Electrochemistry of Electric Vehicles to Address Sustainability of Electrical Energy

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Abstract

The escalating threat of climate change and the pressing need to curb greenhouse gas emissions on a global scale have spurred a renewed focus on sustainable solutions. This alarming trend of greenhouse gas emissions has catalyzed a paradigm shift towards integrating sustainable energy strategies, aiming to mitigate the environmental consequences of energy consumption. A pivotal facet in this transition lies in electrical technologies, particularly exemplified by the electric vehicle (EV) movement. Despite the imperative to diminish the upsurge in greenhouse gas emissions, there remains a noticeable research gap in the electrochemistry of EVs even with a couple of flaws that need to be branched. This literature review meticulously examines the utilization of galvanic cells, redox reactions, and nernst equation concepts in electric vehicles, and underlines current issues relating to the concepts. It is imperative to address these issues to propel the EV industry further towards sustainability. As EVs continue to gain prominence as an eco-friendly alternative to conventional vehicles, understanding and optimizing the electrochemical processes within their batteries are paramount. The investigation into galvanic cells sheds light on the electrochemical mechanisms that power EVs, offering insights into improving energy storage and efficiency. Redox reactions, pivotal in battery chemistry, are analyzed for their role in sustaining EV performance over time. Furthermore, the Nernst equation, a cornerstone of electrochemistry, is critiqued for its applicability in EV batteries. By delving into these topics, this review aims to provide a comprehensive understanding of the electrochemical concepts of EVs, offering valuable insight for researchers committed to accelerating the shift toward sustainable transportation solutions.

Bridging these research gaps is crucial for advancing the global transition to greener mobility options, contributing to a more sustainable future.

Introduction

In recent years, the global imperative for mitigating climate change and reducing the escalating levels of greenhouse gas emissions has intensified. A report by the International Energy Agency revealed that global carbon dioxide emissions rose by 6% in 2021 to 36.3 billion tonnes, marking the highest level (IEA, 2022). This urgent need has prompted a shift towards the development and implementation of sustainable energy solutions as a means to curtail the environmental impact of energy consumption. Electrical technologies are the future and the key to reducing carbon dioxide emissions through electric cars has started the electrical revolution. Despite the increasing need for sustainable energy to reduce yearly increases in greenhouse gas emissions, there is a lack of electrochemistry research to prepare diverse future electrical technologies. The literature review addresses the benefits of utilizing electrochemical concepts and applying them to attaining sustainable energy within the transportation sector. Gaps in current knowledge, directions for future research studies, and considerations for human resource personnel are also addressed.

Methods

Google Scholar, PubMed, and IEEE Xplore databases were searched using combinations of the following keywords: electric vehicles, electrochemistry, Nernst equation, galvanic cell, electrolytic cell, redox reactions, lithium battery, discharge, and recharge. To be included, papers had to be focused on the electrochemical concepts of electric vehicles, specifically concepts that are relevant or applied to the EV battery recharge and discharge. All English-language papers from 2000 to August 31, 2023 were eligible. Other forms of sustainable energy than electrical, such as solar, wind, or hydropower, were excluded as the literature review exclusively analyzes electrical energy for EVs.

Concepts and Limitations

Using electricity in transportation involves employing electric power as an alternative to fossil fuels in various transportation methods, such as locomotives and cars. Electric vehicles (EVs) rely on stored electrical energy in batteries to power their motors. This transition towards utilizing electricity as an energy source is considered sustainable because of its potential to significantly reduce greenhouse gas emissions and dependence on finite fossil fuels (Ardehali & Kamani, 2023). Several electrochemistry concepts are directly applied to EVs and their technology, such as galvanic and electrolytic cells, redox reactions, and the Nernst equation. However, the limitations of these electrochemical concepts hinder the development of applying the concepts to electric vehicles. Understanding and improving these electrochemistry concepts will advance the field of electrical energy in transportation, utilizing a sustainable power source. Consequently, this sustainability of electrical energy minimizes the overall carbon emissions of the transportation industry, contributing to a more environmentally friendly mode of mobility.

Galvanic and Electrolytic Cells

EV batteries function as galvanic cells (voltaic), converting chemical energy into electrical energy. During vehicle discharge, these batteries convert stored chemical energy into electrical energy; subsequently, the anode undergoes oxidation, releasing electrons, while the cathode undergoes reduction, accepting the electrons (Habib & Ibrahimy & Motakabber, 2020). When the battery is being charged, it operates as an electrolytic cell, using electrical energy to drive a redox reaction, so this process releases electrical energy to power the EV. While galvanic cells are used for spontaneous reactions, electrolytic cells are used for non-spontaneous reactions (Chau & Liu & Placke, 2022), requiring an external electrical source to drive redox reactions in the desired direction. Ax external voltage is applied to the battery to reverse the direction of the redox reactions that occur during discharge.

The research into galvanic and electrolytic cells is important for the future of EVs as these cells are the EV batteries that are sought to be improved for consumer bases. The major flaw in galvanic cell research is dendrites, tiny metal deposits that curtail the development of rechargeable batteries. Professor Yi Cui conducted a research study at Stanford University finding that building fast-charging batteries is the future, but dendrites are the biggest hindrance to this anticipated process (Cui & Chiang & Liang, 2015). Professor Cui's galvanostatic experiments provided insights into solving dendrite corrosion, for he was able to find a synergetic effect of lithium nitrate in ether-based electrolytes, preventing dendrite growth. Although this new finding was groundbreaking, previous lithium polysulfide research must be re-evaluated in order to apply this discovery to dendrites increasing in EVs. This dendrite infestation is further backed up by the *Energy & Environmental Science* journal, which explained the uncontrollable dendrite growth toward short-circuiting in solid electrolytes hindering rapid electric battery growth (Geng & Xue & Yao, 2023). Turning galvanic and electrolytic battery cells into a sustainable power source for vehicle electrification is closer to being perfected with potential solutions to limit dendrite growth or remove it altogether.

Redox Reactions

Electric vehicles rely on redox reactions primarily within their battery systems as the reactions are responsible for storing and releasing electrical energy needed to power the vehicle. In the anode of a lithium-ion battery throughout discharge within an EV, lithium ions leave the anode material and travel toward the cathode. As they travel to the cathode, electrons are released, creating a stream of electrical current (Mohamed & Sharkh & Walsh, 2009). This study, published by the Institute of Electrical and Electronics Engineers (IEEE), researched the separation feature of redox flow batteries (RFBs), which “adds a degree of flexibility” allowing power and energy component optimization for vehicles. Experimental performance data from an allvanadium RFB demonstrated that the RFB size and performance are suitable for mobilizing EVs. With further testing and research into allvanadium RFBs, the performance of EVs can be improved as well as environmental sustainability with an additional electrical energy source.

On the other hand at the cathode, lithium ions from the electrolyte intercalate into the cathode material’s crystal structure. Consequently, the release of stored energy occurs, involving the reduction of metal ions. These oxidation and reduction processes use the stored electrical energy in the vehicle’s battery and convert the energy into usable power to propel the EV and operate it. However, the reduction processes can be energy-intensive requiring a significant amount of electricity. Currently, this energy demand is not sustainable by itself, so electrical energy is combined with fossil fuels, which leads to high carbon emissions. *Environment, Development and Sustainability* discussed the reduction processes in chemical reactions as “intensive” and a “new problem,” so more research looking into pure EV batteries and electricity generation is necessary to improve transport energy security and turn into fully electricity-based vehicles with no carbon emissions (Ajanovic & Haas, 2018).

Battery recharging in EVs involves replenishing the stored electrical energy in the vehicle's battery so it can be used for propulsion and operating various systems. An external electrical voltage reverses the electrochemical reactions that occur during discharge. For a lithium-ion battery, lithium ions migrate from the cathode via an electrolyte to the anode material (Ning & Popov, 2004). Simultaneously, electrons flow from the external circuit in the cathode to the anode, constituting an electric current that carries the energy to the battery. Efficient battery recharging is important for the practicality of EVs and has proven to be sustainable; the U.S. Department of Energy found EVs create 3,932 lbs. of carbon dioxide per year compared to 11,435 lbs. for gasoline vehicles (Moseman, 2022).

Nernst Equation

The Nernst equation is used to calculate the equilibrium potential of a cell based on ion concentrations and is crucial to understanding the battery's behavior under various operating conditions. When temperature and current rate range widely in lithium batteries, the conventional equivalent circuit model (ECM) becomes insufficient, needing the Nernst equation to adapt the model (Chen & Zhang & Zhang, 2020). This literature review does not go into the specifics of the Nernst equation; however, in simple terms, the equation shows that the voltage of the EV lithium battery is influenced by the ratio of ions on each side of the battery. Lithium ions move from one electrode to the other as the battery discharges, so the equation predicts how the voltage changes as the ion concentration changes. In addition, temperature changes can affect lithium ion movements within the battery. Combined with “temperature-dependent factors,” the Nernst equation anticipates how temperature fluctuations influence the battery’s voltage and performance (Liu & Zhu & Zheng, 2020). The anticipation allows EV engineers the essential information for implementing effective thermal management systems to maintain the lithium battery’s efficiency.

Crucial to efficiently store and release electrical energy when needed, the Nernst equation allows engineers to make sure these systems reduce the reliance on fossil fuels, shifting towards cleaner energy sources. Although the Nernst equation is important for sustainability, concentration variance is a limiting factor that inhibits the use of the Nernst equation in many situations utilizing electrical energy. The Nernst equation is valid for ideal solutions and assumes activities are equal to concentrations; however, as noted by the Russian Academy of Sciences, the equation is useless when electrolyte concentrations are high because the activity of any type of potential-determining ions in a solution is not related to their concentration by a simple relationship (Avdeev & Andreeva & Anfilov, 2022). In order to study redox properties in several hydrogen compounds, the *Russian scientists* used potentiometry, a technique used to find the concentration of a solute in a solution, on platinum electrodes. It was discovered that the redox potentials of various systems in the experimented solutions were changing drastically due to the active concentrations of Fe(III) and Fe(II) cations changing unequally. As a result, the researchers could not account for the changes in concentration using the Nernst equation and, taking into account the complexity of the system, concluded that this problem could not be solved. Further research and experimentation are necessary to modify the Nernst equation for concentration variance.

Correlating to electric vehicles, electrolyte concentrations vary from use in lithium batteries, so concentrations are never balanced and stable. High fluctuations in electrolyte concentration also harm the environment, for the production and disposal of electrolyte battery material, especially in lithium-ion batteries, create waste management challenges. *Princeton NuEnergy* found only about 5% of lithium-ion batteries were recycled in the United States (Seltzer 2022). Advancements in understanding and improving the underlying principle of the Nernst equation will contribute to more efficient and effective lithium-ion battery and electrolyte recycling leading to an improvement in EV energy sustainability. For example, the Nernst equation is often used to estimate the state of charge of a battery cell based on its voltage (Liu & Zhu & Zheng, 2020). Improving the accuracy of this estimation will help determine the remaining capacity of recycled lithium-ion battery cells. Improvements in understanding the Nernst equation can lead to the development of batteries with better stability and longer lifespan, improving environmental sustainability.

Conclusion

The escalating threat posed by climate change has underscored the critical importance of transitioning towards sustainable solutions to mitigate the adverse impacts of greenhouse gas emissions. The ideal shift towards integrating sustainable energy strategies represents a vital step in addressing this global challenge. Among the various aspects of this transition, electrical technologies, exemplified by the EV movement, play a pivotal role. Despite the urgency to curtail greenhouse gas emissions, there exists a significant research gap within EV electrochemistry, along with noteworthy flaws that require attention.

This literature review has undertaken a meticulous examination of the implementation of galvanic cells, redox reactions, and Nernst equation concepts within the context of electric vehicles. By shedding light on these foundational electrochemical principles, this literature review provided a deeper understanding of the intricate mechanisms underlying EV technology. Moreover, the review identified and highlighted existing issues and challenges with these concepts in the context of EVs. Moving forward, addressing these research gaps and rectifying the identified flaws (dendrites, unsustainable electrical energy, and Nernst equation fallacies) will be crucial for advancing the development of EVs as sustainable solutions for reducing greenhouse gas emissions. As society strives for a more sustainable future, bridging these gaps in knowledge will be instrumental in shaping the trajectory of electric vehicle technology and its role in the broader landscape of sustainable energy solutions.

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