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# Resource Availability and Implications for the Development of Plug-In Electric Vehicles

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**Abstract:** Plug-in electric vehicles (PEVs) have immense potential for reducing greenhouse gas emissions and dependence on fossil fuels, and for smart grid applications. Although a great deal of research is focused on technological limitations that affect PEV battery performance targets, a major and arguably equal concern is the constraint imposed by the finite availability of elements or resources used in the manufacture of PEV batteries. Availability of resources, such as lithium, for batteries is critical to the future of PEVs and is, therefore, a topic that needs attention. This study addresses the issues related to lithium availability and sustainability, particularly supply and demand related to PEVs and the impact on future PEV growth. In this paper, a detailed review of the research on lithium availability for PEV batteries is presented, key challenges are pinpointed and future impacts on PEV technology are outlined.

**Keywords:** electric vehicles; batteries; lithium; Li-ion batteries; resource availability; reserves; lithium intensity; energy; plug-in electric vehicles

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## 1. Introduction

Society relies on minerals and metals for a variety of services. However, these metals and materials are finite resources and therefore, may not always be available when needed. There is an ongoing debate on the availability of certain materials for future use and there is little consensus. Regarding plug-in electric vehicles (PEVs), material availability is critical for long term planning as this can affect efforts to de-carbonize the transportation sector and to increase energy security.

PEVs have the potential to reduce greenhouse gas emissions and dependence on fossil fuels associated with the conventional transportation system [1–6]. This reduction is maximized through the use of renewable energy sources and efficient batteries. As a result, increase in environmental awareness has contributed to electric vehicle sales even during the COVID-19 pandemic when internal combustion engine vehicles sales plummeted [7]. In addition to powering electric vehicles, PEV batteries also have great potential for grid applications [8–11]. Unlike hybrid electric vehicles (HEVs), PEVs rely either partly (plug-in hybrid electric vehicles, PHEVs) or wholly (battery electric vehicles, BEVs) on electricity. A major concern is the availability of some resources used in the manufacture of PEV batteries. A lack of consensus on the availability of resources, particularly lithium leads to concerns about the ability to scale up the manufacture of PEVs [12–14]. Therefore, it is important to examine the availability and sustainability of critical metals that are needed for the manufacture of these low carbon energy technology. To realize a sustainable society, it is particularly important to have adequate understanding of the energy-metal nexus and to address issues related to resource constraints [15].

This study focuses on the issue of lithium availability for PEV batteries. Lithium is essential to making the transition to electrified transportation based on lithium-ion (Li-ion) batteries [16]. Historically, electric vehicles have had a short driving range, but lithium-based battery technologies are capable of longer range and are providing motivation for the switch to PEVs. Li-ion batteries have several advantages including higher energy density and specific power over most other battery technologies. As lithium is a key material used in the manufacture of Li-ion batteries, the demand for lithium for use in the manufacture of batteries for electric vehicles is expected to increase in coming years [17]. Another issue is that lithium is a "geochemically scarce metal" that is found in concentrations that are lower than 0.01% by weight in the earth's crust [18,19]. Based on estimates for medium to long term PEV demand, there is a need for considerable quantities of lithium for PEV battery production. Lithium demand is growing rapidly. Therefore, it is important to examine the availability of lithium in coming years to meet this increasing demand. A comprehensive review of the issues regarding material availability for batteries for PEVs including emergence of alternative battery technologies, supply and demand, economic and geopolitical issues as well as implications for the future of PEVs is presented in the remainder of the paper.

## 2. Energy Storage for PEVs

Several battery technologies exist for use in PEVs including both proven technologies and those still in the development phase. Currently Li–ion, lead acid and nickel metal hydride (Ni-MH) batteries are the dominant battery types for portable rechargeable batteries [20]. However, due to several advantages of Li-ion batteries over other battery chemistries, they have the potential to be the dominant battery type for PEVs, at least in the short to medium term. In the long term, other viable battery technologies may emerge.

When compared to other battery technologies, especially with Ni-MH battery, Li-ion batteries have the best "charge to weight" ratio as well as a lack of memory effect which increases the life cycle of the battery [21]. Below, several current and emerging battery technologies are discussed.

### *2.1. Lead Acid Batteries*

Lead acid batteries are a proven technology commonly used in portable batteries. This type of battery was used in early PEVs such as EV1 by General Motors. A major issue with lead acid batteries is that they have low specific energy and energy intensity [20]. Specific energy for the lead acid battery is in the range of 25–35 W h/kg while specific power is about 150 W/kg [22]. This means that the all-electric range (AER) is short and as such, it is suitable for applications which require short distance travel or applications that can be easily charged in between short trips. Furthermore, the lead acid battery has poor shelf life due to self-discharge. This causes the battery to completely discharge or "die" after a certain amount of time. Lead acid batteries have poor starting performance during cold weather making it problematic during cold winter months. Due to its heavy weight compared to other battery types, lead acid batteries are no longer considered contenders for PEV applications [23].

### *2.2. Nickel Metal Hydride Batteries*

Ni-MH batteries have been successfully used in both HEVs and PEVs. The anode complex is a metal hydride while the cathode is a nickel hydroxide. Ni-MH batteries have relatively good specific power and energy for HEV applications. The energy density of Ni-MH batteries almost doubles that of lead acid batteries [24]. However, the specific energy of Ni-MH batteries does not satisfy the requirements for a fully competitive battery electric vehicle [25]. Specific energy and energy density for the Ni-MH battery are about 70–80 W h/kg and 170–420 Wh/L respectively [26]. The specific power of the Ni-MH battery in HEVs is about 150–400 W/kg [27].

### 2.3. Lithium-Ion Batteries

According to Bini et al. [28], lithium-based batteries are the most important storage systems currently available on the market. Li-ion batteries are commonly used in consumer electronics, including laptops and cell phones, as well as in electric vehicles [29]. Typically, Li-ion batteries consist of graphite anodes [30–32]. Several Li-ion batteries use any one of $LiMn_2O_4$, $LiCoO_2$, and $LiNiO_2$ as cathode materials [33].

Compared to lead acid and Ni-MH batteries, Li-ion batteries have the advantage of higher specific energy [34]. Furthermore, Li-ion batteries have significantly higher energy density compared to Ni-MH and nickel-cadmium (Ni-Cd) batteries [35]. This means that the AER of a PEV using a Li-ion battery can be extended without incurring the high weight penalty experienced in both lead acid and Ni-MH batteries. In addition to their high specific energy, Li-ion batteries have high specific power (500–2000 W/kg) [26]. Furthermore, they have low sensitivity to temperature and have no memory effect [36]. Memory effect, which is observed in Ni-MH and Ni-Cd batteries, causes a battery to gradually lose its maximum capacity when repeatedly charged after only partial discharge. Furthermore, LI-ion batteries have output voltage, about 4.1 V for a single cell, that is approximately two times higher than that of lead acid batteries and three times higher than that of Ni-MH and Ni-Cd batteries [33]. This higher output voltage results in less Li-ion cells in a battery of a given voltage [37]. A further advantage of Li-ion batteries is their long cycle life [38].

A concern about Li-ion batteries is related to safety. Li-ion batteries, unlike other secondary batteries, have high oxidizing and reducing electrode materials and flammable electrolytes that may lead to poor thermal stability (due to thermal runway) and can cause short circuits [39]. However, safety is being improved by employing different strategies including the use of shutdown separators, use of additives in the electrolyte and employing non-flammable electrolytes [40,41] thus increasing the appeal of Li-ion batteries. Despite the safety concerns, which is being improved, low weight, high energy capacity, high power density, long service life, and low price make them one of the best solutions for current PEVs [42].

### 2.4. Other Energy Storage Technologies

In addition to the types of batteries described above, other types of energy storage exist or are in varying stages of development for use in PEV applications. Ni-Cd was successfully used in the past but was banned due to the toxicity of its components [43]. Molten salt batteries including zero emissions batteries research activity (ZEBRA) batteries have been used in some commercial electric vehicles, but have multiple limitations primarily linked to high temperature needed to maintain the metal-salts electrolyte in a liquid state [44]. Furthermore, ZEBRA batteries suffer from low power density and high processing temperature. In comparison, lithium batteries operate at room temperature and do not require pre-heating.

Fuel cells are promising for use in PEVs. Fuel cell electric vehicles (FCEVs) are electric vehicles that generate electricity by a fuel cell that uses hydrogen as an energy source. FCEVs use the electricity generated from a fuel cell to power an electric motor instead of relying on a battery only. The advantages of FCEVs include higher driving range (over 500 km) and faster refuelling (3–5 min) than current battery electric vehicles, but their deployment is still much lower compared to PEVs because of high fuel cost and purchase prices [17,20].

Success of these battery technologies will be dependent on technological improvement. According to Shukla and Kumar [23], much work is still needed before batteries can have quality performance with 5000 deep discharge cycles which is the requirement for such batteries. For PEVs, where the battery is the sole power provider or provides a significant amount of energy used to power a vehicle, there is need for batteries that have deep depletion capacities to accommodate operation of the vehicles.

Other lithium-based chemistries currently under development include Li-sulfur, and Li-air batteries [45]. These batteries have the potential for better battery performance in terms of specific energy. Theoretically, the aforementioned battery technologies can achieve specific energy of more than 2500 Wh/kg [43]. This improvement in specific density translates to improved driving range of PEVs compared to Li-ion batteries. Li-sulfur batteries have received increased attention because of the 4.5 times higher theoretical lithium capacity and lower cost of sulfur cathodes relative to typical Li-ion insertion cathodes. However, sulfur cathodes have several challenging characteristics, and they lead to low cycle life and high self-discharge rates, both of which are problematic for electric vehicle energy storage technologies [20]. Li-air batteries offer a further improvement in specific energy and energy density above Li-sulfur batteries because of their use of atmospheric oxygen to produce power. However, their demonstrated cycle life has been much lower and improving this challenge has proved difficult [20]. Issues related to power density, overpotential, energy density and cycle life need to be addressed. However, progress in the development of these alternative lithium-based batteries may lead to an increase in the overall demand for lithium for PEVs. The transition from Ni-MH batteries to Li-ion battery began after decades of research and development for Li-ion batteries. Therefore, it should be expected that transitioning to Li-air batteries will follow the same developmental cycle [46].

Other possible alternatives to Li-ion batteries include sodium air and zinc air batteries. Zinc-air batteries have the potential to be used in future electric vehicles because of their advanced technology status and higher practically achievable energy density, despite a lower specific energy than Li-air batteries. However, their poor specific power and energy efficiency are a challenge [20].

Currently, there are few non-lithium-based batteries that can compete with lithium batteries. Therefore, substitution of lithium-based chemistries with other chemistries is highly unlikely in the short to medium term. However, with significant technological improvements, other alternatives may become competitive in the long term. For now, the properties of lithium batteries including high power density, high energy density, and long cycle life, make them a more popular choice than other battery technologies.

## 3. Lithium End Use

Lithium is used by a variety of applications because it is a light metal, is very reactive and has a low thermal expansion coefficient [47]. Lithium has high energy and power density due to the fact that it is the lightest solid metal with high electrochemical potential [48]. As a result, it is expected that lithium-based battery technologies will be the energy storage of choice for PEVs in both near term and probable long term [49]. The various uses of lithium are shown in Figure 1. In 2015, secondary batteries, including PEV batteries, became the largest demand for lithium, outgrowing ceramics and glass applications which previously represented the highest demand. Rechargeable batteries, partly driven by PEV demand, are currently dominating lithium use. Miao et al. [50] estimate that Li-ion batteries for electric vehicles will account for the greatest proportion of the battery market in the next decade at a dramatically increasing rate. Furthermore, according to Rosendahl and Rubiano [16], grid storage which currently accounts for a marginal share of lithium end use can grow significantly with the expansion in the use of renewable energy resources such as wind and solar. Based on the projected importance of lithium for future electrified transportation and renewable energy storage, lithium has become a strategic resource [51].

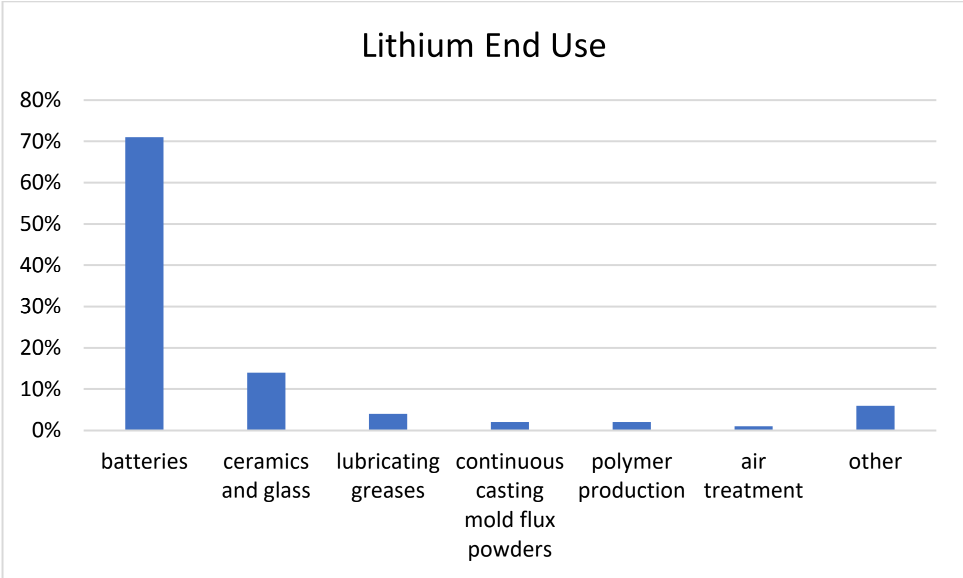


**Figure 1.** Lithium end use [52].

## 4. Occurrence and Availability of Lithium

### *4.1. Geological Overview*

Main types of lithium deposits include brine, minerals, and sea water. Most of the extractable lithium resources are found in minerals and brines. Currently, only a handful of the over 120 lithium-containing minerals known have high concentrations [53]. Some minerals that contain lithium include pegmatites which comprises of spodumene, petalite, lepidolite and eucryptite [54]. Brines constitute the largest and cheapest sources of lithium worldwide. They are located mainly in the salars of South America, particularly the Salar de Atacama in Chile.

Seawater is estimated to contain about 44.8 billion tons of recoverable lithium [55], however, it is uncertain if this deposit is economically feasible to extract and will likely prove to be cost intensive. Lithium concentration in seawater is about 0.17 ppm compared to 1000–3000 ppm in Salar De Atacama [23]. Other issues such as the high concentrations of magnesium available in deposits make extraction of lithium in sea water more complicated due to the similarities in the concentration of both metals [23]. Currently, lithium deposits in sedimentary rocks are not an economically feasible source of lithium considering the low cost to extract the lithium available in brines. Furthermore, a potential source of lithium is the waste streams produced from coal-fired power plants, mining operations and desalination plants [56].

Lithium is produced in various forms such as lithium carbonate, lithium chloride, and lithium hydroxide. However, Li-ion batteries are usually manufactured using lithium carbonate ($LiCO_3$) [57]. According to the United States Geological Survey [52], the United States, Chile and Argentina produce lithium from brine while Australia produces lithium from mineral-based sources. China produces lithium from a combination of brines and minerals.

### *4.2. Lithium Resources and Reserves*

It is important to distinguish between resources and reserves. These definitions determine the quantity of available in the earth crust and the amount that is available for use. Resources are defined by the United States Geological Survey [58] as "*a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible*." On the other hand, reserves are defined as the part of resources that can "*be economically extracted or produced at the time of determination*." [58].

Resources have little relevance for actual supply because merely identifying lithium resources does not mean extraction is feasible. Therefore, reserves, not resources should be considered for production. Reserves are dynamic and can vary based on several factors such as economic and non-economic factors. Some non-economic factors that affect lithium reserves factors include political, regulatory, and social factors [53,59]. Furthermore, innovation and technology can significantly influence the economic feasibility of lithium extraction. For instance, an improvement in technology can make more resources accessible i.e., become reserves. Known lithium resources and reserves are distributed in several countries. It is interesting to note that the current distribution of lithium is less geographically diverse than oil. Figures 2 and 3 show the geographic distribution of lithium reserves and resources respectively [52]. This geographic distribution raises concerns about the geopolitical implications of such a distribution. One concern is that lithium may be subject to similar supply vulnerabilities that other elements such as rare earth elements (REE) have been subjected to in the past. For example, in 2011, there was a spike in REE prices because China, which is a major REE producer, restricted supply. The largest share of lithium reserves and production exists in Chile which produces lithium from salt lakes or salars, particularly Salar de Atacama. Supply is stable presently, but this could change in the future.

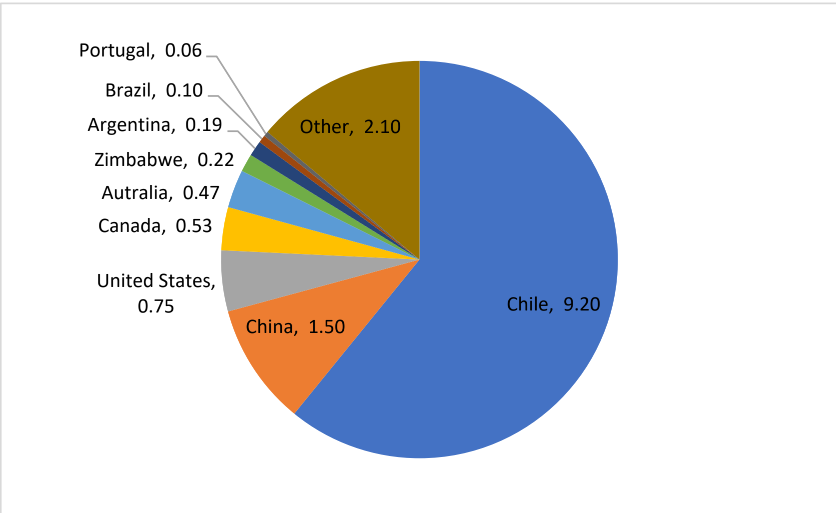


**Figure 2.** Lithium reserves (in million tons) [52].

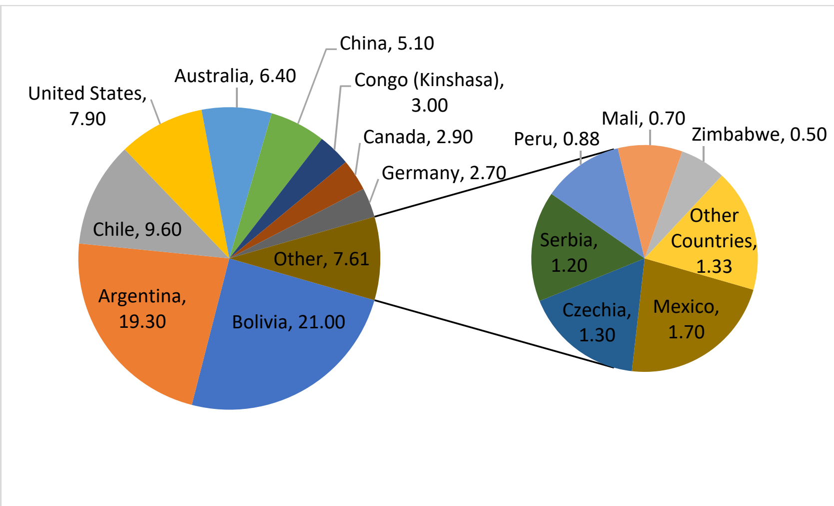


**Figure 3.** Lithium resources (in million tons) [52].

In addition to USGS data, there is a wide range of information on lithium available from several sources as shown in Table 1. These differing estimates are because of the differences in ways that reserves are classified, and the number of deposits included. Given the increase in demand for lithium, and production, as well as the constant change and increase in reserve classifications, one can conclude that lithium exploration and production is developing [57]. Therefore, reserve estimates have changed significantly over time [60]. Evidence of this is shown in Table 1, where more recent studies show significantly higher lithium reserves [61] and resources [52,61] than earlier studies.

**Table 1.** Comparison of lithium estimates.

| Reference | Lithium Resources | Lithium Reserves |
|---|---|---|
| | (Million Tons) | |
| Ambrose and Kendall [61] | 99.5 | 37.5 |
| Clarke and Harben [62] | 39.4 | _ |
| Evans [63] | 29.9 | _ |
| Fasel and Tran [64] | 9.4–21 | 4–6 |
| Grosjean et al. [65] | 37.1–43.6 | _ |
| Gruber et al. [54] | 38.7 | 19.3 |
| Kesler et al. [66] | 30.9 | _ |
| Kushnir and Sandén [67] | _ | 30.0 |
| Mohr et al. [68] | 71.3 | 23.1 |
| Speirs et al. [57] | 65 | 15.0 |
| Tahil [14] | _ | 3.9 |
| Yaksic and Tilton [55] | 64 | 29.4 |
| USGS [52] | 86 | 21.0 |

### *4.3. Recycling*

A major concern about the sustainability of electric vehicles in general is the issue of end-of-life battery disposal, particularly as electric vehicles grow in market share [69]. A potential source of supply of lithium is from recycling. Currently, lithium is only recycled in small quantities. According to a 2011 United Nations Environment Program report, end-of-life recycle rates for lithium was less than 1% [70]. Since then, the first U.S. recycling facility for Li-ion vehicle batteries began operating in 2015 and by 2020, seven other companies located in Canada and the United States began recycling or intended to begin recycling lithium metal and Li-ion batteries [52]. Due to increased demand for lithium by battery applications, there are increases in regulations to guide the proper disposal of these batteries. Battery manufacturers are currently considering mitigating the dependency on lithium by recycling lithium batteries at the end of their lifecycles. However, there is an issue of the economic feasibility of recycling lithium as batteries contain only a small proportion of lithium in the form of lithium carbonate compared to the weight of the battery. In addition, lithium is inexpensive when compared to other elements that make up the battery such as nickel or cobalt. Overall, the average cost of lithium compared to the average cost of the battery is very low. According to Kushnir and Sandén [67], raw lithium accounts for about 1–2% of the electric vehicle battery total cost [67].

Therefore, even though lithium is 100% recyclable, most lithium used in batteries are not recycled due in part to the relatively low cost of newly extracted lithium. Currently, recycled lithium is much more expensive than newly produced lithium. Thus, it is not competitive for battery manufacturers to purchase recycled lithium at a much higher price when lithium from brines is produced at much lower prices. Since it is not economically feasible to extract lithium from batteries due to the low price of newly produced lithium, the focus is on cobalt and nickel which are more expensive [71]. Lithium and manganese are largely neglected. However, with the increasing demand for lithium particularly by automotive applications, recycling is expected to play an important role in the estimation for future viability of lithium for PEV battery production. As PEV demand increases in coming years, and as such demand for Li-ion batteries increases, lithium battery recycling will be critical. In coming years, large quantities of PEV batteries will be at the end of their lifecycle and therefore may be economically feasible to recycle. In the medium to long term, closed loop recycling will be necessary to prevent price fluctuations and potential supply disruptions. Hence, extensive recycling solutions will be critical to the future of PEVs powered by lithium batteries. In addition to the ability of effective lithium recycling to alleviate the issue of limited lithium supply, recycling can help prevent hazardous elements such as zinc, copper, nickel and manganese from ending up in municipal solid waste streams due to improper disposal of spent batteries [56,72,73].

The most common process to recover lithium from used Li-ion batteries is the hydrometallurgical process [74]. The procedure typically involves physical and chemical processes to complete the following steps: end-of-life lithium-ion batteries are dismantled and separated. Cathode materials are dissolved and leached with hydrochloric acid. And then, lithium and other metals are separated and extracted via solvent extraction, chemical precipitation, and electrochemical process [75]. A variety of other chemical processes can also be used. The most common chemical processes include heat treatment, acid leaching [76–78], alkaline leaching [79], or biological leaching [80]. A separation stage follows these processes to recover the metals through chemical precipitation or solvent extraction [81]. Many other methods to recover lithium and other high value metals from end-of-life Li-ion batteries have also been reported [71,82–89].

Challenges facing lithium recycling are mainly price-based because battery recycling facilities need to recover secondary lithium that is competitive with newly produced lithium. As a result, there is no major lithium recycling infrastructure available dedicated to automotive batteries. However, there is a significant potential for recycling of lithium from spent batteries [16]. Gaines and Nelson [90] estimate that lithium recovered from recycling can satisfy between 50–63% of the demand. Without lithium recycling and with rising prices, Rosendahl and Rubiano [16] argue that lithium scarcity will be increasingly evident.

Since recycling end-of-life batteries is not so desirable because of large material and energy losses in the process. Repurposing the used batteries for a different application has emerged as an alternative to recycling. Since batteries may no longer be fit for automotive use after 20% loss of their capacity, second use in stationary energy storage application is an attractive option [91].

### *4.4. Future Supply*

Estimates of lithium reserves and resources vary considerably between different studies and concerns about production rates of lithium being able to meet growing demand have not been sufficiently addressed [53]. A key challenge is the uncertainty about raw material availability [92]. One major factor that will influence lithium availability is the discovery of new deposits. As previously pointed out, it is very likely that additional lithium resources and reserves will be discovered with time, therefore current production and reserve estimates will continue to change over time.

Estimates for future production and availability range widely; from 60,000–110,000 tons for production by 2020 and from 2–20 million tons of available lithium through 2100 and beyond [57]. Actual global lithium production in 2020 was 82,000 tons [52]. This number will likely increase if the price of lithium goes up. For instance, Yaksic and Tilton [55] estimate that 22 million tons of lithium will be available if the price ranges from $1.40 to $2. This number increases by over 100% if the price ranges between $7 and $10 per lb of lithium carbonate, allowing lithium to be extracted from sea water.

### *4.5. Other Factors That Affect Lithium Supply*

In addition to production capacity and availability of reserves, other factors affect the supply of lithium. They include geopolitics, competing applications, policies and regulations and competing demand. Usually, the risks of geographic distribution are undervalued [93]. However, the geographic distribution of lithium may have implications for energy security. This is because lithium is considered a strategic material by many countries and as a result, future supply may be limited as countries transition to a PEV-based transportation system. As previously mentioned, lithium reserves are located in a limited number of countries and as such lithium may be prone to the same issues that are facing the oil industry where political instability in a major oil producing country has a ripple effect worldwide. Currently, about 87% of reserves are located in five countries: Chile, Australia, China, Argentina, and the United States. These countries are mostly politically stable at this time, but this stability is not guaranteed in the coming decades. Furthermore, Bolivia which currently has the most significant lithium resources in the world and could become a major producer in the future is currently faced with both technical and political challenges. Therefore, geopolitical dynamics may limit lithium supply in the future, even if lithium reserves exist. For instance, mining regulations may limit the amount of lithium extracted from certain deposits. A study by Shao et al. [94] found that competition between lithium importing countries became increasingly intense between 2009 and 2018. This competition is expected to increase as more countries make the transition to electrified transportation and renewable energy sources. From a country perspective, it may be necessary for governments to provide incentives such as subsidies for recycling industries in order to enhance resource resilience [95]. It is also necessary to consider the impact of lithium production on the environment and human rights by implementing comprehensive normative frameworks and human rights practices along the entire value chain together with significant investments in environmentally friendly techniques [4].

Other factors that have the potential to affect supply include recycling regulations and technology, competing demand and lead time. Currently, recycling of lithium is insignificant. Lack of recycling in the future will drastically reduce the amount of lithium available for use. Also, in a scenario where there is a significant increase in demand, production infrastructure will need to be expanded which may delay supply. Finally, technology advancement, particularly progress in recycling technology which can recycle lithium from automotive battery at a large scale, will be crucial.

## 5. Demand Forecast for Lithium

Different scenarios for global lithium demand exist due to the uncertainty surrounding future battery sizes and the lithium intensity for these batteries. Furthermore, demand will be influenced by the rate of consumer adoption [96]. Currently, a wide range of battery sizes and material intensity is estimated for lithium. Battery sizes for PEVs are not standardized and, as a result, manufacturers can produce various sizes of PEVs with different weights and AER. A major concern surrounding PEVs is the range limitation. Most customers expect the same amount of range in PEV, particularly the battery electric vehicles, which they would get in a conventional fuelled vehicle (~300 miles). Therefore, it is very likely that vehicle manufactures will focus on extending the range of the vehicle rather than on reducing material intensity [57]. This means that if it is cost effective, both PEV battery sizes and lithium demand will increase in coming years.

### *5.1. PEV Battery Size*

A major focus for future PEVs is the all-electric range which is determined by the rated energy of the battery also referred to as the battery size in kWh. Currently, PEV battery sizes are not standardized and as a result there is a wide range of battery sizes in PEVs on the road today. In general, the larger the battery, the higher the AER of the battery is. This implies that larger batteries are more desirable. However, PEV battery cost increases with the size of the battery. Furthermore, the weight of the battery also increases with battery size. A larger battery size adds to the overall weight of the vehicle and has adverse effects on the efficiency of the vehicle. However, it is expected that as battery technology matures, the size of batteries can be increased without drastic impact on cost and weight.

Table 2 shows characteristics of some BEVs currently in the market. Battery sizes of these vehicles range from 38.3 kWh to 95 kWh while AER range anywhere from 153 miles to over 320 miles. As observed from the table, most models in the table use Li-ion batteries.

**Table 2.** Some Battery Electric Vehicles in the market [97].

| Vehicle | Battery Type | Battery Size (kWh) | All Electric Range (Miles) |
|---|---|---|---|
| 2019 Tesla Model 3 AWD | Li-ion | 75 | 322 |
| 2020 Tesla Model Y AWD | Li-ion | 75 | 316 |
| 2020 Chevrolet Bolt EV | Li-ion | 66 | 259 |
| 2020 Hyundai Kona EV | Lithium polymer | 64 | 258 |
| 2020 Nissan Leaf SL+ | Li-ion | 62 | 215 |
| 2019 Audi e-tron | Li-ion | 95 | 204 |
| 2020 Porsche Taycan 4S | Li-ion | 79.2 | 203 |
| 2020 Hyundai Ioniq EV | Lithium polymer | 38.3 | 170 |
| 2019 BMW i3 EV | Li-ion | 42.2 | 153 |

### *5.2. Lithium Intensity*

Determining the lithium content per unit energy stored in the battery or lithium intensity is necessary to calculate demand for lithium in PEVs. However, this estimation is complicated and, as a result, there are different estimations by various studies which use different methods in their calculation. This difficulty in estimation can be largely attributed to the fact that most information on battery chemistry is proprietary to the battery manufacturers and therefore not easily accessible to the public. In addition, lithium intensity fluctuates depending on the battery chemistry. Methods such as the use of industry data, by direct measurement of a battery and making assumptions about battery composition, and estimation by accounting for real world operating condition have been used [57].

PEVs require significantly larger batteries compared to HEVs. Factors that affect lithium intensity include battery chemistry, size, and the rated performance of the battery. Typically, the rated capacity of a PEV is higher than the actual capacity. This means that PEVs generally use less than their rated battery capacity. Lack of available information and variations in lithium intensity across different battery chemistries together with energy losses and overspecification of lithium intensity makes it challenging to calculate lithium intensity. As a result, researchers, some using different methods, have provided estimates of lithium intensity that widely vary, ranging from 0.108 kg Li/kWh to 0.563 kg Li/kWh [57].

### *5.3. Future Demand*

Various studies have addressed scenarios for future demand of lithium by different technologies. These range from overly optimistic scenarios to very pessimistic ones. However, there are many uncertainties associated with examining future lithium demand. One study estimates that lithium demand will reach 600,000 t/yr by 2050 [98]. A different study, that assumes that future lithium demand would be driven by production of lithium batteries for electric vehicles, estimates that lithium demand will increase to 400,000 t/yr by 2050 (assuming 0.15 kg of Li/kWh) [68]. The authors conclude that under a best estimate scenario, a 100% penetration of electric vehicles cannot be achieved by lithium supply. Furthermore, Maxwell and Mora [99] estimate a demand of over 500,000 t/yr by 2025 and over 1,500,000 t/yr by 2037.

Another study determines the energy storage potential or the "*maximum amount of energy (in TWh) which can be stored by the complete exhaustion of the limiting element of the battery couple*" [49]. The limiting element in each battery couple sets a limit on the number of couples that can be produced because it will be depleted before other elements in the couple. For instance, in a $LiFePO_4$ chemistry, lithium is the limiting element because it is the scarcer metal. The calculation assumes a battery size of 40 kWh and that 100% of the market for the limiting element is used for the manufacture of batteries. This calculation is carried out for many different battery technologies including those that are not suitable for PEV applications. The study uses both short term goals (10–15 years) and long-term goals (40–50 years). Nearly all the battery chemistries can meet the short-term goal (in terms of availability). Furthermore, the results indicate that a significant expansion in production will be needed to meet long term electric vehicle goals.

The BLUE map from the International Energy Agency (IEA) [100] provides information for the annual sales of PEVs by 2030 and 2050. In the BLUE map scenario, $CO_2$ emissions levels from transportation is reduced by 30% in 2050 compared to 2005 levels. A more recent study by IEA [17] uses a stated policies scenario (STEPS) and a sustainable development scenario (SDS) to forecast the electric vehicle market. STEPS reflects all existing policies, policy ambitions, and targets that have been legislated for or announced by governments around the world. SDS assumes that all electric vehicle-related targets and ambitions are met, even if current policy measures are not deemed sufficient to stimulate such adoption rates. PEV sales forecast for the BLUE map are higher compared to STEP but lower compared to SDS in 2025 and 2030. The forecast of PEV sales based on the BLUE Map is shown in Table 3. Table 4. shows the PEV sales forecast based on STEPS and SDS.

**Table 3.** PEV Sales based on a BLUE Map (millions per year) [100].

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| PHEV | 0 | 0.7 | 4.9 | 13.1 | 24.6 | 35.6 | 47.7 | 56.3 | 59.7 |
| BEV | 0 | 0.3 | 2 | 4.5 | 8.7 | 13.9 | 23.2 | 33.9 | 46.6 |
| Total | 0 | 1 | 6.9 | 17.6 | 33.3 | 49.5 | 70.9 | 90.2 | 106.3 |

**Table 4.** PEV global sales by scenario (millions per year) [17].

| | STEP | | | SDS | | |
|---|---|---|---|---|---|---|
| | 2020 | 2025 | 2030 | 2020 | 2025 | 2030 |
| PHEV | 0.969034 | 4.226493 | 7.761233 | 0.969034 | 6.060351 | 10.984190 |
| BEV | 2.008024 | 7.114262 | 14.370678 | 2.008024 | 11.939460 | 28.687724 |
| Total | 2.977058 | 11.340755 | 22.131911 | 2.977058 | 17.999811 | 39.671914 |

Typically, annual global demand of lithium by PEVs can be estimated by multiplying the number of vehicle sales by the battery capacity and the lithium intensity. This is challenging to calculate given the wide range of battery sizes and the differences in lithium intensity per battery. However, a more generalized calculation can be useful in providing insight into future lithium demand. Therefore, BLUE map scenarios (See Table 3) from the International Energy Agency [100] which provides projections for PEV sales is used for calculating demand of lithium from PEVs from 2025 to 2050 as shown in Figure 4. This calculation assumes that Li-ion batteries will account for 100% of PEV battery market and uses lithium intensity of 160 gLi/kWh [67] for this analysis. The battery sizes of 75 kWh, and 17 kWh currently employed in the 2020 Tesla Model 3 AWD (BEV) and 2021 Honda Clarity (PHEV) are used for this calculation. Given that it is expected that battery sizes (and associated range) of PEVs will increase in the future, this calculation can be considered conservative.

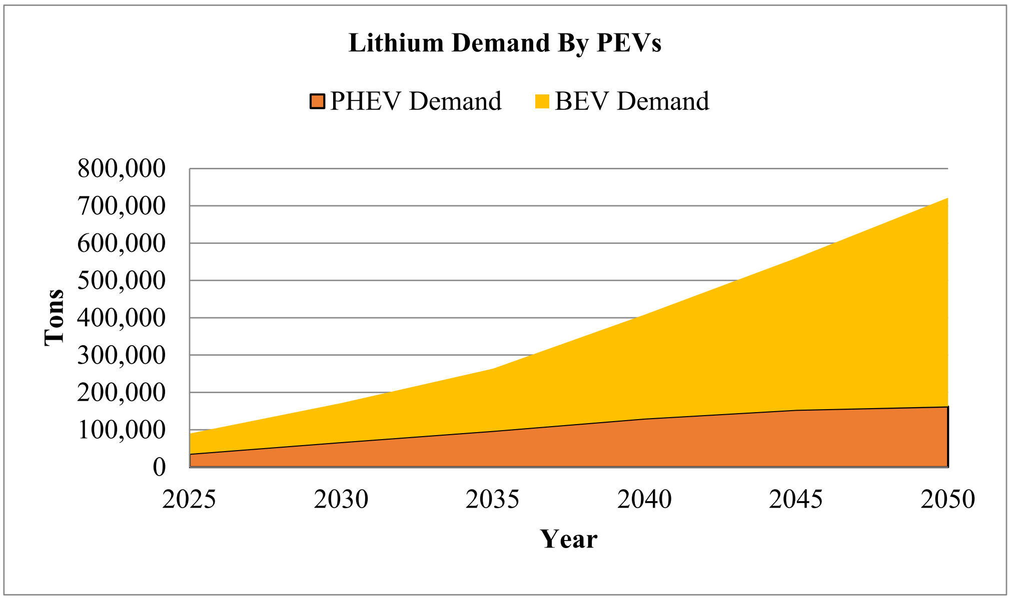


**Figure 4.** Projected Lithium demand from PEVs.

The calculation in Figure 4 shows that lithium demand from PEVs in 2030 and 2050 will be about 171,312 tons and 721,584 tons, respectively. This figure is well above the current production of 82,000 tons [52] and will require a significant ramping up of the current production capacity. According to the International Energy Agency [101], the estimated global lithium production is about 300 kt and about 600 kt in 2030 and 2050 respectively based on a sustainable development scenario. This number also raises concerns about the availability of lithium for use in future PEVs. Currently identified reserves by United States Geological Survey [52] of about 21 million tons will be exhausted if annual sales of vehicles continue at the 2050 rate. However, recycling will be critical at this stage for providing secondary lithium. The total lithium available during this time can be significantly higher if used lithium is recycled at high levels. Battery life of PEVs is projected to be about 10 years; therefore, by 2030 the volume of PEV batteries available for recycling should be considerable. Identification of new reserves will also be crucial. It is important to point out that this calculation does not consider other end uses that require lithium. Demand from these other areas will likely increase in the future, therefore PEV batteries will have to compete with these applications for lithium.

## 6. Conclusions and Future Perspectives

This paper presented an overview of essential trends, discussed the state of the literature, and examined the issue of material availability for future PEV battery technologies. Energy storage is a key consideration for long term planning for PEVs as part of efforts to reduce the negative impacts of the transportation sector. Therefore, it is important to ensure that critical materials needed for battery manufacture are available. Lithium is critical in achieving a successful transition to a more sustainable transportation sector as it is a key component of Li-ion batteries. Due to several advantages over currently available batteries, Li-ion batteries appear to be the energy storage of choice to be employed in PEV applications in coming years. However, lithium is a finite material and therefore increases in demand of PEV will mean further extraction of lithium. It is expected that this demand will grow considerable in the coming years as the transition to PEVs intensifies.

PEV batteries are not the sole end use of lithium. In 2015, secondary batteries, including PEV batteries, became the largest demand for lithium, surpassing ceramics and glass applications which previously represented the highest demand for lithium. Non-automotive rechargeable batteries are a fast-growing segment of lithium demand. These batteries which are used is several applications including electronic devices like cell phones and laptops will likely be competing for lithium with PEVs. Furthermore, global demand for lithium for stationary energy storage will increase considerably with the transition to renewable sources of energy. Other applications that use lithium such as lubricating greases, pharmaceuticals, and continuous casting will also be part of this competition for lithium. It is also possible that new demand for lithium, such as from fusion applications, may emerge.

The findings from this study indicate that future lithium availability could be problematic in coming years. Calculations of demand of lithium using the BLUE map scenarios of IEA suggest that future lithium demand from PEVs far exceed the current production and some projected scenarios for future production. As the demand increases it will be necessary to significantly increase production capacity. By 2050, demand rises to 721,584 tons /yr. Even if this demand remains constant beyond 2050, it will cause a major strain on available reserves (assuming 21 Mt as estimated by the United States Geological Survey). This is without considering other lithium end uses and the effect of recycling. Substitution of Li-ion batteries with alternative battery technologies will ease the pressure on lithium reserves. However, in the short to medium term, it is likely that lithium-based batteries will continue to be used significantly in PEV applications. In the long term, one way to address rapid increases in lithium demand is to evaluate nonconventional sources such as sea water. It is also crucial to extend the life of available lithium reserves through developing more efficient recycling infrastructure for used Li-ion batteries. Therefore, lithium recycling has the potential to play a key role in the future supply chain for Li-ion batteries. A high degree of recycling can also significantly reduce improper disposal of spent Li-ion batteries and the associated negative impacts on the environment and health. In the future, it is critical to develop recycling technologies which focus on better addressing hazardous and toxic materials produced during the recycling process. Furthermore, it may be necessary to develop new battery chemistries that do not need lithium but have better performance and can serve as alternatives to lithium-based ones. Another way to reduce the demand on lithium is to develop new chemistries or optimize existing ones so that they use less lithium.

Lithium has become a global strategic resource due to competing demand from a wide range of applications. Therefore, a major problem to consider is the location of lithium deposits. The switch from oil to lithium is driven by a need to reduce dependence on oil. However, lithium may present similar problems. For example, instability in a major lithium producing country could mean a disruption of supply for other countries that do not have lithium deposits. This may also mean other countries will have to mine more expensive deposits, leading to an increase in the price of lithium. Therefore, future supply may not only be constrained by lithium availability in the earth crust but also by geopolitical dynamics. Hence, diversifying lithium supply chain, given the geopolitical constraints, is key to reducing supply chain risks. This can be accomplished by having mining, production and recycling operations that are geographically dispersed and can reduce supply chain disruptions in the event of local interruptions. It is also necessary to consider environmental impacts of lithium extraction and use along the entire value stream. As the number of lithium mines increase with rising demand, it is necessary to examine the regional impact of mining from both social and environmental perspectives including impacts on water use, indigenous rights, and the environment. In addition to the economic benefits derived from lithium mining and use, environmentally and socially friendly extraction and recycling processes for lithium together with a sustainable supply chain are key to improving the sustainability of PEVs.

Lithium availability is further limited by several factors including economic, technological, and geopolitical ones. To ensure that the growth in the use of PEVs is not adversely impacted, it is necessary to investigate alternative battery technologies. Currently, recycling is not significant. However, as the use of PEVs becomes widespread, recycling will play a key role. Estimating long term lithium supply is faced with many uncertainties. For instance, it is difficult to assess the extent of recycling for the future of PEVs. Therefore, significant changes can occur by 2050. This includes the possibility of discovery of considerable new reserves and the emergence of new battery technologies that greatly outperforms present day battery chemistries. Therefore, future work can develop more robust forecasts for lithium availability and study the various uncertainties related to the lithium supply chain for PEV batteries as demand increases and as mining, recycling and battery technologies evolve.

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