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IoT-Based Battery Management Systems for Electric Vehicles: A Survey

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ABSTRACT: This paper offers an extensive overview of Internet of Things (IoT)-based Battery Management Systems (BMS) designed specifically for electric vehicles (EVs). As EVs become more common, effective BMS becomes essential for maximising battery performance. The integration of Internet of Things (IoT) technologies facilitates advanced energy management methods, real-time monitoring, and predictive maintenance, which improves BMS capabilities. The report examines the trend towards IoT integration and digs into core BMS components. We talk about a range of IoT technologies in relation to BMS architecture, including as sensors, cloud computing, and communication protocols. Along with case studies and examples of implementation, key aspects like energy optimisation tactics, predictive maintenance, and real-time monitoring are presented. Furthermore, issues with scalability, standardisation, and security are covered. Researchers, engineers, and business experts working on the creation and implementation of IoT-based BMS for EVs will find great value in this study.

KEYWORDS: Electric Vehicles (EVs), Battery Management Systems (BMS), Internet of Things (IoT), Real-time monitoring, Predictive maintenance, Energy optimization, Vehicle-to-grid (V2G), Scalability, Case studies, Future directions

I. INTRODUCTION

The advent of Electric Vehicles (EVs) marks a significant shift in the automotive industry towards sustainable and environmentally friendly transportation solutions. Central to the performance and viability of EVs is the efficiency of their Battery Management Systems (BMS). BMS plays a critical role in monitoring, controlling, and optimizing the performance of battery packs, ensuring safety, longevity, and optimal utilization of energy storage. Traditionally, BMS relied on passive monitoring and control mechanisms, with limited capabilities for real-time feedback and proactive management. However, with the rapid advancements in Internet of Things (IoT) technologies, there has been a paradigm shift towards integrating IoT into BMS, unlocking new levels of functionality and efficiency.

This survey paper aims to provide a comprehensive overview of IoT-based BMS tailored for EVs. By leveraging IoT technologies, BMS can now offer real-time monitoring of battery parameters, predictive maintenance capabilities, and advanced energy management strategies. These enhancements not only improve the performance and reliability of EVs but also pave the way for smarter and more sustainable transportation ecosystems.

In this introduction, we will first outline the fundamental components and functions of traditional BMS before exploring the evolution towards IoT integration. We will then discuss the role of IoT technologies in enhancing BMS capabilities and introduce key features and capabilities enabled by IoT. Additionally, we will highlight the significance of this survey and its implications for the future development of IoT-based BMS for EVs.

Currently, lithium-ion batteries (LIBs) not only dominate the battery market for portable electronics but also find widespread application in the automotive and stationary energy storage sectors (Duffner et al., 2021; Lukic et al., 2008; Whittingham, 2012). This is primarily due to the limitations of battery technologies predating lithium, such as lead-acid or nickel-based batteries, as well as those beyond lithium, including sodium-ion batteries (SIBs), which suffer from lower energy density and specific energy compared to state-of-the-art LIBs. Despite the emergence of promising technologies like lithium-metal batteries (LMBs), particularly solid-state batteries (SSBs), which offer the potential for significantly increased energy density and driving range for EVs, further research and development are required to address challenges related to lifetime, fast-charging, and cost.

The global battery industry is experiencing rapid growth, with projections indicating it will exceed 2500 GWh in the next decade (Alliance, 2019). The increasing demand for batteries is driven by various applications, with electric

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mobility being a significant contributor (Fig. 3). As depicted in Fig. 1(b) and (c), different regions and applications show distinct trends in battery demand, with electric mobility playing a substantial role in driving growth. While China's share of the battery industry is expected to decrease gradually, the rest of the world (RoW) is anticipated to increase its percentage, reflecting the global shift towards electric mobility and sustainable energy solutions. Government policies are increasingly advocating for the development of electric vehicles (EVs) and new energy automobiles, which in turn are driving the rapid development of battery materials and vehicular computer science towards smart mobility. With the global imperative of achieving carbon neutrality, China has announced plans to reach its emission peak before 2030. Additionally, in the USA, it is projected that by 2030, 50% of new vehicles will achieve zero emissions, and by 2035, nearly all vehicles in Europe should achieve zero emissions.

To be competitive with fossil fuel vehicles, lithium-ion batteries (LIBs) are expected to achieve an energy density goal of around 500 Wh kg^{-1} for EV applications, a significant challenge given current battery chemistry limitations. Many researchers and institutes consider lithium-metal batteries (LMBs), particularly solid-state batteries (SSBs), as one of the most promising candidates for high-power electric propulsion. However, further technological breakthroughs are needed, particularly in the search for more reliable and safer anode materials. In the realm of technologies beyond lithium, sodium-ion batteries (SIBs) exhibit some comparable key performance indicators (KPIs) to LIBs, further expanding the possibilities for future energy storage solutions.

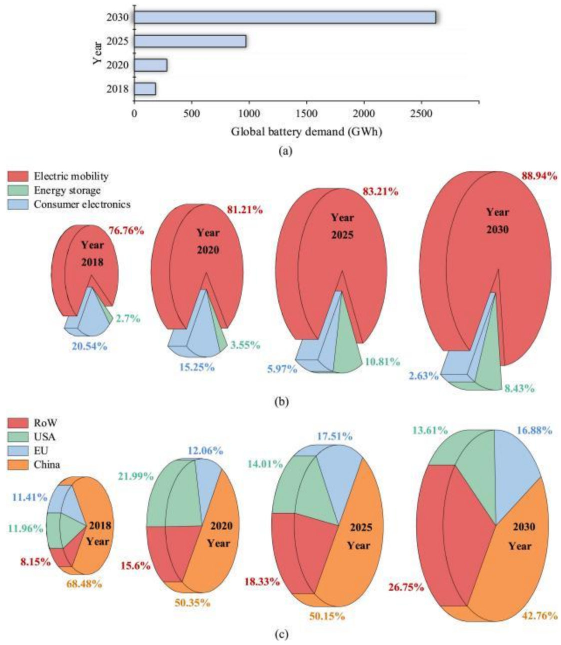

Fig1: Global battery industry. (a) Growth. (b) Demands by applications. (c) Demands by regions.

In addition to the batteries themselves, effective battery management is essential to ensure the reliable and safe operation of electric vehicle (EV) batteries. Throughout the charge/discharge cycling process, battery management systems (BMS) (Xiong et al., 2018b; Hannan et al., 2018) play a crucial role in enabling batteries to achieve optimal performance and extended service lives. These BMS systems are integral components of every EV and perform a range of functions, including:
Battery state estimation,
Battery cell balancing (Ouyang et al., 2019), and pack charging/discharging control (How et al., 2020),
Thermal management (Zhang et al., 2018b; Yu and Chau, 2009), Fault prognosis (Li et al., 2021g) and health diagnosis (Song et al., 2021), and Correspondence. Moreover, emphasizing the power management strategy of drive trains is essential for optimizing energy utilization (Chau and Wong, 2002). Additionally, battery modeling, particularly data-driven models, plays a crucial role in providing virtual representations to simulate battery electrochemical behaviors (Xie et al., 2020a). Regarding hardware aspects, sensors are employed to sense and return various battery parameters for model building and state estimation.
The primary aim of this article is to provide a comprehensive review of (i) the current state-of-the-art and emerging battery technologies, and (ii) the state-of-the-art battery management technologies specifically tailored for Electric

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Vehicles (EVs). Both battery technologies and battery management technologies will be extensively discussed. With a focus on these objectives, the article will delve into the major features, advantages, and disadvantages of various battery technologies and management systems. It will also explore new technological pathways, potential breakthrough directions, and outline future challenges and opportunities in order to propose a development roadmap for EV applications. Ultimately, the integration of advancements in battery chemistry, battery-related technologies, and alternative technologies to replace batteries will be crucial in meeting the future energy demands and advancing electric mobility.

II. ELECTROCHEMICAL ENERGY STORAGE TECHNOLOGIES

The electrochemical energy storage sources are detailed in Figure 4, with power batteries being the mainstream choice for current Electric Vehicle (EV) applications, rather than fuel cells. Occasionally, EVs may feature a hybrid energy storage system comprising batteries and ultra- or supercapacitors (Shen et al., 2014; Burke, 2007), offering high energy density for longer driving ranges and high specific power for instant energy exchange during automotive launch and braking, respectively. While fuel cells can provide zero emissions with satisfactory power and energy densities, their development progress has been relatively slow (Shen et al., 2014). Among various battery types, lead-acid batteries, nickel-based batteries, and particularly Lithium-ion Batteries (LIBs) (Hannan et al., 2018) have played prominent roles at different stages of EV development. Throughout the history of battery development, LIBs represent a significant advancement in battery technology due to their superior Key Performance Indicators (KPIs), especially in terms of high energy, long cycle life, and high safety (Schmuch et al., 2018; Gong et al., 2015; Winter et al., 2018). Additionally, high-temperature batteries, typically operating at 270-400 °C, hold high potential with advantages such as higher specific power and specific energy.

Metal/air batteries are distinguished by the type of metal used as the anode, such as lithium metal or zinc metal. While they offer higher specific energy, they often suffer from insufficient cycle life. On the other hand, flow batteries resemble fuel cells more than conventional batteries. Other metal-ion candidates, including zinc-ion, magnesium-ion, and aluminum-ion batteries, require further research and development to determine their suitability for EV applications. Notably, Sodium-ion Batteries (SIBs) are significantly more advanced compared to other metal-ion technologies (e.g., Mg, Zn, Al). Their market entry for potential applications is expected to occur much sooner (CATL, 2021). Historically, lead-acid batteries were primarily used as "starter batteries" and were not intended to power cars for long driving ranges.

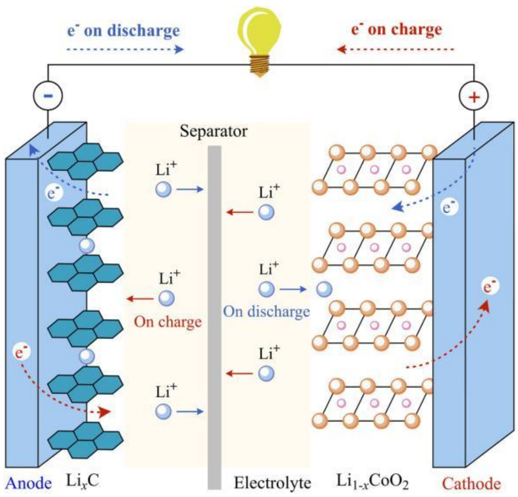

Fig2: Schematic of an exemplified lithium-ion battery cell

III. STATE-OF-THE-ART BATTERIES

For Electric Vehicle (EV) propulsion systems, Lithium-ion Batteries (LIBs) have become widely adopted following successful commercialization, owing to their inherent advantages in energy density, safety, and lifespan. A typical LIB cell consists of three main components: an anode, a cathode, and an electrolyte (which includes a separator). Electrochemical advancements primarily target these components to enhance battery Key Performance Indicators

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(KPIs). As depicted in Figure 5, which illustrates a representative LIB cell, lithium ions shuttle between the two electrodes during the charging and discharging processes (Goodenough, 2018). Additionally, beyond the internal workings of the LIB cell, the external circuit facilitates the flow of electrons for power sourcing and sinking. Importantly, both high energy density and specific energy can be ensured through material selection and battery design (Zhang et al., 2018b).

(i) Battery technologies before lithium

Before the widespread adoption of lithium batteries, two contenders emerged: the lead-acid battery in 1859 and the nickel-based battery in 1899. The lead-acid rechargeable battery continues to find use in specific applications, including vehicle starting, lighting, and ignition. However, its specific energy and energy density remain relatively low, reaching up to 40 Wh kg^{-1} and 90 Wh L^{-1}, respectively, compared to state-of-the-art Lithium-ion Batteries (LIBs) which boast 260 Wh kg^{-1} and 700 Wh L^{-1} at the cell level (Schmuch et al., 2018).

The battery industry then entered a new era with nickel-based batteries, such as the nickel-zinc (Ni-Zn) battery and nickel-metal hydride (Ni-MH) battery. While the Ni-Zn battery offers high specific energy and low material cost, its commercialization has been hindered by its short cycle life. In contrast, the Ni-MH battery found its place in Battery Electric Vehicles (BEVs) and Hybrid Electric Vehicles (HEVs) with specific energy and energy density reaching up to 80 Wh kg^{-1} and 250 Wh L^{-1}, respectively.

Lead-Acid Batteries

Being the first commercial battery, lead-acid batteries have maintained market dominance for over a century, primarily due to their mature technology and low cost (Garche et al., 2017). Valve-regulated lead-acid (VRLA) batteries, in particular, have undergone significant advancements in specific energy, power output, and recharging speed, making them well-suited for vehicle applications (Rand, 2009). Additionally, they exhibit favorable performance characteristics across a wide range of temperatures, high energy efficiency, and offer flexibility in terms of size selection.

Nickel-Based Batteries

Various types of batteries have been developed using nickel oxyhydroxide as the cathode material, including nickel–iron (Ni–Fe), nickel–cadmium (Ni–Co), nickel–zinc (Ni–Zn), nickel metal hydride (Ni–MH), and nickel–hydrogen (Ni–H). Among these, the Ni–Zn battery stands out with its highest cell voltage of 1.6 V nominally within the nickel-based family. Compared to the Ni–Co battery, it offers higher specific energy and is more environmentally friendly due to its non-toxic nature. Additionally, it demonstrates good tolerance to over-charge and over-discharge, high-rate performance for charging and discharging, and operates effectively across a wide temperature range. However, due to the partial solubility of zinc species in the electrolyte, the Ni–Zn battery is limited by a short cycle life of around 300 cycles, severely restricting its commercialization. Despite ongoing research efforts in battery chemistry, it remains a topic of exploration (Zeng et al., 2017; Chen et al., 2019b).

Lithium-based batteries

Lithium-based systems ushered in a new era of high-energy and high-power batteries, gradually replacing other battery technologies such as lead–acid and nickel-based systems. Starting from the late 1960s, a multitude of battery technologies were explored and developed due to the limitations of conventional aqueous batteries in meeting the growing demands for portable energy storage (Demir-Cakan et al., 2019).

Lithium-Metal Batteries

G. N. Lewis initiated experimentation on lithium batteries in 1912 (Lewis and Keyes, 1912; Lewis and Keyes, 1913), predating the development of Lithium-Ion Batteries (LIBs) in 1976. These early Lithium-Metal Batteries (LMBs) utilized metallic lithium as the anode and a non-aqueous electrolyte. They represented a significant technological advancement, offering higher specific energy and energy density with significantly lower weight, exemplified by the coin-type Li/MnO_2 battery. From the 1970s onwards, a range of lithium-metal-based primary systems were developed, exploring various cathode materials including iodine (I), manganese dioxide (MnO_2), pyrite (FeS_2), and others.

Lithium-Ion Batteries

In the 1980s, Goodenough and his collaborators ushered in a new era of Lithium-Ion Batteries (LIBs) for power applications. Figure 6 (bottom) highlights the significant milestones in the development of LIBs, delineating three critical periods—commercialization since 1991, exploration since 2008, and foresight since 2019. The first generation of LIBs utilized $LiCoO_2$ as the cathode material and petroleum coke as the anode material (Mizushima et al., 1980). Subsequent generations of LIBs, known as the 2nd and 3rd generations, witnessed further advancements, particularly in the anode material (hard carbon graphite) and electrolyte, resulting in improved energy density (Winter et al., 2003).

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The current state-of-the-art cathode materials for high-energy LIB cells are the layered lithium nickel cobalt manganese oxides, such as Li[NiCoMn]O2 (abbreviated as NCMxyz), which offer increased capacities and reduced costs compared to LiCoO2. Graphite remains the state-of-the-art anode material.

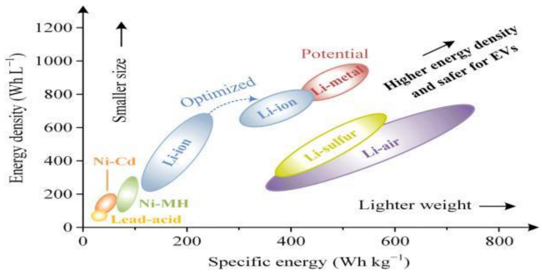

Fig3: Specific energy and energy density of various batteries at cell level.

IV. STATE-OF-THE-ART BATTERY MANAGEMENT

Fundamentals

Traditional charging systems typically incorporate adaptors and plug-ins. Each EV charger typically comprises an alternating current (AC)/direct current (DC) converter with an optional power factor correction (PFC), and a DC/DC converter with unidirectional or bidirectional power flow, as depicted in Figure 10(a) and (b) respectively (Mohammed and Jung, 2021; Tu et al., 2019). High-frequency (HF) transformers are employed for high-efficiency DC/DC conversion with reliable isolation. When an EV is parked for charging, AC electric power can be transferred to the battery pack through the AC/DC converter. The electric machine can then extract energy from the battery pack with the assistance of Battery Management Systems (BMS) and power converters. During Vehicle-to-Vehicle (V2V), Vehicle-to-Home (V2H), and Vehicle-to-Grid (V2G) operations, battery energy can be fed back to the power grid or transferred to other EVs, facilitating coordination with the smart grid and enabling wireless energy trading among vehicular peers.

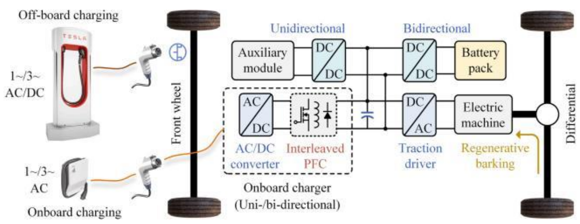

Fig4: On-/off-board charging system for electric vehicles.

Battery state estimation

Battery state estimation methods can generally be categorized into three approaches: direct estimation, model-based, and data-driven. Direct estimation methods typically involve either the look-up table approach or the direct measurement approach. Model-based methods, on the other hand, can be subdivided into two categories: Filter-based methods, which include techniques like the Kalman filter (KF) and particle filter (PF). Observer-based methods, which encompass approaches such as the Luenberger observer, sliding mode observer, and H-infinity/H observer.

The direct estimation method is known for its simplicity and ease of implementation (Wang et al., 2020). A technique for estimating the open-circuit voltage (OCV) was introduced, outlining a detailed implementation process (Ali et al., 2019). This method involves measuring the OCV to establish an offline table and then looking up the State of Charge (SOC) in a straightforward yet accurate manner (Klintberg et al., 2019; Xing et al., 2014). However, the hysteresis characteristic of batteries may introduce differences in measured parameters, leading to estimation errors (Dong et al., 2016), which may not be acceptable in applications requiring high precision, such as aviation or military applications. Alternatively, by utilizing battery current and voltage measurements, the internal resistance can be calculated, allowing for the estimation of SOC, State of Health (SOH), capacity, and other parameters (Laadjal and Cardoso, 2021; Ling and Wei, 2021).

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V. CHALLENGES AND FORESIGHT

In the context of automotive propulsion, two primary challenges for high-energy batteries revolve around the expectations for increased energy density, rapid charging capabilities, and enhanced safety. Addressing these challenges requires the development of the most promising batteries, which are anticipated to emerge from the realms of Lithium-Ion Batteries (LIBs), Lithium-Metal Batteries (LMBs), and advanced technologies that surpass the limitations of lithium-based systems.

Energy density, fast charging, and safety expectations

To advance carbon neutrality, the transition from gasoline vehicles to Electric Vehicles (EVs) presents challenges for existing battery technologies, particularly in the areas of energy density, fast charging, and safety. Both rapid acceleration and sustained cruising are desirable for electric propulsion, heavily reliant on battery energy density (Chau and Chan, 2007; Chau, 2016). Moreover, fast charging is a key objective in the automotive industry, aiming to achieve 80% capacity charging at rates of 3C or 4C. Additionally, the safety of EV batteries has become increasingly paramount, as it directly impacts personal and property safety. However, ensuring battery safety should not come at the expense of energy density (Pham et al., 2018).

Battery technology trends

Promising candidates for advanced battery technologies primarily encompass three streams: (i) Lithium-Ion Batteries (LIBs), (ii) Lithium-Metal Batteries (LMBs), particularly Solid-State Batteries (SSBs), and (iii) alternative ion batteries, with a focus on Sodium-Ion Batteries (SIBs).

Firstly, LIBs are expected to maintain their dominance and drive the growth of EV applications for at least the next decade(s). Lithium titanate-based technology emerges as a potential alternative, particularly for developing fast-charging batteries with long cycle life, suitable for applications where energy density is less critical, such as electric buses. Secondly, there is growing consensus among chemists and research institutes regarding the potential of Lithium Metal as the most promising anode material, surpassing other alternatives. However, the development of Lithium–Oxygen (Li–O) systems remains a significant challenge, requiring extensive fundamental research before practical applications can be realized. Lastly, alternative ion batteries will continue to be explored as avenues for developing novel battery technologies.

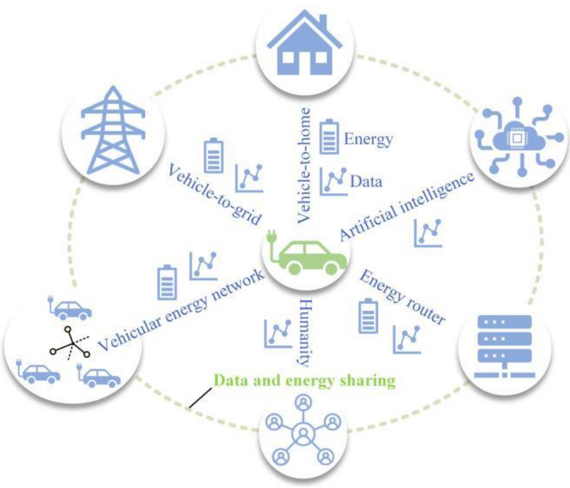

Fig5: Vehicular information and energy internet for data and energy sharing

Smart power electronics

A conventional energy conversion system, as depicted in Figure 27(a), features physically separated components for power electronics and Battery Management Systems (BMS). In this setup, the BMS is responsible for delivering control signals to power converters, while the conventional power electronics oversee charge/discharge management and motor drives (Cao et al., 2021; Li et al., 2021e; Li et al., 2021d). With the rapid advancements in wide bandgap semiconductors, particularly gallium nitride devices, and microcontrollers, power electronics are undergoing significant

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transformation. They are increasingly integrating communication technologies and battery management functionalities alongside power conversion capabilities (He et al., 2020).

Technologies replacing batteries

Advancements in batteries and management technologies have the potential to directly tackle energy and safety concerns. However, they still face some delays, particularly in meeting the pressing demands of the rapidly expanding Electric Vehicle (EV) market. Two alternative technologies, notably wireless power drive, have emerged as potential solutions to mitigate these urgent needs and may even offer alternatives to high-energy batteries.

Move-and-charge

To alleviate the urgency for high-energy capacity, wireless charging technologies present an effective solution (Mi et al., 2016; Tian et al., 2021; Assawaworrarit and Fan, 2020). Each Electric Vehicle (EV) can be equipped with a smaller battery pack and receive wireless power directly from charging lanes while driving on the road. This move-and-charge technology offers flexibility and convenience in charging. In such scenarios, similar to information encryption, wireless energy-on-demand (Liu et al., 2020b) and wireless energy encryption (Liu et al., 2020a) methods can be implemented to ensure energy security for wireless charging systems with multiple pick-ups. Additionally, the harvesting of renewable energy for EV charging serves as another approach to alleviate the demands for high-energy batteries.

Discussion and recommendation

The discussion and recommendation highlight the ongoing advancements in battery technologies, such as Lithium-Ion Batteries (LIBs), Solid-State Batteries (SSBs), and alternative-ion batteries, driven by global efforts to enhance energy density, fast charging capabilities, and safety features. These improvements are expected to significantly enhance the performance of Electric Vehicles (EVs). Furthermore, the integration of sensor-on-chip and smart power electronics will be crucial in efficiently sensing and processing energy and data information. Embracing advanced technologies including computers, servers, and Artificial Intelligence (AI) methods will enable the development of a coordinated vehicular information and energy internet. This infrastructure will facilitate efficient management of power and information flows among a wide array of EVs.

Lastly, wireless power transfer technologies, such as move-and-charge and wireless power drive, represent promising solutions to reduce reliance on high-energy batteries. These technologies have the potential to offer greater flexibility and convenience in charging EVs while addressing the challenges associated with high-energy battery dependency.

VI. CONCLUSION

The most recent batteries and the technology used to manage them for Electric Vehicle (EV) applications are thoroughly examined in this article. It looks closely at key characteristics, benefits, and drawbacks as well as current technical advancements, difficulties, and possibilities. Both the EV battery categorization and the roadmap are explained in detail. New insights, especially on Vehicle-to-Vehicle (V2V) and Vehicle-to-Grid (V2G) operations in wireless EV power networks, are offered. Energy density, fast charging, and safety concerns are emphasised as the main considerations in EV applications. A thorough discussion is provided of various battery modelling, state estimation, and health diagnosis techniques.

The paper emphasises the exciting possibilities of data-driven state prediction, which with data from the first 100 cycles can reach remarkable accuracy levels of over 90.0%. It is also suggested that technologies like wireless power drive and move-and-charge be explored as viable answers to the technological problems involved in creating EV batteries.

Outlining a thorough development plan for Electric Vehicle (EV) batteries that includes advances in battery technologies and alternative solutions is the main goal of this critical analysis. For effective data and energy exchange, special emphasis is paid to the integration of information and energy internet. The review's primary constraints, however, are centred around issues with lithium-ion batteries' (LIBs) energy density, quick charging times, and safety issues. Additionally, shortcomings are identified in real-time state prediction methods based on practical datasets.

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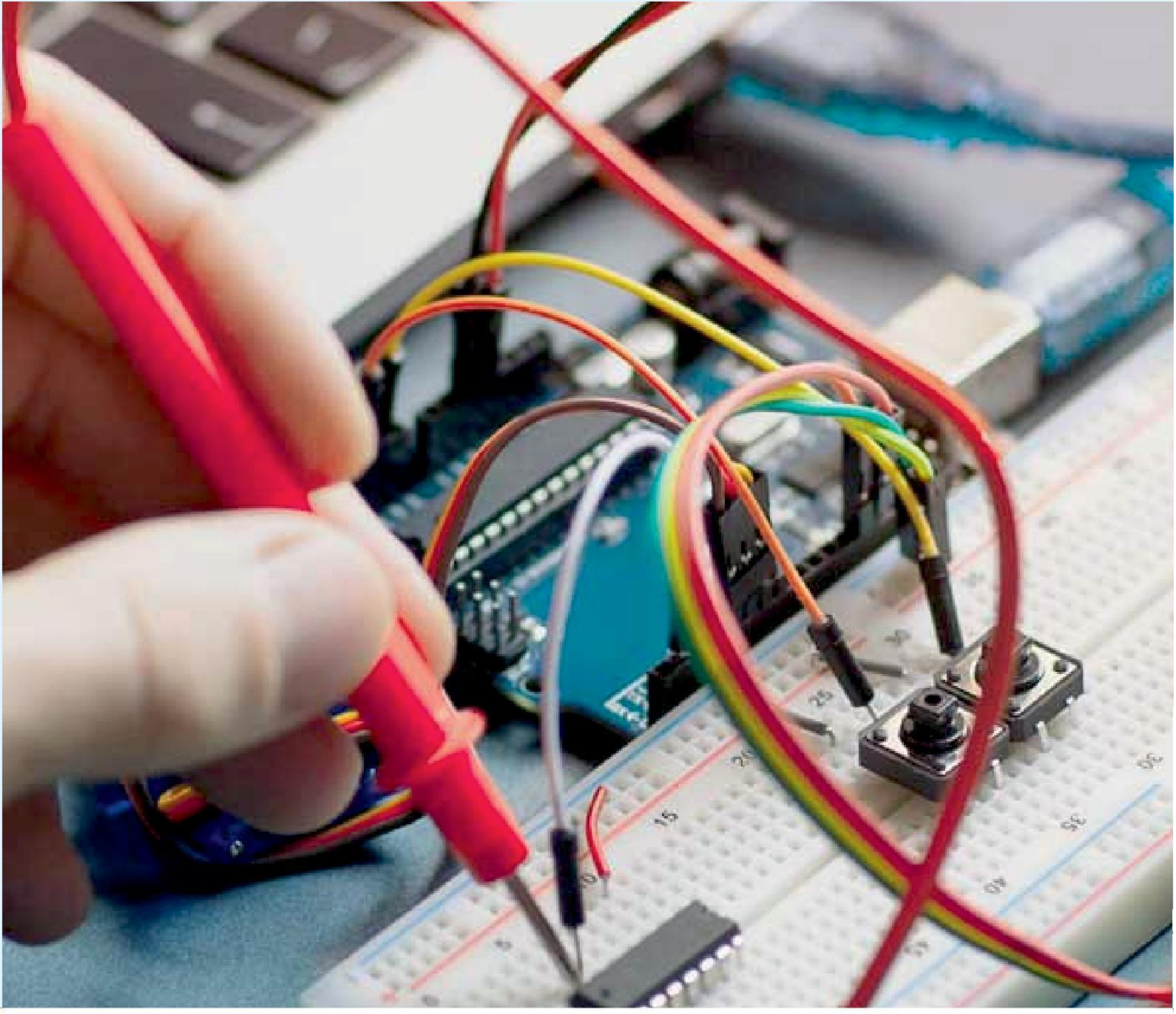

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