Challenges in the Manufacturing and Integration of Solid State Batteries (SSBs) in the Canadian EV Market

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The electric vehicle (EV) industry faces numerous challenges, with one of the most significant being the limitations of liquid-state lithium batteries. These batteries are hindered by higher costs, added weight, and consumer concerns about range, primarily due to their lower energy density compared to gasoline. Experts agree that the future success of electric vehicles hinges on advancements in battery technology.[1] Solid-state batteries, a promising new development, have the potential to transform the EV market by offering significant advantages that could finally make electric vehicles competitive with gasoline-powered alternatives.[2] Solid-state batteries (SSBs) achieve energy densities of 500-700 Wh/L, offering up to 70% higher energy density compared to traditional lithium-ion batteries (LIBs).[3] The use of a solid electrolyte in SSBs not only reduces the risk of fire but also enables the use of lithium metal anodes, a significant change that increases its energy density compared to liquid lithium batteries. However, despite these advantages, SSBs face significant manufacturing costs and challenges, along with the difficulty of integrating entirely new hardware into a market currently dominated by LIBs.

This report aims to address the challenges in the manufacturing of solid state batteries that must be overcome before it can see implementation in the Canadian EV market. It will define an overview of the EV battery development landscape in Canada, introducing important terms and concepts, identify the leading challenges faced by SSBs and analyze solutions from various professors, companies, and researchers.

The primary challenges faced by SSBs are high manufacturing costs and an underdeveloped manufacturing process, challenges in battery design to fulfill engineering validation, the need for robust thermal management solutions, and the difficulty of integration into existing EV production infrastructure. This report will highlight the most current and robust solutions to these problems including the addition of TRIM to ISO standard, open collaboration between EV manufacturers, a Machine-Learning Assisted Advanced Battery Thermal Management System, and investment into various other manufacturing engineering technologies.

To preface this report, a brief explanation of the technical properties of solid state batteries will be outlined. The main difference between SSBs and the widely implemented LIBs is the use of solid electrolytes in place of liquid organic electrolytes. The solid state is an improvement in both aspects of stability and thermal conductivity, avoiding the same dangers of leaking or evaporation as its older counterpart. The positive electrode material of traditional lithium batteries is usually metallic lithium, and the negative electrode material consists of graphite or silicon-based materials. Solid state batteries in comparison have great energy density due to their high-capacity materials- resulting in a higher carrying capacity thanks to their lithium metal anodes. They also have a smaller contact area and higher interface resistance because of the existence of grain boundaries (introduced by the use of solids over liquids), resulting in the faster movement of ions and ergo, faster charging performance.[4]

However, due to the poor electrochemical stability of solid-state batteries, their cycle lifetime can actually be lower than that of traditional lithium batteries. This is an obstacle that is currently being overcome, however the biggest drawback despite having a large number of benefits over lithium-ion, is the expensive manufacturing cost and ongoing improvement of their lifetime cycle (due to requiring newer and higher quality materials compared to LIBs).

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[1] Alanazi, F. (2023). Electric vehicles: Benefits, challenges, and potential solutions for widespread adaptation. *Applied Sciences*, *13*(10), 6016. https://doi.org/10.3390/app13106016
[2] Deng, J., Bae, C., Denlinger, A., & Miller, T. (2020). Electric Vehicles Batteries: Requirements and challenges. Joule, 4(3), 511–515. https://doi.org/10.1016/j.joule.2020.01.013
[3] Alanazi, F. (2023). Electric vehicles: Benefits, challenges, and potential solutions for widespread adaptation.

[4] Li, C., Wang, Z., He, Z., Li, Y., Mao, J., Dai, K., Yan, C., & Zheng, J. (2020). An advance review of solid-state battery: Challenges, progress and prospects. Sustainable Materials and Technologies, 29. https://doi.org/10.1016/j.susmat.2021.e00297, pp. 1-11.

To face the demanding requirements of engineering validation, widespread adoption of more efficient testing mechanisms is crucial. This is why it is imperative the National Research Council's design should be implemented into ISO standard, provided to Canadian manufacturers to streamline the development process. Coupled with a shift to open communication management techniques, manufacturing companies could see a boost in collective industry innovation.

A primary area of improvement in the unrefined manufacturing process lies in the need for more advanced engineering technologies. While many designs take years of research to implement, the long-term solutions they present are necessary to the growth of the industry as a whole. One method of addressing this challenge is to implement a more detailed engineering plan for evaluation of tradeoff, and research into development of a system that can effectively manufacture SSBs at a competitive level with LIBs.

The issue of integrating SSBs into the existing EV infrastructure is a more difficult issue, having little explicit research done into the niche issue. One solution, presented by a commercial EV manufacturer, suggests the retrofitting of a solid-state battery pack onto EV owners' existent vehicles. This solution holds promise for the future sustainability of electric vehicles, however, remains to be evaluated on its full effectiveness due to the company's uncertain track record. Another alternative is to adapt the LIB manufacturing process to accommodate SSBs, rather than researching specific new technologies. While able to reduce costs, this solution has been found unsuccessful at fully adapting the process; still requiring entirely new processes for the solid state battery.

Literature Review

In the review *"Beyond lithium-ion: emerging frontiers in next-generation battery technologies"* by Vedhanarayanan and Lakshmi KC (2024), the authors explore the future of electric vehicle (EV) battery technologies, focusing on the promise of solid-state batteries (SSBs) as a next-generation alternative to conventional lithium-ion batteries (LIBs). They discuss the increasing challenges faced by LIBs, including resource scarcity and thermal risks, and highlight how SSBs could eliminate overheating risks and improve EV performance through their solid grain boundaries and higher energy density. Furthermore, they explore the potential of using alternative minerals like sodium, potassium, and magnesium to expand supply chain options. However, they also emphasize the ongoing need for research and design improvements to fully capitalize on the advantages of SSBs.

The article by Schnell et al. (2019), *"Prospects of production technologies and manufacturing costs of oxide-based all-solid-state lithium batteries,"* delves into the cost challenges and production hurdles in scaling up all-solid-state battery (ASSB) technology. The authors highlight the complexities of material synthesis and the difficulty of producing high-density oxide-based solid electrolytes at a lower cost. They explore alternative methods, such as spark plasma sintering (SPS), which facilitates material densification at reduced temperatures and lowers energy consumption and minimizes defects. The paper shows the importance of optimizing manufacturing processes to reduce costs while maintaining high performance and safety standards.

Similarly, *"Prospects on large-scale manufacturing of solid-state batteries"* by Hatzell and Zheng (2021) discusses the challenges of scaling ASSBs to market. The authors examine the difficulties in integrating solid electrolytes into battery manufacturing processes, traditionally designed for liquid electrolytes, and emphasize the need for innovations in material science. They advocate for the development of more cost-effective and compatible solid electrolytes, as well as the adaptation or creation of new manufacturing lines specifically tailored for ASSBs. The paper stresses the need for improving both production environments and processes to enhance the commercial feasibility of ASSBs, especially for electric vehicles. Together, these articles provide insights into the technological and economic challenges pivotal to advancing ASSB technology.

Kan et al.'s (2024) article, *"Thermal effects of solid-state batteries at different temperatures: Recent advances and perspectives,"* addresses one of the main challenges in SSB technology—thermal management. The authors explore how temperature fluctuations affect the performance and safety of lithium and non-lithium SSBs, offering potential solutions such as improved ionic conductivity, enhanced thermal conductivity, and interface protection. The paper argues that more sophisticated thermal management strategies are crucial to the successful commercialization of SSBs.

Lastly, Wang et al. (2024) in their study *"An extra-wide temperature all-solid-state lithium-metal battery operating from −73°C to 120°C"* showcase an innovative all-solid-state lithium-metal battery (ASS LMB) capable of operating over an unprecedented temperature range. By incorporating a solar-harvesting cathode made from ruthenium oxide nanoparticles (RuO2 NPs) on carbon nanotubes (CNTs), this battery can compensate for heat loss at low temperatures. The study offers a glimpse into the potential of such batteries for use in extreme environments, including aerospace applications.

Together, these articles and studies provide an overview of the current challenges and advancements in solid-state battery development. Together they give a particular focus on cost reduction, scalability, thermal management, and material innovations necessary for their widespread adoption in electric vehicles and beyond.

Challenges

The challenges section identifies three major challenges faced by solid-state batteries, affecting the manufacturing process. First, challenges in developing adaptive thermal management systems, unrefined and expensive manufacturing methods, and issues with integrating solid-state batteries into existing EV infrastructure.

Challenges in Developing Thermal Management Solutions that Can Adapt to Different Climates

One of the major safety and operational concerns of batteries is their ability to perform in various temperatures, whether it be the risk of overheating and catching on fire or less efficient capacity and power in colder climates. While there have been many improvements made to address this issue, the rising problem of battery versatility and longevity in variable conditions remains prominent. From vehicles in 4-season geographical locations such as Canada experiencing temperature ranges as cold as -40°C in the winter to up to 35°C in the summer, battery thermal management systems (BTMS) need to be adaptive. For example, studies have found that lower temperatures can lead to adverse effects such as interface conductance deterioration, travel distance decreasing up to 35% when the temperature drops from 20°C to -26°C, and nearly doubled charging time when the temperature drops from 20°C to -10°C.[2] Furthermore, a study showed that a car under direct sunlight experienced temperatures up to 20°C higher than the surrounding environment, further adding to the increasing concerns of overheating.[5] Beyond geographically variable temperatures, there is also the concern for global market versatility. Climates and environments vary drastically across different regions and a more versatile BTMS may be needed to ensure global competitiveness and streamlined standards when it comes to battery manufacturing. Although countries such as Singapore have taken the initiative to install shaded charging stations to limit the excessive temperature range,

[5] Kan, R., Xu, Y., Chen, R.,et al.. (2024). Thermal effects of solid-state batteries at different temperatures: recent advances and perspectives. Energy Storage Materials, 68, 103366–103366. https://doi.org/10.1016/j.ensm.2024.103366

the safety of electric vehicles should be independent of the infrastructure that a country can offer to increase widespread adoption.[6]

Lithium-ion batteries (LIB), unlike solid-state batteries (SSB), use a liquid electrolyte and have lower operational windows, carrying the risk of short-circuiting and overheating. For SSB, two subcategories can be distinguished: quasi-solid state batteries (QSSB) and all solid-state batteries (ASSB). Quasi-solid-state batteries offer a lower chance of short-circuiting, given they are primarily composed of solid, but contain some liquid or gel-like substances. However, when outside of the operating temperature window, the consequences can be much worse, given highly flammable components used to enhance conductivity. On the other hand, all ASSBs are heralded as the safety solution, with a fully solid electrolyte. However, they experience various other issues, such as initial heat generation and thermal runaway.[1]

Challenges in Integrating SSBs into Existing EVs and EV production infrastructure

This challenge highlights the physical and economic feasibility of transitioning between battery technologies. Despite the majority of existing EVs being tailored for LIBs, SSBs hold several advantages and have shown an increasing trend in adoption. Consequently, manufacturers of SSBs face the challenge of retrofitting new SSBs into battery compartments and circuits that were designed for LIBs operating at different voltage ranges, physical configurations, charging protocols, and various other differences without compromising safety standards and economic feasibility. The reason for integrating SSBs into existing EVs lies in a smoother transition towards SSBs, a more environmentally conscious approach by re-using existing manufacturing processes and vehicles and paving the way for a system that facilitates future upgrades in batteries. Beyond integration into existing EVs, there are also hopes that solid-state batteries can take advantage of the several billions that have been invested into existing LIB infrastructure, leading to a more economical transition.[7] The analysis of the production lines, however, will be dependent on the specific electrodes involved and will be discussed in further detail in the solution section.

From an economic and safety standpoint, there are several considerations including adapting to variable climate conditions and taking advantage of existing EV infrastructure. However, there have been several advancements made in both of these fields which will be covered in the solution section.

Manufacturing Process Challenges

In solid-state battery (SSB) manufacturing, the electrolyte, anode, and cathode are integrated into a single cell. However, producing each component and assembling them into a functional unit poses significant challenges. Typically, the layers of electrolyte, anode, and cathode are stacked and subjected to pressure and heat to ensure proper interfacial contact.

Scaling up the production of SSBs presents additional difficulties, such as the brittleness of solid electrolytes, the reactivity of lithium metal, and the high sintering temperatures required for composite cathodes. Each component must be carefully integrated in a controlled environment, ensuring chemical stability and thermal expansion compatibility among the materials.

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[6] Singapore Joins The Collective 2030 Zero-Emission Vehicle Deployment Goal. (n.d.). Www.mot.gov.sg. https://www.mot.gov.sg/news/press-releases/details/singapore-joins-the-collective-2030-zero-emission-vehicle-deployment-goal/

[7] Subdhan, A. (2024, April 25). Canada's committing tens of billions of dollars to the EV industry. Here's a list of the planned projects so far. The Globe and Mail. https://www.theglobeandmail.com/business/article-canada-ev-battery-plants-list-honda-stellantis

Electrolyte Manufacturing Process and Challenges

In solid-state batteries (SSBs), ion transport between the anode and cathode is facilitated by solid electrolytes, which are typically categorized into three types: polymer, oxide, and sulfide. The first important step in the manufacturing process is choosing the ideal solid electrolyte material to achieve the balance of performance and cost. For this discussion, we will focus on two promising candidates: sulfide-based Li10GeP2S12 (LGPS) and oxide-based Li7La3Zr2O12 (LLZO).[8]

The production of oxide-based electrolytes begins with the synthesis of precursor powders—raw materials chemically treated to form the electrolyte. These powders are created using solid-state processes, where raw ingredients are mixed and heated to trigger a reaction. Alternatively, wet chemical methods can be used, where components are dissolved and combined in a liquid medium to ensure a uniform mixture. They undergo high-energy ball milling once the powders are synthesized, a process where steel balls in a rotating drum grind the powder into finer particles. Ensuring uniform particle size and consistency is essential at this stage. The milled powder is then compressed into thin sheets, either through tape casting, where a slurry of the powder is spread into a thin film, or by uniaxial pressing, which applies pressure in a single direction to form a compacted sheet.[9] Finally, the green (unsintered) sheets are heated to temperatures above 1200°C in a process known as sintering. This step increases the material's density and improves its ionic conductivity, which is needed for high-performance solid-state batteries.

One significant challenge is the high sintering temperature required for oxide-based electrolytes. The energy-intensive process forms cracks or other defects due to the brittle nature of the ceramic material.[10] Moreover, it is difficult to maintain a balance between achieving high density and avoiding grain boundary issues; interfaces where different crystalline grains meet within a material can reduce ion transport. [11] Sulfide-based electrolytes, while offering higher ionic conductivities, face challenges related to their sensitivity to moisture, requiring processing in inert atmospheres to prevent degradation and the release of toxic hydrogen sulfide gas. This makes scalability a significant hurdle as requirement adds complexity and cost to the manufacturing process.[12]

Anode Manufacturing Process and Challenges

Lithium metal is prized for its high theoretical capacity, making it an ideal anode material. The process typically starts with the preparation of a thin lithium metal foil, which can be achieved through methods such as rolling (where the metal is pressed between rollers to achieve the desired thickness) or vapor deposition (a process where lithium is evaporated in a vacuum and condensed onto a surface to form a thin layer). The lithium foil is then laminated onto a current collector, often made of copper, to form the anode.

In some cases, a protective coating is applied to the lithium metal to prevent dendrite formation—needle-like structures that can grow through the electrolyte and cause short circuits. [13]

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[8] Boaretto, N., Garbayo, I., Valiyaveettil-SobhanRaj, S., Quintela, A., Li, C., Casas-Cabanas, M., & Aguesse, F. (2021). Lithium solid-state batteries: State-of-the-art and challenges for materials, interfaces and processing. Journal of Power Sources, 502, 229919. https://doi.org/10.1016/j.jpowsour.2021.229919. p.4.
[9] Schnell, J., Günther, T., Knoche, T., Vieider, C., Köhler, L., Just, A., Keller, M., Passerini, S., & Reinhart, G. (2018). All-solid-state lithium-ion and lithium metal batteries – paving the way to large-scale production. Journal of Power Sources, 382, 160–175. https://doi.org/10.1016/j.jpowsour.2018.02.062 p.161.
[10] Boaretto, N., Lithium solid-state batteries, p.12.
[11] Minkiewicz, J., Jones, G. M., Ghanizadeh, S., Bostanchi, S., Wasely, T. J., Yamini, S. A., & Nekouie, V. (2023). Large-scale manufacturing of solid-state electrolytes: Challenges, progress, and prospects. Open Ceramics, 16, 100497. https://doi.org/10.1016/j.oceram.2023.100497 p.6-7.
[12] Boaretto, N., Lithium solid-state batteries, p.12.
[13] Zaman, W., & Hatzell, K. B. (2022). Processing and manufacturing of next generation lithium-based all solid-state batteries. Current Opinion in Solid State and Materials Science, 26(4), 101003. https://doi.org/10.1016/j.cossms.2022.101003, p.6.

This coating is usually applied using techniques like atomic layer deposition (ALD)and allows for the creation of ultra-thin, uniform layers one atom at a time. The alternative is vapor deposition (PVD), a process which uses vaporized material to coat the surface. These methods are crucial for maintaining the anode's integrity and preventing safety issues during battery operation

The primary challenge in manufacturing lithium metal anodes is preventing dendrite growth, which can lead to short circuits and battery failure. The processes involved in applying protective coatings are typically expensive and difficult to scale. . Additionally, lithium metal is highly reactive with moisture and oxygen, necessitating the use of dry rooms or inert atmosphere environments during the manufacturing process.[9] This requirement significantly increases production costs and introduces challenges in maintaining a consistent and high-quality product. Moreover, ensuring a uniform coating and preventing defects such as voids or cracks during the application process is critical because even minor imperfections can lead to significant performance issues.[9]

Cathode Manufacturing Process and Challenges

The manufacturing process for cathodes in SSBs involves integrating the active cathode material with the solid electrolyte to form a composite cathode. This process typically begins with the mixing of the cathode active material, such as Nickel Manganese Cobalt (NMC) or Lithium Iron Phosphate (LFP), with the solid electrolyte powder. The mixture is then combined with a binder (a substance that helps hold the particles together) and a conductive additive to form a slurry—a thick, viscous liquid. This slurry is then cast into thin films using tape casting or screen printing techniques, where the slurry is spread out in a uniform layer and then dried to remove the solvent.[14] Once dried, the composite cathode layer undergoes a sintering process to densify the material, meaning the particles are fused together through heat to remove voids and improve the ionic and electronic conductivity. The sintering temperature for these layers can be quite high, often exceeding 1000°C, which is necessary to achieve the desired density and performance characteristics.[15]

The challenge lies in the high-temperature sintering process because it can trigger unwanted chemical reactions between the cathode material and the solid electrolyte. These reactions often create resistive layers that hurt the battery's performance. It's crucial to manage the sintering temperature, time, and environment to prevent these reactions, but this becomes even harder when trying to scale up for mass production. Another challenge is ensuring the cathode material and solid electrolyte are mixed evenly and without defects. Any inconsistency or impurities can lead to poor performance or even cause the battery to fail. Plus, the solid electrolyte is brittle, making it difficult to handle without causing damage during assembly.[16]

Challenges in Manufacturing Costs due to a Multitude of Variables and Conditions

The challenge of manufacturing cost is one at the forefront of solid state battery development. Current batteries have been projected to cost over $100/kWh, requiring massive materials processing costs and a high pressure manufacturing process, ergo higher machine operation times and costs.[17] Solid-state batteries require advanced, high-capacity materials to address issues related to poor electrochemical stability, material shortages, and recycling difficulties. As a result, their manufacturing process is both tedious and costly. In contrast, lithium-ion batteries benefit from a more streamlined manufacturing process due to their widespread and long standing adoption.[18]

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[14] Schnell, J., All-solid-state lithium-ion and lithium metal batteries. p.5.
[15] Minkiewicz, J., Large-scale manufacturing of solid-state electrolytes. p.9-11.
[16] Zaman, W., Processing and manufacturing of next generation lithium-based all solid-state batteries. p.3-4.
[17] Princeton University, Vanderbilt University (n.d.). Processing and Manufacturing of Next Generation Lithium Based All Solid-State Batteries. Sciencedirectassets.com. https://pdf.sciencedirectassets.com/272101, p.3-6.
[18] Zhang, Z., Han, WQ. From Liquid to Solid-State Lithium Metal Batteries: Fundamental Issues and Recent Developments. Nano-Micro Lett. 16, 24 (2024). https://doi.org/10.1007/s40820-023-01234-y, p.2.

Another problem arises with the solid state battery architecture. Despite boasting higher energy density thanks to its solid electrolyte base, growths called dendrites can emerge from the shape of the electrode and risk shorting the battery pack.[19] Research to inhibit dendrite growth is currently being conducted. This requires more investment in R&D, a pressing safety and performance issue that must be resolved before batteries can hit the market.

The lack of established factories and supply chains or procedural methods means the manufacturing process of these batteries is systematically unrefined. It's a battery tech yet to see commercial implementation, requiring great investment before it can become so. For many companies, this investment is not an easy tradeoff. The decision must be made to prioritize the solid state's ecological and environmental benefits over profit, projecting long-term benefits. If the battery is eventually mass-produced, this means greater incentive for citizens to invest in the EV market thanks to its ergonomically faster charging infrastructure and elimination of the risk of thermal runaway currently posed by liquid electrolytes. The solid state is a much safer, energy efficient alternative that, if able to see widespread adoption, means mutual benefits for Canada's leading EV companies, government body and citizens alike.

Challenges in Fulfilling Significant Engineering Validation Requirements

Aside from cost, the most crucial milestone of solid state battery development is that of engineering validation. Before widespread adoption can take place in Canada, there are 5 golden rules of battery development that must be met: safety, performance, life, cost, and environmental impact. Designing a battery to meet all of these demands is a challenging feat, currently being tackled by the research & development sectors of many EV companies and labs.[20] This challenge comes from a technical standpoint, largely funded by investments but dependent on the scientists and engineers behind EV companies. There have been significant innovative advancements made, however, years of rigorous testing must be undergone before these battery technologies can be commercialized.

Durability is one of the solid state battery's long standing technical issues. The aim is to develop a flexible battery tech, capable of withstanding cracking while maintaining its high energy density and performance- being the SSB's main advantage over traditional LIBs. The issue of durability arises when a battery has gone through numerous iterations of charge and discharge, resulting in physical cracks appearing in the material between cathodes, anodes, and solid electrolytes. To avoid this major hindrance in battery performance, durability is a top requirement in SSB design. One such example is Toyota and Idemitsu Kosan's collaborative development of a flexible solid electrolyte, one such example of a durability-centric design[21]. Toyota is one of the leading EV companies when it comes to solid state R&D, currently working on their second generation of batteries that aims to provide ranges of more than 1,200 km. Along with other leaders in the industry, the company is currently testing various forms of unimplemented battery technologies- such as a hypothetical high-performance battery using a high-nickel cathode and bipolar structure, projected to offer a charging time of less than 20 minutes and nearly 1000 km of range[14], and aims to achieve compatibility between material specifications and production methods of SSBs. In comparison, Toyota's current bZ4X is only capable of 406 km of range. QuantumScape is another notable leader of battery design, claiming to have succeeded in developing a non-crack-prone separator in a lightweight

[19] Stevens, T. (2023, March 10). Solid State Battery Tech For EV Cars: Challenges Lie Ahead. Motortrend.com. https://www.motortrend.com/features/solid-state-ev-car-batteries-challenges/, p.14.
[20] I. S. (2024, February 3). Charged up: Canadian scientists are in a race to make the next breakthrough in battery tech. Theglobeandmail.com. https://www.theglobeandmail.com/business/article-charged-up-canadian-scientists-are-in-a-race-to-make-the-next/, p.7.
[21] Motavalli, J. (2024, April 1). Can Solid-State Batteries Commercialize by 2030? Techbriefs.com. https://www.techbriefs.com/component/content/article/50354-can-solid-state-batteries-commercialize-by-2030, p.2-3.

and compact cell design that, in testing stages, has successfully been recharged 1,000 times.[22] The need for further testing and validation is emphasized, in order to ensure the safety and performance of the design before it can hit the commercial market.

The rigorous requirements of engineering validation remain to be fully tested before solid state batteries can reach commercialization. Yet many leading EV companies have begun or shown willingness for open collaboration on the engineering design process,[23] boasting promising recent advancements and a hopeful future for the design of commercial solid state batteries.

Solutions

This section will overview the existing solutions for battery thermal management systems and integrating solid-state batteries into existing EV infrastructure, their pros and cons, and an overall evaluation.

Solutions for Developing Thermal Management Solutions that Can Adapt to Different Climates

Machine-Learning Assisted Advanced Battery Thermal Management System

Battery thermal management systems (BTMS) are critical to ensuring batteries remain within safe and effective temperature ranges by providing effective cooling and heating. While there exist several technologies such as air cooling, liquid cooling, heat pipes, and phase change materials, the underlying system and algorithms that operate them remain fixed and concrete. For example, BTMS are often hard-coded with algorithms and temperature sensors and may be less adaptive in the face of volatile weather conditions and environments.[24] Furthermore, with temperature sensors and algorithms, the device is often reactionary—lowering or increasing the temperature after the battery passes a certain threshold. Thus, a possible solution is a machine learning-assisted advanced BTMS that can proactively predict battery failure, provide early warnings of fires, and maintain the longevity of the battery.[25] Researchers have trained ML systems on datasets to take in certain parameters, such as cooling medium properties and battery temperature distribution for models like artificial neural networks (ANN), convolutional neural networks (CNN), and long short-term memory (LSTM) to predict temperature changes based on historical and real-time data.[5]

Pros and Cons. The main benefits of machine learning assistance are the predictive nature and ability to adjust to various climates which can account for more edge cases that may be missed in algorithmic, hard-coded approaches. From a safety point of view, a broader range of scenarios could be accounted for. Furthermore, given that it is ML-assisted and not fully driven, several safety features and boundaries can still be hardcoded, only tapping into ML for additional insight. Therefore, this approach can leverage both the benefits of hard-coded algorithms and machine learning techniques. Finally, from an economic standpoint, ML can also optimize the battery and management system rather than actively being integrated in it. Given the effectiveness of battery management systems based on the accuracy of the equivalent circuit model it is based upon, ML can indirectly improve the system by providing a better estimation of the circuit with essential parameters such as the State of

[22] Motavalli, J. (2023, November 9). Can solid-state batteries commercialize by 2030? Sae.org. https://www.sae.org/news/2023/11/solid-state-battery-status, p.3.
[23] J.M.Leclerc, personal communication, July 15, 2024

[24] Rosen, M. A., & Farsi, A. (2023). Battery Thermal Management System - an overview. Science Direct. 120-124. https://www.sciencedirect.com/topics/engineering/battery-thermal-management-system#:~:text=The%20battery%20thermal%20management%20system,operation%20is%20safe%20and%20efficient.

[25] Li, A., & Weng, J. (2023). Machine learning assisted advanced battery thermal management system: A state-of-the-art review. Journal of Energy Storage, 60(106688). Science Direct. 16-18. https://www.sciencedirect.com/science/article/abs/pii/S2352152X23000853

Charge (SOC)–Open Circuit Voltage (OCV) relationship.[26] Various factors and parameters could be optimized within the battery, avoiding the need for extensive computational simulations and experiments to reach the same thresholds and values to be used.

However, as with most machine learning models, the output and effectiveness of the system will be as good as the data it is trained upon. Therefore, while computational costs could be saved, there would be a greater initial cost for gaining data and training the model, assuming the values are available. Furthermore, as ML acts as an assistive tool, there may be complications in finding the balance between hard-coded algorithms and predictive software, likely requiring new employees and regulations. Finally, the behavior of the machine learning algorithm will be less predictable than hard-coded software and may lead to ethical and legal implications if there is a failure in the BTMS, relating to the standing debate on using AI for risk-management based decision making.[27]

Overall Evaluation. While there may be unpredictability with machine-learning-assisted BTMS, the upside of greater prevention methods and adaptability may be worth exploring. Particularly given the increasingly volatile climate and global demand for EVs, machine learning may gain access to greater datasets and lead to more appropriate responses than hard-coded algorithms. Despite the promising future, this is a domain that could be worth continuing given greater safety regulations and laws.

Extra-wide temperature range solar-dependent ASSB

All-solid-state lithium metal batteries (ASS LMBs), while offering higher energy densities and various safety benefits, are susceptible to a high and narrow operating temperature range of (~55 °C to 70 °C) due to low lithium-ion transfer kinetics.[28] Given these conditions, electric vehicles in volatile environments may lead to hazards with the battery. As a possible solution, researchers have developed an “extra-wide temperature” ASS LMB that operates all the way from −73℃ to 120℃.[6] The technology can be considered a solar-assisted BTMS that leverages solar irradiation to heat the battery up at extremely low temperatures up to 20℃ while higher temperatures remain effective given the electrode design. With such a wide operating window, the battery can withstand most, if not all, of the conditions that would be experienced by an electric vehicle. This is achieved with ruthenium oxide nanoparticles (RuO2 NPs) on carbon nanotubes (CNTs), which convert solar energy into heat.[6]

Pros and Cons. The main benefit is the wide operating temperature of the battery, encompassing climates for electric vehicles and allowing for marketability, versatility, and safety of the battery. Furthermore, the solid-state design is an all-solid-state, reducing the risks associated with gel or liquid substances present in quasi-solid-state designs. Given the heating happens through physical processes and reactions, there is no overreliance on an algorithm or code for the BTMS. Rather, the system works naturally with solar power to adjust the battery conditions and can thus be less susceptible to component or electrical failure. Given the first solution was reliant on machine learning, there is also a stark contrast in predictability given the reactions are known beforehand.

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[26] Siva Suriya Narayanan, S., & Thangavel, S. (2022). Machine learning-based model development for battery state of charge–open circuit voltage relationship using regression techniques. Journal of Energy Storage, 49, 104098. 1-2. https://doi.org/10.1016/j.est.2022.104098

[27] Guan, H., Dong, L., & Zhao, A. (2022). Ethical Risk Factors and Mechanisms in Artificial Intelligence Decision Making. Behavioral Sciences, 12(9), 343. https://doi.org/10.3390/bs12090343

[28] Wang, S., Song, H., Song, X., Zhu, T., Ye, Y., Chen, J., Yu, L., Xu, J., & Chen, K. (2021). An extra-wide temperature all-solid-state lithium-metal battery operating from −73 ℃ to 120 ℃. Energy Storage Materials, 39, 139–145. https://doi.org/10.1016/j.ensm.2021.04.024

However, carbon nanotubes (CNT) can be expensive to produce, even more so given the incorporation of RuO2 nanoparticles, leading to increased complexity and production costs.[29] [30] This would pose several challenges in the manufacturing of solid-state batteries, be inaccessible for various stakeholders, and may be susceptible to production errors. Thus, extensive testing and quality control would need to be done in the production line, increasing costs and slowing down manufacturing speeds. Furthermore, the need for solar energy to optimize performance is an immense drawback, given extreme cold temperatures will mostly occur in the absence of sunlight as a consequence of the strong relationship between sunlight duration and temperature.[31] Thus, the technology would become much less effective at night or under poor weather conditions. Finally, there may be scalability issues given the precision needed to manufacture the ASS LMBs, shedding doubt on the widespread adoption of the technology.

Overall Evaluation. While the wide temperature range directly tackles the issue at hand, there are several concerns related to the manufacturability, scalability, and economical feasibility of the technology. Furthermore, given the solar dependence, the increased versatility provided by the wider temperature range is overshadowed by the narrow window of viability for weather conditions. Overall, given the underlying technology of the research is dependent on weather conditions, the pursuit of this solution would detract from the proposed challenge of increasing versatility to environments. However, achieving a wider temperature range is a goal that can be strived for.

Solutions for Integrating SSBs into Existing EVs and EV production infrastructure

Retrofitting new SSBs into existing EV vehicles

Given the specificity of the faced challenge, there was no explicit research done in the domain. However, by a business case, insights into retrofitting SSB packs into LIBS can be obtained. Mullen Automotive, a commercial EV manufacturer, is in the process of developing a new solid-state polymer battery pack that leverages several advantages over LIBs as touched on throughout this paper. However, rather than completely overhauling the battery system, the company is taking an approach by allowing existing customers to retrofit their existing vehicles with the new battery pack through an undisclosed battery exchange program. This took effect over the Mullen ONE vans, extending the range from 110 miles to over 200 miles.[32] While still in progress, Mullen plans to launch its production in 2025.

Pros and Cons. There are several benefits in retrofitting SSB battery packs onto existing vehicles. First, customer retention and improved services. By allowing Mullen clients to keep their existing vehicles, their customers could reduce the costs that would be experienced during a vehicle upgrade, and also experience the company's dedication to improving the quality of the products they offer over time through their exchange program.[26] Second, the approach is more sustainable, benefiting the environmental stakeholders as the upgrade only covers the changing of one part,

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[29] Isaacs, J. A., Tanwani, A., Healy, M. L., & Dahlben, L. J. (2009). Economic assessment of single-walled carbon nanotube processes. Journal of Nanoparticle Research, 12, 551–562. ResearchGate. https://doi.org/10.1007/s11051-009-9673-3

[30] Su, Z., Guan, J., Liu, Y., Shi, D., Wu, Q., Chen, K., Zhang, Y., & Li, H. (2023). Research progress of ruthenium-based catalysts for hydrogen production from ammonia decomposition. International Journal of Hydrogen Energy. 1020. https://doi.org/10.1016/j.ijhydene.2023.09.107

[31] van den Besselaar, E. J. M., Sanchez-Lorenzo, A., Wild, M., Klein Tank, A. M. G., & de Laat, A. T. J. (2015). Relationship between sunshine duration and temperature trends across Europe since the second half of the twentieth century. Journal of Geophysical Research: Atmospheres, 120(20), 10, 823–810, 836. https://doi.org/10.1002/2015jd023640

[32] Morris, C. (2024, July 19). Mullen Automotive will allow customers to retrofit new Solid-State Polymer Battery Pack, increasing EV range - Charged EVs. Charged EVs. https://chargedevs.com/newswire/mullen-automotive-will-allow-customers-to-retrofit-new-solid-state-polymer-battery-pack-increasing-ev-range/

enhancing the vehicle lifecycle management. However, it is important to note that while not the largest, the battery packs still carry significant environmental impact given the necessary mining that needs to occur.[33] Finally, the supply chain and manufacturing process for the Mullen ONE van model can remain unchanged. As new batteries can be retrofitted onto existing vans, the company can reduce costs and time by continuing with the same line of cars and technology in their systems.

However, the retrofitted design may be less efficient or effective than a complete overhaul of the system as the vehicle itself ages and can lead to lower vehicle energy efficiency.[34] Furthermore, the retrofitting process may not be as simple as it is made out to be. There may be significant operational downtime and the need for consumers to send their Mullen ONE vans in for retrofitting, which may be time consuming and lead to significant opportunity cost. Finally, given the solution analysis is based on a business case, it is important to note that the Mullen company itself faces several delays in releasing vehicles, partially contributed to by its business model of rebadging (rebranding) chinese imported EVs.[35] Consequently, several technological advancements and promises remain in external control and may not have the expected outcome.

Overall Evaluation. Overall, Mullen Automotive marketed a promising and fitting solution to the presented challenge. While the promised technology lies in the future, it sets the premise for a future of retrofitting upgraded batteries and parts which may contribute to further sustainability and improvement of EVs. If the technology can be achieved in an economically feasible and safe manner, then the solution may be worth exploring. However, given the track record of the company, the promises are left for speculation.

Adapting existing LIB manufacturing processes to SSB production

Tackling the challenge from a different perspective, the following solution presents methods to shift existing LIB manufacturing processes to ASSBs, reducing economic costs. However, it is important to note that the manufacturing process for ASSBs will vary depending on the solid electrolyte being used, and thus, this solution may vary depending on the scenario. This particular solution focused on various production scenarios for sulfide and oxide-based ASSBs. Overall, the solution found that the composite electrode fabrication can be adjusted to shift from LIBs to ASSBs, although with some difficulty. However, new manufacturing methods will be required for the solid electrolyte separator layer and the lithium metal anode.[36] The findings are still promising, however, given that composite electrode fabrication differs in quite a few ways between solid and liquid electrolytes, but can still be adapted.

Pros and Cons. By integrating SSB production into existing LIB infrastructure, there can be a greater adoption for the new technology, saving significant costs and time as around 25% of LIB

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[33] Shu, X., Guo, Y., Yang, W., Wei, K., & Zhu, G. (2021). Life-cycle assessment of the environmental impact of the batteries used in pure electric passenger cars. Energy Reports, 7, 2302–2315. https://doi.org/10.1016/j.egyr.2021.04.038

[34] Kosai, S., Nakanishi, M., & Yamasue, E. (2018). Vehicle energy efficiency evaluation from well-to-wheel lifecycle perspective. Transportation Research Part D: Transport and Environment, 65, 355–367. https://doi.org/10.1016/j.trd.2018.09.011

[35] Smith, A. (2019, November 15). Mullen Technologies' road to sell electric sports cars is paved by Tesla's success - Washington Examiner. Washington Examiner - Political News and Conservative Analysis about Congress, the President, and the Federal Government. https://www.washingtonexaminer.com/policy/energy-and-environment/2717450/mullen-technologies-road-to-sell-electric-sports-cars-is-paved-by-teslas-success/

[36] Schnell, J., Günther, T., Knoche, T., Vieider, C., Köhler, L., Just, A., Keller, M., Passerini, S., & Reinhart, G. (2018). All-solid-state lithium-ion and lithium metal batteries – paving the way to large-scale production. Journal of Power Sources, 382, 160–175. https://doi.org/10.1016/j.jpowsour.2018.02.062

cost comes from manufacturing.[37] Furthermore, if adapted, there may be elements of a battery thermal management system that can be migrated as well, reducing some initial challenges and inefficiencies related to heat insulation, dissipation, and overall monitoring.[38]

On the contrary, ASSB manufacturing has a very different process from LIB manufacturing, requiring new methods particularly for integrating lithium metal anodes.[30] While some of the findings come from lab production, the actual integration to an industrial scale can lead to unforeseen costs and issues. Finally, despite having some sections be modifiable, they come so with described difficulty that can outweigh the benefits of adapting existing infrastructure. Even if adapted, the production line may not be the most efficient or suited for large-scale production of ASSBs.

Overall Evaluation. While the possibility of shifting existing manufacturing processes to new technologies is promising and indicates a trend towards a faster-adapting technology, there are various safety, economic, and efficiency concerns that can be raised from this process. Furthermore, a large majority of the production appears to not be modifiable to shift to the new manufacturing methods. However, the solution highlights a positive trend toward more flexible production methods that have some overlap with other technologies.

Solutions for High Costing Manufacturing Process

Solutions for Electrolyte Manufacturing Challenges

Electrolytes made from oxide-based materials like Li7La3Zr2O12 (LLZO), require high temperatures to achieve the necessary material density. This high-temperature process, known as sintering, can lead to energy waste and potential defects like cracks in the material.

One way to address this challenge is by developing new methods that allow sintering at lower temperatures. Techniques such as spark plasma sintering (SPS) and cold sintering processes (CSP) are potential alternatives. SPS combines pressure and electric current to densify materials at lower temperatures, reducing energy consumption and the risk of damage to the electrolyte.[39]

Sulfide-based electrolytes, like Li10GeP2S12 (LGPS), present another set of challenges due to their sensitivity to moisture, which can lead to degradation and the release of toxic gases. To overcome this, one solution is to encapsulate the electrolyte in a protective coating that shields it from moisture. Additionally, advancements in manufacturing environments, such as more cost-effective dry rooms (which control humidity and prevent moisture exposure), can make the production process safer and more economical.[40]

Another solution to reduce cost in electrolyte is by using cheaper raw materials or developing new configurations. Future advancements could involve the development of hybrid electrolytes that combine the best properties of multiple materials. Such materials could be processed at lower temperatures and in less restrictive environments, simplifying production and reducing costs.

Solutions for Anode Manufacturing Challenges

Lithium metal is often used as the anode in SSBs because of its high capacity to store energy. However, lithium metal tends to form needle-like structures called dendrites during charging, which

[37] Liu, Y., Zhang, R., Wang, J., & Wang, Y. (2021). Current and future lithium-ion battery manufacturing. IScience, 24(4), 102332. 1. https://doi.org/10.1016/j.isci.2021.102332
[38] Yu, X., Chen, R., Gan, L., Li, H., & Chen, L. (2022). Battery Safety: From Lithium-Ion to Solid-State Batteries. Engineering. 10-11. https://doi.org/10.1016/j.eng.2022.06.022
[39] Boaretto, N.,Lithium solid-state batteries. p.13.
[40] Minkiewicz, J., Large-scale manufacturing of solid-state electrolytes. p.18.

can puncture the electrolyte and cause the battery to short circuit. To prevent this, manufacturers apply protective coatings to the lithium metal.

In some cases, applying coatings becomes a little trickier since they have to be very thin and uniform in order to be useful. For example, atomic layer deposition (ALD) is a common technique that enhances these applications; however, it is a costly and complicated process to implement in mass production. In this respect, active efforts are being made to make these deposition methods more effective and more easily incorporated into mass production. Besides, using other anode materials that are less easily dendritic than lithium, carbon composites for instance, may be a safer and more cost effective alternative. [24]

Lithium metal has another key issue that cannot be disregarded, that is, it is highly reactive and readily susceptible to oxidation or corrosion if exposed to moisture or air. For these reasons, lithium metal anodes must be produced within dry rooms or similar settings. It is therefore important in overcoming the current limitations on large scale production to improve the technology and speed of manufacture of such specialised environments while reducing the costs.[41]

Solutions for Cathode Manufacturing Challenges

In SSBs, the construction of the cathode generally requires the combination of active materials and solid electrolytes to form a composite layer. This is problematic as the materials have to be uniformly blended and the composite obtained has to be defect free. In its making, such processes encompass the preparation of a slurry of the active material and the solid electrolyte with a binder that brings it all together.

After the slurry is completed, it is processed in the form of thin layers using tape casting or equivalent methods. These layers are subsequently sintered in order to remove pores and increase the electrical conductivity of the material. However, the sintering process requires that very high temperatures be used which may result in chemical interactions between the electrolytes and the cathodes and unwanted products formed reducing the effectiveness of the battery.

To mitigate these issues, manufacturers can use cathode materials that are more stable at lower temperatures or apply protective coatings to prevent reactions during sintering. Additionally, advanced manufacturing techniques like 3D printing allow for more precise control over the cathode structure, improving the distribution of materials and reducing the risk of defects.[42]

Another approach is the development of composite cathodes that integrate the solid electrolyte within the cathode itself, creating a more uniform and stable structure. This method can enhance ion transport within the battery and reduce the likelihood of performance issues due to poor material integration.[27]

Overall Solutions for Manufacturing Process Challenges

Advanced assembly techniques are needed to address the challenges of integrating the various components of SSBs—such as stacking the electrolyte, anode, and cathode layers—. Automated stacking and lamination processes can improve precision and consistency, reducing the chances of errors that could lead to defects in the final product. Implementing real-time quality control systems, like laser-based inspections, can help identify and correct issues during assembly, ensuring higher-quality outcomes.[43]

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[41] Hatzell、K. B., Prospects on large-scale manufacturing of solid state batteries. p.3-4.
[42] Minkiewicz, J., Large-scale manufacturing of solid-state electrolytes. p.9-11.
[43] Schnell, J., Tietz, F., Singer, C., Hofer, A., Billot, N., & Reinhart, G. (2019b). Prospects of production technologies and manufacturing costs of oxide-based all-solid-state lithium batteries. *Energy & Environmental Science*, *12*(6), 1818–1833. https://doi.org/10.1039/c8ee02692k p.1825.

Moreover, enhancing the scalability of SSB manufacturing also calls for advancing technologies of the specialized environments that are required for handling sensitive materials. Quite obviously, the use of modular clean rooms that can be varied in size or complexity to accommodate production requirements, would help in reducing costs as well as enable the desired conditions to be maintained. Additionally, process-conditional changes can be implemented in the form of combining elements of classical lithium-ion cell production and modern solid-state battery manufacturing, enabling the faster transition to mass manufacturing.[27]

Pros and Cons. Engineering advancement in more research the manufacturing process is crucial for developing a scalable production line. The pros of looking into these technologies is that they are something that must be examined to improve or develop new and better processes. Avoiding these and seeking a quicker solution may benefit the company and eventually they will need to be studied anyways. The cons of these solutions are that they are long term goals. Again, each one of these technologies takes years of engineering design and research to perfect and in no way is a short term solution. A diverse set of solutions also present the challenge of not being able to put more focus and perfecting one approach.

Overall Evaluation. A more detailed engineering plan should be discussed and developed for the challenges in manufacturing. Research articles are great at explaining topics but missing key details to really understand the entire process. Therefore, it is great that numerous potential manufacturing approaches are being talked about, but a more detailed engineering plan is needed to evaluate trade off and produce a real system that can be used to effectively manufacture solid state batteries at a competitive price compared to liquid lithium-ion batteries. More diverse research should be looking into the whole engineering process of a specific solid state battery because its process depends on the material itself.

Currently, US companies that are achieving promising results in ASSB manufacturing include Quantumscape, Toyota, and Solid power. Several Canadian companies are developing solid-state batteries (SSBs) for electric vehicles (EVs). Hydro-Québec is researching solid-state battery technology through its Center of Excellence in Transportation Electrification and Energy Storage. Electrovaya, based in Mississauga, is exploring advanced battery materials and architectures for potential solid-state applications. Nano One Materials in Vancouver is developing processes for producing low-cost, high-performance cathode materials, critical for advancing solid-state batteries in EVs.

Solutions for Fulfilling Engineering Validation

Widespread Adoption of the TRIM System

The TRIM (Thermal Runaway Initiation Mechanism) system is a recent advent in the field of EV battery safety testing designed by Canada's National Research Council. The device is a promising innovation for the safety of current and future vehicle designs, capable of using an NRC-patented mechanism to monitor lithium-ion batteries for adherence to the ISO 6469-1:2019/AMD 1:2022 international safety standard for EVs.[44] TRIM specializes in thermal runaway risk-assessment thanks to its strong, adaptable and non-invasive capabilities. The system uses a small pulse of heat to gauge the reaction of an EV battery to external heating, tracking the spread of single-cell heating failure. Intended for use by manufacturers and regulators, the TRIM could introduce a new standard of safety to Canadian EVs, propelling the industry on a faster track to fulfilling engineering validation.

Pros and Cons. TRIM's greatest appeal is its advanced design. The mechanism is capable of incredible precision, able to target a single lithium cell without damaging nearby cells, realistically

[44] National Research Council Canada (2024, February 16). NRC lithium-ion battery safety test sparks international acclaim. Nrc.Canada.ca. https://nrc.canada.ca/en/stories/nrc-lithium-ion-battery-safety-test-sparks-international-acclaim, p. 1-5.

simulate real-world heat conditions, and is reliably equipped with a temperature sensor, preventing the premature failure of any part of the design. The device's small physical size allows for ease of placement in various models and designs.

The issue at the forefront of TRIM's conception lies in EV batteries' risk of overheating brought on by an unstable self-heating state.[30] If damaged or defective, the electrolyte materials are at risk of sparking and causing chain reactions of explosions. While SSBs do not share the same inherent risk of thermal runaway as LIBs, TRIM can aid both manufacturers and regulators in measuring the safety of their products, and researchers in studying and developing solutions to the threat of thermal runaway. While this means TRIM is not a direct solution to the issue of overheating, it provides an accessible platform for study.

The device is currently yet to be implemented into actual ISO standard, and fails to see widespread use, although the NRC reports that several companies and R&D environments have been issued evaluation licenses. Before the TRIM can make a larger noticeable impact, wider public use should be observed.

Overall Evaluation. Given the recent advent of the TRIM, it is difficult to pinpoint specific flaws in its design, or the overall implications of its adopted use in the EV industry. Taking into account only published information, however, the system demonstrates incredibly promising results for the advent of safety testing in Canada.[45] Implementation should be practical, as Canada's National Research Council is heading the design. Should the TRIM see implementation into ISO standard and widespread adoption by manufacturers, the long and difficult process of engineering validation may likely streamline.

Shifting Development to a Software Focus

From a developmental standpoint, EV design is constantly faced by the complexity and challenges of emerging and converging technologies. Canadian engineers must research various fields of design to ensure the "future" of battery technology, meeting the requirements of increased energy density, improved safety, cost, and lifetime. Balancing a modern, adaptable design with these factors is a longstanding problem in the industry[46]. Focusing on one method of development can prove to be difficult and unreliable, with the development lifetime of the EV itself having a documented shift from mechanical to a more software-based focus over the years. One solution is for teams to shift development towards this software-based engineering process, utilizing online databases and embracing transparency in the EV development lifetime.[47]

This means focusing efforts on streamlining the information flow of development companies, promoting open communication between teams and outside partners and suppliers for a bolstered work environment. Sectors such as design, product management, supply chain, and service will be focus targets of this streamlined information flow. In the same framework, harmonizing the provincial and regional management sectors of EV companies is another action that can be taken to streamline the adoption process. A faster design pathway will support the rise of a renewable, circular automobile economy utilizing all aspects of repair, repurposing, and recycling. As reported by the Canadian Vehicle Manufacturers' Association (CVMA), a focus on an improved developmental scene

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[45] National Research Council of Canada (n.d.). Thermal runaway initiation methodology (TRIM): A leading-edge technology solution to improve the safety of battery systems. Nrc-Publication.Canada.ca. https://nrc-publications.canada.ca/eng/view/ft/?id=c32c4684-53e8-422e-9cf5-2845bbe92f33, p. 1-3.

[46] I. S. (2024, February 3). Charged up: Canadian scientists are in a race to make the next breakthrough in battery tech. Theglobeandmail.com. https://www.theglobeandmail.com/business/article-charged-up-canadian-scientists-are-in-a-race-to-make-the-next /, p.6-13.

[47] Hojlo, J. (2021, July 29). Enabling resilient electric vehicle engineering and design. Ibm.com. https://www.ibm.com/blog/enabling-resilient-electric-vehicle-engineering-and-design/, p.3-7.

is not only beneficial for ease of engineering validation but also the growth of the EV market as a whole. A circular economy has the potential to promote innovation, growth, and employment rates.[48]

Pros and Cons. By focusing a greater effort on open collaboration with this software-based approach, companies may combat problems such as miscommunication between teams which otherwise hinder and result in longer development times. To benefit from the constantly evolving technologies of EV battery technology, a larger network of suppliers and partner companies would be advantageous to the overall advancement of Canada's EV market.

However, not every company operates under the same principles. While leading EV manufacturers have expressed a willingness to collaborate with outside partners for collaborative design of next-generation vehicles and technologies, it is impossible to regulate the shift of an entire industry. Large-scale implementation may be difficult, unable to produce instant or significant improvements to development. As a result, this solution is a somewhat flimsy approach to overcoming intensive engineering validation that does hold value, but is not a significant improvement for the overall development landscape, unless large-scale organizational or governmental changes can be made.

Given that electric and autonomous vehicles are introducing new technologies, many automotive OEMs are expanding their ecosystems of partners and suppliers. Managing these growing ecosystems will be yet another challenge unless a company adopts a holistic management approach to the engineering process that connects mechanical, electrical, and software development and can be extended to third-party design tools and teams. This challenge reinforces the need for a digital foundation that enables teams to share data across the design, development, and manufacturing processes, further facilitating coordination between all stakeholders.[42]

Overall Evaluation. While practical in regards to ease of implementation on an organizational level, this solution falls short on a macro scale. A streamlined, software-based development process is more of an indirect quality improvement over a direct response to addressing the significant engineering validation challenges of EV development. Conversely, focusing efforts on the management side of a design process may take away from more important processes, unintentionally hindering progress instead. With that said, this solution still holds merit if implemented gradually into the management practices of development companies. Adopting a streamlined, open-communication workforce can be incredibly beneficial to innovation and the collective growth of the industry; and the transition to a circular EV economy means promising job aspects for Canada outside of just the consumer scene.

Conclusion

Solid state batteries are a promising new battery technology that has great potential to revolutionize the EV industry on multiple fronts. The design offers heightened user safety through the removal of flammable liquid electrolytes, improved energy density and efficiency, and optimized performance thanks to the use of high-capacity materials. Introduced into the Canadian EV market, SSBs have the potential to reduce consumer costs and incentivize large-scale investment into safer, more efficient electric vehicles.

The main challenges facing the implementation of solid state batteries have been identified as significant manufacturing costs, unrefined development techniques and the inherent difficulties of transitioning the standard protocols of an entire industry populated by existent LIBs to SSBs. Coupled with the developing hardware of SSBs which are still being worked on by researchers to fully meet

[48] Call2Recycle (2022, November 29). Opportunity to harmonize EV battery management policies to benefit Canadians, new report finds. Call2recycle.ca. https://www.call2recycle.ca/opportunity-to-harmonize-ev-battery-management-policies-to-benefit-canadians-new-report-finds/, p.1-2.

engineering validation, this battery tech faces significant hurdles in the way of implementation. This report covered these challenges and various solutions posed by professors, companies and researchers which could fast track the battery tech's development.

Solutions pertaining to enhanced thermal management based in Machine-Learning (Battery thermal management system or BTMS) are critical to addressing the unstable heating mechanisms faced by many current EVs, capable of adapting to versatile weather conditions and environments. All-solid-state lithium metal batteries (ASS LMBs) offer another solution to this problem in the form of high energy densities, developed with a wide temperature range of -73℃ to 120℃. The TRIM (Thermal Runaway Initiation Mechanism) system is a promising solution to streamline the extensive design process of SSBs, designed by Canada's NRC to efficiently track the spread of heat failure. Once implemented into ISO standard, this mechanism boasts promising advancements for the country's R&D scene.

In conclusion, significant manufacturing challenges are yet to be overcome before SSBs can reasonably enter the Canadian EV market. Companies, researchers and manufacturers are actively working on robust solutions to the multitude of challenges faced by this technology which, bolstered by the advent of open communication engineering design and newly patented technologies, sees a promising future.

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