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A Comparative Analysis of Conventional Internal Combustion Vehicle and Electric Buses in Austin, Texas

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A Comparative Analysis of Conventional Internal Combustion Vehicle and Electric Buses in Austin, Texas

by

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Dedication

Dedicated to my mom, Elena, my dad, Peter, my brother, Andrés, and my entire family for helping to put me in this position.

Dedicated to the marginalized Black and Brown people in the United States of America and around the world who are victims of environmental injustice and racism through no fault of their own.

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Abstract

A Comparative Analysis of Conventional Internal Combustion Vehicle and Electric Buses in Austin, Texas

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This thesis project examines the life cycle and environmental impact of carbon dioxide (CO_2) and greenhouse gas emissions related to the city of Austin, Texas' transition from conventional diesel buses to electric vehicle buses. I utilized a life cycle assessment model derived from two data sources. I conducted a comprehensive literature review to analyze the energy intensity and greenhouse gas emissions of electric buses and used this information to estimate the effects and externalities of a municipal program that incentivizes individuals to change their form of transportation from private vehicles to public buses. Second, I obtained data from the City of Austin and Austin Capital Metro and analyzed ridership and vehicles miles traveled (VMT) to estimate energy intensity, emissions per passenger mile traveled (PMT), and emissions per vehicle mile traveled. Because electric energy is derived from multiple sources, I considered various electricity production scenarios, including the Austin Energy mix, Electric Reliability Council of Texas's (ERCOT) electricity production makeup, and scenarios using combinations of renewables, fossil fuels and nuclear energy. The goal was to utilize Austin as an example

for other American cities that are considering a transition from diesel buses to electric buses.

The analysis showed that electric buses significantly outperformed their diesel counterparts, on a CO2-equivalent basis, using every electricity mix that was evaluated, for the empty-load, half-load and full-load scenarios. For the electric buses, electricity mixes that used more renewable energy sources (i.e. wind, solar and hydropower) had lower emissions than other options, such as nuclear, coal and natural gas.

The results of this thesis project will be available to policymakers and other stakeholders who are engaged in decisions about enhancing the environmental sustainability of Austin's transit system. I hope that decision-makers within Austin Energy's and ERCOT's leadership will find this report valuable. I would like to share the results with other cities, in the hopes of encouraging transportation systems throughout the country to consider large-scale change to advance sustainability and mitigate the transportation-related aspects of climate change.

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SECTION 1: STATEMENT OF PROBLEM

As the United States and other nations seek to achieve a more sustainable, renewable, carbon-neutral future, the electrification of the transportation sector is an attractive approach for achieving this vision. “In 2019, the transportation sector accounted for 29% of all greenhouse gas emissions in the United States, more than any other single sector” (EPA, 2019). Consequently, short- and long-term initiatives or efforts to reduce emissions economy-wide must address transportation issues.

Conventional internal combustion vehicles use fossil fuels such as gasoline and diesel and convert roughly 17%-21% of primary on-board energy into secondary, kinetic energy. In contrast, electric vehicles generally convert 85%-90% of on-board primary energy into kinetic energy (Hanley, 2018). Because electric vehicles are approximately four times more efficient in on-board energy conversion, they are a very appealing option for personal vehicles and public transportation, including buses and light-rail trains.

Electric vehicles have a number of advantages when compared to their internal combustion vehicle counterparts. In addition to their efficiency in energy conversion, electric vehicles require significantly less maintenance (Winters, 2021), are quieter on city streets, have faster acceleration, and have a longer use-phase of their life cycle. According to Mike Winters, a money reporter from CNBC, the maintenance costs of electric vehicles are 31% lower than those of fossil fuel-powered internal combustion vehicles (Winters, 2021). In addition to their efficiency profile, future developments in electric vehicle and battery technology might facilitate progress toward a more reliable energy grid. There is an argument that the proliferation of electric vehicles will actually put too much stress on the electrical grid, making it less reliable to the consumer. It is possible that electric vehicle batteries could serve as energy storage devices and transfer power to the energy grid during hours of peak demand (Noel, Zarazua de Rubens, Kester, Sovacool, 2018). This technology can be exhibited by the Ford F-150 Lightning, which was released in 2022.

In the United States, millions of cars are purchased each year. During 2015-2020, more than 17 million cars were purchased per year (Wayland, 2020). According to the Pew Research Center, in June 2021, only 7% of American adults reported owning an electric or hybrid vehicle, and 39% adults reported that they would consider purchasing an electric car (DeSilver, 2021). While a sizeable proportion would consider purchasing an electric vehicle, a higher proportion was not reported, for two key issues (Frangoul, 2021). First, prospective buyers may experience “range anxiety” because electric cars do not usually have as long a range as their traditional, internal combustion counterparts. In addition, longer trips may require recharging and car owners may be reluctant to extend their travel time in order to recharge the car battery. Additionally, they may likely have fear of getting stuck or stranded before finding a charging station for their electric vehicle. While many electric vehicles can be equipped with rapid chargers, this adaptation can have a negative impact on the integrity and durability of the battery if it is used on a regular basis. However, this technology is improving and may not be as large an issue in the future.

Second, the lack of a robust charging infrastructure hinders widespread adoption of electric vehicles. This issue can be categorized as a “chicken-or-the-egg” scenario because uptake of electric vehicles will likely follow a phase of expanding the charging infrastructure, and the charging infrastructure would be expected to expand in response to more significant purchasing of electric vehicles. These interrelated changes must occur to achieve the goal of increasing the proportion of electric vehicles, yet investment in the infrastructure is required without guarantees regarding consumer behavior.

While these aforementioned issues associated with electric vehicles are valid, there are substantial advantages as well. First, consumers can charge their vehicle at home, which is a significant convenience. Second, electricity to power a vehicle is cheaper than gasoline, on a per mile basis. Third, government incentives can subsidize a portion of the cost to consumers. These are several other advantages associated with electric vehicles.

Despite a rapid increase in electric vehicle ownership over the last decade (Breetz & Salon, 2018), electrification within the public transportation sector has not been common. According to the Argonne National Laboratory and Alternative Fuels Data Center, electric vehicle sales in the United States increased from nearly 18,000 units in 2011 to more than 320,000 units in 2019, nearly a twenty-fold increase (Zhou, 2019). More recently, in 2021, there were over 487,000 electric vehicles sold in the United States, an increase of 89% compared to 2020 (Lopez, 2022). Furthermore, the same group reported that the number of vehicle miles traveled by electric vehicles has risen from 0.1 billion in 2011 to 13.6 billion in 2020, more than one hundredfold increase. As a result of these temporal changes, electricity consumption for electric vehicles (in GWh) has increased from 20 GWh in 2011 to 4,400 GWh in 2020 in the United States.

The conversion of these 51.2 billion vehicle miles traveled by electric vehicles in the United States from 2011 to 2019, as compared to conventional gasoline and diesel vehicles, has saved close to 10 million metric tonnes of CO_2 emissions (Gohlke & Zhou, 2020). In 2019, the last full year before the Covid-19 pandemic, there were 12.5 billion electric vehicle miles traveled in the United States, a large number but small in comparison to 3.26 trillion miles traveled by all personal vehicles (Bureau of Transportation Statistics, 2020). While 12.5 billion miles traveled is significant, it only accounts for about 0.387% of all vehicle miles traveled for all vehicles in the country.

According to LMC Automotive, in 2021 only 4% of domestic car sales were projected to be electric vehicles (Wayland, 2021b).

According to the International Energy Agency, in 2019 global electric vehicle sales were roughly 2.1 million units, approximately 2.6% of all vehicle sales (International Energy Agency, 2020). Furthermore, 2019 sales of electric vehicles increased more than 40% relative to the previous year, which indicates global growth in the electric vehicle industry. It is paradoxical that the proportion of electric vehicle sales is small yet there has been a dramatic increase in the total number of electric vehicle miles traveled. This could indicate that consumers have less range anxiety than before. However, the increase in electric vehicle sales has not yet fully taken hold, as it relates to vehicle miles traveled. These two trends are currently in direct opposition to one another, but in the future, as increasing numbers of electric vehicles start to replace fossil fuel-powered internal combustion vehicles, the percentage of all vehicle miles traveled that are driven by electric vehicles will start to climb more as well. Consequently, as seen with the analysis done by the Argonne National Laboratory, as electric vehicle miles traveled increase significantly in the future, the CO_2 emissions associated with personal vehicles will decrease.

Currently, nuclear and fossil fuels such as coal and natural gas serve as the baseload for electricity production, due to their dispatchability (Popovich, 2018). While renewable energy sources, are appealing, some of them, such as wind, solar and hydroelectric, only operate and produce energy when there is sunlight, wind, and water available. There are other less intermittent, more dispatchable renewable options, such as geothermal and biomass energy. Furthermore, some forms of renewable energy might not be available during times of peak demand, which limits their usefulness for societal energy management without energy storage solutions such as batteries. For example, solar power generates maximal energy during the late morning and early afternoon but the period of peak demand in warm climates is late afternoon and evening or late evening in cold climates. Therefore, as battery storage improves, solar deployment will likely follow in kind (Mohammed, Mustafa & Bashir, 2014).

Wind power is subject to similar limitations as solar power, although the electricity generated from wind is more variable and less predictable (Ren et al, 2017). As is the case with solar power, improvements in battery storage capacity are anticipated to enhance the utility of renewable electricity generation from wind and place renewable energy in a competitive position relative to fossil fuels, which can provide electricity throughout all times of the day.

Historically, fossil fuels are abundant and have had a comparatively lower cost of energy production than renewable sources, which results in fossil fuels representing the majority of base load electricity production. Currently, however, renewables are cheaper than coal, as well as gas, with the high price of gas, and wind and solar have lower levelized cost of energy (LCOE) than fossil fuel sources in many regions of the United States. From a life cycle perspective, fossil fuels produce many more greenhouse gases as compared to renewable sources of energy such as solar, wind, biomass, hydropower, and nuclear.

With advances in technology, renewable sources of energy for base load electricity production will produce far fewer greenhouse gas emissions than fossil fuels, including natural gas, coal, and other petroleum products. Technological improvements in battery storage technology are enabling for scaled-up deployment of renewable sources to serve base load needs.

The electrification of energy loads which have traditionally been powered by fossil fuels is termed “environmentally beneficial electrification” (Dennis, Colburn and

Lazar, 2016). Over time, many societal benefits are anticipated due to the increased proportion of electric vehicles, relative to internal combustion vehicles. Some of these benefits include improved vehicle performance, economic savings to vehicle owners, reductions in ambient noise within communities, reductions in greenhouse gas emissions and criteria pollutants, and renewable energy integrations (Noel, Zarazua de Rubens, Kester & Sovacool, 2018).

The largest societal benefits associated with electrification of the transportation sector are the reduction in emissions of criteria pollutants and greenhouse gases. Although completely halting the marginal emission of greenhouse gases would not reduce the impact of greenhouse gases that have already been emitted into the atmosphere, because some greenhouse gases, such as hydrofluorocarbons and perfluorocarbons, can last thousands of years, reducing the production of greenhouse gas emissions is an essential first step. Thus, electrification is a compelling priority, especially for the transportation sector, which accounts for the highest proportion of greenhouse gas emissions in the Unites States, as previously stated.

Economic factors are important to consider when analyzing the environmental sustainability of the transportation system. Throughout the United States and all over the world, people who cannot afford personal vehicles rely on public transportation, including buses, trains, taxis, on-demand car services such as Uber and Lyft, ferries, scooters and rickshaws. Whereas there is ample data on the impact of personal electric vehicles on greenhouse gas emissions and climate change, there is a substantially less information regarding the impact of electric vehicles within the public transportation sector, namely buses.

Although the modes of public transportation vary across the world, expanding public transportation ridership and enhancing the public transportation infrastructure could have significant societal benefits on global scale, including reductions in greenhouse gas emissions, reduced road traffic and accidents, enhanced longevity of roads and other transportation structures, fostering a sense of community, and increased community development, and equity. The reduction in greenhouse gas production also has a positive effect on human health, in the form of lower asthma rates due to less particulate matter in the air, as well as other benefits (National Institute of Environmental Health Sciences, 2017). Thus, there is a direct benefit to human health associated with reducing greenhouse gas emissions, in addition to societal benefits and positive effects on ecosystems around the world.

To achieve expansion of public transportation infrastructure, policymakers and researchers must consider equity. For example, bus and rail routes should include lower-income areas to ensure that the transportation system is accessible to all community residents. Since some areas may not be economically viable for bus or rail service, city planners could consider shuttles or express buses, which differ in their routes and number of stops.

In November 2020, the city of Austin, Texas voted to invest $7.1 billion to expand the rail infrastructure, invest in electric buses, and install a new electric charging hub on the west side of the city through a program called "Project Connect" (Oldman, 2020). The population housed in the Central Texas region, surrounding and including Austin, is expected to increase by 70% in the next two decades, from 2.4 million people in 2020 to roughly 4.1 million in 2040, and this type of population growth will impact the transportation sector throughout the central portion of the state (Oldman, 2020).

To address the population's transportation needs, the city of Austin plans to use the funds to build and expand four MetroRapid routes, which will promote connectivity within and between different parts of the city. First, the Orange Line, which runs through the campus of University of Texas at Austin, will connect North Austin and South Austin. Second, the Blue Line will run from downtown Austin to the Austin-Bergstrom International Airport in southeast Austin. Third, the Red Line will be expanded to connect to other rail lines within the city as well as MetroRapid and Capital Metro routes in various other areas of Austin (Oldman, 2020).

Fourth, the Green Line services the historically underserved and disenfranchised east side of Austin and other surrounding areas. Also, there will be a fully electric bus fleet, a rail system that is partially underground beneath downtown Austin, and expanded bus and rail routes (A New Transit Plan for Austin - Project Connect by Capital Metro, 2021). These expanded rail lines and bus systems will not only serve the community in a practical sense, but they will hopefully also exhibit how a successful, electric-powered transit system can function. If it goes well, other cities around the country will be able to use Austin as an example and plan similar electric transportation infrastructure systems accordingly, to serve their respective city's transportation needs.

Austin's Project Connect is intended to accomplish several environmental and societal goals, including setting a national standard for sustainable and environmentally-friendly transit system operations, reducing the transportation system's carbon footprint though electrification, using renewable sources of energy such as solar and wind as major sources of energy, building an all-electric fleet of buses and using battery and energy storage capacity to reduce consumption and waste (A New Transit Plan for Austin - Project Connect by Capital Metro, 2021).

While Austin's expansion of public transportation infrastructure will increase access to transportation across the city, the electric charging hub will be based in west Austin, which is a more affluent and less diverse sector of the city. Despite the city's ambitious plan to promote public transportation, it is challenging to ensure equitable distribution of public transportation across disadvantaged racial, ethnic or socioeconomic groups. In an effort to mitigate the risk of inequity, Project Connect will create thousands of stable, well-paying local jobs, ensure community access to healthcare, education, entertainment, and foster a sense of community (A New Transit Plan for Austin - Project Connect by Capital Metro, 2021). Also, $300 million are being used to ensure bus lines serve people in the neighborhoods and communities in which they live (Oldman, 2020).

The primary challenge involves the large-scale transition of Austin’s public transportation infrastructure from conventional, fossil fuel-powered vehicles to a transportation system powered by electricity. The impact of the vehicular change is amplified by the renewable energy sources that will power the electric vehicles, resulting in a significant decrease in the entire system’s carbon footprint. Also, reduction in criteria pollutants, such as PM2.5 (particulate matter with width of 2.5 microns) and PM10 (particulate matter with width of 10 microns), will have immense local public health benefits. In addition, electrification and battery storage as well as expansion of rail transit and charging infrastructure for electric vehicles are critical components of this significant transition for the transportation system of a major American city.

SECTION 2: RELEVANCE OF THE PROBLEM

The electrification of Austin's public buses may seem like a prudent choice from an environmental perspective because of the elimination of all tailpipe emissions. However, there are impacts associated with harvesting the materials to create batteries for electric buses, cities need to create a charging infrastructure to power the buses, and energy is needed to generate the electricity that is used to power the buses. Also, the end-of-life stage of a bus's or any vehicle's life cycle has to be taken into account to fully analyze its emissions. A life cycle analysis of the environmental impact of the bus fleet would provide a more accurate understanding of how an electric bus impacts the environment, as compared to a conventional, fossil fuel-powered bus in the Austin Capital Metro Bus fleet.

A comprehensive analysis would account for all phases of emissions, including raw material extraction, material and component manufacturing, vehicle assembly and manufacturing, transport, fuel cycle (electricity generation), vehicle use and end-of-life/disposal. Using a life cycle assessment or evaluating existing life cycle assessments of electric buses, one would be able to compare each phase of emissions from an electric bus to that of a conventional diesel or gasoline bus, and thereby determine which phases could be optimized to reduce emissions and which phases outperform conventional buses or require improvement for widespread adoption.

The goal is that this analysis would be useful to Capital Metro and the city of Austin, Texas as a way to improve the efficiency and environmental footprint of its bus fleet. The analysis may be applicable to other cities around the world which seek successful models of electrification of city buses.

SECTION 3: BACKGROUND

Chapter 1: Infrastructure Challenges and Implications

As the United States (U.S.) and countries around the world continue to urbanize, there are a number of challenges and stresses on infrastructure systems that must be considered to ensure positive societal development. According to the United Nations' (UN) Population Division, "83% of the U.S. population currently lives in urban areas, up from 64% in 1950. By 2050, 89% of the U.S. population and 68% of the world population is projected to live in urban areas" (United Nations, 2018). This rapid increase in urbanization over the next three decades will test the infrastructure systems of cities around the world, including wastewater treatment facilities, roads and highways, hospitals and emergency services, and electricity production.

For Project Connect and the electrification of the public transportation sector in Austin, Texas, the production of electricity using renewable resources and expansion of the charging infrastructure are two crucial developments that are needed to ensure and secure a successful transition from internal combustion diesel buses to electric buses. While this thesis focuses on the transition from diesel buses to electric buses in Austin, other cities in the U.S. and other countries will likely consider similar transitions, from gasoline- and diesel-powered vehicles to cleaner natural gas-powered and electric vehicles. In the U.S., the transition from internal combustion vehicles to electric vehicles and the expansion of charging infrastructure will require significant governmental and private investment, at the municipal, state, and federal levels.

In March 2021, the Biden Administration outlined a $174 billion plan "to spur the development and adoption of electric vehicles that includes money to retool factories and boost domestic supply of materials, tax incentives for EV buyers, and grant and incentive programs for charging infrastructure" (Wayland, 2021a). This plan is a part of the Bipartisan Infrastructure Law (Infrastructure Investment and Jobs Act) that President Joe Biden signed into law on November 15, 2021, which, according to The White House website, will "rebuild America's roads, bridges and rails, expand access to clean drinking water, ensure every American has access to high-speed internet, tackle the climate crisis, advance environmental justice, and invest in communities that have too often been left behind" (The White House, 2021).

A key element of efforts to address the global climate crisis, both domestically and internationally, is the expansion and proliferation of access to a reliable and affordable electric charging network. According to AlixPartners, a global consulting firm, "$300 billion will be needed to build out a global charging network to accommodate the expected growth of EVs by 2030, including $50 billion in the U.S. alone" (Wayland, 2021a).

There are different types of electric charging systems, and the cost of electrification is strongly related to the installation costs. Level 1 chargers are 120-volt chargers and are typically used within homes, workplaces, and public charging sites. On average, Level 1 charges can charge a vehicle at a rate of 3 to 5 miles of range per hour. Level 1 chargers are more commonly used for plug-in hybrid electric vehicles (PHEVs) due to their smaller battery size, as compared to battery electric vehicles (BEVs). The major disadvantage of Level 1 chargers is the slow speed at which the vehicle charges.

Level 2 chargers are 208-volt to 240-volt chargers and are also used within homes, workplaces and public charging sites. Level 2 chargers add 12 to 80 miles of range per hour and are more commonly used on BEVs because they can charge the larger battery more quickly. While the Level 2 charger has the advantage of efficiency, the cost of installation of most Level 2 chargers, may be a barrier for home installation, as most Level 2 chargers cost $250 to $1,000 for installation. Level 3 chargers are 400- to 900-volt chargers which are used in public charging locations and typically add 3 to 20 miles of range per minute charged (Moloughney, 2021). According to J.D. Power, one of the main drawbacks to Level 3 chargers is that frequent rapid-charging can accelerate battery degradation (Choksey, 2021). In addition, this could require supplemental investment on the part of consumers to upgrade electrical circuitry and paneling in their homes. Therefore, for electric vehicle owners, it is advisable to avoid frequent use of rapid chargers. For electric buses, replacement batteries already onboard the bus are an option, as well as rapid chargers. However, the battery degradation when using rapid chargers will need to be mitigated, since an electric bus is likely to use its full charge before the end of its day.

Chapter 2: Personal Vehicles and American Investment in Electric Vehicles

As The United States becomes less dependent on fossil fuel-powered vehicles and more reliant on electric vehicles, expansion of charging infrastructure will be very important. According to the United States Department of Energy, in 2019, electric vehicles, both BEVs and PHEVs, accounted for only 2% of the 17 million new vehicles sold (Wayland, 2021a). However, there seems to be significant momentum for the proliferation of electric vehicles in present-day and in the future.

According to Forbes, Tesla has accounted for about 74% of all electric vehicles (430,000 vehicles) sold in the United States over the last three years (McCarthy, 2021). Tesla, an American electric automaker, which moved its headquarters from Palo Alto, California to Austin, Texas in 2021 and has manufacturing facilities throughout California and other parts of the United States, briefly reached a trillion-dollar valuation in late 2021. “Tesla's route to a trillion-dollar valuation was a relatively short one, driven by a global policy push and investor enthusiasm for an electric vehicle future” (Sharma, 2021). Although this article presents a more pessimistic view of Tesla’s future, it illustrates that the electric vehicle industry is growing significantly and will likely do so for the foreseeable future, especially if technology maintains pace with consumer demand.

Tesla is not the only auto manufacturer to jump on the electric vehicle trend. Rivian, Nikola, Polestar, Proterra and Bollinger are all American auto manufacturers with their foot in the electric vehicle space. Li Auto and NIO, Arrival, Terra Motors, and Cocoa Motors, among others, are all foreign electric vehicle manufacturers, based in China, the United Kingdom, India and Japan, respectively. Additionally, auto manufacturers known for conventional internal combustion vehicles are banking on the transition to electric vehicles. General Motors, Ford, Stellantis (with brands such as Fiat, Chrysler, Dodge, Jeep, among others) Toyota, BMW, Audi, Mercedes-Benz, Honda, and Hyundai, and others, are all either producing or have announced manufacturing of purely electric or hybrid-electric vehicles.

On Thursday, January 28, 2021, General Motors announced that they would phase out their internal combustion engines by 2035 and focus on electric and other vehicle types. For GM, a company that has made its money on sporty cars such as the Chevrolet Corvette and Chevrolet Camaro as well as large SUVs and trucks like the Cadillac Escalade, GMC Yukon and Chevrolet Silverado, this represents an enormous pivot in their business plan. As one of the Big 3 American automakers that had been passed up in efficiency, reliability and innovation primarily by Japanese titans Honda and Toyota, General Motors is seeking to improve its standing in the American and global auto marketplace. In 2011, General Motors made a large step by producing the Chevrolet Volt PHEV (Plug-In Hybrid Electric Vehicle). Furthermore, they manufactured the Chevrolet Bolt EV in 2016, which was the first BEV (battery electric vehicle) from a legacy OEM (original equipment manufacturer) with over 200 miles of range at a reasonable sticker price for the consumer.

General Motors was the United States' largest auto manufacturer, until it was recently passed in 2021 by Toyota (Boudette, 2021) and is currently the fourth-largest auto manufacturer in the world. Internal combustion vehicles (gasoline- or diesel-powered) comprise 98% of General Motors' sales and all of its profits. Also, General Motors' vehicle fleet underperformed the average American car by 2.4 mpg (Colias, 2021). Moving forward, General Motors has set the goal to sell only vehicles without tailpipe emissions starting in 2035 and to be carbon neutral by 2040. As previously mentioned, GM produced the Volt PHEV from 2011 to 2018, and the Bolt EV since 2016.

In 2022, GM will kick off its campaign into electric vehicles with the 2022 GMC Hummer EV. According to the Chevrolet website, the Bolt EUV, redesigned Bolt EV, electric Equinox, Silverado EV and electric Blazer have already been announced. Cadillac, Buick and GMC, other General Motors brands, have also announced several electric vehicles that will be released in the near future. Additionally, there are other manufacturers that have announced similar pledges to General Motors.

Ford, which is headquartered in Dearborn, Michigan, is the third-largest domestic and fifth-largest global auto manufacturer (Wagner, 2020). In February 2021, Ford announced a $29 billion investment, with $22 billion towards electric vehicles and $7 billion towards autonomous vehicles, through the year 2025 (Baldwin, 2021). This amount represents a notable portion of Ford’s revenues during that timeframe, which indicates Ford’s strong commitment and bet on the current trajectory of the electric vehicles industry. Although Ford did not make a similar pledge as far as phasing out their production of internal combustion vehicles, they have joined General Motors in committing to the production of electric vehicles. Ford has also invested about $500 million in Rivian, which is an all-electric vehicle manufacturing startup company headquartered in Irvine, California with a manufacturing facility in Normal, Illinois and some other facilities in California (Palo Alto and Carson), Plymouth, Michigan and a couple other countries (Baldwin, 2021).

Furthering their commitment to electric vehicles, Ford announced an investment in four new factories, including three batteries factories and a truck plant, which would cost roughly $11.4 billion, and create around 11,000 jobs. These factories will enable Ford to produce one million electric vehicles per year by the end of the current decade

(Boudette, 2021). By 2023, Ford will be able to produce about 600,000 electric vehicles, which would make it the second-largest electric vehicle domestic manufacturer behind Tesla. This production would come from the Ford Mustang Mach-E, F-150 Lightning and E-Transit (Wayland, 2021d). As auto manufacturers, both domestic and abroad, continue to ramp up their production of electric vehicles, they will also be forced to extract larger amounts of resources to meet consumer demand.

Chapter 3: Resources Required to Manufacture Electric Vehicles and Their Environmental Impact

While all internal combustion and electric vehicles require resources to be manufactured and have measurable environmental footprints, the majority of emissions attributable to internal combustion vehicles are derived from the use phase (Keoleian & Sullivan, 2012) . This is also true for BEVs, however a larger portion of life cycle emissions are attributable to extraction and manufacturing (Evrard et al, 2021). As the U.S. and other countries around the world pursue vehicle electrification, many resources will be needed in increasing quantities. For example, lithium-ion batteries dominate the rechargeable battery market and are anticipated to increase in storage capacity from 15.9 GWh in 2015 to 93.1 GWh in 2024 (Desjardins, 2016). Though other battery chemistries are in development, lithium-ion batteries will likely continue to dominate the automotive market for the foreseeable future.

Concurrent with advances in technological capacity is an increase in demand for the underlying components, including natural resources. According to a study in the journal *Communication Materials*, “demand is estimated to increase by factors of 18–20 for lithium, 17–19 for cobalt, 28–31 for nickel, and 15–20 for most other materials from 2020 to 2050, requiring a drastic expansion of lithium, cobalt, and nickel supply chains and likely additional resource discovery” (Xu et al, 2020). These estimates underscore the potential environmental impact of the transition to electric vehicles, including extraction and refinement of minerals and production of vehicular components. Additionally, the transportation of minerals from their source to a production site represents an additional environmental impact.

Lithium-ion batteries usually combine lithium with nickel, manganese, cobalt, and aluminum or iron within one major component of the battery. Another major element of lithium-ion batteries is graphite. All of the aforementioned minerals used in lithium-ion batteries, except iron, are considered critical and are incorporated within various technologies. While reserves of these minerals exist throughout the world, there are specific locations with especially rich resources, which creates challenges for ensuring a robust and growing supply.

Cobalt is currently an important component in lithium-ion batteries and its sources are concentrated in the Democratic Republic of the Congo. Cobalt mining is an extremely pollutive activity that contaminates air, soil, drinking water, plants and wildlife in surrounding areas. Currently, the Democratic Republic of the Congo accounts for approximately 70% of global cobalt production and over 50% of global cobalt reserves (Ambrose & O'Dea, 2021). It is important to note that the Democratic Republic of the Congo has an unstable government system and is considered rife with corruption. These political factors influence the overall impact of cobalt mining on the environmental, human rights and human health aspects of wellbeing. While current battery technology is moving away from cobalt, it is still an important mineral for batteries used in EVs today. In the future, cobalt will likely be a less important element, and these mining practices could be mitigated and lessened.

Apart from geographic differences in the availability of mineral resources, there are significant disparities in the global distribution of resources for lithium-ion batteries, such as cobalt. According to a study into cobalt's cycle of use, China, Japan and the United States account for "65% of the cobalt fabricated and manufactured into end-use products (a total of 37 Gg Co)" (Harper, Kavlak, & Graedel, 2011). Thus, there is a great discrepancy between the country which provides the source material (Democratic Republic of Congo) and the countries in which the material is consumed. Similar to many other forms of natural resources, developing countries possess a natural resource or commodity that is important to the global economy and is exploited by developed countries but at the risk of harm to the government and people from the source countries.

Historically, many developed nations have exploited the diamond resources derived from countries such as Botswana, the Democratic Republic of the Congo, and South Africa, and the profits from the diamond industry rarely impact those who work in the mines. There is a similar dynamic within the petroleum industry. Venezuela, Saudi Arabia, Iran, Iraq, Kuwait, the United Arab Emirates, Libya and Nigeria rank first, second, fourth, fifth, seventh, eighth, tenth and eleventh in documented oil reserves (Stebbins, 2019). Among the Middle East sources of oil, many of the governing regimes rank below the 50th percentile by the World Bank Worldwide Governance Indicators (WGI) (Kaufmann, Kray & Mastruzzi, 2011), which indicates political instability and inequality that can often be directly traced to the lack of wealth distribution generated from the production of crude oil and its products.

Chapter 4: Geopolitical Implications and Consequences of Electric Vehicles

As the demand for electric vehicles increases in the coming decades, control of the resources that are required for production of batteries and vehicles will be a significant geopolitical issue. An example from the oil industry is instructive. According to a 2013 study by Jeff Colgan of Brown University, "[crude oil was] linked to between one quarter and a half of all interstate conflicts globally between 1973 and 2012." Turning to decarbonization efforts, similar conflicts could potentially arise over the control of resources needed to promote decarbonization, including battery production (Sanderson, 2018). However, there is a potential that the increased global trade in minerals lead to cooperation and peace. While rare-earth elements, metals and other natural resources are essential to support a more sustainable and environmentally-friendly future, countries or states that are endowed with these resources may also be characterized by political challenges that have the potential to complicate global efforts. If recycling of materials in these electric batteries becomes more widespread and developed, the potential for geopolitical conflict attributed to the resources in batteries will be reduced.

For example, China is a dominant producer of rare earth elements which are used in computers, smartphones, LED lights, and electronic displays. "Some analysts say China mines more than 70% of the world's rare earths and is responsible for 90% of the complex process of turning them into magnets. A White House report has estimated that China controls 55% of the world's rare-earth mining and 85% of the refining process" (Zhai, 2021). China is a country with a powerful government that plans to lead global efforts in sustainability. Thus, China's endowment of rare earth elements could be interpreted as a major geopolitical advantage because the country is favorably positioned to meet the demand of its growing middle class and can provide rare earth elements to other countries, including the U.S. and Japan. It is possible that China could use its supply of rare earth elements as a bargaining chip in negotiations with other nations over issues related to natural resources as well other issues.

China's influence in the acquisition of rare earth minerals is not restricted to the domestic sphere. For example, China has been involved in securing resources in other countries, particularly Chile. "A Chinese company, Tianqi Lithium, snapped up a significant stake in Chile's largest lithium producer, SQM, despite opposition from some in the South American country who say that the deal is handing China a monopoly over lithium supply…as part of the 'Made in China 2025' plan to advance high-end manufacturing, the government wants to establish a grip on the production of electric cars and clean energy technology" (Sanderson, 2018). The Chinese company's action demonstrates China's ability to apply political and economic power in order to advance its national goals. As the demand for electric batteries and vehicles grows around the world, the economic stakes will also grow and there is the potential for significant geopolitical tensions and even conflicts.

Chapter 5: Data Set

Throughout this research, several sources of data were analyzed. First, the Oak Ridge National Laboratory Energy Data Book and Argonne National Laboratory's Greenhouse Gases, Regulated Emissions and Energy Use in Technologies (GREET) model were used references for the life cycle assessment that was developed for this thesis project. Second, peer-reviewed literature on life cycle impacts of electric mobility informed the development of the life cycle assessment model. Third, data from the city of Austin and Austin's Capital Metropolitan Transportation Authority (Capital Metro) on vehicle miles traveled and ridership, among other factors, were used to analyze and predict the potential effects of the city's transition from conventional diesel buses to electric buses. Fourth, electricity generation and associated emissions data from Austin Energy (the utility serving the city of Austin, Texas), the Electric Reliability Council of Texas (ERCOT), the grid that covers the deregulated market for roughly 75% of the state of Texas, as well as other utilities and regions that could be candidate cities for a transition from conventional buses to electric buses, were used as inputs to the life cycle assessment models created to estimate greenhouse gas emissions for charging of electric transportation vehicles.

Once the initial data was acquired from existing peer-reviewed literature and paired with Austin Capital Metro's ridership and vehicle miles traveled data, different combinations of fossil fuels and renewables were analyzed in order to predict which scenarios are anticipated to be the most environmentally-friendly.

In the peer-reviewed journal article, "Real-world performance of battery electric buses and their life-cycle benefits with respect to energy consumption and carbon dioxide emissions" published in *Energy*, the parameters of empty-load, half-load, and full-load buses are defined. The energy intensity per unit of distance traveled for three passenger load scenarios (empty-load, half-load, and full-load electric buses) were 175 kWh/100 km, 184 kWh/100 km, and 191 kWh/100 km, respectively (Zhou et al, 2016). The following chart summarizes the aforementioned figures.

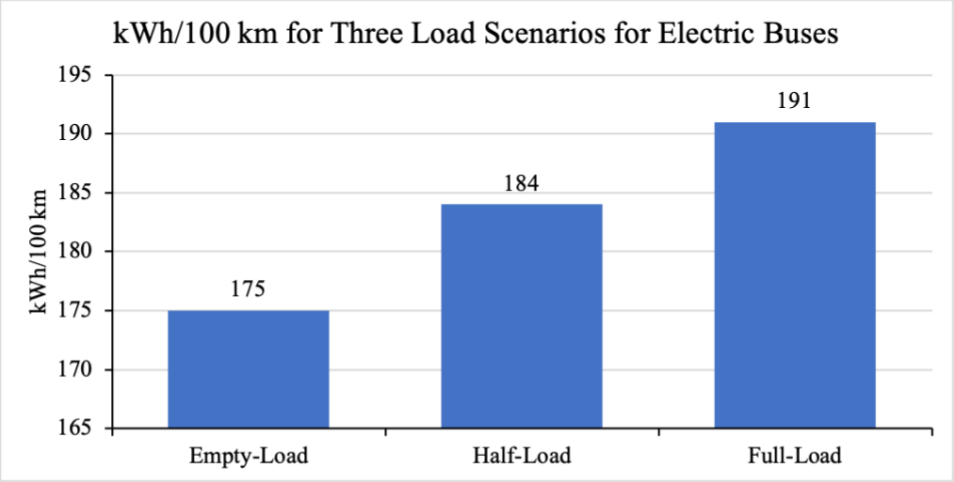

Figure 1: kWh/100 km for Three Load Scenarios for Electric Buses

For all scenarios that estimated the life cycle emissions of electric buses for different electricity mixes, I used these energy intensities per unit of distance traveled numbers. For conventional diesel buses with the empty-load, half-load and full-load passenger scenarios, the information from same journal article was used, with emissions of 1,700g CO2-eq/km, 1,850g CO2-eq/km and 2,150g CO2-eq/km for the respective load types.

Once the energy intensity for each of the three scenarios was ascertained, I used emissions intensity on a per-kWh basis to estimate the life cycle emissions for electric buses powered by different electricity mixes. For coal electricity production, the National Renewable Energy Laboratory's "Life Cycle Assessment of Coal-fired Power Production" was used. In this report, the average life cycle emissions for electricity production from coal is 1,022g CO2-eq/kWh (Spath et al, 1999). For natural gas electricity production, I used the "Comparative Life-Cycle Air Emissions of Coal, Domestic Natural Gas, LNG, and SNG for Electricity Generation" from *Environmental Science and Technology*. This article estimates the life cycle emissions for electricity production from domestic natural gas to be 567g CO2-eq/kWh (Jaramillo, Griffin & Matthews, 2007).

For wind energy electricity production, *Energy Policy*'s "Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey" was used. This article calculated the life cycle emissions for electricity production from wind energy to be 34g CO2-eq/kWh (Nugent & Sovacool, 2014). For solar energy electricity production, *Energy Policy*'s "Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey" was used. This article estimated the life cycle emissions for electricity production from solar energy to be 50g CO2-eq/kWh (Nugent & Sovacool, 2014).

For nuclear energy electricity production, *Energy Conversion & Management's* "Life cycle energy and greenhouse gas emissions of nuclear energy: A review" was cited. The author reported that the life cycle emissions for electricity production from nuclear energy was 65g CO2-eq/kWh (Lenzen, 2008). For hydropower electricity production, "Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power" from *Renewable and Sustainable Energy Reviews* was cited. The authors estimated the life cycle emissions for electricity production from hydropower to be 30g CO2-eq/kWh (Raadal et al, 2011). For biomass energy electricity production, *Sustainability's* "Evaluation of the Life Cycle Greenhouse Gas Emissions from Different Biomass Feedstock Electricity Generation Systems" was cited. The authors asserted that the life cycle emissions for electricity production from biomass is 291g CO2-eq/kWh (Kadiyala, Kommalapati & Huque, 2016).

Chapter 6: Methodologies

The general methodology for this thesis was a broad literature review that drew from a large number of peer-reviewed articles that address the advantages and disadvantages of electrification of buses in cities. Additionally, information reported in the peer-reviewed literature will be analyzed to determine whether there are unaccounted-for externalities associated with a purely electric bus fleet for a city transportation system.

Although the use of an existing life cycle assessment from the peer-reviewed literature will serve as a useful and data-driven guide, my analysis will be limited by the fact that the detailed specifications of buses analyzed in the literature and those which will be used in Austin will likely be different. Additionally, inputs into the life cycle assessment for the city of Austin, such as sources of components and their greenhouse gas footprints, are not known. Despite these limitations, the life cycle assessment will serve as a first step in analyzing the environmental impact for the entire life cycle of a Capital Metro Austin electric bus, a broader analysis than a study of tailpipe emissions.

Once the life cycle assessment has been completed, I will develop recommendations for improvement of certain phases of the life cycle of buses. Although the life cycle assessment based on the published literature will not be a perfect representation of the challenge in Austin, it will provide a structure and foundation into which the specifications of existing buses in the Capital Metro Austin fleet can be incorporated. In addition to recommendations regarding improvements to the different stages of the buses' life cycle, a thorough overview of the literature will identify externalities, both positive and negative, that might be associated with transitioning from a conventional fossil fuel-powered bus system to one powered by electricity, and considering a range of production sources.

To resolve a portion of the issues that will arise from using an existing life cycle assessment methodology, I will develop a simple life cycle analysis tool that compares electric buses with conventional fossil fuel combustion buses, based on carbon dioxide-equivalent (CO_2-equivalent) emissions per vehicle-mile-traveled (VMT). This simplified life cycle model will be used to compare Austin’s current bus fleet to an all-electric fleet. Because there may be differences in the electricity fuel mixes used to power the buses, I will analyze the greenhouse gas outputs to determine an optimal mix that maximizes reliability while reducing emissions. Several sources of data, outlined in the Data section, will be used as inputs to inform these emissions data models.

I plan to submit a scholarly paper based on my analytic approach and recommendations. I also plan to share the findings with Austin officials as they transition to an electric bus fleet and hope my results provide useful information for their decision-making.

SECTION 3: FINDINGS AND RESULTS

My analysis generated several results that could be used to inform the adoption of electric buses. For the comparison of the life cycle emissions of different buses, CO_2-equivalent was used. Additionally, there were three scenarios that were considered for the buses in this analysis; empty-load, half-load and full-load, as defined by "Real-world performance of battery electric buses and their life-cycle benefits with respect to energy consumption and carbon dioxide emissions" in *Energy*. As a baseline for the empty-load, half-load and full-load scenarios, diesel bus emissions served as the comparison. Additionally, to simplify my analysis, there were no changes in air temperature and cooling loads, which would have a profound effect on emissions in the use phase of the buses.

I assessed ten electricity mixes for each of the three load scenarios. First, we evaluated Austin Energy's electricity production. This electricity mix as of 2021, is comprised of 27% natural gas, 11% coal, 7% nuclear energy, 32% wind energy, 2% biomass energy, and 21% solar energy. The data on the energy mix was combined with life cycle emission numbers from papers mentioned in the Data Set chapter. The second electricity mix based was on an analysis of ERCOT's electricity production, which is comprised of 0.1% biomass energy, 19% coal, 7% natural gas (simple cycle), 36% natural gas (combined cycle), 0.1% hydropower, 10% nuclear energy, 4% solar energy, and 23% wind energy (Electricity Reliability Council of Texas). Neither Austin Energy's mix nor ERCOT's mix were assumed to take into account intelligent charging, which would further reduce emissions.

Third, 100% wind energy, with 34g CO2-eq/kWh, from *Energy Policy*'s "Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey" was used (Nugent & Sovacool, 2014). Fourth, 100% solar energy, with 50g CO2-eq/kWh, from *Energy Policy*'s "Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey" was used (Nugent & Sovacool, 2014). Fifth, 100% nuclear energy, with 65g CO2-eq/kWh from *Energy Conversion & Management's* "Life cycle energy and greenhouse gas emissions of nuclear energy: A review" was used (Lenzen, 2008). Sixth, 100% hydropower, with 30g CO2-eq/kWh from *Renewable and Sustainable Energy Reviews*' "Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power" was used (Raadal et al, 2011).

The seventh production blend analyzed a combination of 50% wind energy and 50% solar energy, with emissions intensities defined by published articles and highlighted in the Data Set chapter. Eighth, a combination of 75% wind energy and 25% solar energy was analyzed, with emissions intensities outlined in journals in the Data Set chapter. Ninth, 25% wind energy and 75% solar energy was used, with emissions intensities outlined in journals in the Data Set chapter. The tenth and final production combination was 20% nuclear energy, 40% wind energy, and 40% solar energy, with emissions numbers from articles described in the Data Set chapter. The following table summarizes the electricity mixes that were analyzed in this thesis:

	Type of energy	Source
Mix 1	Austin Energy	32% wind, 27% natural gas, 21% solar, 11% coal, 7% nuclear, 2% biomass
Mix 2	ERCOT	0.1% biomass, 19% coal, 7% natural gas (simple cycle), 36% natural gas (combined cycle), 0.1% hydropower, 10% nuclear, 4% solar, and 23% wind
Mix 3	Renewable, wind	100% wind
Mix 4	Renewable, solar	100% solar
Mix 5	Renewable, nuclear	100% nuclear
Mix 6	Renewable, hydropower	100% hydropower
Mix 7	Combination	50% solar, 50% wind
Mix 8	Combination	25% solar, 75% wind
Mix 9	Combination	75% solar, 25% wind
Mix 10	Combination	20% nuclear, 40% solar, 40% wind

Table 1: Summary of electricity mix scenarios

Figures 2-4 illustrate the life cycle emissions associated Austin Capital Metro's total vehicle miles traveled during Fiscal year 2019 and considering the three different load scenarios (empty-load, half-load and full-load):

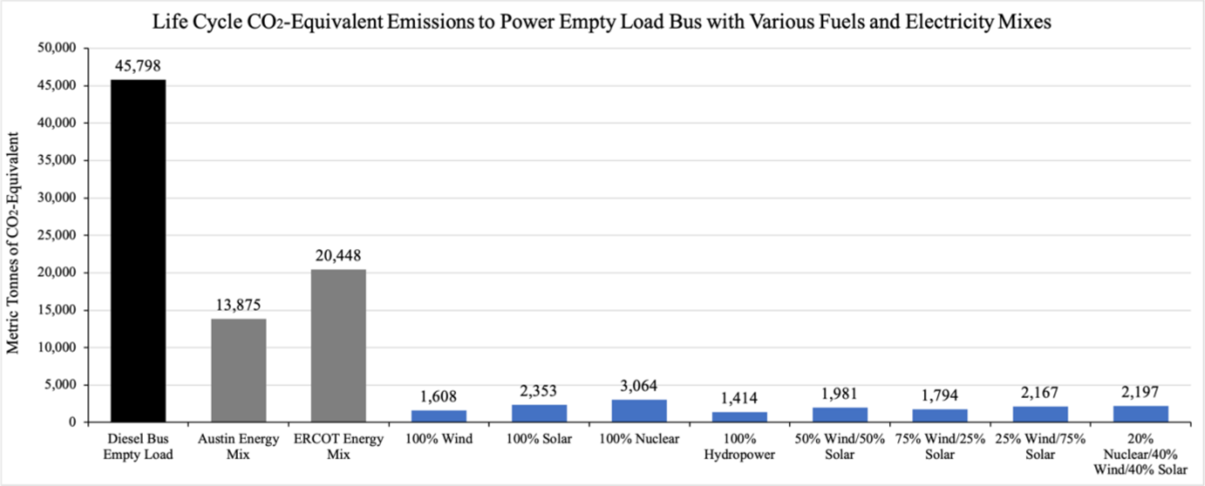

Figure 2: Life Cycle CO_2-equivalent Emissions associated with Empty-Load Buses, by Fuel and Electricity Mixes

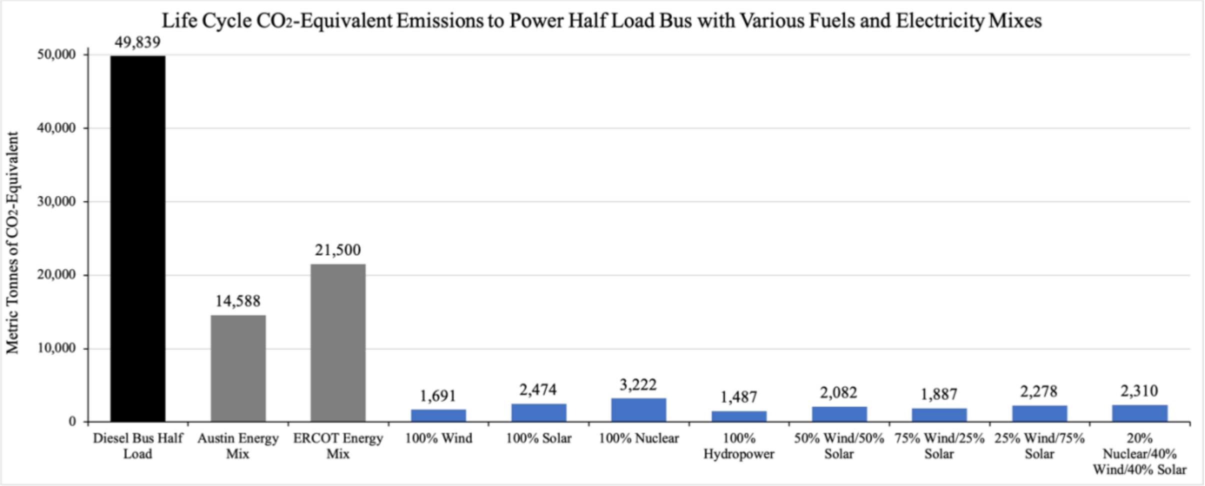

Figure 3: Life Cycle CO_2-equivalent Emissions associated with Half-Load Buses, by Fuel and Electricity Mixes

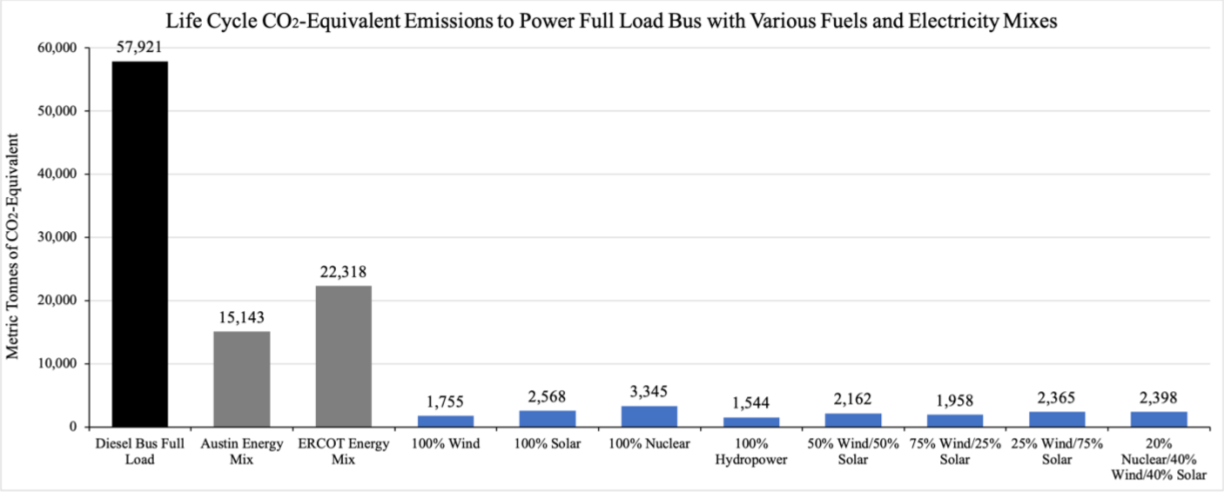

Figure 4: Life Cycle CO_2-equivalent Emissions associated with Full-Load Buses, by Fuel and Electricity Mixes

Based on the data presented in the three figures, the distribution of life cycle CO_2 emissions follows a similar pattern across the three load scenarios (empty, half and full). In each figure, the diesel-powered bus, depicted in the black bar on the far-left of each figure, has the highest amount of CO_2 emissions, followed by the ERCOT Energy Mix, Austin Energy Mix, and nuclear energy. The remaining seven scenarios for electricity generation (100% wind energy, 100% solar energy, 100% hydropower, 50% wind energy/50% solar energy, 75% wind energy/25% solar energy, 25% wind energy/75% solar energy and 20% nuclear energy/40% wind energy/40% solar energy) have significantly lower emissions than the diesel bus, Austin Energy or ERCOT Energy mixes.

It is reasonable to assume that the adoption of renewable energy technologies will lower emissions for each energy mix scenarios. While one may assume that cities should simply switch their electricity mixes to the lowest emitter in order to significantly reduce emissions, cities have different needs and may have limited resources to fulfill their energy needs. Additionally, until battery and storage technologies become more efficient, reliable, and cost-effective, there will be an ongoing need for fossil fuel or nuclear options to fulfill the baseload needs of electricity providers. Due to the intermittent nature of solar, wind, and hydropower, it can be difficult for utilities in some regions to rely on these renewable resources for baseload energy generation. Intelligent and flexible charging will also help the grid incorporate renewables more reliably. Furthermore, hydropower has worked well in Norway, Iceland and parts of the United States' Pacific Northwest region. Renewable resources may be better for peak load because they fluctuate, depending on the time of day, wind speed, and water flow, respectively.

SECTION 4: CONCLUSIONS

As discussed in the Results chapter of this paper, the electric buses, regardless of the electricity mix used, had significantly fewer greenhouse gas emissions than the diesel internal combustion vehicle buses. Electric buses using Austin Energy’s and ERCOT’s electricity mix saved 2-3 times the emissions in comparison to diesel buses. Furthermore, electric buses paired with electricity mixes with more renewables, namely solar, wind and hydropower had even lower levels of greenhouse gas emissions. These buses reduced greenhouse gas emissions by over 90%.

Additionally, nuclear energy can be more easily relied upon than renewables to fulfill baseload energy needs while emitting far less CO_2 and other greenhouse gases. Therefore, for utilities looking to decarbonize their electricity production, renewables could be used for peak load.

Nuclear energy is compatible with baseload, and that is how it is usually deployed. According to a Vox article, “the EIA [Energy Information Administration] calculates overnight construction costs for new US power plants ordered in 2014. Advanced nuclear reactors are estimated to cost $5,366 for every kilowatt of capacity. That means a large 1-gigawatt reactor would cost around $5.4 billion to build, excluding financing costs. By contrast, a new wind farm costs just $1,980 per kilowatt. A new gas plant costs just $912 per kilowatt, or one-fifth as much” (Plumer, 2016). Consequently, the proliferation of nuclear energy will require significant capital investment, upfront and over time.

While the transition from an economy dominated by fossil fuels to one dominated by renewables is likely underway, fossil fuels will have a role to play in energy needs to the foreseeable future. They are able to fuel power plants and other industrial technologies with different patterns of availability, which is valuable to the reliability of an energy grid. The rise of renewables, paired with improvements in their efficiency and proliferation, will likely fuel a cleaner and more secure energy future, especially for transportation systems like Austin Capital Metro’s, which is emphasizing renewables as a critical piece of infrastructure. However, many more cities, specifically those with lagging public transportation systems and large populations, will need to take similar steps in order for the country and the world to further reduce emissions associated with transportation systems.

SECTION 5: FUTURE STUDY

There are additional research questions to answer. For example, it would be useful to conduct an original life cycle assessment based on Austin Capital Metro’s conventional diesel and electric buses rather than using published fleet averages. This assessment would have involved identifying different components of each type of bus and tracking their environmental impacts. These impacts would be categorized as greenhouse gas emissions, air quality, water, land use, and other impacts. Such an analysis would extend the analysis of environmental impacts beyond my focus on greenhouse gas emissions. An expanded analytic approach would have allowed me to study multiple stages of the life cycle model and the impact on emissions. In doing so, manufacturers of these parts, and the bus as a whole, would be able to find ways to cut their emissions in stages that accounted for the greatest emissions.

Also, in future study, I would have liked to explore the economic and public health benefits of the reductions in criteria pollutants, such as PM2.5, PM10, CO (carbon monoxide), NO_x and SO_x. This would further magnify the impacts of ICV buses when compared to EV buses on a life cycle basis.

I would have also liked to conduct a similar analysis outlined above for hydrogen fuel cell buses, which are seen as another form of transportation for the future. However, I chose to focus on electric buses, since the city of Austin already voted to invest billions of dollars in electric infrastructure and transportation.

In my analyses, I relied on peer-reviewed articles to estimate the life cycle emissions associated with operating an electric bus. While the literature provided a proxy for the variables of interest, a more in-depth, original analysis that would have assessed the equipment being deployed by Austin Capital Metro might have illuminated some key details that are lost from aggregated data.

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