Optimizing Energy Efficiency in Hybrid Electric Vehicles through Adaptive Battery Management and Converter Technology

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Abstract- - ***Hybrid Electric Vehicles (HEVs) are crucial for improving energy efficiency and sustainability, as they combine an internal combustion engine, an electric motor, a battery pack, and a power converter. This analysis showcases important innovations that include new power converters and adaptive battery management systems, which promise HEVs will use less fuel and emit less pollutants. These technologies improve the efficiency of energy utilization, maximize battery life, and optimize overall vehicle performance through improved SOC predictions, thermal management, and dynamic control methods. Advanced techniques in SOC estimation include adaptive filtering, machine learning algorithms, and hybrid models as key elements to the effective energy management of HEVs. This review also discusses the integration of wide bandgap semiconductors with IoT-based systems, which are crucial in developing more reliable and efficient HEVs. It therefore supports the emergence of clean modes of transport consistent with international sustainable development goals as well as other climate change abatement measures.***
Keywords ***Hybrid Electric Vehicles (HEVs), Energy Optimization, Advanced Smarter Battery Management Systems (BMS), Power converters.***

I. INTRODUCTION

Power HEVs combine an internal combustion engine (ICE) with an electric motor and battery in order to attain greater economy and environmentally friendly performance. While the electric motor adds additional torque during low-speed or acceleration phases, the ICE typically powers the vehicle in high-speed or heavy-load scenarios to help reduce emissions and fuel usage [1]. Another advantage of HEVs is the regenerative braking system, in which the energy lost through braking is captured and fed into the battery for future use. This solution provides efficient and smooth supply of power, thus making HEVs a good option to reduce the environmental impact of traditional gasoline-powered vehicles without sacrificing performance. HEVs are mainly classified into three categories according to how their power sources interact: parallel, series, and series-parallel hybrids. With a parallel hybrid like the Honda Insight, both electric and internal combustion engines can push the wheels independently, while only in the case of series hybrids like the Chevrolet Volt, ICE is used purely to recharge the battery and is not used at all to provide the power [2]. Series-parallel hybrids, like the Toyota Prius, integrate both approaches into one, enabling variable operation modes for maximum energy efficiency in different conditions. HEVs are an important step in developing sustainable transportation systems, balancing the need for reduced emissions with the growing demands of modern automotive technology.

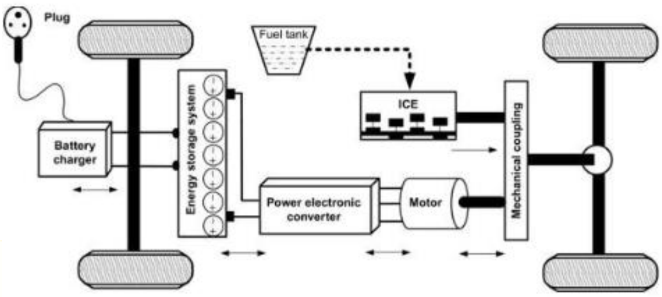

Figure 1 Hybrid electric vehicle block diagram [3]

Figure 1 shows a schematic for a Hybrid Electric Vehicle, with the battery incorporated into the powertrain. The wheels and other in-vehicle operations are powered by a combination of energy recovery devices, mechanical linkage through an electric motor and internal combustion engine, a power electronic converter, and energy storage. Energy efficiency is the very basis of HEVs, since it directly cuts down on fuel consumption, lowers operating costs, and contributes to environmental sustainability. HEVs are reducing dependence on fossil fuels in response to the growing demand for greener, more efficient transportation solutions. Better energy efficiency means less fuel consumption, saving consumers money and encouraging broader energy conservation [4]. HEVs optimize the use of stored electrical energy, minimizing waste and supporting sustainable mobility. This can reduce their greenhouse gas emissions significantly and will help mitigate climate change. Transport is one of the sectors contributing to the emission of global CO_2 . Adoption of HEVs will help this sector to cut down emissions significantly without major infrastructure changes. In HEVs, efficient energy management ensures better usage of the internal combustion engine as it reduces its operation time and the pollutants generated. Additional features such as regenerative braking and adaptive powertrain control systems capture and reuse energy that would otherwise be wasted, further improving efficiency [5]. HEVs not only support environmental goals but also appeal to a wider market due to their balance of performance, cost-effectiveness, and environmental benefits. Thus, as the desire for more economical and environment-friendly vehicles becomes the demand of customers, HEV adoption will further increase. Also, adaptive battery management systems along with high efficiency power converters that are improving and becoming advanced help in the improvement of HEV appeal. These innovations put HEVs at the forefront as a transitional step toward fully electric vehicles, aiding the global shift toward cleaner and more sustainable transportation [6].

BMS and power converters are major improvements in HEVs, aimed at optimizing energy use and directing power to the battery in an efficient manner. BMS tracks critical parameters like state of charge, health of the battery, and temperature for smooth operation with minimal energy loss and battery wear over time [7]. Precise control provided by the BMS extends the lifespan of the battery and improves energy recovery through regenerative braking systems. Power converters, on the other hand, manage and adjust the flow of electrical energy from the electric motor to the battery under varying load conditions. Advanced power converters using adaptive wide bandgap technologies reduce energy losses, improve efficiency, and enhance overall system performance. These technologies combine to achieve efficiency in energy consumption, emission reductions, and supporting the sustainability of HEVs.

I. Fundamentals of the Powertrains of Hybrid Electric Vehicles

It is critical for HEVs to integrate smoothly all the key parts, which comprise an electric motor, a battery, power converters, and an ICE. The primary power source of an HEV is the ICE, which, in most HEVs, operates using conventional fuels such as gasoline or diesel. ICE Optimized for High Performance Often functions as a generator in hybrid systems, providing immediate torque for propulsion and supporting regenerative braking. It has two roles: It powers the vehicle and recovers energy during deceleration. The battery works as an energy storage unit supplying power to the electric motor while operating in pure electric mode, and storing the energy recovered during regenerative braking. Modern HEVs mainly employ lithium-ion batteries, because they have high energy density and a long lifetime [8]. Power converters are used to manage the flow of electrical energy between the battery and motor. Voltage and current can be controlled in an efficient manner by the converter. Further improvements in converter technology help to increase efficiency by minimizing energy losses and energy recovery. Altogether, these elements collaborate in perfect synergy to reduce the consumption of fuel, decrease emission, and, as a result, reduce waste energy, in which HEVs are an innovative solution in shifting toward sustainable transport.

A. Internal Combustion Engine (ICE)

An internal combustion engine is one of the hybrid electric vehicles' main power sources. Such engines usually burn gasoline or diesel. The power is provided directly or indirectly to the wheels by the electric generation. Fuel efficiency and reduced emissions are the fruits of the HEV's ICE being fine-tuned at higher efficiency levels than any conventional car [9]. In hybrids such as series hybrids, the ICE works mainly as a generator and only starts when the battery needs to be recharged. Thus, HEVs limit the operating range of the ICE to maximize energy efficiency and reduce their adverse impacts on the environment.

B. Electric Motor

Electric motors are part and parcel of HEVs. In electric-only mode, it will power the wheels, and in assisting ICE during demanding periods, such as acceleration, it will do that. It gives electric motors a characteristic that provides instantaneous torque, making the vehicle better and more responsive in its performance [10]. The regenerative braking system uses an electric motor because it acts like a generator where it absorbs energy in the kinetic form and reconverts into electrical energy used to charge a battery. Propulsion and energy recovery are associated with the motor; therefore, it is a critical component of improving the energy efficiency and reducing the total amount of fuel used by the vehicle.

C. Battery

In HEVs, the battery acts as an energy storage system. It feeds energy to the electric motor and conserves the one obtained by using regenerative braking. Most present-day HEVs use lithium-ion batteries as they possess superior energy density with a high lifecycle and efficiency levels. This ensures electric-only running at low speed or for some distance and decreases fuel consumption exponentially [11]. In addition to this, monitoring and regulation for parameters such as SOC, temperature, and voltage require a strong and efficient BMS to operate the battery securely and optimally. Proper integration into the overall HEV system is fundamental in attaining all the benefits arising from energy as well as those related to the environment from these kinds of vehicles.

D. Power Converters

This power converter regulates the flow of electrical energy in between the battery, the electric motor, and the remaining components of the vehicle. The device controls the levels of both voltage and current in order to successfully transfer power efficiently over a broad range of operating conditions. For example, the DC-DC converters manage voltage between high-voltage battery and electric motor, and an inverter changes DC of the battery into AC to power the motor [12]. Advanced high-efficiency adaptive power converters should be employed to minimize the loss of energy and maximize HEV system performance. They are also to facilitate maximum recovery through regenerative braking as part of efforts aimed at improving the efficiency of energy utilization in vehicles.

Hybrid Electric Vehicles depend on energy flow and control to improve performance, efficiency, and sustainability. The driving conditions govern dynamic decoupling of the flow of energy among the HEVs in the electrical motor, the battery, power converters, and ICE. They are connected between the electric motor and the ICE if there is high demand and for example during acceleration, but under conditions of running the motor at low speeds or under electric-only modes, power draws directly from the battery [13]. Kinetic energy captured during the deceleration of a car is fed back into electrical energy and then stored in the battery for future use. The power converter adjusts voltage and current to ensure efficient transfer between components. Advanced control systems will allow for a seamless transition between sources of power and ensure optimum performance under varied operating conditions. In addition, it maximizes fuel efficiency and minimizes emissions.

E. Challenges in battery performance and energy optimization

One of the biggest challenges in HEV battery performance and energy optimization is related to low energy density, which puts a constraint on its range along with electric efficiency. Then, another problem with battery degradation in HEVs related to temperature changes, charge-discharge cycles, and overloading is considered challenging. Since such estimations rely on actual real time values of SOC and SOH, high-accuracy estimations become the most problematic issue for preventing overcharging, deep discharging, and overall energy inefficiency [14]. The second challenge comes in the form of thermal management, where the risk of overheating easily undermines both safety and performance. Maximization of energy flow between the battery, power converters, and electric motor under all kinds of driving conditions, like stop-and-go traffic, demands advanced algorithms as well as seamless integration. This will be key to improving overall dependability and energy efficiency along with the service life of batteries in HEVs.

F. Efficiency

HEVs are said to be difficult machines to achieve with high energy efficiency due to power losses in batteries, electric motors, and other power converters. Batteries mostly lose energy because of inefficiency in charge-discharge cycles that result in wastage of the energy as heat. With variations in driving conditions, the voltage and current characteristics of the HEVs' power converter performance is meant to be regulated between the battery and motor; however, such differences lead to some wastage of energy. Other complicating factors in energy optimization are the frequent stop-and-go traffic and high acceleration demands and varied load conditions [15]. The HEV system's regenerative braking feature, though of much use, suffers the additional effect of being hindered by its own inefficiencies due to current limitations in the technologies for storage and conversion of energy. The answer to such inefficiencies is proper optimization of the flow of energy within the HEV system to ultimately ensure the maximum performance with minimal waste.

G. Longevity

The biggest challenge for HEVs is the battery lifespan. Charge-discharge cycles degrade battery health if subjected to frequent fluctuations in temperatures. Degradation accelerates with deep discharging, overcharging, and poor thermal management and shortens the lifespan of the battery in due course. SOC and SOH must be kept under stringent observation and regulation not to destroy battery cells [16]. This further intensifies the situation; under heavy-duty driving situations like gradients or towing loads, it becomes still more demanding on the battery, with an adverse effect on its lifetime. It is therefore crucial to design advanced BMSs that can predict, adapt, and counter such impacts to design long-life batteries that work without fails.

H. Cost Considerations

One of the most significant obstacles for HEV uptake is the high cost of the battery. Indeed, one third of the car's cost lies in its batteries. Despite high energy density and efficiency in new technologies such as lithium-ion, they are rather expensive, and the extraction and processing of some of these rare materials such as cobalt and nickel can be very expensive. Besides, when these batteries reach a certain age or degrade, their replacement can cost too much to the consumers [17]. Lowering the entire costs of the vehicle during its lifecycle requires improving efficiency and lifespan for the battery. Other higher front-end costs occur with more sophisticated energy optimization systems including adaptive BMS and high efficiency power converters. This makes it a big challenge for the manufacturers to do HEVs as cheap and as appealing to a mass market as possible by balancing their advancement in technology with cost-effectiveness.

II. Battery Management Systems (BMS) in HEVs

Hybrid Electric Vehicle Battery Management Systems continuously monitor such key parameters as SOC, SOH and temperature to ensure safe and efficient running. Optimization in terms of energy usage, overcharging and deep discharging prevention, and maximization of life are offered by the BMS through advanced algorithms and real-time adjustments [18]. The BMS can enhance the entire performance, dependability, and efficiency of energy usage by the HEV through effective transfer of energy from the battery to other vehicle parts. The critical parameters for battery management are tracked and monitored by the battery management system of a hybrid electric vehicle so as to ensure that the reliability of the battery operation is safe and efficient. It is, therefore, protected from being overcharged and from conditions fully discharged with chances of overheating or overwork, which first may cause safety problems. The flow of energy is optimized so that stored energy is efficiently used. Overall, the vehicle's performance improves with the help of BMS. It keeps the battery at a much more extended life since charge and discharge cycles are regulated while minimizing the degradation impact [19]. Advanced BMS systems use adaptive algorithms and real-time control for smooth integration of the battery with the electric motor and power converters. BMS is unavoidable to maximize efficiency while reducing HEVs' operation cost and give durability to an extended period over other vehicles in their operation.

The architecture of a BMS in HEVs has several critical components, ensuring safe, efficient, and reliable operation of the battery. There is a core component-the BMU that is responsible for measuring vital parameters, such as voltage, current, temperature, and SOC, for every cell [20]. The Control Unit interprets all of these pieces of information through sophisticated algorithms, like optimization algorithms that guarantee a charge/discharge cycle in relation to optimizing performance and thermal condition control. An ideal design would be for the Thermal Management System to ensure operation within the desired temperature range. Overheating will cause cell damage or a drop-in efficiency. A Fault Detection and Protection Unit is implemented for the protection against overvoltage's, undervoltage, and short-circuit that might destroy the system. The BMS encompasses a Communication System. This permits it to establish good communication with all other sub-units installed within the automobile such as an electric motor, power converters, as well as with the central unit that controls everything on a vehicle via a CAN controller or in some cars at a real time basis [21]. In an architectural point of view, BMS designs are either modular central where all the cells are or else controlled by one control unit or else distributed in groups of cells with individual modules. This modularity ensures scalability and ability to adapt variation in configurations of batteries in HEVs. These three enable the battery to function in efficiency and safety as well as have reliability for optimization of energy besides a long life of batteries within HEVs.

A. Adaptive battery management techniques

Adaptive Battery Management Techniques in hybrid electric vehicles are therefore meant to work toward optimizing battery performance, efficiency, and/or extending lifespan by dynamically adjusting to the real-time conditions. The most common techniques include SOC estimation to precisely monitor the amount of energy remaining in a battery so that overcharging or deep discharging is avoided, SOH monitoring to evaluate the remaining capacity and trends of degradation of a battery through data-driven models to perform predictive maintenance, and thermal management by controlling the battery temperatures within an [22] optimal range to avoid overheating and freezing. All these technologies seamlessly integrate monitoring and control to enable safe, efficient energy use, as well as very high reliability for HEVs.

1. State of Charge (SOC) Estimation: SOC estimation is the vital adaptive technique applied in the management of the battery to calculate the remaining charge in the battery. The right SOC estimation ensures maximum energy utilization without any issues that might come up such as overcharging or deep discharging, which degrades battery performance. Traditionally, Coulomb counting and open-circuit voltage measurement are applied but supplemented with more sophisticated adaptive methods based on Kalman filters, machine learning algorithms, or hybrid models combining physics-based and data-driven approaches [23]. More advanced methods adaptively consider changing driving conditions, the impact of aging batteries, and other environmental influences in the context of accurately predicting the SOC in real-time to allow effective energy management within HEVs.

2. State of Health (SOH) Monitoring: SOH monitoring means the health and capability of performance of a battery. It can measure the remaining capacity and ability to deliver a discharge from the battery, but with time, charge-discharge cycles, temperature differences, and chemical degradation decreased the health of the battery. The adaptive techniques of SOH monitoring are through using data-driven models and machine learning to identify slight changes in the behavior of the battery [24]. These systems predict degradation trends and identify faults early using historical data combined with real-time measurements. SOH monitoring will enable proactive maintenance, extend the life of batteries, and ensure the reliability and safety of HEVs.

3. Thermal Management: In adaptive battery management, thermal management is critical in keeping the battery in an optimal temperature range to avoid issues like thermal runaway that could damage cells or pose safety risks. Advanced thermal management systems employ sensors and adaptive controls to dynamically monitor and regulate battery temperature [26]. All have high-load situations and heating means that dissipate heat through phase-change materials and liquid or air cooling, guaranteeing optimal cold-weather operations. Adaptive strategies can change this strategy on aspects cooling and heating so that real-time data and drive patterns can achieve energy efficiency in safety and lifespan of the battery.

III. (SOC) PREDICTION

SOC is a very accurate prediction that directly influences the efficient running of HEVs since it predicts the time that will be taken by the vehicle to switch between the internal combustion engine and the electric motor, which are two significant factors influencing energy management and performance as well as battery life. SOC defines the charge available in the battery. Precise SOC estimation will make sure that the energy is consumed at an optimum rate without overcharging or deep discharging, which degrades the battery capacity and health in general. Moreover, it gives the right predictions about the range, which builds up confidence for drivers under various changing driving conditions. In addition to improving efficiency, the need for precise SOC prediction also includes safety and durability [27]. Incorrect estimation leads to thermal runaway, overloading, or poor energy flow, which raises the risk of battery failure or accidents. Real-time accuracy in SOC prediction is therefore achieved by employing advanced techniques, such as Kalman filtering, neural networks, and hybrid physics-data models, considering factors such as battery aging, temperature variation, and varied load demands. With the integration of these adaptive methods, HEVs can achieve seamless energy management, improved performance, and extended battery life, which makes SOC prediction a cornerstone of modern Battery Management Systems (BMS).

A. Traditional SOC Prediction Methods

Coulomb counting is one of the most widely used traditional methods for predicting SOC in batteries. The method measures SOC through the integration of charge that flows into and out of the battery over a period of time. Starting from an initial known SOC, the technique tracks the net charge and discharge activity to predict the remaining charge. Although simple and logical, Coulomb counting is still prone to cumulative errors: it relies on initial SOC that are not too accurate, a drifting measurement in time, and battery efficiency will vary with every condition. Yet, it remains a basic methodology and is sometimes combined with additional techniques to boost accuracy [28]. The OCV method estimates the SOC based on how the battery's terminal voltage is proportional to its charge level under rest conditions. Due to the predictable manner in which the OCV of a battery varies with SOC, this method can provide fairly accurate estimations under static conditions. The major drawback is its dependence on the battery being under stable, unloaded rest conditions, something that cannot be allowed to occur in actual time for the HEV. The temperature and aging of the battery can also affect the OCV methods, causing distortions in the voltage-SOC relationship. However, OCV methods are still useful for SOC calibration when used with dynamic techniques, such as Coulomb counting.

B. Advanced SOC estimation techniques

1. ***Adaptive Filtering:*** Adaptive filtering techniques, such as Kalman filters and particle filters, are widely used in SOC estimation. These are adaptive to dynamic and uncertain conditions. The Kalman filter predicts SOC based on the modelling of the battery system as a state-space system. It updates predictions based on real-time measurements. It is very effective in noise reduction and measurement inaccuracies, which helps in achieving more accurate SOC estimations even under changing operating conditions [29]. In the line of Kalman filters, particle filters have also been utilized for SOC tracking. On a probabilistic basis and with sampling at multiple possible states, they offer adaptability to linear or non-Gaussian models of batteries. Real-time, noise-resistant adaptive filters ensure accuracy on any modern battery management system.

2. ***Neural Network and Deep Learning Approach:*** Neural networks and deep learning have lately been recognized as the most efficient tools for SOC estimation, relying on the possibility of such structures to represent complex, nonlinear dependencies within a battery system. Such approaches make use of historical and real-time data to train models, which then allow accurate prediction of SOC under conditions such as temperature, load profiles, and aging of the battery [30]. The approaches of deep learning, such as CNNs and RNNs, improve the accuracy of prediction since they could extract temporal dependencies and very complex patterns in battery behavior. Their adaptability makes these models extremely effective for applications where traditional methods would be difficult, scenarios with a high variability, or even limited knowledge of system behavior.

3. ***Hybrid Models Combining Physics-Based and Data-Driven Methods:*** Hybrid models combine the advantages of physics-based techniques with the benefits of data-driven methods to provide more comprehensive, accurate, and detailed SOC estimation. The first-principle-based electrochemical model uses a set of equations describing the behavior of batteries and offers high accuracy but requires large computational resources and systematic knowledge. Data-driven methods depend on empirical data or machine learning

for faster adaptability in predictions [31]. Hybrid models combine the accuracy of physics-based approaches with the flexibility of data-driven techniques, thus overcoming the shortcomings of each individual method. The hybrid models are therefore very effective for real-world SOC estimation in HEVs, ensuring reliable and efficient battery management.

IV. Converter Technologies in HEVs

Hybrid Electric Vehicles are equipped with power converters that supply an efficient form of energy transfer and regulation between the battery, electric motor, and other systems of a vehicle. Voltage levels in a vehicle are managed using power converters in order to facilitate high-voltage battery operation within low-voltage auxiliary systems while recovering energy using regenerative braking [32]. The key types of converters in HEVs include the DC-DC converters, inverters, and rectifiers, which separately serve a particular function that helps the electrical and propulsion systems in the vehicle.

A. DC-DC Converters

These converters regulate and alter the voltage levels between a car's high-voltage battery and its low-voltage auxiliary systems. The auxiliary systems in a vehicle comprise lighting, infotainment, and control electronics. In HEVs, the converters serve a vital role for maintaining the power supply to various components in a vehicle with minimal fluctuations. They also allow the regenerative braking system in which energy generated by an electric motor is captured and then stored back to a battery [33]. High efficiency DC-DC converters minimize loss, enhance performance in HEVs, and assure compatibility of diverse demands in different voltages within HEVs.

B. Inverters

Inverters change direct current from the battery to alternating current that the electric motor requires for movement. They are necessary for an electric motor's smooth and efficient operation, allowing dynamic torque and speed changes. High-performance inverters make use of PWM techniques and wide bandgap semiconductors like silicon carbide (SiC) to realize high efficiency with less heat generation [34]. The optimization in the conversion process enables inverters to contribute significantly to the overall energy efficiency and performance of the HEV, especially under acceleration and high-load conditions.

C. Rectifiers

Rectifiers do the opposite function of inverters: they convert the AC produced by the electric motor during regenerative braking to DC to recharge the battery. This process is critical in energy recovery; HEVs capture kinetic energy that would otherwise go to waste [35]. Newer rectifiers are designed to be efficient in all speeds and loads, maximizing energy recapture at deceleration. This way, their regenerative braking helps enhance energy efficiency without relying so much on the internal combustion engine and consequently reduces fuel consumption and emissions.

Road transport currently absorbs a significant portion of the global fossil fuel, as well as CO2 and other pollutants. Whereas adoption of eco-driving techniques is the fastest and most economical measure, use of HEVs and PHEVs is slowly gaining recognition as a strategy in reducing transportation energy use. In this study, two technologies were explored, focusing on how these two technologies could be combined in use for linked HEVs and PHEVs [36]. In an effort to provide a brief introduction to the framework, we will briefly compare the advantages, disadvantages, and effectiveness of current approaches for fusion road information incorporation into single-vehicle and multi-vehicle scenarios, respectively. A range of future directions in EMS with regard to eco-driving methods and cooperative optimization is also presented. This detailed analysis does well to present the importance and potential impacts of these approaches toward resolving environmental problems in transportation systems, which would be useful to potential scholars and professionals in industry.

Since hybrid electric vehicles must simultaneously raise energy economy, roadway security, and driving comfort, several power components need to be coordinated properly. In contrast, earlier approaches designed for these multi-objective co-optimization problems can lead to misleading optimization for the car in complex and varied driving situations [37]. In an effort to overcome the shortcomings, this paper presents a novel Nash bargaining game-based multi-objective optimization controller. Here, longitudinal dynamic control and energy management approach are taken as two separate players. Nash equilibrium is selected as the threat point, which is solved through a linear quadratic game strategy. Then, using the alternate direction method of multipliers (ADMP), NBS is computed. The simulation results indicate that the proposed controller is better than the centralized controller in preserving the optimality and resilience of the control performance and even better than the hierarchical optimization controller, where the fuel consumption is improved by an average of 5.6%.

Microgrids (MGs) often incorporate various energy sources to improve the reliability of the system, such as intermittent methods, like solar panels and wind turbines. In the integrated system, MGs become stronger and more capable of withstanding challenges. Furthermore, BESS units are connected to MGs in order to offer grid-supporting services such as peak shaving, load compensation, power factor quality, and source failure operation. In this case, an energy management system (EMS) is required to be integrated with the MGs that include BESS. Hence, SoC equalization is one of the techniques for satisfying EMS requirements and balancing the internal load among BESS units for MG operation. In this paper, we present an overall review of EMS strategies to balance the SoC of BESS units based on centralized and decentralized control, multiagent systems, and other new concepts, like nonlinear strategy design, optimal algorithms, and classification of agents into groups [38]. Moreover, in this paper, we also discuss alternative solutions for the enhancement of EMS and related strategies about the topology of the power converter: redundancy-based topology, modular multilevel converter, cascaded-based converter, and hybrid-type systems. Besides, optimization processes to minimize operational costs, which take into account SoC equalization, are discussed in this article. Finally, second-life BESS units are discussed as an emerging topic, with a focus on their operation within specific power converters topologies to achieve SoC balance.

The ability of the soil to carry out fundamental tasks is consequently a reflection of the health of the ecosystem since it helps to offer a wide range of ecosystem products and services. Since soil organic carbon (SOC) is the major factor of many soil activities and related ecosystem services, it has become an essential indicator of soil quality. Conversely, due to unsustainable practices and agricultural development, SOC stocks are declining globally. Growing realization, especially at the policymaker level, of the fact that soil is a nonrenewable resource and that it supports all life on Earth has driven the European Green Deal to develop policies aimed at preserving and restoring SOC [39]. Non-harmonized variance remains in national SOC monitoring strategies that keeps hindering the monitoring of national SOC stocks at the European level. The evaluation of the goals stated by the various EU directives frequently requires extra and contrasting SOC data, even though the majority of policy goals may be assessed by some SOC indicators (i.e., baseline and potential SOC stocks). An overview of five active SOC monitoring initiatives throughout Europe is provided in this study, along with a discussion of how national programs may be coordinated to assess objectives at the EU level. To demonstrate the possibilities for harmonizing and standardizing SOC evaluation, a case study including five nations with wildly disparate soil monitoring regimes was presented. We conclude from this research that though SOC monitoring methods can be harmonized, they cannot be standardized. In addition, we propose five sampling methods that the Draft Directive on Soil Monitoring and Resilience will probably standardize.

Besides producing green hydrogen or other high-value products from renewable electricity, solid oxide cells (SOCs) are known for their outstanding efficiency in directly converting any fuel into electricity. They allow for the simultaneous generation of thermal energy, electricity, and hydrogen according to demand. To enhance performance and ensure long-term stability, considerable research has been devoted to developing high-performance electrodes during the last few decades. Among these, one successful approach has been the development of in-situ heterostructure electrodes or surfaces, which are characterized by special compositions and architectures different from the bulk phase [40]. This paper first gives a short overview of the recent developments concerning the creation of in-situ heterostructures for SOCs. After that, we critically analyze the inherent weaknesses of the heterostructure's in-situ formation and systematically discuss seven existing approaches. It is our hope that this review, coming at a time when this field is alive with innovation, will supply insight into the root cause of performance improvements and provide a scientific framework for designing optimal efficiency electrodes by rational design.

Table 1 Evaluation of Key Innovations in Energy Management and Environmental Systems

References	Topic	Key Focus	Approach/Technology	Advantages	Challenges
[36]	HEVs and PHEVs with Eco-Driving	Energy efficiency in road transport and environmental sustainability	Integration of eco-driving and connected HEV/PHEV strategies	Low-cost, immediate impact, reduces energy consumption	Limited in complex multi-vehicle scenarios; requires cooperative optimization
[37]	Multi-Objective Optimization in HEVs	Energy management and dynamic control using game theory	Nash bargaining game, linear quadratic game approach, ADMM	Improved fuel efficiency (5.6%), robust and optimal control performance	Misleading optimization in complex driving scenarios
[38]	Energy Management in Microgrids	Reliable power distribution and BESS state-of-charge (SOC) balancing	Centralized and decentralized EMS, multi-agent systems, advanced topologies	Improved reliability, reduced operational costs, second-life BESS utilization	Complex EMS integration; managing diverse converter topologies
[39]	Soil Organic Carbon (SOC) Monitoring	Preserving and restoring soil health as part of the European Green Deal	Harmonization of SOC monitoring strategies across Europe	Increases soil sustainability awareness, supports EU-level environmental goals	Non-harmonized national SOC monitoring strategies; diverse data needs for EU directives
[40]	Solid Oxide Cells (SOCs)	High-efficiency energy conversion	In-situ heterostructure electrodes development	High efficiency, versatile applications	Limitations in current heterostructure construction

		and green hydrogen production		(electricity, hydrogen, thermal energy), long-term durability focus	techniques; need for optimal electrode design

V. CONCLUSION

The HEVs in this study emphasize how they can promote energy efficiency and sustainability through internal combustion engines, electric motors, batteries, and power converters. Such a study further emphasizes transformative innovations such as adaptive battery management systems and advanced power converters, enabling optimized energy usage, extended lifespan of the battery, and better performance for the vehicle. Advanced SOC prediction techniques include adaptive filtering, machine learning, and hybrid models. These are critical for the accurate management of batteries and optimization of energy consumption. These technologies together reduce fuel consumption, operational costs, and emissions. They provide a sustainable alternative to traditional vehicles. In the future, machine learning, IoT-based systems, and wide bandgap semiconductors will be integrated to further advance energy efficiency and reliability. These innovations do not only enhance the market viability of HEVs but also position them as a critical bridge to fully electric vehicles, thereby significantly contributing to the alleviation of global transportation and environmental challenges.

REFERENCESS

[1] Urooj, A., & Nasir, A. (2024). Review of hybrid energy storage systems for hybrid electric vehicles. *World Electric Vehicle Journal*, *15*(8), 342. https://doi.org/10.3390/wevj15080342

[2] Abed, M. A. N., Altahir, A. A. R., & Abdulhadi, A. (2024). A Review of Hybrid Electric Vehicle Configurations: Advances and Challenges. *Kerbala Journal for Engineering Sciences*, *4*(3).

[3] Upadhyay, Abhishek & Dalal, Mihir & Sanghvi, Naman & Singh, Vaibhav & Nair, Sheeja & Scurtu, Ionut Cristian & Dragan, Cristian. (2021). Electric Vehicles over Contemporary Combustion Engines. IOP Conference Series: Earth and Environmental Science. 635. 012004. 10.1088/1755-1315/635/1/012004.

[4] Urooj, A., & Nasir, A. (2024). Review of intelligent energy management techniques for hybrid electric vehicles. *Journal of Energy Storage*, *92*, 112132. https://doi.org/10.1016/j.est.2024.112132

[5] Sun, B., Zhang, Q., Mao, H., & Li, Z. (2024). Validation of a statistical-dynamic framework for predicting energy consumption: A study on vehicle energy conservation equation. *Energy Conversion and Management*, *307*, 118330. https://doi.org/10.1016/j.enconman.2024.118330

[6] Recalde, A., Cajo, R., Velasquez, W., & Alvarez-Alvarado, M. S. (2024). Machine Learning and Optimization in Energy Management Systems for Plug-In Hybrid Electric Vehicles: A Comprehensive Review. *Energies*, *17*(13), 3059. https://doi.org/10.3390/en17133059

[7] Esho, A. O. O., Iluyomade, T. D., Olatunde, T. M., & Igbinenikaro, O. P. (2024). A comprehensive review of energy-efficient design in satellite communication systems. *International Journal of Engineering Research Updates*, *6*(02), 013-025. https://doi.org/10.53430/ijeru.2024.6.2.0024

[8] Munsi, M. S., & Chaoui, H. (2024). Energy Management Systems for Electric Vehicles: A Comprehensive Review of Technologies and Trends. *IEEE Access*. https://doi.org/10.1109/ACCESS.2024.3371483

[9] Joshi, A., Kumar, C. V., Rani, B. K., Hussain, M., & Suvonova, L. (2024). Finite element analysis of internal combustion engine cylinder head. In *E3S Web of Conferences* (Vol. 564, p. 11001). EDP Sciences. https://doi.org/10.1051/e3sconf/202456411001

[10] Gonzalez, P., Buigues, G., & Mazon, A. J. (2023). Noise in electric motors: A comprehensive review. *Energies*, *16*(14), 5311. https://doi.org/10.3390/en16145311

[11] Chen, M., Ma, G., Liu, W., Zeng, N., & Luo, X. (2023). An overview of data-driven battery health estimation technology for battery management system. *Neurocomputing*, *532*, 152-169. https://doi.org/10.1016/j.neucom.2023.02.031

[12] Nkembi, A. A., Cova, P., Sacchi, E., Coraggioso, E., & Delmonte, N. (2023). A Comprehensive Review of Power Converters for E-Mobility. *Energies*, *16*(4), 1888. https://doi.org/10.3390/en16041888

[13] Nyamathulla, S., & Dhanamjayulu, C. (2024). A review of battery energy storage systems and advanced battery management system for different applications: Challenges and recommendations. *Journal of Energy Storage*, *86*, 111179. https://doi.org/10.1016/j.est.2024.111179

[14] AL-Jumaili, A. H. A., Muniyandi, R. C., Hasan, M. K., Singh, M. J., Paw, J. K. S., & Amir, M. (2023). Advancements in intelligent cloud computing for power optimization and battery management in hybrid renewable energy systems: A comprehensive review. *Energy Reports*, *10*, 2206-2227. https://doi.org/10.1016/j.egyr.2023.09.029

[15] Mohammed, A. S., Atnaw, S. M., Salau, A. O., & Eneh, J. N. (2023). Review of optimal sizing and power management strategies for fuel cell/battery/super capacitor hybrid electric vehicles. *Energy Reports*, *9*, 2213-2228. https://doi.org/10.1016/j.egyr.2023.01.042

[16] Li, B., Liu, Z., Wu, Y., Wang, P., Liu, R., & Zhang, L. (2023). Review on photovoltaic with battery energy storage system for power supply to buildings: Challenges and opportunities. *Journal of Energy Storage*, *61*, 106763. https://doi.org/10.1016/j.est.2023.106763

[17] Mateen, S., Amir, M., Haque, A., & Bakhsh, F. I. (2023). Ultra-fast charging of electric vehicles: A review of power electronics converter, grid stability and optimal battery consideration in multi-energy systems. *Sustainable Energy, Grids and Networks*, 101112. https://doi.org/10.1016/j.segan.2023.101112

[18] Waseem, M., Ahmad, M., Parveen, A., & Suhaib, M. (2023). Battery technologies and functionality of battery management system for EVs: Current status, key challenges, and future prospectives. *Journal of Power Sources*, *580*, 233349. https://doi.org/10.1016/j.jpowsour.2023.233349

[19] Kurucan, M., Özbaltan, M., Yetgin, Z., & Alkaya, A. (2024). Applications of artificial neural network based battery management systems: A literature review. *Renewable and Sustainable Energy Reviews*, *192*, 114262. https://doi.org/10.1016/j.rser.2023.114262

[20] Ria, A., & Dini, P. (2024). A Compact Overview on Li-Ion Batteries Characteristics and Battery Management Systems Integration for Automotive Applications. *Energies*, *17*(23), 5992. https://doi.org/10.3390/en17235992

[21] Naseri, F., Kazemi, Z., Larsen, P. G., Arefi, M. M., & Schaltz, E. (2023). Cyber-physical cloud battery management systems: review of security aspects. *Batteries*, *9*(7), 382. https://doi.org/10.3390/batteries9070382

[22] Kumar, R. R., Bharatiraja, C., Udhayakumar, K., Devakirubakaran, S., Sekar, S., & Mihet-Popa, L. (2023). Advances in batteries, battery modeling, battery management system, battery thermal management, SOC, SOH, and charge/discharge characteristics in EV applications. *Ieee Access*. https://doi.org/10.1109/ACCESS.2023.3318121

[23] Lin, Z., Huang, Z., Yang, S., Wu, C., Fang, S., Liu, Z., ... & Zou, Y. (2024). Survey on task-centric robot battery management: A neural network framework. *Journal of Power Sources*, *610*, 234674. https://doi.org/10.1016/j.jpowsour.2024.234674

[24] Wu, L., Lyu, Z., Huang, Z., Zhang, C., & Wei, C. (2024). Physics-based battery SOC estimation methods: Recent advances and future perspectives. *Journal of Energy Chemistry*, *89*, 27-40. https://doi.org/10.1016/j.jechem.2023.09.045

[25] Vignesh, S., Che, H. S., Selvaraj, J., Tey, K. S., Lee, J. W., Shareef, H., & Errouissi, R. (2024). State of Health (SoH) estimation methods for second life lithium-ion battery—Review and challenges. *Applied Energy*, *369*, 123542. https://doi.org/10.1016/j.apenergy.2024.123542

[26] Lv, Y. G., Wang, Y. T., Meng, T., Wang, Q. W., & Chu, W. X. (2024). Review on thermal management technologies for electronics in spacecraft environment. *Energy Storage and Saving*, *3*(3), 153-189. https://doi.org/10.1007/s40820-023-01126-1

[27] Kim, E., Kim, M., Kim, J., Kim, J., Park, J. H., Kim, K. T., ... & Min, K. (2023). Data-driven methods for predicting the state of health, state of charge, and remaining useful life of li-ion batteries: A comprehensive review. *International Journal of Precision Engineering and*

Manufacturing, *24*(7), 1281-1304. https://doi.org/10.1007/s12541-023-00832-5

[28] Sesidhar, D. V. S. R., Badachi, C., & Green II, R. C. (2023). A review on data-driven SOC estimation with Li-Ion batteries: Implementation methods & future aspirations. *Journal of Energy Storage*, *72*, 108420. https://doi.org/10.1016/j.est.2023.108420

[29] Khan, A., Shafi, I., Khawaja, S. G., de la Torre Díez, I., Flores, M. A. L., Galvlán, J. C., & Ashraf, I. (2023). Adaptive filtering: issues, challenges, and best-fit solutions using particle swarm optimization variants. *Sensors*, *23*(18), 7710. https://doi.org/10.3390/s23187710

[30] Araújo, A. L. D., da Silva, V. M., Kudo, M. S., de Souza, E. S. C., Saldivia- Siracusa, C., Giraldo- Roldán, D., ... & Moraes, M. C. (2023). Machine learning concepts applied to oral pathology and oral medicine: a convolutional neural networks' approach. *Journal of Oral Pathology & Medicine*, *52*(2), 109-118. https://doi.org/10.1111/jop.13397

[31] Kasilingam, S., Yang, R., Singh, S. K., Farahani, M. A., Rai, R., & Wuest, T. (2024). Physics-based and data-driven hybrid modeling in manufacturing: a review. *Production & Manufacturing Research*, *12*(1), 2305358. https://doi.org/10.1080/21693277.2024.2305358

[32] Kotb, R., Chakraborty, S., Tran, D. D., Abramushkina, E., El Baghdadi, M., & Hegazy, O. (2023). Power electronics converters for electric vehicle auxiliaries: State of the art and future trends. *Energies*, *16*(4), 1753. https://doi.org/10.3390/en16041753

[33] Ali, A., Mousa, H. H., Shaaban, M. F., Azzouz, M. A., & Awad, A. S. (2023). A comprehensive review on charging topologies and power electronic converter solutions for electric vehicles. *Journal of Modern Power Systems and Clean Energy*. https://doi.org/10.35833/MPCE.2023.000107

[34] Acharige, S. S., Haque, M. E., Arif, M. T., Hosseinzadeh, N., Hasan, K. N., & Oo, A. M. T. (2023). Review of electric vehicle charging technologies, standards, architectures, and converter configurations. *IEEE Access*, *11*, 41218-41255. https://doi.org/10.1109/ACCESS.2023.3267164

[35] Kumar, S., Jammeh, S., Samb, R., & Singh, A. (2024). Efficient DC–DC power converters for fuel- cell electric vehicle: A qualitative assessment. *IET Power Electronics*. https://doi.org/10.1049/pel2.12819

[36] Wang, Z., Dridi, M., & El Moudni, A. (2023). Co-optimization of eco-driving and energy management for connected HEV/PHEVs near signalized intersections: A review. *Applied Sciences*, *13*(8), 5035. https://doi.org/10.3390/app13085035

[37] Ruan, S., Ma, Y., Yang, N., Yan, Q., & Xiang, C. (2023). Multiobjective optimization of longitudinal dynamics and energy management for HEVs based on nash bargaining game. *Energy*, *262*, 125422. https://doi.org/10.1016/j.energy.2022.125422

[38] Fagundes, T. A., Fuzato, G. H. F., Silva, L. J. R., dos Santos Alonso, A. M., Vasquez, J. C., Guerrero, J. M., & Machado, R. Q. (2024). Battery Energy Storage Systems in Microgrids: A Review of SoC Balancing and Perspectives. *IEEE Open Journal of the Industrial Electronics Society*. https://doi.org/10.1109/OJIES.2024.3455239

[39] Meurer, K. H., Hendriks, C. M., Faber, J. H., Kuikman, P. J., van Egmond, F., Garland, G., ... & Bispo, A. (2024). How does national SOC monitoring on agricultural soils align with the EU strategies? An example using five case studies. *European Journal of Soil Science*, *75*(2), e13477. https://doi.org/10.1111/ejss.13477

[40] Gao, Y., Liu, K., Qi, L., Hou, Z., Chang, Y., & Tao, Z. (2024). The approaches to conducting in-situ heterostructure electrodes for SOCs: A mini review. *Sustainable Materials and Technologies*, e01107. https://doi.org/10.1016/j.susmat.2024.e01107