Review Article

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A Review on Hybrid Vehicle Technologies and Strategies

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ABSTRACT

Hybrid electric vehicles and plug-in hybrid electric vehicles are very important in the development of sustainable transportation. The review work has focused on technologies and strategies applicable to these vehicles, with an emphasis on energy management strategy, state-of-charge optimization, and regenerative braking systems. It also examines the roles dedicated hybrid transmissions and solid-state batteries play in relation to performance improvements, long life, and efficiency. The advanced control methods consisting of model predictive control, Sequential quadratic programming, and fuzzy control are compared for the most potential fuel economy range with minimal emission. In addition, the application of neural networks and genetic algorithms in dynamic programming is discussed, giving the sense of potentiality of these approaches in further refinement of energy management. The review further elaborates on the environmental impact of hybrid electric vehicles and plug-in hybrid electric vehicles by considering CO_2, NO_x, and particulate matter emissions, while updating the efficiency of the Real Driving Emissions test cycle to meet compliance at Euro 6d-temp. In this respect, emerging technologies such as Proton exchange membrane fuel cells, Hybrid renewable energy systems, and photovoltaic systems are discussed for the further reduction of the environmental footprint of hybrid vehicles.

Keywords: Hybrid electric vehicles; Energy Management Strategies; State of Charge optimization;

1. INTRODUCTION

Hybrid electric vehicles and plug-in hybrid electric vehicles are on the rise, providing more efficient and sustainable transportation solutions that can compete with traditional internal combustion engine vehicles (Alsuwian *et al.* 2023b). These vehicles drastically reduce fuel consumption and emissions while retaining a performance level comparable to that of petrol cars, also providing the option of using conventional electric powertrains (Shah *et al.* 2022).

A detailed review is required on the well-established energy management strategies and state-of-charge optimization in hybrid vehicles as well as regenerative systems to identify the research gaps between the technologies (Obu and Raji, 2022a). New technologies such as dedicated hybrid transmissions, solid-state batteries, and machine learning algorithms are improving the efficiency and performance of vehicles and need to be studied for further optimization in these fields (Sabarish *et al*. 2023a).

A much deeper discussion on the contribution to the debate on sustainable mobility is necessary to analyze the most recent topics and challenges in hybrid vehicle technology, particularly emphasizing Hybrid electric vehicles and plug-in hybrid electric vehicles, due to their potential to significantly reduce the environmental footprint of transportation systems by lowering greenhouse gas emissions, enhancing fuel efficiency, and integrating renewable energy sources through electrification. Different technologies of hybrid vehicles are listed in Fig.1.

2. HYBRID ELECTRIC VEHICLES

Reinforcement learning was a model-free technique that optimized energy management in hybrid electric vehicles by adapting to driving scenarios like worldwide harmonized light vehicles test cycle and FTP-75 (Acquarone *et al.* 2023). It utilized a backward quasi-static modelling approach to simulate powertrain dynamics, integrating real-time feedback, fuel consumption data, electric motor losses, and battery state monitoring (Anselma *et al*. 2021b). Lithium-ion batteries, supplemented by ultracapacitors, supported advanced energy management strategies (Baskar *et al*. 2021), while fuel cell hybrid vehicles used Pontryagin's minimum principle for power optimization (Fu *et al.* 2022). Dynamic torque coordination and deadbeat-direct torque and flux control improved performance in brushless axial-flux machines (Tong *et al.* 2023) plug-in hybrid electric vehicles employed K-means clustering and bi-level optimization models to balance costs and emission (Zeynali *et al*. 2021) supported by real-time vehicle-specific power models (Kozina *et al.* 2023) and portable emission measurement systems for emissions

assessment (Skobiej and Pielecha, 2022). Intelligent charging strategies with smart grids and vehicle-to-grid systems enhanced sustainability and grid stability (Badhoutiya, 2023). Data-driven modelling using Python and CAN data, along with advanced heating, ventilation, and air conditioning systems (König *et al*. 2022) and thermal management, further optimized energy efficiency, ensuring compliance with real driving emissions protocols (Jaworsk *et al*. 2023) and improving vehicle adaptability and environmental performance (Singh *et al*. 2022b). Additionally, power-on downshift control enhanced hybrid electric vehicle performance by optimizing transmission dynamics during shifts (Xu *et al*. 2022d), while lifetime prediction models helped manage battery state-of-health and degradation (Anselma *et al.* 2021b). Real-time load prediction in fuel cell vehicles improved energy distribution and system efficiency (Fu *et al.* 2022). Finally, dynamic torque coordination strategies helped to improve power-split performance in plug-in hybrid electric vehicles during engine start-ups (Su *et al*. 2021). MATLAB Simulink is utilized for software implementation in developing a low-cost electronic control unit for hybrid electric vehicles, alongside microcontrollers like Arduino Uno and Raspberry Pi for hardware. It incorporates Analog-to-Digital converters for converting throttle input signals, voltage and current sensors for battery monitoring, and a PI controller for managing throttle control, ensuring effective operation of the vehicle's systems (Swaminathan *et al.* 2023). All these technologies are depicted in Fig. 2. The impact of emission hurdles in hybrid electric vehicles during cold starts, when high power was needed, highlighted the need for advanced thermal management and engine calibration to ensure efficient emissions (Bagheri *et al.* 2021). Advanced power management strategies play a significant role in how hybrid electric vehicles can address energy shortages and environmental problems (Jiang *et al.* 2021). The critical importance of a strategic optimization approach in hybrid electric vehicles technology is highlighted as essential for innovation and sustainability (Priyadharshini and Shankarganesh, 2024). The focus is on fuel cell hybrid electric vehicle, discussing technological challenges and suggesting policy interventions to support zero-emission vehicles (Waseem, 2023).

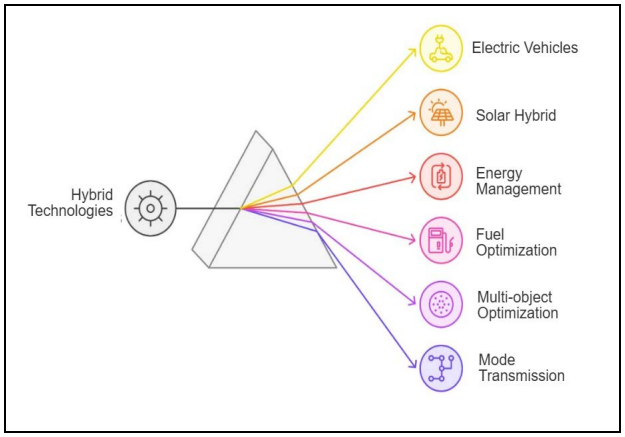


Fig. 1: Different concepts of hybrid technologies

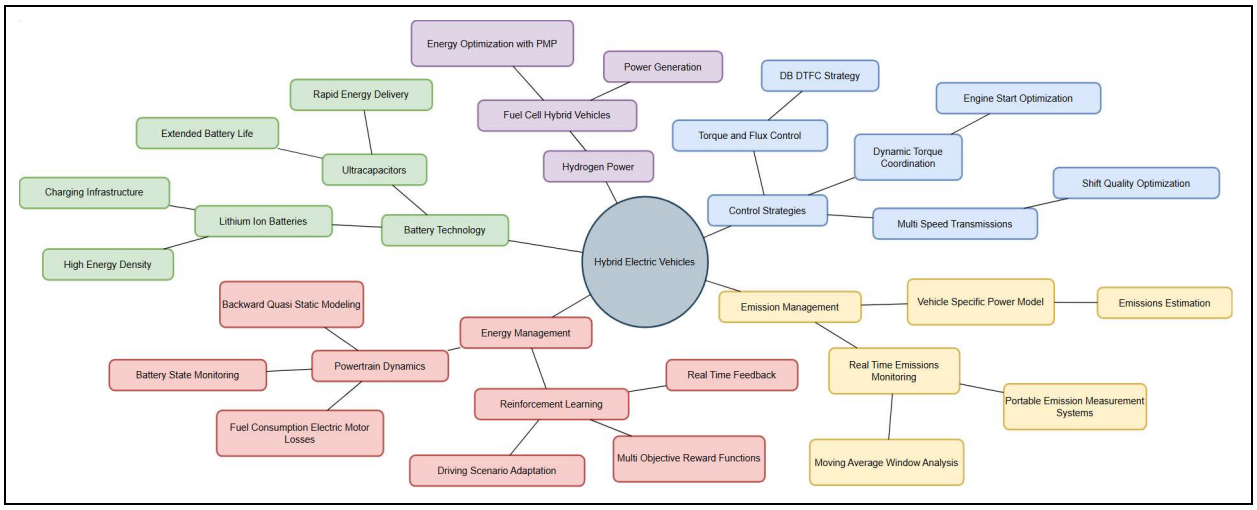


Fig. 2: Different technologies in hybrid electric vehicles

3. SOLAR HYBRID VEHICLE

Hybrid systems, such as crystalline silicon panels combined with solar heat collectors, increased electrical efficiency (~15%) and thermal energy extraction by using high-efficiency thermal contact materials (Zakharchenko *et al.* 2004). Theoretical models were validated by empirical testing, and performance was monitored with digital thermometers and data acquisition systems (Zakharchenko *et al*. 2004). Solar PV generation optimization took into account historical weather data and was coupled with battery storage. This system was sized using a two-stage deterministic and stochastic approach to maximize energy delivered to Plug-in

Electric Vehicles from green electricity (Wu *et al.* 2017). Predictive capabilities were improved by machine learning, which provided better grid stability and cost savings (Zakharchenko *et al*. 2004). Battery Management Systems, induction motors, and regenerative braking improved fuel efficiency (Selvan, 2016). A simulation of solar powered hybrid electric vehicles utilized maximum power point tracking for photovoltaic cells, DC-DC converters for voltage regulation, and efficiency with switched reluctance motors (Prasad *et al.* 2023). Solar powered hybrid electric vehicles and hybrid electric vehicles achieved range extension and emissions reduction thanks to energy-efficient and environmentally sustainable Proton exchange membrane fuel cells and regenerative braking (Chowdhury *et al.* 2016). Various technologies such as MEAN and MERN stacks were employed for system optimization (Deepak, 2023). Fig. 3 shows all these technologies used by solar hybrid vehicles.

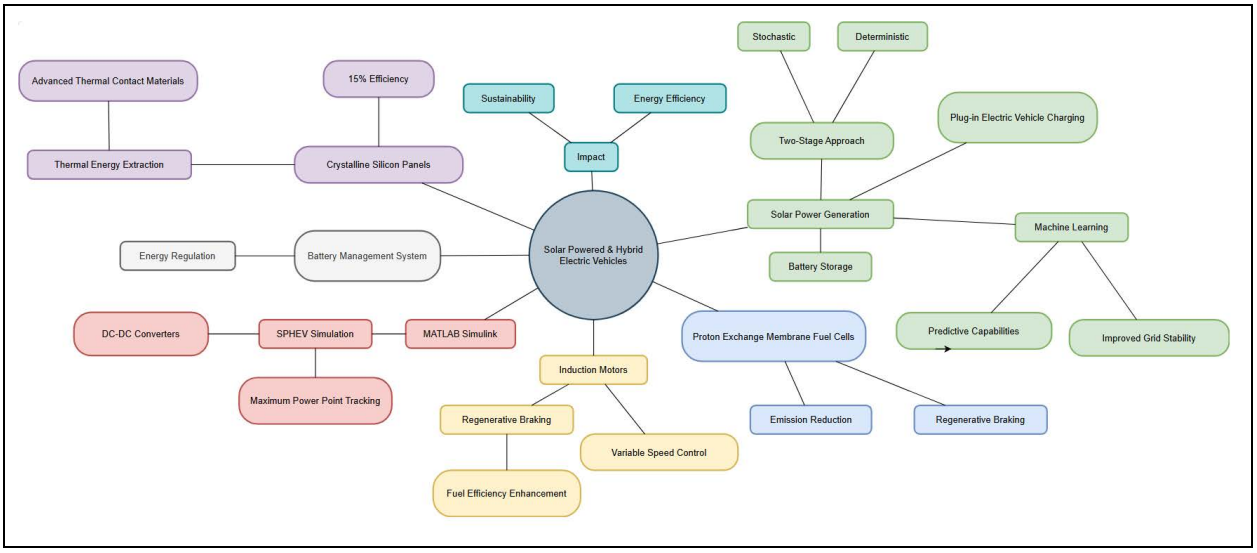


Fig. 3: Solar hybrid vehicles

4. ENERGY MANAGEMENT

Fuzzy control of dynamic power partitioning for fuel cell hybrid electric vehicles using a moving average filtering algorithm improves fuel cell durability (Lin *et al.* 2022). Proton exchange membrane fuel cells enhance efficiency, managed by a neural network optimized by genetic algorithms (Min *et al*. 2022; Tang *et al.* 2023b; Bai and Liu, 2021). Power-split hybrid vehicles use ANN control of torque split, trained with dynamic programming, reducing emissions (Huo and Meckl, 2022; Tegani *et al*. 2023; Zhuang *et al.* 2017b). Pontryagin's minimum principle, dynamic programming, and neural networks boost adaptability and fuel economy in real-time (Wei *et al*. 2022; Tegani *et al*. 2023), with co-simulation environments and support vector machines optimizing hybrid powertrain efficiency and mode transitions (Chen *et al*. 2014; Musa *et al*. 2024; Lee *et al.* 2022). Neural network-based online energy management for multi-mode power split hybrid vehicles further improves efficiency and adaptability in powertrain systems (Naguib *et al*. 2022). Energy recovery systems like Thermoelectric generators and kinetic energy recovery systems significantly reduce fuel consumption (Tang *et al*. 2023b; Kamal and Adouane, 2022). Energy control strategies such as equivalent consumption minimization strategy and proportional-integral controllers stabilize energy flow (Guo *et al.* 2021; Zhang *et al*. 2020d; Zhang *et a*l 2023a). Deep learning also improves state of charge estimation in hybrid systems (Wang *et al*. 2023; Vellingiri *et al.* 2022). Practical energy management is achieved using AI-based flatness theory and fuzzy control (Lin *et al*. 2022; Chen *et al*. 2014; Tegani *et al.* 2023). Power-split plug-in hybrid electric vehicles use neural networks and dynamic programming for energy management, enhancing mode transitions and power delivery (Karabiyik *et al.* 2023; Zhuang *et al.* 2017b). Control strategies like real-time optimization in hybrid ships and embedded control for battery–supercapacitor hybrid energy storage systems improve efficiency (Bai and Liu, 2021; Lee *et al*. 2022) . Real-time predictive energy management systems prolong battery lifespan under varying conditions (Guo *et al*. 2021). Supervisory control strategies further improve drivability and energy recovery (Aletras *et al.* 2023).

Advanced hybrid and co-estimation techniques for state of health and remaining useful life estimation significantly enhanced the safety and performance of electric vehicles, driving the industry towards sustainability (Alsuwian *et al*. 2024a). Genetic algorithms are critical in optimizing energy management strategies for fuel cell hybrid electric vehicles, increasing their operational efficiency (Lu *et al*. 2022). The optimization of energy management systems is essential for improving the market viability of fuel cell hybrid

electric vehicles (Obu and Raji, 2022b). While advancements in energy management system for electric vehicles are notable, challenges in economic feasibility and renewable energy integration remain (Sabarish *et al.* 2023b; Saiteja and Ashok, 2022). Furthermore, sophisticated energy management system are pivotal for minimizing emissions in hybrid electric vehicles, necessitating ongoing research to refine their design. Continuous innovation in energy management control strategies is vital for enhancing fuel efficiency and adaptability to dynamic driving conditions in hybrid electric vehicles (Xu *et al*. 2019b). The above-discussed energy management technologies are shown in Fig. 4.

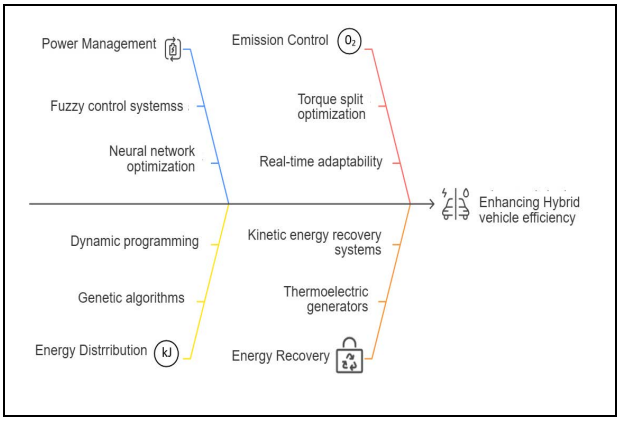


Fig. 4: Technologies used for energy management

5. FUEL CONSUMPTION OPTIMIZATION

Utilizing the Slope-weighted energy-based rapid control analysis algorithm for rapid, near-optimal control of battery state of charge, the Parallel P2 hybrid powertrain blended torque from the internal combustion engine and MG to increase efficiency in conjunction with battery use on demand (Anselma, 2022). Energy management systems with fuzzy logic control strategies dynamically allocates power between the internal combustion engine and electric motor, optimized by the DIRECT algorithm to improve fuel consumption, emissions, and component sizing (Ben *et al*. 2023). Dynamic control strategies like Dynamic Programming and Model Predictive Control were implemented in hybrid electric vehicles and hybrid solar vehicles to minimize fuel consumption and emissions over driving cycles such as urban dynamometer driving schedule, Economic commission for europe, New european driving cycle, and federal test procedure (Yadav *et al*. 2023). The PER-TD3 deep reinforcement learning algorithm optimized fuel consumption and emissions in plug-in hybrid electric vehicles with diesel engines, outperforming traditional methods (Xu *et al*. 2022c). Simulations validated strategies like series hybrid transmission and series-parallel hybrid transmission for enhancing energy efficiency and reducing emissions (Preitl and Bauer, 2007). Hybrid solar vehicles incorporated photovoltaic systems to improve sustainability through reduced fuel reliance (Minh *et al.* 2022). Simulink models simulated hybrid electric vehicles driving cycles, validating fuel consumption improvements through regression analysis and energy management systems optimization (Zhou *et al.* 2022) PER-TD3 was further validated by incorporating catalyst temperature management and reducing NO_x emissions in diesel plug-in hybrid electric vehicles (Xu *et al*. 2022c). These advancements in hybrid vehicle technology contributed to improved sustainability and vehicle performance (Fig. 5).

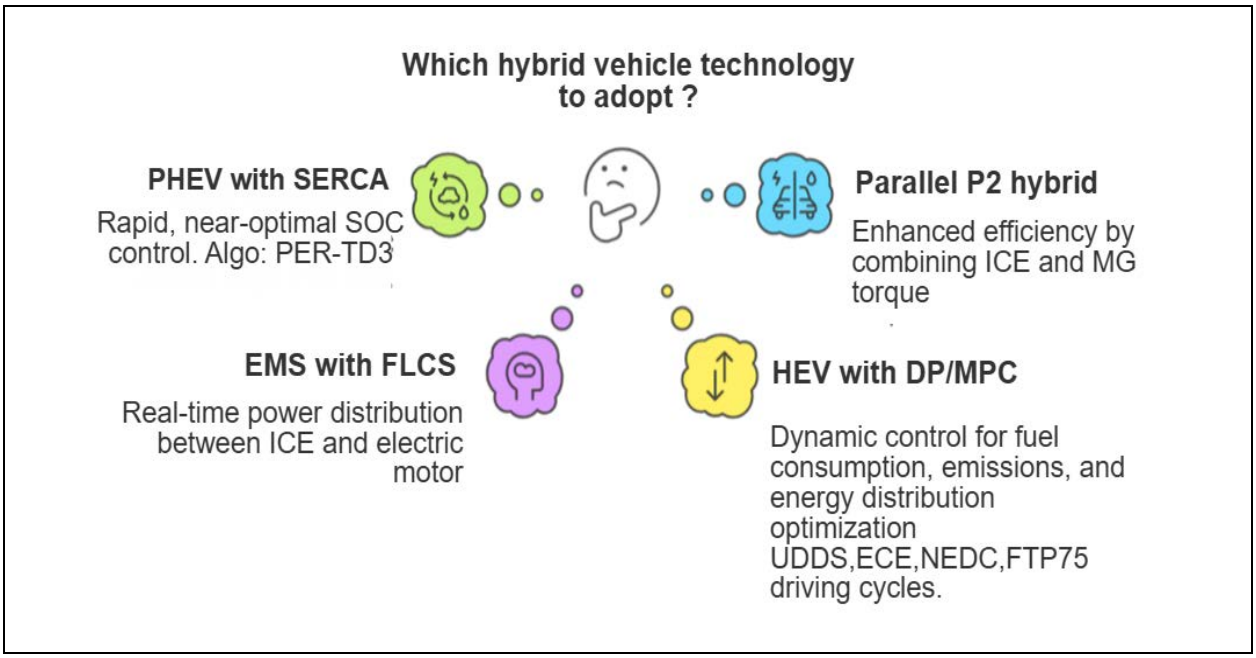


Fig. 5: Fuel optimization

Technologies like the innovative direct liquid cooling system for battery poles exhibited exceptional performance, paving the way for advanced optimizations and exploration of diverse cooling channel geometries and fluid characteristics (Martellucci and Capata, 2023). Additionally, the innovative hybrid electric vehicle model significantly diminished reliance on the internal combustion engine without compromising performance, showcasing a transformative approach to enhancing vehicle efficiency and addressing critical environmental challenges (Narwaria, 2023). Furthermore, hybrid electric vehicles were poised to revolutionize transportation by significantly reducing petroleum consumption and toxic emissions, propelled by stringent environmental regulations and heightened public awareness, with advanced hybrid architectures offering superior efficiency despite their complexity and cost (singh *et al*. 2023a).

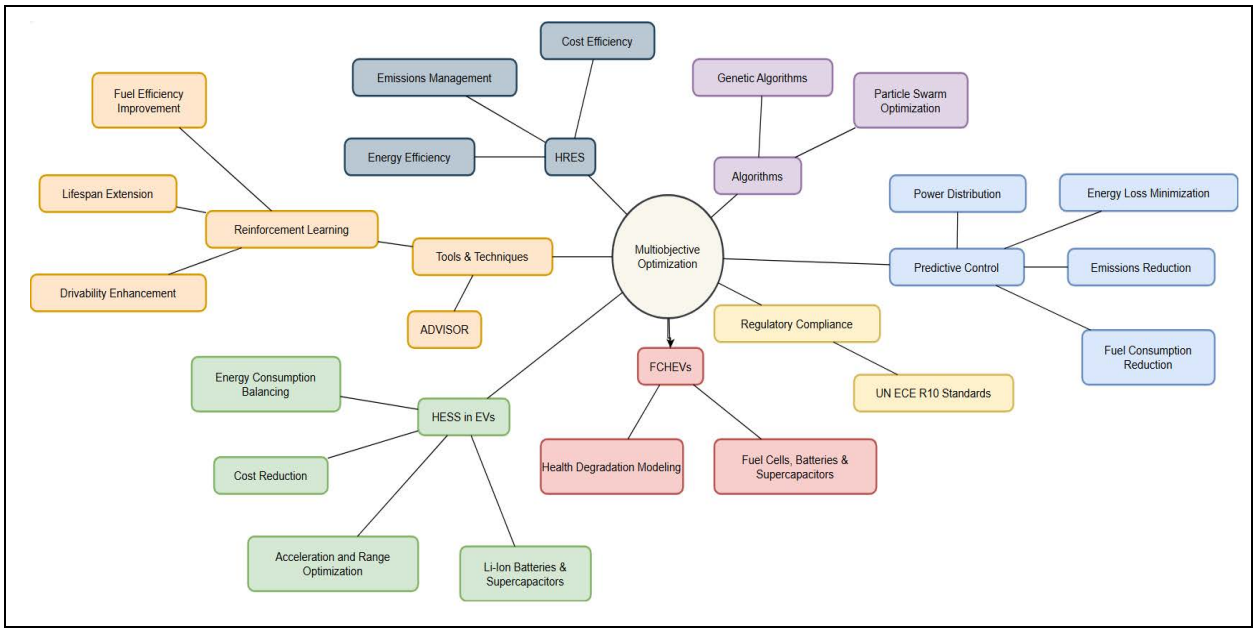


Fig. 6: Multi object optimization

6. MULTI OBJECT OPTIMIZATION

Hybrid energy storage systems with Li-ion batteries and supercapacitors utilized advanced multi-objective optimization algorithms like genetic algorithms and particle swarm optimization to improve energy consumption, acceleration, range, and cost, thereby enhancing electric vehicle performance and sustainability (Xiao *et al.* 2022). Predictive control was developed using health degradation models for fuel cells, batteries, and supercapacitors, optimizing power distribution to reduce energy loss, emissions, and fuel consumption in fuel cell hybrid electric Vehicles (Sellali *et al*. 2022). ADVISOR and reinforcement learning tools were employed to enhance energy management strategies, improving drivability, fuel efficiency, and component lifespan (Lyu *et al*. 2024). Hybrid renewable energy systems optimization using genetic algorithms and particle swarm optimization balanced energy efficiency, cost, and emissions, achieving robust and ecological designs (Dimitrova and Marechal, 2016). Simulations showed significant improvements in fuel consumption, CO_2 emissions, and energy storage life, satisfying UN ECE R101 legal requirements (Dimitrova and Marechal, 2016). Additionally, multi-objective optimization strategies improved vehicle performance by balancing fuel consumption, emissions, and system lifespan (Holjevac *et al.* 2020; Maheri *et al.* 2022). Furthermore, optimization algorithms such as the DIRECT algorithm have been applied to series hybrid electric vehicles, demonstrating significant improvements in efficiency and sustainability (Rihab *et al.* 2021). These all are described in Fig. 6.

7. MODE TRANSMISSION

The dynamic modeling of vehicle speed, torque demand, and power distribution used sliding mode control to manage mode transitions in Through-The-Road hybrid electric vehicles (Li *et al.* 2021). Simulations showed that improved drivability and vehicle stability were achieved by dynamically adjusting the engine, motor, and clutch in a coordinated manner, avoiding obtrusive torque transfer between states. Predictive sliding mode control for finite-time linear quadratic regulator-based optimal control strategies in dedicated hybrid transmissions aimed to reduce vehicle jerk and maintain constant drive torque while managing driveline oscillations, which enhanced real-time robustness (Ren *et al.* 2022). The dual-loop control

architecture included an outer loop designed for drivability and inner loops for clutch control, calculating the optimal time to engage the clutch using a particle swarm optimization algorithm to minimize mode transition duration and energy loss (Yang *et al.* 2020). Clutch engagement displacement was synchronized by fuzzy controllers for torque disturbance minimization in parallel hybrid electric vehicles, working alongside the adaptive equivalent consumption minimization strategy to smooth transitions and optimize fuel consumption (Tang *et al.* 2024). This integrated strategy, studied in a co-simulation environment, improved fuel consumption and reduced torque ripple throughout the engine's operating range, enhancing drivability and energy efficiency in hybrid electric vehicles (Zhao *et al*. 2022b). Fig. 7 shows different technologies used in mode transmission.

Technologies claimed that the method for energy management was ultimately state of charge constraint preserving but admitted that it resulted in a small increment of fuel consumption equal to 1.9% and this approach demonstrated and confirmed improved hybrid electric vehicle performance (Zhang *et al*. 2023).

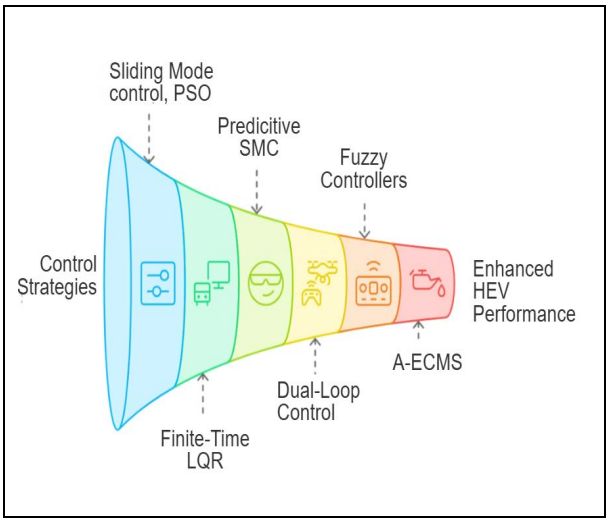


Fig. 7: Different technologies used in mode transmission

8. POWER TRAIN

A combination of dynamic programming and Pontryagin's minimum principle optimized energy management and power-source sizing in hybrid powertrains by iteratively solving backward-facing simulations for various driving cycles (e.g., UDDS, HWFET, and FTP-72) to optimize the trade-off between SOC, fuel consumption, and emissions (Kwon *et al*. 2021; Gao *et al*. 2022; Benitez *et al*. 2023). Engine efficiency was boosted due to the presence of turbocharging and energy recovery systems, alongside other advanced control strategies like SERCA and Dijkstra's algorithm for optimizing mode shifts and gear transitions (Deng *et al*. 2024; Anselma, 2019a; Zhuang *et al,* 2020). These configurations employed MATLAB/Simulink-based multimode hybrid simulations, genetic algorithms, and particle swarm optimization methods to investigate the vehicle performance and emissions reduction design spaces (Tran *et al*. 2021; Soldo *et al*. 2022; Shetty and Dawnee, 2014). Using real-time control frameworks, predictive algorithms, and machine learning helped to distribute energy better, reduce losses, and increase sustainability (Pei *et al*. 2018; Zhao, 2022a; Yue *et al*. 2023). Topological and graph-based approaches were proposed for the systematic design of series, parallel, and power-split hybrids while advanced energy management systems integrated with AI ensured that the power delivery was optimized, providing a more sustainable transport solution (Yang *et al*. 2024a; Xu and Wang, 2023a; Çeliksöz and Kılıç, 2024; Tran *et al*. 2019a; Zhuang *et al*. 2020). Fig. 8 shows hybrid power train optimization cycle.

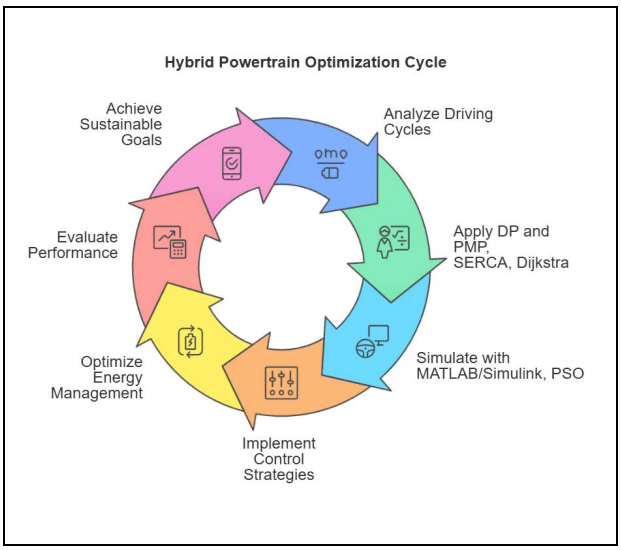


Fig. 8: Powertrain optimization

9. STORAGE SYSTEM

Hybrid energy storage systems for electric vehicles consist of improved designs employing battery-supercapacitor, battery-fuel cell, and supercapacitor-fuel cell systems to elevate energy utilization and performance (Zhang and Li, 2019c). Energy flow was well controlled over a wide range of operating conditions through the application of rule-based, optimization-based, and AI-driven control strategies (fuzzy logic, neural networks) (Podder *et al*. 2021). Fuel cell hybrid electric vehicles utilized Multi-objective particle swarm optimization for optimized energy management using MATLAB (Abdeldjalil, *et al.* 2023). Recurrent neural networks, specifically long short-term memory networks, forecasted road load impact on the energy stored in a battery pack, allowing an energy management system to determine the optimal distribution of power between

internal combustion engines and electric motors, which led to much better use of energy (Kamalakannan *et al*. 2023). A low pass filter and fuzzy logic control were used for hybrid energy storage system management to distribute power between batteries and supercapacitors in semi-active mode, improving battery lifecycle and vehicle performance across various driving cycles (Abdeldjalil *et al*. 2023). This full system addressed key issues regarding no-emission transportation solutions (Podder *et al.* 2021). Fig. 9 shows various technologies used in energy storage.

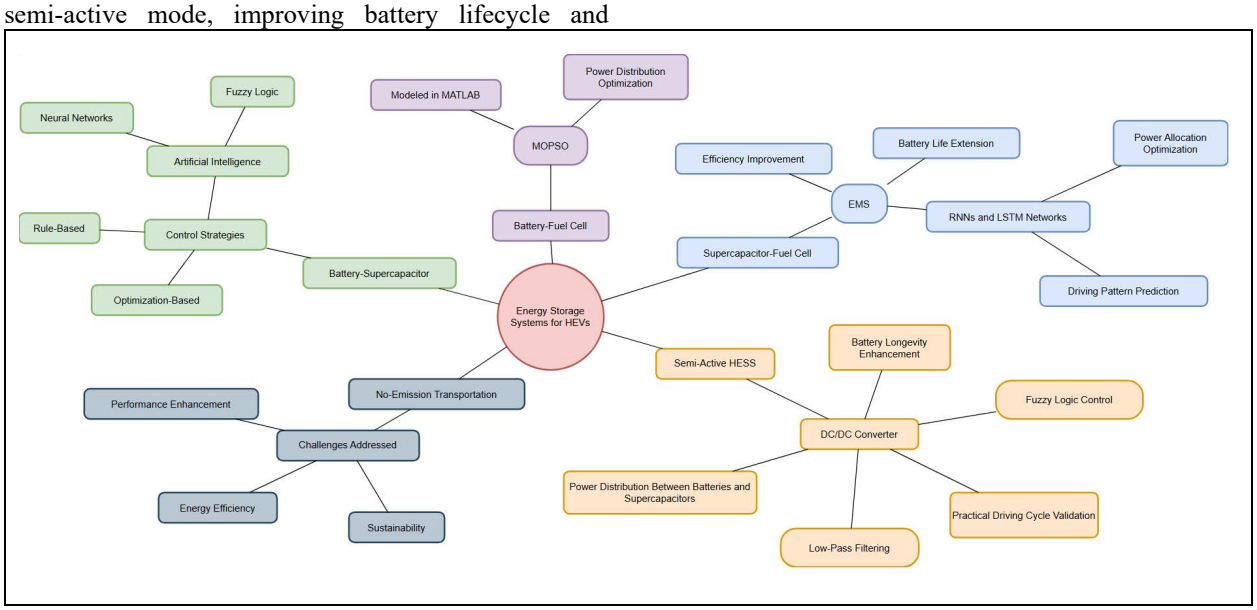


Fig. 9: Technologies used in energy storage

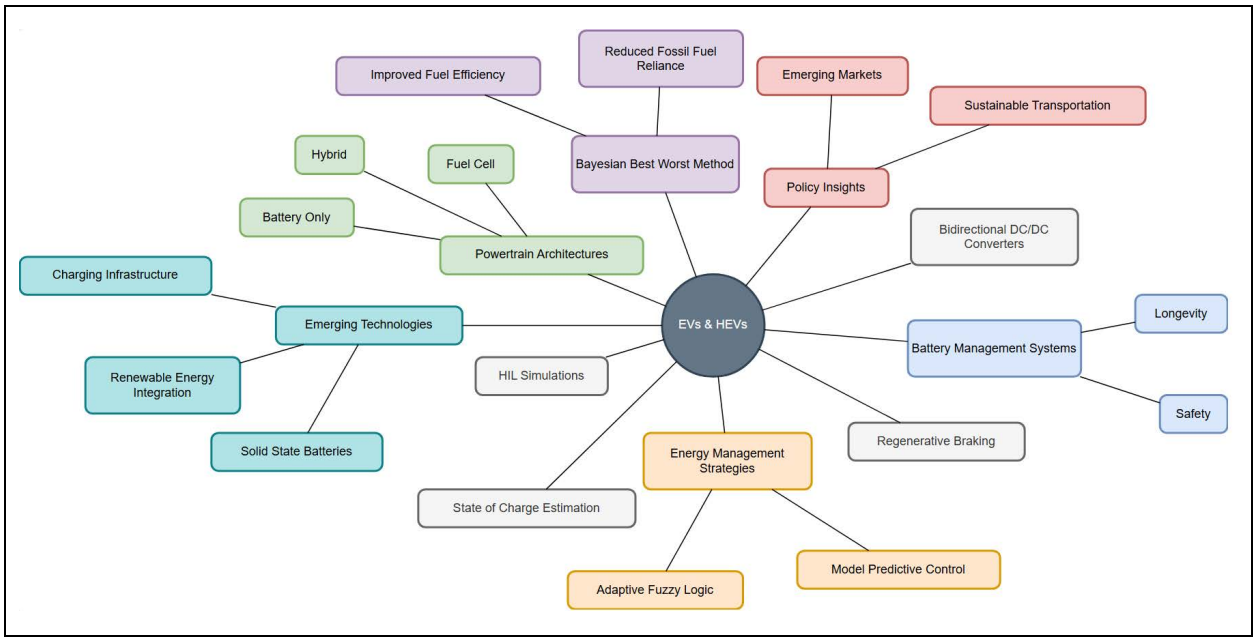


Fig. 10: Different technologies used to develop hybrid electric vehicles

10. DEVELOPMENT OF HYBRID ELECTRIC VEHICLES

Bidirectional DC/DC converters dramatically changed how energy flowed and how efficiently it could be utilized in both electric vehicles and hybrid electric vehicles; They also performed variably with differing powertrain architectures of battery only, fuel cell, or hybrid configurations—impacting the overall system performance and associated emissions solution (Ehsani and Moore, 2021). Energy management strategies, including adaptive fuzzy logic and model predictive control, optimized energy distribution, while State-of-Charge estimation algorithms and battery management systems ensured battery safety and durability (Limon *et al.* 2023). While Hardware-in-the-Loop simulations

validated these solutions, more advancements from solid-state batteries, an optimized charging infrastructure, and the integration of renewable energy took energy efficiency to the next level (Ehsani and Moore, 2021). hybrid electric vehicles used regenerative braking to recover energy, and the Bayesian Best-worst method listed factors such as less dependence on fossil fuels and fuel-efficient operation among the primary drivers of hybrid electric vehicles adoption, suggesting useful directions for emerging market policy regarding sustainable transport (Limon *et al.* 2023). Cutting-edge communication and computational technologies played a pivotal role in optimizing the performance and security of plug-in electric vehicles. Robust communication protocols proved indispensable for efficient energy management and dynamic interactions with the power grid and charging infrastructure, ultimately propelling the widespread adoption of EVs into a sustainable future (Ehsani and Moore, 2021). Fig. 10 shows different technologies used to develop hybrid electric vehicles.

11. CONCLUSION

Hybrid electric vehicles and plug-in hybrid electric vehicles are a big step forward for cleaner and sustainable transportation. This review points out the major technologies and strategies that help the operation in a more efficient way. New hybrid technologies will be paramount in both reducing the environmental impact and weaning our appetite for fossil fuels, as the automotive industry continues to evolve. Policymakers, manufacturers, and researchers need to come together as partners to tackle existing barriers and push for greater scale deployment of these vehicles. With support of innovations and growth in sustainable transport infrastructure we could be on the right track for a cleaner, highly efficient urban mobility future.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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