-bikes could provide critical backup electricity supply during grid outages or natural disasters, making e-bike fleets exceptionally well-suited to provide emergency power when and where it is needed most [2].

However, substantial technical challenges across fields like systems engineering, power electronics, electrochemistry and controls still remain to fully realize the potential of multi-source self-charging energy-autonomous e-bike systems at commercial scale [4]. The "Multi-Source Self-Charging Electric Bicycle" applied research initiative aims to address these challenges through an ambitious effort to create a fully self-reliant electric bicycle prototype integrating solar panels, wind turbines, vibration energy harvesting, and regenerative braking capabilities coordinated by an intelligent Electrical Control Unit (ECU) [5, 6]. This transformative self-charging approach aims to help overcome critical range and charging limitations of traditional electric bicycles, aligned with broader efforts to achieve sustainable, low-carbon transportation futures [3].

II.RELATED WORK

Numerous research efforts have explored various aspects of self-charging and sustainable electric vehicle technologies, with a specific focus on electric bicycles (e-bikes). The following literature review highlights relevant previous work in this domain. Energy harvesting techniques for self-charging systems have been extensively studied. Dias et al. [1] designed a controller to regulate the current in an alternator rotor winding, enabling energy harvesting from an exercise bike. Corno et al. [2] introduced an intelligent charge-sustaining strategy for hybrid e-bikes, allowing adaptive battery charging from the rider's pedalling effort. The development of efficient motor controllers and power management systems for e-bikes has also been a key area of investigation. Khan et al. [3] designed an affordable brushless DC (BLDC) motor controller using an Arduino microcontroller for pedal-assist e-bikes in Bangladesh. Kallihal et al. [4] developed a control strategy for plug-in hybrid electric two-wheelers, aiming to reduce fuel consumption and emissions in Indian cities. Several studies have focused on the design and fabrication of self-charging e-bike prototypes. Hussain et al. [5] demonstrated an e-bike with a DC motor and dual battery sets, enabling self-charging through wheel rotation. Karthikeyan et al. [6] implemented a self-charging electric vehicle using rotational energy harvesting from a dynamo coupled to the rear wheel and solar panels.

Optimization models and strategies for self-charging systems have been proposed to enhance power transfer efficiency and range. Khalid et al. [7] presented an optimization model for a self-charging system (SCS) of electric vehicles, incorporating battery pack dynamics and wireless charging technology. Researchers have also explored various self-power generation mechanisms for e-bikes. Patil et al. [8] designed and tested a self-power generating bike using an alternator and DC booster for battery charging during motion. Sindagi et al. [9] developed a self-recharging e-bike incorporating regenerative braking and dual battery switching for extended range.

Recent work has focused on integrating multiple energy sources and advanced control systems for self-charging e-bikes. Thiyagesan et al. [10] presented a prototype that utilizes solar panels, regenerative braking, and optimized switching for self-charging. Koli et al. [11] explored integrating renewable generations like solar and wind for self-charging electric vehicles. Beyond self-charging capabilities, researchers have also investigated enhancing the functionality and user experience of e-bikes. More [12] designed an embedded system to add smart features to electric bicycles, such as calorie measurement, biometric unlocking, GPS tracking, and system analytics. Performance assessment and testing of self-charging e-bike prototypes have been conducted to evaluate their real-world viability. Ibrahim et al. [13] focused on the design, implementation, and testing of a self-charging electric bicycle, assessing its performance across different speeds and gradients. While the existing literature provides valuable insights into various aspects of self-charging electric vehicles, opportunities remain for further innovation and integration to realize practical, efficient, and sustainable e-bike solutions for urban mobility.

III.METHODOLOGY

The proposed Multi-Source Self-Charging Electric Bike (MSSCEB) aims to address the limitations of conventional electric bicycles, such as limited range and frequent recharging requirements, through an innovative integration of solar energy harvesting and intelligent power management utilizing multiple sources.

System Overview: The MSSCEB incorporates an efficient electric pedal-assist motor that provides the primary propulsion, allowing riders to pedal with electric assistance for an extended range and reduced effort. For continuous self-charging, the system integrates the following components:

- **High-Efficiency Solar Panels:** Mounted on the rear carrier, these panels harvest energy from sunlight while riding, charging the on-board batteries.

- **Generator:** A generator, either a dynamo or a small portable generator powered by an alternative fuel source, is integrated into the system to generate electricity for charging the batteries.

Electrical Control Unit (ECU) The Electrical Control Unit (ECU), designed using the Arduino platform, orchestrates real-time coordination between the solar panels, generator, dual swappable battery packs, and the drive motor. The key functions of the ECU include:

- **Dynamic Battery Swapping:** The ECU alternates between two battery packs, allowing one pack to power the motor while the other is charged from the solar panels and generator.
- **Power Distribution Optimization:** Algorithms optimize the power flow from the solar panels and generator to the batteries and motor, ensuring efficient usage of the generated energy.
- **Motor Control for Pedal Assist:** The ECU controls the electric motor to provide a smooth pedal-assist experience, amplifying the rider's pedalling input.

Power Train Integration The innovative power train combines the pedal-assist motor, dual battery packs synchronized by the ECU, solar panels replenishing the batteries, and the generator providing an additional charging source. Through this fusion of multiple energy sources managed by the intelligent ECU, the MSSCEB prototype demonstrates self-sustaining electric bicycle operation without the need for frequent stops to recharge from external sources.

Objectives By overcoming range anxiety and providing a convenient, zero-emission mobility solution, the MSSCEB project aims to accelerate the adoption of electric bicycles as a practical and eco-friendly mode of urban transportation.

IV. BLOCK DIAGRAM AND WORKING

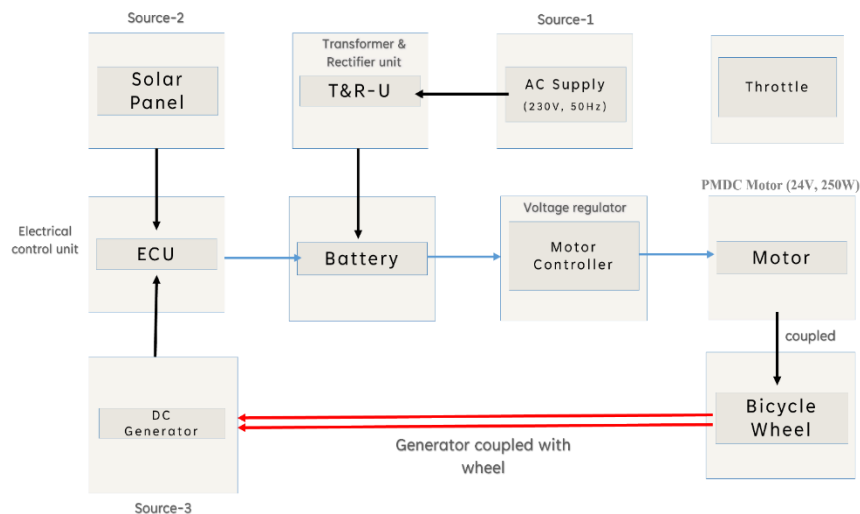


Fig (a): Block Diagram

The Multiple Source Self-Charging Electric Bicycle (MSSCEB) integrates three power sources: a solar panel, a generator connected to the bicycle wheel, and a mains supply. Both the solar panel and generator provide DC power, while the mains supply delivers AC power, converted to DC by a transformer and rectifier unit (T&R-U).

Working:

The core of MSSCEB comprises a dual lithium-ion battery setup, each pack rated at 12V, 7.5Ah. An Electronic Control Unit (ECU), powered by an Arduino board, orchestrates the management of battery packs and energy sources. Voltage sensor modules continuously monitor the state of charge (SoC) of both battery packs.

When one battery pack's SoC drops below a predefined threshold of 30%, the ECU triggers a switch using relays. The depleted pack is then connected to the charging sources - the solar panel mounted on the rear carrier and the regenerative motor coupled to the rear wheel. Simultaneously, the fully charged battery pack powers the 24V, 250W DC motor that propels the bicycle forward.

The regenerative motor, functioning as a generator during braking or deceleration, converts kinetic energy into electrical energy to recharge the batteries. This regenerative braking system not only enhances the overall efficiency but also recovers energy that would otherwise be dissipated as heat, further optimizing the bicycle's energy usage.

Additionally, the solar panel mounted on the rear carrier harnesses solar energy, providing a supplementary renewable charging source during rides. The ECU employs maximum power point tracking (MPPT) algorithms to extract the maximum available power from the solar panel under varying environmental conditions.

In cases where both battery packs become depleted, riders have the option to plug the charger into a standard wall outlet for recharging. Once the first battery pack is fully recharged, the ECU seamlessly switches the roles, connecting the freshly charged pack to the motor controller while diverting the depleted pack to the charging sources. This cyclic process, managed intelligently by the ECU, ensures continuous operation, effectively increasing the bicycle's range and overall efficiency.

Through the innovative integration of solar energy harvesting, regenerative braking, and intelligent dual-battery power management facilitated by the ECU, the MSSCEB exemplifies a truly self-sustaining and eco-friendly urban mobility solution, significantly reducing the need for frequent external charging stops while promoting sustainable transportation practices.

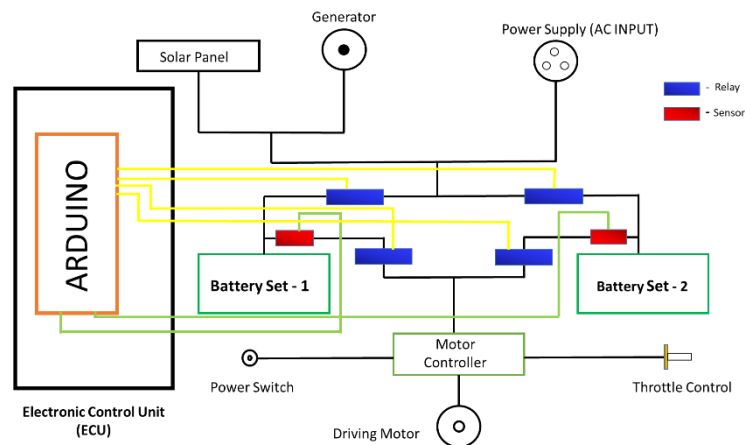


Fig (b): Electronic Control Unit (ECU)

The Electronic Control Unit (ECU) functions as the central decision-making component within the project, akin to the brain, overseeing energy management based on prevailing conditions. Comprising essential elements such as the Arduino UNO board, 250V relays, and voltmeter modules, the ECU operates as the nerve center, orchestrating crucial tasks to optimize battery usage and motor performance. Upon activation of the electric bicycle, the ECU springs into action, powered on to initiate its operational cycle. Its first task involves assessing the voltages of both battery packs through the voltmeter modules. This initial voltage check serves as the foundational data for subsequent decision-making processes.

With voltage data in hand, the Arduino UNO board housed within the ECU assumes the role of the analytical core, processing the voltage information to determine the most efficient allocation of resources. Specifically, it identifies the battery pack with the lowest voltage, signaling a priority for recharging. Simultaneously, the other battery pack, with a relatively higher voltage, is earmarked for powering the motor, ensuring uninterrupted operation of the electric bicycle. Crucially, the operation of the ECU hinges on the seamless coordination of the 250V relays. These relays act as the conduits for executing the ECU's decisions, facilitating smooth transitions between charging and motor power modes. Their functionality ensures that the electric bicycle experiences minimal disruption during the switching process, maintaining a steady and reliable performance throughout.

As the electric bicycle continues its journey, the ECU remains vigilant, constantly monitoring the state of charge (SoC) of both battery packs. When the SoC of the battery pack in use approaches a predetermined threshold, typically set at 30%, the ECU springs into action once more. This time, it orchestrates a seamless switch, redirecting the depleted battery pack to the recharging source while activating the fully charged battery pack to power the motor. In essence, the ECU serves as the linchpin of the project, harnessing the collective capabilities of its components to ensure efficient energy management and sustained performance of the electric bicycle. By intelligently allocating resources and seamlessly coordinating operations, the ECU embodies the project's ethos of self-sufficiency and eco-friendliness, contributing to a greener and more sustainable mode of urban transportation.

V. DESIGNING

The construction of an e-Bike capable of charging from multiple energy sources and intelligently managing battery switching aims to enhance efficiency and prolong battery lifespan.



The hardware components utilized in this innovative e-Bike project are as follows:

1. **DC Motor (24V, 250W):** Powers the bicycle for propulsion.
2. **Motor Controller:** Regulates the speed and power output of the DC motor.
3. **Motor Clamp:** Secures the DC motor to the bicycle frame.
4. **Batteries (4no, 12V, 7.5Ah):** Provide energy storage for the e-Bike's operation.
5. **Arduino UNO Board:** Serves as the brain of the Electronic Control Unit (ECU), managing decision-making processes.
6. **2 Channel 250V Arduino Relays:** Facilitate switching between battery packs for optimal energy utilization.
7. **DC Generator:** Converts mechanical energy from the bicycle wheel into electrical energy during braking for battery recharge.
8. **Voltmeter Module for Arduino:** Monitors battery voltages to inform the ECU's decision-making.
9. **Solar Panel:** Harvests solar energy to supplement battery charging during rides, enhancing sustainability.
10. **Bicycle:** The physical platform on which the e-Bike components are mounted and integrated.

The bicycle model is developed and tested, and the ECU functionality is simulated using specialized software. In this project, careful consideration is given to component selection and integration to achieve seamless operation and efficient energy management. The ECU, simulated using advanced software, orchestrates the intelligent management of energy sources and battery switching to optimize performance and prolong battery lifespan. Through the integration of multiple energy sources and smart decision-making algorithms, the e-Bike project represents a significant advancement in sustainable urban transportation technology.

Software Components:

The Arduino Integrated Development Environment (IDE) was used to program the Electronic Control Unit (ECU) for managing the charging and discharging cycles of the two battery packs in the electric bike system. The ECU code, written in C++, continuously monitors the voltage levels of both batteries through analog inputs connected to voltage sensors.

When a battery's voltage drops below a predefined threshold, the ECU activates relays to disconnect that battery from the load (motor) and connect it to the charging sources (solar panel and regenerative braking system). Simultaneously, the other battery pack, if sufficiently charged, is connected to the load to power the electric bike's motor.

This alternating charging and discharging cycle, controlled by the ECU, ensures that one battery is always charging while the other powers the load, maximizing the range and efficiency of the system. The ECU code also displays battery voltage levels and the system's current state (charging or supplying load) on an LCD for user feedback.

The Arduino IDE's user-friendly interface and compatibility with various libraries and hardware components made it a suitable choice for programming the ECU and integrating it with the electric bike system's components.

VI.RESULTS AND ANALYSIS

1, Test Run using only One Set of Batteries: In this configuration, the electric bike system operated using a single set of lead-acid batteries without any charging or battery swapping mechanism. The batteries were allowed to discharge continuously until reaching the predetermined low voltage threshold of 23.8V, representing approximately 30% state of charge (SoC).

Trial No.	Initial Battery Voltage (V)	Final Battery Voltage (V)	Distance Covered (km)	Top Speed (km/h)	Average Speed (km/h)
1	24.2	23.8	7.5	17	15
2	24.1	23.8	6.45	16	13
3	24.2	23.8	6.8	17	14

Table 1:Results Obtained using only One set of Batteries

Across the trials, the average time taken for a single set of batteries to discharge from the initial voltage to the low voltage threshold of 23.8V was approximately 29 minutes. This limited operational time and range highlight the need for a more efficient power management system to extend the bike's capabilities.

2, Test Run using Two Sets of Batteries (Continuous Discharge): In this configuration, the electric bike system utilized two sets of lead-acid batteries connected in parallel. The batteries were allowed to discharge continuously, with the second set taking over once the first set reached the low voltage threshold of 23.8V.



Trial No.	Initial Battery 1 Voltage (V)	Initial Battery 2 Voltage (V)	Final Battery Voltage (V)	Distance Covered (km)	Top Speed (km/h)
1	24.2	24.2	23.8	15	17
2	24.1	24.2	23.8	14	16
3	24.2	24.0	23.8	14	17

Table 2:Results Obtained using two set of Batteries

With the continuous discharge of both battery sets, the average time taken for the system to reach the low voltage threshold of 23.8V was approximately 59 minutes. While this configuration doubled the operational time compared to using a single battery set, it still lacked an efficient power management strategy to further extend the range and optimize battery utilization.

3, Test Run using Both Sets of Batteries (ECU + Charging): In this configuration, the electric bike system incorporated the Electronic Control Unit (ECU) to intelligently manage the charging and discharging cycles between the two battery sets. The ECU alternated between charging one battery set using the solar panel and regenerative braking system while the other set powered the motor, aiming to maximize the range and efficiency of the system.

Trial No.	Initial Battery 1 Voltage (V)	Initial Battery 2 Voltage (V)	Final Battery Voltage (V)	Distance Covered (km)	Top Speed (km/h)	Average Speed (km/h)
1	24.2	24.2	23.8	18.52	17	15
2	24.1	24.2	23.8	17.2	16	14
3	24.2	24.2	23.8	18.52	17	15

Table 3:Results Obtained using ECU+ Two set of Batteries

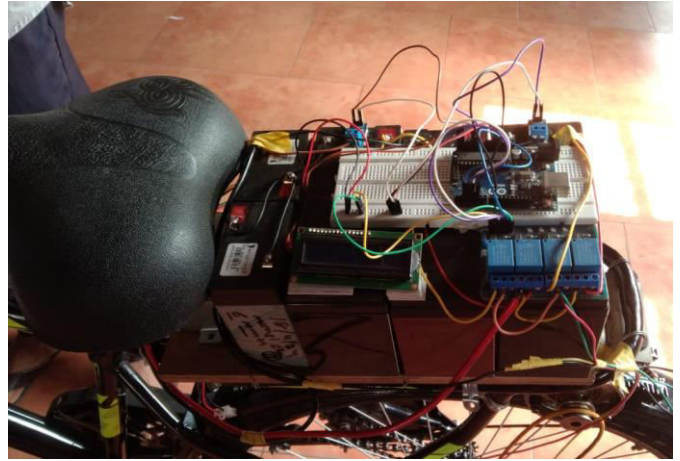
With the integration of the ECU and the intelligent charging mechanism, the average time taken for both battery sets to reach the low voltage threshold of 23.8V was approximately 74.1 minutes. This represents a significant improvement of approximately 20.5% compared to the continuous discharge configuration, demonstrating the effectiveness of the proposed power management strategy.

Additionally, the distance covered and average speeds achieved in this configuration were notably higher, further highlighting the benefits of the ECU-controlled charging system in extending the range and overall performance of the electric bike.

The results clearly demonstrate the advantages of incorporating an intelligent power management system, such as the ECU, in conjunction with multiple charging sources (solar panel and regenerative braking) and a dual battery architecture. By optimizing the charging and discharging cycles, the electric bike's range and operational time can be significantly enhanced, making it a more practical and reliable solution for urban mobility.



Fig(c): Developed Model



Fig(d): Developed Electronic control unit

The developed prototype of the electric bike system is shown in the accompanying figures. Fig(c) depicts the overall model of the electric bicycle, which incorporates the dual battery architecture, the solar panel for supplementary charging, and the electronic control unit (ECU). The ECU, housed in a compact enclosure, acts as the brain of the system, intelligently managing the charging and discharging cycles of the two battery packs. Fig (d) showcases the ECU developed for this project, which is based on an Arduino board and connected to the necessary components such as relays, voltage sensors, and an LCD display. The ECU continuously monitors the battery voltages and dynamically switches between charging one battery pack while the other powers the motor, ensuring optimal utilization of the available energy sources and extending the overall range and operational time of the electric bike.

VII.CONCLUSION

The multi-source self-charging electric vehicle system, exemplified by the prototype electric bike, addresses range limitations and dependence on external charging infrastructure, significant barriers to electric vehicle adoption. By integrating solar panels, regenerative braking, and intelligent battery management, this approach extends the vehicle's range, promotes energy efficiency, and reduces operational costs. The prototype bike achieved a 20.5% efficiency increase compared to a single-battery system, demonstrating the technology's potential.

While the current prototype highlights the feasibility and advantages, areas for improvement include addressing weight, complexity, and potential higher initial costs. Future developments could incorporate advanced energy storage technologies, explore additional renewable energy sources, integrate wireless charging, and enable intelligent routing and energy optimization through autonomous and connected vehicle technologies.

The multi-source self-charging electric vehicle concept represents a significant step towards a more sustainable and eco-friendly transportation future, aligning with efforts to combat climate change and promote sustainable development. Overcoming challenges and hurdles through continued research, innovation, and collaboration among stakeholders will be crucial in bringing the benefits of this technology to the mainstream and revolutionizing electric mobility towards a cleaner, more efficient, and more sustainable transportation ecosystem.

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