

McMaster University

Faculty of Earth and Environmental Sciences

ENVIRSC 4MI3: Independent Study in Earth and Environmental Sciences

Problematic Materials in Electric Vehicle Development



(Hudson, 2019)

By Justin Isenberg-Verrall

Under supervision of Dr. Luc Bernier

August 5th, 2021

Table of Contents

0.	Abstract	...	3
I.	Introduction	...	4
II.	Problems with Various Materials	...	7
	A. Lithium	...	7
	B. Cobalt	...	12
	C. Nickel	...	16
	D. Manganese	...	20
	E. Graphite	...	21
	F. Rare Earth Elements	...	22
III.	Potential Solutions	...	26
	A. Extraction	...	26
	1. Lithium	...	26
	2. Cobalt	...	28
	3. Nickel	...	30
	4. Manganese	...	31
	5. Graphite	...	32
	6. Rare Earth Elements	...	33
	B. Recycling	...	35
	1. Batteries	...	35
	2. Electric Motors	...	37
	C. Emerging Electric Vehicle Technologies	...	38
	1. Batteries	...	39
	2. Electric Motors	...	41
IV.	Conclusions	...	43
V.	References	...	44

0. Abstract

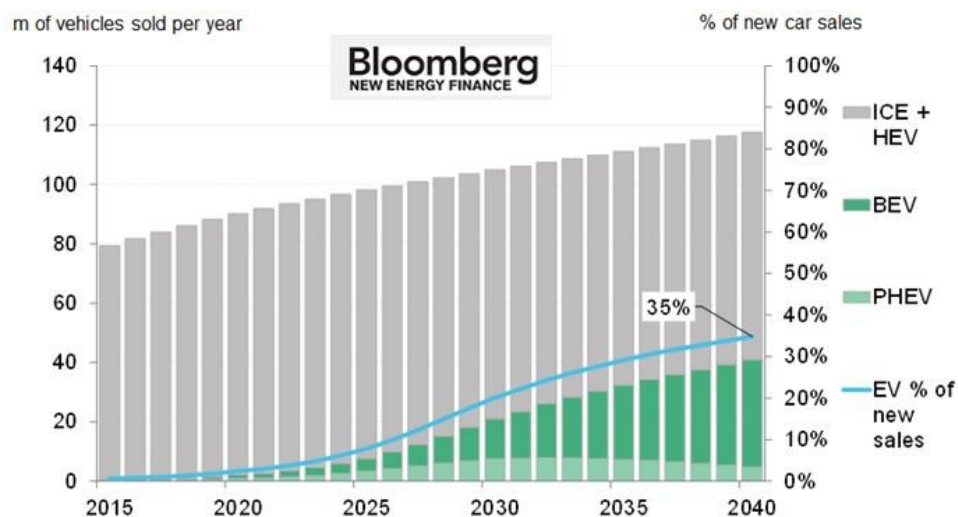
Electric vehicles (EVs) will be rapidly adopted in the next two decades because of emissions targets, technological advancements, sinking prices and industry development. These factors provide the astonishing projection of a 9000% increase of EV sales from 2015 to 2040. There are problems associated with certain materials used in electric vehicle development, and these problems are projected to grow exponentially, along with EV sales. This paper first describes these problems and follows with their potential solutions. The materials discussed are lithium, cobalt, nickel, manganese, graphite and rare earth elements. The problems associated with these materials include environmental destruction, health-damaging extraction operations, inhumane working conditions and supply deficiencies. The solutions entail new and/or updated extraction methods, new recycling processes, and new and/or improved electric vehicle technologies. The conclusion states that these problems are *immense*, that adequate solutions *do* exist, and that *swift* action is necessary to successfully introduce a sustainable electric vehicle industry.

I. Introduction

Electric vehicle sales increased by 43% in 2020, and are projected to be at least 35% of new car sales by 2040 (Dans, 2021) (NEF, 2016). This translates to 41 million electric vehicles (EVs) on the road, or a 9000% growth from 2015. This mass adoption of EVs, or ‘EV boom’, is anticipated because of the following four reasons (Dans, 2021). Firstly, the climate crisis, along with other environmental problems, has been universally realized as one of humanities largest current challenges. In an effort to reduce the effects of climate change, governments around the world have set emissions targets and other environmental regulations. Examples include the United States, which will require almost all new cars to be electric by 2030, the EU, which will require at least 30 million EVs on the road by 2030, and China, which targets 60% of new vehicle sales to be electric by 2035 (Harvey, 2021) (Patel, 2020) (Bloomberg News, 2019).

Figure 1

Electric Vehicle Sales Projections (NEF, 2016)



Secondly, several technologies (batteries, motors, thermal management, power electronics, etc.) have improved drastically over the past decade (Dans, 2021). Some of the most important of these technological strides are batteries costing under \$100 per kilowatt-hour, the ability to travel over 500 km on a single charge, and battery thermal management systems which can safely and efficiently control the temperature of the battery pack (Dans, 2021) (Tesla, 2021). Thirdly, the cost of EVs has significantly decreased over the past few years due to more efficient systems and processes, lower material costs, government incentives and other causes. These recent changes will allow EVs to compete with internal combustion vehicles both performance-wise and financially within the next few years (Dans, 2021).

Lastly, over the past five years major vehicle producers around the world have poured their resources into developing EVs as quickly as possible. Industry giant GM has committed to a complete transition to only EVs, Volkswagen has launched its electric vehicle line 'ID', Hyundai and Apple are collaborating on an EV line, and so on. In the startup world; Tesla has produced over 1 million vehicles, Rivian; a promising electric truck startup, has announced an investment round of \$2.65 billion, and numerous other startups around the world are developing EVs for different applications (Richter F. , 2020) (Rivian, 2021). These factors will completely reshape the automotive industry in the next 10 years, signifying the demise of internal combustion vehicles and the mass adoption of electric vehicles.

EV production requires many materials that are not used in internal combustion vehicles. This is because the material properties needed for electric motors, battery packs, power electronics, and other components, are quite different than the needs of internal

combustion systems. Some of these materials have daunting problems associated with their extraction and/or post-use. These materials are lithium, cobalt, nickel, manganese, graphite, neodymium and dysprosium. The first section of this paper describes the challenges associated with these ‘problematic materials’. The second section outlines potential solutions to these problems. The paper concludes with general remarks, formed from the findings presented below.

II. Problems with Various Materials

A. Lithium

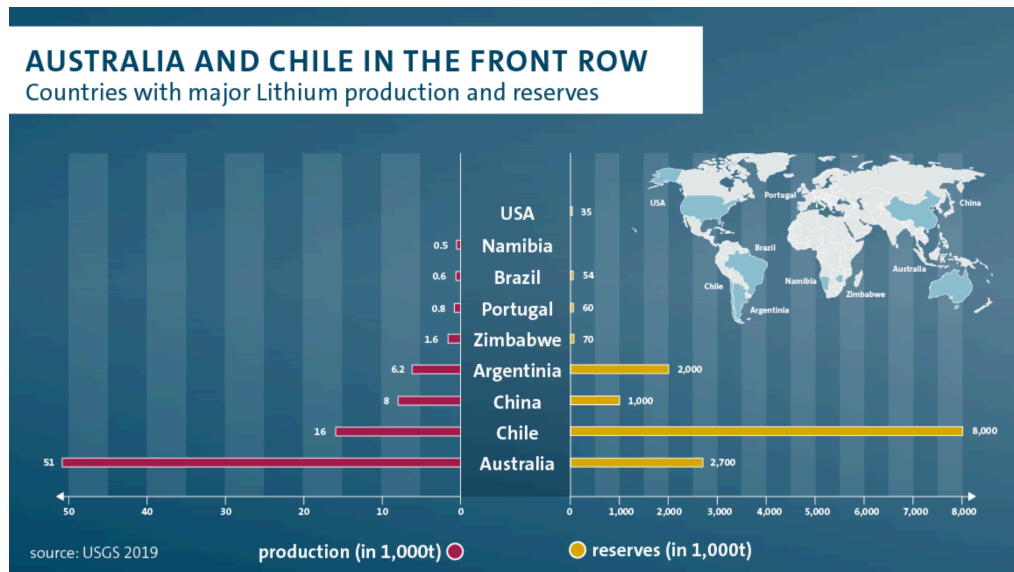
Lithium is used in the lithium-ion (Li-Ion) batteries that power electric vehicles, along with many other devices. In each cell of the battery pack, lithium is used in the cathode, anode and electrolyte (BSLBATT, 2019). Lithium is universally used in EV batteries because of its exceptionally high energy density, slow self-discharge, low maintenance, and lack of necessary priming (NuEnergy Blog, 2019). It is a silver-white alkali metal, and is soft to the point of being able to cut like butter (Anne Marie Helmenstine, 2019). The challenges with lithium extraction include immense water usage and contamination, wildlife damage, indigenous land destruction and a potential supply deficiency. Lithium recycling is still in its infancy; it is a difficult, costly, and energy-consuming process that must be advanced and scaled-up rapidly in order to have a meaningful positive effect.

Currently, lithium is predominantly extracted in Chile, Australia, China and Argentina, as seen in Figure 2 below (Volkswagen, 2018). Additionally, there are considerable reserves in the United States and Bolivia that will soon be utilized on a larger scale (NuEnergy Blog, 2019) (Lipton, 2021). Lithium is extracted in two different ways. In the United States, China and Australia, it is mined from rock and treated with chemicals to produce a useful form (IER, 2020). In Chile, Argentina and Bolivia, deep holes are drilled in salt flats, called salars, and mineral-rich brine is pumped to the surface. After several months the water evaporates, leaving a mixture of manganese, potassium, borax and lithium salts, which is then filtered and placed into another

evaporation pool. The final evaporation process takes 12 to 18 months, thereafter the mixture is filtered sufficiently such that lithium carbonate can be extracted.

Figure 2

Countries with Major Lithium Production and Reserves (Volkswagen, 2018)



The salars of Chile, Argentina, and Bolivia are incredibly energy and water consuming, and harm indigenous peoples. The lithium extraction process in salars consumes 500,000 gallons of water per metric ton of lithium extracted (IER, 2020). The largest salt flat in the world, Bolivia's Salar de Uyuni, as well as a large salt flat in Chile called 'Salar de Atacama', each consume 65% of their entire region's water supply (NuEnergy Blog, 2019). This resulted in devastations for farmers in the area, who now must find other ways to get water (IER, 2020). Additionally, the process causes the ground water table to sink, which results in rivers, streams, and wetlands carrying less water, and potentially completely drying out in the near future (Boddenberg, 2018). Members of communities located near salars have voiced about increased droughts,

which threaten livestock and kill vegetation (Volkswagen, 2018). However, it is possible that climate change, copper mining, tourism and agriculture may also place a role in these droughts.

Figure 3

Polluted Water in a Chilean Lithium Mine (Off-Grid Energy, 2016)



In addition to water usage, the salars cause harm to indigenous peoples. SQM, one of the world's largest lithium producers, is located in Chile. Neglecting the federal law, SQM did not consult indigenous peoples before recently developing a large mine (Boddenberg, 2018). The water loss from mines such as this makes it almost impossible for the indigenous peoples to live off the land.

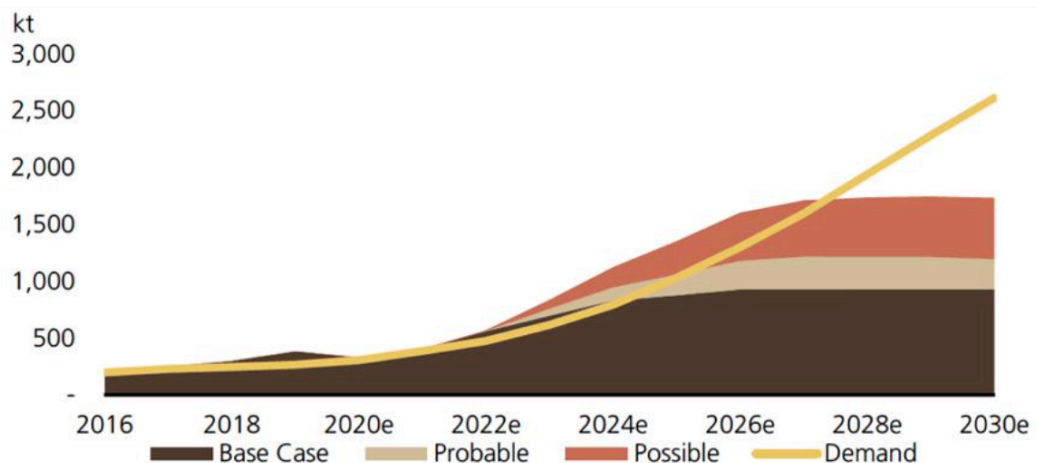
The lithium mines of the United States, China and Australia contaminate water and destroy wildlife. A research group in Nevada found negative effects on wildlife up to 150 miles downstream of a mine (IER, 2020). Across the Pacific, hundreds of dead fish, yak, and oxen were found in China's Liqi River from lithium-produced contaminated

water (NuEnergy Blog, 2019). Following this, the locals protested the Ganzizhou Rongda lithium mine, which was temporarily shut down to address the environmental concerns. The mine quickly reopened and within months the river filled with dead fish once again.

Lithium is projected to encounter supply issues as early as 2025 (Runkevicius, 2020). Global lithium reserves are estimated to contain 14 million tons of lithium (Volkswagen, 2018). Annual global production was 85,000 tons in 2018, so there are 165 years of supply with current demand and no recycling (Volkswagen, 2018). However, the supply of lithium increased by 335% between 2008 and 2018 (Volkswagen, 2018). It is projected that we will need 13 times more battery power in 2030 than we need today. This translates to the supply may be unable to meet the demand of lithium as early as 2025, as shown in Figure 4. Glyn Lawcock, Global Head of Mining Research, wrote: “There is not sufficient supply to meet this demand projection based on our knowledge of known projects today. That includes all projects whether they are under construction, in feasibility or still in exploration” (Runkevicius, 2020).

Figure 4

Lithium Supply – Demand Balance (Runkevicius, 2020)



Lastly, lithium recycling infrastructure is troublesome. Battery recycling is very important because of the dangerous tendencies of batteries in landfills, and for the sake of continuity of electric vehicles and other electronics. In landfills, batteries leach toxic chemicals into the ground (NuEnergy Blog, 2019). These chemicals find their way into streams, lakes and eventually the ocean. Crops grown near landfills often absorb these chemicals from the ground, and they end up in our food. Lithium-ion batteries also have a tendency to explode in landfills, due to their degradation and the influence of hot temperatures. These explosions can start fires that release greenhouse gasses and toxins into the air, and they are difficult to control.

Currently, less than 3% of batteries are recycled in the U.K., with similar numbers globally (NuEnergy Blog, 2019). The lithium in old batteries is not readily usable, because it has built up dendrites (deformities) that render it useless. The batteries that are recycled are often put through recycling processes that destroy the lithium at some point during the process. These processes are energy-intensive and therefore are almost never financially viable.

In summary, there are many worrisome problems regarding lithium. Its extraction in salars inflicts environmental damage, which causes live-changing problems for farmers and indigenous peoples. Its extraction in North American and Chinese mines contaminate water and destroy wildlife. Lithium may encounter supply issues as early as 2025, and recycling efforts are quite rare and logistically unviable.

B. Cobalt

Cobalt is the primary ingredient in the cathode of most lithium-ion batteries (Hampstead, 2018). It is used because it allows for high energy density and for its ability to quickly discharge (Brighten Solar Co. , 2018). Cobalt is a hard, silver-grey metal that does not naturally exist on Earth (Hampstead, 2018). Rather, it is formed by supernovas over billions of years. It is either mined directly or scavenged as a by-product of copper and nickel mining (Hampstead, 2018). The problems with cobalt extraction include neglectful and dangerous labour conditions, child labour, supply chain corruption, environmental damage, and supply limitations.

Over half of the world's cobalt supply is mined in the Democratic Republic of Congo (DRC) (Amnesty International Ltd, 2016). The DRC government estimated that 20% of this cobalt is mined by artisanal miners in the south of the country. Artisanal miners work independently, using their own resources, rather than as part of large operations with proper equipment. These workers mine cobalt either by digging underground or scavenging larger mining operations. The collected rocks are then washed, sifted, and sorted in streams/lakes nearby.

There are approximately 130,000 artisanal miners in this region, often referred to as *creuseurs*. Of this 130,000, UNICEF estimated that 40,000 were children as young as age four (Amnesty International Ltd, 2016). The creuseurs mine with basic tools, if not with their hands. Hand-dug mines can borrow tens of metres into the ground, without proper structural support or ventilation. Although there are no figures of accidents or fatalities, accidents in these mines are very common and complete collapses are frequent (Amnesty International Ltd, 2016) (CBS News, 2018). Many of the children must work

in order to pay for their education, because their parents' wages alone are not sufficient. As a result of the rise of child labour, the DRC released an action plan to eliminate child labour in 2011, although four years later (at the time the report was written), the plan was still not officially adopted by the government (Amnesty International Ltd, 2016). Instead, government officials often control access to mining sites and demand illegal payments from artisanal miners.

The work is extremely strenuous on the adults, and even more so on the children (Amnesty International Ltd, 2016). Children interviewed by researchers claimed to have worked for up to twelve hours straight, whereas adults work up to 24 hours, returning from the mine the day after their entry. The work often involves carrying heavy loads and other physically enduring actions, and only pays \$1-2 per day. Additionally, inhalation of cobalt particles can induce respiratory sensitization, asthma, shortness of breath, and decreased pulmonary function. Sustained skin contact with cobalt can lead to dermatitis. Chronic exposure to cobalt can cause hard metal lung disease, which can be fatal. Above all this, researchers found that the creuseurs did not have the most basic protective equipment, such as gloves, masks or appropriate clothing.

Another danger arises from the strong presence of uranium in the southern DRC (Lena Mucha, 2018). Many mines have recorded alarmingly high radiation levels, which is very damaging to the miners' health (Lena Mucha, 2018). As mining waste makes its way into rivers and streams, the uranium and other particulates pollute the surrounding ecosystems (Lena Mucha, 2018).

Figure 5

Thirteen Year-Old Charles, Sorting Cobalt (Amnesty International Ltd, 2016)



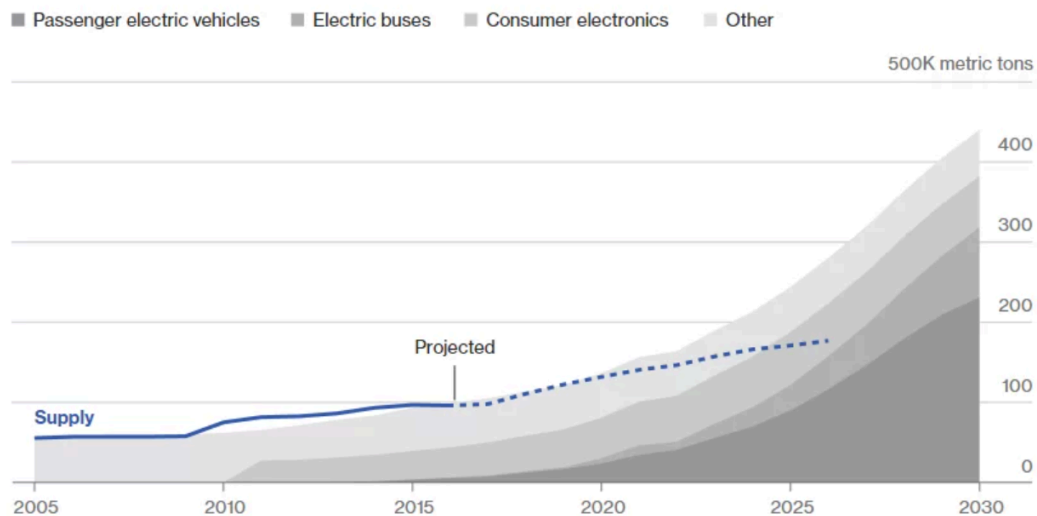
Members of the supply chain of cobalt have failed at taking responsibility for their supply and ensuring ethical and legal operations of their suppliers. For example, Congo Dongfang Mining International (CDM) is one of the largest companies buying cobalt from artisanal miners (Amnesty International Ltd, 2016). Huayou Cobalt, the parent company of CDM, sells cobalt products to battery manufacturers, which then sell to consumer brands. These brands include Samsung, Apple, Microsoft, and Tesla (CBS News, 2018). The Organization for Economic Co-operation and Development (OECD) outlined a guide for due diligence operations for supply chains, however both Huayou Cobalt and its buyers have failed to follow its instructions. Many companies denied buying from Huayou Cobalt, as there are no laws that require companies to report their cobalt supply chains.

The supply of cobalt may soon be unable to meet the demand of the EV boom. Joule published a study which found that cobalt supply will meet the lower demand

estimates, but may have issues meeting rapid EV adoption, which was defined with the example of Tesla's target of 500,000 Model 3's each year by 2018. In reality, Tesla only sold 145,846 Model 3's in 2018, however they delivered 499,550 vehicles in 2020 (Cain) (Shahan, 2021). Bloomberg New Energy Finance projected that cobalt supply will not meet its demand as soon as 2021 (Li-Cycle, 2018). Additionally, China is the largest refiner of cobalt, and does not sell to non-Chinese customers. The majority of their excess refined cobalt is used for industrial purposes or small consumer electronics, and EV manufacturers get the scraps (Hampstead, 2018). Furthermore, the supply of cobalt from the DRC is relatively unstable because of the DRC's deep corruption and recent detrimental wars (Desjardins, ENERGY Cobalt: A Precarious Supply Chain, 2017).

Figure 6

Cobalt Supply – Demand Balance (Li-Cycle, 2018)



Cobalt may be recovered in the Li-Ion battery recycling process with fewer issues than lithium. There is a recent surge in recycling infrastructure, but the pace at which it

must grow to meet global recycling demand is immense. Recycling infrastructure is discussed in the *Solutions* section. By 2035, the EU will require all EV batteries be recycled with at least 20% cobalt recovered, and other countries are expected to set similar regulations (First Cobalt Corp., 2021). The problem is that these regulations will take effect over 10 years after cobalt supply is projected to be at a deficit.

In summary, the extraction of cobalt in the DRC is very dangerous and harmful towards many of its workers, which include children. The artisanal miners are exposed to many safety risks, short-term and long-term health risks, and government corruption. Members of its supply chain have failed to take responsibility over their supply. There are concerns regarding the supply of cobalt, which may run a deficit as early as 2021. Cobalt recycling must be exponentially scaled up to create a true effect on its extraction.

C. Nickel

Nickel is being rapidly adopted as a primary cathode material, even surpassing cobalt in Tesla's batteries (Desjardins, Nickel: The Secret Driver of the Battery Revolution, 2017). It is used because it can increase the energy density of the battery while also reducing its cost. Nickel is a hard, silver-gold metal that can be found in the Earth's crust, core, and even in plants and animals (Nickel Institute). It can be mined from two different types of deposits: sulphide and laterite (Rice, 2020). Sulphide deposits describe nickel in hard rock, formed from the crystallization of magma. Laterite deposits are found in bedrock subjected to certain conditions of rainfall, drainage, and temperature. Mining sulphide deposits has a relatively low impact on the environment and is therefore referred to as 'clean nickel', whereas mining laterite deposits is very

detrimental to the environment and is referred to as 'dirty nickel'. The problem with nickel is that the EV boom will require a large increase in laterite deposit use, which will be disastrous for the environment. Additionally, the locating and generating of new nickel mines may be too slow to meet its projected demand.

The demand for nickel will grow alarmingly fast in the next decade. The amount of nickel used in EV battery cathodes has increased by 240% in only the past 4 years (Desjardins, Nickel: The Secret Driver of the Battery Revolution, 2017). In 2017, the EV industry demanded 70,000 tonnes of nickel. When EVs capture only 10% of the automotive market, which is predicted to happen by 2026 in Figure 1, the industry is projected to demand 400,000 tonnes of nickel. Sulphide deposits make up only 37% of nickel deposits and the highest extraction rate is currently being performed at most known sulphide nickel deposits. New developments of sulphide deposits are rare, small, and expensive to find. This leaves us with a quickly growing dependency on laterite nickel deposits (Desjardins, Nickel: The Secret Driver of the Battery Revolution, 2017).

In contrast with laterite deposits, sulphide deposits cause less environmental damage, cost less, and produce higher-grade nickel. Sulphide mining, smelting and refining each cause less environmental damage than laterite deposits. The higher-grade nickel produced from sulphide deposits is key in the creation of nickel metal and nickel sulphate, which is primarily used for cell cathodes.

Laterite deposits cause devastating environmental harm in many forms, and the extracted products cannot readily be used in batteries. Firstly, smelting laterite deposits requires many multiples more of energy than sulphide deposits, because of their lower and varying concentration of nickel (Rice, 2020). Currently, this process is predominantly

fueled by burning coal. This process is so energy intensive that it would take approximately four years of driving an electric vehicle to negate the carbon dioxide emissions of producing the battery alone.

Alternatively to smelting, laterite deposits can undergo a process called high-pressure acid leaching (HPAL) (Rice, 2020). HPAL produces less emissions than smelting, yet still several multiples more than the most polluting forms of sulphide deposits (Rice, 2020). Additionally, HPAL produces unstable and hazardous waste, acid slurry, and magnesium sulphate effluent. These waste products are either stored in the surrounding areas or deposited into the deep sea, which are both very environmentally harmful.

Seventy-five percent of laterite-nickel is produced in the Indonesian and Philippine tropical rainforests. These rainforests are extremely densely populated with wildlife and are key players in the environmental well being of our planet. Laterite deposits are low grade, shallow and widespread, so strip mining is used to efficiently obtain the nickel. Strip mining requires the removal of everything from the surface of the land, including all natural life. Approximately forty percent of nickel mines in Sulawesi, Indonesia stripped intact rainforest.

Figure 7

Hengjaya Mine (Laterite Nickel), Indonesia (Batten, 2018)



Lastly, laterite deposits tend to reside in ridges and hilltops. When rainfall flows over ridges and hilltops that have been stripped of vegetation, it carries debris pulled from the land with it. On the small islands that contain nickel, this debris ends up in the ocean, onto coral reefs. These reefs are extremely important to the ecosystems surrounding them, and this process accelerates the already looming global problem of coral reef extinction, which is caused by rising temperatures, pollution and exploitation.

The skyrocketing of nickel demand is projected to create a supply deficit of nickel in the near future. Ian Glasenberg, the CEO of Glencore, stated that a demand of 400,000 tonnes of nickel per year, projected to happen by 2026, would create a global nickel supply deficit (Desjardins, Nickel: The Secret Driver of the Battery Revolution, 2017). Furthermore, a scenario of 100% EVs would demand 2.2 million tonnes of nickel per year. An important factor to consider is that nickel sulphate, the material used for cathodes, makes up less than 10% of nickel supply. Wood Mackenzie stated: “Although the capacity to produce nickel sulphate is expanding rapidly, we cannot yet identify enough nickel sulphate capacity to feed the projected forecasts.”

Similarly to cobalt, nickel may be recovered in the Li-Ion battery recycling process with fewer issues than lithium. Recycling infrastructure is discussed in the *Solutions* section. By 2035, the EU will require all EV batteries be recycled with at least 12% nickel recovered, and other countries are expected to set up similar regulations (First Cobalt Corp., 2021). These regulations, however, will take effect approximately 9 years after nickel supply is projected to be at a deficit.

In Summary, the steep increase of nickel used in batteries, along with the EV boom, will create a sharp rise in nickel demand in the next decade. This demand must be met with the increase of laterite nickel mining, or ‘dirty nickel’. Mining laterite deposits is extremely energy-intensive, often produces harmful hazardous waste, and destroys rainforests and coral reefs. Nickel may encounter a supply deficit as early as 2026. Nickel recycling must be exponentially scaled up to create a true effect on its extraction.

D. Manganese

Manganese is being rapidly adopted in EV cell cathodes because it can lower production costs, increase energy density, and increase safety through greater thermal stability (Palisade Research, 2017). Manganese is a grey, hard and brittle metal (BYJU'S). It can be found in rock also containing iron and other minerals, and can be mined at shallow depths. As the demand for manganese increases with mass EV adoption, there are concerning issues regarding its supply.

The continuous increase of steel use, the EV boom, and increased use in cell cathodes is causing a surge in manganese demand. Tesla announced that it plans on producing cathodes that contain one-third manganese on its battery day in 2020, while the

Nissan Leaf and Chevrolet Volt are currently manufactured with approximately 60% manganese cathodes (CleanTechnica, 2020) (Palisade Research, 2017). The supply of manganese has actually been declining due to historical lack of demand, at a maximum rate of 8.6% in 2016. This is rapidly changing, as the demand is projected to reach 28.2 million tonnes by 2022 (1.6 times the global demand peak in 2014), the supply will have to be quickly increased.

Similarly to cobalt and nickel, manganese may be recovered in the Li-Ion battery recycling process with fewer issues than lithium. Recycling infrastructure is discussed in the *Solutions* section. There are no specific targets for manganese recovery as of yet.

E. Graphite

Graphite is the material of choice for most cell anodes (Investing News Network, 2018). Most EV manufacturers use 10-30 times more graphite than lithium in their batteries (Heintz, 2016). It is used because its atomic structure allows the anode to last a very long time (Investing News Network, 2018). Graphite is a form of crystalline carbon, found in metamorphic and igneous rock (King). It is extracted through either open-pit or underground mines. As graphite demand increases with mass EV adoption, there is concern regarding its supply.

Graphite can be characterized into many types. The four main types are: flake, amorphous, vein, and synthetic (Investing News Network, 2018). Only flake graphite may be used for batteries, and specifically only large flakes are suitable. Most graphite is extracted in China, India and Brazil, however various deposits such as Lac Gueret in Quebec are being tested for graphite types.

The annual demand for graphite is currently more than any other material discussed in this paper, and is projected to grow to over 3 million tonnes per year by 2035 (O'Dea). A report by industrial minerals predicted that Tesla's Gigafactory alone increased large-flake graphite demand by 37% from 2016 to 2020 (Heintz, 2016). Additionally, amidst the clean energy revolution, production of new fuel cells and nuclear reactors will require large amounts of graphite as well. Graphite is extremely abundant in the Earth's crust, at 300 million megatonnes, so its long-term supply is safe for at least 75 years (O'Dea). However, on a shorter time-scale, the Union of Concerned Scientists report that its supply may reach a deficit. Additionally, graphite is not a material of focus in Li-Ion recycling circles. This is most likely because its problems are overlooked in comparison to the more pressing supply issues of lithium, cobalt and nickel.

F. Rare Earth Elements

Rare earth elements: neodymium, dysprosium, terbium, and occasionally others are used in the magnets of many electric vehicle motors. These elements are silver metals of various harnesses, and are extracted from materials such as lanthanide mineral ores, bastnasite and monazite (Minerals Education Coalition) (Hart, 2020).

There are many types of electric vehicle motors, including synchronous motors, induction motors, DC motors, and switch reluctance motors. Many EV companies use motors containing permanent magnets, such as permanent magnet synchronous motors, interior permanent magnet motors, and permanent magnet switch reluctance motors. These companies include Tesla, Nissan, Chevrolet, Zero motorcycles and others (Pradhan, 2019). Neodymium is universally used in these permanent magnet motors

because it can produce a large force and maintain a universal magnetic flux along its body. Neodymium however has a relatively low operating temperature limit, so it is often combined with dysprosium and terbium to maintain the magnet's strength at higher temperatures (Edison, 2019).

There are two common extraction methods used for these rare earth elements (REEs). The first method involves removing and transporting topsoil into a leaching pond and adding chemicals to isolate the desired materials (Earth.org, 2020). The second method entails pumping underground soil to a leaching pond at the surface, to then undergo the same process to separate the materials. These processes are both extremely detrimental to surrounding areas and their inhabitants. Additionally, these rare earth materials may encounter a short-term supply deficit in the next decade.

The neodymium and dysprosium extraction processes are often devastating to their surrounding environments. The chemicals that separate the REEs from the other materials pollute the air, groundwater, and cause erosion. A Daily Mail correspondent travelled to Baotou, China, which is home to over 70% of global dysprosium reserves, and the largest REE mine, to report on its conditions (IER, 2013). He found that the fumes produced were overwhelming and far-reaching, plants unable to grow near the factories, and mass animal deaths as the factories expanded. Nearby villagers reported hair and teeth loss, severe skin and respiratory diseases, children born with weak bones, and rapidly increasing cancer rates. Additionally, a study found that radiation levels in the nearby lakes were ten times higher than the surrounding areas. When it rains in Baotau, the water turns black from coal dust, which covers the majority of the area

(Maughan, 2015). Figure 8 displays the Baotou Lake, which is used as dumping grounds for the process's byproducts.

Figure 8

Baotou Lake, China - Polluted by Rare Earth Element Mining (Parry, 2011)



As a result of the EV boom, the demand for both of these metals is projected to increase massively. EV demand for neodymium is projected to increase from 700 tonnes per year in 2017 to 30,000 tonnes per year by 2030 (Edison, 2019). Similarly, EV demand for dysprosium is projected to increase from 270 tonnes per year in 2017 to 10,000 tonnes per year by 2030. China controls the supply of these REEs, reaching a maximum of 97% of the market share in 2006. In 2010, China imposed export quotas on REEs, causing a 30% decrease of their production in that year alone. The World Trade Organization ruled these quotas unjust, and they were removed soon after. Since 2010, China has been decreasing its exports to focus on domestic production and reduce environmental harm from the mining (Sander Hoenderdaal, 2013).

Global demand of neodymium was 3,300 tonnes more than the available supply in 2017. This deficit will rise exponentially if the production is not immediately increased (Desai, 2018). Although China contains the majority of REE deposits, there are still significant deposits across the world. The issue here is that it is very expensive to open new mines because of the complex process to extract REEs from the materials that they are found in (Desai, 2018). In addition to neodymium, “Energy” published a study that concluded that there will be a short-term supply deficit of dysprosium (Sander Hoenderdaal, 2013).

Permanent magnet motor recycling is in its infancy (Roskill, 2018). The processes currently used involve extracting the REEs from the magnets, which is extremely energy-intensive and expensive. This is partially because as electronics become more complex, so does the recycling of some of their components. For example, REEs in touch screens are distributed on a molecular level (Marshall, 2014). Recycling becomes even more undesirable when considering its environmental impact. Yale University industrial ecologist Thomas Graedel claims that recycling rare earths can be more environmentally harmful than mining them. For these reasons, technological advancements must be made for REE recycling to become advantageous.

In summary, the extraction of rare earths used for electric vehicle magnets damages the nearby environment and its inhabitants. This damage includes pollution, ecosystem destruction, health deficiencies and diseases. The supply of REEs is unstable, and in some cases has already encountered a deficit. REE recycling technology must become less energy-intensive and costly for it to solve any of these problems.

III. Potential Solutions

A. Extraction

Extraction solutions include the improvement of current mining operations, the development of new mining operations, the improvement of current extraction technologies, and the development of new extraction technologies.

1. Lithium

The extraction challenges with lithium include immense water usage and contamination, wildlife damage, indigenous land destruction and supply limitations. Although there is little change to the current operations causing these problems, there are new technologies that can help usher in a new, sustainable, and more capable lithium extraction industry.

Schneider Electric and Wartsila have developed sustainable and reliable lithium mine power systems (Wartsila, 2021). These power systems include thermal power generation along with other renewables, microgrids and energy storage systems to create less costly and environmentally harmful extraction operations. These systems cut carbon emissions by up to 20% and cost by up to 40%. This technology can cut carbon emissions and may incentivize greater supply, however it does not solve any of the issues with the actual extraction process.

Lilac Solutions has developed a completely new method to extract the lithium from salt brines. As discussed earlier, the conventional process involves placing the salt water into an evaporation pool, filtering the leftover mixture of manganese, potassium,

borax and lithium salts, and then placing the mixture into another evaporation pool (IER, 2020). The final evaporation process takes 12 to 18 months; thereafter the mixture is sufficiently filtered to extract lithium carbonate. Instead, Lilac's process involves adding hydrochloric acid to the salt water (Lilac Solutions). This reaction isolates the lithium via an ion exchange. Rather than 12 to 18 months, the process is complete in just 2 hours. Unlike the conventional process, the ion exchange method operates in a closed loop fashion, negating any evaporation and returning the salt water to the ground. Lilac claims that this process recovers 80% of lithium, compared to 40% from current mining operations. Additionally, the ion exchange process is less expensive, engulfs a much smaller plot of land, and enables projects to start faster. This method can also operate in lithium reserves that contain lower grades of lithium, previously thought to be of no use for batteries. Lilac has received \$20 million in funding, led by Bill Gates' Breakthrough Energy Ventures.

Lilac Solutions has partnered with Controlled Thermal Resources to open a lithium mine at an enormous lithium site in California (Richter A. , 2020). CTR uses geothermal power for lithium extraction, meaning that the processes energy is 100% renewable. CTR claims that this mine will “deliver a consistent and secure supply of battery-grade lithium products with the highest sustainability credentials” (Richter A. , 2020). Lilac and CTR's technology directly addresses and claims to have the potential to solve all environmental problems with lithium extraction. Additionally, because it may operate with lower grades of lithium, it may help counter the projected supply deficit.

2. Cobalt

The issues with cobalt extraction include neglectful and dangerous labour conditions, child labour, supply chain corruption, environmental damage, and supply limitations. Progress has been made in regards to several of these issues, providing hope for the future of cobalt.

The Amnesty International report: “This Is What We Die For” brought the grim cobalt extraction process to the forefront of the media. Changes started being made just years after, and Amnesty International published an article 3 years after the report, which provided updates in the cobalt world (Amnesty International, 2019). The article states that following the 2016 report; many companies publicized their cobalt supply chains, including Apple, BMW, Daimler, Renault and Samsung. Additionally, Amnesty has documented its vision of an ethical battery; one which does not harm people’s rights or the environment in its creation. This document includes tracking supply chains, documenting and addressing human rights violations. Amnesty has presented this vision to relevant companies, investors, governments and consumers in hopes of its adoption.

In addition to Amnesty, another driver of ethical extraction of cobalt is the Fair Cobalt Alliance (FCA). FCA is an organization co-founded by Huayou Cobalt, a company which buys much of the cobalt from artisanal mines and failed to follow OECD’s guidelines for supply chain due diligence (The Impact Facility). FCA is dedicated to changing the cobalt extraction problems through a multi-faceted approach. FCA is working in artisanal mines to introduce responsible mining practices, improve site management and incentivise mining investment. FCA has aided artisanal mine operators in the control and monitoring of children in the mines, and has supported the enrolment

of children in nearby schools to challenge child labour in the region. In hopes of tackling the root cause, FCA has begun investing in various sustainable, income-generating opportunities to create healthy career options for adults in the region. Members of the FCA include Tesla and Glencore, and its supporters include Lifesaver and Volvo.

Figure 9

Fair Cobalt Alliance Provides Equipment to Artisanal Miners (Flaherty, 2020)



Lastly, there are several new cobalt operations being explored. For example, Fuse Cobalt has been redeveloping the large mineral-rich region of Cobalt, Ontario, in hopes of starting mining operations in 2021 (Northern Ontario Business, 2021). The proposed mining site has produced very high cobalt levels, and is located just 2 kilometres from First Cobalt's refinery. In addition, this mine contains high-grade cobalt and is in one of the safest mining jurisdictions in the world (CleanTechnica, 2020). Fuse is backed

through supply agreements with Glencore, First Cobalt, and Tesla. In light of these findings, Jeff Bezos, Bill Gates and others funding the Breakthrough Energy Fund are sponsoring the search for more cobalt in the surrounding region.

These solutions provide hope for the future of cobalt mining, however they do not define a clear path to ending the horrible practices in the DRC. It is hard to predict if this new effort of organized pressure on the supply chain and mines, combined with the increased supply of other regions will be enough to solve these problems.

3. Nickel

The problems with nickel extraction include the increasing reliance on laterite nickel deposits, which are extremely environmentally detrimental, and a possible short-term supply deficiency. There has been no progress to lessen the damage of laterite mining, however new sulphide deposits are being discovered, and new technologies are being developed to lessen the need for laterite mining.

There are two recently discovered, large sulphide deposits in Canada currently being explored. Glencore's Sudbury Integrated Nickel Operations (SINO) has mostly emptied its existing mines, but has found a new orebody 1500 metres below an existing mine (Kelly, 2021). Although this mine may be quite large, it is a very dangerous operation because of its depth, and must be explored slowly and carefully. Nearby in Timmins Ontario, a low-grade deposit has recently been discovered that is considered to be one of the 10 largest sulphide deposits in the world (Ross, 2021). This mine is being rapidly developed, and is operated environmentally-consciously; using hydroelectricity, electric construction vehicles, and is hoping to run a net-zero operation.

Several new processes are being explored to combat these growing extraction issues. LionOre has developed a hydrometallurgical technology called Activox, which negates the need for smelting via using ultra-fine grinding and an oxidation process for sulphide deposits (Canadian Mining Journal, 2006). This technology can extract nickel from low-grade deposits, previously labelled economically unfeasible. Activox is also projected to increase nickel production, and will do so by 500% in a large mining facility in Botswana. Bioleaching is another process being explored to extract nickel from low-grade sulphide deposits and waste dumps, previously thought to be unfit for extraction (Wollschlaeger, 2017). This process utilizes microorganisms to separate the mineral from its surroundings (Merriam-Webster). Bioleaching has successfully extracted nickel from a low-grade commercial site in Finland and will soon be implemented in more low-grade mines globally (Wollschlaeger, 2017). The low-grade deposits of which Activox and bioleaching are targeting are abundant, so this method appears promising in solving the issues associated with nickel extraction.

4. Manganese

The issue with manganese extraction is an approaching supply deficit. Several new mining operations are underway in hopes of becoming global suppliers and preventing this from happening.

Examples of new operations include Maxtech Ventures Inc., which is developing several high-grade manganese mines in Brazil (Palisade Research, 2017). The area's manganese deposits are recorded to span at least 250 km, and the regions deposits are very shallow and allow for an easy extraction process. Menar has recently been granted

access to begin its large manganese mining operation in northern South Africa (Creamer Media's Mining Weekly, 2020). This deposit contains approximately 1 million tonnes of manganese ore. The mine should start recovering ore by mid 2021. Mangan Chvaletice has just been granted greater exploration rights for its manganese operations in Czech Republic (Euro Manganese Inc. , 2021). These mines are expected to begin commercial production of high-purity manganese in late 2024. These new operations, along with few others, hope to be enough to avoid a supply deficit in the next decade.

5. Graphite

The worry with graphite extraction is a short-term supply deficit, as large-flake deposits are rare and difficult to find. Several new mining operations are underway in hopes of finding large flakes and producing enough graphite to match the demand of the forthcoming EV boom.

Graphite one is commencing its Alaskan Graphite Creek mining operation in 2021 (Kin Communications Investor Relations, 2021). This is a large-flake, high-purity graphite deposit, which meets all battery requirements (Investing News Network, 2018). Additionally, it is the largest identified high-purity deposit in the United States (Kin Communications Investor Relations, 2021). In Quebec, Berkwood Resources is currently developing its new property, which has attained test samples containing high-grade large graphite flakes. These samples were taken from large geophysical anomalies, which proposes that the entire sections of earth are filled with graphite. These operations, along with others on their way, hope to be the source of graphite needed for the near future of electric vehicles.

6. Rare Earth Elements

The extraction issues with rare earth element extraction include environmental devastation, health risks, a single and unstable supply source, and a potential short-term supply deficit. Organizations and new technologies hope to provide a sustainable REE industry for the future. New operations around the globe hope to disrupt the China-dominant supply chain of today.

Little is being done in Baotou to change the mine's devastating impact on the local people, wildlife, and environment. Locals in the area have recently started mobilizing against the mine; using the media, petitions and complaint letters to fight the damage being done (Environmental Justice Atlas, 2020). Other than financial compensation (in part) to local farmers and environmental assessments conducted, no progress has been made to better this situation. Furthermore, some activists have been arrested, and there have been false and misleading governmental claims regarding the situation.

As REEs become ever more important, the Rare Earth Industry Association has formed to regulate and communicate various aspects of the industry (Tunnicliffe, 2019). Project Associate Gwendolyn Bailey claimed that most of the association's members "are committed to adding transparency and sustainability to the rare earth value chain", and "developing a sector that has environmental concerns at its core." He continued to state that the association would work with the industry to create life-cycle analyses, environmental profiles and industry standards.

In regards to a short-term supply deficiency, many new mines across the globe are in development to open in the near future. In The Northwest Territories, the first

Canadian REE mine is being developed (CBC, 2021). It is currently ending a 3-year small demonstration project that will quickly be expanded into a full-size, commercial operation. In Georgia, America, a new site has recently commenced development (Mahoney, 2021). Several year ago, Northern Minerals secured \$6 million in funding for a new mine in Western Australia (Jamasmie, 2014). Once operational, these mines will be valuable pieces of the rare earth supply chain.

Lastly, many new REE extraction technologies are emerging, and have promising features to innovate the industry. Researchers at Purdue University have developed a new technology for REE extraction (Leotaud, 2020). Rather than the acid-based separation techniques that destroy the surrounding environment, it utilizes ligand-chromatography; a highly specific macromolecular binding interaction between a biomolecule and another substance. This method produces no detrimental environmental impact and yields high-purity metals (99%). In England, the University of Exeter has recently published findings, which state that contrary to previous beliefs, chlorine and fluorine are not the two elements that make REEs soluble (Mine, 2021). Instead, these elements are sodium and potassium. This discovery will allow mining companies to target these elements instead and find deposits much faster, using fewer resources, and which contain higher purity/yields of rare earths. Additionally, sodium and potassium are over 60 times more abundant in the Earth's crust, giving hope that there are more deposits around the globe than previously thought. Imago will help speed up the exploration process even more through its camera system and machine learning algorithm. This ultra-smart software creates a network of deposit images, which details the material makeup of a defined area.

This allows companies to better predict which areas contain the largest deposits and makes the exploration process more efficient.

As of yet, the damage being committed in Baotou hasn't changed. Permanent magnets are still not being recycled because the technology isn't commercialized yet. The solutions listed above have the power to prevent the growth of these problems, and the next few years are crucial to implement these solutions and change the grim nature of this industry for the better.

B. Recycling

Recycling solutions explore the new companies and technologies that hope to fuel recycling efforts of these critical materials.

1. Batteries

Many of the problematic materials used in electric vehicle lithium-ion batteries can be efficiently recycled, however this is not currently being done. Under 5% of Li-Ion batteries are recycled in the UK, U.S., EU, and Australia (Jacoby, 2019). These extremely low recovery rates are a result of a lack of economic feasibility, which is due to the absence of used EV batteries and the technical limits of the recycling process. Until very recently, Li-Ion recycling has been limited to small academic groups, as there has not been enough demand to incentivize commercial research into improving the process and making it economically feasible. As the market is projected to rapidly increase in the coming decade, this is changing very quickly. Companies around the world are working hard to get a piece of this new Li-Ion recycling industry.

Leading this charge is Li-Cycle. Headquartered just north of Toronto, Canada, it will finish construction of the largest Li-Ion recycling plant in North America in 2021 (Kumagai, 2021). Li-Cycle claims that this plant will be able to recover over 95% of the batteries' lithium, cobalt and nickel. Additionally, it plans on running on zero wastewater and zero emissions. In China, Brunp Recycling Technology Co. is Asia's largest Li-Ion recycler. Across its quickly growing 6 facilities, it can process 120,000 tonnes of battery waste annually at a 99.3% recovery rate of cobalt, nickel and manganese (CATL). Sweden's Northvolt, founded by ex-Tesla executives in 2016, is successfully running its experimental plant, and plans to complete its full-scale plant in 2021 (Kumagai, 2021). In 2017, former Tesla CTO J.B. Straubel founded Redwood Materials in Nevada. Redwood plans to recycle electronics (predominately EV batteries) and become a raw materials supplier. It is among the 5 recipients of the \$2 billion Amazon Climate Pledge Fund. These companies barely scratch the surface, with dozens of others working to enter the Li-Ion recycling business. This upcoming industry will inherit part of the supply of these problematic materials, reducing many of the problems associated with their extraction and rebelling against projected supply deficits.

Figure 10

Used Batteries At Redwood Materials' Recycling Facility (Jeniece Pettitt, 2021)



2. Electric Motors

Permanent magnet recycling is currently energy-intensive and expensive, though there is significant research to discover new methods (Fraunhofer-Gesellschaft, 2015). The U.S. Department of Energy's Critical Materials Laboratory and Ames Laboratory have developed a new permanent magnet recycling method. This method involves dissolving the magnets in water-based solutions, utilizing hollow fiber membranes, organic solvents and neutral extractants to separate the REEs. It enables a one-step process to recover REEs from used magnets, and is consequentially more environmentally friendly and less expensive than the standard recycling process. This process can recover over 99% of the REEs. This technology was non-exclusively licensed to Momentum Technologies in 2016 to develop an economically viable industrialized system to recycle magnets (Office of Technology Transitions, 2016).

Alternatively, the Fraunhofer Research Institution for Materials Recycling and Resource Strategies has developed a method of recycling the entire magnet as a whole (Fraunhofer-Gesellschaft, 2015). This process is less energy-intensive and considerably cheaper because there are many less stages (Fraunhofer-Gesellschaft, 2015). The researchers have successfully run a demonstration plant, and are now optimizing the process for commercial use.

On a commercial level, Urban Mining Company has raised \$25 million for its REE recycling and production facilities (Vinoski, 2020). UMC claims that it will be able to produce thousands of tonnes of magnets per year, manufactured from its recycled supply.

These new permanent magnet recycling technologies are much needed to incentivize recycling efforts across the globe. Now that this technology exists, new operations must be erected in the coming decade to fight the need to source REEs from Baotou and to create a circular economy for permanent magnets.

C. Emerging Electric Vehicle Technologies

Various emerging electric vehicle technologies will have an impact on the material problems discussed. Battery and motor technology are explored below as a potential solution to some of the problems.

1. Batteries

Electric vehicle battery technology has been rapidly changing over the last few years. There are many innovations being made on lithium-ion cells, as well as promising new types of batteries being produced. These changes can strongly impact the challenges associated with certain problematic materials, for the better or for the worse.

Lithium-ion batteries are universally used in EVs because they are currently the best technology available. Over the past few years several innovations have been made to Li-Ion batteries. In the early stages of EVs, lithium manganese oxide (LMO) cathodes were used for their high energy density and low cost (Danylenko, 2019). LMO cathodes are predominantly constructed using lithium and manganese, and as they have been phased out due to their lack of durability, individual EV batteries have demanded less of these materials. The next popular cathode chemistry was the Nickel Cobalt Aluminum (NCA) battery. These batteries rely significantly more on nickel, using less lithium, cobalt and manganese. They are also cheaper to produce than LMO batteries. These batteries have been the most popular type of cells in EVs until very recently.

Nickel Manganese Cobalt (NMC) batteries have taken over the industry in the past few years, due to their stable chemistry and low cost. NMCs use very little cobalt, creating a much smaller demand for this problematic material. Current trends show both NCA and NMC batteries relying less on cobalt and manganese, switching to over 80% nickel (Desjardins, Nickel: The Secret Driver of the Battery Revolution, 2017). These trends have taken some pressure off of all problematic material supplies, except for nickel, which is rapidly-increasing in demand.

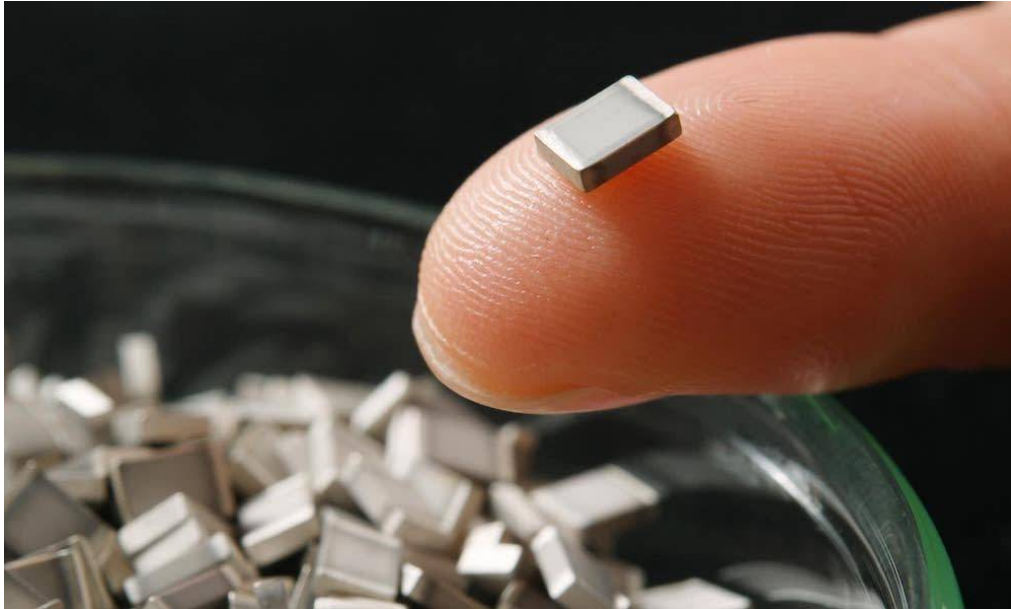
A new battery type for vehicle applications, Lithium Iron Phosphate (LFP) batteries are being used by some EV companies and will be introduced into certain Tesla models shortly. Unlike LMOs, NCAs and NMCs, LFPs are not a type of lithium-ion cell, but house entirely different cell chemistry. These batteries are the safest type of EV batteries and are highly energy-dense, making them especially useful for larger vehicles like trucks and busses (Danylenko, 2019). These batteries contain no cobalt, nickel, or manganese, and instead use iron and phosphate (Desjardins, Nickel: The Secret Driver of the Battery Revolution, 2017). Of these two substitutes, phosphate extraction may be problematic in the near future, though this is beyond the scope of this paper.

Lastly, solid-state batteries are projected to change the world in the next decade(s). A ‘regular’ battery contains a heavy liquid electrolyte, which separates the positive and negative terminals of the cell. Instead of a liquid, a solid-state battery uses a much lighter and more compact solid electrolyte (Teague, 2021). This technological innovation can produce up to 10 times more energy (and range) as a current Li-Ion EV battery does. Additionally, solid-state batteries can charge faster and last many more cycles than Li-Ion batteries. Lastly, liquid electrolytes are a safety concern in EVs, and require expensive and heavy cooling systems to ensure they don’t explode. Solid-state batteries also negate the need for these systems, freeing up even more space at a lower price. This innovation is extremely promising, as these batteries are being developed for commercial-grade EVs in the next decade. Many groups throughout the world are developing these batteries, each with their own unique materials. Although the problems associated with solid-state cell materials are difficult to predict, these cells have a much

longer lifespan, and thus already have a problematic material advantage when compared to Li-Ion batteries.

Figure 11

Small Solid-State Battery (Peterson, 2018)



2. Electric Motors

The issues with rare earth elements in electric vehicles are caused from the permanent magnet motors that demand them. There are however, new types of motors being developed which may decrease or eliminate the need for permanent magnets.

Permanent magnets are currently used in EVs because of their high power and efficiency capabilities, low weight and robustness (A. Loganayaki, 2019). The most promising new motor technology that can overtake permanent magnet motors is the Switched Reluctance Motor (SRM). Many companies developing SRMs use no REEs, because the technology allows for this and also as a commitment to reliable supply chains

and sustainability. New technology allows for the precise control needed for SRMs, which are now simply constructed, extremely efficient and powerful (Liquip, 2021).

Among many SRM manufacturers is Enedym, a startup from McMaster University in Hamilton, Canada. Enedym states that their motors could be up to 40% less expensive than current models used in the industry (Enedym). Another promising motor company, Advanced Electric Machines (AEM) claimed to have created the “world’s most sustainable electric vehicle motors” (Billington, 2021). AEM’s motors are also powered by SRM technology, and contain no magnets. AEM claims that one of their motors can deliver 50% more power at 35% less weight compared to the industry’s leading permanent magnet motor. Lastly, global automotive manufacturer MAHLE has just unveiled its new magnet-free electric motor. Although little is known about the motor thus far, MAHLE explained that it combines various aspects of different motor types to construct a highly efficient, magnet-free motor (MAHLE, 2021).

These new motors have the potential to eliminate REE demand from the electric vehicle industry. This could abolish any contribution to the poor conditions in Baotou, and any issues that arise with rare earths supply.

IV. Conclusions

The magnitudes of these problems are *immense*. From inhumane labour conditions in the DRC, to the destruction of rainforests in Indonesia, to the health problems documented in Baotau, this is not sustainable development. By pushing for a rapid transition to electric vehicles in order to meet emissions targets, this industry is actually damaging the planet and its inhabitants in numerous ways. These problems are not only here to stay, but will exponentially worsen along with the EV boom. Without promptly combatting these issues in the next decade, one of the largest forms of ‘clean technology’ would result in a complete failure, only changing the ways in which the planet is destroyed.

Adequate solutions for almost each problem *do* exist. Brilliant minds from around the world have revealed countless new technologies in the past decade that can truly solve many of these problems. Economical and sustainable extraction and recycling methods, paired with innovative electric vehicle technologies can greatly reduce the negative impacts of these materials, or eliminate the need for their extraction completely. Many of these solutions are well supported financially and otherwise, and have the potential to be widely utilized in the near future.

Swift action is necessary. The electric vehicle industry is at a tipping point; it can become the sustainable transportation that we so dearly need it to be, or it can end up as just another form of our planet’s demise. In the coming decade, the solutions presented in this paper must be applied globally to their appropriate problems to ensure that electric vehicles do not come at a cost that we cannot afford to pay.

V. References

- A. Loganayaki, R. B. (2019, March 15). *Permanent Magnet Synchronous Motor for Electric Vehicle Applications*. Retrieved July 31, 2021, from IEEE Xplore: <https://ieeexplore.ieee.org/document/8728442>
- Amnesty International. (2019, March 21). *Amnesty challenges industry leaders to clean up their batteries*. Retrieved July 11, 2021, from Amnesty International: <https://www.amnesty.org/en/latest/news/2019/03/amnesty-challenges-industry-leaders-to-clean-up-their-batteries/>
- Amnesty International Ltd. (2016). *“THIS IS WHAT WE DIE FOR” HUMAN RIGHTS ABUSES IN THE DEMOCRATIC REPUBLIC OF THE CONGO POWER THE GLOBAL TRADE IN COBALT*. Amnesty International Ltd.
- Anne Marie Helmenstine, P. (2019, November 3). *10 Cool Facts about Lithium*. Retrieved June 10, 2021, from ThoughtCo.: <https://www.thoughtco.com/lithium-element-facts-608237>
- Batten, K. (2018, July 13). *Indonesia nickel miner launches \$150M IPO*. Retrieved June 28, 2021, from Mining Journal: <https://www.mining-journal.com/base-metals/news/1342424/indonesia-nickel-miner-launches-usd150m-ipo>
- Bhave, R. R. (2015, August 10). *Critical Materials Institute rare-earth recycling invention licensed to U.S Rare Earths*. Retrieved July 28, 2021, from Oak Ridge National Laboratory: <https://www.ornl.gov/news/critical-materials-institute-rare-earth-recycling-invention-licensed-us-rare-earths>
- Billington, J. (2021, April 1). *UK COMPANY CREATES ‘WORLD’S MOST SUSTAINABLE ELECTRIC VEHICLE MOTORS’*. Retrieved August 2, 2021, from Advanced Electric Machines: <https://advancedelectricmachines.com/uk-company-creates-worlds-most-sustainable-electric-vehicle-motors/>
- Bloomberg News. (2019, September 6). *China Mulls Goal of 60% of Auto Sales to Be Electric by 2035*. Retrieved June 8, 2021, from Bloomberg: <https://www.bloomberg.com/news/articles/2019-09-06/china-mulls-target-for-60-of-auto-sales-to-be-electric-by-2035>
- Boddenberg, S. (2018, August 11). *Living Planet: The problem with lithium mining*. Retrieved June 12, 2021, from DW: <https://www.dw.com/en/living-planet-the-problem-with-lithium-mining/av-46211787>
- Brighten Solar Co. . (2018, June 28). *Batteries: Why Does Cobalt Matter?* Retrieved June 17, 2021, from Brighten Solar Co. : <https://brightensolarco.com/batteries-why-does-cobalt-matter/>
- BSLBATT. (2019, February 2). *What Materials are in a Lithium-Ion Battery?* Retrieved June 8, 2021, from BSLBATT: <https://www.lithium-battery-factory.com/materials-lithium-ion-battery/>
- BYJU'S. (n.d.). *Manganese - Mn*. Retrieved June 27, 2021, from <https://byjus.com/chemistry/manganese/>
- Cain, T. (n.d.). *TESLA MODEL 3 SALES FIGURES*. Retrieved June 19, 2021, from GOODCARBADCAR: <https://www.goodcarbadcar.net/tesla-model-3-sales-figures-usa-canada/>
- Canadian Mining Journal. (2006, August 20). *NICKEL REFINERY – Commercial Activox plant*

- planned*. Retrieved July 21, 2021, from Canadian Mining Journal: <https://www.canadianminingjournal.com/news/nickel-refinery-commercial-activox-plant-planned/>
- CATL. (n.d.). *Battery Recycling*. Retrieved July 27, 2021, from CATL: <https://www.catl.com/en/solution/recycling/>
- CBC. (2021, July 15). *Canada's 1st rare earth mining project starts production*. Retrieved July 25, 2021, from yahoo! news: <https://ca.news.yahoo.com/canadas-1st-rare-earth-mining-192819793.html>
- CBS News. (2018, March 6). *The toll of the cobalt mining industry on health and the environment*. Retrieved June 17, 2021, from CBS News: <https://www.cbsnews.com/news/the-toll-of-the-cobalt-mining-industry-congo/>
- CleanTechnica. (2020, September 3). *Battery Day Reveals Elon Musk's Intention For Manganese In EVs*. Retrieved June 27, 2021, from CleanTechnica: <https://cleantechnica.com/2020/09/23/battery-day-reveals-elon-musks-intention-for-manganese-in-evs/>
- CleanTechnica. (2020, September 22). *What Tesla & Cobalt Mining In Canada Have In Common*. Retrieved July 20, 2021, from CleanTechnica: <https://cleantechnica.com/2020/09/22/what-tesla-and-cobalt-mining-in-canada-have-in-common/>
- Creamer Media's Mining Weekly. (2020, September 25). *New manganese mine edges closer to opening*. Retrieved July 22, 2021, from Creamer Media's Mining Weekly: https://www.miningweekly.com/article/new-manganese-mine-edges-closer-to-opening-2020-09-11/rep_id:3650
- Dans, E. (2021, January 24). *The Five Factors Driving The Mass Adoption Of Electric Vehicles*. Retrieved June 8, 2021, from Forbes: <https://www.forbes.com/sites/enriquedans/2021/01/24/the-five-factors-driving-the-mass-adoption-of-electricvehicles/?sh=61cf69ef39d6>
- Danylenko, M. (2019, September 6). *What Materials are Behind the EV Battery Revolution?* Retrieved July 29, 2021, from Matmatch: <https://matmatch.com/blog/what-materials-are-behind-the-ev-battery-revolution/>
- Desai, P. (2018, March 12). *Tesla's electric motor shift to spur demand for rare earth neodymium*. Retrieved June 29, 2021, from Reuters: <https://www.reuters.com/article/us-metals-autos-neodymium-analysis-idUSKCN1GO28I>
- Desjardins, J. (2017, January 9). *ENERGYCobalt: A Precarious Supply Chain*. Retrieved June 19, 2021, from Visual Capitalist: <https://www.visualcapitalist.com/cobalt-precarious-supply-chain/>
- Desjardins, J. (2017, October 30). *Nickel: The Secret Driver of the Battery Revolution*. Retrieved June 20, 2021, from Visual Capitalist: <https://www.visualcapitalist.com/nickel-secret-driver-battery-revolution/>
- Earth.org. (2020, July 14). *How Rare-Earth Mining Has Devastated China's Environment*. Retrieved July 1, 2021, from EARTH.ORG: <https://earth.org/rare-earth-mining-has-devastated-chinas-environment/>
- Edison. (2019, January 29). *Electric Vehicles and Rare Earths*. Retrieved June 29, 2021, from Edison: <https://www.edisongroup.com/edison-explains/electric-vehicles-and-rare-earths/>
- Enedym. (n.d.). *Technology*. Retrieved August 2, 2021, from Enedym: <https://enedym.com/technology/>
- Environmental Justice Atlas. (2020, August 4). *Bayan Obo world biggest rare earths mine, Baotou, Inner Mongolia, China*. Retrieved July 25, 2021, from Environmental Justice Atlas: <https://www.ejatl原因.org/conflict/bayan-obo-world-biggest-rare-earths-mine-baogang-group-baotou-inner-mongolia-china>
- Euro Manganese Inc. . (2021, July 20). *Euro Manganese Secures Extension of Chvaletice*

- Development Rights to 2026*. Retrieved July 22, 2021, from Yahoo! Finance: <https://ca.finance.yahoo.com/news/euro-manganese-secures-extension-chvaletice-213000149.html>
- First Cobalt Corp. (2021, February 17). *First Cobalt Studies Battery Recycling for Nickel, Copper and Cobalt Recovery*. Retrieved June 27, 2021, from CISION: <https://www.newswire.ca/news-releases/first-cobalt-studies-battery-recycling-for-nickel-copper-and-cobalt-recovery-885966402.html>
- Flaherty, N. (2020, August 24). *Fair Cobalt Alliance for sustainable batteries*. Retrieved August 5, 2021, from EENews Europe: <https://www.eenewseurope.com/news/fair-cobalt-alliance-sustainable-batteries>
- Fraunhofer-Gesellschaft. (2015, September 2). *Recycling permanent magnets in one go*. Retrieved July 10, 2021, from PHYS.ORG: <https://phys.org/news/2015-09-recycling-permanent-magnets.html>
- Hampstead, J. P. (2018, January 3). *The trouble with cobalt*. Retrieved June 17, 2021, from FREIGHTWAVES: <https://www.freightwaves.com/news/2018/1/3/the-trouble-with-cobalt>
- Hart, L. (2020, January 7). *Mining for Neodymium*. Retrieved June 29, 2021, from Cline Mining: <https://www.clinemining.com/mining-for-neodymium.html>
- Harvey, F. (2021, March 11). *New US vehicles must be electric by 2030 to meet climate goals – report*. Retrieved June 8, 2021, from The Guardian: <https://www.theguardian.com/environment/2021/mar/11/new-us-vehicles-must-be-electric-by-2030-to-meet-climate-goals-report>
- Heintz, R. (2016, May 24). *Is There Enough Graphite to be Mined for the Electric Car Market?* Retrieved June 28, 2021, from Thermofisher Scientific: <https://www.thermofisher.com/blog/mining/is-there-enough-graphite-to-be-mined-for-the-electric-car-market/>
- Hudson, T. (2019, July 14). *Car On Road*. Retrieved May 30, 2021, from Pexels: <https://www.pexels.com/photo/car-on-road-2770933/>
- IER. (2013, October 23). *Big Wind's Dirty Little Secret: Toxic Lakes and Radioactive Waste*. Retrieved June 30, 2021, from Institute for Energy Research: <https://www.instituteforenergyresearch.org/renewable/wind/big-winds-dirty-little-secret-rare-earth-minerals/>
- IER. (2020, November 12). *The Environmental Impact of Lithium Batteries*. Retrieved June 12, 2021, from Institute For Energy Research: <https://www.instituteforenergyresearch.org/renewable/the-environmental-impact-of-lithium-batteries/>
- Investing News Network. (2018, May 3). *Graphite's Role in the Electric Vehicle Revolution*. Retrieved June 28, 2021, from INN: <https://investingnews.com/daily/resource-investing/battery-metals-investing/graphite-investing/rising-graphite-demand-in-the-electric-vehicle-revolution-amidst-graphite-supply-concerns-2/>
- Jacoby, M. (2019, July 14). *It's time to get serious about recycling lithium-ion batteries*. Retrieved July 27, 2021, from Chemical & Engineering News: <https://cen.acs.org/materials/energy-storage/time-serious-recycling-lithium/97/i28>
- Jamasmie, C. (2014, August 18). *New rare earth mine coming to Western Australia*. Retrieved July 25, 2021, from Mining.com: <https://www.mining.com/new-rare-earth-mine-coming-to-western-australia-95619/>
- Jeniece Pettitt, P. L. (2021, April 10). *Former Tesla CTO JB Straubel tackles battery recycling with Redwood Materials*. Retrieved August 5, 2021, from CNBC: <https://www.cnbc.com/video/2021/04/10/jb-straubels-redwood-materials-ex-tesla-cto-tackles-battery-recycling.html>
- Kelly, L. (2021, April 20). *Sudbury nickel miner's technology 'ecosystem' aims to find safe ultra*

- deep mining solution*. Retrieved July 21, 2021, from Northern Ontario Business: <https://www.northernontariobusiness.com/industry-news/mining/sudbury-nickel-miners-technology-ecosystem-aims-to-find-safe-ultra-deep-mining-solution-3648045>
- Kin Communications Investor Relations. (2021, July 20). *Graphite One Announces 2021 Drilling Program is Underway*. Retrieved July 22, 2021, from Kin Communications Investor Relations: <https://kincommunications.com/2021-news/graphite-one-announces-2021-drilling-program-is-underway/>
- King, H. M. (n.d.). *Graphite*. Retrieved June 28, 2021, from Geology.com: <https://geology.com/minerals/graphite.shtml>
- Kumagai, J. (2021, January 5). *Lithium-Ion Battery Recycling Finally Takes Off in North America and Europe*. Retrieved July 27, 2021, from IEEE Spectrum: <https://spectrum.ieee.org/energy/batteries-storage/lithiumion-battery-recycling-finally-takes-off-in-north-america-and-europe>
- Lena Mucha, T. C. (2018, February 28). *The hidden costs of cobalt mining*. Retrieved June 19, 2021, from The Washington Post: <https://www.washingtonpost.com/news/insight/wp/2018/02/28/the-cost-of-cobalt/>
- Leotaud, V. R. (2020, May 10). *New technology to be game-changer in rare earths extraction*. Retrieved July 27, 2021, from Mining.com: <https://www.mining.com/new-technology-promises-to-be-a-game-changer-in-the-extraction-of-rare-earths/>
- Li-Cycle. (2018, April 3). *Cobalt: the DRC and the Role of Lithium-ion Battery Recycling*. Retrieved June 20, 2021, from Li-Cycle: <https://li-cycle.com/news/cobalt-the-drc-and-the-role-of-lithium-ion-battery-recycling/>
- Lilac Solutions. (n.d.). *Lithium Extraction*. Retrieved July 10, 2021, from Lilac Solutions: <https://www.lilacsolutions.com/technology>
- Linquip. (2021, March 1). *Everything About Switched Reluctance Motor*. Retrieved July 31, 2021, from Linquip: <https://www.linquip.com/blog/switched-reluctance-motor/>
- Lipton, I. P. (2021, May 6). *The Lithium Gold Rush: Inside the Race to Power Electric Vehicles*. Retrieved June 10, 2021, from The New York Times: <https://www.nytimes.com/2021/05/06/business/lithium-mining-race.html>
- MAHLE. (2021, May 5). *MAHLE develops highly efficient magnet-free electric motor*. Retrieved August 2, 2021, from MAHLE: <https://www.mahle.com/en/news-and-press/press-releases/mahle-develops-highly-efficient-magnet-free-electric-motor--82368>
- Mahoney, N. (2021, July 22). *US wants to reclaim critical rare earth supply chain*. Retrieved July 25, 2021, from Freightwaves: <https://www.freightwaves.com/news/us-wants-to-reclaim-critical-rare-earth-supply-chain>
- Marshall, J. (2014, April 7). *WHY RARE EARTH RECYCLING IS RARE — AND WHAT WE CAN DO ABOUT IT*. Retrieved August 4, 2021, from Ensia: <https://ensia.com/features/rare-earth-recycling/>
- Maughan, T. (2015, April 2). *The dystopian lake filled by the world's tech lust*. Retrieved June 30, 2021, from BBC: <https://www.bbc.com/future/article/20150402-the-worst-place-on-earth>
- Merriam-Webster. (n.d.). *bioleaching*. Retrieved July 21, 2021, from Merriam-Webster: <https://www.merriam-webster.com/dictionary/bioleaching>
- Mine. (2021, January). *On the hunt: the new technologies changing mineral exploration*. Retrieved July 27, 2021, from Mine: https://mine.nridigital.com/mine_jan21/mineral_exploration_technologies
- Minerals Education Coalition. (n.d.). *Dysprosium*. Retrieved June 29, 2021, from MEC: <https://mineralseducationcoalition.org/elements/dysprosium/>
- NEF, B. (2016, February 25). *Electric vehicles to be 35% of global new car sales by 2040*. Retrieved June 8, 2021, from Bloomberg NEF: <https://about.bnef.com/blog/electric-vehicles-to-be-35-of-global-new-car-sales-by-2040/>

- Nickel Institute. (n.d.). *About Nickel*. Retrieved June 20, 2021, from Nickel Institute: <https://nickelinstitute.org/about-nickel/>
- Northern Ontario Business. (2021, January 12). *Cobalt explorer primed for action in 2021*. Retrieved July 20, 2021, from Northern Ontario Business: <https://www.northernontariobusiness.com/industry-news/mining/cobalt-explorer-primed-for-action-in-2021-3253356>
- NuEnergy Blog. (2019, April 7). *PRESERVING THE ENVIRONMENT: WHY IS LITHIUM USED IN BATTERIES?* Retrieved June 9, 2021, from NuEnergy: <https://www.nuenergy.org/preserving-the-environment-why-is-lithium-used-in-batteries/>
- Off-Grid Energy. (2016, June 22). *All About Lithium*. Retrieved June 12, 2021, from Off-Grid Energy Australia: <https://www.offgridenergy.com.au/all-about-lithium/>
- Office of Technology Transitions. (2016, September 6). *ORNL Licenses Rare Earth Magnet Recycling Process to Momentum Technologies*. Retrieved July 28, 2021, from ENERGY.GOV Office of Technology Transitions: <https://www.energy.gov/index.php/technologytransitions/articles/ornl-licenses-rare-earth-magnet-recycling-process-momentum>
- O'Dea, H. A. *Electric Vehicle Batteries Addressing Questions about Critical Materials and Recycling*. Union of Concerned Scientists. Union of Concerned Scientists.
- Palisade Research. (2017, March 24). *Manganese – the third electric vehicle metal no one is talking about*. Retrieved June 27, 2021, from Mining.com: <https://www.mining.com/web/manganese-the-third-electric-vehicle-metal-no-one-is-talking-about-it-heres-how-to-take-advantage/>
- Palisade Research. (2017, March 24). *Manganese – the third electric vehicle metal no one is talking about*. Retrieved July 22, 2021, from Mining.com: <https://www.mining.com/web/manganese-the-third-electric-vehicle-metal-no-one-is-talking-about-it-heres-how-to-take-advantage/>
- Parry, S. (2011, January 26). *In China, the true cost of Britain's clean, green wind power experiment: Pollution on a disastrous scale*. Retrieved June 30, 2021, from Daily Mail: <https://www.dailymail.co.uk/home/moslive/article-1350811/In-China-true-cost-Britains-clean-green-wind-power-experiment-Pollution-disastrous-scale.html>
- Patel, E. K. (2020, December 3). *EU Aims to Have 30 Million Electric Cars on the Road by 2030*. Retrieved June 8, 2021, from Bloomberg Green: <https://www.bloomberg.com/news/articles/2020-12-03/eu-aims-to-have-30-million-electric-cars-on-the-road-by-2030>
- Peterson, M. (2018, August 16). *This Incredible New Battery Tech Is Safer, Lasts Longer Than Lithium-Ion*. Retrieved August 5, 2021, from iDROP News: <https://www.idropnews.com/news/this-incredible-new-battery-tech-is-safer-lasts-longer-than-lithium-ion/80420/>
- Pradhan, C. (2019, March 14). *Types of Motors used in EVs and why BLDC Motors are widely used*. Retrieved June 29, 2021, from ElectricVehicles.in: <https://electricvehicles.in/types-of-motors-used-in-evs-and-why-bldc-motors-are-widely-used/>
- Reporter, C. M. (2008, July 29). *New manganese mine planned for Namibia*. Retrieved July 22, 2021, from Creamer Media's Mining Weekly: <https://www.miningweekly.com/article/new-manganese-mine-planned-for-namibia-2008-07-29>
- Rice, C. (2020, September 27). *Electric Vehicles: The Dirty Nickel Problem*. Retrieved June 21, 2021, from Clean Technica: <https://cleantechnica.com/2020/09/27/electric-vehicles-the-dirty-nickel-problem/>
- Richter, A. (2020, March 16). *CTR and Lilac Solutions to unlock massive sustainable lithium*

- resource in the U.S. Retrieved July 10, 2021, from Think Geoenergy:
<https://www.thinkgeoenergy.com/ctr-and-lilac-solutions-to-unlock-massive-sustainable-lithium-resource-in-the-u-s/>
- Richter, F. (2020, March 10). *Tesla's Road to 1,000,000*. Retrieved June 8, 2021, from Statista:
<https://www.statista.com/chart/21083/tesla-cumulative-vehicle-production/>
- Rivian. (2021, January 19). *Newsroom*. Retrieved June 8, 2021, from Rivian:
<https://rivian.com/newsroom>
- Roskill. (2018, August 30). *Rare earths: Is magnet recycling a solution?* Retrieved July 10, 2021, from Roskill: <https://roskill.com/news/rare-earths-is-magnet-recycling-a-solution/>
- Ross, I. (2021, February 9). *Could Timmins become Northern Ontario's new nickel capital?* Retrieved July 21, 2021, from Sudbury Mining Solutions Journal:
<https://www.sudburyminingsolutions.com/news/could-timmins-become-northern-ontarios-new-nickel-capital-3368866>
- Runkevicius, D. (2020, December 7). *As Tesla Booms, Lithium Is Running Out*. Retrieved June 13, 2021, from Forbes: <https://www.forbes.com/sites/danrunkevicius/2020/12/07/as-tesla-booms-lithium-is-running-out/?sh=2f2adf2b1a44>
- Sander Hoenderdaal, L. T.-W. (2013, January 1). *Can a dysprosium shortage threaten green energy technologies?* Retrieved June 30, 2021, from ScienceDirect:
<https://www.sciencedirect.com/science/article/abs/pii/S0360544212008055>
- Shahan, Z. (2021, January 1). *499,550 Tesla Sales In 2020 (CleanTechnica Charts)*. Retrieved June 19, 2021, from CleanTechnica: <https://cleantechnica.com/2021/01/01/troy-teslike-estimates-502692-tesla-sales-in-2020/>
- Teague, C. (2021, April 30). *What You Need to Know About Solid-State Batteries*. Retrieved July 30, 2021, from Autoweek:
<https://www.autoweek.com/news/technology/a36189339/solid-state-batteries/>
- Tesla. (2021). *Model 3*. Retrieved June 8, 2021, from Tesla:
https://www.tesla.com/en_CA/model3
- The Impact Facility. (n.d.). *Fair Cobalt Alliance (FCA)*. Retrieved July 20, 2021, from The Impact Facility: <https://www.theimpactfacility.com/commodities/cobalt/fair-cobalt-alliance/>
- Tunnicliffe, A. (2019, October 24). *Will the new Rare Earth Industry Association reshape the industry?* Retrieved July 25, 2021, from Mining Technology: <https://www.mining-technology.com/features/83925/>
- Vinoski, J. (2020, June 11). *Urban Mining Company's Rare Earths Recycling Helps Us Tackle Chinese Dominance*. Retrieved July 28, 2021, from Forbes:
<https://www.forbes.com/sites/jimvinoski/2020/06/11/urban-mining-companys-rare-earths-recycling-helps-us-tackle-chinese-dominance/?sh=48f6d88225ea>
- Volkswagen. (2018). *Lithium Mining - What You Should Know About The Contentious Issue*. Retrieved June 10, 2021, from Volkswagen:
<https://www.volkswagenag.com/en/news/stories/2020/03/lithium-mining-what-you-should-know-about-the-contentious-issue.html#>
- Wartsila. (2021, June 22). *World's first sustainable lithium mining power solution launched*. Retrieved July 10, 2021, from Mining Review Africa:
<https://www.miningreview.com/battery-metals/worlds-first-sustainable-lithium-mining-power-solution-launched/>
- Wollschlaeger, S. (2017, September 6). *Enhanced methods for nickel recovery from low-grade ores and bleed streams*. Retrieved July 21, 2021, from emew Blog:
<https://blog.emew.com/enhanced-methods-for-nickel-recovery-from-low-grade-ores-and-bleed-streams>