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Tri-Source Hybrid Electric Vehicle: Solar-Assisted Regenerative Architecture for Zero-Emission Mobility

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Abstract
This work introduces an innovative Tri-Source Hybrid Electric Vehicle (HEV) framework that synergistically integrates solar energy harvesting, regenerative braking, and a fallback internal combustion (IC) engine to achieve low-emission and energy-resilient mobility. The architecture is designed to prioritize renewable energy utilization while maintaining operational reliability under variable environmental and driving conditions. A photovoltaic subsystem, regulated by a Maximum Power Point Tracking (MPPT) controller, ensures continuous solar charging with adaptive response to irradiance fluctuations. Concurrently, a regenerative braking unit recovers kinetic energy during deceleration, enhancing overall energy efficiency. The IC engine, decoupled from primary propulsion, is employed solely during critical battery depletion, controlled by a supervisory Battery Management System (BMS) and a real-time power flow algorithm to optimize hybrid operation.
Prototype-level validation confirms measurable improvements in energy conversion efficiency, extended driving range, and minimized grid dependency compared to conventional hybrid systems. Emission assessments indicate a substantial reduction in tailpipe pollutants, aligning with India's national clean mobility and renewable energy directives. The proposed tri-source configuration provides a scalable and sustainable pathway toward next-generation zero-emission transportation, balancing energy autonomy, environmental stewardship, and practical feasibility.

Keywords**—** Hybrid Electric Vehicle (HEV), Solar-Assisted Charging, Regenerative Braking, Maximum Power Point Tracking (MPPT), Battery Management System (BMS), Energy Efficiency, Zero-Emission Mobility, Sustainable Transportation.

I. Introduction

The combined challenges of escalating global pollution and the rapid depletion of finite crude oil reserves, driven largely by the burgeoning consumption in the transportation sector, necessitate the development of sustainable energy alternatives for mobility. The primary focus has shifted to battery electric vehicles (EVs) due to their capacity for significant localized emission reduction. However, the widespread adoption of pure EVs introduces two critical technical limitations. Firstly, the substantial charging demand places an increased, often infeasible, load on existing electrical grids, particularly in energy-deficit regions. Secondly, the environmental benefit is mitigated if the vehicle batteries are charged using electricity generated from fossil fuel-based power plants, a process that merely decentralizes, but does not eradicate, pollution.

Consequently, research efforts are concentrated on integrating supplementary, renewable power sources directly into the vehicle architecture, thereby accelerating the development of highly efficient hybrid electric vehicle (HEV) systems that utilize two or more distinct onboard energy sources [1,2].

to power it. Hybrid Electric Vehicles (HEVs) combine both solar and electrical energy. An integration of energy regeneration and simultaneous battery charging is a pivotal advancement in the realm of electric vehicles (EVs). This innovative technology seeks to enhance the overall efficiency and sustainability of EVs by harnessing and converting energy during deceleration and braking. Energy regeneration involves the recuperation of kinetic energy typically lost as heat during these processes, channeling it back into the vehicle's battery system for storage and later use [3].

Simultaneous battery charging complements this approach by allowing the vehicle to recharge its battery while in motion, further extending its range and reducing dependency on traditional charging infrastructure. This symbiotic combination not only maximizes energy utilization but also contributes to an eco-friendlier transportation ecosystem. As the automotive industry continues to evolve, the integration of energy regeneration and simultaneous battery charging stands out as a key solution for addressing energy efficiency and sustainability challenges in the electric vehicle landscape [4].

II. Background

The motivation behind creating regenerative and solar charging electric vehicles lies in addressing key challenges facing traditional transportation

Environmental Concerns: Regenerative braking reduces energy waste during braking, making EVs more efficient and environmentally friendly by maximizing energy usage.

Range Anxiety: Solar charging and regenerative braking help extend the range of EVs, mitigating concerns about running out of power during journeys.

Sustainability: By harnessing renewable energy sources like sunlight, solar charging reduces reliance on non-renewable energy sources, aligning with global efforts to combat climate change.

Cost Savings: Utilizing regenerative braking and solar charging can potentially reduce energy costs for EV owners, offering long-term financial benefits.

Overall, integrating regenerative and solar charging technologies into electric vehicles represents a holistic approach to creating more sustainable and efficient transportation systems [4,5].

Context of the Research

The study is set within the dynamic landscape of electric mobility, where advancements in technology play a crucial role in shaping the future of transportation. The framework also acknowledges the significance of concurrent charging through an alternator, introducing a dual emphasis on enhancing battery efficiency while the vehicle is in motion. As electric vehicles gain increasing popularity, there is a growing need for solutions that not only boost the overall effectiveness of battery systems but also introduce innovative charging methods beyond the conventional stationary charging stations. The integration of regenerative braking and solar charging systems opens up an intriguing pathway for simultaneously powering the vehicle and recharging the battery, potentially addressing concerns related to both range anxiety and charging infrastructure. To sum up, the research on "Energy Generation" is strategically positioned within the evolving electric vehicle industry with the aim of contributing to the future of transportation. It seeks to explore novel possibilities in electric vehicle battery efficiency and assess the viability of concurrently charging the battery using regenerative and solar charging technology.

Statement of the problem

Solar energy constitutes a highly abundant and clean renewable energy resource. For vehicular applications, solar collection methodologies are broadly categorized into passive solar systems and active solar systems. This classification is based on the mechanism of energy capture, its subsequent distribution, and the method of conversion used to generate usable electric power. The inherent zero marginal cost of solar irradiation makes its direct utilization for onboard power generation a highly feasible and advantageous technical consideration for enhancing vehicle autonomy and sustainability.

Objectives of the study:

Solar energy represents a highly abundant, clean, and renewable resource critical for advancing vehicular sustainability. Onboard solar collection is systematically categorized into passive and active systems, where the latter manages the capture, distribution, and efficient conversion of solar irradiation into usable electric power. Leveraging the inherent technical feasibility and zero marginal cost of solar charging significantly enhances vehicle autonomy. This comprehensive system architecture extends beyond the power generation stage, incorporating an advanced design focused on operational integrity and occupant protection. Specifically, the proposed vehicle system integrates sophisticated safety features and establishes a comprehensive framework for real-time monitoring, assessing both functional vehicle performance metrics and critical driver physiological data [6].

Environmental Sustainability: Reduce greenhouse gas emissions by utilizing renewable solar energy and capturing kinetic energy during braking, thus decreasing reliance on fossil fuels and mitigating climate change.

Energy Efficiency: Maximize energy efficiency by harnessing solar power to charge electric vehicles and utilizing regenerative braking technology to recapture and store kinetic energy, minimizing minimizing energy waste.

Cost Savings: Decrease operational costs associated with traditional fuel-based vehicles by utilizing free solar energy for charging and extending the vehicle's range through regenerative braking, reducing the need for frequent charging.

Promotion of Renewable Energy: Encourage the adoption of renewable energy sources by integrating solar charging infrastructure, thereby promoting the growth of the solar energy industry and reducing dependence on non-renewable resources.

Enhanced Vehicle Performance: Improve the overall performance and longevity of electric vehicles by optimizing battery charging through solar power and extending battery life through regenerative braking, leading to more reliable and sustainable transportation solutions.

Grid Stability: Reduce strain on the electrical grid by utilizing distributed solar charging stations, which can help balance energy demand and supply, especially during peak hours, thereby enhancing grid stability and reliability.

Community Resilience: Foster community resilience by decentralizing energy production and storage through solar charging infrastructure, allowing for greater energy independence and resilience during natural disasters or grid outages [7,8].

III. Present Status of EV Energy Utilization & Cost Analysis

The adoption of electric vehicles (EVs) is often considered a step toward sustainable mobility; however, their true environmental impact depends largely on the source of the electricity used for charging. As highlighted by industry experts, EVs cannot be regarded as a complete green solution unless the charging energy is derived from renewable and clean sources. Transitioning to a 100% renewable-based charging network is therefore essential to achieve real emission reduction goals [1].

In India, companies such as Mahindra Electric have introduced models like the eVerito, equipped with a 16 kWh battery, capable of achieving a driving range of up to 181 km on a single charge. The vehicle requires approximately 11.5 hours for full charging with a slow AC charger and about 1.5 hours with a fast DC charger. The operating cost is estimated at around ₹1.15 per kilometer, considering an energy consumption of 18 units at an electricity rate of ₹7 per unit [10,11].

According to data reported by BESCOM (Bangalore Electricity Supply Company), the fixed electricity charges for EV charging infrastructure are ₹60 per kW for low-tension (LT) AC chargers and ₹190 per kW for high-tension (HT) DC chargers. The energy rate is approximately ₹5 per kWh, irrespective of usage. Assuming an average EV requires 15 kWh per day for charging, the daily cost amounts to about ₹75 per vehicle based on a 30-kWh battery capacity. Consequently, for a fleet of one million EVs, the cumulative daily cost would be approximately ₹75 million (₹7.5 crore), translating to ₹27.37 billion (₹2737 crore) annually—highlighting the significant energy and economic implications of large-scale EV adoption [12].

Furthermore, the quality and stability of the power supplied from the electrical grid play a critical role in reducing “charge anxiety” among users and ensuring the reliable operation of EV charging systems.

Maintaining consistent grid quality is therefore vital for both consumer confidence and the performance of charging infrastructure [13].

Charging Time Analysis:

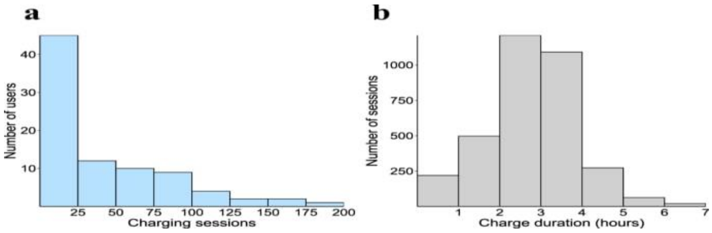

Figure 1: Charging time analysis

Figure 1 shows the systematic analysis of charging time taken by vehicles for charging the vehicles. Predictive modelling, optimization of charging patterns, and adaptive control strategies. These intelligent systems aim to tailor the charging and discharging cycles based on user performance and external factors. Innovations include grid storage, stationary energy systems, and backup power solutions, contributing to sustainable battery usage. We introduce the EV Charging Profiles and Waveforms (EV-CPW) dataset, which is now accessible to the public [14,15].

Energy Consumption and Cost Estimation:

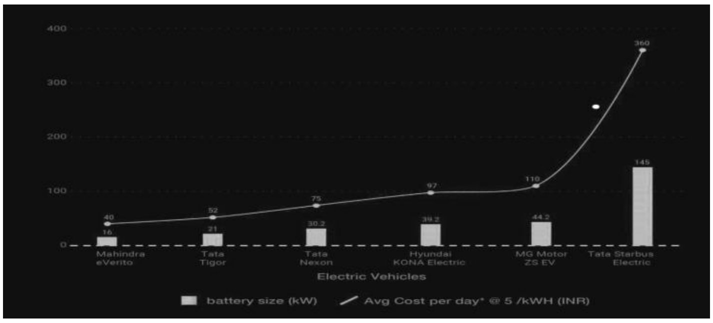

Figure 2: Energy Consumption and Cost Estimation

This dataset encompasses charging profiles and detailed cost estimation did by different companies. A comprehensive power quality analysis, encompassing power factor, distortion, harmonic analysis, and load behavior, is conducted on the EVs. The results are then compared to the EV standard recommendations put forth by standards agencies. It's important to note that an average cost and capacity of battery depend on its size [16,17]. The energy cost is more because the insufficient charging stations and lack of technologies developed in vehicles. Both Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) are compatible with AC charging, while a smaller subset of EVs, typically only BEVs, can utilize DC charging. Researchers emphasize the pivotal role of developing a resilient charging infrastructure and integrating it seamlessly with the electrical grid. This encompasses the investigation of smart charging solutions, grid management techniques, and the overarching impact of charging infrastructure on the overall efficiency of EV battery charging [18,19].

Smart charging algorithms and control strategies emerge as key focal points in the literature, addressing the need for real-time monitoring, predictive analytics, and adaptive control systems. These systems take into account variables such as battery state, grid conditions, and user preferences to optimize the charging process. Energy management strategies are explored, with a specific focus on peak shaving to alleviate grid load during high-demand periods. This involves the optimization of charging schedules and distribution to enhance overall system efficiency [20,21]. Moreover, the integration of renewable energy sources, such as solar and wind, into EV charging stations is extensively discussed to improve sustainability and reduce the carbon footprint associated with EV charging as shown in Fig. 3

Electric vehicles (EVs) operate without producing tailpipe emissions, thereby eliminating direct air pollutants such as carbon monoxide, nitrogen oxides, and particulate matter. This characteristic significantly reduces greenhouse gas emissions and supports efforts toward cleaner urban environments. By relying on electricity instead of fossil fuels, EVs contribute to lowering the overall dependence on petroleum-based energy sources, helping to mitigate the effects of climate change. Moreover, due to the inherent design of electric motors, EVs deliver instant torque, enabling superior acceleration and smoother performance [22,23]. This enhanced power response has encouraged many automobile manufacturers to develop high-performance electric models that often exceed the capabilities of their conventional internal combustion engine (ICE) counterparts.

Battery charging curve:

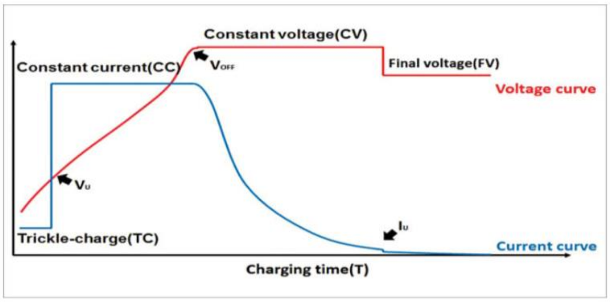

Figure 3. Battery Charging Curve

The optimization of thermal management plays a pivotal role in discussions surrounding charging efficiency. Various studies explore advanced cooling and heating systems designed to maintain an optimal battery temperature, ensuring efficient charging while safe guarding battery health [24]. Scrutiny of user behavior and charging patterns aims to understand their impact on charging efficiency. This encompasses investigations into user preferences, charging habits, and the potential for implementing demand response strategies to optimize charging during periods of low grid demand. Economic feasibility studies and analyses of government policies are crucial components of existing literature. These studies delve into financial incentives, pricing models, and regulatory frameworks, all aimed at enhancing overall charging efficiency [25]. The strategic placement of charging stations and considerations of accessibility are also vital aspects, addressing concerns related to range anxiety and promoting widespread electric vehicle (EV) adoption. The literature further explores innovations in charging cables, connectors, and materials to improve charging efficiency. On-going efforts include advancements in conductive materials, contactless charging, and enhanced power electronics. Additionally, battery swapping technologies are under examination as an alternative to traditional charging methods, seeking to reduce charging time by exchanging depleted batteries with fully charged ones [27]. In summary, this comprehensive literature review encompasses diverse dimensions of research on the EV charging system, as illustrated in the block diagram shown in Fig. 3
Innovations in technology used for charging, connectors, and materials are examined to improve charging efficiency and vehicle life. Advancements in conductive materials, solar charging, regenerative braking and improved power electronics are part of on-going efforts to enhance the overall efficiency of EV. The battery swapping technologies are explored as an alternative to traditional charging methods, aiming to reduce charging time by swapping depleted batteries with fully charged ones [28,29]. In essence, this comprehensive literature review encapsulates the diverse dimensions of research on advance EV block diagram shown in Fig. 4.

A hybrid electric vehicle integrating both solar energy charging and regenerative braking has been developed and tested to offer an environmentally friendly alternative to conventional internal combustion (IC) engine vehicles. The system utilizes a Maximum Power Point Tracking (MPPT) charge controller to charge a 12 V, 80 Ah battery using a 120 W, 18.6 V solar panel. In addition, regenerative braking based on a DC generator mechanism is implemented to recover kinetic energy during braking, which can be redirected to support auxiliary loads within the vehicle [30,31]. Although the system demonstrates effective operation and emission-free performance, its high initial cost remains a major challenge. Enhancements in battery state-of-charge estimation and rapid charging methods are expected to further improve the system’s efficiency, reliability, and overall practicality for future applications [32].

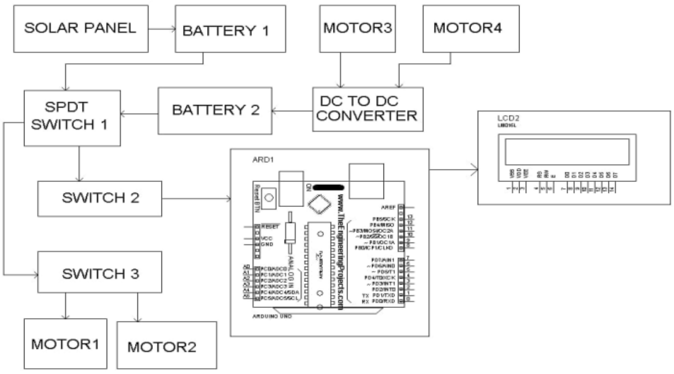

Figure 4. EV block diagram

Figure 4 illustrates the block diagram of the developed prototype. The vehicle employs four electric motors for propulsion, powered by two separate batteries mounted on the front and rear shafts, respectively. The electrical energy generated through the system is stored in these batteries, and the amount of energy produced is indicated using LED indicators and an LCD display for real-time monitoring. This configuration offers several advantages in terms of power distribution, energy recovery, and operational efficiency, as summarized below: An Innovative Battery Chemistries

Advancements in Lithium-Ion Technology: On-going research focuses on enhancing the energy density, charging speed, and lifespan of lithium-ion batteries, the predominant type used in electric vehicles (EVs). Innovations include the integration of silicon anodes, solid-state electrolytes, and advanced materials to improve overall performance. Solid-State Battery Technologies: Solid-state batteries present the potential for increased energy density, enhanced safety, and extended lifespan compared to traditional liquid electrolyte batteries.

B. Efficient Battery Thermal Management:

Utilization of Advanced Thermal Management Systems: Advanced systems regulate EV battery temperature, ensuring optimal operating conditions. Technologies such as liquid cooling, phase-change materials, and active thermal control systems are employed to prevent overheating and enhance overall battery performance.

C. Rapid Charging Innovations:

Ultra-Fast Charging Technologies: Initiatives aim to significantly reduce charging times through the development of high-power chargers and advancements in charging protocols. Technologies based on gallium nitride (GaN) are explored to enable faster charging without compromising battery health.

D. Intelligent Battery Management Systems (BMS):

Smart BMS Optimization: Intelligent BMS optimizes charging and discharging processes, monitors real-time battery health, and implements strategies to prevent overcharging or deep discharging. Machine learning algorithms within BMS adapt to user behavior, enhancing overall efficiency [32].

E. Energy Harvesting and Regeneration: Regenerative braking systems are designed to capture and transform kinetic energy generated during braking into electrical energy, which is then redirected back into the battery. This innovative technology enhances overall efficiency by harnessing energy that would otherwise dissipate as heat during the braking process.

F. Wireless Charging Advancements:

Inductive and Resonant Wireless Charging: Wireless charging technologies eliminate the need for physical connectors, providing convenient and efficient charging. On-going research focuses on improving efficiency and standardization of wireless charging systems for EVs.

G. Second-Life Battery Applications:

Repurposing Used EV Batteries: Exploration of secondary applications, such as stationary energy storage, extends the lifespan of used EV batteries, contributing to sustainable energy solutions and minimizing waste.

H. Predictive Analytics and Machine Learning:

Enhanced Battery Management: Predictive analytics and machine learning algorithms analyse vehicle, charging infrastructure, and external data to predict user behavior and optimize charging schedules, enhancing energy efficiency.

I. Grid Integration and V2G Technology:
Vehicle-to-Grid (V2G) Technology: Bidirectional energy flow between EVs and the electrical grid enables EVs to provide support during peak demand, potentially earning revenue for EV owners.
J. Advanced Electrode and Electrolyte Materials:
- Development of Advanced Materials: Research focuses on advanced materials for electrodes and electrolytes to improve energy density, charge/discharge rates, and overall battery performance.
K. Block chain Integration for Security:
- Secure Charging Ecosystem: Block chain technology secures and streamlines transactions within the EV charging ecosystem, enhancing transparency, security, and efficiency.
L. Dynamic Charging Systems Implementation:
- Charging While in Motion: Dynamic charging systems allow EVs to charge while in motion, addressing range anxiety concerns and enabling continuous operation. This technology is explored for public transportation and high-traffic routes.
M. Optimized Charging Strategies:
- Intelligent Charging Approaches: Development of intelligent charging strategies, including time-of-use charging and demand response mechanisms, optimizes energy consumption, reduces peak loads on the grid, and lowers charging costs for EV owners. [23].
N. Environmental Sustainability Measures:
- Sustainable Practices: Sustainable manufacturing processes, recycling programs, and eco-friendly disposal methods contribute to the environmental sustainability of EV batteries. Researchers explore ways to minimize the environmental impact of battery production and end-of-life processes.

IV. Methodology

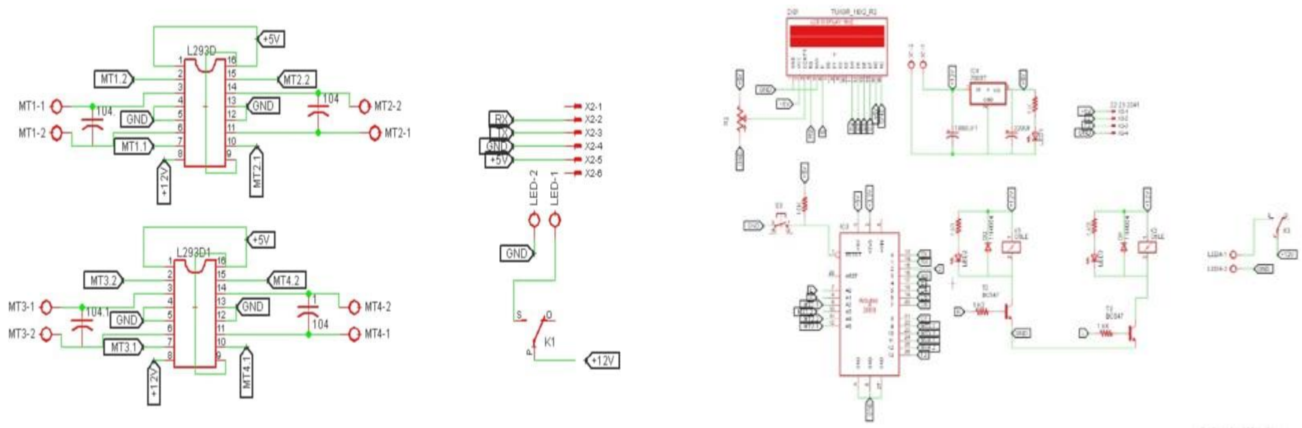

Figure 5: Interfacing Diagram

Improving the efficiency of electric vehicle (EV) battery charging and enhancing the overall efficiency of EVs in terms of average kilometers (KM) involves a multi-faceted methodology. Below are key approaches: Advanced Charging Infrastructure: Establish an extensive and advanced charging infrastructure network, including fast-charging stations strategically placed for convenient access. Utilize high-power chargers and implement technologies that enhance charging speed without compromising battery health. Smart Charging Algorithms: Develop intelligent charging algorithms that consider factors such as grid demand, energy prices, and optimal charging times. Incorporate machine learning to analyses user behavior and adapt charging schedules for maximum efficiency.
Extreme fast charging (XFC) systems represent a paradigm shift in charging experiences, mirroring the refueling speed of internal combustion engine (ICE) vehicles. These systems can manage power exceeding 350 kW with an internal DC bus voltage of 800 Vdc, enabling a rapid battery recharge time of approximately 5 minutes. XFC stations incorporate advanced power electronic modules, including solid-state transformers (SST), isolated DC-DC converters, and front-end AC-DC converter steps and controllers. While the setting up cost of XFC is significant, combining multiple XFC systems in a station design offers the potential to reduce operational and capital investments, increasing economic feasibility. Furthermore, SST technology provides advantages over traditional line-frequency transformers in XFC stations by converting medium voltage levels into low voltage levels and providing galvanic isolation [34].

Dynamic Charging Systems:

Explore the implementation of dynamic charging systems that enable EVs to charge while in motion. This addresses range anxiety concerns and ensures continuous operation, especially on high-traffic routes and public transportation networks.

Wireless Charging Technologies: Investigate and enhance wireless charging technologies, allowing for seamless and efficient charging without physical connections. Optimize the efficiency of inductive and resonant wireless charging systems for widespread adoption. Regenerative Braking Optimization:

Improve regenerative braking systems to capture and convert more kinetic energy into electrical energy during deceleration. Enhance the efficiency of energy recovery systems to maximize the range extension through regenerative braking [34].

Battery Thermal Management: Implement advanced thermal management systems to regulate battery temperature effectively. Optimize cooling and heating mechanisms to maintain an optimal temperature range, ensuring efficient charging and discharging processes.

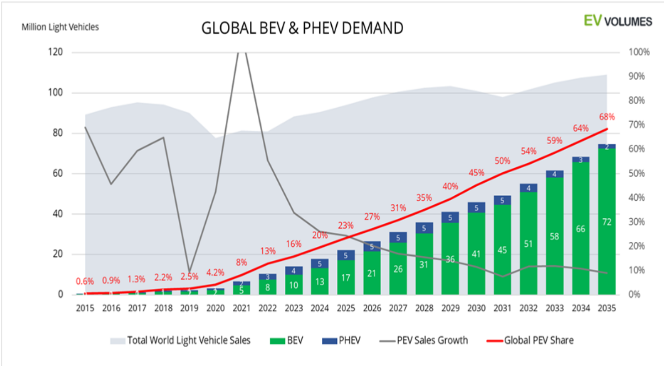

Figure 6. EV Forecast to 2035

Integrate V2G technology to enable bidirectional energy flow between EVs and the grid. Allow EVs to feed excess energy back to the grid during peak demand, contributing to grid stability and potentially earning revenue for EV owners.

Enhanced Battery Management Systems (BMS):

Develop advanced BMS with real-time monitoring and adaptive control capabilities. Implement features that optimize charging and discharging parameters based on battery health, usage patterns, and external conditions in Fig. 6 User Education and Engagement: Launch educational programs to inform EV users about efficient charging practices. Encourage users to adopt optimal charging habits, such as avoiding frequent deep discharges and utilizing off-peak charging hours. Global market will lead EV technology up to 2035.

V. Electrify & Optimize Technologies

Explore cutting-edge technologies for enhancing EV battery charging

Discuss advancements in charging infrastructure. Analyze smart grid integration and demand response strategies. Collaborate with utilities to implement incentive programs that encourage off-peak charging. Provide reduced electricity rates during specific hours to shift charging demand away from peak periods, benefiting both users and the grid.

Collaboration with Renewable Energy Sources:

Integrate EV charging infrastructure with renewable energy sources, such as solar and wind. Prioritize the use of clean energy for charging, reducing the environmental impact and promoting sustainable practices. Continuous Research and Development: Invest in on-going research and development to explore emerging technologies, materials, and methodologies that can further improve EV battery efficiency and charging capabilities. Describe the research design detail the methods used for data collection, explain the tools and technologies employed Provide a rationale for the chosen methodology

VI. Case Studies

Tesla Supercharger Network:

Background: Tesla has implemented a widespread Supercharger network globally, aiming to provide convenient and rapid charging for Tesla EV owners. Case Study: Tesla's Supercharger stations, strategically placed along highways, facilitate fast-charging for long-distance travel. This case study delves into the network's impact on EV adoption, user experience, and the scalability of fast-charging infrastructure. Case Study: This case study examines the practical application of V2G in a fleet of Nissan Leaf vehicles. It assesses the impact on grid stability, potential revenue generation for fleet operators, and the overall feasibility and benefits of bidirectional energy flow.

Smart Charging Algorithms in City EV Fleets: Background: An electric taxi company integrates energy harvesting technology, such as solar panels on vehicle roofs, to supplement battery charging. Regeneration data is scrutinized to evaluate the efficiency of regenerative braking systems, considering factors such as energy recovered and braking patterns. The contribution of regenerative braking to the overall range extension of the EV is assessed, along with the influence of driving habits and terrain on regeneration efficiency. Comparative analyses across different EV models offer insights into variations in charging and regeneration performance [30].

The findings lead to personalized recommendations for users to optimize charging habits and driving behavior. Infrastructure providers receive insights on usage patterns for expansion or improvement. Automakers benefit from data-driven suggestions for enhancing regenerative braking systems and overall charging efficiency. Policymakers gain insights for informed decisions on EV infrastructure development and incentives. Environmental impact analysis considers factors such as the energy source for charging and reductions in brake wear, ensuring a holistic understanding of EV charging and regeneration dynamics. This data-driven approach supports stakeholders in making informed decisions for the continued advancement of the electric vehicle ecosystem. Interpret the results in the context of EV battery charging optimization use charts, graphs, and statistical analysis to support findings.

VII. Challenges And Future Directions

Identify challenges encountered during the research Propose recommendations for overcoming these challenges.

Discuss potential future research directions EV stock is significantly increased in 2021 when compared to previous years and the total number of battery electric cars on road to over 16.5 million. As shown in Fig. 6, the largest EV market belongs to China where cumulative EV sales reached 9.4 million in 2021, which represented 50% of global EV stock [14]. The second largest EV market belongs to Europe with 2.3 million annual sales of light duty EVs and the United States has the third largest EV market [12], [15]. Currently, the focus on electrified transportation has garnered significant interest from both governmental bodies and private entities aiming to achieve carbon neutrality by 2040. This commitment is evident through sustained policy backing, incentives, and subsidies, as depicted in Figure 6. Overcoming the substantial hurdle lies in implementing safe measures to charge batteries while electric vehicles are in motion. electrified transportation has attracted much attention from governments and private stakeholders to move towards carbon neutrality in 2040 through consistent policy support, incentives, and subsidies from the governments as shown below Fig. 7. The big challenge is to charge batteries while running EV with all safety measure.

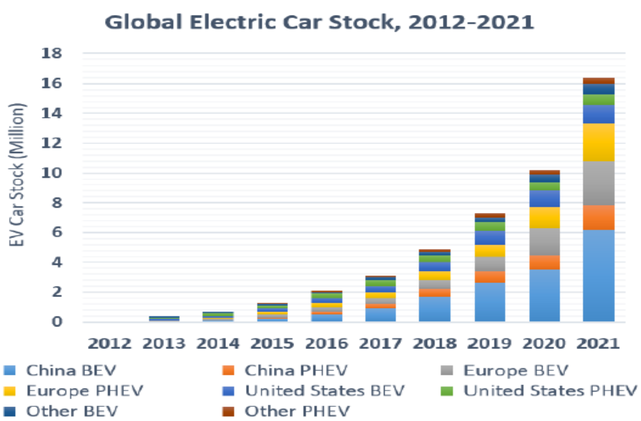

Figure 7. Electric passenger car stock, 2012-2021 [22].

VIII. Conclusion

The integration of solar-assisted charging and regenerative braking within a hybrid electric vehicle represents a practical approach toward achieving sustainable, emission-free transportation. The developed prototype confirms that a dual-energy recovery system can substantially enhance operational efficiency while minimizing grid dependency. Although economic constraints currently limit large-scale implementation, advancements in battery materials, MPPT algorithms, and lightweight solar technologies are expected to improve both system performance and affordability.

Future developments should prioritize smart energy management, rapid charging protocols, and adaptive regenerative control to maximize power utilization in varying driving conditions. Furthermore, integrating predictive analytics and vehicle-to-grid (V2G) communication can enable real-time optimization of charging patterns and energy exchange. Overall, this research contributes to the advancement of next-generation hybrid electric mobility, offering a technically sound pathway toward cleaner and more resilient energy systems in transportation.

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