

Comparative Review on Energy Management for Hybrid Electric Vehicles in Smart Cities

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Abstract. This paper reviews different ways to manage energy in Hybrid Electric Vehicles (HEVs) for smart cities by looking at three separate studies. Initially, it explores a structured approach to solving energy management issues in HEVs, comparing three known methods and highlighting one that can be used in real-time. Next, it discusses a creative use of Petri Nets (PNs) for managing energy, either on its own or with the Global Positioning System (GPS). This part points out the benefits of using GPS to manage energy better during different driving conditions. Lastly, the paper talks about the need to improve energy management in a specific type of HEV to address current environmental and energy challenges. It mentions the use of a Genetic Algorithm (GA) to improve energy management strategies, aiming to extend the life of the vehicle's fuel cell and improve energy efficiency. Through these discussions, this review aims to provide a clear understanding of how energy management in HEVs can be improved in smart city settings.

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1 Introduction

The escalating concerns surrounding global warming and the associated rise in respiratory diseases have thrust the dialogue on sustainable automotive technologies into the spotlight. According to the Intergovernmental Panel on Climate Change (IPCC), a significant 14% of global greenhouse gas (GHG) emissions are attributed to the transport sector, with a whopping 80% originating from road transport. Against this backdrop, Hybrid Electric Vehicles (HEVs) emerge as a promising avenue to curtail fuel consumption and emissions compared to conventional vehicles. The essence of HEVs lies in their reversible energy storage apparatus and electric machines, which enable idle off capability, regenerative braking, power assist ability, and potential for engine downsizing. The bidirectional functionality of electric actuators and the storage system allows for the preservation and utilisation of energy generated during engine operation and vehicle deceleration. However, the advent of an additional energy storage device introduces a new realm of complexities, chiefly, the efficient distribution of power demand between the engine and the battery, orchestrated by the energy management strategy.

The energy management strategy in HEVs is pivotal in minimising fuel consumption and emissions over a driving cycle without compromising the vehicle's performance. The crux of energy management hinges on the judicious allocation of power request between the on-board energy sources, typically a battery or other electrical storage devices and the fuel tank. This allocation determines the engine power and battery power at any given time, and in more complex powertrains, other control variables such as the repartition of torque between electric machines or the transmission ratio. The overarching objective is to navigate through the additional degrees of freedom and ascertain the most efficient way of splitting the power demand. The energy management problem in HEVs can be construed as an optimal control problem, where the goal is to minimise a performance index over an extended period, the driving cycle, by employing a sequence of instantaneous control actions. Various strategies have been delineated in literature to address this problem, ranging from numerical methods for global and local optimisation to analytical optimisation methods and heuristic methods.

A notable method of energy management is the Equivalent Consumption Minimisation Strategy (ECMS), which has been lauded for its real-time implementability and efficient performance in comparison with other strategies like Dynamic Programming (DP) and Pontryagin's Minimum Principle (PMP). The ECMS framework, when viewed through the lens of the minimum principle, can be seen as an implementation of the optimal solution to the energy management problem. This revelation augments the confidence in employing strategies based on equivalent consumption minimisation. The discourse on energy management also extends to the realm of Battery Management Systems (BMSs), which are instrumental in ensuring the safe operation of the battery. Accurate estimation of the State of Charge (SoC) is imperative for proper management of the battery pack, which in turn, is crucial for the safe, robust, and reliable operation of modern EVs and HEVs. The SoC estimation plays a pivotal role in devising efficient control strategies to manage the battery's energy and ensure its safe operation, thereby extending and optimising the battery lifetime.

Furthermore, the narrative transitions to a novel terrain of energy management by amalgamating the road navigation system with a simple rule-based optimisation methodology. This hybridisation aims to enhance the energy management procedure, reduce fuel consumption and emissions, and improve the fuel economy of HEVs. The rule-

based strategy (RbS) coupled with the Global Positioning System (GPS) data emerges as a promising avenue to attain enhanced energy management and reduced fuel consumption and emissions. The synergy between these diverse strategies and methodologies underscores the multifaceted nature of energy management in HEVs, and the potential for innovative solutions in mitigating the environmental impact of road transport. Through a meticulous examination of the three distinct studies, this review seeks to furnish a holistic understanding of the energy management paradigms in HEVs, and their implications in the broader narrative of sustainable urban mobility in smart cities.

2 Review and discussion

In a study by Serrao et al. (2011), a comparative analysis of energy management strategies for hybrid electric vehicles (HEVs) was conducted [1]. The study encapsulated the energy management conundrum in HEVs and juxtaposed three renowned methodologies for resolving the ensuing optimisation quandary: Dynamic Programming (DP), Pontryagin's Minimum Principle (PMP), and Equivalent Consumption Minimisation Strategy (ECMS). These strategies were scrutinised and compared in a methodical fashion, illuminating their substantial equivalence. The study also proffered simulation outcomes to exemplify the application of these strategies. The cardinal objective of the energy management strategy was to curtail fuel consumption over a driving cycle whilst not compromising the vehicle's performance. The theoretical underpinning for each strategy was elucidated in depth utilising the same formal framework. Among the trio of strategies, ECMS was pinpointed as the sole strategy implementable in real time, with its equivalence with PMP and DP vindicating its use as an optimal strategy and facilitating more effective tuning.

The Dynamic Programming (DP) approach is a mathematical technique used for solving complex problems by breaking them down into simpler subproblems. It's a method often used for optimisation in various fields including operations research and economics. Pontryagin's Minimum Principle (PMP) is a mathematical principle used for optimal control theory, which is the theory used to choose optimal solutions given certain constraints. It's named after the Russian mathematician Lev Pontryagin. The Equivalent Consumption Minimisation Strategy (ECMS) is a real-time implementable energy management strategy that aims to minimise the equivalent fuel consumption by optimally splitting the power demand between the engine and the battery. Each of these strategies has its own set of advantages and disadvantages, and their comparative analysis in the context of energy management in HEVs provides a rich understanding of their practical implications and effectiveness.

Table 1. Comparative Analysis of DP, PMP, and ECMS for HEV Energy Management [4-8]

Parameter/Strategy	Dynamic Programming (DP)	Pontryagin's Minimum Principle (PMP)	Equivalent Consumption Minimization Strategy (ECMS)
Objective	Aiming to minimise a performance indicator over a prolonged duration	Aiming to minimise a performance indicator over a prolonged duration	Aiming to minimise a suitably defined immediate cost function at each juncture

Implementability	Unfeasible in real time due to the prerequisite of having prior knowledge of the entire driving cycle	Not delineated	Feasible in real time
Optimization Horizon	The full extent of the driving cycle	The full extent of the driving cycle	Momentary, at each juncture
Formalisation	Numerical methodologies for overarching optimisation	Analytical optimisation methodologies	Immediate minimisation methodologies
Equivalence	Analogous to PMP and ECMS concerning the optimisation problem resolved	Analogous to DP and ECMS concerning the optimisation problem resolved	Analogous to DP and PMP concerning the optimisation problem resolved
Application	Simulation-oriented comparison	Simulation-oriented comparison	Simulation-oriented comparison, with an emphasis on real-time enactment
Outcome	Yields the optimal solution over the designated driving cycle but unimplementable	Yields an analytical problem framework for swifter numerical resolution	Yields a result proximate to the global optimum if the immediate cost function is aptly defined

In this tabulation, the comparative analysis of three distinct strategies for energy management in Hybrid Electric Vehicles (HEVs) is delineated. The Dynamic Programming (DP) strategy, although optimal, is rendered unimplementable in real time due to the necessity of prior knowledge regarding the entire driving cycle. On the other hand, Pontryagin's Minimum Principle (PMP) provides an analytical framework for a faster numerical resolution, albeit without a clear indication of its real-time implementability. The Equivalent Consumption Minimisation Strategy (ECMS), however, emerges as a real-time implementable strategy, focusing on minimising a defined immediate cost function at each juncture of the driving cycle.

Each strategy, while having its unique objective and methodology, is found to be analogous to the others in terms of the optimisation problem being resolved. The application of these strategies is explored through simulation-based comparisons, with ECMS having an additional emphasis on real-time enactment. The outcomes of these strategies elucidate the optimal solutions and the feasibility of their implementation in real scenarios, thereby providing a nuanced understanding of their applicability and effectiveness in the realm of HEV energy management.

The findings from the study by Serrao et al. (2011) significantly contribute to our review article titled "Comparative Review on Energy Management for Hybrid Electric Vehicles in Smart Cities". The detailed comparison among DP, PMP, and ECMS as tabulated provides a clear understanding of the strengths and limitations of each strategy in managing the

energy in HEVs efficiently. Particularly, the real-time implementability of ECMS stands out as a crucial advantage in the context of smart cities, where real-time energy management is pivotal for optimizing fuel consumption and reducing emissions amidst varying urban driving conditions. The formalization and comparative analysis of these energy management strategies provide a solid foundation for further exploring and tuning real-time implementable strategies like ECMS in the broader framework of energy management in smart cities.

Another study by Ramadan et al. (2017) delves into the exploration of an efficient energy management strategy for Hybrid Electric Vehicles (HEVs) through a combined GPS/Rule-Based Methodology [2]. The research proposes a flexible use of Petri nets (PNs) for energy management in Hybrid Electric Vehicles (HEVs) with advanced hybrid features and a serial design. This can be either without the use of a global positioning system (GPS), termed as a 'GPS-free' system, or in conjunction with it, known as a 'GPS-registered' system. The paper contrasts the PN approach with two fuzzy logic methods, evaluating them based on fuel efficiency and the time taken to converge. The research takes into account both short urban journeys of 30 km and longer highway routes of 240 km, starting with a battery charge level (SoC) at 50% and varying daily driving patterns. Simulation outcomes distinctly highlight the enhanced efficiency of the new GPS-registered approach in refining the energy management of HEVs and cutting down on fuel usage. Additionally, the research underscores the significance of precise SoC assessments and the pivotal role of Battery Management Systems (BMS) in guaranteeing the dependable, sturdy, and secure functioning of HEV batteries.

Table 2. Comparative Analysis of GPS-Free and GPS-Registered Energy Management Systems in HEVs [9-12]

Parameter	Description	GPS-Free System	GPS-Registered System	Comparison
Fuel Consumption	The amount of fuel consumed during the trips	Higher	Lower	GPS-Registered system shows lower fuel consumption
Convergence Time	The time taken for the system to stabilize	Longer	Shorter	GPS-Registered system stabilizes faster
Trip Types	Types of trips considered in the study	30 km urban and 240 km highway	30 km urban and 240 km highway	Both systems were tested on the same trip types
Initial SoC	Initial State of Charge	50%	50%	Same initial SoC for both systems
Daily Driving Cycles	Different daily driving cycles considered	Various standard cycles	Various standard cycles	Both systems were tested on various standard driving cycles

The GPS-registered methodology proposed in the study presents a novel approach to enhance the energy management of HEVs, which is crucial for the integration of HEVs in smart cities. The reduced fuel consumption and improved efficiency demonstrated by the GPS-registered system align with the objectives of optimizing energy management in HEVs for better sustainability and lower emissions in smart cities. This study's methodology and findings provide a substantial basis for further exploring and comparing various energy management strategies, contributing to the broader discussion on promoting HEVs' efficiency and sustainability in smart urban environments.

Another study by Lü et al. (2020) delves into the intricacies of energy management within Fuel Cell Hybrid Electric Vehicles (FCHEVs) by employing a Genetic Algorithm (GA) based approach [3]. The study meticulously explores various energy management strategies to enhance the efficiency and performance of FCHEVs. The focal point of the investigation is the application of Genetic Algorithm in optimizing the energy management strategies, alongside a detailed examination of other modern optimization methods and control strategies.

Table 3. Comparative Analysis of Energy Management Strategies in Fuel Cell Hybrid Electric Vehicles (FCHEVs) by Lü et al. (2020) [13-16]

Key Aspect	Description	Method/Technique Used	Advantages	Limitations
Genetic Algorithm (GA) Application	Application of GA in optimizing energy management strategies for FCHEVs.	Genetic Algorithm (GA)	Superior optimization performance.	Heuristic, may not always find the global optimum.
Optimization Objectives	Guidance for optimal control strategy and structural design of the fuel cell hybrid power system.	Optimization rules and parameters	Improving energy utilization efficiency and extending fuel cell life.	Requires precise definition of optimization objectives.
Hybrid Power System (HPS) Control	Various methods for energy management of HPS.	Fuzzy rule control, deterministic rule control, global optimization method	Real-time monitoring and control of hybrid power transmission system.	Each method has its own set of limitations.
Deterministic Rule Control	Real-time monitoring of the hybrid power transmission system based on a rule table or flow chart.	Rule table or flow chart	Direct and straightforward control strategy based on predefined rules.	May not adapt well to changing or unforeseen conditions.
Global	Solving global	Global optimization	Can handle	Traditional

Optimization Strategy	solutions based on real-time changes in the optimization problem.	methods	irregular problems.	methods like dynamic programming may have longer solution time.
Modern Optimization Methods	Integration of modern optimization methods in energy management of HEVs.	Neural networks, particle swarm optimization, dynamic programming	Potential in achieving energy saving and real-time predictions.	May require high computational resources.
Proton Exchange Membrane Fuel Cell (PEMFC) in FCHEVs	Essential component providing the primary power source	Fuel Cell Technology	High energy efficiency and low emissions	Limited power density for peak power demands
Auxiliary Power Supplies	Necessity of auxiliary power supplies like batteries or supercapacitors.	Batteries, Supercapacitors	Compensate for peak power required for system operation.	Additional components may increase system complexity and cost.

Lü et al. (2020) embarks on a comprehensive exploration to ascertain optimal energy management strategies for FCHEVs. The study underscores the pivotal role of Genetic Algorithm in navigating the complex landscape of energy management, offering a robust framework for optimizing the operational parameters of FCHEVs. The investigation also delves into the realm of Hybrid Power System (HPS) control, shedding light on various methods including Fuzzy Rule Control, Deterministic Rule Control, and Global Optimization Strategy. Each of these methods presents a unique set of advantages and limitations, painting a nuanced picture of the energy management ecosystem within FCHEVs. The study further highlights the Proton Exchange Membrane Fuel Cell (PEMFC) in FCHEVs, alongside the necessity of auxiliary power supplies like batteries or supercapacitors to compensate for peak power requirements. The discourse extends to modern optimization methods like Neural Networks, Particle Swarm Optimization, and Dynamic Programming, showcasing their potential in achieving energy saving and real-time predictions, albeit at the cost of high computational resources.

The detailed analysis and comparative assessment of various energy management strategies by Lü et al. (2020) provide a rich foundation for understanding the dynamics of energy management within HEVs, particularly in the context of smart cities. The insights garnered from the study, especially the potential of Genetic Algorithm in optimizing energy management strategies, offer a valuable perspective in evaluating the efficiency and performance of HEVs. This aligns seamlessly with our objective of dissecting the energy management paradigms in HEVs to foster a sustainable and efficient urban transportation framework.

3 Future Scope of Research

The realm of Hybrid Electric Vehicles (HEVs) and their energy management is a burgeoning field with a plethora of avenues yet to be explored. The intersection of HEVs with smart city infrastructure presents a fertile ground for innovative research, aimed at not only enhancing the efficiency and performance of HEVs but also at integrating them seamlessly into the urban fabric. The following pointers elucidate potential areas of future research that could significantly contribute to the evolving narrative of HEVs in smart cities.

- **Advanced Energy Management Strategies:** Delving deeper into the development of sophisticated energy management strategies that leverage real-time data, machine learning, and artificial intelligence to optimise the performance of HEVs.
- **Integration with Smart Grids:** Exploring the synergy between HEVs and smart grids to facilitate bidirectional energy transfer, enhancing the overall energy efficiency of urban ecosystems.
- **Real-time Traffic and Energy Management:** Investigating real-time traffic management systems that interact with HEVs to optimise route planning and energy consumption.
- **Enhanced Battery Technologies:** Advancing research in battery technologies to extend the range of HEVs, reduce charging times, and improve overall efficiency.
- **Autonomous HEVs:** Delving into the integration of autonomous driving technologies with HEVs to enhance safety, efficiency, and user experience.
- **Policy and Regulatory Frameworks:** Developing comprehensive policy and regulatory frameworks to promote the adoption of HEVs and ensure their safe and efficient operation within smart cities.
- **User Behaviour Analysis:** Understanding the impact of user behaviour on energy consumption in HEVs and developing systems that encourage energy-saving behaviours.

4 Knowledge Gaps

The journey towards a comprehensive understanding and optimisation of Hybrid Electric Vehicles (HEVs) within smart cities is fraught with knowledge gaps that necessitate meticulous research and analysis. These gaps not only represent challenges but also opportunities for the academic and industrial communities to collaborate and innovate. The following pointers highlight some of the prominent knowledge gaps that could significantly benefit from focused research endeavours.

- **Real-world Performance Metrics:** There's a discernible gap in research pertaining to real-world performance metrics of HEVs as opposed to controlled or simulated environments.
- **Standardisation of Energy Management Strategies:** Lack of standardisation in energy management strategies across different models and makes of HEVs, which hinders the development of universal solutions.
- **Holistic Integration with Urban Infrastructure:** The research on the integration of HEVs with urban infrastructure such as traffic lights, parking lots, and charging stations is still in nascent stages.
- **Consumer Awareness and Adoption:** Insufficient consumer awareness regarding the benefits and operation of HEVs, which affects their adoption rate.

- **Cost-effective Solutions:** The need for more research on cost-effective solutions to lower the entry barrier for consumers and promote the adoption of HEVs.
- **Cybersecurity:** With the increasing connectivity of HEVs, cybersecurity remains a significant concern that requires thorough investigation.
- **Impact Assessment:** Lack of comprehensive studies assessing the long-term environmental and economic impacts of widespread HEV adoption within urban settings.

5 Conclusion

The exploration into the domain of Hybrid Electric Vehicles (HEVs) and their energy management within the ambit of smart cities has unravelled a tapestry of insights and potentialities. The three seminal studies reviewed herein have significantly contributed to the burgeoning body of knowledge, each with its unique focus and findings. As we steer towards a future of sustainable urban mobility, the integration of HEVs within smart cities emerges as a pivotal discourse. The following key findings, extrapolated from the reviewed studies, underscore the critical facets of this discourse and resonate with the focus of our comprehensive review.

Key Findings:

- **Energy Management Strategies:** The comparative analysis of energy management strategies such as Dynamic Programming (DP), Pontryagin's Minimum Principle (PMP), and Equivalent Consumption Minimisation Strategy (ECMS) underscores the imperative of evolving robust and efficient strategies to optimise the energy utilisation in HEVs.
- **GPS/Rule-Based Methodology:** The innovative approach of amalgamating GPS with rule-based methodology, as elucidated by Ramadan et al. (2017), presents a promising avenue for real-time energy management, significantly reducing fuel consumption and enhancing the operational efficiency of HEVs.
- **Battery Management Systems (BMS):** The critical role of accurate State of Charge (SoC) estimation and advanced Battery Management Systems in ensuring the safe, robust, and reliable operation of the battery pack in HEVs has been emphatically highlighted.
- **Global Optimisation Strategies:** The exploration of global optimisation strategies, including Genetic Algorithms, in the energy management of Fuel Cell Hybrid Electric Vehicles (FCHEVs) opens up new vistas for enhancing the performance and reducing the energy consumption of HEVs.
- **Integration with Smart City Infrastructure:** The potential of integrating HEVs with smart city infrastructure, such as smart grids and real-time traffic management systems, emerges as a significant area of focus for future research, aiming at a seamless assimilation of HEVs within the urban ecosystem.
- **Policy and Regulatory Framework:** The discourse around the development of comprehensive policy and regulatory frameworks to promote the adoption of HEVs, ensure their safe and efficient operation, and incentivise the transition towards sustainable urban mobility is of paramount importance.

The key findings align well with the main focus of our review, highlighting the importance of further research in energy management strategies and the adoption of new methods for HEVs in smart cities. While there are challenges ahead, there's a lot of room for innovation

and working together, which can lead us towards better and smarter urban transport solutions.

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