Alternatives to Lithium-Ion Batteries for Electric Vehicles

Albert Kragl
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Abstract

With man-made climate change becoming increasingly severe every year, the need for vehicles powered by alternative energy sources is now greater than ever. Although there are electric vehicles commercially available today, their limited driving range and high price makes them unappealing to many consumers. In order to move past these limitations, researchers have begun investigating different types of batteries with the goal of finding a battery that can reliably store more energy than a traditional lithium-ion battery. This paper analyzes the feasibility of two battery types—lithium-sulfur and lithium-air—as potential replacements for lithium-ion batteries in electric vehicles. Although both batteries demonstrate high theoretical energy densities, the lithium-air battery has a much higher practical energy density when compared to lithium-sulfur, as well as a lower environmental impact and a greater number of charge cycles. The lithium-air battery also demonstrates a higher energy density and lower environmental impact when compared to lithium-ion. These results make lithium-air technology the best candidate to replace lithium-ion batteries in the near future.

Introduction

Since the commercial introduction of the lithium-ion battery in the early 1990s, virtually every consumer product that uses a rechargeable battery has adopted this technology. However, with climate change becoming a greater problem every year, the demand for electric vehicles (EVs) in particular has, understandably, grown dramatically—they are arguably the best long-term replacement for traditional gas-powered vehicles. Unfortunately, they have some major drawbacks, namely driving range and price, that have largely limited their commercial success in the past few years. An encouraging option that could help overcome these limitations is developing a new battery technology to be used in EVs, as there are promising alternatives that could offer both a greater driving range and better vehicle value for the same price, while also potentially lowering environmental impact. By using existing lithium-ion technology as a baseline, this paper will analyse the feasibility of lithium-sulfur and lithium-air batteries as commercial alternatives for electric vehicles by investigating the energy density and environmental impact of each, as well as the number of times each battery can be recharged.

Background

In 2014, the transportation sector in the United States accounted for 26% of total U.S. carbon dioxide emissions that year, with 90% of vehicles using petroleum-based fuel ("Sources of Greenhouse," n.d.). Considering carbon dioxide and its close connection to climate change, vehicle manufacturers have slowly begun to invest more in the research and production of vehicles that emit little-to-no amounts of the problematic gas. Of all manufacturers, Tesla Motors has undoubtedly generated the greatest public interest in EVs; its current flagship car, the Model S, can drive for more than 500 km on a full charge when equipped with the 100 kWh battery in the 100D model (“Model S,” n.d.). However, to buy the car with this battery, one would need to spend over $100,000 USD if they wished to purchase the car up-front—even the cheapest model with a significantly lower driving range costs more than $80,000 (“Model S,” n.d.). Tesla showed awareness of this by introducing the Model 3, which comes with a base price of $35,000. However, its driving range is estimated to be only 345 km, which is significantly lower than the Model S. The price of EVs on its own is not so much the issue, as prices will continue to drop over time; rather, the main concern is achieving a greater driving range for the same price. This range of 345-500 km is too low for many consumers, and EVs are likely to remain niche products until they can achieve a range of at least 800 kilometres (Wilcke & Kim, 2016, p. 44). Lithium-sulfur and lithium-air batteries both have the potential to achieve this due to their high theoretical energy densities (measured in Watt-hours per kilogram, Wh/kg).

With current lithium-ion batteries, the only way to increase an EVs driving range would be to have a bigger battery, which would quickly become impractical in a car due to weight and size considerations. However, the two alternatives have the potential to store more energy in the same mass, which would essentially solve the driving range problem if the batteries could be scaled to a large enough size. Additionally, it is important to consider the long-term feasibility of these solutions; to do this, the potential environmental impacts of each solution will also be assessed by looking at the availability of materials, their extraction processes, and the percentage of materials that can be realistically recycled. Lastly, the lifetime of each battery type will be assessed by looking at the number of charge cycles that each can go through without a significant drop-off in performance. The minimum should be 200 charge cycles, and ideally 400 to give a lifetime driving range of 320,000 kilometres in an EV, which is around the maximum lifetime range a typical car could achieve (Wilcke & Kim, 2016, p. 46).

Analysis

In order to have a good baseline for comparison, the advantages and disadvantages of the currently widespread lithium-ion battery will be assessed first. The typical lithium-ion battery has an energy density in the range of 200-600 Wh/kg, although the majority have densities closer to 200 Wh/kg (Savage, 2011). Assuming the Tesla Model S's 100 kWh battery has an energy density of 200 Wh/kg, it would weigh 500 kilograms; with its driving range of around 500 kilometres, the battery would have an approximate energy consumption of 20 kWh/100km. Considering that the energy consumption of EVs is unlikely to decrease by any significant amount, the need for a battery with a greater energy density is evident. Due to its fundamental chemistry, the energy density of the lithium-ion battery is dependent on the volume, and hence mass, of the battery (Wilcke & Kim, 2016, p. 45). This, combined with the stagnation in lithium-ion technology development, makes increasing EV driving range with the lithium-ion battery difficult.

In terms of environmental impact, lithium-ion batteries do reasonably well, but there is also room for improvement. Lithium-ion batteries will typically be comprised of metals such as lithium, lithium-metal oxides, graphite and cobalt, with lithium and graphite being the two main materials used for the cathode and anode (Daniel, 2008). Lithium in particular is a key ingredient, but worldwide reserves of the metal are not infinite; rather, they are projected to not last very long at all. If the current global demand for lithium does not change, lithium reserves are estimated to last 365 years—however, with the growth of EV production and the creation of infrastructure such as Tesla Gigafactories (which will help Tesla produce 500,000 cars per year by 2020), production is expected to increase dramatically, and the same lithium reserves could last as few as 17 years (Hunt, 2015). This demonstrates the need for effective battery recycling.

The goal is to reach near-100% recycling rates, although currently less than 1% of lithium-ion batteries are recovered and recycled (Zeng, Li, & Singh, 2014, p. 1138). In order for lithium-based batteries to be feasible in the long-term, major improvements need to be made in recycling processes and infrastructure.

In terms of its charge cycles and long-term performance, the lithium-ion battery does well; data gathered by Tesla showed that the typical Model S battery only saw a 10% decrease in capacity after the first 100,000 miles driven (Lambert, 2016). Considering that one full cycle is equivalent to around 500 km, or 310 miles, 100,000 miles corresponds to approximately 321 charge cycles. This is suitable for an EV, as the average vehicle would drive 200,000 miles and go through 642 charge cycles before its battery could hold only 80% of its original charge. This 80% mark is generally considered to be the point where a battery's capacity has changed significantly.

Now that a baseline for comparison has been set, we can begin to look at the two proposed alternatives. The first of the two, the lithium-sulfur battery, has several attractive properties, namely its energy density: it has a theoretical energy density of 1500 Wh/kg, three times higher than what is achievable with lithium-ion (Kim et al., 2013, p. 1079). If a 500 kg battery with this energy density were placed in the Tesla Model S, its driving range would climb to a whopping 3750 km, which is 7.5 times greater. Another study suggests the theoretical energy density of lithium-sulfur is 2600 Wh/kg, which would give an even greater driving range (Li et al., 2015, p. 11342). It is important to note that these are only theoretical estimates, however, and that the actual energy density would decrease drastically once other components were added to the battery.

In terms of its basic chemistry, the lithium-sulfur battery converts lithium and sulfur into lithium sulfide (Kim et al., 2013, p. 1076). The environmental considerations for lithium are the same as in the lithium-ion battery, but the use of sulfur in the cathode is much better, since it is a very abundant element. This means that in the long-term, the lithium-sulfur battery is likely to be more feasible than the lithium-ion battery. However, like many other mining processes, the extraction of sulfur can have adverse environmental impacts on a surrounding area, although with gradual improvements in mining technology these environmental impacts should become less severe.

The lithium-sulfur battery's major drawback comes in its lifecycle. Although certain battery designs have reached 170 charge cycles, the fundamental design of the battery encourages lithium dendrite growth on the lithium anode, which leads to a continuous decay in the battery's capacity (Kim et al., 2014, p. 5359). While some designs have attempted to avoid this, it largely remains an issue. In order for this battery to be feasible in an EV, a stable configuration needs to be discovered that can allow the battery to recharge hundreds of times without any major decomposition in the cathode, anode and electrolyte.

The second alternative, the lithium-air battery, shows perhaps the most promise for the future of EV batteries. Like the lithium-sulfur battery, the lithium-air battery also has a very high theoretical energy density, with values as high as 13,500 Wh/kg being reported (Jung et al., 2012, p. 584). Even assuming a reduction factor of one due to the weight of additional components, the practical energy density would still be higher than what is offered by current lithium-ion technology (Jung et al., 2012, p. 584). Another study reported a practical energy density of 800 Wh/kg, compared to a theoretical energy density of 3460 Wh/kg (Wilcke & Kim, 2016, p. 61-62). In the Tesla Model S, using the same battery mass of 500 kg for comparison, this energy density of 800 Wh/kg would give a driving range that is four times greater, at around 2000 km. This well exceeds the proposed 800 km minimum requirement for EVs, and makes this aspect of the lithium-air battery more than satisfactory. Another important factor to consider is the battery's capacity; unlike the lithium-ion battery, whose capacity depends on its volume, the capacity of a lithium-air battery depends on its surface area (Wilcke & Kim, 2016, p. 45). It is therefore possible to have a light battery that can also store high amounts of energy, which is very appealing in the context of an EV.

Lithium-air batteries also have a much lower environmental impact than current lithium-ion batteries. Lithium-air batteries differ slightly from the other two batteries in terms of chemistry, as a gas is used in the internal reaction; the battery reacts lithium ions with oxygen on the surface of the electrode, forming lithium peroxide (Wilcke & Kim, 2016, p. 45). While lithium-sulfur features one abundant element, sulfur, the lithium-air battery uses the even more abundant and accessible element of oxygen. This combined with other aspects of its design could mean that lithium-air batteries would have 4 to 9 times less environmental impact over the long term than lithium-ion batteries (Zackrisson et al., 2016, p. 310). As with the other two batteries, however, the presence of lithium in the battery necessitates the need for proper recycling in order for the design to be feasible in the long term. If the batteries were properly recycled, another 10 to 30% of production-related environmental impact could be avoided (Zackrisson et al., 2016, p. 310).

Similar to the lithium-sulfur battery, the lifecycle of the lithium-air battery is currently its greatest drawback. Two hundred charge cycles were achieved using one design, but this was only done by limiting the battery's discharge to less than its theoretical maximum (Wilcke & Kim, 2016, p. 46). Another project in 2016 only managed to reach 50 cycles before the battery failed, although it is predicted their design will eventually reach 200 cycles (Zackrisson et al., 2016, p. 304). Despite these seemingly disappointing results, improvements have been made in this aspect of lithium-air batteries. It is fairly well known that this is the main limitation of the technology, so intense effort is being invested to achieve a greater number of charge cycles. It is likely that most designs will reach at least 200 charge cycles, which meets the minimum requirement established for EVs. The table below summarizes the key aspects of each battery type.

	Energy density	**Environmental Impact**	**Lifetime/Charge Cycles**
Lithium-ion	200-600 Wh/kg, typically closer to 200 Wh/kg	Highest, due to use of various metals	400+ cycles 20% decrease in capacity after 200,000 miles driven
Lithium-sulfur	1500-2600 Wh/kg (theoretical)	Intermediate	Maximum of 170 cycles
Lithium-air	3460-13,500 Wh/kg (theoretical) 800 Wh/kg (practical)	Lowest, due to the use of oxygen in the battery	50-200 cycles, expected to increase beyond 200

Table 1: Summary of each battery type

Conclusion

The lithium-ion battery has long been the industry standard due to its reliable performance, and it has done its job well for decades. In order to further advance EV technology, however, lithium-ion batteries will not be enough. Considering the three criterion that were laid out at the start of the paper, it is clear that the lithium-air battery is the best choice for the future of EVs. Lithium-air has demonstrated energy densities exceeding those demonstrated by lithium-sulfur, while also having less environmental impact. If an effective recycling system were also to be put into place, then lithium-air batteries could power EVs for the foreseeable future. As the lifetime of the lithium-air battery continues to improve, we may soon be seeing an uptick in the quantity of high-range EVs, which will hopefully lead to a greener future.

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