Efficient Power Management Strategy and Challenges of Hybrid Renewable Energy Based Electric Vehicles - A Review

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Abstract*—Forging a new paradigm in the automobile industry, hybrid electric vehicles (HEVs) coupled with renewable energy sources are a result of the increased focus on sustainable transportation. To better understand the difficulties involved in deploying hybrid renewable energy-powered electric vehicles, this article explores effective power management solutions. Power management techniques that are complex are required when integrating renewable energy sources, including solar and wind, with hybrid electric vehicles. Although the use of renewable energy in electric vehicles appears promising, several obstacles prevent widespread use. This study tackles dynamic difficulties such as the requirement for robust energy management systems, the intermittent nature of renewable energy sources, and the limited storage capacity aboard. The paper outlines new technological developments that aim to improve the incorporation of renewable energy sources into electric vehicles as a solution to the issues that have been highlighted. This review addresses the challenges associated with incorporation of renewable energy and electric vehicles. Addressing the challenges requires collaboration among stakeholders, technological advancements, and supportive policies to foster the widespread adoption of sustainable transportation solutions. The study highlights the effectiveness of various power management systems through case studies that show how hybrid renewable energy-based electric vehicles are used in the real world. The effective power management techniques and difficulties related to hybrid electric vehicles powered by renewable energy sources are thoroughly examined in this research. It adds to the current conversation on sustainable transportation by tackling the ever-changing problems and putting forward creative solutions, which could influence developments that could influence the direction of electric mobility in the future. The optimal utilization of energy provided from renewable sources, such solar panels or wind turbines, is ensured by effective power management. A cleaner and more sustainable transportation system is made possible by an effective power management plan, which maximizes the use of renewable energy. HREVs can benefit from the best grid conditions, electricity costs, and charging periods when they are integrated with smart charging infrastructure.

***Keywords*—Renewable Energy, Power Management, Electric Vehicles, Opportunities, Challenges**

I. Introduction

Hybrid electric vehicles (HEVs) that incorporate renewable energy sources have emerged as a result of the global search for ecologically responsible and sustainable transportation options [1]. This represents a major shift in the automotive industry. This paradigm change is consistent with the need to lessen the use of fossil fuels, improve overall energy efficiency, and lessen the impact on the environment. This study discusses the inherent difficulties in integrating hybrid renewable energy systems with electric vehicles and explores the crucial elements of creating an effective power management strategy. Conventional hybrid electric cars promise lower pollution and better fuel economy by combining internal combustion engines with electric propulsion technologies [2]. The progression of these automobiles towards the integration of sustainable energy sources, such solar, biomass, mechanical vibration and wind power, brings a fresh perspective to the industry [3]. Reducing transportation's carbon footprint and increasing fuel efficiency are the two goals of integrating renewable energy, which is in line with international efforts to mitigate climate change.

The successful integration of renewable energy into hybrid electric cars is contingent upon the implementation of efficient power management [4]. Examination is needed to maximize energy flow, power flow, and overall efficiency in hybrid electric vehicles that run on renewable energy sources. Investigate the difficulties in integrating renewable energy sources with electric hybrid cars. This entails tackling challenges related to irregularity and fluctuation as well as maximizing the use of energy produced from renewable sources. To achieve the best possible energy harvesting, storage, and usage, complex control systems are needed due to the intrinsic variability and intermittency of renewable sources. The need to create sophisticated algorithms and control techniques that can smoothly transition between conventional and renewable power sources while dynamically managing power flows is acknowledged in this work. There are difficulties in integrating renewable energy with electric vehicles [5]. This study recognizes and tackles several dynamic issues, such as the erratic nature of renewable energy sources, the capacity constraints of onboard energy storage, and the requirement for reliable energy management systems. These difficulties call for creative ways to maximize the utilization of renewable energy sources while preserving the dependability and efficiency anticipated from electric cars.

This research aims to present an extensive review of effective power management techniques for electric vehicles that are hybrid and powered by renewable energy sources. The goal of the study is to offer significant knowledge to the expanding corpus of research on sustainable transportation by looking at technology developments and approaches that tackle problems. In the following sections of this paper, we will focus on facets of effective power management, including sophisticated algorithms, new developments in technology, and case examples demonstrating practical implementations. The thesis will also investigate the effects of changing environmental factors on the overall effectiveness of electric vehicles powered by hybrid renewable energy sources [6]. In closing, the report will suggest possible directions for further research and development, highlighting joint efforts from the academic community, business community, and policymakers. In navigating the challenging terrain of hybrid renewable energy-powered electric vehicles, this study acknowledges and tackles the obstacles that come with this cutting edge of technology while highlighting the game-changing possibilities of effective power management techniques. An in-depth analysis of the challenges and effective power management strategies associated with hybrid renewable energy-based electric vehicles (HREVs) greatly advances our knowledge of the present and potential futures of sustainable mobility. The review provides insights into how HREVs improve energy distribution among various components, fostering advancements in control algorithms and energy storage systems, by evaluating the most recent developments in power management. It showcases cutting-edge techniques and best practices together with practical examples that have improved the efficiency and performance of vehicles.

II. Efficient Power Management Strategy for HEVS

In order to maximize the advantages of renewable energy integration, optimize energy consumption, and improve overall vehicle performance, hybrid renewable energy-based electric vehicles (HREVs) must have effective power management [7]. Classification of energy management strategies (EMSs) for hybrid electric vehicles (HEVs) has been shown in Fig. 1. To harvest energy from renewable sources like solar panels and regenerative braking, installing sophisticated energy harvesting devices is important. The vehicle's overall power supply is aided by these technologies, which transform ambient energy into electrical energy. High-capacity and effective energy storage devices, like ultra-capacitors, improved lithium-ion batteries, or other cutting-edge technology, should be integrated [8]. When there is a spike in demand or not enough energy produced from renewable sources, these systems store excess energy and use it to power the system. Using intelligent algorithms are important for charging and discharging that take into account current data, road conditions, and energy availability [9]. To extend the life of the energy storage system and guarantee steady performance, balance the state of charge (SOC) of the system by optimizing the charging and discharging cycles. To predict driving patterns, energy demand, and the availability of renewable energy, apply machine learning algorithms and predictive analytics. By facilitating proactive decision-making, predictive energy management enables the car to optimize power distribution in accordance with projected needs. Use adaptive control techniques that can respond dynamically to changing road conditions, elevation changes, and energy availability.

Taking into account variables like speed, load, and road gradient, these systems make sure that the electric motor, internal combustion engine (if any), and renewable energy sources all receive power distribution that is efficient. Include real-time monitoring devices to keep tabs on the energy storage system's operation as well as the creation of renewable energy and the distribution of power overall. Give the control system feedback so that it can instantly modify according to the vehicle's and energy systems' present conditions. Investigate vehicle-to-grid connectivity, which enables HREVs to feed extra energy back into the grid in addition to consuming it. With the ability to transfer energy in both directions, V2G capabilities improve grid stability and present chances for income production [10]. Provide intuitive user interfaces that give drivers up-to-date details on energy use, the contribution of renewable energy sources, and overall vehicle efficiency. Include drivers in the power management process so they can decide what suits their needs and preferences for driving.

Integration is vital for smart grid technology with HREVs to allow communication between the grid and the vehicle [11]. Because of this integration, demand response is made easier, enabling the car to modify its patterns of charging and discharging in response to changes in the grid, electricity rates, and the availability of renewable energy sources. During deceleration, optimize regenerative braking devices to capture and transform kinetic energy into electrical energy. Make sure that the total power management plan is seamlessly integrated in order to optimize energy recovery and minimize the need for friction brakes. Equip the energy storage and powertrain components with effective temperature management systems. An ideal capacity for energy storage and release is ensured by proper thermal regulation, which also improves battery performance and durability [12]. In order to manage power in HREVs efficiently, a comprehensive strategy that takes into account the interactions between different energy sources, storage systems, and control algorithms is needed. The EMS has always been a key research topic in the field of HEVs, and its strategies and control algorithms emerge endlessly. At present, the EMSs of HEVs can be classified according to the topological structure shown in Fig. 1 that can be divided into two categories: the RCS and the optimization-based control strategy (OCS). For these tactics to remain relevant in the ever-changing field of sustainable transportation, it is imperative that research and technological developments continue.

III. Renewable Energy Sources for HEVS

For hybrid electric vehicles (HEVs), selecting renewable energy sources is essential to advancing ecologically responsible and sustainable mobility [14]. Solar energy, which is captured by photovoltaic panels mounted on the outside of the car and provides a portable and renewable energy source, is one of the best options. Another possible energy source is wind energy, which may one day be used to power moving automobiles through the integration of wind turbines. Hydropower, which uses hydroelectric generators to capture energy from flowing water, also offers the possibility of stationary charging. The core heat of the Earth is the source of geothermal energy, which can offer steady, uninterrupted electricity for stationary electric vehicle charging. A renewable source of biofuels or biogas is provided by biomass energy, aiding in the switch away from fossil fuels. While location-specific, tidal and wave energy can be used for water-based EVs or stationary charging. By absorbing and transforming kinetic energy during deceleration, regenerative braking systems also improve efficiency through kinetic energy recovery. The suitability of these sources is contingent upon geographical factors, the evolution of infrastructure, and the continuous progress in renewable energy technology. A thorough strategy, perhaps incorporating information from several sources, is essential to promoting an environmentally friendly future for electric cars.

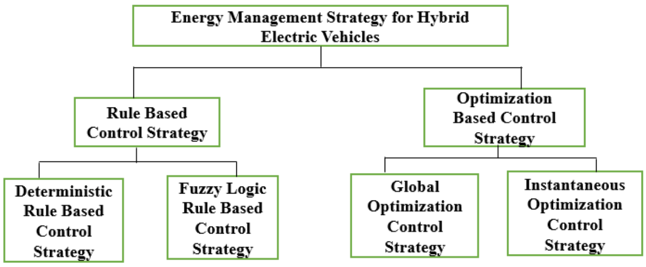

Fig. 1. Classification of energy management strategies (EMSs) for hybrid electric vehicles (HEVs) [13]

Nonetheless, it is reasonable to assume that wind and solar energy are suitable sources for EV charging infrastructure [15]. With appropriate storage capacity to support the charging process during the fluctuation of sources, a charging station can be either non-hybrid (using both solar and wind power) or hybrid (using both sources). The size of the power generator is primarily determined by the charging method (slow, medium, or quick). However, there are environmental drawbacks to using battery storage [16]. The study indicates that global electronic mobility demand will boost the production of batteries by 2030 to around 1725 GWh, and nickel will be the dominant raw material in the lithium-ion battery. Currently, batteries' demand represents 4% of the annual global nickel production, and the gradual scenario is that nickel demand would rise to 34% of present mining production in 2030 [17]. Even if nickel is an important component for plants, like every metal and chemical, the quality of the environment for flora and fauna may be negatively affected by its excessive amounts. As a result, nickel is strictly controlled and subjected to rigorous evaluations under a variety of legislative frameworks. Emerging renewable energy sources continue to be essential to the goal of a cleaner and more sustainable future for electric cars (EVs). Solar energy that is abundant in a given area is particularly useful for developing solar charging stations as well as for direct integration into electric vehicles [18]. Wind energy shows promise in harnessing the dynamic energy of moving air during travel, especially with regard to aboard or roadside wind turbines.

IV. HYBRID RENEWABLE ENERGY FOR EVS

Electric vehicles (EVs) with hybrid renewable energy systems (REES) combine many renewable energy sources to produce electricity for EV charging and operation. By utilizing the complementing qualities of several renewable energy sources, this strategy seeks to improve the sustainability and dependability of EV charging infrastructure. Hybrid systems can help create a more dependable, robust, and sustainable infrastructure for charging electric vehicles by combining various renewable energy sources and storage options. A comparative table of hybrid renewable energy for electric vehicles has been shown in Table 1. This will ultimately lessen the environmental effect of transportation.

- Solar and wind integration: solar energy can be captured by installing photovoltaic (PV) panels on parking lots, charging stations, and other appropriate spaces. Wind energy can be harnessed by integrating small wind turbines into charging stations or other structures.
- Energy storage systems: systems for storing extra energy, such lithium-ion batteries, can be used to store energy produced during high-renewable energy production periods. Then, at times of low output of renewable energy or high demand, this stored energy can be used. When necessary, electric vehicles with bidirectional charging capability can be used as mobile energy storage units by returning excess energy to the grid or other linked vehicles.
- Microgrids: building EV charging station microgrids can improve energy resiliency. Depending on the availability of renewable energy, these microgrids can either function independently or link to the larger grid.
- Smart grid technologies: the integration of renewable energy sources, load balancing, and improved energy distribution management are made possible by the use of smart grid technologies. This minimizes reliance on non-renewable sources during periods of high demand and guarantees the effective use of energy that is available.
- Hybrid systems management: making use of sophisticated algorithms and control systems to maximize the performance of hybrid renewable energy systems. This entails forecasting solar and wind energy output, controlling energy storage, and making snap judgments for the best use of energy in the moment.
- Geographical considerations: choose where to put charging stations depending on the local availability of renewable resources. For instance, sunny places could prefer solar energy, whereas coastal areas might benefit from wind power.
- Government incentives and policies: the implementation of sustainable EV charging infrastructure can be accelerated by promoting the use of hybrid renewable energy systems with the help of incentives and supportive regulations.
- Public awareness and education: spreading knowledge about the advantages of hybrid renewable energy for EV charging among the general population helps promote

acceptance and more environmentally friendly transportation options.

V. Methodology of Using Renewable Energy in (EVs)

Utilizing clean and sustainable energy sources requires a complete strategy for energy harvesting, storage, and utilization in electric vehicles (EVs) [19]. Equip the electric car with renewable energy harvesting devices to extract energy from sustainable sources. Install photovoltaic panels on the outside of the car to harness solar energy and generate electricity. To save the additional energy produced by photovoltaic, a central controller is required to redirect the generated power to the battery, as illustrated in Fig. 1. Put in place regenerative braking systems, which gather braking kinetic energy and transform it into electrical energy. Install energy conversion devices to transform captured energy into a format that can be stored. To convert solar panels' direct current (DC) into alternating current (AC) for usage in vehicles, utilize inverters and power electronics. Keep converted energy in ultracapacitors or other high-capacity batteries, among other energy storage devices. Optimize the utilization of stored renewable energy by implementing clever algorithms for charging and discharging [20]. When there is abundant renewable energy available, such as when the car is parked in the sun, give charging priority. To save the additional energy produced by photovoltaics, a central controller is required to redirect the generated power to the battery, as illustrated in Fig. 2. Optimize the release of stored energy in accordance with driving circumstances and energy requirements. Examine how the electric car can return extra energy to the grid while it's not in use by taking advantage of V2G capabilities. Through V2G connection, the car can function as a mobile energy storage device, improving grid stability and facilitating a greater integration of renewable energy sources.

Table 1. Comparative table of hybrid renewable energy for electric vehicles

Criteria	Solar/Wind Hybrid	Solar/Battery Hybrid	Wind/Battery Hybrid	Solar/Wind/Battery Hybrid
Energy Sources	Solar, Wind	Solar	Wind	Solar, Wind
Primary Energy Capture	Photovoltaic panels, Wind turbines	Photovoltaic panels	Wind turbines	Photovoltaic panels, Wind turbines
Energy Storage	Battery	Battery	Battery	Battery
Storage Technology	Lithium-ion or other advanced batteries	Lithium-ion or other advanced batteries	Lithium-ion or other advanced batteries	Lithium-ion or other advanced batteries
Energy Storage Capacity (kWh)	Variable	Variable	Variable	Variable
Microgrid Integration	Yes	Yes	Yes	Yes
Smart Grid Technologies	Yes	Yes	Yes	Yes
Vehicle-to-Grid (V2G)	Potential	Potential	Potential	Potential
Geographical Suitability	Depends on solar and wind availability	Depends on solar availability	Depends on wind availability	Depends on solar and wind availability
Flexibility and Scalability	Moderate	High	Moderate	High
Implementation Cost	Moderate-High	Moderate-High	Moderate-High	High
Environmental Impact	Low carbon footprint	Low carbon footprint	Low carbon footprint	Low carbon footprint
Reliability and Redundancy	Enhanced reliability	Enhanced reliability	Enhanced reliability	Enhanced reliability
Public Awareness and Acceptance	Moderate awareness	High awareness	Moderate awareness	High awareness

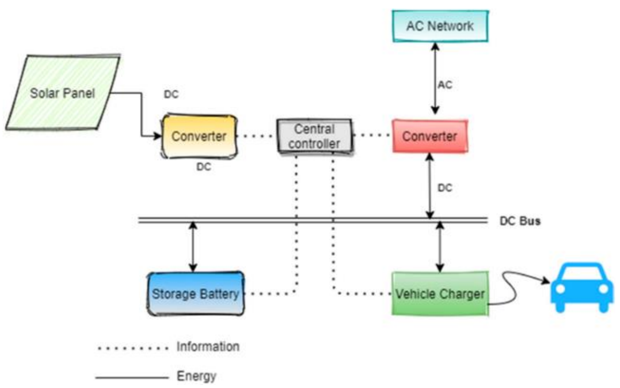

Fig. 2. EV Charging Infrastructure with a renewable source [22]

Smart grid technologies [21]. To control the temperature of the energy storage system in particular, install effective thermal management systems. Effective use of renewable energy in electric vehicles (EVs) requires multiple components to work in concert with one another. When a vehicle is operating, ambient energy is captured by energy harvesting equipment like solar panels or regenerative systems. By converting mechanical or solar energy into electrical power, these gadgets serve as sustainable sources to augment the electrical power required for propulsion. Regenerative braking recovers kinetic energy during deceleration and stores it as electrical energy for future use, which increases efficiency even further. Supercapacitors and other sophisticated batteries are examples of energy storage devices that receive this energy. By balancing the erratic power demands of the vehicle with the sporadic energy generation from renewable sources, these storage devices are essential to the maintenance of a steady power supply. This will contribute to the overall temperature of the electric car. Optimal energy storage and release capabilities are ensured by proper heat regulation, which also improves battery performance and durability.

VI. Opportunities of HREVs

There are several potentials with Hybrid Renewable Energy-Based Electric Vehicles (HREVs) that correspond with the objectives of environmental impact reduction, energy efficiency, and sustainability [23]. These chances demonstrate how important a role HREVs might play in the shift to a more robust and sustainable transportation ecosystem. HREV adoption is anticipated to become a crucial aspect of the automotive scene in the future as technology develops and environmental concerns gain more attention on a worldwide scale.

- By incorporating renewable energy sources into the vehicle's power system, hybrid electric vehicles (HEVs) present a chance to lessen reliance on conventional fossil fuels [24].
- HREVs advance energy security by enhancing the variety of energy sources utilized in transportation [25]. Reliance on imported fossil fuels is decreased and the energy supply chain's resilience is increased by the incorporation of renewable energy, which is frequently obtained domestically.
- Energy efficiency is better overall with HREVs since they use several energy sources, such as renewable energy gathering and regenerative braking [26].
- Through V2G connectivity, HREVs can function as mobile energy storage units, assisting the grid [27].
- The total environmental effect of transportation is decreased when renewable energy is incorporated into HREVs [28].
- Intelligent communication and coordination between the vehicle and the grid are made possible by the seamless integration of HREVs into smart grid systems [29].

VII. Challenges of HREVs

For hybrid renewable energy based electric vehicles (HREVs) to fully achieve the potential of sustainable and effective mobility, several integration problems relating to hybrid renewable energy sources must be resolved [30]. To address these issues, industry players, legislators, researchers, and manufacturers must work together to develop technologies, foster innovation, put supportive laws into place, and create hybrid renewable energy-based electric vehicles that are a viable and sustainable option for transportation in the future.

- The discontinuous nature of renewable energy sources like wind and solar power is one of the main problems. Maintaining a steady and dependable power source for the electric car is challenging when energy generation is inconsistent [31].
- The amount of renewable energy that can be stored and used is limited by the onboard energy storage capacity of HEVs, which is often the case [32].
- To respond to changing driving conditions, energy consumption, and the availability of renewable resources, optimizing the distribution of power between conventional and renewable sources requires sophisticated algorithms and control systems [33].
- Dealing with various energy conversion processes and compatibility difficulties is necessary when integrating many renewable energy sources into a single hybrid system [34].
- The total cost of the car may increase if renewable energy technologies are integrated [35].
- The adoption of electric vehicles that run on hybrid renewable energy is greatly influenced by regulatory and legislative frameworks. Market expansion may be impeded by confusing laws, inconsistencies in legislation, and a dearth of incentives [36].

VIII. Discussion

Advanced power management techniques are needed when renewable energy sources are included in hybrid electric vehicles (HEVs) [37]. Optimizing energy consumption, maintaining smooth transitions between traditional and renewable power sources, and improving HEV performance all depend on effective power management [38]. The incorporation of hybrid renewable energy systems into electric cars poses dynamic obstacles, notwithstanding the possible advantages [39]. One major obstacle is the sporadic nature of renewable energy sources like wind and solar power. Systems for adaptive power management that can respond to shifting energy availability are needed to handle this unpredictability. It is crucial to address the issues around energy storage [40]. Enhancing the energy storage capacity and efficiency of renewable energy in hybrid electric vehicles (HEVs) requires technological developments in energy storage, such as improvements in battery systems, capacitors, and other storage media [41]. One of the main topics of discussion is the integration of electric vehicles that run on hybrid renewable energy into smart networks. Power management in hybrid electric vehicles (HEVs) that run on renewable energy sources is contingent upon the integration of cutting-edge technology and techniques. Regenerative braking systems, which gather and store kinetic energy during braking and transform it into electrical energy for later use, are one essential component. The car can also capture ambient energy and lessen its reliance on traditional charging methods by including energy harvesting technology, like solar panels. Advanced algorithms enable predictive energy management, which optimizes the distribution of power across the internal combustion engine, electric motor, and battery by analyzing driving habits and topography. Precise control over energy flow is possible thanks to intelligent power electronics, which includes sophisticated inverters and converters. By allowing HEVs to feed extra energy back into the grid, vehicle-to-grid (V2G) integration promotes grid stability and rewards vehicle owners. Advanced Battery Management Systems (BMS) optimize charging and discharging procedures while ensuring the battery of the car is healthy and operating efficiently. Real-time adaptive control relies heavily on multi-objective optimization algorithms, which continuously optimize power management by taking into account a variety of variables like fuel economy, pollution reduction, and battery life. These technologies are combined to enable effective and sustainable power consumption for hybrid electric vehicles (HEVs) running on renewable energy, which lowers environmental impact and improves overall performance.

Effective demand-response mechanisms are made possible by a two-way communication structure between cars and the grid [42]. This enables HEVs to interact with the grid intelligently in response to signals related to pricing, energy availability, and overall grid conditions.

It is essential to talk about how hybrid renewable energy systems in electric vehicles affect the environment [43]. The incorporation of renewable energy sources mitigates greenhouse gas emissions; nevertheless, the environmental impact of these vehicles is also influenced by manufacturing concerns, disposal at the end of life, and life cycle analysis. The comprehensive sustainability features of HEVs are examined in this section. One important aspect of the conversation is the financial feasibility of putting effective power management techniques into hybrid electric vehicles powered by renewable energy sources [44]. The topic of future directions and probable difficulties is covered in the conversation. The determination to overcoming obstacles and progressing the field is demonstrated by the exploration of potential areas for future research and development, including improved energy storage materials, artificial intelligence for predictive energy management, and cooperative efforts between the energy and automotive industries [45]. Effective power management techniques and associated difficulties in hybrid electric cars powered by renewable energy sources are explored from multiple angles [46]. With an eye on advancing the incorporation of renewable energy into the mainstream automobile landscape, this discussion advances the ongoing conversation on sustainable transportation by exploring technological developments, practical applications, and wider issues.

IX. Conclusion

In terms of sustainable transportation innovation, the effective integration of renewable energy into hybrid electric vehicles (HEVs) is at the forefront. The complex terrain of power management techniques and the corresponding difficulties in utilizing hybrid renewable energy-based electric vehicles to their maximum potential have been examined in this study. Smoothly switching between traditional and renewable energy sources, optimizing energy use, and guaranteeing HEV dependability all depend on effective power management. The study has highlighted the necessity for flexible solutions, recognizing the ever-changing obstacles associated with incorporating renewable energy sources into electric cars. Innovations in energy storage have been highlighted as being essential to overcoming obstacles in the way of integrating renewable energy sources. These examples provide a detailed grasp of the abilities, difficulties encountered, and efficacy of various strategies in various operational contexts, assisting with further deployments. Recognizing that technology is always evolving, the study has suggested future directions for research and development. Through navigating the intricacies of power management and tackling related obstacles, our research adds to the body of knowledge that drives the automobile sector toward a more sustainable and environmentally friendly future.

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