The Future of Rechargeable Battery Technology: Lithium-air and Its Potential Use in Electric Vehicles

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Abstract— For the past decade the lithium-ion battery has had great success in powering many of our rechargeable energy needs. It's ability to hold more energy than other conventional batteries is what has kept it at the top of the battery pyramid for more than a decade. However, to create a more sustainable future, scientists and engineers have continued to search for a battery technology that could one day replace the Li-ion and solve its many limitations. One of the most intriguing and promising of these technologies is called lithium-air, which could potentially allow electric vehicles to become just as efficient as their gas-powered counterpart. Lithium-air takes in oxygen from the atmosphere and uses that oxygen to react with the lithium-ions from the anode, rather than only reacting with the carbon as lithium-ion batteries do. This paper will discuss briefly the limitations of the Li-ion battery before describing the Li-air technology and the problems that are preventing it from leaving the development stage. Engineers have designed several prototypes of the lithium-air battery, which could potentially resolve these problems and allow the technology to achieve its theoretical potential. A working Li-air battery will benefit electric vehicles and, in a broader sense, sustainability in general.

Key Words—air, battery, electric-vehicles, lithium, lithium-air rechargeable, next generation battery

BATTERIES OF TODAY

Throughout any given day, we have a constant need of energy to power and run the various appliances we come across. For our energy demands to be met, we have created numerous ways to generate and distribute this energy across the population for all needs to be satisfied. Electricity generated from, for example, a power plant, can be harnessed and distributed through power lines that lead to houses and buildings in need of electricity for them to run properly. This method is effective for powering stationary objects commonly found in your household such as a lamp or toaster, but isn't very useful when you need power on the move. This raises a problem of how we can store and access energy from any place at any time of choice. A practical solution to this problem is the battery. Batteries are commonly found in a good majority of objects of everyday life. Be it your cell phone or Honda Civic, a battery is most likely used to power the system that allows that device to operate. Batteries are popular and frequently utilized in today's society because of how accessible they are. Unlike a power plant, a battery can be shipped to any destination to provide power to a multitude of needs. This portability is one of the many reasons batteries have become as popular as they are today. The public has realized just how useful a portable carrier of energy can be, and thus they have done remarkably well in markets around the world. One primary example of batteries that has seen significant success is the lithium-ion battery. This battery was a remarkable step in rechargeable batteries, as it can charge faster and store more energy than most of its predecessors. This has made it well sought out by many companies using rechargeable batteries in their products, such as Tesla electric automobiles [1].

While we have made many improvements in the field of batteries from the dawn of their creation, there is still much room for improvement. For example, while rechargeable batteries are growing in popularity, they are yet incapable of competing with the monstrous energy density of fossil fuels such as gasoline. These sources of energy, especially in the automobile industry, have dominated markets for years. Without a revolution in battery technology, this will remain the case for many years to come.

There is a chance, however, that we could see the dominance of fossil fuels challenged in our lifetime. A new innovative battery, called lithium-air, has the theoretical energy density to rival that of even gasoline. Potentially, this battery could supersede lithium-ion batteries in all they have accomplished so far. This battery has yet to be manufactured and patented on a global scale; however, recent studies and articles indicate that it is well on its way to being successfully created and in turn patented (for example, researchers at the University of Cambridge are researching the solid-state prototype of the lithium-air battery). Throughout this paper, lithium-air batteries and all their components will be analyzed, as well as their potential marketability, specifically in the field of electric vehicles.
On the most basic level, all battery technologies function in the same way. A battery is simply a device that can store electrical energy in the form of chemical energy, and later convert that energy into electricity [2]. It’s important to note the fact that the electricity is stored as chemical energy, because this is the underlying principle upon which all batteries are engineered.

Expanding upon this basic definition, for electricity to be stored as chemical energy there needs to be chemical reactions taking place. This is where cells come into play. Every battery consists of one or more power generating compartments called cells, and every cell consists of the same three components: two terminals called the anode and cathode, and a conductive liquid/gel called the electrolyte that separates the two [2]. These three components are essential for the necessary chemical reactions to take place that allow the battery to discharge electricity into the circuit. During discharge, the chemical on the negative anode releases electrons, which then travel through the circuit [2]. At the same time, the positive ions created by the departure of the electrons are released the opposite direction into the electrolyte [2]. This process is shown in figure 1, where the ions are shown as yellow circles and the electrons as arrows on the outer circuit.

This process will continue until no more ions flow through the electrolyte, which means the battery is fully charged [2]. The battery design and the chemical processes described in this section are the basic design and processes for all modern rechargeable batteries, including lithium-ion and lithium-air. However, there are considerable differences in different battery technologies’ characteristics. The characteristics of a battery are determined by the types of materials used for its components. These characteristics include capacity (total amount of energy it can deliver) and its voltage (potential difference in charge between anode and cathode) [4]. An article published by the American Physical Society gave this analogy: “Imagine that a battery is a like a tank of water being drained by a hose. The volume of the tank is the capacity of the battery and the pressure in the hose is its voltage” [4]. In other words, capacity is how much charge a battery can hold,
and voltage is the force with which the electrons want to travel through the circuit. Therefore, the design and chemistry of lithium-ion is very important to understand in order to fully realize the differences and improvements between its characteristics and those of lithium-air.

**Design, Chemistry, and Characteristics of the Lithium-ion Battery**

The lithium-ion battery is the gold standard of current mass produced rechargeable batteries, and every other new battery technology is in the race to try and improve upon it. Li-ion follows all the basic rechargeable battery principles explained in the previous section, but in this section the specifics of the Li-ion will be explained.

As stated in the previous section, every battery consists of the same three components: the negative anode, positive cathode, and the electrolyte. The cathode of a lithium-ion battery is made from lithium cobalt oxide (LiCoO$_2$), and the anode from carbon (graphite). The electrolyte is typically a combination of lithium-salts (such as LiPF$_6$, LBF$_4$, or LiClO$_4$) in an organic solvent (such as ether) that can conduct positive ions. As the battery charges, the lithium cations move through the electrolyte from the cathode to the anode, and during discharge those ions move back across to the cathode [5]. The only things different from our definition of the battery given in the last section is that we have specified the material of the electrodes and electrolyte, as well as the type of cations, which are traveling back and forth. Now that we know the materials used for the different battery components, we can discuss more in depth the chemistry of the battery as well as its characteristics.

Below is a diagram depicting the flow of lithium ions in a typical Li-ion cell, taken from Battery University, a website dedicated to teaching the public about batteries and started by the founder of Cadex Electronics, Isidor Buchmann.

**FIGURE 3 [6]**

*Flow of lithium ions in Li-ion battery*

This diagram shows the movement of lithium-ions during discharge and charge. As the battery discharges electricity into a circuit to power a device, the graphite cathode undergoes oxidation (loss of electrons) and releases lithium ions (shown as grey circles in the diagram) into the electrolyte to travel to the lithium cobalt oxide cathode. The cathode experiences reduction (gain of electrons) and accepts the lithium ions [6]. This process stops once the anode has oxidized all available lithium ions (meaning battery is depleted) or the circuit is broken (device using battery is turned off/no longer takes in power) [6].

During charging this action is reversed, and now the LiCoO$_2$ cathode experiences oxidation, and releases its lithium ions back into the electrolyte to travel to the graphite anode. The anode experiences reduction and accepts the Li ions. This process stops once all available lithium ions have been oxidized and travel to the carbon anode (battery is fully charged) OR circuit has been broken (power supply taken away/unplugged) [6]. Below is a diagram of how the lithium-ions are positioned when they are in the LiCoO$_2$ cathode.

**FIGURE 4 [6]**

*Position of Li ions within the Li-ion battery cathode*

This diagram shows how the lithium-ions are sandwiched between layers of cobalt oxide when they are situated in the cathode.

The chemistry of the Li-ion isn’t much more complicated when compared to other batteries, but it has certain characteristics that have made it so popular of a battery technology. The combination of LiCoO$_2$ as the cathode material, graphite as the anode material, and the organic electrolyte gives the Li-ion battery a voltage of 3.6 Volts, which is more than twice that of a standard AA alkaline battery. This gives it a much better energy per volume ratio (energy density) than an ordinary alkaline battery or other common rechargeable batteries [7]. Energy density is a very important characteristic of a battery, because the goal is to have as much energy storage capacity as possible in as small as possible volume.

The key behind the lithium-ion’s incredible energy density is the fact that lithium is used as the charge carrier. Lithium is the third smallest element behind helium and hydrogen, and because of its small size it can carry a positive charge in a very small amount of space [7]. This means that you can fit more lithium ion particles per unit space than larger particles, such
as nickel (another element frequently used in other rechargeable batteries). Having more particles per volume produces a greater amount of energy (think of energy as the rate of water coming out of a hose, if you turn the pressure up by increasing the amount of water in the pipes, the water will come out faster and greater pressure). Li-ion’s energy density, and its ability to recharge, is what makes it such an attractive battery to power portable devices where a small battery with a large power storage is ideal (such as in cell phones).

However, it is important to realize that Li-ion batteries are still many times less energy dense than gasoline, which stores its energy in chemical bonds [7]. Therefore, despite Li-ions greatness in terms of the current battery technology, the search is still on for a new battery technology capable of rivaling the energy density of gasoline. Engineers are hopeful that a technology called lithium-air can be the technology that enables batteries to compete with the energy density of fossil fuels. The details of this technology will be reviewed in the next several sections.

**Design of the Lithium-air Battery**

Before the chemistry and characteristics of the lithium-air battery can be discussed, a basic understanding of the lithium-air design must be held. As stated in the previous section on basic battery principles, all batteries contain an anode, cathode, and electrolyte. Li-air is no exception. However, the materials that make up these components are both unique and important to the overall operation of the battery. Every cell consists of a lithium metal anode, a porous carbon cathode, and an electrolyte [8]. At this point, this will seem eerily similar to the lithium-ion battery, but the major differences are in the material used to create the cathode.

The major distinction between the lithium-ion and lithium-air batteries can be seen in their names. The “air” that gives Li-air its name comes from the battery’s open cell architecture, where oxygen is directly absorbed from the atmosphere during the discharge process at the cathode [8]. This special cathode is called the “air-electrode”. The contribution the oxygen being absorbed from the atmosphere is extremely important to the characteristics of the Li-air, and will be discussed in detail in the next sections on the chemistry and characteristics of the battery.

**The Chemistry of the Lithium-air Battery**

The chemistry behind the function of Li-air is unique because the materials used to make up its components are unique to this battery technology. In this section, the chemistry reactions taking place during discharge and charging will be discussed. Below is the basic cell design of a Li-air battery.

You can see from figure 5 the general layout of components in an Li-air battery. There is both the Li-metal anode, and the air-electrolyte that absorbs oxygen from its surroundings. Note that this diagram shows the movement of ions during discharge, not charge.

During discharge, the battery follows several steps allowing it to discharge electricity into a circuit, which is then harnessed to power an electrical device. Naveed and Waheed Akhtar state these reactions very clearly in their article published in the International Journal of Energy Research on Li-air technology. “During the discharge, the Li-metal anode oxidizes to LiO2 and electrons flow through an external circuit, while LiO2 diffuses toward the cathode via the electrochemical potential gradient. The atmospheric oxygen (O2) is reduced at the porous cathode, forming Li2O2 and other products such as Li2O in less extent” [8]. What this tells us is that the chemistry of Li-air is pretty much the same as the Li-ion in the way that it undergoes oxidation to create lithium ions and release electrons, but different in that the reduction process at the cathode uses outside oxygen. The chemical reactions described above can be seen in their chemical equation form in figure 6:

**FIGURE 5 [4]**  
Basic cell structure of a Li-air battery

**Formula of Lithium-air Reaction**

The reaction at the anode is the oxidation of lithium metal to create the lithium cation and an electron. At the cathode, the lithium cations undergo reduction and react with the oxygen to form the cathode discharge products (Li2O2 or Li2O).

The reaction is reversible to allow for recharge, as the lithium now in the cathode oxidizes to create an electron and a lithium cation. The electron travels back through the circuit as the lithium cation goes through the electrolyte back to the lithium metal anode [8]. The chemistry behind the lithium-air battery highlights the differences between it and a typical
lithium-ion battery, as well as how it incorporates outside oxygen into its chemical reactions.

**Characteristics of Li-air**

The theoretical energy density of a Li-air battery is much larger than that of lithium-ion. This is because, unlike the lithium-ion, the cathode active material in Li-air is oxygen that is absorbed during the discharge process from external air, and thus does not occupy any of the battery volume [8]. As such, Li-air can store a large amount of energy in a smaller volume than Li-ion. Combine this with the fact that lithium has an extremely large specific energy (energy per unit mass) of $1.14 \times 10^4$ Wh/kg (Watt hours per kilogram) and you get a battery capable of packing a lot of energy into a very small volume/mass [8]. The diagram below illustrates how high Li-air’s theoretical specific energy is compared to other battery technology.

![Theoretical and practical energy densities diagram](image)

**FIGURE 7 [8]**

Theoretical and practical energy densities

Notice how much larger the theoretical specific energy of Li-air is compared to every other battery. This is what has caught the attention of engineers and battery enthusiasts, because the potential of a working Li-air battery is so high. However, it’s also important to notice the red column, which is the practical specific energy. Although theoretically a Li-air battery could have the specific energy of the green column, researchers have only been able to achieve the specific energy of the red column, and this only in a controlled experimental environment and not for a sustained amount of time. This makes it very apparent that there are problems with the technology that must be solved before it can be used commercially, but the potential is there. These problems and potential solutions will be discussed in the following sections.

**CURRENT LITHIUM AIR TECHNOLOGIES**

The concept of lithium-air batteries and achieving their uniquely high energy density in a successful prototype has been a very alluring challenge to numerous scientists. This has prompted a multitude of prototypes to be created, all competing to become the first to get patented. In the following subsections, a detailed analysis of a few promising prototypes will be provided to better illustrate where the lithium-ion battery is in its developmental stage.

**Aprotic Lithium-air Batteries**

The aprotic Li-air battery is what was discussed in the previous section, and is the most basic form of an Li-air. Originally developed by Kuzhikalail Abraham, of the research and development company EIC Laboratories, it consists of an Li-metal anode, a liquid organic electrolyte, and a porous carbon cathode [8]. As discussed in the previous section on the chemistry of lithium-air batteries, the chemical reactions during discharge create the compounds Li$_2$O$_2$ and to a lesser extent Li$_2$O in the cathode. These are the cathodes discharge products. These discharge products are insoluble in the organic electrolyte, and thus could potentially block the pores in the cathode and harm the catalysts of the cathode because they cannot dissolve into the electrolyte [8]. Accumulation of these discharge products on the cathode can dramatically reduce the penetration of oxygen, which is necessary for the discharge process to occur [8]. This will affect the performance of the cathode as well as the discharge capacity (amount of energy output per charge). The figure below shows the effects of this phenomenon.

![Accumulation of cathode discharge products on cathode](image)

**FIGURE 8 [8]**

Accumulation of cathode discharge products on cathode

The black on the cathode represents accumulation of discharge products on the cathode. This problem could potentially limit the life span of the battery as well as the practical energy density of the battery, and thus must be resolved in order to create a long lasting and efficient Li-air battery which lives up to its theoretical energy density.

Another shortcoming of the basic aprotic Li-air battery is the problem of filtering out all the other substances in air besides oxygen (i.e. water) [8]. The presence of these unwanted substances could react with the volatile lithium-
metal anode and throw off the necessary chemical reactions need to take place for discharge. In summary, a better system must be engineered to solve for these problems.

**Aqueous Lithium-air Batteries**

The aqueous lithium-air battery, researched heavily by Nobuyuki Imanishi of Mie University in Japan, improves on the established aprotic lithium battery in that it provides a solution to the clogging of insoluble discharge products in the pores of the cathode. In this model of the lithium-air battery, the electrolyte between the anode and cathode is an aqueous solution that will dissolve the products of the cathode. This will allow these products to pass through the cathode membrane freely, without slowing the flow of electrons in the battery, which in turn increases its energy output [8]. There are two unique aqueous solutions that would potentially be used in this prototype. There is an alkaline electrolyte solution and an acidic electrolyte solution.

Alkaline Solution: \(4\text{Li} + \text{O}_2 + 2\text{H}_2\text{O} \rightarrow 4\text{LiOH}\)

Acidic Solution: \(4\text{Li} + \text{O}_2 + 4\text{H}^+ \rightarrow 4\text{LiOH} + 2\text{H}_2\text{O} + \text{Li}^+\)

**FIGURE 9 [8]**
Formulas for reaction in battery for alkaline and acidic electrolytes

These aqueous solutions improve the battery in ways besides the dissolving of problematic products of the cathode. For starters, aqueous solutions are inexpensive to create and offer high ionic conductivities (or the rate that the cations flow across the electrolyte) [8]. This would reduce the overall cost of the battery, making it more efficient and more desirable as a supplier of energy. The aqueous battery would also help deal with the inherent problem aprotic batteries have with moisture in the air. Because the equation is already balanced with the presence of water (via the aqueous solution that is the electrolyte), it could take in oxygen from the air much faster due to the fact it wouldn’t have to filter out moisture in the air completely; however, safety precautions would still need to be taken to prevent the lithium-metal anode from reacting violently with the water inside the battery [8].

While the aqueous lithium-air battery does not solve all the problems of the aprotic design (such as the reactivity of lithium-metal anodes with water), it does take a big step into the creation of a Li-air battery ready for production.

**Hybrid Lithium-air Batteries**

So far two prototypes of the lithium-air battery have been discussed: aprotic and aqueous. The hybrid Li-air battery essentially combines both into one, and is being researched by Ping He at Nanjing University. A hybrid battery consists of an Li-metal anode immersed in organic electrolyte, and an air-electrolyte (porous carbon cathode) interfaced with an aqueous electrolyte [8]. Between these there is a thin film of solid-state Li+ conducting membrane, which separates the aqueous and non-aqueous electrolytes, but allows lithium ions to permeate through it. Below is a diagram of the discharge process in a hybrid Li-air battery.

![Diagram of discharge process in a hybrid lithium-air battery](image)

**FIGURE 10 [5]**
Discharge process of a hybrid lithium-air battery

This combines the organic non-aqueous electrolyte of the aprotic system with the aqueous electrolyte of the aqueous electrolyte. The diagram shows that oxygen permeates into the air-cathode where the reduction reaction takes place. This occurs at the same time as lithium ions diffuse through the non-aqueous electrolyte, permeate through the solid-state membrane, and then through the aqueous electrolyte to the cathode [5]. Thus, the chemical reactions taking place are a hybrid of both the aqueous and aprotic prototypes.

There are several benefits of using such a system for the Li-air battery. It was developed to combat the effects of the discharge products as well as the moisture from the air [5]. For example, since the air-electrode is interfaced with aqueous electrolyte, the discharge products will not clog the cathode’s pores because they are soluble in the aqueous electrolyte. Also, the Li-metal anode is protected from any negative reactions with water because it is immersed in non-aqueous solution, and the solid-state membrane prevents water in the aqueous solution as well as any moist air water from reaching the anode.

The problem with the hybrid Li-air battery is that they provide a lesser power density. This will impact the battery over long-term use [5]. One reason for this is because of the Li ion conducting membrane, which separates the aqueous and non-aqueous compartments of the cell. This membrane lowers the electrolyte conductivity and makes it harder and longer for the ions to travel to the cathode. So, while this prototype fixes the problems of discharge products and moist air, it does so by sacrificing some of its power.
Solid-state Lithium-air Batteries

The final improvement on the aprotic lithium-air design comes in the form of the solid-state lithium-air battery, which was originally developed by X. Zhu at the Hong Kong University of Science and Technology. A solid-state battery is one where the electrolyte is a solid that provides protection to the anode of the battery (it basically acts as a shell), and is also conductive to the Li⁺ ions [8]. This means the solid coating can protect the anode from moisture, oxygen, carbon dioxide, and nitrogen in the air, while still acting as an electrolyte to allow the lithium ions to pass through it [9]. For a better understanding of this system, see figure 10 below.

Another factor that gives the solid-state prototype the edge is the filter that it is equipped with. This filter would act like other filters previously proposed for the lithium-air battery in that it would filter out all substances, while letting in pure oxygen. This unique model has one special exception. While most filters noticeably slow down the batteries reaction rate due to their slow process of extracting oxygen from the air, this particular design of filter would be exponentially faster [9]. The components of this filtered battery include: a porous lithium aluminum titanium phosphate cathode (allowing the lithium ions to enter the cathode), an ultra-thin solid-state electrolyte layer (ensuring high diffusion rates of the lithium ions over the electrolyte), and silicone-oil films coated onto the pore surfaces of the cathode (preventing the reaction being interfered with extraneous molecules like water, thus keeping the reaction rate of lithium and oxygen high) [9]. With a filter that does not hinder the output of the battery, as well as the solid-state design that protects the anode from being interfered with by extraneous compounds, this specific prototype demonstrates remarkably high energy outputs and reaction rates.

It is important to realize that in each battery design we see significant improvements that put lithium-air one step closer to getting patented. These prototypes are not invented in a vacuum, and will hopefully continue to add onto each other until the perfect lithium-air battery is realized.

POTENTIAL APPLICATION IN ELECTRIC VEHICLES

A major reason lithium air batteries have received so much attention is their capability to revolutionize the automobile industry. There are many reasons the automobile industry would look to utilize electric cars more often (if not absolutely) instead of the combustible engines most companies currently use to power their cars.

In today’s age, our society relies heavily on the combustible engine. This has been seen as a logical decision based on the abundance of fossil fuels found in the earth, as well as the relatively simple method of transferring these fuels into mechanical energy. This is done through harnessing the heat from the combustion of fossil fuels and then converting it into power. This is a method we have used for decades, yet it is only about twenty percent effective in harnessing all the energy from its reactions. When compared to batteries, which maintain ninety percent of the energy transferred from their internal reactions, the combustible method of harnessing energy is clearly the inferior where efficiency is concerned [10]. Therefore, it is logical for the automobile industry to turn to a system that will run more efficient, and in turn make their customers all the happier.

Another advantage to utilizing lithium-air batteries is that their energy densities (or the amount of energy that can be extracted from a substance, per amount of volume that substance takes up) are completely unprecedented when compared to other batteries in circulation today. Gasoline has an energy density of about 1700 Wh/kg, this has been unrivaled by standard batteries of the current day and age, which presently only reach about 370 Wh/kg [11].

![Energy densities compared between batteries and gasoline](image)
One of the major reasons lithium-ion run electric cars are not immensely popular today is that they cannot compete with the mileage cars running on gas can achieve. Customers are reluctant to purchase a vehicle they will have to stop and refuel more frequently than with a gasoline fed engine. This in turn prompts auto manufacturers to be equally reluctant to build and sell a product they think will have little commercial success [12]. The lithium-air powered vehicle could change all of this. With an energy density equal to that of gasoline, electric cars running on their system will be able to achieve similar mileage per charge as the combustion engine vehicles do per fueling. This eliminates the customer hesitation for purchasing electric vehicles, and should thereby eliminate any hesitation for the automobile industry to manufacture these vehicles.

Prominent companies such as Tesla—receiving additional funding from other electronic superpowers such as Panasonic—have invested billions in battery manufacturing plants such as their Gigafatory in Nevada in the hopes to further advance and mass produce their current lithium-ion model [1]. From a business point of view this has been seen as somewhat risky since batteries are not yet effective enough to compete with the miles attained per gallon of gasoline. Yet even the lithium-ion battery indicates substantial room for development and improvement, so Tesla and others see the risk as worth it considering the current growth rate of rechargeable batteries, which has been a consistent 5-8 percent in recent years [4]. This steady increase in the development of batteries indicates more advanced battery technology in the years to come; however, there is a limit to how much this battery technology can expand, and within the not so distance future we will see a halt in battery developments, as their theoretical energy densities will have been reached, thus rendering lithium-ion and other rechargeable batteries incapable of improvement. Lithium-air’s density, on the other hand, is so huge that our current technology could steadily improve for years before maximum energy output is reached and improvement is halted.

Because of lithium-air’s energy density, there is a real likelihood that if they are successfully developed, it will no longer be such a risky business venture to invest in their mass production. If completed, there could be a complete revolution in the automobile industry, seeing electric vehicles equipped with lithium-air batteries capable of overtaking current car models and setting a new precedent for how our modes of transportation are powered.

Now, before you invest heavily in the battery technology industry, it’s time for a reality check. The fact is lithium-air has not been successfully completed and patented. So, while it has the potential for revolutionizing the technology of our transportation industry, it has not yet been perfected, and thus has not yet been seriously considered for use by Tesla and Panasonic (much less the smaller electronic companies, who cannot afford to take such risks over theoretical technology). It would be inaccurate to classify lithium-air as anything but a prototype, so it’s no wonder why it has not received international attention as the solution to our energy crisis.

All this being said, don’t give up on Lithium-air quite yet. With its potential for improvement and its theoretical capabilities rivaling that of any battery previously developed, lithium-air deserves the utmost attention and dedication required to turn theory into reality.

**LOOKING TO THE FUTURE**

Having the ability to rival fossil fuels in their energy outputs is a one of the biggest contributors to lithium-air desirability, yet there is plenty more they offer to contribute to the world at large.

Some positive contributions they could make—if widely adopted by society—would be the effective reduction in harmful emissions produced by fossil fuel run vehicles. This would then lead to a decrease in pollution and reduction in global warming—something quite desirable for a generation facing a potential environmental crisis. According to the Environmental Protection Agency (EPA), more than a quarter of the air pollution in the United States can be attributed to harmful emissions produced by fossil fuel driven automobiles [13]. The switch to lithium-air driven vehicles would help significantly eliminate this pollution, seeing as it has the potential to rid the United States and the world of this enormous amount of pollution due to transportation. This exchange of combustion powered engines to lithium-air designs would also contribute to the fight against global warming. Through combustion of fuels like gasoline, harmful compounds such as carbon dioxide are released. Gases of the like, termed “greenhouse gases”, act as an insulator, absorbing and trapping heat from sunlight in our atmosphere and in turn increase the overall temperature of the planet (temperatures that we acknowledge are increasing at an unprecedented rate) [14]. This rise in temperatures has coincided with some major problems we today face as a society (for example, the ice caps melting at an alarming rate) [14]. Any difference we could make to aid this dilemma would be invaluable, and a twenty-five percent reduction in CO₂ emissions would certainly be a start.

This is clear motivation to make the switch from fossil fuels to batteries, yet the energy density limitations of lithium-ion batteries have prevented this exchange from occurring. Realistically speaking, investors are too hesitant to invest in weak output batteries like lithium-ion that cannot compete with gasoline driven cars mile for mile. With lithium-air batteries and their potential for 1700 Wh/kg energy density, this swap is not only feasible but logical, considering lithium air batteries have similar energy densities as most fossil fuels. With lithium-air batteries incorporated into our lives on a large enough scale, we could see a monumental change in the condition of our environment. With the reduction in consumption of harmful fossil fuels and instead utilizing lithium-air as a power source for transportation, we could see
serious problems such as global warming and air pollutions be set on the path to being controlled, and ultimately corrected.

This leads to the prediction that Lithium-air batteries have the potential to make a huge impact on the world around us. Their implementation in electric vehicles could very well eliminate use of the combustion engine in vehicles as we know it. This would lead to a cleaner, more efficient, and drastically more sustainable transportation industry than the one we know today.

SOURCES


ADDITIONAL SOURCES


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