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RECENT ADVANCES IN GRID-CONNECTED SOLAR EV CHARGING SYSTEMS: DESIGN, OPTIMIZATION, AND CHALLENGES

Jyoti Kushwaha
M.Tech Scholar
Department of Electrical Engineering
Aryabhatta College of Engineering and Research Center, Ajmer, Rajasthan, India

Jitendra Kumar Sharma
Assistant Professor
Department of Electrical Engineering
Aryabhatta College of Engineering and Research Center, Ajmer, Rajasthan, India

Abstract- The increasing adoption of electric vehicles (EVs) has emerged as a sustainable solution for reducing greenhouse gas emissions, lowering operating costs, and minimizing dependence on fossil fuels. EVs utilize rechargeable battery systems as their primary energy source, requiring efficient and reliable charging infrastructure. Solar photovoltaic (PV) technology offers a clean and renewable method for generating electricity to support EV charging applications. A grid-connected solar charging system integrates PV panels with the utility grid to ensure continuous power availability and improved energy management. The incorporation of Battery Storage Systems (BSS) further enhances system flexibility by storing excess solar energy and supplying power during periods of low solar irradiance or high charging demand. Such hybrid charging stations reduce the burden on the utility grid, improve energy utilization, and enhance overall system reliability and economic viability. This review presents a comprehensive overview of solar-powered EV charging systems, various categories of electric vehicles, grid-connected charging architectures, and recent methodologies employed in the design and optimization of solar EV charging infrastructure. The study also discusses key design considerations, operational challenges, and future prospects for developing efficient, sustainable, and intelligent EV charging networks.

Keywords- *Electric Vehicles (EVs), Solar Photovoltaic (PV) System, Grid-Connected Charging Station, Battery Storage System (BSS), Renewable Energy, EV Charging Infrastructur, Energy Management, Sustainable Transportation.*

INTRODUCTION

The concept of electric vehicles (EVs) dates back to the nineteenth century, with early developments occurring during the 1880s. However, the widespread adoption of EVs gained momentum only in the twentieth and twenty-first centuries due to technological advancements in battery systems, power electronics, and electric propulsion technologies. Unlike conventional internal combustion engine (ICE) vehicles, electric vehicles operate using electric motors powered by rechargeable battery packs and do not require complex gear-shifting mechanisms. The overall performance of an EV largely depends on factors such as battery capacity, driving range, charging infrastructure, and motor efficiency [1].

One of the most significant advantages of electric vehicles is their environmentally friendly operation. EVs produce zero tailpipe emissions during operation, thereby contributing to the reduction of greenhouse gas emissions and improving urban air quality. The replacement of conventional fuel-powered vehicles with EVs helps reduce pollutants such as carbon monoxide (CO), hydrocarbons (HC), particulate matter, nitrogen oxides (NOx), volatile organic compounds (VOCs), ozone-forming compounds, and lead emissions. Although indirect emissions may arise from electricity generation sources used for battery charging, the overall environmental impact remains considerably lower than that of traditional vehicles. The integration of renewable energy resources with EV charging infrastructure can further minimize carbon emissions and promote sustainable transportation.

Electric motors offer several technical benefits, including high power-to-weight ratios, instant torque generation, high efficiency, and reduced maintenance requirements. The absence of clutches and multi-speed gearboxes simplifies the vehicle drivetrain and enhances reliability. EVs can provide superior acceleration performance, especially at lower speeds, because electric motors deliver maximum torque from standstill conditions [2]. In many modern EV designs, the motors are directly coupled to the wheels, enabling efficient power transmission and regenerative braking capabilities. These features contribute to improved vehicle performance, energy efficiency, and driving comfort.

1.1 Renewable Energy

Renewable energy refers to energy derived from naturally replenishing resources that are continuously available in the environment. These resources include solar energy, wind energy, hydropower, biomass, geothermal energy, tidal energy, and biogas. Renewable energy technologies have gained considerable attention worldwide due to growing concerns about climate change, depletion of fossil fuel reserves, and environmental sustainability. According to various energy policies and regulations, renewable energy sources play a crucial role in achieving energy security and reducing greenhouse gas emissions.

Solar radiation serves as the primary source of most renewable energy forms. Wind energy, for example, originates from uneven heating of the Earth's surface by solar radiation, creating pressure differences that generate atmospheric motion. Renewable energy systems offer numerous advantages, including reduced environmental impact, sustainable energy production, lower operational costs, and enhanced energy independence. The integration of renewable energy with electric vehicle charging infrastructure provides an effective solution for sustainable transportation and smart energy management.

1.2 Wind Energy

Wind energy is one of the fastest-growing renewable energy technologies worldwide. Wind is created due to atmospheric pressure differences caused by uneven solar heating of the Earth's surface. These pressure gradients result in the movement of air masses from high-pressure regions to low-pressure regions. The Earth's rotation further influences wind patterns through the Coriolis effect, resulting in complex global and regional wind circulation systems.

The utilization of wind energy dates back several centuries when windmills were employed for agricultural activities, water pumping, grain milling, and navigation. Modern wind energy systems convert the kinetic energy of moving air into electrical energy using wind turbines. Wind power generation offers several benefits, including zero fuel consumption, low greenhouse gas emissions, and reduced dependence on conventional energy sources. Due to technological advancements, wind energy has become a major contributor to renewable electricity generation and plays an essential role in supporting sustainable energy systems.

1.3 Solar Photovoltaic (PV) Electricity Generation

Solar photovoltaic (PV) technology converts sunlight directly into electrical energy through the photovoltaic effect. Solar cells, typically manufactured using semiconductor materials such as silicon, absorb solar radiation and generate electrical current. Solar PV systems have emerged as one of the most promising renewable energy technologies due to their scalability, reliability, and decreasing installation costs.

The electricity generated from solar PV systems can be utilized for residential, commercial, industrial, and transportation applications. In electric vehicle charging infrastructure, solar PV systems provide a clean and sustainable energy source that reduces reliance on conventional grid electricity. Another major solar energy technology is Concentrated Solar Power (CSP), which converts solar radiation into thermal energy before generating electricity. However, photovoltaic systems remain the most widely adopted solar technology due to their simplicity, modularity, and ease of integration with battery storage systems and smart grids.

RELATED RESEARCH

Evelyn-Astrid et al. (2018) proposed a modeling, design, and control approach for DC-DC converters using the state-space averaging method. Their work focused on managing power flow among batteries, ultracapacitor-based energy storage systems (ESS), and load demands. The proposed converter architecture employed dual half-bridge topologies to achieve efficient energy transfer and system stability. The control strategy was developed using alternating-current equivalent circuit models, enabling improved dynamic response and energy management performance.

Mochamad Abdul et al. (2018) investigated advanced battery charging technologies for Battery Energy Supply (BES) systems. The study highlighted the growing demand for efficient battery charging solutions and examined various power converter topologies utilized in modern charging systems. The authors emphasized the importance of converter efficiency and voltage regulation during charging operations. Although several converter designs demonstrated satisfactory charging performance, challenges associated with switching losses and load-sharing mechanisms remained significant research concerns.

Karri Hemanth et al. (2019) presented a bidirectional DC-DC converter designed specifically for electric vehicle charging applications. The proposed converter operated in both buck and boost modes, providing a wide voltage conversion range while reducing the number of components compared with conventional bidirectional converter designs. Detailed analyses of voltage and current transfer characteristics, semiconductor stress levels, and passive component sizing were conducted. Experimental validation using a 3.2 kW prototype demonstrated the converter's effectiveness in EV charging and energy storage applications.

Milad Babalou et al. (2019) explored modular multilevel converter (MMC) technology for battery testing systems used in electric vehicles, renewable energy systems, and mobile electronic devices. The study reviewed the application of MMCs in high-voltage and medium-voltage power conversion systems. The authors identified capacitor voltage balancing as a major challenge in DC-DC converter implementations based on MMC architectures. To overcome this issue, hybrid converter structures incorporating AC-DC and DC-AC stages were investigated.

Hossein Gholizadeh et al. (2021) proposed a high step-up DC-DC converter suitable for renewable energy and electric vehicle applications. The converter design incorporated voltage multiplier cells integrated with a conventional boost converter topology. Both ideal and non-ideal operating conditions were analyzed to evaluate voltage gain, efficiency, and component stress characteristics. The proposed configuration demonstrated enhanced voltage conversion capability while maintaining high efficiency and reduced switching losses.

Jun Mei et al. (2021) introduced a non-isolated bidirectional DC-DC converter optimized for energy storage systems. The converter consisted of two series-connected boost converter stages and incorporated switched-capacitor cells on the high-voltage side. A coupled inductor replaced multiple inductors on the low-voltage side, reducing component count and improving power density. The proposed design achieved efficient bidirectional power transfer between battery storage systems and electric vehicle charging networks.

Kun Qu et al. (2021) developed a non-isolated bidirectional buck-boost DC-DC converter integrated with a sliding mode control strategy for lightweight electric vehicle applications. The proposed system included advanced sensing and control components such as voltage sensors, current sensors, operational amplifiers, output comparators, and microcontroller-based control units. Experimental results demonstrated improved voltage regulation, system stability, and energy management performance, making the converter suitable for next-generation electric mobility solutions.

ELECTRIC VEHICLE OVERVIEW

It is the holy grail of electric cars because it doesn't need internal combustion engines to move them. At 90%–95% of the total energy they use, electric motors are very energy-efficient. When an electric car has a battery, a port to charge it, and a charger, these three parts are very important. Other important parts are the DC/DC converter and the power electronics controller, as well. This is another important part of an electric car. Battery-powered electric cars are moved by an electric motor that converts the stored electricity into mechanical torque. When electric cars (EVs) are charged with low-emission power sources, they help the environment. When the batteries run out, the grid comes in and gives them a boost. It must have a battery that can store the energy it needs in order for an electric car to work, Because lithium-ion batteries are light and don't need a lot of attention, they are often used in electric cars. In order to make these lithium ion batteries, they cost more to make than nickel-metal hydride and lead-acid batteries.

There are some Li-ion batteries that have a shelf life of up to 12 years if they are properly cared for. In order to recharge the battery, the car's charging connector connects to an outside power source through a charger. It takes an alternating current supply from the power source and turns it into a form that can be used to charge the battery through a charging port. When the battery is being charged, it keeps a close eye on the battery's voltage, current, temperature, charge status and other important things like that. The car's DC/DC converter converts the high voltage direct current (DC) from the battery to low voltage direct current (DC) for the car's accessories to run on (DC). By controlling the flow of electricity from the traction battery, the power electronics controller makes sure the traction motor runs at the right speed and has the right torque. Regenerative braking is a must if you want to keep the car's strength and make it more energy efficient. Uses the mechanical energy from the engine to make electricity that can be sent back into the battery.

Hybrid and battery electric cars both use regenerative braking to help them go further. Regenerative braking is when the electric motor of a car can be used to move it forward while the brake is on. 15% of the energy needed to accelerate can be reused. Even though it's good, it can't fully charge the electric car. The drive system moves the car forward by transferring mechanical energy to the traction wheel. It doesn't matter what parts you use to make an electric car because it doesn't need a traditional gearbox. Some wheel-by-wheel systems use a lot of small motors to power each wheel. Differential housing and an electric motor can also be used to power the rear wheels, but this isn't the only way to go. The parts of a gasoline-powered car are more complicated and hard to understand than the parts of an electric car. Electric cars, on the other hand, won't be able to reach the same speeds as cars that run on gasoline.

If there is a large series of vehicles in operation, the provision of additional services from electric vehicles is a very viable option [40] As Kempton et al. [40] In 2001, due to power restrictions, only one electric vehicle was able to enter the power market or establish a business relationship with the power agency.

There are many reasons behind the installation of electric car chargers. First, in the current market situation, individual participation in small groups is prohibited. In addition, it allows for the simplest connection to the DSO in troubleshooting. The use of appropriate strategies can reduce the risk of traffic accidents.

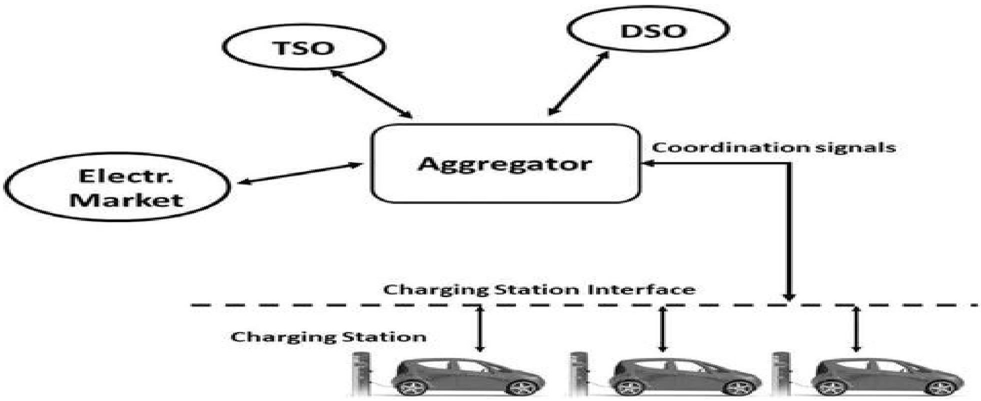

Figure 1. Simplified EV coordination framework: transmission system operator (TSO), distribution system operator (DSO), electric market, and charging stations for EVs.

With the increase in PV penetration of low-power power lines, EV load control can improve feeder performance and reduce investment requirements for infrastructure upgrades. In plates with such a high permeability, there is a constraint to keep in mind. The customer will evaluate the improvement in reliability, quality, and price. We expect a significant change in the quality of power in the near future, which aims to reduce the long-term changes in power growth that occur in the environment of decentralized RES production. In theory, we know that balancing car loads can promote a local balance between production and consumption, which can reduce power shortages and overheat.

TYPES OF ELECTRIC VEHICLES

People in China, the United Kingdom, the United States of America, and Germany still buy electric cars the most. Electric cars are becoming more popular all over the world. BEVs are a subset of HEVs and

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PHEVs. Hybrid electric vehicles (HEVs) are also a subset (BEV).

4.1 Hybrid electric vehicle

Internal combustion engines and electric motors make up the parts of a hybrid electric vehicle. The battery in this car is charged by the engine and the kinetic energy that is released when the car is going up and down. They are called "hybrids" because of the power converter that they use that combines a gas engine with an electric motor. Hybrid electric vehicles have become very popular around the world because they can run at full speed without needing to be charged. This is because they can run at full speed without needing to be charged.

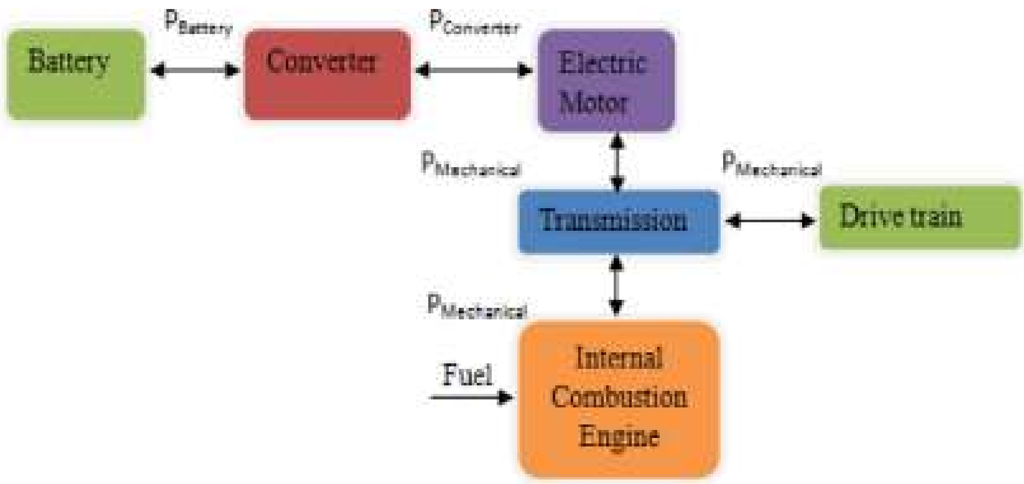

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Figure 2. Power flow of parallel HEV

By electrifying the drive train, they may also drastically reduce their fuel use. The HEV may be connected in a number of topologies, depend on the kind of hybrid system. In a series hybrid, the wheels are powered only by electricity. The motor is powered by the battery or the generator. Either the battery or the generator is used to power the motor. Battery power is supplied to the electric motor via an integrated circuit engine. Battery or engine/generator power is determined by a computer that monitors the amount of energy being generated. Both the engine/generator and regenerative braking are used to power the battery pack [24]. Smaller internal combustion engines are common in series HEVs, which have bigger batteries and larger motors. Using ultra-caps, which increase the battery's efficiency and hence cut down on waste, they may do this. When braking, they store the kinetic energy and release it during acceleration. The following are some of the benefits of a series hybrid drive train for them: Since the internal combustion engine and drive wheels are mechanically decoupled, it is possible for the IC engine to operate within a small range of performance that is optimized for torque and speed. In contrast, there are some disadvantages to using a series hybrid drive train. They are. It will be less efficient because the energy has to go from mechanical to electrical and then back again.

4.2 Plug-in hybrid electric vehicle

PHEVs have both a gasoline engine and an electric motor (PHEV). People who drive these cars use gas, but they have a big battery that can be charged with electricity. There are a lot of good things about plug-in hybrid electric cars: Reductions in the use of petroleum It is thought that PHEVs use 30 to 60% less oil than traditional cars do. A plug-in hybrid car reduces the country's dependence on oil because most of the electricity used in the United States comes from the country itself. Emissions of greenhouse gas It's common for PHEVs to emit less greenhouse gas than traditional cars. Some of the time, however, the amount of gas that is released depends on the process that is used to make electricity.

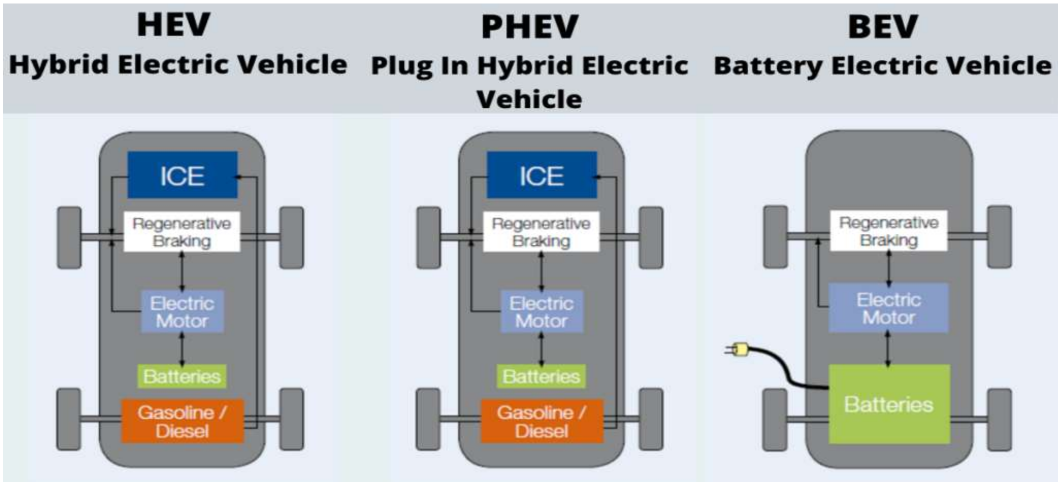

Figure 3. Classification of Electric vehicle[43]

India has emerged as one of the fastest-growing automotive markets in the world and is gradually embracing electric mobility as a sustainable transportation solution. Despite significant government initiatives and increasing environmental awareness, the penetration of electric vehicles (EVs) in the Indian automobile sector has remained relatively limited compared to conventional fuel-powered vehicles. During the early stages of EV adoption, annual sales remained modest, reflecting challenges such as high battery costs, limited charging infrastructure, and consumer concerns regarding driving range. However, recent technological advancements, policy support, and investments in charging networks have accelerated the growth of the EV sector.

The Government of India has introduced several initiatives, including the Faster Adoption and Manufacturing of Electric Vehicles (FAME) scheme, to promote electric mobility and reduce dependence on fossil fuels. Market forecasts indicate substantial growth in EV adoption over the coming decades, with electric vehicles expected to constitute a significant portion of new vehicle registrations. The transition toward electric transportation is further supported by advancements in battery technology, renewable energy integration, and smart charging solutions.

India's journey in electric mobility began with early electric vehicle models such as the Reva electric car, which was introduced in the early 2000s and later acquired by Mahindra Electric. Although the initial market response was limited, the vehicle demonstrated the feasibility of electric transportation in Indian conditions. Subsequently, hybrid vehicles such as the Toyota Prius and Toyota Camry Hybrid were introduced, showcasing alternative propulsion technologies that combine internal combustion engines with electric motors. In recent years, electric buses, electric two-wheelers, electric three-wheelers, and electric passenger vehicles have been deployed and tested across several Indian cities, contributing to the country's transition toward sustainable mobility.

The increasing adoption of EVs is expected to play a crucial role in reducing greenhouse gas emissions, improving urban air quality, and enhancing energy security. However, the success of this transition depends heavily on the development of efficient charging infrastructure, renewable energy integration, and advanced energy management systems.

DISCUSSION AND FUTURE SCOPE

The present research primarily focuses on the energy storage and control systems associated with electric vehicle charging infrastructure. To develop an efficient and reliable charging framework, renewable energy sources such as solar photovoltaic systems, battery storage units, and utility grid connections have been considered. Various power electronic converters, including boost converters and inverters, have been incorporated into the system architecture to facilitate effective energy conversion and power management. Furthermore, optimization techniques have been utilized to improve the operational efficiency of the charging station under varying load conditions.

A comprehensive investigation was carried out to address critical challenges associated with electric vehicle charging systems. The study involved the careful selection of battery storage technologies with appropriate ratings and operational characteristics. Renewable energy integration was considered an essential component for reducing dependence on conventional grid power and enhancing environmental sustainability. Advanced converter topologies and intelligent control strategies were employed to ensure efficient energy transfer between renewable sources, battery storage systems, and electric vehicle loads.

The proposed charging infrastructure was evaluated through the simulation of two different electric vehicle charging stations operating under varying State of Charge (SOC) conditions. The analysis demonstrated the ability of the system to provide uninterrupted charging services while maintaining stable operating conditions. The integration of battery storage systems significantly improved charging reliability and reduced fluctuations in power availability. The results indicated that the proposed configuration can effectively support electric vehicle charging requirements while minimizing stress on the utility grid.

The operational strategy of the charging station is based on battery State of Charge management. When the battery SOC exceeds 90%, the stored energy is utilized to supply power directly to electric vehicles, thereby reducing dependence on the utility grid. Conversely, when the SOC falls below 90%, the battery storage system is recharged through the grid and renewable energy sources to maintain adequate energy reserves. This strategy ensures continuous availability of charging power while optimizing energy utilization and enhancing system reliability.

Future research can further improve the performance of renewable energy-based EV charging systems through the implementation of advanced Maximum Power Point Tracking (MPPT) techniques for solar photovoltaic and wind energy systems. Intelligent MPPT algorithms can maximize energy extraction under varying environmental conditions, thereby improving overall system efficiency. Additionally, hybrid renewable energy systems integrating solar, wind, and battery storage technologies can provide more reliable and sustainable charging solutions.

Although the proposed system demonstrates satisfactory long-term performance, power quality issues remain an important area for future investigation. Challenges such as voltage sags, voltage swells, harmonics, flicker, and transient disturbances can negatively affect system operation and reduce the effectiveness of renewable energy integration. The increasing use of power electronic converters can further influence power quality characteristics and energy efficiency.

To address these challenges, advanced compensation devices such as Distribution Static Compensators (DSTATCOM), Static Synchronous Compensators (STATCOM), Unified Power Quality Conditioners (UPQC), and active filtering techniques can be incorporated into future charging station designs. These technologies can improve voltage regulation, enhance power factor correction, reduce harmonic distortion, and increase overall system stability. DSTATCOM can effectively support load compensation and reactive power management, while STATCOM devices contribute to system security and voltage stabilization.

Furthermore, the integration of artificial intelligence, machine learning, and predictive analytics can significantly enhance energy management capabilities. Accurate forecasting of solar irradiance, wind speed, electricity demand, and charging requirements can enable more efficient scheduling and control of energy resources. Smart energy management systems equipped with advanced optimization algorithms can further improve charging station performance, reduce operational costs, and support large-scale deployment of electric vehicles.

In conclusion, the continued development of renewable energy-based charging infrastructure, advanced energy storage systems, intelligent control techniques, and power quality enhancement technologies will play a vital role in accelerating electric vehicle adoption and establishing a sustainable transportation ecosystem for the future.

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