Zinc-Air Batteries and Electric Vehicles

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Abstract

Title: Zinc-Air Batteries and Electric Vehicles

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The effects of climate change are as severe as never before, thereby pressuring governments and communities alike to take concrete measures to mitigate its impact. Recognizing the contribution of transport emissions to global warming has led to a shift towards electric mobility. However, the poster child of electric vehicle batteries – lithium-ion battery – is not as unflawed as it likes you to believe. Plagued by sustainability concerns, the question arises whether there is an alternative to the lithium-ion battery.

This thesis compares and contrasts a zinc-air battery with a lithium-ion battery, to assess its viability to power electric vehicles. While zinc offers abundant resources and enhanced safety, technical hurdles hinder its commercial adoption.

Expert insights have confirmed that zinc-air batteries have great potential for a number of applications, but technical challenges must be overcome before ZABs can be made commercial. Market penetration is likely to begin within this decade, targeting smaller vehicle segments such as two- and three-wheelers. In 10-15 years, full market penetration across all vehicles is expected.

Keywords: Zinc-Air Batteries, Lithium-Ion Battery, Electric Vehicles, Mobility, Climate Change, Transportation Emissions, Sustainability, Technical Challenges

Sumário

Título: Baterias de Zinco-Ar e Veículos Elétricos

Autor: Noah Fiene

Os efeitos das alterações climáticas são mais graves do que nunca, pressionando assim os governos e as comunidades a tomarem medidas concretas para mitigar o seu impacto. O reconhecimento da contribuição das emissões dos transportes para o aquecimento global levou a uma mudança para a mobilidade elétrica. No entanto, o exemplo das baterias dos veículos elétricos - a bateria de iões de lítio - não é tão perfeito como se quer fazer crer. Assolada por preocupações de sustentabilidade, coloca-se a questão de saber se existe uma alternativa à bateria de iões de lítio.

Esta tese compara e contrasta uma bateria de zinco-ar com uma bateria de iões de lítio, para avaliar a sua viabilidade para alimentar veículos elétricos. Embora o zinco ofereça recursos abundantes e maior segurança, os obstáculos técnicos impedem a sua adoção comercial.

Os conhecimentos dos especialistas confirmaram que as baterias de zinco-ar têm um grande potencial para uma série de aplicações, mas é necessário ultrapassar os desafios técnicos antes de as ZAB poderem ser comercializadas. É provável que a penetração no mercado se inicie nesta década, visando segmentos de veículos mais pequenos, como os de duas e três rodas. Dentro de 10 a 15 anos, prevê-se a penetração total no mercado de todos os veículos.

Palavras-chave: Baterias de zinco-ar, Bateria de iões de lítio, Veículos elétricos, Mobilidade, Alterações climáticas, Emissões nos transportes, Sustentabilidade, Desafios técnicos

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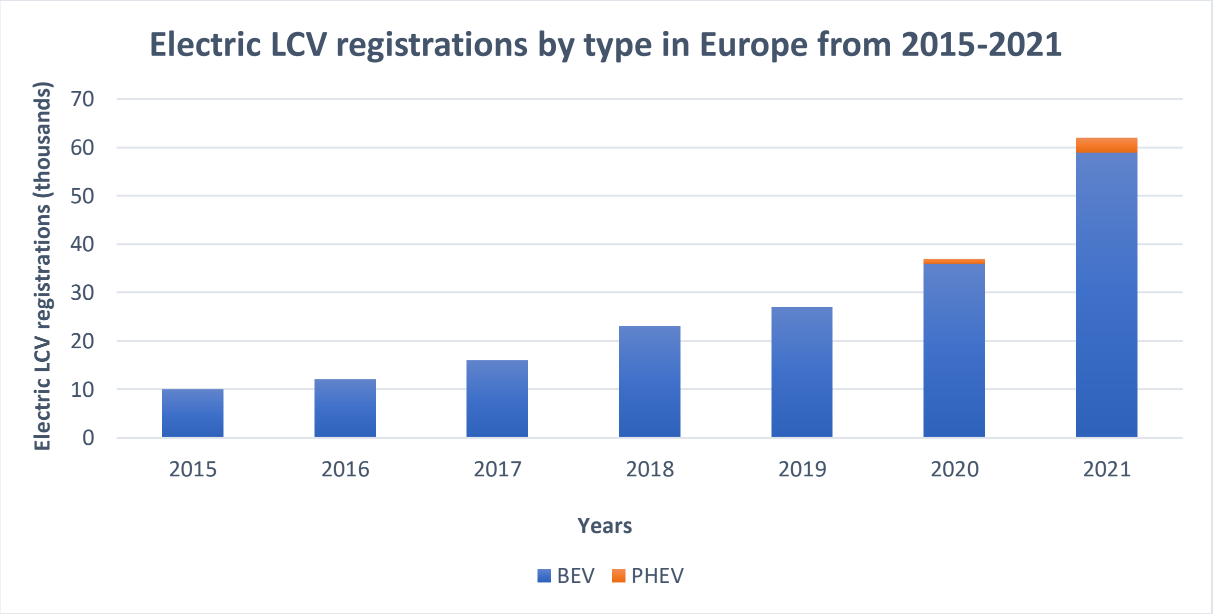
Zinc-Air Batteries and Electric Vehicles

1. Introduction

The European union's Fit for 55 program is the most comprehensive agreement to date, legally binding the EU to cut its carbon emissions by 55% in 2030 (Ovaere & Prost, 2022). This agenda was advanced to achieve the goals of the Paris agreement. Transport emissions accounted for 22% of the EU's total greenhouse gas emissions in 2019 (Transportation & Environment, 2023). However, public campaigns such as 'future for Fridays' have pressured lawmakers into taking action. Purchase subsidies for electric vehicles (EVs) were renewed and expanded. All 27 member states of the EU have some form of incentive in place to promote the purchase of an electric vehicle (ACEA, 2022).

Comparing 2021 and 2022, battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and hybrid electric vehicles (HEVs) recorded an increase in sales within the EU of 28%, 1.2% and 8.6%, respectively. During the same time, natural gas vehicles (NGVs), petrol and diesel vehicles had stagnating year-over-year sales of 57.6%, 12.8% and 19.7% (ACEA, 2023). Figure 1 illustrates the growth in registrations of electric light commercial vehicles (LCVs) within Europe from 2015 to 2021. These LCVs are predominantly battery-powered, witnessing a surge of approximately 50,000 registrations over the span of these seven years. The trajectory distinctly demonstrates an upward trend.



Graph 1: Electric LCV registrations by type in Europe from 2015-2021

Cutting emissions in this sector is one of the key challenges to reaching the climate goals. Internal combustion engines (ICEs) were the dominant method of powering vehicles over the past century. However, ever more noticeable climate change has left politicians with no other choice than to send the ICE into retirement. Average Co2 emissions of new car registrations are to be reduced by 37.5% by 2030, compared to 2021 (Statharas et. al., 2019). To work towards this transition, lithium-ion batteries (LIBs) have emerged as the most viable alternative to regular ICEs. LIBs combination of high energy & power density, a long service life, environmental friendliness with regards to their Co2 emissions as well as their light weight (Chen et. al., 2021), has led them to become the preferred method of powering EVs. Over the past decade, cost has substantially decreased, from $924/kwh in 2011 to $137/kwh in 2020 (Statista, 2020).

However, there are a number of obstacles and shortcomings that need to be considered. Firstly, EVs, as opposed to consumer electronics, require a much greater amount of energy, only achieved by assembling many batteries to form a battery pack. This process results in challenges pertaining to cost, stability, consistency, vehicle weight, and safety (Chen et. al., 2021). Further, the limited availability of lithium and other necessary raw materials poses another problem. Worldwide lithium reserves are estimated to stand at 22 million tons as of January 2022 (U.S. Geological Survey, 2022). A standard electric vehicle contains around 8kg of lithium (Castelvecchi, 2021), while global lithium production amounted to 100,000 tons in 2021 (World Economic Forum, 2022). This amounts to enough lithium to produce 11.4 million batteries. Extrapolating from these figures, while considering other factors such as growing demand for EVs as well as other important uses for the metal, lithium supply shortages are expected to set in by 2025 (Paoli & Gül, 2022). Finally, lithium extraction is a water-intensive process. The extraction of one metric ton of lithium requires 50,000 gallons of water (Rangarajan et. al., 2022). The large majority of lithium resources are found in Australia, Chile and Argentina. Natural phenomena such as droughts might impede extraction in these places, as well as potential government regulations to protect the environment from harmful mining processes. All these factors have prompted researchers to explore other battery types.

This research paper will build on the assumption that lithium resources will not be sufficient to satisfy worldwide needs and will consequently explore another type of battery: Zinc-Air Batteries (ZABs). Firstly, zinc's widespread availability offers a potential buffer against supply chain disruptions and, using the basic economic concept of supply and demand, is therefore unlikely to be subject of steep price increases. Secondly, the research community has been examining ZABs for decades, suggesting a consistent and deep-rooted interest in this technology. Finally, there are contrasting opinions on the feasibility of ZABs. Considering these factors, this paper explores the following research question:

Are Zinc-Air batteries a realistic alternative to Lithium-Ion batteries in electric vehicles?

1.1 Academic & Managerial Relevance

In the current research landscape on alternative battery technologies, there is a noticeable gap: few to no studies have directly compared ZABs with LIBs. While many research papers dive into individual aspects of batteries, like cost or energy density, this study seeks to offer a broader perspective by comparing multiple parameters of both battery types. Moreover, by bringing in expert opinions, it aims to provide a clearer picture of how viable ZABs might be for EVs. For managers and business leaders, this analysis can be a valuable resource by highlighting current challenges within LIB technology, points out advantages and disadvantages of ZABs, and offers insights that can help shape future strategic decisions of firms involved in the electric vehicle sector. For instance, research like this not only informs managers about an incoming war for lithium, but helps them explore alternatives and be a first mover in other types of batteries.

2. Literature Review

This section examines the current state of ZAB in comparison to their lithium-ion counterparts. Specifically, the batteries will be explored along six parameters: Energy density, cycle life, cost, abundance of materials, safety, and environmental impact. It will also discuss management theories related to Davis' technology acceptance model, Roger's diffusion of innovation theory and Teece's dynamic capabilities theory.

2.1 Introduction to Zinc-Air Batteries

Zinc based batteries have been around for over a century, ever since being first patented by Thomas Edison in 1901. Advancements in zinc battery technology over the past decades have led to the emergence of zinc-ion (ZIB) and zinc-air batteries (ZAB). ZIBs easy assembly process and high safety specifications allow them to be substituted for LIBs in certain applications such as large-scale energy storage (Guo & He, 2023). In comparison with LIBs however, they are much heavier, thereby disqualifying them for integration in EVs (Gourley et al., 2023). ZABs, however, are lighter, lower cost, have great energy density and are extremely secure (Yadav et al., 2022). The inherent properties of ZABs make them a promising candidate for LIBs in electric vehicles.

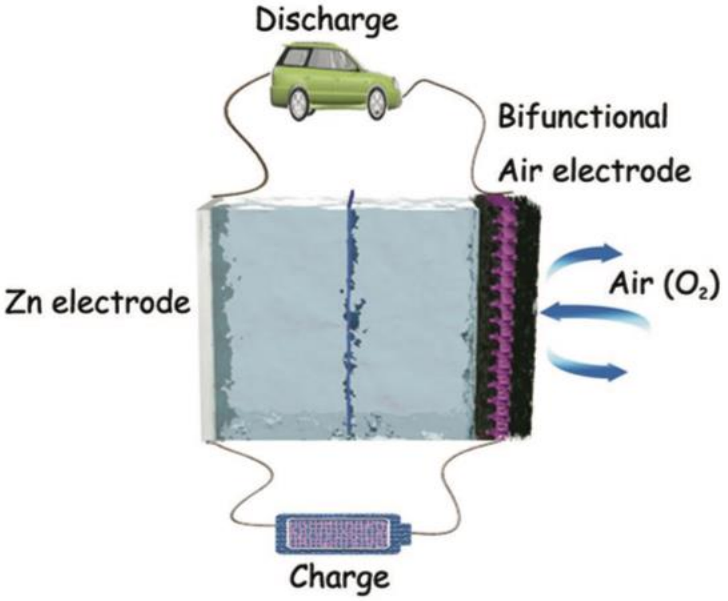


Figure 1: Configuration of a rechargeable Zinc-Air Battery with two electrodes (taken from Pan et al., 2018.)

Figure 1 illustrates a simplified version of a rechargeable ZAB. On the left side is the anode, consisting of zinc electrodes. On the right side is the cathode, made up of air electrodes. This is where oxygen diffuses through into the reaction chamber. The chemical process to create electricity is as follows: Once oxygen has passed through the cathode, it reacts with zinc from the zinc anode. The zinc oxidizes, thereby losing electrons; and the oxygen reduces, thereby gaining those electrons. This exchange of electrons, also known as the redox reaction, produces the electricity (Pan et al., 2018).

ZABs are distinguishable into two types: Primary and secondary batteries, of which the latter includes electrically rechargeable and mechanically rechargeable batteries. Primary batteries are intended for single use operation (Yadav et al., 2022), making them unfit for deployment in EVs. Secondary batteries are rechargeable, either electrically by connecting a charger, or mechanically by physically swapping out the depleted negative metal with a new one (Arai et al., 2020). Some scholars agree that mechanically rechargeable batteries are better suited for mobility applications than their electrical counterparts. Arai et al. (2020) support this notion due to their shorter recharging time. Li & Dai (2014) exemplify their simplicity by referencing an experiment conducted by 'Electric Fuel Limited of Israel'[2]. Already in the 1990's, the company deployed a mechanically rechargeable ZAB in a postal vehicle, enabling it to travel 300-350km on one charge (Li & Dai, 2014). Another experiment included a 12m and 20-ton bus able to run on a single charge for the entire day. Recharging the battery took no more than 5 minutes. Even though the state of these particular ZABs might be outdated, it certainly demonstrates the underlying benefits of this technology. The process is shown in Figure 2.

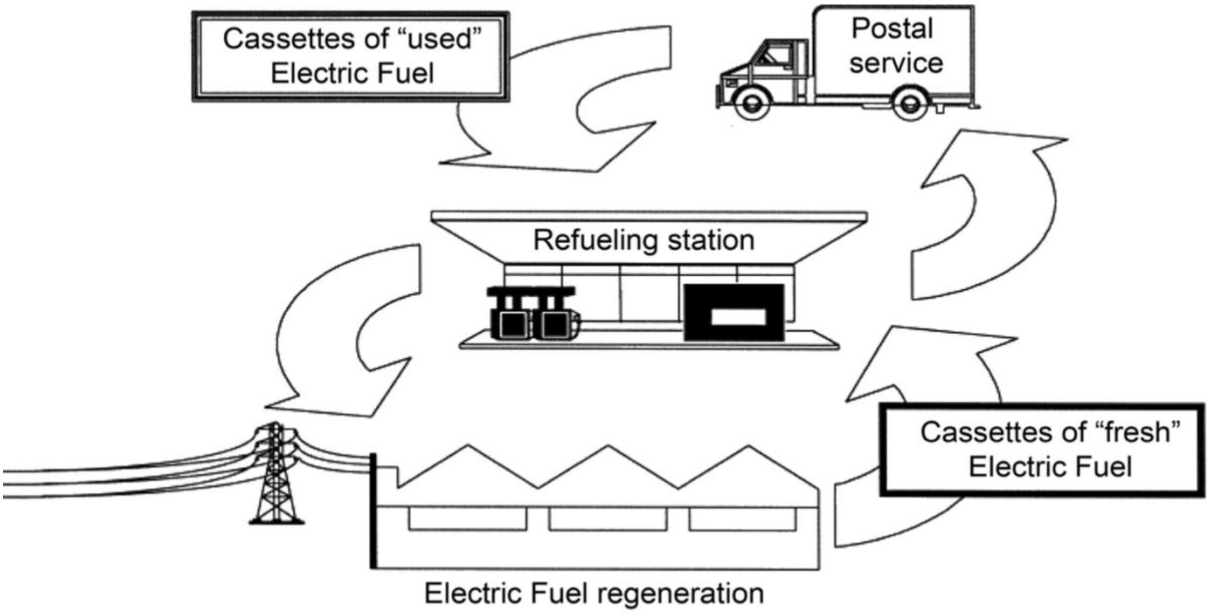


Figure 2: Schematic diagram of the Electric Fuel Ltd. System operation

2.2 Energy Density of Zinc-Air & Lithium-Ion Batteries

Energy density refers to "the amount of energy that can be contained within a given volume" (EERE[3], 2022). It is a crucial factor in determining a battery's suitability for electric vehicles (EVs), as it directly impacts the weight of the required battery pack. A higher energy density allows for a lighter battery pack (Pierri et al., 2021), which in turn enhances the overall performance of an EV by reducing the negative impact of excessive weight on factors such as range, acceleration, and handling.

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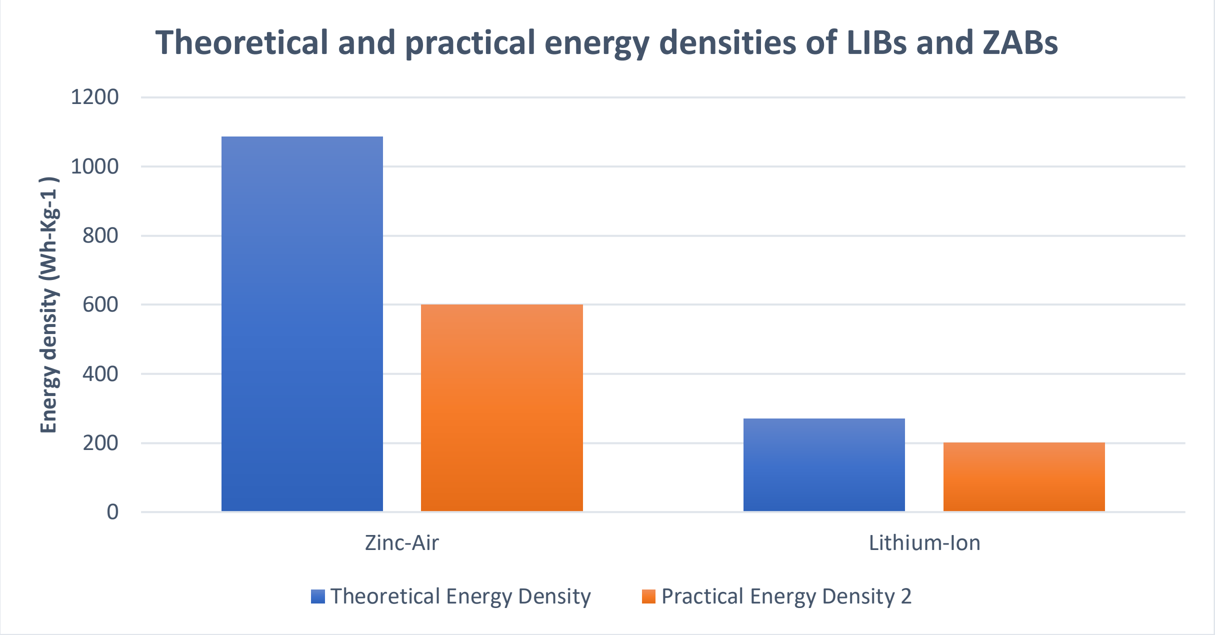
[2] Now Arotech

[3] EERE refers to the United States Office of Energy Efficiency & Renewable Energy



Graph 2: Theoretical and practical energy density of lithium-ion and zinc-air batteries, measured in Wh/kg

Energy density can be split into multiple categories including theoretical and practical energy density, both expressed as watt hours per kilogram (Wh/kg). Theoretical energy density refers to the maximum potential energy that can be stored in the material due to its inherent physical properties. Practical energy density refers to the amount of energy a battery can store per unit of mass. Consequently, the more energy dense a battery is, the less mass of battery is required for providing one kwh, which implies a more efficient utilization of resources (Peters & Weil, 2016).

As illustrated in *Graph 2,* the ZAB's high theoretical energy density of 1086 Wh/kg dramatically exceeds that of a standard LIB, which measures around 200 Wh/kg (Meng et al., 2022). Li et al. (2022) report theoretical energy densities of 100-270 Wh/kg for standard LIBs. Even by 2030, LIBs are expected to realize a theoretical energy density of 'only' 500 Wh/kg, which does not suffice to satisfy the growing demand of the EV market (Cao et al., 2019). ZABs achieve their high density by using air from the environment as one of the main components in the electricity generation process. Thus, a smaller portion of space and weight inside the cell needs to be allotted to the cathode, thereby achieving a greater 'energy per unit of weight or volume' than many other batteries (Arai et al., 2020). It should be noted that when theoretical energy density is considered as the prime factor, ZABs are not necessarily considered in the development of solutions to replace LIBs, because battery types exist that exhibit even higher theoretical energy density (Cao et al., 2019).

Zhang et al. (2019) emphasize the restrictions of current LIB technology, stating that its practical energy density is predominantly capped at below 350 Wh/kg. Interestingly, much of the existing literature on the subject indicates energy density limitations of approximately 200 Wh/kg for LIB technology, which is also visualized in *Graph 2*. In any case, this cap on energy density is insufficient to meet future demand in the realm of electric mobility. In contrast, ZABs have been demonstrated to exceed these energy density limits. According to reports from various studies, ZABs in practical applications have displayed energy densities ranging from 350 to 500 Wh/kg (Christensen, 2018; Lu, 2017). This range notably surpasses that of the conventional LIBs, to be seen in *Graph 2.*

Furthermore, certain advancements in ZAB technology hint at the potential for even higher energy densities. Lu et al. (2022) report instances where ZABs have achieved energy densities up to 600 Wh/kg, nearly double that of advanced LIBs. Consequently, the inherent properties of ZABs, particularly their superior energy density, make them a promising candidate for next-generation electric vehicle applications.

2.3 Cycle Life of Zinc-Air & Lithium-Ion Batteries

The cycle life of batteries in electric vehicles is critical to their long-term performance and economic feasibility. Cycle life is important for determining EV battery longevity, dependability and maintenance requirements. It is defined as the maximum number of charge and discharge cycles a battery can endure while retaining a specified percentage of its initial capacity, typically 80%, until it reaches the designated End-of-Life threshold (Palacín & de Guibert, 2016; Haram et al., 2021). Rechargeable ZABs face a challenge in terms of their cycle life, which restricts their potential for widespread commercial application (Meng et al., 2022). They suffer from cycle degradation, thereby limiting their life cycle (Tran et al., 2021). However, there are multiple promising developments to overcome this obstacle. For instance, the cost-effectiveness of ZABs opens up the possibility for battery pack replacements during the vehicle's lifetime (Toussaint et al., 2010). Therefore, the lifespan of a battery does not necessarily have to be as long as the life of the vehicle.

As research develops, scientists continue to improve the performance of ZABs. French researchers had already developed a ZAB capable of lasting 200 cycles, equivalent to 5000 hours of operation, as early as 2010 (Toussaint et al., 2010). In 2022, tested a ZAB for 1000 cycles and achieved a stable performance throughout (Nagy et al., 2022). However, no remarks were made about the energy efficiency. If energy efficiency was low, the results are not applicable to the real world.

An Indian company named ‘Thunderzee’ has claimed to have invented a ZAB that is able to last up to 5000 cycles (Motortrend, 2021). Table 1, provided by the company, compares their ZAB to other battery types including lithium-ion. In terms of longevity, the ZAB clearly outlasts the LIB, of which the life span is only 300-500 cycles.

	Lithium-Ion	**Thunderzee’s Zinc-Air**
Charge/Discharge Cycles	300-500	5000

Table 1: Thunderzee Product Solution – Zinc-Air Battery

Adopting a radically different strategy to tackle the cycle duration limitation, Sherman et al. (2018) propose a solution involving a dual-battery system, which incorporates both lithium-ion and zinc-air elements. The zinc-air element acts as a range-extender, aiding in prolonging the achievable mileage. During the simulated test, the vehicle demonstrated superior efficiency compared to an electric vehicle solely equipped with a LIB, managing to extend its travel range by as much as 75 km and doing so at a substantially lower cost. Due to the fact that the ZAB is not the primary powering mechanism in this constellation, the frequency at which it needs to be charged, reduces significantly (Sherman et al., 2018). The authors state that only 100 cycles are needed for it to enjoy a ten-year lifespan.

Li-ion batteries (LIBs) in electric vehicles (EVs) have faced challenges due to their constrained storage capacity and a finite number of charge/discharge cycles (Luong et al., 2022). While a LIB's maximum lifespan is capped at around 10,000 cycles, the real-world mileage equates to roughly 200,000–250,000 km. However, the emerging trend of rapid charging at rates exceeding 50 kW could potentially reduce this projected distance. It's noteworthy that the capacity of these batteries diminishes by approximately 20% after undergoing 300 to 500 full discharge and recharge cycles (Luong et al., 2022). One factor that can greatly influence a battery's longevity is its depth of discharge (DoD) — with 100% DoD signifying the complete depletion and subsequent recharge of the battery's energy (Miao et al., 2019).

Depth of Discharge (DoD) (in %)	Discharge Cycles
100%	300-600
80%	400-900
60%	600-900
40%	1000-3000
20%	2000-9000
10%	6000-15,000

Table 2: Cycle Life[4] as a function of discharge

Table 2 clarifies the difference that DoD can make over the course of a battery's lifetime. Just by reducing DoD by 20%, the number of discharge cycles can be increased up to threefold. Recognizing the implications of DoD on battery health, manufacturers have incorporated software controls within their Battery Management Systems (BMS). These controls ensure batteries neither deplete nor recharge beyond certain limits, thereby extending their useful life (Miao et al., 2019).

2.4 Cost of Zinc-Air & Lithium-Ion Batteries

LIBs, the current benchmark for electric vehicles, started with high costs. In 2008, the price was a substantial $1,355 per kilowatt-hour. This was especially significant for passenger vehicles, as Li and Dai (2014) demonstrated that a LIB pack for a vehicle with a 240-mile range would cost over $30,000. Illustrated by Graph 3 (Statista, 2022), a clear trend of cost reduction emerged over the years. By 2022, advancements in battery technologies, chemistries, and manufacturing volume had brought the price down to an estimated $153 per kilowatt-hour (Office of Energy Efficiency & Renewable Energy). Still, LIBs, despite their declining price, continue to be a substantial expense. Zhang et al. (2019) supported this, noting that the cost remained relatively high at around $150 per kilowatt-hour.

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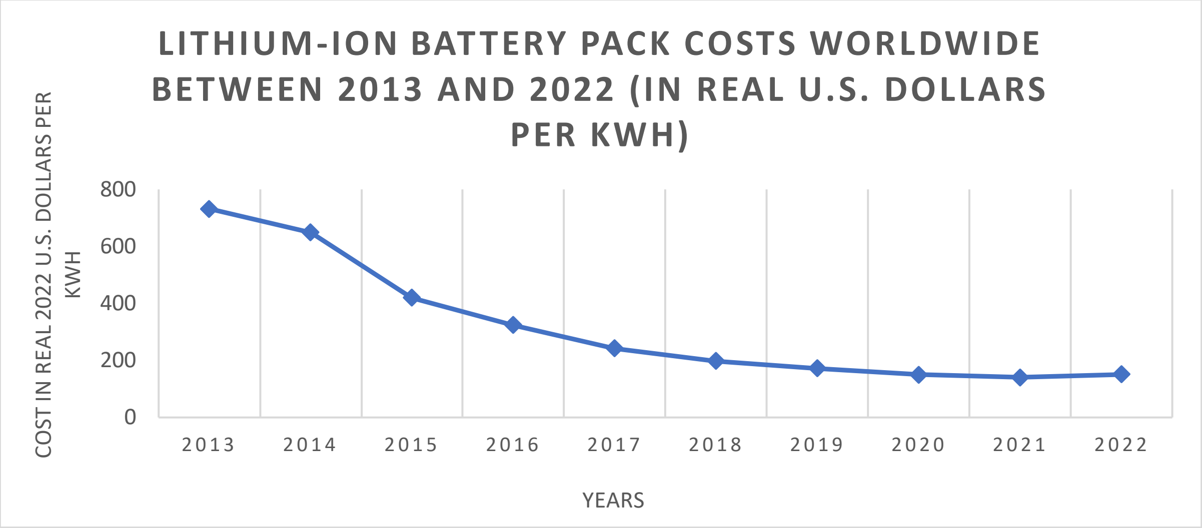
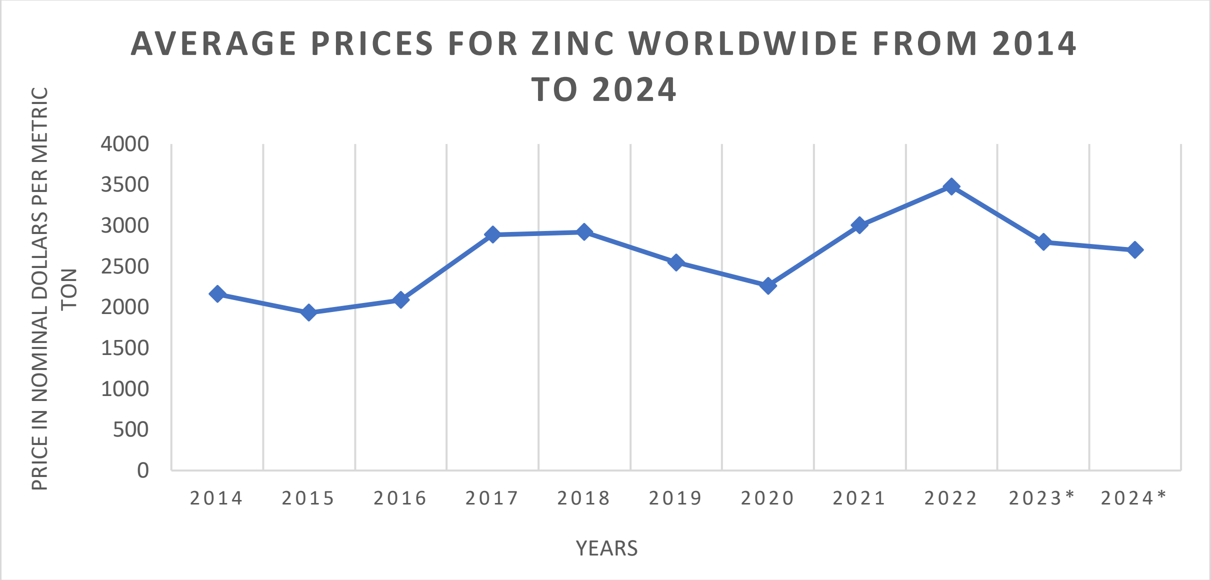
[4] Useful lifetime defined as 80% energy performance threshold



Graph 3: Lithium-ion battery pack costs worldwide between 2013 and 2022 (in real U.S. dollars per kwh) (taken from O'Dea, S., 2023)

Affordability of ZABs has been a consistent theme in the literature over the years. In 2010, Toussaint et al. highlighted the cost-effectiveness of zinc at 1€/kWh and the overall battery cost at around 4-5€/kWh, attributed to the low cost and straightforward fabrication of the zinc anode. This was echoed in 2018, by both Li et al. and Christensen, who noted that zinc, with a low cost of 2 USD/kg, was significantly cheaper than lithium at 8 USD/kg. Sherman et al. (2018) further validated these cost advantages, noting that ZABs, due to their manufacturing process and reliance on abundant, cost-effective materials, hold a distinct economic edge over their lithium-ion counterparts. As shown by Graph 4, the average price of zin has remained relatively stable, at around $2600 per metric ton.



Graph 4: Average prices for zinc worldwide from 2014 to 2024 (taken from O'Neill, A., 2023)

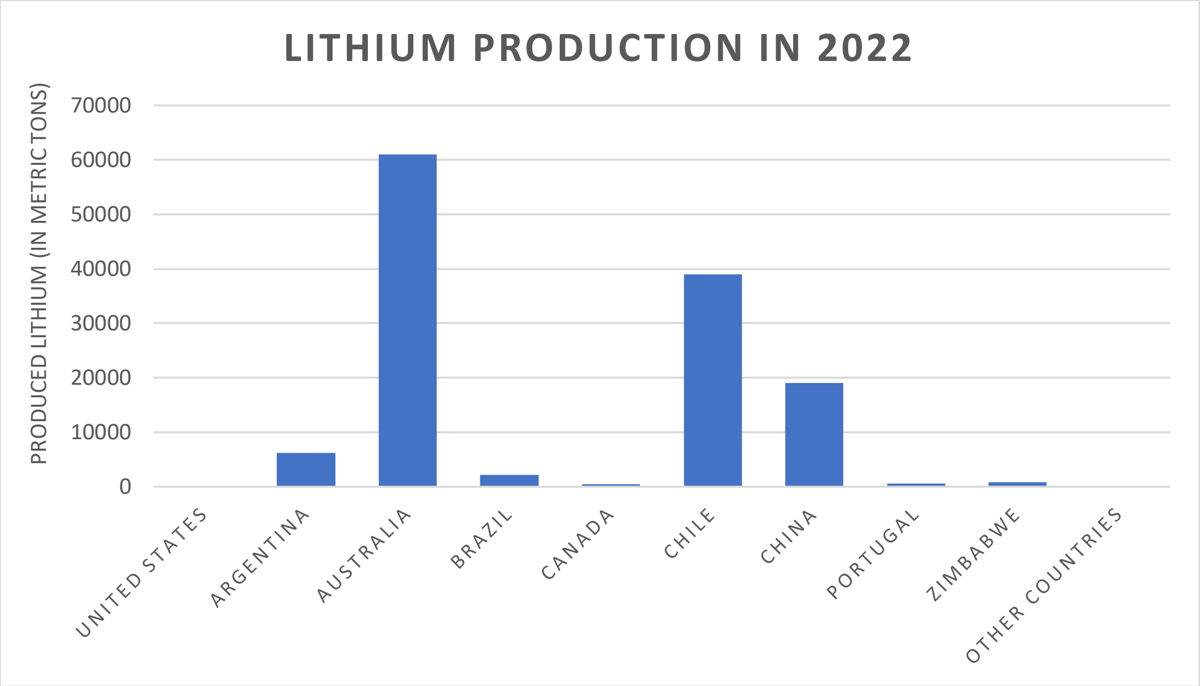
In the commercial sector, Eos Energy Storage has mirrored these academic insights. They initially sold their ZAB, designed for grid storage solutions, for \$160/kWh, but reduced the price to \$95/kWh for orders fulfilled in 2022 (Business Wire, 2017). In 2019, NantEnergy successfully installed ZABs for large-scale energy storage, establishing 3000 systems across nine nations, all at a production cost of just US\$100 per kWh (Leong et al., 2022). It's important to note that this is a grid storage solution, so the output, discharge, and ultimately cost might differ from an electric vehicle application. However, these figures do give a good indicator of how economically feasible ZABs can be.

Looking ahead, the potential of ZABs in electric vehicles is promising. Phil Black (2012) suggested that Eos' low-cost zinc battery technology could enable an electric vehicle with a range of over 350 km to be produced at the same cost as a gasoline-powered vehicle. These figures suggest a trajectory of continued cost reduction for ZABs, enhancing attractiveness for widespread application in electric vehicles.

Furthermore, the cost of zinc has remained stable, with the London Metal Exchange listing the price of zinc at 2456.00 in 2023. This stability, combined with the potential for ZABs to be manufactured at very low cost – less than \$10/kWh as estimated by Li and Dai (2014) – further underlines the economic viability of ZABs as a potential alternative to LIBs in electric vehicles.

2.5 Abundance of Materials

Zinc's inherent attributes make it an attractive resource for use in electric vehicle batteries. As the 23rd most abundant element in Earth's crust and the fourth most produced metal, zinc is widely accessible (USGS, 2022). In comparison to lithium, currently dominating the battery sector, it boasts 300 times greater reserves (Toussaint et al., 2010). This aspect makes zinc a highly promising power source for metal-air batteries. Furthermore, it supports a logical transition to zinc in battery technologies, not only from an economic perspective but also in terms of sustainability. In essence, the utilization of zinc guarantees an abundant and reliable supply, assuring its continued feasibility in the foreseeable future.



[5] *Graph 5: Lithium Production in 2022, measured in metric tons (taken from USGS, 2023)*

Graph 5 shows lithium production in 2022, sorted by countries. Australia produced the most lithium, 61.000 tons. Second is Chile, producing 39.000 tons. These two nations alone account for approximately 70% of the global lithium yield. China produced around 19.000 tons of lithium last year. The data vividly highlights the existing oligopoly within the lithium market, where a trifecta of nations dominates nearly 90% of the entire production, despite the widespread demand across developed nations. This unequal production landscape places import-relying countries at a disadvantage, while benefiting the very few supplying the market.

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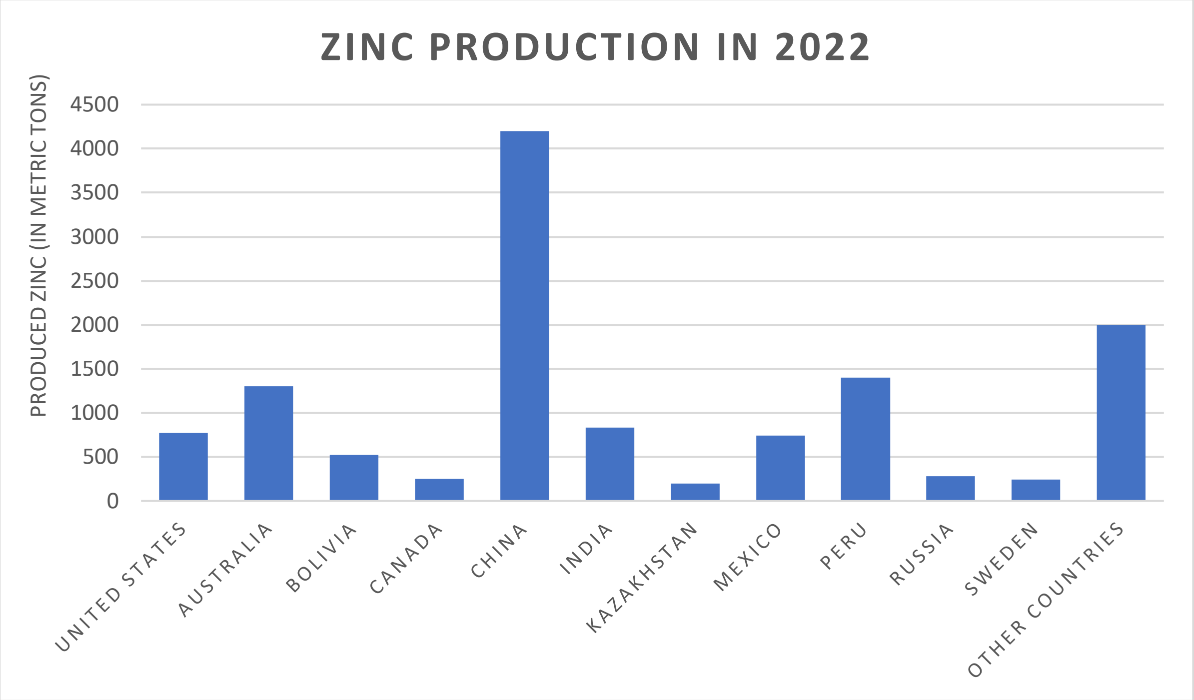
[5] *Data for United States has been with withheld to avoid disclosing company proprietary data; data for 'other countries' is not available*

It should be noted that the production value of the United States is not publicly disclosed, thereby the proportions might be slightly distorted. However, the crux of the production dilemma – the fact that a small number of countries dominate production – remains.

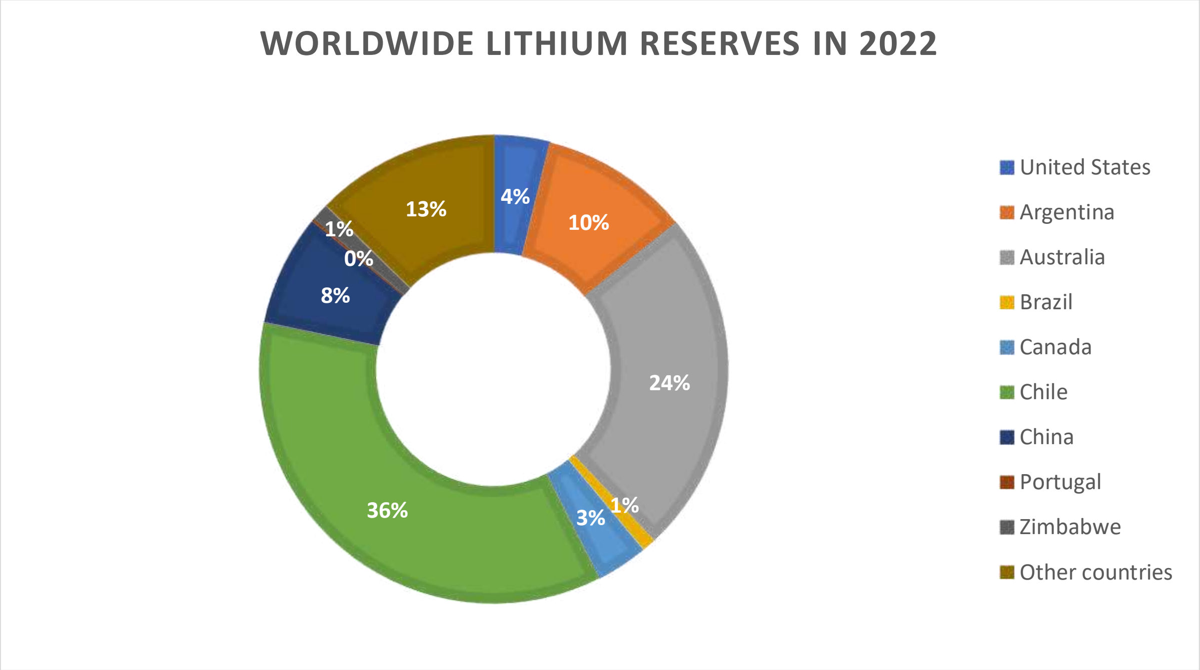


Graph 6: Zinc Production in 2022, measured in thousand metric tons (taken from USGS, 2023)

Graph 6 visualizes production of zinc in the year 2022. Immediately, the huge difference between China and the rest is noticeable. China produced around 4200 metric tons of zinc last year. The second closest individual country is Peru with close to 1500 metric tons. It is evident, that the majority of produced zinc originates from China. In contrast to lithium production, a much wider range of countries is producing zinc. Given this distribution, it's evident that there are not a handful of countries monopolizing the zinc market. This more diversified production suggests a potentially more stable supply chain, decreasing global reliance on a single nation and mitigating potential vulnerabilities in the zinc market.

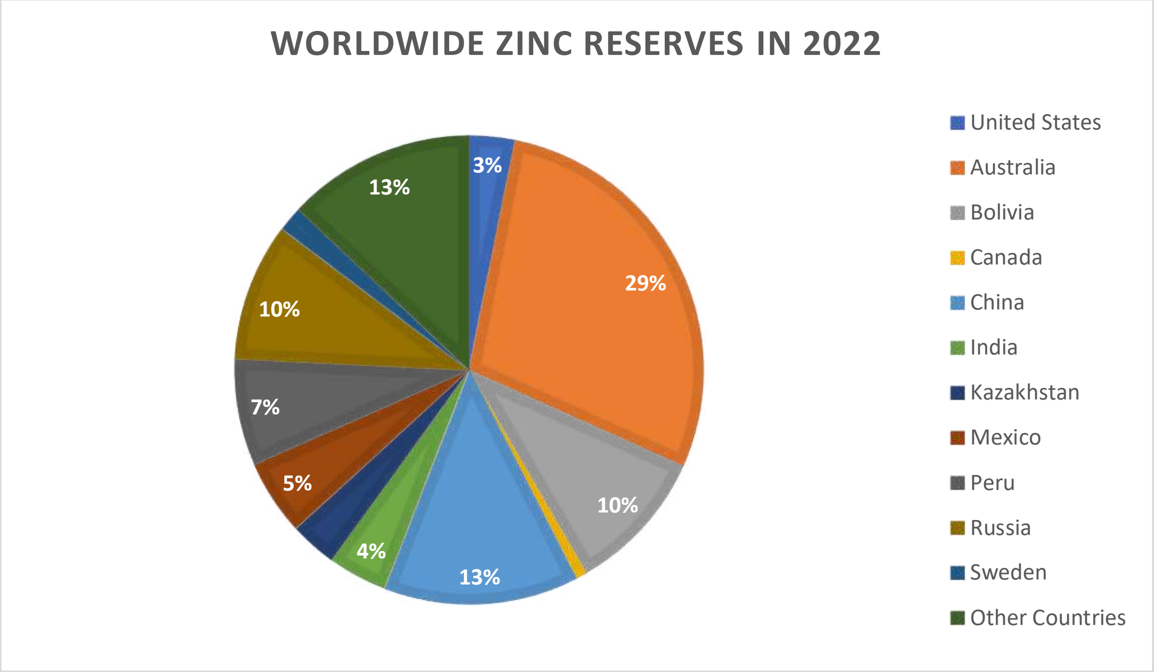
When discussing material resources and reserves, the distinction between the two must be explained. This paper will use the definitions of the U.S. Department of Interior (DOI). Resources are the material assets that are estimated to exist but are (in some cases) unidentified and hence, unextracted. Reserves are material assets that are identified and extractable, yet the magnitude of that inventory is limited by many considerations, including cost of drilling, taxes, price of the mineral commodity being mined, and the demand for it (DOI, 2023). The DOI (2023) quantifies worldwide lithium resources to be 98 million tons.

With terrestrial reserves estimated around 14 million tons and an even more expansive 230 million tons submerged in seawater, lithium appears plentiful at first glance. However, some sources disagree with these figures, as some estimates suggest that the actual reserves might range between 22 to 80 million tons – a disparity that underscores the uncertainty surrounding lithium's real abundance (Luong et al., 2022). The authors highlight projections that, given current consumption rates, lithium sourced from these documented reserves could potentially be depleted by 2080, as EV manufacturing continues its upward trajectory. Subsequently, while lithium remains indispensable in today's battery technologies, questions persist regarding its long-term viability as a primary resource. The DOI (2023) estimates reserves to be 26 million tons and breaks down the distribution amongst countries, as shown in Graph 7.



Graph 7: Worldwide Lithium Reserves in 2022, categorized by country

Chile has 36% of global lithium reserves, with Australia (24%) and Argentina (10%) placing second and third, respectively. Consequently, 70% of the world's lithium reserves are owned by only three countries. This, again, can have a considerable impact on pricing and supply dynamics in the future.



Graph 8: Worldwide Zinc Reserves in 2022, categorized by country

Graph 8 visualizes Australia's dominance when it comes to zinc reserves. Almost a third of global zinc reserves are within Australian territory. China, Bolivia and Peru make up the second 30%. The rest is divided amongst multiple other nations. Similar to lithium, zinc reserves are not equally divided amongst states, with only four countries accounting for almost 60% of zinc reserves. However, due to the fact that zinc exists in much greater abundance, supply shortages and consequent price hikes are significantly less likely.

2.6 Safety of Zinc-Air Batteries

In the pursuit of sustainable alternatives to conventional LIBs for electric vehicle applications, ZABs have emerged as a promising contender, in part due to their superior safety profile. LIBs, despite their widespread application, have been associated with high costs and potential safety issues, such as thermal instability and reactive oxygen discharge products, making them less desirable compared to ZABs (Mainar et al., 2018). Moreover, LIBs must be operated within a specific safe range that is influenced by charge rate, temperature, and voltage, with deviation from this range risking rapid performance degradation and safety issues (Chen et al., 2019). In contrast, ZABs, with the key component being zinc, a metal with low reactivity, present an environmentally safe alternative that can be handled safely even in oxygen and humid conditions.

The merits of ZABs include high theoretical capacity, low price, and intrinsic safety, which make them particularly appealing (Shang et al., 2022). The semi-open battery design and the use of a water electrolyte further strengthens their safety profile, which together give ZABs a distinct safety advantage over alternatives such as Lithium-Sulfur batteries and the more affordable but energy-dense lead-acid batteries (Meng et al., 2022; Toussaint et al., 2010). Unlike LIBs, which are prone to combustion, ZABs use water as an electrolyte, greatly enhancing their safety (Rohira, 2022). An exemplification of this safety focus is e-Zinc's system, which employs a non-flammable, water-based electrolyte, negating the risks of thermal runaway and fire (e-Zinc, n.d.).

Nonetheless, ZABs do have certain challenges to overcome. During the electrical recharging process, non-uniform local current densities can lead to the formation of zinc dendrites on the anode surface. These dendrites can break off, reducing battery capacity and potentially causing a short circuit if they make contact with the other electrode, leading to cell failure (Sherman, et al., 2018). Therefore, separators in rechargeable batteries must be designed to resist perforation by zinc dendrites to ensure safety and long-term reliability (Li & Dai, 2014).

In conclusion, while ZABs offer improved intrinsic safety over LIBs (Rohira, 2022), addressing technical challenges such as dendrite formation remains critical to fully harness their potential as a safe and efficient alternative for electric vehicle applications.

2.7 Environmental Impact of Zinc-Air Batteries

Zinc-air batteries have garnered significant attention for their exceptional environmental profile. Zinc, as a core component, offers advantages not only in cost but also in terms of environmental protection, primarily because of its superiority over lithium in conservation and recycling (Meng et al., 2022). Notably, the inherent nature of zinc-air batteries contributes to their "excellent environmental friendliness" (Zhong et al., 2023). This eco-friendliness is further accentuated by the absence of toxic or inflammable substances in these batteries, solidifying their status as both safe and environmentally benign energy storage systems (Toussaint et al., 2010; Mainar et al., 2018). Such sustainable attributes, combined with the recyclability of zinc, position ZABs as not only special within the metal-air category, but also as a remarkably viable technology for electrochemical energy storage (Frattini, 2022).

The surge in EV adoption, driven by the pressing concerns of climate change, positions LIBs at the forefront of efforts to transform the transportation industry into a 'green' sector. As standard EVs rely on LIBs for power, the environmental impact of these batteries becomes paramount. Despite a decade of mass production, there remains considerable debate in the literature about the true environmental footprint of LIBs. Duan et al. (2020) advocate for LIBs as storage devices, in part due to their "environmental friendliness". Chen et al. (2019) argue the same point in their paper. However, certain literature suggests that the sourcing and production process of lithium is not as clean as commonly believed. Table 3 exhibits the Co2 emissions of throughout the lifecycle of an EV (Mitsubishi-iMiEV) vs a petrol car (Ford Focus) (Luong et al., 2022).

Co2 Emissions (g/km)	**Mitsubishi-iMiEV**	**Ford Focus**
Raw material production	163.7	100.9
Manufacturing	34.1	37.3
Transportation	2.6	1.4
Operation	2.2	253
Decommissioning	0.194	0.012
Total	202.8	392.6

Table 3: A comparison of CO2 emissions from the manufacturing and operation of an EV versus a petrol car

Overall, a petrol car emits almost twice as many Co2 emissions over its lifetime as an EV. Disregarding operational aspects, an EV emits 200.6 g/km of Co2, as opposed to 139.6 g/km from a petrol car. It could be argued that only the overall level of emission counts – end of discussion. Yet, a more comprehensive approach would scrutinize emissions across all stages of the lifecycle, pinpointing where the bulk of emissions occur, in order to strategize effective reductions. This detailed analysis is crucial as it reveals the pressing issue of high emissions during the sourcing and production processes of LIBs. If alternative battery types, which emit considerably less Co2 during these initial stages, were to reach the technological prowess of LIBs, they would arguably present a more environmentally-sound option, aligning better with the sustainability objectives of electric mobility. Specifically, Zn/Air could "reduce the environmental impact of production between 4 and 9 times when compared with conventional LIBs and by recycling, up to 30% of production related environmental impact could potentially be avoided" (Santos et al., 2020).

2.8 Review of Key Concepts and Innovation

2.8.1 Technology Acceptance Model

The technology acceptance model (TAM) was introduced by Fred Davis in 1985 to predict consumer's usage of new technologies (Salloum et al., 2019). He introduced 'perceived usefulness' and 'perceived ease of use' as the predictors for usage levels (Masrom, 2007). Perceived usefulness refers to the degree of user's belief that using the technology will positively impact their performance; perceived ease of use refers to how effortlessly the user believes the usage to be. Marangunić & Granić (2014) found that perceived ease of use also has an effect on perceived usefulness. The TAM is illustrated by Figure 3.

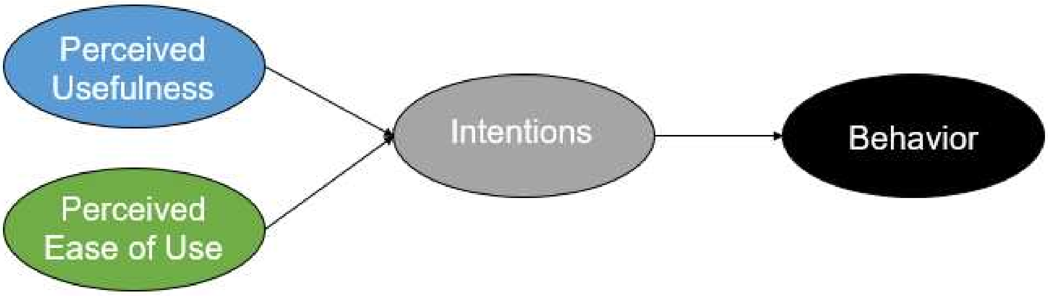


Figure 3: Technology Acceptance model as originally described by Davis, 1985 (figure taken from Worthington, 2021)

Perceived usefulness of ZABs can be numerous. As previously mentioned, ZABs exhibit multiple advantages compared to LIBs. For instance, ZABs thermal range is larger, meaning they can be operated in more extreme temperatures. This can be of great value to people living in regions, where climate reaches its extreme conditions. Moreover, safety issues are almost completely eradicated due to the chemical nature of the battery.

To define perceived use of ease for the consumer, battery usage can be divided into two categories: usage while driving, and usage while charging. Usage while driving bears no change compared to the usage of an LIB. The driving experience, which is subject to acceleration and responsiveness, amongst others, is equivalent to that of an LIB. The perceived use of easy when it comes to the charging process, depends on how exactly that process is going to look. The spent zinc anode has to be either mechanically replaced or electrochemically recharged. In case of mechanical replacement, ease of use for the customer could be negatively impacted, as he would have to procure a new anode – which need to be made available at appropriate stations – then swap out the anode and give the depleted anode back to the station, where it can be replenished with fresh zinc. Assessing this process' perceived ease of use for customers is challenging, but there are potential pain points that could diminish its attractiveness.

2.8.2 Diffusion of Innovation Theory

Rogers (1983) defines diffusion as the process by which "an innovation is communicated through certain channels over time among the members of a social system". Innovation is characterized by five attributes: Relative advantage, compatibility, complexity, trialability, observability, as shown by Table 4 (Oldenburg & Glanz, 2008).

Attribute	**Key Questions**
Relative Advantage	Is the innovation better than what was there before?
Compatibility	Does the innovation fit with the intended audience?
Complexity	Is the innovation easy to use?
Trialability	Can the innovation be tried before making a decision to adopt?
Observability	Are the results of the innovation visible?

Table 4: Attributes influencing the rate of diffusion of innovations (Rogers, 1983) (taken from Oldenburg & Glanz, 2008)

Amongst others, relative advantages can be economic, social and utilitarian (Oldenburg & Glanz, 2008). Zinc's cost is a fraction of lithium's, making ZABs cheaper than LIBs for companies and end-users. This has been proven by Hagman (2020), who found the total cost of ownership of BEVs to be competitive with ICEVs. It also provides a social edge over LIB, thanks to its greater abundance and less harmful mining process.

To assess compatibility, the preferences of the audience must be known. Consumer preferences are numerous and differ across demographics. In Germany, driving performance was the top factor to consider for 58% of potential buyers (Kantar, 2023). In Singapore, the price factor topped the list (52%). 36% of British potential buyers considered cost savings on fuel and maintenance as the primary factor to consider, while 49% of American potential buyers listed availability of charging stations as the leading consideration. Therefore, in order to successfully diffuse throughout society, ZABs must fully satisfy these considerations. Right now, they do not yet achieve the desired driving performance and range[6], and there are no charging stations available. It is not possible to make any determinations about and price or cost elements yet, because a commercial vehicle containing a ZAB is not for sale yet. However, due to the abundance of zinc, it could be argued, that ZAB-powered vehicles could be cheaper than LIBs in the long-term.

The complexity associated with adoption aligns with Davis' 'perceived ease of use' factor. The actual driving experience is likely to be close to identical for the end user, but the charging process could entail some pain points, depending on what the charging process is actually going to look like. It is common to be able to try a car before purchasing it, hence trialability is an easy aspect to satisfy. The end user can test both its driving performance as well as charging process to ensure he is comfortable with both. Observability refers to whether the results of the innovation are visible. These can be both directly experienced by the user, such as increased range or faster acceleration, or consumed passively through marketing efforts, such as environmental benefits of the vehicle. Besides the attributes, that determine the rate of diffusion of an innovation, the theory involves a model, that segments the market into two parts, as well as five types of customers. Figure 4 illustrates this model.

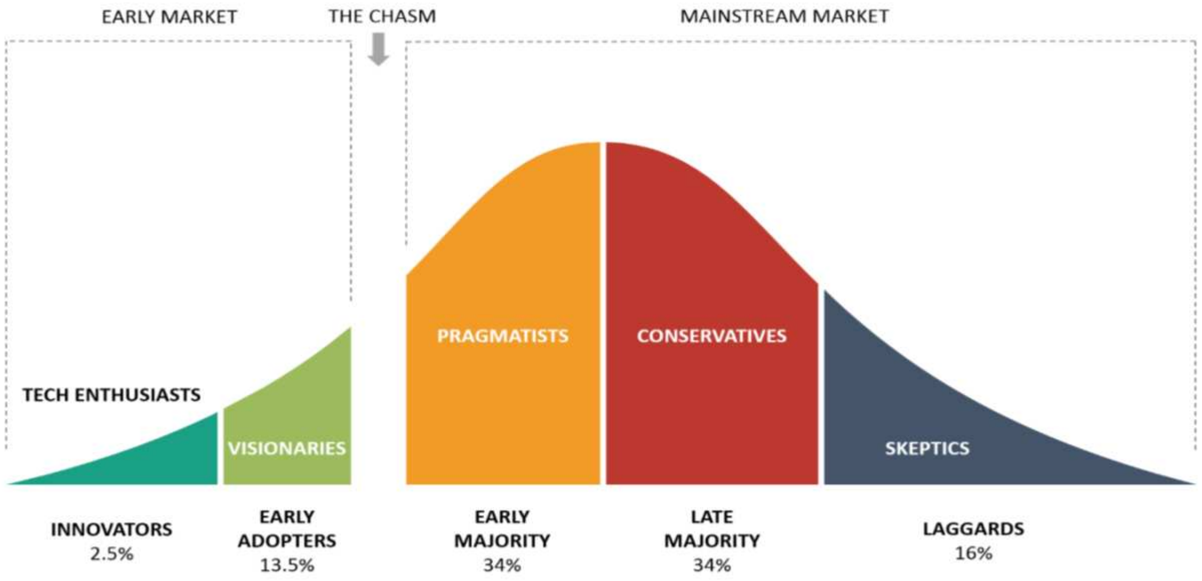


Figure 4: The innovation diffusion theory model with adopter classification by Rogers (1983) and the Chasm as defined by Moore (1999) (figure taken from Business2U)

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[6] Not in lab tests, but in a mass-market, commercial vehicle

The model is segmented into two markets, the early and mainstream market. Each market is inhabited by multiple types of consumers, as classified by Rogers (1983). Innovators are typically the first to use a new technology. They are the risk takers, willing to act on little information and experience (Wani & Ali, 2015). Early adopters are decisive in the further diffusion of the technology (Kaasinen, 2005). Their opinion carries a lot of weight within society, hence a positive assessment from this group is crucial. However, while Moore (1999) does not negate the importance of early adopters, he argues that preferences between the early and mainstream market customers are severe. According to him, technologies ‘must cross the chasm’ in order to successfully diffuse throughout the entire market. The early majority segment is driven by not wanting to be the last to adopt, but also having enough information to make an informed decision (Wani & Ali, 2015). Late majority users and laggards often come from poorer backgrounds and only buy when peer pressure is exerted (Rogers, 1995).

2.8.2 Dynamic Capabilities

Barreto (2010) defines a dynamic capability as the firm’s potential to systematically solve problems, formed by its propensity to sense opportunities and threats, to make timely and market-oriented decisions, and to change its resource base. To draw parallels between the dynamic capability theory and ZAB technology, this paper will reference three factors proposed by Wang et al. (2007), that commonly represent dynamic capabilities across firms: Adaptive capability, absorptive capability, and innovative capability.

A firm possessing adaptive capability can identify and capitalize emerging market opportunities (Hofer et al., 2015). Without it, firms struggle to adapt to changes in the environment and survive in the market (Vu, 2020). Car or battery manufacturers[7], who currently employ LIBs in their vehicle, need to be able to identify a superior battery technology early, in order to maintain a competitive advantage. The issues related sustainability, supply chain and cost of LIBs (Rajaeifar et al., 2022), will push manufactures to proactively adjust their sourcing and production processes, to ensure they can survive a shift in the industry.

Absorptive capability is recognizing the value of innovative, external information, combining them, and applying them to improve the business (Cohen & Levinthal (1990). Manufacturers can do this by enlisting the efforts of research centers and start-ups, who have specialized

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[7] Depending on if the car manufacturer produces batteries himself (like Tesla from 2023 onwards), or procures them from a specialized company

knowledge on future battery technologies, such as zinc-air. Being able to efficiently incorporate that knowledge into their own processes will determine, how competitive that firm will be in the future. Absorptive capability is paramount for success in the face of technological change (Wang et al., 2007).

Innovative capability is a firm's capacity to develop new products and/or markets, by complementing the strategic orientation with innovative processes (Wang et al., 2007). These include new product innovation and method of production, risk taking by executives, and novel solutions (Miller & Friesen, 1983). Betting on ZABs as the future battery technology would require all of these factors: ZAB on a commercial, mass-product scale would be a new product, the production processes need to be altered to accommodate for this change in technology. These efforts require enormous investments into R&D, production facilities and partnerships and are therefore high-risk. This shows the need for innovative capability within a firm.

3. Research Methodology

This section outlines the research methodology used in this thesis. By providing the research methodology, the researcher describes the steps he has undertaken, to arrive at a conclusion to his research question (Mishra & Alok, 2017). When done correctly, research is of vital significance. It leads to discovery and innovation, improves decision making, and aids in identifying trends (Gupta & Gupta, 2022).

3.1 Research Design

Complementing the literature review, primary data was collected through semi-structured expert interviews. These were split into two parts. The first was open-ended questions and in the second part experts were asked to rank 6 statements on a 1-5 Likert scale. This data collection complemented the literature review in section 2. Our triangulation approach endorsed by Turner et al. (2017) and Burton & Obel (2011), among others, describes combining a variety of sources and methods to better validate insights gathered.

3.2 Data Collection

The following paragraphs describe the methods used to gather the data discussed in Chapter 4.

3.2.1 Primary Data Collection – Expert Interviews, Part 1

Semi-structured interviews combine elements from standardized, largely open-ended surveys, and free form, open-ended sessions (Adams, 2015). This form of data collection is appropriate in a variety of conditions, including when asking in-depth, open-ended questions and seeking the independent thoughts of an expert (Adams, 2015). A different form of primary data collection, such as large-scale surveys, was not an option, if the scope of the research question was to be maintained. Due to the very specialized knowledge required to give valuable insights that help to answer the research question, the average person would not be good candidate due to the lack of knowledge.

The interview process followed the steps outlined by Dejonckheere & Vaughn (2019), as illustrated in Table 5.

Step	Task
1	Determining the purpose and scope of the study
2	Identifying participants
3	Considering ethical issues
4	Planning logistical aspects
5	Developing the interview guide
6	Establishing trust and rapport
7	Conducting the interview
8	Memoing and reflection
9	Analyzing the data
10	Demonstrating the trustworthiness of the research
11	Present findings in a paper or report

Table 5: Steps to designing and conducting semi-structured interviews (taken from DeJonckheere, M., & Vaughn, L. M., 2019)

This qualitative methodology does not require a large sample size as in-depth insights may be obtained by purposeful sampling (Dejonckheere & Vaughn, 2019). Interviewees were selected based on scope of work and experience, selected from various fields ranging from scientists working on battery composition in the lab to consultants who advise some of the world's biggest automotive companies. All interviews were conducted via Zoom or Microsoft Teams and were set for ~30 minutes and generally lasted around 45 minutes. The candidates, outlined below in Table 6 were carefully vetted to ensure suitability.

Code	Position	Company Type	Years of Experience	Country	Reason for interviewee selection
S1	Chief Scientist	A research institute for the study and development of electrochemical energy storage devices	~ 10	DE	Research focuses on LIBs and the exploration of other materials
S2	Scientist	A research institute for the study and development of electrochemical energy storage devices	~ 5	DE	Research focuses on enhancing the efficacy, durability, and affordability of batteries
S3	Scientist	A research institute for the study and development of electrochemical energy storage devices	~12	DE	Research focuses on modelling of innovative battery technologies
S4	Scientist	University	~20	Korea	Professor at the Department of Chemical Engineering
S5	Scientist	Research Center at University	~8	India	In collaboration with automobile manufacturers, him and his team develop ZABs for two- and three-wheelers
M1	Founder & CEO	Startup that has raised $8m+, including a $1.8m grant from the State of California	~ 20	USA	Is developing the next generation of safe, powerful and efficient batteries, specifically ZABs
M2	COO	Established company in the energy sector	~15	USA	Developed energy storage products using zinc-air technology and is now starting to venture into the transportation market
M3	CEO	Subsidiary of a large OEM in the battery sector	~25	USA	Used to develop ZABs for consumer electronics and after being acquired now R&D for mobility applications
M4	Business Advisor	Startup working on zinc-air batteries in cooperation with a university research team	~15	DE	Assists in the technical, but especially strategic and financial aspects of the company
M5	Head of research team	Clean-tech company, with more than 700 customers in 70 countries and annual revenue of ~$150 million	~10	ES	Responsible for the oversight of development of prototypes, tests and trials
C1	Consultant	International consultancy with per annum revenues of ~ 800€ million	~ 3	DE	Strong industry knowledge within the automobile sector
C2	Consultant	Consultancy boutique in the automobile industry, with around ~130 employees and annual revenue between 5-10 million euros	~7	DE	Specialized on the electric vehicles market with experience in working with OEMs, car manufacturers and start-ups

Table 6: Interviewees of the semi-structured expert interviews

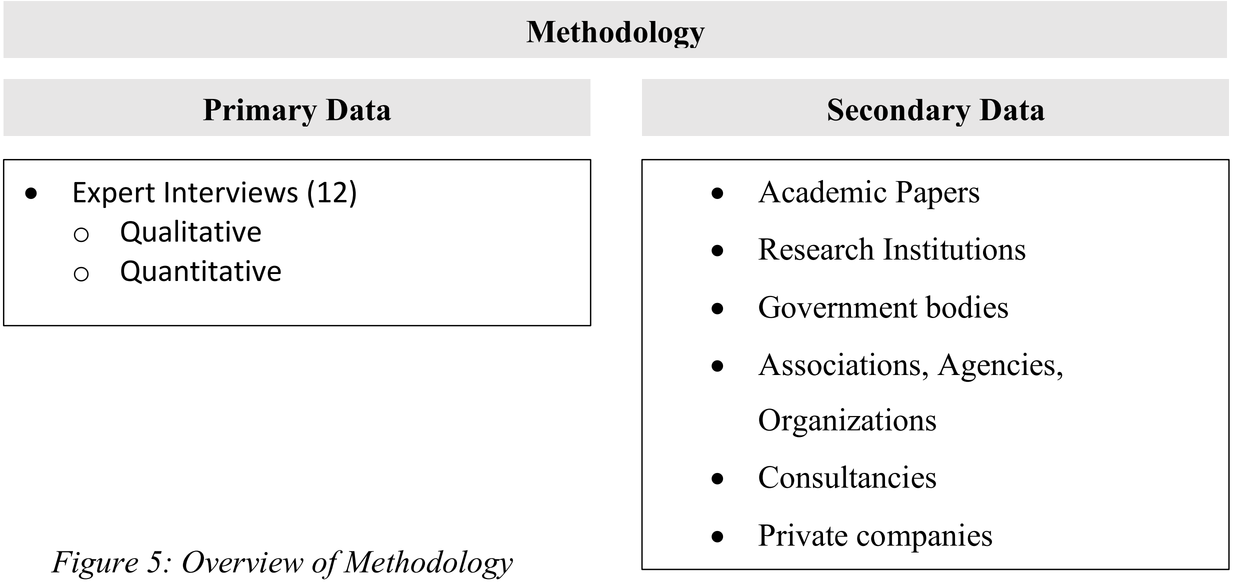
Results were analyzed using qualitative content analysis (QCA) (Fenzl & Mayring, 2010; Mayring, 2015) which categorizes responses (Grodal et al., 2020) and follows an inductive approach (Mayring, 2019). Categorization allows the researcher to extrapolate generalizable claims from data findings (Van Maanen, 1979). According to Corbin & Strauss (1990), the core of categorization is examining raw data, then developing larger groupings based on experts' mentions of similar ideas or thoughts, and finally clustering these into emerging categories that allow for theory building.

3.2.2 Primary Data Collection – Expert Interviews, Part 2

The second part of the interviews involved ranking statements on a Likert scale, ranging from 1 to 5 (Simms et al., 2019), with 1 meaning 'strongly disagree' and 5 'strongly agree'. The Likert scale method was chosen because it is easy to construct and yields reliable results (Taherdoost, 2019). Analysis of quantitative data thereby can be used to complement qualitative insights. While the qualitative part reflected the depth and breadth of experts' knowledge, the quantitative element indicated their specific stance on certain topics.

3.2.3 Secondary Data Collection

Secondary data was collected through academic articles and journals, publications of research institutes like Fraunhofer and government bodies such as the DOI, associations like the ACEA and IEA, consultancies like McKinsey & Company, as well as private companies and organizations.



Methodology

Primary Data

- Expert Interviews (12)
  - Qualitative
  - Quantitative

Secondary Data

- Academic Papers
- Research Institutions
- Government bodies
- Associations, Agencies, Organizations
- Consultancies
- Private companies

Figure 5: Overview of Methodology

4. Analysis & Findings

Expert interviews consisted of two parts. In part I, experts were asked open-ended questions in the form of a semi-structured interview, to gather qualitative insights. Part I will be analyzed in section 4.1. The data of the Likert scale segment in part II will be analyzed in section 4.2.

4.1 Expert Interviews – Part I

Interview insights were categorized into 4 different categories: technology of ZABs, supply chain issues of LIBs, timeline, and future outlook. Where appropriate, those domains consisted of subcategories, to ensure comprehensive coding of the insights.

4.1.1 Advantages, Disadvantages, and Applications of ZAB Technology

Zinc is more abundant (S1, S3, S4, M1, M2, M3, M5) and also more sustainable due to its non-toxic nature (S1, M2, M4). They are inherently safer than LIBs due to their chemical composition (S3, S4, S5, M2, M3, M4). This composition also enables zinc-air batteries perform better in a wider range of temperatures (S4, M1, M3). Finally, the metal is available at a fraction of the price and enables firms to cut costs (S5, M1, M4, M5). The purifying effect, that ZABs naturally have by releasing oxygen, was mentioned by S4.

ZAB Technology	S1	S2	S3	S4	S5	M1	M2	M3	M4	M5	C1	C2	Ratio
Advantages													
Abundance	X		X	X	X	X	X	X		X			**8/12**
Safety			X	X	X		X	X	X				**6/12**
Cost Savings					X	X			X	X			**4/12**
Greater temp. range				X		X		X					**3/12**
Sustainability	X						X		X				**3/12**
Purifying effect				X									**1/12**

Table 7: Insights on the advantages of ZAB Technology

ZABs exhibit low power density which could pose a barrier to commercialization (S2, S3, S5, M2, M3, M5). They suffer from chemical issues such as energy efficiency (S1, M1), sluggish kinetics (S4, M4) and zinc's irreversibility (S4). Their cyclability is subpar, compared to modern LIBs (S1, S2, M4). Rechargeability is still an issue (S1, S2, M2). During downtime, the ZAB must be air sealed to keep it from continuously discharging (M1). Air moisture also presents a problem for zinc-based batteries (M2).

Disadvantages													
Low Power Density		**X**	**X**		**X**		**X**	**X**		**X**			**6/12**
Cyclability	**X**	**X**							**X**				**3/12**
Rechargeability	**X**	**X**					**X**						**3/12**
Energy efficiency	**X**					**X**							**2/12**
Sluggish kinetics				**X**					**X**				**2/12**
Zinc's Irreversibility				**X**									**1/12**
Closing an open system						**X**							**1/12**
Air moisture						**X**							**1/12**

Table 8: Insights on the disadvantages of ZAB Technology

S4, M1, M4, M5 identified four-wheel vehicles as a suitable application for ZABs. M1 identifies long-range vehicles and trucks as the best choices, due to their continuous discharge profile. Two-wheelers (S5, M4, M5) and three-wheelers (S5, M5) also present ideal mobility applications for ZABs. Further applications include Planes and Drones (S4) and small utility vehicles (M4). ES2 specifically stated that ZABs are only suited for stationary storage applications.

Applications													
Four-wheel vehicles				**X**		**X**			**X**	**X**			**4/12**
Two-wheelers					**X**				**X**	**X**			**3/12**
Three-wheelers					**X**					**X**			**2/12**
Long-range cars						**X**							**1/12**
Planes				**X**									**1/12**
Drones				**X**									**1/12**
Trucks						**X**							**1/12**
Small Utility Vehicles									**X**				**1/12**
Stationary storage[8]		**X**											**1/12**

Table 9: Insights on the mentioned applications of ZAB Technology

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[8] This specific category ‘stationary storage’ refers to the claim, that ZABs can only be used within stationary applications such as power grids

4.1.2 Supply Chain Issues of LIBs

Sustainability of the lithium supply chain remains a pressing concern (S2, S4, S5, M2, M4, C1, C2). Its scarcity poses a problem amidst increased demand (S2, S3, S5, M2, M4, M5). Even though prices have substantially decreased, lithium extraction continues to be a significant price point in the supply chain (S5, M2, M4, C2).

Supply Chain Issues of LIBs	S1	S2	S3	S4	S5	M1	M2	M3	M4	M5	C1	C2	Ratio
Sustainability		X		X	X		X		X		X	X	**7/12**
Scarcity		X	X		X		X		X	X			**6/12**
Cost					X		X		X			X	**4/12**

Table 10: Supply chain issues of lithium-ion batteries

4.1.3 Estimated timeline until a prototype is ready and until commercialization of ZABs

Within the interviews, a prototype was defined as a battery that has completed lab testing and is ready for field testing. Estimates of a prototype varied from ~3 years (S5) to ~7 years (M2, M4). M1, M2 and M5 estimate a prototype in ~5 years. As seen in Table 11, only experts who were part of a start-up or company in the process of developing prototypes, could provide an estimated time horizon. S5 is part of a university research center that collaborates with a large OEM in the mobility industry and was therefore also working on a prototype.

Timeline	S1	S2	S3	S4	S5	M1	M2	M3	M4	M5	C1	C2	Ratio
ZAB Final Prototype													
In ~5 years						X		X		X			**3/12**
In ~7 years							X		X				**2/12**
In ~3 years					X								**1/12**

Table 11: Estimated timeline for a prototype of a zinc-air battery

Only experts directly working on zinc-air technology provided commercialization timeframes for ZABs. Others, who work on battery technologies not involving zinc-air, did not give an estimate. S5 and M4 propose ZAB technology to be commercial within 10-15 years. According to M1 and M2, zinc-air technology is viable in the next 5-10 years. S1 posited that ZABs will not be capable of powering EVs in the next 10-15 years. Generally, the closer an expert was to having a prototype ready, the sooner he expected commercialization of ZABs to follow.

Interestingly, M2 expected to have a working prototype in ~7 years, but commercialization in 5-10 years.

Commercial													
ZABs will be viable[9] in next 5-10 years					**X**				**X**				**2/12**
ZAB viable in 10-15 years						**X**	**X**						**2/12**
ZABs will not power EVs in the next 10-15y	**X**												**1/12**

Table 12: Estimated time until zinc-air batteries will be commercialized

4.1.4 Future Outlook

Almost all experts agreed that the future mobility market will be characterized by several battery technologies (S1, S2, S3, S5, M1, M2, M3, M4, M5, C1). For now, lithium will remain the dominant battery type, due to factors such as technological advancement and consumer acceptance. Several experts mentioned the emergence of solid-state batteries, due to their higher safety profile and faster charging capabilities (S4, M3, M5). S4 suggested zinc would be a temporary solution until even more efficient technologies such as hydrogen fuel cells are viable, while M5 suggested possible hybrid models between LIBs and ZABs. M2 was strongly convinced, that lithium-based batteries will become obsolete because of their toxicity.

Future Outlook	**S1**	**S2**	**S3**	**S4**	**S5**	**M1**	**M2**	**M3**	**M4**	**M5**	**C1**	**C2**	**Ratio**
Battery market													
Battery types will co-exist, adapted to specific categories	**X**	**X**	**X**		**X**	**X**	**X**	**X**	**X**	**X**	**X**		**10/12**
Lithium stays dominant	**X**	**X**	**X**		**X**	**X**		**X**	**X**	**X**	**X**	**X**	**10/12**
Sold-State Batteries			**X**					**X**		**X**			**3/12**
ZABs as a temporary or hybrid solution				**X**						**X**			**2/12**
LIBs will not play a role							**X**						**1/12**

Table 13: Expert predictions on the future battery market

The majority of experts agreed that a variety of batteries will segment the market. Specifically suggested were sodium-ion (S1), hydrogen fuel cells (S4), zinc-nickel (M1) and lithium-sulfur (M5).

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[9] 'Viable' is defined as 'from a technological and economic standpoint, ZABs can be used to power EVs'

Battery Types to emerge													
Sodium-Ion	**X**												**1/12**
Hydrogen Fuel Cells				**X**									**1/12**
Zinc-Nickel						**X**							**1/12**
Lithium-Sulfur										**X**			**1/12**

Table 14: Expert predictions on emerging battery types in the future

Consultants did not have chemical engineering knowledge nor specific knowledge about zinc-air batteries, hence, the interview covered more general topics such as EV market growth and possible barriers.

Political regulation can inhibit electric vehicle market growth (C1). Even though overall political ambition cannot be denied, European countries suffer from regulation that can inhibit that growth. These said regulations can include reduced incentives or bureaucratic hurdles in securing permits for factories or charging stations. C1 also viewed consumer acceptance as a possible barrier, possibly due to cost or supply chain issues. A charging network could alleviate that barrier, but if not, it can also impede further market growth (C2).

Barriers to EV market growth													
Political Regulation											**X**		**1/12**
Consumer Acceptance											**X**		**1/12**
Charging Infrastructure												**X**	**1/12**

Table 15: Expert predictions on potential barriers to future EV market growth

4.2 Expert Interviews – Part II

All 12 experts were asked to rank the same statements from 1 (strongly disagree) to 5 (strongly agree). The questions and answers from each expert can be found in Appendix 7.2. Following are the results of the Likert Scale questions, illustrated as charts. All statements were ranked by all experts.

4.2.1 Frequency Distribution of Likert Scale Responses

LQ1: This question aimed to explore, whether experts believed that ZABs could become a realistic alternative to LIBs within a given timeframe. Six experts disagreed, when asked whether ZABs could become a dominant[10] force in the EV market within the next decade. This

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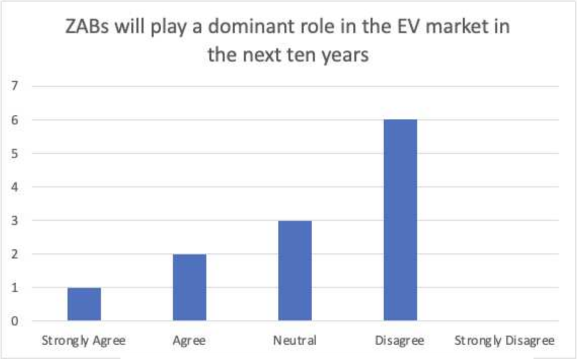
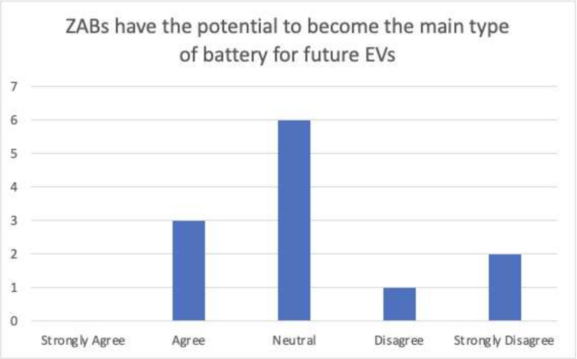
[10] 'Dominant' was defined as a technology capturing the majority market share i.e. being employed in the greatest number of vehicles in a calendar year

does not imply, that they doubt the potential of zinc-air technology; rather the timeframe is too short. Three experts were neutral, likely because they were not experts in the ZAB field. Finally, two agreed and two strongly agreed with the statement. They are likely nearing the development of a functional battery, that meets industry standards.

LQ2: This question explored the experts' assessment of the ZABs potential and whether it can be a realistic option in the future, irrespective of the timeframe. The majority of experts voted neutral. In part, this can be attributed to the unfamiliarity of a number of experts with this specific technology. The other reason is likely the uncertainty about technological hurdles that must be overcome. Three experts agreed with the statement, while one disagreed and two strongly disagreed.



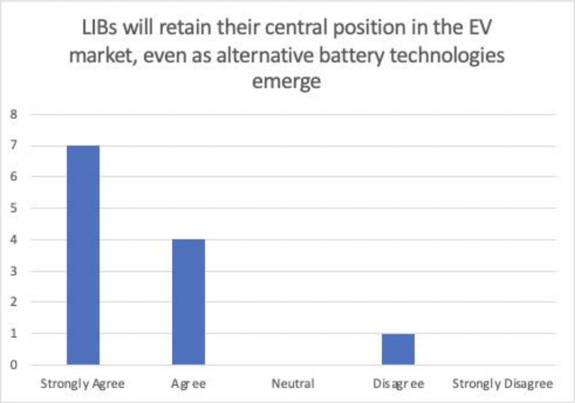
Graph 9: Likert Question 1



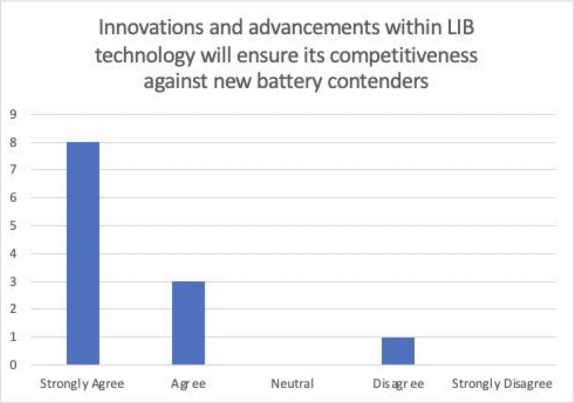
Graph 10: Likert Question 2

LQ3: This question sought to investigate the experts' opinion, on whether LIBs will continue to be the major battery type in the market, even as new technologies emerge. The statement did not refer to any specific rival technology. 11 of 12 experts strongly agreed or agreed. Only one expert disagreed. This is likely to be related to supply chain issues such as cost, scarcity, sustainability and toxicity.

LQ4: This question focused on R&D within LIB technology. It aimed to explore experts' opinions on whether LIB technology will continue to improve and therefore enable it to stay relevant. Eight experts strongly agreed and three experts agreed. Only one expert disagreed.



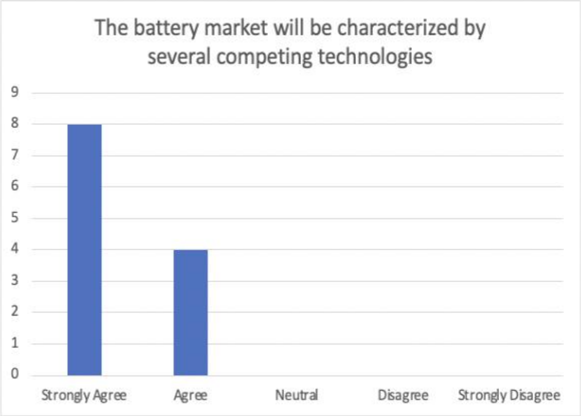
Graph 11: Likert Question 3



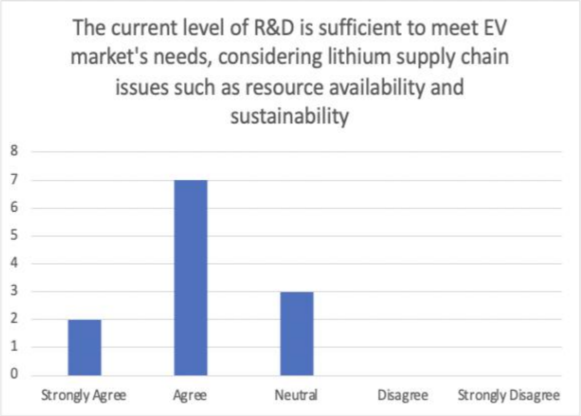
Graph 12: Likert Question 4

LQ5: This question aimed to find out, whether experts believed that multiple battery types could co-exist. Eight strongly agreed and 4 agreed.

LQ6: As discussed in sections 1 and 2, lithium and its supply chain suffer from serious problems, such as pollutive extraction, toxicity and scarcity. This question aimed to explore, whether the industry is on the right trajectory to ensure a sustainable future for the EV market and its batteries. Overall, the sentiment was positive. Two experts strongly agreed and seven agreed. Three experts chose neutral, but none disagreed or strongly disagreed.



Graph 13: Likert Question 5



Graph 14: Likert Question 6

4.2.2 Statistical Analysis of Likert Scale Responses

Statistical analysis of the Likert scale statements was conducted to find out whether the opinion of managers and scientists differed significantly. Likert scales are ordinal in nature, but can be treated as interval an interval scale (Wu & Leung, 2017). Two sample t-tests require interval data and are well suited to compare two independent groups (Keselman & Othman, 2004). Sullivan & Artino Jr. (2013) state that parametric tests, such as the two-sample t-test, can be used to analyze Likert scale responses. Certain assumptions must be met to reliably conduct the test (Rasch et al., 2011): 1) Observations should be independent 2) Data should be roughly normally distributed 3) The two samples should have about the same variance 4) Data was obtained using random sampling. All assumptions were met.

The experts were categorized distinctly: Five scientists, five managers, and 2 consultants. The following analysis compared the 'scientist' group with the 'managers' group. We conducted a number of statistical procedures to analyze the responses.

First, we calculated the mean response of each group. Mean data was relatively similar across all questions. The biggest discrepancies were for questions 2 and 4. Managers believed slightly more that ZABs had the potential to become the main type of battery for future EVs, with a mean of 3,4. Scientists were more confident that LIB will stay competitive thanks to innovations within that technology. The outlook on ZABs in the future was relatively neutral for both. Managers were slightly skewed towards the potential of ZABs to become the main type of battery for future EVs.

Next, we conducted the two-sample t-test. The results in all cases were not significant at any level. This leads us to the conclusion, that there was no significant difference in opinion between managers and scientists, concerning any of the statements that were asked.

Statement	Mean Response (Managers)	Mean Response (Scientists)	T-Statistic	P-Value
LQ1: ZABs will play a dominant role in the EV market in the next ten years	2.8	3	-0.29	0.77
LQ2: ZABs have the potential to become the main type of battery for future EVs	3.4	2.2	1.32	0.23
LQ3: LIBs will retain their central position in the EV market, even as alternative battery technologies emerge	4.2	4.6	-1	0.36
LQ4: Innovations and advancements within LIB technology will ensure its competitiveness against new battery contenders	3.8	4.8	-1.48	0.19

LQ5: The battery market will be characterized by several competing technologies	4.8	4.6	0.65	0.54
LQ6: The current level of R&D is sufficient to meet EV market's needs, considering lithium supply chain issues such as resource availability and sustainability	4	4	0	1

Table 16: Overview of statistical analysis of each Likert question between two expert groups

5. Discussion

Thus far, this paper compared LIBs and ZABs in a number of topics, by reviewing the scientific and academic literature. To complement this assessment, expert interviews were conducted to gain first-hand insights on the current state of ZABs as well as their future and the entire EV market altogether. This section will synthesize the findings from all three sources of input, the literature review, the qualitative interviews and the quantitative Likert scale responses, to answer the research question: “Are Zinc-Air batteries a realistic alternative to Lithium-Ion batteries in electric vehicles?”

5.1 Current & Short-Term Outlook (<1 year)

The current answer to this question is no. Unequivocally, every expert has refuted the idea that ZABs are ready for use in electric vehicles right now: “These factors suggest that ZABs are unlikely to be used in electric vehicles in the next 10-15 years” (S1); “no ZAB matches the standard of today’s LIB” (S3); “given the technical obstacles, it will be some time before we see them deployed in EVs” (M3).

Some technical challenges that ZAB face have been outlined in section 2, before being emphasized by experts. We discussed the issue of cycle degradation, which limits the battery’s life cycle. S3 and M4 both agreed that “unequal dendrite deposition can occur as part of the charging mechanism” (S3), which negatively impacts cycle life. Within this topic, we have discovered some interesting disagreements between the literature and the experts. Toussaint et al. (2010) suggested that battery pack replacements can be viable due to zinc’s low cost. Contrarily, S1 argues that “the difficulties in replacing the electrodes and the entire battery pack are significant, and we do not have a cost-efficient solution to this technical challenge”. The most important takeaway is that the theoretical knowledge appears to be present, but the practical implementation issues are not yet solved. This bodes well for the future. Furthermore, this discrepancy suggests inefficient knowledge sharing mechanisms within the industry. Research centers and universities should collaborate closer together with companies to advance applications such as ZABs.

5.2 Medium-Term Outlook (1-5 years)

Sherman et al. (2018) introduced a dual-battery system where a ZAB serves as a range extender for a LIB. They found that this configuration significantly increased the range and also reduced the overall lifetime cost of the battery. Echoing this, Expert S5 highlighted the potential of a "hybrid system between a LIB and ZAB" to "decrease the amount of lithium needed and increase their life cycles." This expert anticipates such hybrid systems to be market-ready within the next five years, marking it a promising avenue. This aligns with the mean expert response scores[11] of 4.2 and 4.6 to the statement "LIBs will retain their central position in the EV market, even as alternative battery technologies emerge," indicating a strong belief in the continued relevance of LIBs. However, the challenges associated with LIBs, especially sustainability, remain. Hybrid systems that merge lithium-ion and zinc-air technologies could address these challenges, enhancing sustainability, extending battery life, and reducing costs. Further validating this idea, experts almost exclusively strongly agreed, that the future battery market will accommodate multiple battery types. This statement had a mean response score of 4.8. The statement, though not explicitly about dual-battery systems, suggests the potential coexistence of different battery types.

Looking at pure ZAB solutions in four-wheelers, experts were largely pessimistic. However, S5 is working on a different target market: two- and three-wheelers. His team "wants to start mass producing and supplying vehicle manufacturers in the second half of 2025". By targeting the two- and three-wheeler market, S5 overcomes an often-mentioned problem of ZABs, namely low power density. S2, S3 and M3 were all in consensus, about zinc-air technology suffering from limited power density, which cannot match modern LIBs. S5 recognized this, stating "ZABs have a relatively low power system, at least when compared with today's LIBs. So we are targeting the two- and three-wheeler market, which is very popular here in India. These vehicles are smaller and lighter, thereby not requiring a power density as high as for four-wheel vehicles". This is evidence that, despite their current power density limitations for four-wheel vehicles, ZABs show promise for effective use in two- and three-wheelers in the

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[11] Of managers and scientists, respectively

near future. Considering Diffusion of Innovation Theory, introducing ZABs into the market at a smaller scale can be a good idea to test both performance and market acceptance. It is reasonable to assume, that users have fewer reservations about using a ZAB-powered scooter than a ZAB-powered car, given that they have not had any experience with the technology before. Innovators and early adopters can test the technology within smaller vehicle applications. If it's well perceived at this stage, this can serve to reduce resistance towards ZABs, when they are introduced to the mass market. This was echoed by C2, who argued that "any new battery model has to go through a similar cycle as LIBs once, but the inhibitions are likely not to be as severe, the barriers not as high".

5.3 Long-Term Outlook (5+ years)

The future of the battery market, according to the experts, appears as follows: Multiple battery types will exist in the market and be distinguished according to different vehicle applications[12]. This statement had response means for managers and scientists of 4.8 and 4.6, respectively. This signifies strong agreement amongst almost all experts. According to the experts, the LIB remains the dominant technology among the future multitude of batteries. Managers assessed LQ3 and LQ4 with 4.2 and 3.8, respectively. Scientists' mean responses for LQ3 and LQ4 were 4.6 and 4.8 respectively. Multiple experts raised concerns about the lithium supply chain, such as M2, who criticized lithium's toxicity and argues that "lithium has to go away". S4 recognizes that there are "enough lithium resources to satisfy the demand for the next few decades", but encourages the hunt for new materials and battery composition to start now, because it is a lengthy process until a battery is ready for commercialization. This is in line with Luong et al., who present evidence that lithium resources will be depleted by 2080. To combat this projection, new battery types must be introduced to slow down lithium usage.

S1, S2, S3 and M4 were all in agreement that ZABs are unlikely to become a commercial power source for EVs within the next 10 years, citing issues such as low power density or technological immaturity of ZABs as reasons. Scientists ranked the statement "ZABs will play a dominant role in the EV market in the next ten years" with a mean response of 3, while managers had a mean response score of 2.8. While both groups were relatively neutral, it is interesting that managers ranked lower than scientists. Three out of five managers have plans for a prototype. One could assume this would normally induce a sense of optimism. S5, M1,

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[12] E.g. Two-wheelers, Three-wheelers, Four-wheelers, Sports cars, SUVs, Utility Vehicles, etc.

M3 are all working on a prototype to be ready in 2, 5 and 8 years respectively. If those plans are successful, we could have a commercial product in less than 10 years. Moreover, some of the experts are not directly active in the field of zinc-air.

Based on the foregoing, we can state generally that as an innovative phenomenon, ZABs can be framed in light of strategic management theory discussed in the Literature Review. The trajectory of adoption is consonant with variables associated with the Technology Acceptance Model proposed by Davis (1985) and Rogers' (1983) Diffusion of Innovation Theory. In addition, we can view adoption of ZABs by certain firms for light vehicular use in terms of Teece's (1997) Dynamic Capabilities as amplified by Barreto (2010). These firms, responding to issues related to LIBs, are adapting to exogenous challenges by adopting ZABs as an innovative solution. However, as stated above, this does not represent a secular change for the automotive industry writ large.

6. Conclusion

Based on our research, findings, and analysis the immediate answer to the Research Question, "Are Zinc-Air batteries a realistic alternative to Lithium-Ion batteries in electric vehicles?" has to be 'no' due to current technical limitations. However, a number of arguments can be made that ZABs will, in fact, be a realistic alternative to LIBs in due course. On one hand, they have certain properties such as inherent safety or an abundance of material, that are extremely advantageous for an EV battery. Additionally, insights from both academic literature and experts suggest that there will be promising advances in overcoming current technical challenges.

6.1 Limitations

Language barriers can arise when interviewing experts from different countries and cultures. Despite rigorous translation, there is always the potential of translation losses, which might have an impact on the quality and accuracy of data obtained, as well as lead to misconceptions or misstatements.

A limited sample size limits statistical significance and generalizability of findings. There is a danger that the views of a small group will not be indicative of the broader expert community. This can result in skewed conclusions. However, it may also be argued that expert opinions allow for meaningful generalization because experts are knowledgeable in their fields and we can reasonably extrapolate from views expressed.

6.2 Future Research

This paper has uncovered discrepancies between academic literature and practical expertise, for instance the topic of swapping battery packs related to cost. Future research could delve more deeply into these discrepancies to reveal reasons for inconsistencies.

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7. Appendixes

7.1 Semi-structured Questions from Expert Interviews

7.1.1 Interview with Expert S1

Code: S1 | Date: 05.07.2023 | Duration: 30 minutes

What advantages do you think ZABs offer over LIBs?
ZABs could theoretically score points for their higher energy density and environmental friendliness, as zinc is an abundant and environmentally friendly material. However, we face a number of technical challenges that currently dwarf these advantages.

What current challenges do ZABs face that could hinder their mass adoption in electric vehicles (EVs)?
The difficulties in replacing the electrodes and the entire batteries in ZABs are significant and make their use in mass products impractical. It is a mechanical challenge to which we currently do not have a cost-efficient solution. In addition, the energy efficiency of ZABs is currently 60-80%, compared to 95% for LIBs. Also, the cyclability of LIBs is simply better than of ZABs. These factors mean that ZABs are unlikely to be used in electric vehicles in the next 10-15 years.

Have there been any significant recent breakthroughs in ZAB technology that could potentially overcome these challenges?
Here at this institute, we do not focus on the zinc-air technology, hence I cannot say that there have been any advances in the ZAB field from our side. I am not aware of any breakthroughs to date that could overcome these fundamental technical problems. I know that there have been improvements, but still not to the extent that zinc-air technology would be considered market-ready.

Considering the supply chain factor, how do you envision the future of the EV battery market? What role could ZABs play in this future?
Despite the fact that zinc is abundant and ZABs have some potential advantages, I expect LIBs to remain the dominant technology in the EV battery market due to their higher efficiency and proven performance for at least 10-15 years. Zinc availability is certainly a plus for ZABs, but it is not the decisive factor for mass adoption. Technical and economic aspects are more important.

Do you think there is another form of battery besides ZABs and LIBs that could eventually dominate the EV battery market?
I believe that it is entirely possible for different battery types to coexist, each adapted to specific requirements of different vehicle segments. Diversity can lead to a stronger, more adaptable industry.

For any new battery type, a number of changes would need to be considered to allow for a possible transition, including cost analysis, policy regulations and manufacturing scalability. Talking specific types, sodium-ion batteries could play a complementary role in the future of the EV battery market. They are rechargeable and already in use in some electric car prototypes. It remains to be seen how this technology will develop further and whether it can achieve a dominant position in the market. But based on my extensive experience in this field, I believe that LIBs will remain the dominant technology in electric cars for the next 10-15 years due to their high energy density and proven performance.

7.1.2 Interview with Expert S2

Code: S2 | Date: 06.07.2023 | Duration: 30 minutes

What advantages do you think ZABs offer over LIBs?
ZABs are predominantly important in applications where energy density rather than power density is the primary concern. Compared to LIBs, they are particularly useful in stationary storage due to their ability to store higher amounts of energy over a longer period of time.

What current challenges do ZABs face that could hinder their mass adoption in electric vehicles (EVs)?The low power density of ZABs, around 100 Wh/kg, is a key challenge hindering their application in electric vehicles. A battery pack of 300 kg would only deliver about 25 kW or 34 hp, resulting in suboptimal performance for a vehicle weight of 2 tons. Furthermore, the inactivation of the active material and the change in electrolyte properties is a technological obstacle. This is due to the fact that ZABs are open systems, which makes them difficult to control and maintain compared to closed systems such as LIBs.

Also there is the issue of cyclability, which I know current research is also focusing on. It should be possible to achieve several thousand charge cycles with acceptable capacity losses (<30%), which is currently not the case.

Have there been any significant recent breakthroughs in ZAB technology that could potentially overcome these challenges?
Future research should focus on improving the cycle stability of ZABs. This could be achieved by improving the electrolytes and separator materials as well as the design of the air electrode, on which the losses during charging and discharging strongly depend.

Considering the supply chain factor, how do you envision the future of the EV battery market? What role could ZABs play in this future?
ZABs could play a role in applications with higher energy density requirements, while their suitability for electric vehicles is still limited due to low power density. However, geopolitical factors could influence the search for alternative battery technologies, as the availability of lithium is limited. Especially additive materials like Cobalt are very concentrated. We cannot

expect LIBs to remain the only solution for energy storage. It is therefore necessary to explore and develop other options to ensure diversity and sustainability of energy storage technologies.

Do you think there is another form of battery besides ZABs and LIBs that could eventually dominate the EV battery market?
Battery technology is a field with numerous possibilities. Despite the dominance of LIBs and the potential of ZABs in certain applications, there is room for other technologies that could still be under exploration. Given the diversity of requirements and application areas, as well as differences in resource availability, it is very likely that different battery technologies will co-exist. Each battery type has its own strengths and weaknesses, and the selection of the appropriate battery technology will depend heavily on the specific application. Until all that is figured out, LIBs will surely remain the dominant technology for the 10 years or so.

7.1.3 Interview with Expert S3

Code: S3 | Date: 06.07.2023 | Duration: 25 minutes

What advantages do you think ZABs offer over LIBs?
There are a lot of aspects to consider when it comes to batteries and 'deciding' which one is best. Application, Cost, Density etc. In theory, ZABs have a very high theoretical energy density, but that alone does not translate well to EV application. Natural zinc resources are far greater than those of lithium as well as a whole lot cheaper. A great advantage is the safety aspect. ZABs are aqueous, meaning water-based. LIBs carry flammable solvents that can cause the battery to catch fire. This does not happen with water-based batteries like ZABs.

What current challenges do ZABs face that could hinder their mass adoption in electric vehicles (EVs)?
One of the main challenges are of course the technical issues. Like I said before, ZABs have high theoretical energy, but suffer from rather low power density, which is essential to power a conventional vehicle. Then there is the issue of dendrite formation which occurs when the charging mechanism allows for unequal dendrite deposition.

Have there been any significant recent breakthroughs in ZAB technology that could potentially overcome these challenges?
As far as I am aware, there has not yet been a ZAB developed that matches the standard of today's LIBs.

Considering the supply chain factor, how do you envision the future of the EV battery market? What role could ZABs play in this future?
Lithium and its battery-associated metal like cobalt are a rare commodity and therefore we will eventually have to find other battery compositions to rely on. So in theory, if ZABs should one day meet the technical standards required, it could become an industry-standard. But in the short to medium term (5-10 years), I believe that lithium-based battery's will continue to be the standard.

Do you think there is another form of battery besides ZABs and LIBs that could eventually dominate the EV battery market?
While I do think that multiple battery technologies will serve the market, it would be incredibly hard to pinpoint the specific ones at this stage. There are so many different battery compositions, each with their own advantages and disadvantages. Current LIBs are so called 'liquid-state batteries', but I believe that solid-state batteries are likely to play a major role in the future. Nio for instance has recently launched their EV with a solid-state battery. The biggest inhibitor in that regard is cost, but as technology develops and cost decreases, I do think that solid-state batteries are likely to dominate.

7.1.4 Interview with Expert S4

Code: S5 | Date: 07.07.2023 | Duration: 30 minutes

What advantages do you think ZABs offer over LIBs?
Because of their many advantages, ZABs are among the most promising next-generation battery technologies. They feature a high level of flexibility and safety. Furthermore, zinc is plentiful and has little environmental impact.

The purifying effect of ZABs is one of its most significant advantages. Because ZABs operate as a half-open structure, similar to hydrogen fuel cells, oxygen circulation from the air is necessary for charging and discharging. Because fuel cells simply have a discharge mechanism, the air may be cleansed by an air filter, which is referred to as passive technology. However, in addition to their passive function, zinc-air cells may exhale pure oxygen into the atmosphere by dissolving zinc oxides during the charging process. This is referred to as active air purification technology. In a one ampere hour scale battery, the purified air amount is generally one liter per hour.

What current challenges do ZABs face that could hinder their mass adoption in electric vehicles (EVs)?
Previous zinc batteries that used liquid electrolytes all failed because of sluggish kinetics for the oxygen reaction and reduction, as well as zinc's irreversibility.

Have there been any significant recent breakthroughs in ZAB technology that could potentially overcome these challenges?
The issues I mentioned earlier, such as the slow kinetics and irreversibility of zinc, prompted us to design solid-state electrolytes such as functionalized biocellulars that can efficiently transport hydroxyl ions without parasitic reactions. Then, as an ion exchange solid-state electrolyte, we developed a chitosan via battery cellulosic, named CBC. These materials are primarily composed of bio cellulose and chitosan, which have been cross-linked via quaternary connections. This dramatically increased the anti-freezing properties of the battery. Water is transported inside the CBCs, but in a molecular rather than liquid form. This is a significant

distinction from typical zinc-air batteries that use liquid electrolyte. As a result, even at freezing temperatures like -20 degrees Celsius, our all-solid-state batteries could retain excellent battery performance and stability. As a consequence, we developed a commercially feasible one-hour ampere scale flexible plastic pouch cell. These pouch cells provide a driving range of 800-900 miles per charge and may be fully recharged in 15 minutes.

Considering the supply chain factor, how do you envision the future of the EV battery market? What role could ZABs play in this future?
We have enough lithium resources to satisfy the demand for the next few decades, but research for materials to be used must start now, because the process is a long one. Depending on adoption rates of LIB-based vehicles and how the discussion around lithium mining will turn out, we will eventually be dependent on another resource to power our cars. We are currently simplifying and scaling up the method for the air cathode and solid electrolyte for the process of production and scaling up. Our cells potentially power drones, electric cars, and airplanes.

Do you think there is another form of battery besides ZABs and LIBs that could eventually dominate the EV battery market?
So I have briefly mentioned hydrogen fuel cells before already. It is critical to recognize that the only significant difference between these systems is the anode. A hydrogen fuel cell's anode is just hydrogen, which is not recyclable, but a zinc-air battery is. Because these two technologies are so close, I see zinc-air batteries acting as a bridge between lithium-ion batteries and hydrogen fuel cells.

7.1.5 Interview with Expert S5

Code: S5 | Date: 10.07.2023 | Duration: 45 minutes

What advantages do you think ZABs offer over LIBs?
We are competing with one of the most mature technologies in the world, which is the LIB. A major advantage of ZABs is the cost factor. The production cost is one-third of the production cost of lithium-ion. When that cost further decreases as the processes mature, I expect it to be literally dirt cheap.

Also, these batteries are incredibly safe because we use a water-based electrolyte inside.

What current challenges do ZABs face that could hinder their mass adoption in electric vehicles (EVs)?
Like I said, we use water-based electrolytes inside, which makes the battery incredibly safe. The downside of this is that it is a relatively low power system, at least when compared with today’s LIBs. So we are targeting the two-wheeler and three-wheeler market, which is very popular here in India. The power density doesn’t need to be as high, because scooters or rickshaw is lighter. I think two-wheelers alone make up between 70-80% of vehicles in our country. Our batteries have an energy capacity of 1.3 kw/h and can go up to 2.6 kw/h, which is a great number for these types of vehicles.

Apart from that, we are not facing fundamental issues, but we are working on adapting the batteries to the mobility environment – and this is a two-fold problem. Firstly, our stationary packs and the mobility packs have different drive profiles. The stationary packs have a steady output of energy, while mobility packs must be able to release energy at different rates. That brings me to the second challenge, which is the difference between lab testing and reality. Realistic conditions are very varied. So first we conducted standard charge/discharge experiments. Once those basic requirements were satisfied, we then subjected them to the realistic drive profiles. Here, it's not only about the charge/discharge rate, but about temperature and humidity for example. Once those tests are passed, the packs can go into field testing. We have had batteries fail, but we use those results to improve the battery constantly.

What is the timeline for ZABs and their mainstream application in electric vehicles?
We have the material, the equipment and even the battery. To do all the necessary reliability tests, will take around two years. We want to start mass manufacturing and supplying the vehicle manufacturers in the second half of 2025.

Considering the supply chain factor, how do you envision the future of the EV battery market? What role could ZABs play in this future?
Resource availability plays a huge role of course. India is famous for its zinc and is one of the largest zinc manufacturers in the world, so we have the material right here 'in front of our doorstep'. A few months ago, a large lithium reserve was discovered in the north of India. This gives India resources to be competitive within the next decade, but thinking beyond that, we have to be able to source sustainability at a competitive price. We can do that much better with zinc than lithium.

Do you think there is another form of battery besides ZABs and LIBs that could eventually dominate the EV battery market?
During my time in this field, I have worked on a number of potential solutions, including aluminum air, lithium sulfur, sodium ion, and now zinc-air. For our target market, so two- and three-wheelers, I think zinc-air batteries are the best solution. But it is very hard to make them compatible for a four-wheel electric vehicle. The properties would be great, the safety profile, resources, but the energy profile needs to be increased. Until that happens, I think lithium-ion batteries will be used in electric vehicles of that size, and for the foreseeable future (-2030) also throughout the entire mobility market.

7.1.6 Interview with Expert M1

Code: M1 | Date: 10.07.2023 | Duration: 60 minutes

What advantages do ZABs offer over LIBs?
Firstly, an important measure of battery power is specific energy, which is output relative to weight. Usually, like LIBs, batteries have a metal anode and a metal cathode. In ZABs however, the anode is air, thereby reducing weight by 2 or doubling specific energy. We achieve a specific energy of 300-400 Wh/kg for our ZABs.

Secondly, the materials used for ZABs are much cheaper. LIBs use a lot of Nickel, which currently costs around $20k per metric ton. For zinc, this price is around $2k.

Thirdly, ZABs' operating range is within a much wider range of temperature without requiring a thermal management system. This eliminates both cost and weight.

- LIB: Store: - 20 to 55 ; Operate: 0 – 45-55
- ZAB: Store: - 30 – 60-70 ; Operate: -20 – 55-60

This is important when thinking about application in different regions of the world. These batteries must be reliable in all kinds of weather or conditions.

What are the current challenges that ZABs face, which could hinder their mass adoption in electric vehicles?

ZABs run when exposed to air. When the car stops, the battery keeps on discharging because the battery is still exposed to air. To overcome this problem, a system is needed that shuts of the air supply and isolates the battery. This would ensure no more discharge. This is a problem especially when short distances are the norm. Imagine you get in your car, drive 20 minutes to university, stay there the entire day only to come back and find your battery empty, because this whole time it was continuing to discharge. Therefore, ZABs might be better suited for long-range vehicles such as trucks (when the usual drive is 5-7 hours, the battery is empty anyway, you charge and then continue your drive).

A second problem is air moisture. You don't want moisture from the air to react with the battery, as this would create a zinc-paste that would clog up the battery.

Scientist from another interview said: "The energy efficiency of ZABs is currently 60-80%, compared to 95% for LIBs. Also, the cyclability of LIBs is simply better than of ZABs. These factors mean that ZABs are unlikely to be used in electric vehicles in the next 10-15 years".

The researcher refers to roundtrip efficiency, which is how much energy you get out in relation to how much energy you put in. The LIB has an efficiency of ~92%. ZAB efficiency is indeed not as good as LIBs, but still we achieve an efficiency rate of 78-88% due to a very efficient zinc anode.

When it comes to cyclability, the Lithium-Ion-Phosphate battery (which is the technologically currently most advanced version; used by Tesla for instance) claimed to get up to 10000 cycles. However, this is due to very low Depth of Discharge. In a realistic setting, with around 60-80% discharge, the battery can achieve around 4000 cycles. To emphasize the importance of recognizing DoD – we simulated a ZAB in a BMW and got up to 54,000 cycles, however at only 5% DoD. At full depth of discharge, the battery can reach around 1000 cycles.

What is the timeline for ZABs and their mainstream application in electric vehicles?

From our current standpoint, we are confident to have a pre-production prototype ready in 5-7 years. This PPP will be tested in cooperation with automobile manufacturers, run through rigorous analysis and safety protocols. Usually between having a pre-production prototype and having a product that is ready to be mass produced and used, another 5 years usually pass.

Considering the availability of lithium and zinc, how do you envision the future of the EV battery market? What role could ZABs play in this future?
Zinc is the 4th most mined metal in the world. It's abundance is one of its great benefits. Specifically, Zinc batteries, and not just ZABs but also Zinc-Nickel batteries for instance, I see a mix of batteries on the market in the future. Zinc-Nickel batteries are great for urban electric vehicles (less than 300km), while ZABs should be used for long-range electric vehicles.

It is important to consider timelines here. Within the next 10 years, I don't think ZABs will play a major role, simply because technological breakthroughs concerning ZABs are just starting to happen. But looking at the decade 2030-2040, ZABs do have the potential to become a reliable source of propulsion.

Regarding LIBs, I believe they will hit a plateau. They'll be good enough to further be the reliable standard motor, but leave enough room for other battery types to come along and partake.

Do you think there is another form of battery besides ZABs and LIBs that could eventually dominate the EV battery market?
I think an interplay of different batteries, depending on what's needed, will be the future of the EV market. I personally believe Lithium will play the greatest role in the foreseeable future (5-15 years), simply because of its properties, the momentum of the technology and its current market position.

7.1.7 Interview with Expert M2

Code: M2 | Date: 13.07.2023 | Duration: 25 minutes

What advantages do ZABs offer over LIBs?
Lithium is hazardous, may cause fires or explosions, and requires cobalt. Zinc, on the other hand, is non-toxic and relies only on natural and technological components.

What are the current challenges that ZABs face, which could hinder their mass adoption in electric vehicles?
Right now, our product line includes only zinc-air batteries for stationary applications. That has been our market for about five years, but we are starting to venture into the transportation market. There is this conundrum of sprint vs marathon. What I mean by that is, our units can last 72 hours, are sufficiently powered for almost seven days. But we also need to get sufficient energy release, so quick release vs steady release. This is something we are working on currently.

What is the timeline for ZABs and their mainstream application in electric vehicles?
Our problem right now is the rechargeability aspect. ZABs are already well established in consumer electronics, but are not rechargeable. So we have figured out, how to efficiently recharge the battery, but the size is too big to be viable for an electric vehicle. So that is a step we have to master, in order to give ZABs a realistic chance in the electric vehicle market. It is hard to put a time estimate on it, but I can say that that is still a while away, at least 8-10 years.

Considering the supply chain factor, how do you envision the future of the EV battery market? What role could ZABs play in this future?
Lithium has to go away. The toxicity of lithium is really cobalt. 80% of it is from the Congo. A car used to require about 18 pounds of cobalt per car, so it was a placeholder. Or better said, it is a placeholder.

So in the interim I think it's going to be a hybrid system in which you need a combination of lithium and zinc, but the goal for us is to get lithium to go away and completely have hydrocarbon free, rare or scarce metal free, toxic metals gone.

Do you think there is another form of battery besides ZABs and LIBs that could eventually dominate the EV battery market?
There definitely are people more qualified to speak on that, and of course there will be many different opinions. So as a general statement, I do think that car manufacturers will have multiple options to choose from, depending on what kind of car they want to put on the market.

7.1.8 Interview with Expert M3

Code: M3 | Date: 14.07.2023 | Duration: 20 minutes

What advantages do ZABs offer over LIBs?
There is a key distinction in the nature of the battery between zinc and lithium-ion systems, with zinc batteries having much higher availability of the initial resource, much higher operability, a wider temperature range, a greater safety factor, and minimal risk of a thermal runway.

What are the current challenges that ZABs face, which could hinder their mass adoption in electric vehicles?
The main argument against ZABs as a power source for electric vehicles is the power density, which ZABs cannot yet match. Electric vehicles are very sensitive when it comes to weight. So if you can only deliver sufficient power density by using a huge battery, that is not going to work for an electric car.

What is the timeline for ZABs and their mainstream application in electric vehicles?
Currently we are working on securing funding to intensify R&D efforts. We have a timeline for a ready-to-test prototype for 2026. We want to test the prototype in a re-modelled Peugeot

e-208. Refining the prototype and getting it ready for market usually takes about 12-18 months. We also have to think about manufacturing the battery on a large scale. Facilities cost time and money, so that will also be another hurdle to overcome.

Considering the supply chain factor, how do you envision the future of the EV battery market? What role could ZABs play in this future?
I have been working in this industry for about 25 years, and there has always been a mix of new technologies to be applied to specific use cases. As the market matures and technology develops, we will see an influx of new technologies that can cater to the most specific segments.

Given the advantages of ZABs, I am confident that they will have a significant impact in the industry, but given the technical obstacles, I don't think they are going to be a motor of choice in this decade. For the foreseeable future, I am certain the LIBs will continue to power the majority of EVs.

Do you think there is another form of battery besides ZABs and LIBs that could eventually dominate the EV battery market?
Battery architecture, in theory, is almost limitless. It is hard to imagine one or two single battery types to fill every niche there is, small passenger cars, SUVs, Utility vehicles, all with different requirements. Ford and BMW are testing solid-state batteries, so that is likely to be a promising route.

7.1.9 Interview with Expert M4

Code: M4 | Date: 14.07.2023 | Duration: 30 minutes

What advantages do ZABs offer over LIBs?
They are ecologically friendly, which supports the worldwide movement toward green and sustainable technology. Second, ZABs are renowned for their strong safety profile, which lowers the dangers connected with explosions or battery failures. Finally, ZABs are inexpensive, mostly because there is a lot more zinc than lithium in the world.

What are the current challenges that ZABs face, which could hinder their mass adoption in electric vehicles?
For a long time, the problem of ZABs has been that they faced issues of chemical instability, causing sluggish kinetics. This is because of the alkaline electrolytes that caused a so-called parasitic reaction, that then leads to irreparable electrochemical damage. In collaboration with a research team from university research center, we have developed a new battery chemistry using a non-alkaline, aqueous electrolyte. Running on this, our battery can now do 320 cycles and 1,600 hours. It is not quite yet at the standard it has to be in order to be employed in electric cars, but this is a huge step towards our goal.

What is the timeline for ZABs and their mainstream application in electric vehicles?

That is a tough question. LIBs are so established right now and I don't see ZABs – or any other type of battery for that matter – competing for the number one spot in that regard right now. Our plan is to have a working prototype by 2030 that can satisfy standard requirements, so things like cycles, energy density etc. If we were to have a battery installed in a production car before 2033, I'd be very happy! But more realistically, we are approaching 2035.

Considering the availability of lithium and zinc, how do you envisage the future of the EV battery market? What role could ZABs play in this future?
The reason companies are even looking to rival LIBs is because lithium is not limitless, it's dirty and it's expensive. Zinc is about 20x more abundant and it's very cheap – around 3-4x cheaper than lithium. So, from a natural resource point of view, zinc makes a lot more sense than lithium. If we can overcome the technical challenges and rival LIBs in that matter, then I think ZABs are a great alternative!

Do you think there is another form of battery besides ZABs and LIBs that could eventually dominate the EV battery market?
Definitely. There are so many different applications within the transportation market. Scooters, three-wheelers, passenger cars, utility vehicles, even methods like trains and planes and ships. ZABs are not going to be an option for all of these, but realistically, I think everything from two-wheelers to passenger cars, as well as small utility vehicles like forklifts for example are a great market. But it's going to be a very interesting battle to see what batteries will eventually power what vehicles. LIBs are definitely going to be the standard for at least another 8-10 years, I think.

7.1.10 Interview with Expert M5

Code: M5| Date: 19.07.2023 | Duration: 30 minutes

What advantages do ZABs offer over LIBs?
ZABs are part of the metal-air family. These are suitable for both mobile purposes (two- three- and four-wheel) and stationary uses because of their high energy density. The irons that we use and the cell design and the specific chemistry of the battery decides what kind of application we can use the battery for. We work mainly with sodium and with zinc. Zinc is good because it is cheap, and naturally occurs a lot. Also, it has great energy density which is a basic requirement if you want to create a battery for the EV market.

What are the current challenges that ZABs face, which could hinder their mass adoption in electric vehicles?
We are continuing working on electrolytes at the lab size right now since having a stable electrolyte is crucial for having high performance. In order to prevent all the drawbacks of liquid electrolytes, such as water evaporation, we are also switching to solid electrolytes. Therefore, developing solid electrolytes and designing the cathode are now our two key responsibilities. We need an open structure because the cathode, which is the oxygen in these

batteries, has to get into the battery to force chemical reactions and thereby produce electrical current. This will be our goals for the next years.

What is the timeline for ZABs and their mainstream application in electric vehicles?
The tasks I have just talked about are what we are working on currently and will be for a few more years. We estimate that we have a first prototype in 2026 and a final prototype by 2028. Then we need to establish a manufacturing process and scale the production.

Considering the availability of lithium and zinc, how do you envision the future of the EV battery market? What role could ZABs play in this future?
The way that the market currently works, so only relying on lithium along with the other needed materials like cobalt, is not sustainable. There will be changes to this industry. I can imagine that hybrid systems between different types of batteries are the first to arrive, before completely new battery systems will be able to sufficiently power electric vehicles. So, for example, imagine a hybrid power system between a LIB and ZAB. It would decrease the amount of lithium needed as well as increase their life cycles. Due to the complementing nature of the ZAB module in this scenario, the technical requirements are not as demanding, so it can potentially be a solution we see in the market before we see ZABs on their own. This is not what we are specifically working on. But I would deem it as realistic to see these hybrid systems in the market within the next few years (~5 years)

Do you think there is another form of battery besides ZABs and LIBs that could eventually dominate the EV battery market?
Current technology is based on liquid electrolyte chemistry. But within the next few years, solid-state batteries will replace them. The liquid electrolytes are flammable, so a solid structure is much safer. Also, the charging process is faster because they hold more energy. So, I would say that is the industry's main priority, the development of solid-state batteries. Lithium-Sulphur batteries can be well suited for this, and then of course water-based zinc-air batteries. By now there are many companies and research teams exploring other options, new materials to make better batteries, so I think over the next 5-10 years we will see many different options, but all of them along Lithium. I don't see a 'short-term' future without lithium batteries.

7.1.11 Interview with Expert C1

Code: C1 | Date: 24.07.2023 | Duration: 35 minutes

From a market perspective, do you see the shift from LIBs to another type of battery technology on the horizon?
Horizon is a relative term. If we are talking within the next 5 years. Definitely no. Within the next 10, pretty unlikely. But further down the line, I do think that the market will have to accommodate multiple types of electric batteries. That is because right now, the focus of most companies is to supply the passenger car market, so the average car that you and your next-door neighbor own. The needs of the average consumer are relatively homogenous. But as

research develops, it is likely that batteries will appear that are better suited for different needs – short vs long range, speed, fast charging vs overnight. So yes, to make a long story short: I think the future EV market will accommodate different types of batteries, which will each satisfy a specific ‘niche’ in the market.

In terms of consumer acceptance, how prepared do you think the automotive industry is for the introduction of vehicles not powered by LIBs, but another battery – ZABs for instance?
Consumer acceptance, especially when it comes to such essential products like cars, is a tricky construct. Overall, the mainstream electric vehicle is not that young. Looking at Tesla for example, the model S, which is their flagship model, went into production in 2012. Back then, consumer acceptance was still very low due as people were sceptic of the performance of an all-electric vehicle. For example, users were scared they were going to run out of battery in the middle of the highway. In the industry, we call this ‘range anxiety’. But over the past 5-6 years, consumers have slowly warmed up to the idea as they’ve seen that EVs do indeed meet their needs.

If we are now looking at a new technology, consumers claim they want the technology to be good for the environment, preferably domestically produced etc. But when it comes down to it, the characteristics the consumer cares most about are functionality – so distance, speed of recharge, as well as safety, and cost. Just like with the lithium-based batteries over the past 10+ years, any new technology is going to have to prove itself and build up social acceptance.

Given the current trends in the automotive industry, what are the key factors or drivers that will determine the success of a particular battery technology in the EV market?
Looking at the industry side, the single most important factor determining whether a technology is going to play a role, is cost. The levelized cost per kw/h is what gives a technology the greatest competitive advantage. Only then, factors like safety, environmental footprint etc come into play.

How do you assess the readiness of the automotive supply chain to accommodate a potential shift towards other emerging battery technologies like ZABs?
As long as the economic incentive stands, so a possibility for companies to save and thereby make money, the supply chain does not pose a significant issue. Obviously, suppliers must be contracted, manufacturing plants built or remodeled and safety standards put in place, but all that has been successfully done for all kinds of technologies to have emerged previously.

What do you consider to be the main barrier for future growth of the EV market?
That is a hard question to give one exact answer to, because a lot of things are related. I’ll explain my point using the example of charging infrastructure. One could say that consumer acceptance is the biggest barrier, but that has, in part, to do with charging infrastructure. If the charging network would be more extensively developed, people would feel safer knowing they can charge their car almost anywhere if they run low on battery. But charging network is also a question of political ambition. Where are charging stations allowed to be installed? How long

does it take for companies to get approval from the respective authorities? As you see, there are many factors to be considered.

There are multiple issues with the current supply chain, such as the impact on the environment of mining lithium. However, in politics, keeping the promise (climate agreements) the dismay of few is an easy price to pay, especially if those are poor communities that have no power. So it might be unsustainable and unethical, but I think supply of lithium will continue to flourish for the next decades or so at least.

7.1.12 Interview with Expert C2

Code: C2 | Date: 26.07.2023 | Duration: 30 minutes

From a market perspective, do you see the shift from LIBs to another type of battery technology on the horizon?
No, not within the next 10-12 years. In fact, during that time frame, the lithium market will continue to grow. That has multiple reasons. Firstly, the demand for electric vehicles. This is in large part due to political efforts to combat global warming. In Europe, there is the climate target plan; the US under Joe Biden has agreed to re-submit to the terms of the Paris climate agreement, which China is also part of. These markets are amongst the biggest in terms of growth for the electric vehicle market and projections are that those markets will grow by around 400% (US & EU) and 50% for the Chinese market by 2030. That growth is going to require a lot of lithium. This brings me to my second point: there is no technology that is able to match current LIB standards. At least not on a commercial scale and at a competitive price.

In terms of consumer acceptance, how prepared do you think the automotive industry is for the introduction of vehicles not powered by LIBs, but another battery – ZABs for instance?
Here we have to distinguish between acceptance of electric vehicles overall, and specific types of propulsion. Electric vehicles are becoming more and more popular, in part due to political efforts like incentives, in part due to concerns being eradicated, the most present ones being driving range, extra cost, and charging (both time and infrastructure). The technology has proven itself and mitigated many of the concerns that customers used to have. A new battery model would have to go through a similar cycle as LIBs once did, but the inhibitions are likely not to be as severe, the barriers not as high. If the technology performs well with a small subset of customers, coupled with the right marketing, it could be a great disruptor within the industry.

Given the current trends in the automotive industry, what are the key factors or drivers that will determine the success of a particular battery technology in the EV market?
The mass market for vehicles, including electric vehicles essentially boils down to life-cycle economics. You can have the greatest motor or wheel or seat in the world – if it cannot be mass manufactured at profit margin, it will not be used. Every little detail along the entirety of the car's lifecycle is optimized towards profit maximization. The lithium battery is already commercialized and by the forces of economics, prices have significantly dropped and will

likely continue to do so. This makes if considerably harder for new technologies to compete. A way around this would be if the base materials are naturally cheaper, giving it a natural competitive advantage in terms of supply and cost of sourcing. Apart from that, most manufacturers have a diverse product line, offering sports cars, family cars, SUVs, urban-use vehicles. It makes sense that different offerings are built on different technologies that can more accurately cater to the need of that specific customer.

How do you assess the readiness of the automotive supply chain to accommodate a potential shift towards other emerging battery technologies like ZABs?
Good question – and difficult to answer, since we have not seen another battery technology emerge in that sense. If we orientate ourselves along the LIB example, traditional OEMs are at risk because the batteries – not all, but a large proportion – are manufactured by companies outside that traditional supply chain. Many new technologies are not the work of large, established manufacturers, but small start-ups or research institutes. Either, the traditional suppliers buy those technologies in the early stages and build a manufacturing process around it, or start-ups use that specialized knowledge to their advantage to build a dominant position in the supply chain.

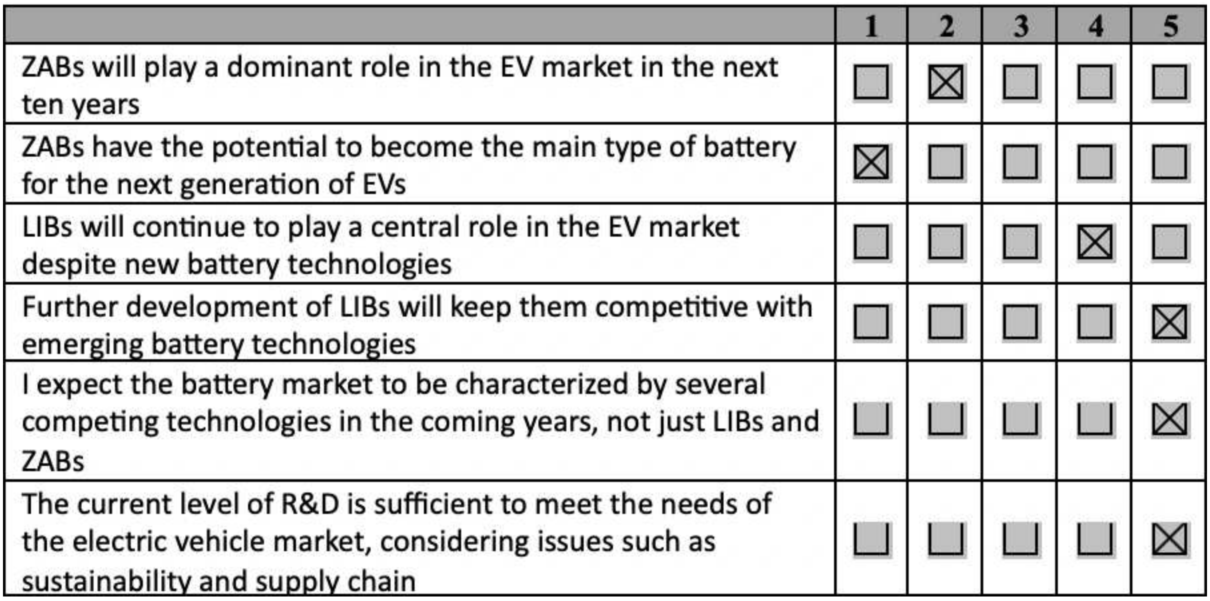
Yes, there are challenges with the current supply chain. Extracting lithium is expensive, it's dirty (which defeats the entire point of EVs in the first place), and it is geopolitically difficult, because only a few countries have large resources.

What do you consider to be the main barrier for future growth of the EV market?
At this point, charging infrastructure is still not at a satisfactory level, and it keeps many people from switching their traditional car for an electric one. Germany has announced \$2.8 billion to go into expanding the charging network, and China close to \$400 million. Those are just two examples that signify that governments are actively trying to counteract anyone's reservation against EV's.

7.2 Likert Scale Questions from Expert Interviews (Quantitative data)

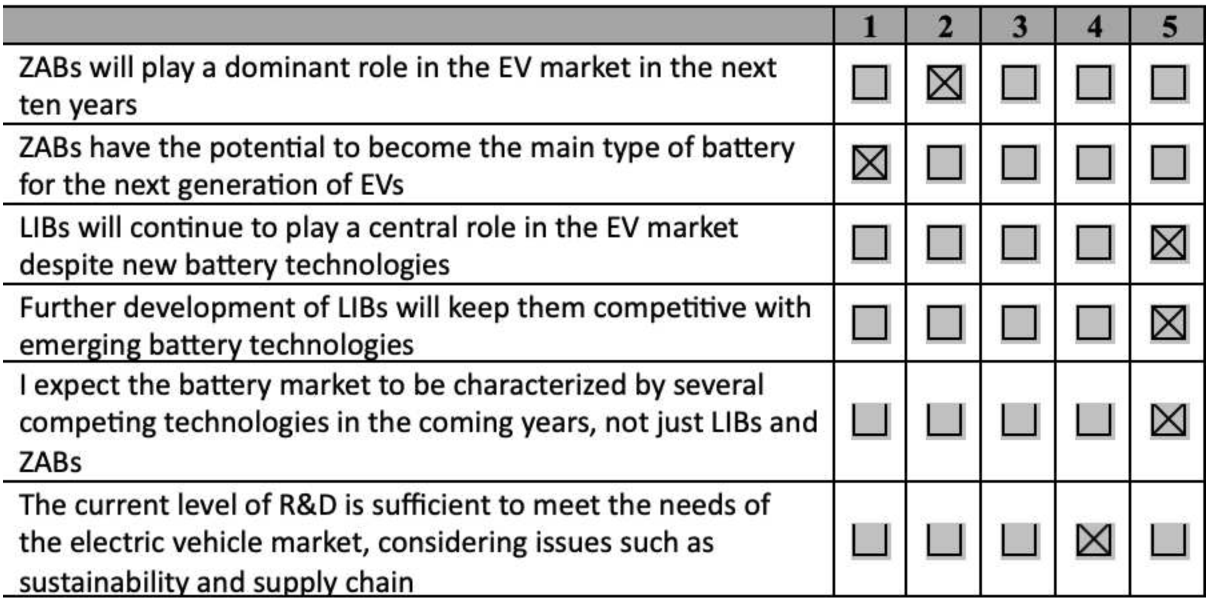
1 = Strongly disagree | 2 = Disagree | 3 = Neutral | 4 = Agree | 5 = Strongly agree

S1



	1	2	3	4	5
ZABs will play a dominant role in the EV market in the next ten years	☐	☒	☐	☐	☐
ZABs have the potential to become the main type of battery for the next generation of EVs	☒	☐	☐	☐	☐
LIBs will continue to play a central role in the EV market despite new battery technologies	☐	☐	☐	☒	☐
Further development of LIBs will keep them competitive with emerging battery technologies	☐	☐	☐	☐	☒
I expect the battery market to be characterized by several competing technologies in the coming years, not just LIBs and ZABs	☐	☐	☐	☐	☒
The current level of R&D is sufficient to meet the needs of the electric vehicle market, considering issues such as sustainability and supply chain	☐	☐	☐	☐	☒

S2



	1	2	3	4	5
ZABs will play a dominant role in the EV market in the next ten years	☐	☒	☐	☐	☐
ZABs have the potential to become the main type of battery for the next generation of EVs	☒	☐	☐	☐	☐
LIBs will continue to play a central role in the EV market despite new battery technologies	☐	☐	☐	☐	☒
Further development of LIBs will keep them competitive with emerging battery technologies	☐	☐	☐	☐	☒
I expect the battery market to be characterized by several competing technologies in the coming years, not just LIBs and ZABs	☐	☐	☐	☐	☒
The current level of R&D is sufficient to meet the needs of the electric vehicle market, considering issues such as sustainability and supply chain	☐	☐	☐	☒	☐

S3

	1	2	3	4	5
ZABs will play a dominant role in the EV market in the next ten years	☐	☒	☐	☐	☐
ZABs have the potential to become the main type of battery for the next generation of EVs	☐	☒	☐	☐	☐
LIBs will continue to play a central role in the EV market despite new battery technologies	☐	☐	☐	☐	☒
Further development of LIBs will keep them competitive with emerging battery technologies	☐	☐	☐	☐	☒
I expect the battery market to be characterized by several competing technologies in the coming years, not just LIBs and ZABs	☐	☐	☐	☒	☐
The current level of R&D is sufficient to meet the needs of the electric vehicle market, considering issues such as sustainability and supply chain	☐	☐	☒	☐	☐

S4

	1	2	3	4	5
ZABs will play a dominant role in the EV market in the next ten years	☐	☐	☐	☒	☐
ZABs have the potential to become the main type of battery for the next generation of EVs	☐	☐	☐	☒	☐
LIBs will continue to play a central role in the EV market despite new battery technologies	☐	☐	☐	☐	☒
Further development of LIBs will keep them competitive with emerging battery technologies	☐	☐	☐	☐	☒
I expect the battery market to be characterized by several competing technologies in the coming years, not just LIBs and ZABs	☐	☐	☐	☐	☒
The current level of R&D is sufficient to meet the needs of the electric vehicle market, considering issues such as sustainability and supply chain	☐	☐	☐	☒	☐

S5

	1	2	3	4	5
ZABs will play a dominant role in the EV market in the next ten years	☐	☐	☐	☐	☒
ZABs have the potential to become the main type of battery for the next generation of EVs	☐	☐	☒	☐	☐
LIBs will continue to play a central role in the EV market despite new battery technologies	☐	☐	☐	☒	☐
Further development of LIBs will keep them competitive with emerging battery technologies	☐	☐	☐	☒	☐
I expect the battery market to be characterized by several competing technologies in the coming years, not just LIBs and ZABs	☐	☐	☐	☒	☐
The current level of R&D is sufficient to meet the needs of the electric vehicle market, considering issues such as sustainability and supply chain	☐	☐	☐	☒	☐

M1

	1	2	3	4	5
ZABs will play a dominant role in the EV market in the next ten years	☐	☒	☐	☐	☐
ZABs have the potential to become the main type of battery for the next generation of EVs	☐	☐	☐	☒	☐
LIBs will continue to play a central role in the EV market despite new battery technologies	☐	☐	☐	☐	☒
Further development of LIBs will keep them competitive with emerging battery technologies	☐	☐	☐	☒	☐
I expect the battery market to be characterized by several competing technologies in the coming years, not just LIBs and ZABs	☐	☐	☐	☐	☒
The current level of R&D is sufficient to meet the needs of the electric vehicle market, considering issues such as sustainability and supply chain	☐	☐	☐	☐	☒

M2

	1	2	3	4	5
ZABs will play a dominant role in the EV market in the next ten years	☐	☒	☐	☐	☐
ZABs have the potential to become the main type of battery for the next generation of EVs	☐	☐	☐	☒	☐
LIBs will continue to play a central role in the EV market despite new battery technologies	☐	☒	☐	☐	☐
Further development of LIBs will keep them competitive with emerging battery technologies	☐	☒	☐	☐	☐
I expect the battery market to be characterized by several competing technologies in the coming years, not just LIBs and ZABs	☐	☐	☐	☒	☐
The current level of R&D is sufficient to meet the needs of the electric vehicle market, considering issues such as sustainability and supply chain	☐	☐	☐	☒	☐

M3

	1	2	3	4	5
ZABs will play a dominant role in the EV market in the next ten years	☐	☐	☒	☐	☐
ZABs have the potential to become the main type of battery for the next generation of EVs	☐	☐	☒	☐	☐
LIBs will continue to play a central role in the EV market despite new battery technologies	☐	☐	☐	☒	☐
Further development of LIBs will keep them competitive with emerging battery technologies	☐	☐	☐	☒	☐
I expect the battery market to be characterized by several competing technologies in the coming years, not just LIBs and ZABs	☐	☐	☐	☐	☒
The current level of R&D is sufficient to meet the needs of the electric vehicle market, considering issues such as sustainability and supply chain	☐	☐	☒	☐	☐

M4

	1	2	3	4	5
ZABs will play a dominant role in the EV market in the next ten years	☐	☐	☒	☐	☐
ZABs have the potential to become the main type of battery for the next generation of EVs	☐	☐	☒	☐	☐
LIBs will continue to play a central role in the EV market despite new battery technologies	☐	☐	☐	☐	☒
Further development of LIBs will keep them competitive with emerging battery technologies	☐	☐	☐	☐	☒
I expect the battery market to be characterized by several competing technologies in the coming years, not just LIBs and ZABs	☐	☐	☐	☐	☒
The current level of R&D is sufficient to meet the needs of the electric vehicle market, considering issues such as sustainability and supply chain	☐	☐	☐	☒	☐

M5

	1	2	3	4	5
ZABs will play a dominant role in the EV market in the next ten years	☐	☐	☐	☒	☐
ZABs have the potential to become the main type of battery for the next generation of EVs	☐	☐	☒	☐	☐
LIBs will continue to play a central role in the EV market despite new battery technologies	☐	☐	☐	☐	☒
Further development of LIBs will keep them competitive with emerging battery technologies	☐	☐	☐	☒	☐
I expect the battery market to be characterized by several competing technologies in the coming years, not just LIBs and ZABs	☐	☐	☐	☐	☒
The current level of R&D is sufficient to meet the needs of the electric vehicle market, considering issues such as sustainability and supply chain	☐	☐	☐	☒	☐

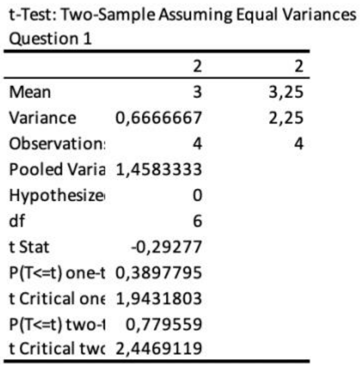
C1

	1	2	3	4	5
ZABs will play a dominant role in the EV market in the next ten years	☐	☒	☐	☐	☐
ZABs have the potential to become the main type of battery for the next generation of EVs	☐	☐	☒	☐	☐
LIBs will continue to play a central role in the EV market despite new battery technologies	☐	☐	☐	☐	☒
Further development of LIBs will keep them competitive with emerging battery technologies	☐	☐	☐	☐	☒
I expect the battery market to be characterized by several competing technologies in the coming years, not just LIBs and ZABs	☐	☐	☐	☒	☐
The current level of R&D is sufficient to meet the needs of the electric vehicle market, considering issues such as sustainability and supply chain	☐	☐	☒	☐	☐

C2

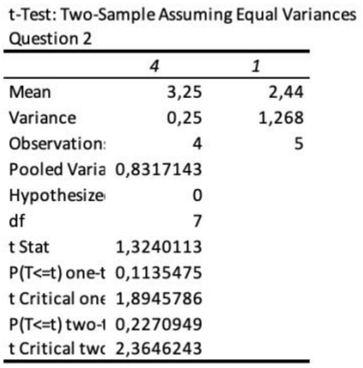
	1	2	3	4	5
ZABs will play a dominant role in the EV market in the next ten years	☐	☐	☒	☐	☐
ZABs have the potential to become the main type of battery for the next generation of EVs	☐	☐	☒	☐	☐
LIBs will continue to play a central role in the EV market despite new battery technologies	☐	☐	☐	☐	☒
Further development of LIBs will keep them competitive with emerging battery technologies	☐	☐	☐	☐	☒
I expect the battery market to be characterized by several competing technologies in the coming years, not just LIBs and ZABs	☐	☐	☐	☐	☒
The current level of R&D is sufficient to meet the needs of the electric vehicle market, considering issues such as sustainability and supply chain	☐	☐	☐	☒	☐

7.3 Statistical Analysis of Likert Scale Questions



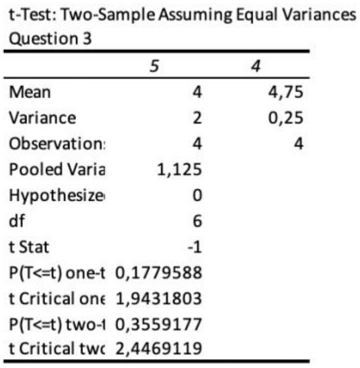
t-Test: Two-Sample Assuming Equal Variances
Question 1

	2	2
Mean	3	3,25
Variance	0,6666667	2,25
Observation	4	4
Pooled Varia	1,4583333	
Hypothesize	0	
df	6	
t Stat	-0,29277	
P(T<=t) one-t	0,3897795	
t Critical one	1,9431803	
P(T<=t) two-	0,779559	
t Critical tw	2,4469119	



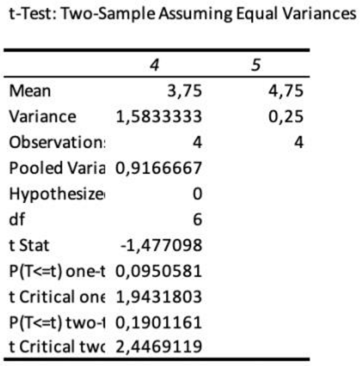
t-Test: Two-Sample Assuming Equal Variances
Question 2

	4	*1*
Mean	3,25	2,44
Variance	0,25	1,268
Observation	4	5
Pooled Varia	0,8317143	
Hypothesize	0	
df	7	
t Stat	1,3240113	
P(T<=t) one-t	0,1135475	
t Critical one	1,8945786	
P(T<=t) two-	0,2270949	
t Critical tw	2,3646243	



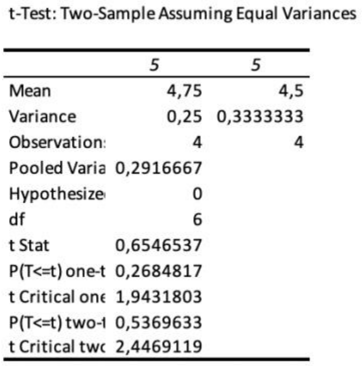
t-Test: Two-Sample Assuming Equal Variances
Question 3

	5	*4*
Mean	4	4,75
Variance	2	0,25
Observation	4	4
Pooled Varia	1,125	
Hypothesize	0	
df	6	
t Stat	-1	
P(T<=t) one-t	0,1779588	
t Critical one	1,9431803	
P(T<=t) two-	0,3559177	
t Critical tw	2,4469119	



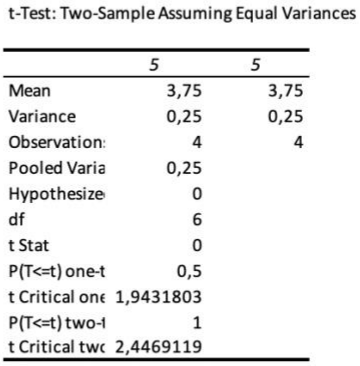
t-Test: Two-Sample Assuming Equal Variances

	4	*5*
Mean	3,75	4,75
Variance	1,5833333	0,25
Observation	4	4
Pooled Varia	0,9166667	
Hypothesize	0	
df	6	
t Stat	-1,477098	
P(T<=t) one-t	0,0950581	
t Critical one	1,9431803	
P(T<=t) two-	0,1901161	
t Critical tw	2,4469119	



t-Test: Two-Sample Assuming Equal Variances

	5	*5*
Mean	4,75	4,5
Variance	0,25	0,3333333
Observation	4	4
Pooled Varia	0,2916667	
Hypothesize	0	
df	6	
t Stat	0,6546537	
P(T<=t) one-t	0,2684817	
t Critical one	1,9431803	
P(T<=t) two-	0,5369633	
t Critical tw	2,4469119	



t-Test: Two-Sample Assuming Equal Variances

	5	*5*
Mean	3,75	3,75
Variance	0,25	0,25
Observation	4	4
Pooled Varia	0,25	
Hypothesize	0	
df	6	
t Stat	0	
P(T<=t) one-t	0,5	
t Critical one	1,9431803	
P(T<=t) two-	1	
t Critical tw	2,4469119	