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619 S. Olive Street, Suite 200, Los Angeles CA 90014 • (949) 450-7155 • www.EcoMotion.us

Transit Buses:
The Advent of Electrification

An EcoMotion White Paper

by Eric Getz
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Introduction

In 2017, the electric car movement is considerably underway and well known throughout the US. Tesla and its visionary CEO Elon Musk are household names throughout the country and nearly every major automotive manufacturer has invested in this movement in some form. However, ask someone about electric buses and you are hard pressed to find anyone who can confirm their existence, let alone anyone who's actually seen one in person. Yet the electric bus movement is quietly advancing to be on pace with the electric car movement. Much like the electric car industry, the electric bus sector has greatly benefitted from recent advances in electric technology, falling battery prices, and a growing number of heavily funded companies vying for dominance in a market ripe with an immense potential for growth. Indeed, due to several factors unique to the bus transit industry it will almost certainly surpass electric cars very soon in terms of market penetration.

This paper will cover the factors behind the high potential for growth of the electric bus market and why electric buses are making increasingly more economical and technological sense when compared to Compressed Natural Gas (CNG), hybrid, and diesel-powered buses. It will break down the fundamental technological challenges electric buses face as well as how the different types of buses and current manufacturers are addressing these challenges.

Growth Potential

From a long-term sustainability perspective, it is not hard to see the immense growth potential for electric vehicles. Fossil fuel free transportation and zero tail pipe greenhouse gas (GHG) emissions are largely part of what most tech leaders and Silicon-Valley magnates have envisioned as an inevitable part of the future. We are, however, seeing in the electric car market that this transition will take some time. The economics and direct benefits to the vast majority of car buyers are still far from in place to see any significant market penetration. When it comes to electric buses, however, the market is such that significant industry adoption within the next ten years is by no means out of the question.

One of the key aspects in understanding the growth potential for the electric transit bus sector is its fundamental relation to sustainability. From a global perspective, a crucial problem for most major cities is pollution and GHG emissions. Indeed, with a growing world population and rapid urbanization, the number of people living in cities is projected to double within 20 years, further exacerbating these problems. Within these cities, the number one source of pollution and GHG emissions is the transportation sector. Not surprisingly heavy-duty vehicles such as buses are one of the worst sources of GHG emissions due to their inefficiency and high volume of travel. The vast majority of cities, however, are in charge of their transit fleets and therefore, for cities, bus fleets are also the most controllable source of emissions. Accordingly, with more and more major cities in the U.S. and abroad committing to cutting GHGs and upholding the climate protection standards of the Paris Accord, electrifying their bus fleets is one of the most straightforward ways for cities to stick to these commitments. Thus, cities, the primary buyers of electric buses, as a general rule place much more value on the environmental benefits of their electric bus purchase than an average car buyer might when considering an electric car.

The second important factor in understanding the growth potential for electric buses is the utilization rate of buses as compared to cars. Buses, particularly those used for public transportation fleets, are utilized four times as many hours per day as standard cars and thus fuel costs inherently make up much more of the life-cycle costs of a bus than they would for a car. This is crucial when one considers that outside of environmental reasons, the main benefit of electrical vehicles is their efficiency. Thus, for the average car buyer this increased efficiency is not enough to justify the added price of purchasing an electrical car, but for a city agency whose diesel buses not only travel tens of thousands of miles every year but also do so as some of the least efficient vehicles on the road, the 80% increase in efficiency most electric buses provide is much more enticing.

Electric Buses: City Driving

In addition to the obvious benefits electric buses provide in terms of a dramatic increase in efficiency and zero tailpipe GHG emissions, there are several more features unique to an electric drivetrain that address common issues with city driving.

Regenerative breaking

Electric motors work by converting electrical energy to mechanical energy, however, they can also be reversed to do the opposite, therefore acting as a generator. This enables one of the hallmark features of electric vehicles, regenerative breaking. With regenerative breaking, electric buses can convert (with over 90% efficiency) the momentum from the wheels when they need to slow down into an electrical load that can be used to recharge their batteries on route. When considering how much transit buses stop and start, the ability recapture lost energy while breaking can have a significant impact on a given bus’s overall efficiency.

Torque

One of the great benefits of an electric motor is its ability to provide a large amount of torque very quickly. Because torque in an electric motor is a function of current and current flows almost instantaneously, many electric motors can reach maximum torque from zero rpm which results in much faster acceleration. This is particularly useful for transit buses, which because of their sizeable weight require a significant amount of torque to accelerate. Moreover, as transit buses are constantly stopping and starting they require power at low speeds which is precisely what the high torque provided by an electric motor is able to do. This is another reason why electric buses are more efficient than any alternative.

Noise

A common complaint with diesel and even CNG city transit buses is the noise they produce. Because they do not have a combustion engine, electric buses are significantly quieter than diesel and CNG buses. Not only does this lessen noise pollution and improve the image of cities but it also expands the serviceable areas and times for transit agencies by allowing them to increase bus service to areas where or at times when bus service is currently not allowed due to noise issues.

The Range Problem

For as long as electric vehicles have been in existence, the most common complaint has been their relatively short range. This lack of range of electric vehicles as compared to their fossil fueled counterparts can be almost entirely explained through the concept of energy density. Energy density is the amount of energy a battery can store relative to its size; the higher energy density a system has, the longer it can output energy. Fossil fuels and their products have some of the highest energy densities of all resources. Batteries, on other hand, do not and, as a result, one needs many more pounds of batteries than gasoline in order to power a vehicle an equivalent distance. This is why Teslas weigh significantly more than gas powered vehicles (about 1,200 pounds more on average) and why over 1,600 pounds of each Tesla's total weight is devoted to batteries. Thus, in order to make-up for the lack of energy density, electric vehicle manufacturers face the challenge of balancing the need for more batteries to give the vehicle more range with the need to minimize weight in order to maximize range and efficiency.

Typically, when range is a problem with a vehicle, the most obvious solution is to simply recharge/refuel a vehicle more frequently. However, electric batteries also struggle in this area as compared to fossil fuels because of another factor called power density. It is important to note here the distinction between power and energy. While they are certainly interrelated, they are not synonymous; in the context of battery powering a system, energy is what one delivers to system and power is the *rate* at which the energy is delivered. Accordingly, energy density relates to capacity (amount of energy) and power density has to do with speed.

Therefore, the higher power density a system has the more energy the system can deliver and receive in a short amount of time. Accordingly, the higher power density a vehicle's batteries have the faster it can recharge. Most batteries or electric storage devices have low power density and therefore can take a significant amount of time to recharge. Furthermore, those that have high power density typically also have low energy density. Thus, we arrive at a larger issue not only present in the electric vehicle industry but in all industries who in some form depend heavily on the use of batteries: the struggle of achieving an energy storage mechanism with both high energy density and high power density.

Unfortunately, although our technology in this field has made great strides, as of recently the electrical community is still far from truly resolving this struggle. Nonetheless, they have certainly made progress and the different approaches to addressing and working around these fundamental problems are in many respects what separates the variety of vehicles in the electric bus sector.

In general, there are two distinct electric bus categories: non-autonomous and autonomous. It is important to note in this case that autonomous is not referring to driverless buses but rather whether or not their electrical source is on board (autonomous) or reliant on an external source (non-autonomous).

Non-Autonomous

Non-autonomous buses work around the energy and power density struggle entirely by not storing energy (saving the significant weight from lack of on-board batteries) and tapping into a direct electric source. Accordingly, this means being limited to a fix route and can entail significant investment in infrastructure as well. The most common non-autonomous electric buses are trolley buses powered through overhead cable lines. While the number of trolley buses is steadily decreasing, they are several other new forms of non-autonomous vehicles that are being developed.

One of the more promising developments are online electric vehicles (OLEVs). Originally created by the Korea Advanced Institute of Science and Technology (KAIST) in 2010, these vehicles are currently being developed by the Massachusetts start-up OLEV Technologies. OLEVs work by charging wirelessly through electromagnetic induction while moving. To facilitate this charging, a system power cables are installed about a foot under the pavement of a given OLEV's route to create a magnetic field that maximizes induction. These underground cables then interact with a "pick up" module attached underneath the OLEV in order to charge and power the vehicle over designated segments.

This technology is still in its development phase and OLEV is currently trying to overcome inefficiencies and charging alignment issues that surround wireless charging. Moreover, even when these issues are worked out OLEVs will still face high installation and significant infrastructure costs inherent to implementing non-autonomous vehicles. Thus, for the immediate future, the autonomous electric sector appears to have the advantage.

Autonomous

Again not to be confused with driverless buses, autonomous electric buses are what one typically imagines when thinking of a standard vehicle as they are free-range buses that are not limited to a certain route. Unlike non-autonomous buses, however, they are very much affected by the struggle between power density and energy density and therefore generally fall into two categories: fast charging and slow charging. As a whole, however, this market is dominated by two major players with models that span both of these categories: Proterra and BYD.

Proterra

Proterra, the number one U.S. electric bus manufacturer, is headquartered in Burlingame, California. Led by several former Tesla executives and managers, Proterra is expanding and recently opened up a second manufacturing plant outside of Los Angeles. While still a relatively small company, Proterra is quickly having an impact on the industry and in terms of technology is in many ways overtaking Chinese competitor, BYD. Proterra has focused on offsetting the significant weight of electric batteries, building its buses out of lightweight composite materials and the frame itself out of carbon fiber. Even with batteries installed it is still one of the lightest buses on the market. Moreover, one of Proterra's notable achievements is its variety of battery types and flexible capacity that enable a purchaser to customize its bus purchase based on his or her intended route and general usage. Proterra's buses come in 40 or 35-foot models with customizable capacity and the option of one of the following battery types:

- *Catalyst FC Battery Series*: Taking advantage of its lithium titanate batteries, the FC series has high power density that enables it to charge quickly but sacrifices energy density and therefore has limited range. More so than any other model, the FC takes advantage of Proterra's automated charging system that communicates wirelessly with an overhead charging arm which automatically stops the bus underneath it when the charger is in place.

Range	49-62 mi
Energy Level	79-105 kWh
Charge Time	10-13 min

- *Catalyst XR Battery Series*: The XR series is best for low to medium mileage routes due to its range but can also be supplemented by Proterra's aforementioned on-route charging in order to accommodate longer routes.

Range	136-193 mi
Energy Level	220-330 kWh
Charge Time	< 3hrs

- *Catalyst E2 Battery Series*: With a maximum range of 350 miles, the E2 series has one of if not the most efficient battery storage systems on the market and is truly a game changer in terms of being able to service long routes without the need for on-route charging.

Range	251-350 mi
Energy Level	440-660 kWh
Charge Time	< 3.5-5hrs

BYD

BYD (Build Your Dreams), is a Chinese company that is not well known outside of its home country but is nonetheless currently the world's largest battery and electric vehicle manufacturer, not to mention the world's number one seller of electric buses. Indeed, its own battery factory is nearly eight times larger than Tesla's recently opened "Gigafactory." BYD has been expanding in the U.S. and has recently opened a factory in Lancaster, California and an office in Los Angeles. BYD recently won a contract with LA Metro to fulfill 60 electric buses in Metro's new plan to convert its entire bus fleet to electric by 2030. According to BYD, its iron-phosphate batteries are among the safest, least toxic, and longest lasting in the industry. BYD's model selection offers more options in terms of bus size than Proterra.

- *K9 Electric Transit Bus*: The K9 comes in both 35 and 40-foot versions (as well as a related 30-foot version called the K7) and is BYD's most popular electric bus. Moreover, the K9 was also the model of the 60 electric buses LA Metro recently ordered.

Range	145-161 mi
Energy Level	270-324 kWh
Charge Time	3-4 hrs

- *K11 Electric Transit Bus:* The K11 is BYD's latest and longest model at 60 feet and although its range is listed at 200 miles, several sources claim that its range is more around 275 miles.

Range	200 mi
Energy Level	591 kWh
Charge Time	3hrs

Capabus: A Fast Charging Alternative

Fast charging electric buses such as Capabus developed by Sinuatec Automobile Technologies and its Chinese partner in Shanghai, use ultracapacitors, energy storage devices of incredible power density but very low energy density (only 5% of the energy of lithium batteries). This enables Capabus to charge quite quickly (30-45 seconds) but also means they have very limited range (~3 miles). Because most buses make frequent stops, however, they have been able to devise a system where Capabuses are able to recharge quickly from overhead "electric umbrellas" every few miles at each bus stop. Shanghai has been testing around 17 of these buses since 2006 and is scheduled to receive 60 more over the next year. These buses are still in development and Sinuatec is in the process of building a new model with a range of 20 miles in between charges. While currently far from the mainstream electric bus market, Capabus and other fast charging electric buses are an intriguing alternative for the future as slow charge buses continue to work through problems of range and charge time.

Range Revisited

Now that we have covered the fundamental challenge electric vehicles face when it comes to range as well as the current models and options in electric bus world, the question arises as to what critical point is for the range of these electric buses in terms of being a feasible alternative to diesel, CNG, and hybrid. Unlike other factors, electric buses do not need to outdo or even compare to their competitors in terms of range but rather they need to be able to meet the daily mileage needs for an average bus route. According to General Transit Feed Specification data, the typical U.S. bus route is less than 200 miles (322 km) a day. Thus, 200 miles appears to be the magic number.

As we saw in the previous section, both BYD and Proterra now have models that exceed this number and thus in some ways have now met the critical point in the electric bus world. This a big improvement from even just two years ago and is a large part of the reason why there is a growing buzz around the electric bus movement. As these models are the most recent ones for both manufacturers, it would be safe to assume that every subsequent model released in the future will likely see a further improvement in range. So in essence, the largest challenge electric vehicles face, range, in the electric transit bus world is less of a problem today than it has ever been before and will only continue to improve.

Bus Cost Comparison

Like any product, electric buses will only begin to see widespread adoption when they have a clear advantage when compared to competitors. Moreover, as with most things in our society the driving force behind industry adoption is economic advantage. Below is a breakdown of the costs associated with each of the major bus types.

Type	Hybrid	Diesel	CNG	EV (Proterra)
Initial Cost	~$600,000	~$390,000	~$460,000	~$750,0003
Efficiency	4.58 MPG	3.86 MPG	3.27 MPG	21.4 MPGe
Cost per Mile	63 cents	84 cents	74 cents	19 cents

Table 1

Initial Costs

A review of manufacturers' literature as well as academic reviews reveals some interesting trends about initial costs. Notably, when it comes to the initial cost of transit vehicles there is a good amount of variance. Indeed, Chicago Transit Authority recently purchased a fleet of diesel buses at $600,000 each, and Greensboro, North Carolina's transit system recently spent $714,000 for each of the hybrid buses it just bought.[1] Typically, diesel is the cheapest followed by CNG at around $30,000-$70,000 more, followed by hybrid buses and then of course electric buses. However, although it is certainly the most expensive up front, electric bus prices have by far the sharpest downward trajectory of the group considering a few years ago the average one sold for around a million.

Fuel Costs

As can be seen in the table above, electric buses, due to their efficiency and the low price of electricity, are by far the lowest in terms of fuel costs. When comparing fuel efficiency between vehicles with alternative fuel types like electricity, the EPA has developed a figure called Miles Per Gallon Equivalent (MPGe). To calculate MPGe, one simply finds out how many miles an electric vehicle can go using the equivalent energy that is contained in a gallon of gas (33.7 kWh). In this particular case as seen above, the MPGe for electric buses is nearly five times that of the closest comparison.

Maintenance Costs

With heavily utilized vehicles such as buses, maintenance can often be a significant expense over the lifetime of a bus. As can be seen in Figure 1, electric buses require less than half the maintenance of any other bus type. This low-maintenance is another unique feature of electric

[1] MacKechnie, Christopher. "How much Does a Bus Cost to Purchase and Operate?" ThoughtCo, 2017.

vehicles. All-electric powertrains require much less maintenance than combustion engines that essentially contain controlled explosions. Not only do electric buses have 30% fewer parts as compared to diesel but they also have significantly less than fluids, moving parts, and filters.

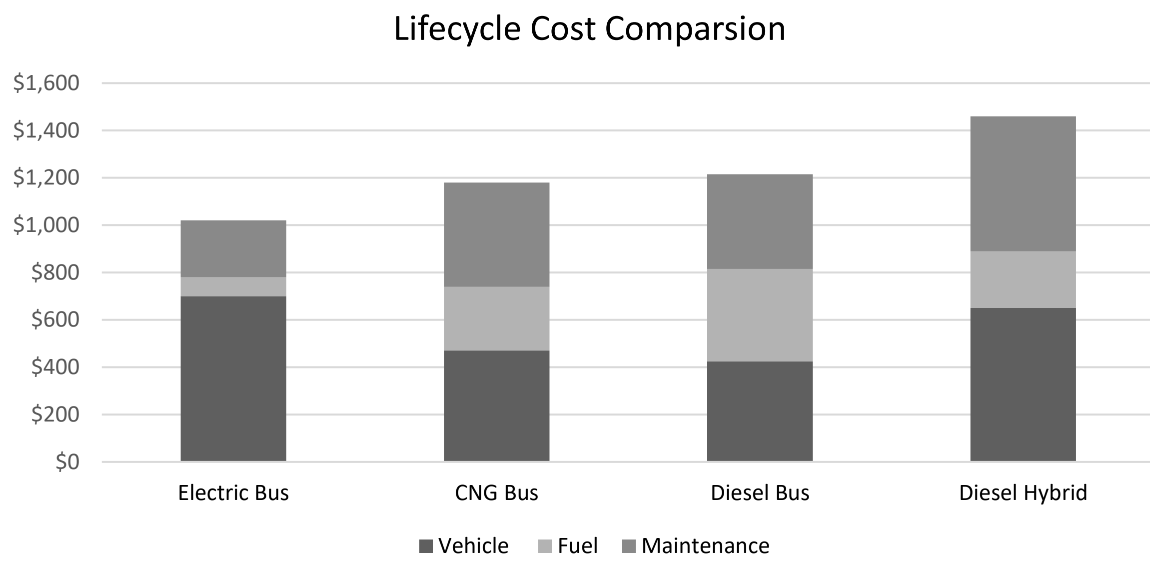

Figure 1. Data Source: Proterra Inc. 2016

Lifecycle Costs

The lifecycle cost of a vehicle, arguably the most important measure of its value, is the sum of the initial costs, fuel, and maintenance costs of a vehicle over its lifetime (usually 12 years). As can be seen in the above figure, the lifetime cost of a standard electric bus (in this case the Proterra Catalyst, Proterra being the leading North America electric bus manufacturer) is noticeably lower than any other bus types with its low fuel and maintenance costs more than making up for its high initial cost. In fact, according to the California based electric bus company Proterra, its buses will each typically save a transit agency around $400,000 over each bus's lifetime. Whatever the actual dollar amount is for lifecycle savings, it is widely agreed upon that electric buses are cheaper by a reasonable margin over their lifetimes when compared to alternatives. Thus, with the sustainability advantage as well as the lifecycle cost factor clearly now on the side of electric buses the question then arises of why electric buses are not already dominating the market. The answer to this question, at least for the past few decades, has always centered around one issue: range anxiety. Nonetheless, as we have seen earlier in this paper, the electric bus industry has made significant improvements in this area and range is becoming less and less of a problem with every new electric bus model released.

CNG Buses: A Case Study

One of the most compelling cases for both the environmental need as well as the expected rate of industry adoption for electric buses is that of Compressed Natural Gas (CNG) buses. CNG buses arrived on the transit scene with the promise of cheaper and cleaner fuel and in a relatively short time grew to their current position at over 25 % of the transit bus market. This rapid adoption was due not only to the dropping price of natural gas but also largely because CNGs were seen as much more environmentally friendly than diesel. Indeed, almost every bus or vehicle fueled by CNGs proudly notes its status as a clean air or low emissions vehicle in bold text on its side. In some respects, this is true: CNGs are better for local air quality then diesel. However, recent studies have cast doubt on whether or not CNGs really do provide as much of a positive environmental impact as they are said to have.

A significant factor to consider with CNGs is the methane leakage from the drilling and production of natural gas. A 2014 study by scientists from Stanford, Harvard, and MIT found that methane leakage is likely underreported and underestimated by the natural gas industry and concluded that CNGs are "not likely to reduce greenhouse gas emissions" as compared to diesel.[1] *In a 2016 study, by Columbia University on New York's transit fleet researchers found that because their CNG buses were 25% less fuel efficient than diesel buses their annual* CO_2 *emissions for fleet operations only were actually 8% higher than diesel.*[2] *Nonetheless, even if the CNGs did in fact meet the environmental standards their manufacturers claim, they would still each be releasing several hundred thousand pounds of GHGs every year.*

These recent studies are stark reminders of the fact that CNG buses and even hybrid buses are simply temporary solutions or stepping stones until a more sustainable product such as an electric bus is a feasible method of transport. However, the fact that CNG and alternatively fueled buses like hybrids already consist of 50% of the transit buses in the U.S. with relatively small environmental benefits speaks to the likelihood of the rapid adoption of electric buses when they are technologically up to par. In other words, if CNGs and alternatively fueled buses were able to take over half the market with minimal improvements in fuel costs and emissions, imagine how much faster electric buses with significantly lesser fuel costs and zero GHG emissions will eventually be adopted.

1 Aber, Judah. "Electric Bus Analysis for New York City Transit." Columbia University, 2016.
2 Koch, Wendy. "Natural gas vehicles worse for climate than diesel ones?" USA Today, 2014.

Conclusion: A Bright Future

In the world of transit buses, it is no longer a question of which technology will ultimately win out in terms of cleaner diesel, hybrid, CNG, EV, or hydrogen fuel cells but how fast electrics will dominate the market. Recent improvements and rapid price drops in battery technology are quickly dispelling any naysayers who doubt the ability of electric buses to be cost and range effective. Indeed, all industry trends and increasing market competition and interest point to even more cost cuts and technological improvements in the near future. Batteries on average continue to steadily and consistently improve by 5% every year and typically see their prices half every five to six years. Furthermore, as this paper has already covered, buses are inherently poised to reap more of the advantages of electric vehicles than any other market. Everyday more and more cities and transit authorities from the U.S., Europe, and China, such as Los Angeles and Park City are starting to invest more and more in electric buses and even commit to going all-electric in the near future. By 2025, Proterra CEO Ryan Popple predicts half of all new bus purchases will be electric and by 2030 nearly all of them. While admittedly quite ambitious, such a prediction is not out of the question given the current state of the electric buses and how far they have come so far. One thing, however, is for certain: the future of the electric bus industry is getting brighter by the day and its tremendous potential for growth can no longer be ignored.