

Electric Vehicle Integration: Classification, Battery Technologies, and Optimization Approaches

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Abstract: The growing urgency to mitigate climate change by reducing greenhouse gas emissions and carbon dioxide has driven the global adoption of electric vehicles (EVs). To support this shift, investments in advanced charging infrastructure and information technology are crucial. This study aims to investigate the impact of EVs on power systems, exploring optimal charging strategies that benefit both consumers and aggregators. Key optimization objectives, including power loss minimization, electricity cost reduction, and peak load management, are examined alongside various optimization methods and algorithms. Additionally, this paper reviews the classification and components used in EVs, requirements of Electric Vehicles, comparison between different Electric Vehicles in terms of driving unit, input source, advantages and disadvantages, Optimization Techniques aspects. The research underscores the necessity for effective planning and operational management to ensure a seamless integration of EVs into the power grid.

Keywords: Battery, Electric Vehicles, Hybrid EVs, EV Motors, Optimization Techniques.

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1. Introduction

In many countries, energy and environmental issues are among the most critical challenges. The use of fossil fuels is a major contributor to environmental degradation. To address these concerns, various technologies have been introduced worldwide. Among them, Plug-in Hybrid Electric Vehicles (PEVs) stand out as one of the most promising solutions. India's commitment to next-generation mobility has gained significant momentum under the current government. However, the foundation was laid earlier with the launch of the National Electric Mobility Mission Plan (NEMMP) 2020 in 2013 by the previous Congress-led administration. This highlights a continued, bipartisan effort toward promoting green mobility and electric vehicle adoption. Electric vehicles (EVs) are powered by one or more electric motors using energy stored in rechargeable batteries, eliminating the need to burn petrol or diesel and avoiding the release of harmful emissions. Currently, EVs can be categorized into three main types: Solar-powered electric vehicles, Hybrid electric vehicles (HEVs) that combine internal combustion engines with battery power and Battery electric vehicles (BEVs), which run entirely on on-board battery packs. While discussions on sustainable mobility often focus on battery electric vehicles, Plug-in Hybrid Electric Vehicles (PHEVs) also play an important role in environmental conservation. In the Indian market, several electric four-wheelers have been introduced, including the Hyundai Kona Electric,

Mahindra e-Verito, Mahindra e2o, Porsche Taycan, Tata Tigor EV (2019) and MG ZS EV. However, to achieve significant progress towards becoming an EV-dominant nation, many more such models and initiatives will be necessary.

Based on their topology and component technologies, electric machines in vehicles can operate in two primary modes: a) As a motor, providing positive torque and speed to drive the vehicle forward. b) As a generator, producing electrical energy—either from the internal combustion engine or through regenerative braking—to recharge the battery. Series Hybrid Electric Vehicles (Series HEVs) are most effective in stop-and-go traffic conditions, as there is no direct mechanical link between the engine and the wheels. This setup offers high flexibility and efficiency. Parallel Hybrid Electric Vehicles (Parallel HEVs) feature a configuration where both the internal combustion engine and the electric motor are connected to the mechanical transmission, allowing them to power the vehicle independently or together. Series-Parallel Hybrid Electric Vehicles (Series-Parallel HEVs) combine the characteristics of both systems. They include an additional direct mechanical connection between the generator and the traction motor via the transmission, offering the advantages of both series and parallel hybrids.

Hybrid Electric Vehicles (HEVs) are energy-efficient technologies that combine two or more conventional power sources to generate, store, and deliver energy to the vehicle's load. Typically, HEVs are equipped with an internal combustion engine and an

electric motor (EM), along with DC-AC and AC-DC power converters. This integrated system allows for efficient power management, and such vehicles are commonly referred to as Hybrid Electric Vehicles (HEVs).

India's public transportation system serves as a vital pillar of the country's economic growth. Currently, the transport sector contributes approximately 5.5% to the nation's GDP. However, it is largely dependent on hydrocarbon-based fuels such as petrol and diesel, which, while energy-rich, release harmful gaseous emissions into the environment. Electric transportation offers a sustainable alternative to reduce these negative environmental impacts. As part of its long-term vision, India aimed to produce around 10 million electric vehicles, including both two-wheelers and four-wheelers, by the year 2020. According to the Prime Minister's roadmap, the goal is for India to transition to a 100% electric vehicle transportation system by 2030. Organizations like the Energy Science Society of India (ESSI) are playing a key role in promoting awareness about renewable energy sources, green technologies, biofuels, energy storage systems, energy-efficient devices, and sustainable energy solutions.

With the rapid advancement of electric vehicle (EV) and smart grid technologies, the battery has emerged as the most critical component for energy storage, drawing significant attention from researchers and industry experts alike. Current trends in research and development suggest that the next generation of high-energy lithium-ion battery (LIB) systems will soon be available for use in electric transportation. However, the widespread adoption of EVs faces several challenges, primarily due to high costs and limited public awareness, particularly concerning the safety features and driving range of EV batteries. Among all EV components, the battery pack, which consists of the battery itself and the Battery Management System (BMS), accounts for approximately 40% of the vehicle's total cost. While BMSs are commonly used in portable electronic devices such as laptops, computers, and mobile phones, these versions are not suitable for EV applications. This is mainly because EV battery packs require a significantly larger number of cells, necessitating a more advanced BMS. Therefore, EV BMS systems must be specifically designed to monitor and manage the data generated by each individual cell within the battery pack to ensure optimal performance, safety, and reliability.

The adoption of electric vehicles (EVs) in India faces several key challenges, including the lack of robust charging infrastructure, limitations in battery performance, a significant supply-demand gap, the difficulty in establishing a closed-loop system for battery recycling, and the need for supportive public

policies and business models. Researchers continue to tackle complex issues related to enhancing the energy density, power capability, monitoring, and safety of lithium-ion batteries. These factors are crucial, as the progress of electric vehicle technology is heavily reliant on the development of advanced battery technologies and Battery Management Systems (BMSs). A BMS is responsible for overseeing all aspects of battery operation, including monitoring, safety, efficiency, and control. In fact, BMS has become a significant focus of research over the past decade, particularly from the perspectives of control systems and power electronics, as discussed in detail by Foad Samadi et al., 2015.

2. Classification and Components Used in EVs

There is a significant opportunity to foster clusters of innovation and commercial development across India within the emerging supply chain for components used in zero-emission and low-emission vehicles. These essential components include, but are not limited to: AC electric motors, Power electronic converters, Battery packs, Ultracapacitors (supercapacitors), Lightweight and advanced material technologies, Powertrain integration systems and Prototype simulation and testing tools. EV readiness infrastructure, which involves grid integration through micro-grids, smart grids, and advanced metering technologies, Software and control systems. This evolving ecosystem presents a substantial opportunity for India to become a global leader in electric vehicle manufacturing and innovation.

3. Requirements of Electric Vehicles

An ideal electric vehicle (EV) must meet a set of key performance specifications to ensure optimal operation under various conditions. These include: High efficiency across a wide speed range, particularly to support regenerative braking, High torque and power density, Strong low-speed torque for effective starting, acceleration, and hill climbing, High power output at higher speeds for efficient cruising, A wide Constant Power Speed Range (CPSR), Fast dynamic response for quick adaptation to changing driving conditions, Reliable operation under frequent start-stop conditions, Capability to perform in harsh environments, including exposure to dust, water, and extreme temperatures (hot and cold), Intermittent overload capability, handling up to twice the rated power when needed, Low frequency of service and maintenance requirements, Durability and robustness for long-term use, Fault tolerance and safety in case of component failures, Low noise operation for comfort, Cost-effectiveness to ensure market viability. These specifications form the foundation for designing high-performance, reliable,

and efficient electric vehicles suitable for diverse driving and environmental conditions.

4. Classification of EVs

Battery-powered electric vehicles (EVs) can be classified based on their fuel requirements into three main types: Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), and Fuel Cell Electric Vehicles (FCEVs), as presented in Table I. Furthermore, based on their powertrain configuration, hybrid EVs are categorized as Series Hybrid EVs in Fig.1, Parallel Hybrid EVs in Fig.2, and Series-Parallel Hybrid EVs, as illustrated in Fig.3.

TABLE-I
Comparison between different Electric Vehicles

Type of EV	Driving Unit	Input Source	Advantages	Disadvantages
Battery Electric Vehicles (BEVs)	Battery, Ultra-capacitor	Electric grid charging facilities	• Zero emissions • Independence from crude oil • Short range (100–200 km) • Commercially available	• High battery cost and limited capacity • Limited driving range • Long charging time • Limited charging infrastructure
Hybrid Electric Vehicles (HEVs)	Battery, Ultra-capacitor, Internal Combustion Engine (ICE)	Gasoline stations, Electric grid charging facilities	• Very low emissions • Long driving range • Dual power sources: fuel and electricity • Commercially available	• Complex system with both electrical and mechanical drive trains • Energy source management • Battery sizing and efficiency • Performance depends on driving conditions
Fuel Cell	Electric motor	Hydrogen,	• Very low or zero	• High cost of fuel cells

Type of EV	Driving Unit	Input Source	Advantages	Disadvantages
Fuel Cell Vehicles (FCEVs)		Methanol, Gasoline, Ethanol	• emissions • High efficiency • Not dependent on electricity supply • Commercially available	• Challenges in fuel production • Limited fueling infrastructure

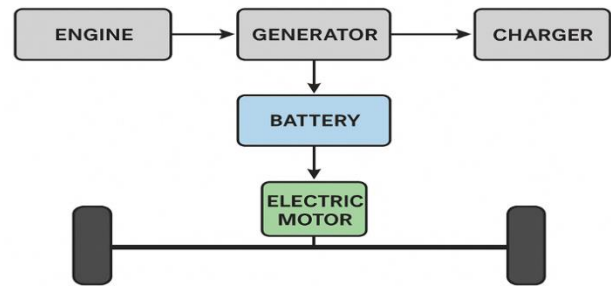


Fig.1. Series Hybrid Electric Vehicle

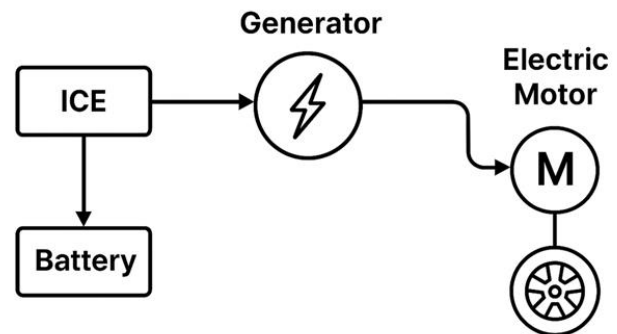


Fig.2. Parallel Hybrid Electric Vehicle

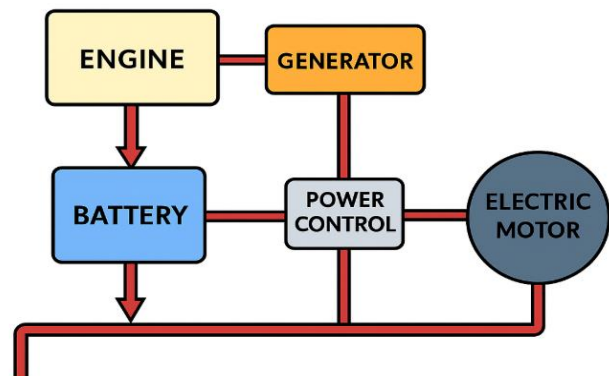


Fig.3. Series Parallel Hybrid Electric Vehicle

5. Optimization Techniques

To address various challenges, numerous optimization models and algorithms have been proposed in the literature. For example, Haiming Fu et al. (2018) highlighted that the simultaneous connection of a large number of Plug-in Electric Vehicles (PEVs) to the power grid can cause power fluctuations or even electricity shortages, disrupting the regular supply for basic loads. To mitigate this, they proposed a genetic algorithm to optimize the charging and discharging power of PEVs. Flah Aymen et al. (2019) focused on managing power within electric vehicles to enhance vehicle autonomy. Their approach involves optimizing power usage by controlling consumption in critical areas, enabled through vehicle-to-building wireless communication. M. Faizal et al. (2019) reviewed the challenges and opportunities related to the mass market deployment of EVs. They categorized these challenges in terms of developing a sustainable business model encompassing economic, technological, social, and environmental aspects. The study also discussed the impact of government policies on EV adoption and projected future market trends up to 2030. Ahmed M. Ali et al. provided a comprehensive review of different power management strategies and the latest real-time optimization methods, highlighting promising approaches for EV energy management. Imran Rahman et al. examined the use of optimization techniques specifically applied to the development and management of EV charging infrastructure. Optimization involves achieving smooth and efficient coordination among electric motors, batteries, and combustion engines so that they operate within their peak efficiency ranges. This process can be seen as a systematic journey that includes personal motivation, understanding driving patterns, calculating power and energy requirements, sizing subsystems appropriately, developing control strategies to ensure harmonious operation, calibrating these strategies, conducting tests and validations, and iterating the process until the desired performance is reached. Various optimization techniques used in this context are summarized in Section VI.

6. Different Optimization Techniques

Energy Management Strategies

1. Rule-Based Methods

- **Fuzzy Rule-Based Control**
 - Traditional (Conventional) methods
 - Adaptive methods
- **Deterministic Rule-Based Control**

- Thermostat-based control (On/Off)
- Power follower (Baseline method)
- Frequency-based control
- Optimal engine operating point
- Optimal engine operation line
- Optimal engine efficiency region
- System-level optimal operation point

2. Optimization-Based Methods

A. Real-Time Optimization

- **Equivalent Cost Minimization Strategy (ECMS)**
 - Conventional ECMS
 - Adaptive ECMS
 - Telemetric ECMS
- **Model Predictive Control (MPC)**
 - Linear Time-Varying MPC
 - Nonlinear MPC
 - Stochastic MPC
 - Stochastic MPC with Learning (SMPCL)
- **Intelligent Control using Machine Learning**
 - Neural Networks (NN)
 - Elman Neural Networks (ENN)
 - Support Vector Machines (SVM)
 - Recursive Least Squares (RLS)
 - Other machine learning algorithms
- **Extremum Seeking Control (ES)**
- **Robust Control**

B. Global Optimization

- **Static Optimization Methods**
 - **Derivative-Free Methods**
 - Simplex Method
 - Complex Method
 - DIRECT Algorithm
 - Stochastic Search Techniques:
 - Genetic Algorithm (GA)
 - Simulated Annealing (SA)
 - Particle Swarm Optimization (PSO)
 - Evolutionary Algorithm (EA)
 - Bees Algorithm (BA)
 - Parallel Chaos Optimization Algorithm (PCOA)
 - Space Exploration and Unimodal Region Elimination (SEUMRE)

- Hybrid Genetic-Particle Swarm Optimization
- **Gradient-Based Methods**
 - Sequential Quadratic Programming (SQP)
- **Indirect Methods**
 - Dynamic Programming (DP)
 - Pontryagin's Minimum Principle (PMP)
- **Direct Methods**
 - Direct Collocation (Transcription) Methods
 - Conventional
 - Improved (Pseudo-Spectral Method)
- **Other Optimization Techniques**
 - Game Theory-Based Optimization
 - Stochastic Optimal Control
 - Nonlinear Optimal Regulation

7. Battery

The design of battery management systems (BMS) from a control theory perspective has been extensively analyzed, highlighting several open research areas. A generalized BMS model offers significant advantages over currently available systems, notably its fault tolerance and enhanced battery protection. This model includes multiple battery modules that monitor and balance a string of battery cells (Hu Rui et al., 2011). M. Chen et al. and G.A.R. Mora et al. (2006) proposed a digital lithium battery charging and protection system using a Digital Signal Processor (DSP). However, replacing a microcontroller with a DSP substantially increases the cost of the BMS. In India, the adoption of electric vehicles (EVs) faces challenges such as insufficient charging infrastructure, battery performance issues, supply-demand imbalances, lack of closed-loop systems, and gaps in public policy and business models. To address these issues, various optimization models and algorithms have been proposed in the literature. For instance, Haiming Fu et al. (2018) examined how the simultaneous connection of many Plug-in Electric Vehicles (PEVs) to the power grid can cause power fluctuations or shortages, affecting basic load usage. They proposed a genetic algorithm to optimize the charging and discharging power of PEVs. Flah Aymen et al. (2019) focused on optimizing power management within electric vehicles to enhance autonomy by controlling power usage in critical zones through vehicle-to-building wireless communication. M. Faizal et al. (2019) reviewed the challenges and opportunities in mass-market EV deployment, categorizing them based on the development of sustainable business models encompassing economic, technological, social, and

environmental factors. They also discussed how government policies influence EV adoption and projected market trends through 2030. Ahmed M. Ali et al. provided a comprehensive review of various power management methods and the latest real-time optimal control strategies, highlighting promising approaches. Imran Rahman et al. addressed optimization techniques specifically applied to EV charging infrastructure. Recent research shows rapid advancements in lithium-ion (Li-ion) battery technology, focusing on developing cells with higher power and energy densities. Equally important is improving battery management systems to ensure safety, reliability, stability, performance, and cost efficiency. Given the specific requirements of smart grids and EVs—such as deep charge/discharge protection and precise state-of-charge (SOC) and state-of-health (SOH) estimation—the need for advanced BMS technology is stronger than ever. A proficient BMS should incorporate accurate algorithms to monitor the battery's functional status and employ state-of-the-art protection mechanisms to prevent harmful and inefficient operating conditions. Different types of batteries are summarized in Table II.

TABLE-II
Different Types of Battery

Comparison of Battery Technologies

Sl. No	Battery Technology	Advantages	Disadvantages
1	Lithium Cobalt Oxide (LiCoO ₂)	High power and energy density	Safety concerns, high cost
2	Nickel Cobalt Aluminum (NCA)	High power and energy density, long calendar and cycle life	Safety concerns
3	Nickel Manganese Cobalt (NMC)	High power and energy density, good cycle and calendar life	Safety concerns
4	Lithium Polymer (LiMnO ₄)	High power density, good calendar life	— (Not specified – add if needed)
5	Lithium Iron Phosphate (LiFePO ₄)	Excellent safety	Lower energy density, shorter calendar life

8. EV Motors

The induction motor (IM) has recently attracted renewed research interest due to advanced design and control concepts applicable in electric vehicles (EVs).

These motors typically operate at a constant flux magnitude even when torque demand is low, which results in good dynamic performance. However, the efficiency of conventional IM drives drops significantly—by about 25% to 30%—when operated below base speed while maintaining rated flux to meet lower torque demands. Therefore, in applications such as EVs, where the motor must function efficiently across a wide load range, energy-efficient control strategies are crucial. Efficiency-optimized control, adopted in nearly 90% of such applications, not only provides ongoing economic benefits but also positively impacts the global environment. Induction motors possess excellent operational characteristics. Their robustness, reliability, low cost, and ease of control make them widely used in various fields, including machine tools, robotics, fans, pumps, compressors, paper mills, steel industries, automation, traction systems, ship propulsion, and cement mills. Consequently, IM drives are the most commonly employed machines worldwide, accounting for about 70% of all industrial applications. Several decades ago, IM drives operated only at a fixed speed determined by the supply voltage frequency and the number of machine pole pairs, making wide-range speed control unimaginable. Moreover, controlling the speed of IM drives has always been more challenging than DC motors because the direct relationship between motor current and torque, present in DC motors, does not exist in IMs. Zhang, P., Yan, F., Du, C., et al., provide a quantitative bibliometric analysis of energy management strategies for hybrid electric vehicles (HEVs) for the first time. Their work includes content analysis and qualitative evaluation of various energy management strategies used in HEVs. They reveal essential characteristics such as the advantages, disadvantages, interconnections, and improvement potential of these strategies from a control theory perspective. Furthermore, the study highlights emerging trends aimed at enhancing HEV performance, including driving cycle recognition and prediction algorithms, integrated multi-objective coordinated optimization, balancing computational complexity with optimization effectiveness, and establishing fair and credible evaluation systems. This paper not only offers a comprehensive review of HEV energy management strategies but also emphasizes future research directions. It aims to broaden the perspective of researchers and foster the development of simple, practical, low-cost, and high-performance energy management controllers for HEVs. Electric motors play a major role in HEV applications. Table I lists the types of motors used in EVs, totaling approximately 150 models. Brushed DC motors are commonly used in power seats, power windows, door locks, HVAC dampers, sunroofs, pedal extenders, windshield wipers, radiator shutters, trunk/hatch lifts, and trailer hatch lifts.

Brushless DC motors find applications in steering wheel extend/tilt mechanisms, ventilated seats, HVAC blowers, Electric Variable Valve Timing (EVVT), AC compressors, radiator fans, oil pumps, water pumps, turbochargers, fuel pumps, power steering, ride stabilization, and traction motors. Stepper motors are used primarily for steerable headlights. Table III provides a detailed list of motors employed in EVs.

TABLE-III
Motors used in EV Applications
Comparison of Motor Types

Sl. No	Motor Type	Advantages	Disadvantages	Typical Applications
1	Brushed DC Motor	• Simple to drive • Low cost	• Complex construction due to brushes • High maintenance • High EMI due to brushes	Basic motion and movement control
2	Brushless DC Motor	• No brushes, hence low EMI • High efficiency • Moderate construction complexity	• Complex drive electronics • Higher cost	High-speed or torque control systems
3	Stepper Motor	• Accurate positioning • Low cost • Simple control interface	• Can produce noise and resonance • Generates heat, lower efficiency	Precise position control applications

9. Conclusion

This paper provides a thorough analysis of optimization techniques for Hybrid Electric Vehicles (HEVs). It covers classifications of Electric Vehicles (EVs), their key components, and performance requirements. A comparative evaluation of different types of EVs is also included. The study emphasizes optimization methods for EV applications, highlighting the most effective approaches. Additionally, it examines various battery technologies and assesses different electric motors used in EVs.

References

- [1] Zuo-Jun Max Shen, c, Bo Feng, Chao Mao and Lun Ran, "Optimization models for electric vehicle service operations: A literature review" *Transportation Research Part B*, 128 (2019), PP. 462–477.
- [2] Emilia Silvas, Theo Hofman, Nikolce Murgovski, Pascal Etman and Maarten Steinbuch, "Review of Optimization Strategies for System-Level Design in Hybrid Electric Vehicles", *IEEE Transactions on Vehicular Technology*, DOI 10.1109/TVT.2016.2547897,
- [3] Hillol Kumar Roy, Paul Jennings and Andrew McGordon , "A Generalized Powertrain Design Optimization Methodology to Reduce Fuel Economy Variability in Hybrid Electric Vehicles" *IEEE Transactions on Vehicular Technology*, March 2014, DOI: 10.1109/TVT.2013.2283749
- [4] Ahmed M. Ali ID and Dirk Söffker, "Towards Optimal Power Management of Hybrid Electric Vehicles in Real-Time: A Review on Methods, Challenges, and State-of-The-Art Solutions" *Energies*, 2018, doi:10.3390/en11030476.
- [5] M. Faizal1, S. Y. Feng, M. F. Zureel, B. E. Sinidol, D. Wong and G. K. Jian, "A Review on Challenges and Opportunities of Electric Vehicles (EVS)" *Journal of Mechanical Engineering Research and Developments (JMERE)* 42(4) (2019) 130-137.
- [6] Haiming Fu, Yinghua Han, Jinkuan Wang and Qiang Zhao, "A Novel Optimization of Plug-In Electric Vehicles Charging and Discharging Behaviors in Electrical Distribution Grid" *Journal of Electrical and Computer Engineering*, 2018.
- [7] Flah Aymen and Chokri Mahmoudi, "A Novel Energy Optimization Approach for Electrical Vehicles in a Smart City" *Energies* 2019.
- [8] M. Faizal1, S. Y. Feng2, M. F. Zureel, B. E. Sinidol, D. Wong and G. K. Jian, "A Review on Challenges and Opportunities of Electric Vehicles (EVS)", ISSN.1024-1752.
- [9] Zuo-Jun Max Shen, Bo Feng, Chao Mao and Lun Rand, "Optimization models for electric vehicle service operations: A literature review", *Transportation Research Part B*, 128 (2019) 462–477.
- [10] Imran Rahman, Pandian M. Vasant, Balbir Singh Mahinder Singh, M. Abdullah-Al-Wadud and Nadia Adnan, "Review of recent trends in optimization techniques for plug-in hybrid and electric vehicle harging infrastructures", *Renewable and Sustainable Energy Reviews*, 58(2016)1039–1047
- [11] Chan, C.C. The state of the art of electric and hybrid vehicles. *Proc. IEEE* 2002, 90, 247–275.
- [12] Zhang, P.; Yan, F.; Du, C. A comprehensive analysis of energy management strategies for hybrid electric vehicles based on bibliometrics. *Renew. Sustain. Energy Rev.* 2015, 48, 88–104.