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"Advanced Technologies In Electric And Hybrid Vehicles"

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Abstract: The global automotive industry is shifting towards electric and hybrid vehicles to address environmental concerns and reduce fossil fuel dependence. Key advancements in battery technology, such as lithium-ion and solid-state batteries, have improved energy capacity, safety, and charging times. Enhanced power electronics, motor designs, and regenerative braking systems increase overall efficiency and performance. The use of lightweight materials and development of fast-charging networks extend vehicle range and usability. Furthermore, the integration of digital tools like artificial intelligence and vehicle-to-grid communication is revolutionizing vehicle connectivity and energy management. This paper examines these innovations and their role in driving the future of sustainable transportation.

Keywords: Electric Vehicles (EVs), Hybrid Electric Vehicles (HEVs), Battery Technology, Lithium-ion Batteries, Solid-State Batteries, Battery Management Systems (BMS), Power Electronics, Electric Motors, Regenerative Braking, Lightweight Materials, Fast Charging, Vehicle-to-Grid (V2G), Artificial Intelligence (AI), Sustainable Transportation, Energy Efficiency.

I. INTRODUCTION

The growing need to reduce carbon emissions and dependence on fossil fuels has accelerated the shift toward sustainable transportation. Electric vehicles (EVs) and hybrid electric vehicles (HEVs) have become leading alternatives to traditional internal combustion engine (ICE) vehicles. Technological advancements in batteries, electric drivetrains, and power electronics have significantly improved their range, efficiency, and performance. Lithium-ion and solid-state batteries now offer higher energy density and faster charging. Regenerative braking, smart energy management, and lightweight materials further enhance overall vehicle efficiency. Integration of vehicle-to-grid (V2G) systems and artificial intelligence enables smarter, more connected transportation. This paper explores these advanced technologies, their current applications, and future potential in reshaping mobility.

As the demand for clean transportation grows, manufacturers and researchers continue to invest in innovation to overcome existing limitations. Challenges such as charging infrastructure, battery recycling, and high production costs remain critical areas of focus. By examining current trends and breakthroughs, this study aims to provide insights into the direction of future developments in EV and HEV technology. Ultimately, these advancements will play a pivotal role in creating a cleaner, smarter, and more sustainable transportation ecosystem.

II. LITERATURE REVIEW

The rapid advancement of electric and hybrid vehicle technologies has been extensively documented over the past decade. Battery technology remains a primary focus, as it directly impacts vehicle range, charging time, and cost. Lithium-ion batteries currently dominate the market due to their high energy density and long cycle life. Research into solid-state batteries has shown promise, offering improved safety, faster charging, and greater energy storage capabilities, potentially overcoming the limitations of traditional lithium-ion cells (Tarascon & Armand, 2001; Goodenough & Park, 2013).

Battery management systems (BMS) play a crucial role in ensuring battery safety and longevity by monitoring cell voltages, temperatures, and charge states. Studies emphasize the importance of advanced BMS algorithms that enable real-time fault detection and thermal management, significantly improving performance and reliability in EVs and HEVs (Zhang et al., 2017; Piller et al., 2001).

Power electronics and electric motor designs have also evolved rapidly. Innovations in semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN) have led to more efficient, compact, and thermally robust inverters and converters.



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These advances directly translate to improved energy efficiency and power density in electric drivetrains (Baliga et al., 2013; Kim et al., 2020). Meanwhile, permanent magnet synchronous motors (PMSM) and induction motors are widely researched for their high torque-to-weight ratios and reliability (Krause et al., 2013).

Regenerative braking technology, which recovers kinetic energy during deceleration, has become a standard feature in EVs and HEVs. Studies show that efficient energy recovery can improve overall vehicle efficiency by up to 20%, especially in urban driving conditions (Gao et al., 2015). Integration with intelligent energy management systems further optimizes the power split between electric and internal combustion engines in hybrid models (Lin & Gao, 2018).

Lightweight materials such as aluminum alloys, magnesium, and carbon-fiber composites are increasingly used to reduce vehicle mass. This reduction in weight is crucial for extending driving range and improving acceleration without sacrificing safety. Research highlights challenges related to material costs and manufacturability, but ongoing development aims to make these materials more affordable and scalable (Anderson & Shkolnikov, 2019).

The deployment of fast-charging infrastructure and wireless charging technology is critical for user convenience and widespread EV adoption. Recent studies have explored the potential of highpower chargers capable of delivering 150 kW or more, enabling 80% charge in under 30 minutes (Smith et al., 2020). Wireless charging, while still emerging, offers the potential for seamless and automated recharging, especially for urban and fleet applications (Kurs et al., 2007).

Lastly, the integration of digital technologies such as artificial intelligence (AI), machine learning, and vehicle-to-grid (V2G) communication is reshaping electric mobility. AI algorithms enable predictive maintenance, optimized route planning, and adaptive energy management, enhancing the overall user experience (Zheng et al., 2021). V2G systems allow vehicles to interact with the grid, providing energy storage and load balancing services that benefit both consumers and utilities (Lund & Kempton, 2008).

In summary, the literature indicates that ongoing advancements across multiple technological domains are essential to overcoming the challenges facing electric and hybrid vehicles. These innovations collectively contribute to making EVs and HEVs more efficient, reliable, and userfriendly, thereby accelerating their adoption and impact on sustainable transportation.



III. VEHICLE ARCHITECTURE

Fig.1. Advanced Technologies in electric and hybrid vehicles



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The image illustrates the architecture of advanced technologies used in electric and hybrid vehicles through a side-view diagram of the vehicle with clearly labeled components. At the heart of the system is the electric motor, which drives the wheels using power supplied by a high-capacity battery pack. In hybrid vehicles, an internal combustion engine is also integrated to provide additional power and extend the driving range. The power electronics controller plays a crucial role by managing the flow of energy between the battery, motor, and engine, ensuring optimal performance and efficiency. A DC-DC converter steps down the high voltage from the main battery to supply power to low-voltage systems such as lighting and infotainment, supported by an auxiliary battery. The onboard charger facilitates charging from external electric sources, while high-voltage cables connect and distribute power across the vehicle's electrical systems. Together, these components form a sophisticated and integrated system designed to optimize energy use, reduce emissions, and enhance the driving experience in modern electric and hybrid vehicles.

IV. KEY TECHNOLOGIES

a. Electric Propulsion System

The electric propulsion system is the heart of electric and hybrid vehicles. It replaces or complements the traditional internal combustion engine by using electric motors to drive the wheels. Key components include:

• Electric Motor: Converts electrical energy into mechanical energy. Common types are induction motors, permanent magnet synchronous motors (PMSM), and brushless DC motors.

Motor Controller: Regulates motor speed and torque by adjusting the electrical power delivered to the motor.
Transmission System: Often simplified compared to conventional vehicles, it transfers the motor's power to

the wheels.

Electric propulsion systems are valued for their high efficiency, instant torque delivery, and reduced mechanical complexity.

b. Battery Technology

Batteries serve as the main energy storage unit in electric and plug-in hybrid vehicles. They supply power to the electric motor and onboard electronics. Essential aspects include:

• **Battery Types**: Lithium-ion batteries are the most common due to their high energy density, long cycle life, and light weight. Other types include nickel-metal hydride (NiMH) and solid-state batteries (an emerging technology).

• **Battery Management System (BMS)**: Monitors and controls battery parameters such as voltage, current, temperature, and state of charge to ensure safe and efficient operation.

• **Charging Infrastructure**: Supports recharging batteries through Level 1 (standard outlets), Level 2 (faster home charging), and DC fast charging (rapid public charging).

Battery advancements are crucial for increasing vehicle range, reducing charging time, and enhancing safety.

c. Power Electronics

Power electronics manage the flow and conversion of electrical power in electric and hybrid vehicles. These systems ensure that energy is efficiently delivered from the battery to the motor and vice versa during regenerative braking. Key components include:

• Inverters: Convert direct current (DC) from the battery into alternating current (AC) for the electric motor.

• **Converters**: DC-DC converters adjust voltage levels between the battery and various vehicle systems (e.g., 400V to 12V for accessories).

Onboard Chargers: Convert AC from charging stations to DC for battery charging.

High-efficiency power electronics are vital for minimizing energy losses and improving overall vehicle performance.

d. Energy Management System (EMS)

An energy management system oversees how energy is distributed and used within the vehicle. In hybrid vehicles, EMS decides when to use the internal combustion engine, electric motor, or both, optimizing fuel economy and performance. In electric vehicles, it manages:

• Energy Flow Optimization: Determines the best way to use and conserve energy under different driving conditions.

• **Thermal Management**: Regulates the temperature of batteries, motors, and power electronics to ensure reliability and longevity.

Regenerative Braking Control: Captures and stores kinetic energy during braking for reuse.

The EMS plays a central role in balancing power demand, battery life, and driving efficiency.



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V. HYBRID SYSTEM CONTROL STRATEGIES

Hybrid system control strategies are essential in managing how hybrid electric vehicles (HEVs) utilize both the internal combustion engine and the electric motor to achieve optimal fuel efficiency, performance, and reduced emissions. These strategies rely on several key technologies that work together to ensure smooth operation. At the core is the Powertrain Control Unit (PCU), which makes real-time decisions on power distribution based on vehicle speed, battery level, and driving conditions. Supporting this is the Battery Management System (BMS), which monitors and controls the health, temperature, and charge of the battery to ensure safety and longevity. The Energy Management System (EMS) determines the most efficient way to use energy from both power sources, often using strategies such as rule-based logic, optimization algorithms, fuzzy logic, or machine learning to adapt to various driving situations. Electric drive systems, including electric motors, inverters, and controllers, enable both propulsion and regenerative braking, converting kinetic energy back into stored electrical energy. The internal combustion engine operates under strict control to deliver power only when necessary, often being shut off or restarted automatically to conserve fuel. Additionally, advanced transmission systems like electronic CVTs and power-split devices help blend power seamlessly between the engine and motor. Overall, these integrated technologies and intelligent control strategies are what make hybrid vehicles efficient, responsive, and environmentally friendly.

VI. REGENERATIVE BRAKING TECHNOLOGY

Regenerative braking technology is a key innovation in electric and hybrid vehicles that allows the vehicle to recover and reuse energy that would otherwise be lost during braking. Unlike traditional braking systems, which convert kinetic energy into heat through friction and dissipate it, regenerative braking captures this kinetic energy and converts it into electrical energy using the electric motor, which acts as a generator during deceleration. This recovered energy is then stored in the vehicle's battery for later use, improving overall energy efficiency and extending driving range. The system works seamlessly with conventional friction brakes in what is known as a "blended braking" system to ensure smooth and safe stopping. Regenerative braking not only enhances fuel economy and reduces battery charging frequency but also decreases wear on the mechanical brake components, leading to lower maintenance costs. As a result, it plays a vital role in the sustainability and performance of modern electric and hybrid vehicles.

VII. RECENT INNOVATIONS AND FUTURE TRENDS

Recent innovations in electric and hybrid vehicle technology focus on improving efficiency, performance, and sustainability. Solid-state and fast-charging battery technologies are enabling longer ranges and quicker recharging times. Advanced driver assistance systems (ADAS), artificial intelligence, and vehicle-to-everything (V2X) communication are enhancing safety and enabling semi-autonomous driving. Regenerative braking, wireless charging, and vehicle-to-grid (V2G) integration are also becoming more common, helping optimize energy use and grid support. Additionally, manufacturers are using more eco-friendly materials and modular platforms to reduce environmental impact and boost production flexibility. These advancements are shaping the future of cleaner, smarter, and more connected mobility.

VIII. CASE STUDIES OR INDUSTRY EXAMPLES

Several leading automotive companies have implemented advanced technologies in their electric and hybrid vehicles, serving as strong industry examples. **Tesla**, for instance, has pioneered overthe-air software updates, AI-based autopilot features, and energy-efficient powertrains in its fully electric lineup. **Toyota**, a hybrid pioneer, continues to evolve with its Prius and has introduced solid-state battery prototypes aimed at faster charging and longer range. **Hyundai and Kia** have adopted regenerative braking systems with customizable levels and integrated solar roofs to assist battery charging in models like the Hyundai Ioniq. **General Motors (GM)** is transitioning to an allelectric future with its Ultium battery platform, which supports a variety of vehicle sizes and types. Meanwhile, **Ford** has successfully launched the Mustang Mach-E and F-150 Lightning, combining traditional performance with electric innovation. These case studies reflect the industry's move toward smarter, more sustainable mobility solutions.

IX. CONCLUSION

In conclusion, electric and hybrid vehicles are rapidly transforming the future of transportation through continuous advancements in technology. Innovations in battery systems, regenerative braking, energy management, and intelligent control strategies are making these vehicles more efficient, reliable, and environmentally friendly. With the integration of AI, connectivity, and sustainable manufacturing practices, the automotive industry is moving toward cleaner and



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smarter mobility solutions. As governments and consumers increasingly prioritize sustainability, the adoption of these advanced technologies will play a critical role in reducing emissions and shaping the next generation of transportation. Continued research and development, combined with supportive policies, will accelerate the shift toward widespread use of electric and hybrid vehicles, ultimately contributing to a greener and more sustainable planet.

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