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Counting Zero Emission Buses in the United States and the Importance of Their Technological Development Needs

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Summary

The zero emission bus industry has experienced rapid growth. However, there is limited data on the growth and deployment of zero-emission buses across the United States. While transit buses in general have been counted by the Federal Transit Administration and organizations like American Public Transportation Association, the separation of ZEBs in these counts are limited and there have been few systemic counts of zero emission buses in American fleets. Since ZEBs are still considered a new technology this information has been deemed difficult to find. Through extensive research by looking at a variety of funding sources and their allocation, outreach to transit agencies and OEM's, and analysis of media reports, this information can be obtained in order to give a round house projection. These numbers are important to track due to the priority that many states across the country have placed on transitioning to zero emission buses over the course of the next few decades. Tracking these numbers also highlights which regions are making significant advances in deployments and which ones are lagging. This information can be used to address systemic challenges in deploying buses and their infrastructure.

Understanding the techological development needs of these buses is also very important. While the number of ZEBs have grown by 37 percent in the last year, these buses have still encountered some technological challenges while they continue to be deployed. Aspects such as heating, ventilation, and air conditioning affect the efficiency and performance of these vehicles. Buses also need to reduce energy consumption and maximize the amount of onboard energy that can be stored to improve their performance. While these challenges can seem like a roadblock in the success of these vehicles, technological solutions are being developed in order to counteract these problems.

Keywords: bus, public transport, heating, energy storage, hydrogen

1 Introduction

The transit industry has undergone a major shift towards electrification and zero emission drivetrains. As of September 2019, there were 2,255 zero emission buses deployed or on order in the United States. While this is still a small percentage of the overall transit bus fleet, zero-emission bus (ZEB) deployments have experienced growth in all regions of the country. Keeping track of this growth and presenting this information to the public will play an intricate part in the success of moving to a nationwide completely ZEB fleet.

The drive towards transit bus electrification has been fuelled by several factors. First, government funding for ZEBs has helped to develop this market. The Federal Transit Administration (FTA) has provided funding for ZEBs to multiple transit agencies through the Low and No Emission Bus Program (Low-No) and the Bus and Bus Facilities Grant Program. Many states have also awarded funding for ZEBs through VW Settlement Funding. California and New York also have Voucher Incentive Programs that help to lower the capital expenses associated with purchasing a zero-emission vehicle. Governmental policy has also encouraged the transition to zero-emission transit. California's Innovative Clean Transit Regulation mandates that transit agencies begin purchasing ZEBs and requires that by 2029, all new bus purchases will be zero-emission. Lastly, deployments have been bolstered by the increasing technological maturity of ZEBs, with many buses being considered a one-to-one replacement for a traditional internal combustion bus. These factors have greatly accelerated the adoption of ZEBs and will encourage strong growth in the future.

2 *Zeroing in on ZEBs* Count

In 2019, CALSTART produced the second edition of its annual ZEB count for the United States titled *Zeroing in on ZEBs: The Advanced Technology Transit Bus Index*. This annual report counts both the current number of ZEBs deployed and the total number ordered by transit agencies. It is currently one of the only reports of its kind available with this information. The total number of ZEBs in the United States as of September 29, 2019 was 2,255. This represents an increase of 37 percent since the previous count was done in 2018, in which the total number of ZEBs was 1,650 [1].

2.1 Methodology

Zeroing in on ZEBs details the official count of ZEBs in the United States. As one of the few reports that details this number, this data was collected from research and personal correspondence with transit agencies and bus manufacturers. Much of this information was obtained primarily from the FTA's Low-No program. Each state released its recipients for each of the Low-No awards and which agencies would be purchasing ZEBs. CALSTART's research analyzed this information in addition to media reports and press releases that detailed the amount of the award and the number of buses purchased.

This information obtained from this nationwide count was cross-referenced with outreach to various transit agencies and bus manufacturers. Other funding opportunities, besides federal funding, were identified as avenues for transit agencies to pay for ZEBs and were included in the report. This included various other sources of funding at the state and local level, as well as available funds from the Volkswagen Settlement. Details from the allocation of this funding and settlement money was compiled to determine which agencies purchased or were planning to purchase ZEBs. After the collection of the data, the number of buses was compiled and reported in *Zeroing in on ZEBs*.

2.2 Results and Breakdown

The total number of ZEBs in the United States active and on-order is 2,255. Currently 202 transit agencies have ZEBs in their fleets across the United States. Of those 202, 56 of them are in California. The average number of ZEBs per state in the U.S. was 44. The West Coast has and continues to have the strongest showing of ZEBs. California is the national leader for ZEB deployments with over 1,000 buses.

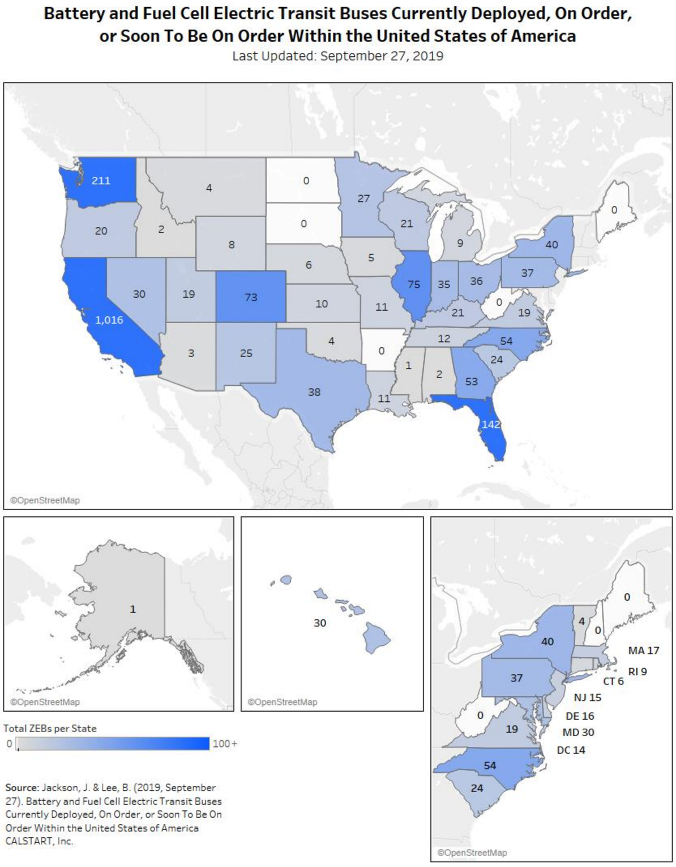

Figure 1: Final U.S. ZEB Count by State [2]

The region with the largest amount of growth was the West Coast, which added over 300 new ZEBs in the last year. California, which remains the nation's leader in the absolute number of ZEBs, saw a nearly 16% increase in deployments from the previous year. California's Innovative Clean Transit Regulation, which mandates that most transit agencies begin purchasing ZEBs by 2023, has contributed to strong growth in the state. Washington State is behind California with the second highest number of deployments. Florida has become one of the fasest growing states for ZEBs, more than doubling their number of deployments from the previous year. Many Southern States also exhibited strong growth in ZEB deployments. Georgia, Virginia, and North Carolina more than doubled their count from the previous year as well. Colorado has emerged as a growing hub of ZEBs, particularly with growth in the Metro Denver area. The Midwest has also emerged as a regional ZEB hub with Minnesota, Michigan, Wisconsin, Illinois, and Ohio experiencing rapid growth in ZEB deployments.

Multiple states added ZEBs for the first time in 2019. These states include Mississippi, Arizona, Rhode Island, Wyoming, and Kansas. All of these states purchased no more than ten ZEBs. Nearly every U.S. state has at least one ZEB deployment.

3 Zero Emission Bus Technological Development Needs

The rapid electrification of buses has introduced several technological challenges for these vehicles. One of the major challenges is that zero-emission vehicles do not have an internal combustion engine. This creates problems because previous vehicle technologies were reliant on the internal combustion engine to provide power or heat that other auxiliary components could use. In the absence of an internal combustion engine, these auxiliaries must be powered with electricity produced from the battery, which forces the propulsion system and the auxiliary equipment to compete for power. Unfortunately, the power consumption attributable to auxiliary equipment can be substantial and in the most adverse circumstances, auxiliary equipment can be responsible for as high as 70% of power consumption [3]. Unfortunately, the high-power consumption by auxiliary equipment can severely reduce the range of ZEBs under certain circumstances. This negative impact on bus performance has acted as a barrier to further adoption of zero-emission transit buses and poses a threat to the continued growth of the ZEB market.

The key constraint that electrified transit buses face is that they consume large amounts of power but have limited energy storage capacity. This "power problem" is a major obstacle that the transit industry has struggled to overcome because increasing energy storage capacity on a ZEB is very difficult. On an electric bus, energy storage capacity could theoretically be increased by adding additional batteries. However, batteries are heavy and take up a large amount of space. The installation of additional batteries could also potentially have negative impacts on the structural integrity and safety of the bus. Increasing energy storage for a hydrogen fuel cell bus would entail installing more hydrogen tanks on the bus. However, hydrogen tanks are also heavy and since they are typically placed on the roof of the vehicle, could have implications for structural integrity. Furthermore, hydrogen tanks are expensive. As a result, there are limited options for increasing energy storage capacity with current technology.

Improving battery and hydrogen storage capacity should be a technological development priority. However, some auxiliary systems use a disproportionately large amount of power and have major impacts on bus performance. As a result, increasing energy efficiency and reducing the amount of energy used by bus systems and auxiliary equipment will also be vital for improving bus performance. This section will identify technological development needs for major energy storage and energy efficiency technologies that have a high potential to address the power problem that buses face.

3.1 Heating, Ventilation, and Air Conditioning (HVAC)

HVAC and environmental climate control play a major role in the passenger's experience and comfort. If the transit agency fails to provide high quality HVAC, this can have the potential to affect bus ridership. As a result, it is vital that HVAC systems reliably meet performance needs. However, HVAC and especially heating, is responsible for a significant amount of energy consumption on a bus and is the piece of auxiliary equipment that consumes the most energy. In extremely hot and cold conditions, up to 40% of the battery capacity can be consumed by the HVAC system [4]. This parasitic load has dramatically decreased the range and performance of ZEBs as it competes with the propulsion system for power from batteries or the fuel cell. Heating has been more problematic than cooling. As a result, this problem is particularly pronounced in regions with cold climates, like the northern and northeastern parts of the country. The power problem caused by the HVAC system is one of the main reasons why the number of ZEBs in these regions have been limited.

ZEBs have particularly struggled with providing heating for the bus in a manner that does not decrease its range or performance. Traditional internal combustion engine buses were able to either use an auxiliary heater or capture waste heat and use it to heat the bus cabin. However, since ZEBs do not have access to waste heat, they have generated heat by using electric resistance heating. However, electric resistance heating is very energy intensive and quickly drains the bus's finite energy storage capacity.

There have been some promising potential solutions to the HVAC problem. Heat pumps provide an alternative to using electric resistance heating. Instead of generating heat, heat pumps save energy by capturing heat from air outside of the bus and transferring it to the inside of the bus. This greatly reduces the HVAC system's parasitic load. Heat pumps are very useful because they can produce heat even when the exterior temperature is colder than the interior temperature. However, heat pumps become less energy efficient in cooler climate conditions. In temperatures below 7°C, the heat exchanger becomes less efficient and heat pumps become ineffective in sub-freezing conditions [5].

Heat pumps are currently being used in European markets and heat pumps that use carbon dioxide (R744 refrigerant) as the medium to transfer heat are becoming increasingly popular. The use of carbon dioxide as a refrigerant has additional environmental benefits as it has lower greenhouse gas potential than traditional refrigerants and sequesters carbon dioxide. The introduction of heat pumps to the transit sector has been limited in the United States. This technology is currently in the early stages of commercialization in American markets. As of writing, NYSERDA and CALSTART are in the process of demonstrating a heat pump on transit buses. Further demonstrations will need to be conducted to facilitate commercial development for this technology.

While heat pumps are an attractive solution for heating, this technology has limits, especially in very cold weather. As a result, many transit operators in cold climate regions have considered installing fuel-fired heaters (using fossil fuels like diesel, propane, or compressed natural gas) on their ZEBs to generate heat. By using these heaters, at least during the coldest months of the year, they hope to maximize passenger comfort and bus performance.

The use of fuel-fired heaters poses several challenges for transit buses. Fuel-fired heaters produce greenhouse gases, particulate matter, and NOx emissions which reduces the environmental and public health benefits of the bus. These emissions raise legitimate questions about whether a bus using a fuel-fired heater is really a "zero-emission" bus, which can cause reputational harm to the industry. Currently, there are few regulations on the use of fuel-fired heaters. Some states have restrictions on the climate conditions under which fuel-fired heaters can be used. Under federal law, fuel-fired heaters are unregulated. As a result, there are no regulations that limit emission levels from fuel-fired heaters. This has raised concerns that emissions from a fuel-fired heater can be substantial. Since many diesel and compressed natural gas buses use aftertreatment and ultra-low NOx technologies, there is a risk that a fuel-fired heater can potentially produce a disproportionately large amount of emissions. To mitigate these concerns, emissions from fuel-fired heaters need to be benchmarked and a Clean Emission Protocol and an emissions standard also need to be developed for fuel-fired heaters to minimize the amount of emissions they release.

3.2 Ultracapacitors

Ultracapacitors are a technology that stores energy and they differ from batteries as they are non-electrochemical. While batteries use chemical reactions to store energy, ultracapacitors use an electric field (i.e., store energy electrostatistically). Ultracapacitors are ideal for short term energy needs as they are capable of quickly absorbing and releasing energy. Ultracapacitors are used in situations where large amounts of energy need to be released quicker than a battery is capable of discharging and they can often be used to bridge short term and long-term power gaps. However, while ultracapacitors can quickly absorb and release energy, they have limited energy storage capability. Ultracapacitors can operate in a wide range of temperature conditions without its performance being affected. In addition, ultracapacitors are more durable, lighter, and have a much longer lifespan than batteries. As a result, ultracapacitors can address many of the problems that batteries face.

Ultracapacitors are not new technologies in the transit sector. Previously, bus manufacturers have introduced ultracapacitor-powered "capabuses" that replace all energy storage systems with an ultracapacitor and use the ultracapacitor as the power plant for the bus. Since ultracapacitors have low energy storage capabilities, these capabuses have limited range. As a result, they are typically used on shorter urban routes and must quickly recharge at every bus stop. Manufacturers like Chariot and Higer have released capabuses and some have been deployed in China and Europe. However, due to their limited range, capabus deployments will likely be restricted to urban areas. Ultracapacitor technology would have to improve substantially for capabuses to have an equivalent range as a normal battery electric bus.

Ultracapacitors also have energy storage applications on battery electric and fuel cell electric buses. Since ultracapacitors are capable of quickly absorbing and discharging large amounts of power, they are well suited for complementing existing energy storage systems on buses and increasing energy efficiency. Simulations indicate that ultracapacitors can improve the efficiency of a battery electric and fuel cell electric bus. In addition, ultracapacitors can be used, instead of batteries, to provide power during times of high-power demand. This can reduce the burden placed on the battery and extend its life [6]. Currently, ultracapacitor deployment in electric buses is limited, especially in American markets. Some European bus manufacturers previously released hybrid buses that used diesel engines with ultracapacitors as range extenders [7]. The main barrier to the use of ultracapacitors is that while they can deliver large amounts of power, their total energy storage capacity and density are relatively low.

One function that ultracapacitors are well suited for is capturing energy from regenerative braking, which involves converting the bus's kinetic energy during braking and converting it to electrical power. Research indicates that current regenerative braking systems paired with a battery can recover 60-70% of the energy lost during deceleration. However, since the amount of power generated by the regenerative braking system exceeds the battery's capacity to absorb it, regenerative braking systems are not as efficient as they can be. Since ultracapacitors can quickly absorb high levels of power, they could have applications in regenerative braking systems. Research simulations indicate that ultracapacitors can theoretically capture up to 88% of the energy lost during deceleration, which would mark a substantial improvement in regenerative braking [8]. This would increase the overall efficiency of the bus as it would be able to recover more energy from braking. Despite the potential for improvement, recent experiments indicate that the power electronics attached to the ultracapacitor limit its performance and that when these inefficiencies are considered, the ultracapacitor can only capture 67% of the energy lost during deceleration [9]. As a result, to receive the energy efficiency benefits of an ultracapacitor, more research will need to be conducted to better integrate power electronics. More real-world testing will also be needed to identify and address power inefficiencies and get the maximum value from ultracapacitors.

3.3 Next Generation Power Electronics

Power electronics are a vital part of the circuit systems in electric buses and electric vehicles in general. Power electronics, which are made from semiconductors, are used to open and close circuits and regulate power flow within a circuit. Currently, power electronics are a mature technology and are made from silicon. However, silicon power electronics have a narrow bandgap and produce a lot of heat in small spaces with limited ventilation [10]. In addition, silicon power electronics have high power losses and experience efficiency reductions at high temperatures [11]. Power electronics in electric buses oftentimes experience high temperatures, which creates a hostile environment to silicon electronics. Electric buses need wide bandgap switches that can switch faster and operate over a wider range of temperatures. In addition, wide bandgap power electronics have the potential to reduce the size and weight of power electronics and increase energy efficiency [12]. This would provide obvious benefits to electric buses as it would decrease the size of bus components, reduce component weight, and increase energy efficiency of the bus.

Several materials have been identified as promising for use in wide bandgap power electronics. Gallium Nitride is a wide bandgap material that is already used in lighting. However, Silicon Carbide and Gallium Oxide have been identified as materials that can be used in transportation-related power electronics. These materials have a much wider bandgap than silicon. Switches made with these materials have the benefit of being able to switch faster, which allows the power electronics to be more energy efficient. In addition, these materials allow the circuit to be smaller, which can reduce the size and weight of power electronics. These power electronics also produce less heat, can operate with smaller thermal control systems, and can function at higher temperatures [13]. Research indicates that using wide bandgap power electronic in electric vehicles, and especially in drive motors, can improve overall vehicle energy efficiency by 15% [14]. This would mark a substantial vehicle energy efficiency improvement and would help to improve the performance of electric buses. As a result, further research should be conducted to further develop and commercialize this technology.

3.4 Batteries

Batteries use chemical reactions to store energy and are the primary form of energy storage on a bus. Both battery electric buses and fuel cell electric buses use batteries for energy storage. However, while fuel cell electric buses primarily use the battery to regulate power flow from the fuel cell to the drive system, battery electric buses are much more reliant on the battery for capacity. As a result, battery electric buses would benefit from having increased storage capacity. While it would be impractical to increase storage capacity by increasing the amount of batteries on the bus, energy storage capacity can be increased by improving the energy density (watt-hours per kilogram) and capacity (Amp-hr) of the battery.

The discovery of new battery chemistries has led to a major increase in battery energy density and capacity as well as a sharp decrease in price. Currently, the predominant chemistry is the lithium-ion (Li-ion) battery that is currently in wide use in electric buses and vehicles in general. Some common variants of the Li-ion battery systems are nickel-manganese-cobalt (NMC) and nickel-cobalt-aluminium (NCA) and lithium-iron phosphorus (LiFePO). Batteries have a certain voltage and capacity rating per design.

While battery technology has rapidly improved, it still lacks in some instances the energy density needed to attain the vehicle range that transit operators require. Many battery electric buses have a range of approximately 150 miles. However, many transit agencies have routes that exceed 150 miles. As a result, on many bus routes, battery electric buses are not considered to be a drop-in replacement for standard diesel buses. In addition, there are other factors that can prevent a battery electric bus from being a drop-in replacement. The performance of batteries can be adversely affected by extremely hot or cold temperatures, meaning that range can be reduced in certain circumstances. In addition, batteries also degrade over time, especially if the battery is subjected to many charge cycles, is not kept within its optimal state of charge, or is exposed to extreme weather conditions. Battery technology still needs to undergo technological development to improve storage capacity, efficiency, and cycle lifetime. These improvements will bring batteries closer to achieving performance parity with a diesel bus under all conditions.

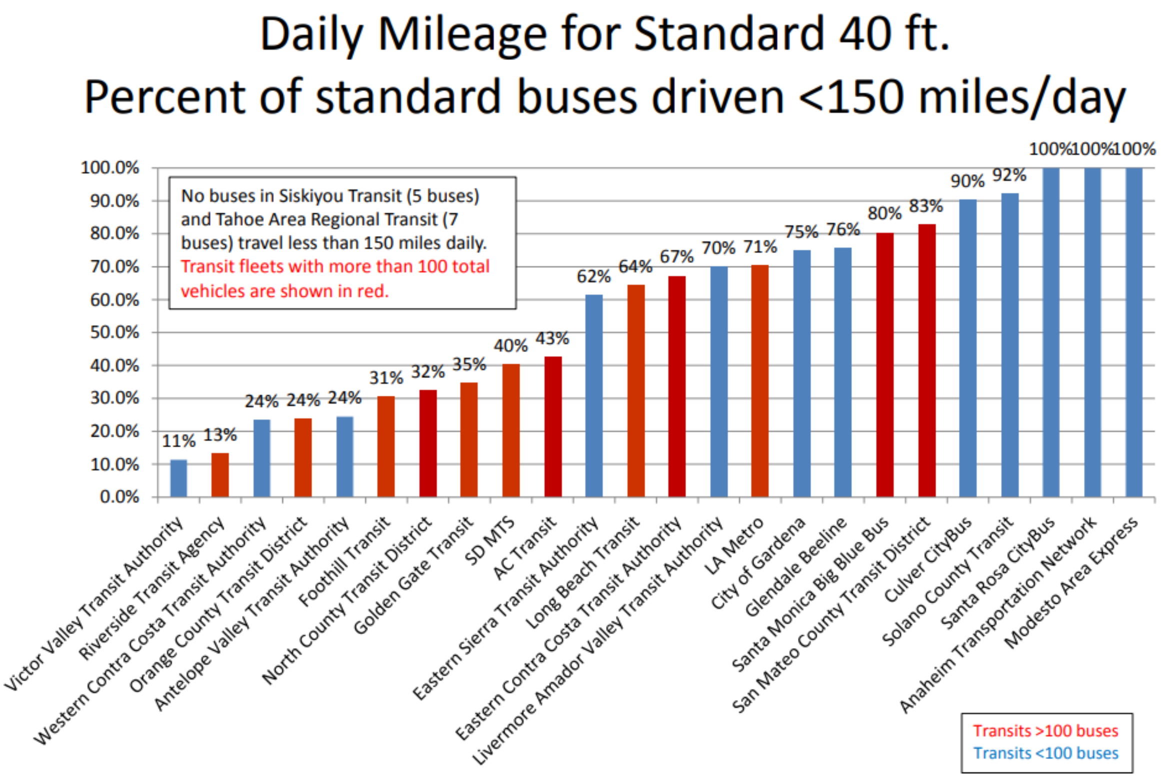

Figure 2: Percent of Standard Buses Driven < 150 miles/day [15]

While battery energy storage density has rapidly improved, the rate of density improvements has slowed. Some industry commentators have noted that energy storage density has started to plateau and that future density gains will become increasingly difficult to obtain as batteries approach the theoretical maximum of battery storage. It is expected that many of the short-term gains in density will be achieved by reducing the weight of packaging, rather than increasing the efficiency of the battery modules themselves [16]. To continue improving battery density, other battery chemistries might need to be explored. As a result, further research should be conducted on all promising battery chemistries to develop lighter, smaller, and more energy dense batteries.

3.5 High Pressure Hydrogen Storage

Hydrogen fuel cell buses are generally considered to be a drop-in replacement for diesel buses. One of the main reasons for this is that hydrogen has the highest energy per mass of any fuels. However, the challenge with hydrogen is that it has low energy per volume, since it is a low-density gas at ambient temperature. As a result, hydrogen must be compressed to increase its energy density. For vehicle applications, the typical storage solution for hydrogen is in a gaseous form at 350-700 bar pressures, with most light-duty vehicles fuelling at 700 bar and most buses fuelling at 350 bar. The transit bus industry has expressed an interest in exploring 700 bar fuelling which would allow them to increase the amount of hydrogen stored on a bus. Advanced storage solutions are needed to further improve hydrogen energy density, store more hydrogen on a bus, and improve range. In many areas, and especially in remote areas, there are transit operators that have extended routes. For example, Victor Valley Transit Authority has some routes that are up to 400 miles long. As a result, developing 700 bar fuelling is important for increasing range and serving extended routes without having to refuel.

700 bar fuelling poses unique challenges. The high pressure of the hydrogen during fuelling causes temperatures in the tank to increase. This is problematic because the integrity of the tank will be threatened if temperatures exceed 85°C. As a result, 700 bar dispensers must precool the hydrogen to -40°C before the hydrogen can be dispensed. However, the chillers that provide the cooling are expensive (costing $100,000-$200,000 per dispensing hose) and is energy intensive, adding about $0.50 per kg of hydrogen [17]. Further research needs to be conducted to understand the implications that 700-bar fuelling will have for storage tanks and hydrogen fuelling infrastructure. Efforts will need to be undertaken to reduce the costs associated with precooling.

Standards will also need to be developed for 700 bar fuelling for heavy duty vehicles. SAE J2601 provides standards for 700 bar fuelling for light duty vehicles that have a capacity of less than 10 kg of hydrogen. SAE J2601-2 provides standards for 350 bar fuelling for heavy duty vehicles but only optional standards for 700 bar fuelling for heavy duty vehicles. As a result, there is a gap in the standards for high pressure hydrogen fuelling for buses. This gap will need to be filled to facilitate the standardization of 700 bar fuelling equipment and fuelling procedures.

4 Discussion and Conclusion

While ZEBs are now considered to be a mature technology, they can still benefit from technological advances in energy storage and energy efficiency. The main challenges that ZEBs now face is increasing the amount of onboard energy storage and improving energy efficiency to extend the range of the bus. Since battery electric buses currently do not have an equivalent range as an internal combustion engine bus, they are not considered to be a drop-in replacement. This has implications for transit operators because it means that they would have to purchase extra buses to maintain the same services as they do with internal combustion engine buses. As a result, solving the power problem would mark a breakthrough for battery electric buses. Fuel cell electric buses, on the other hand, are a drop-in replacement. However, increasing energy storage and addressing the power problem on fuel cell electric buses can help to further increase the bus's range and improve its capabilities. This development would be beneficial as it could potentially allow fuel cell electric buses to be used on long-distance commuter or inter-city routes.

HVAC systems and fuel-fired heaters are important to the growth of ZEBs outside of places with warmer climates. In colder climates, ZEBs require heat in order to keep the inside of the bus warm and maintain passenger comfort. Fuel-fired heaters provide heat without drawing energy from the battery of the bus. While these buses use a zero-emission drivetrain, the fuel-fired heater produces emissions, meaning that the bus is technically not a "fully" zero-emission vehicle. This topic will continue to grow as ZEB deployments grow in regions, like the Midwest and the Northeast, that have colder climates. The question of whether or not there is an alternative to heating a bus with a fuel-fired heater in extremely cold climates remains unanswered.

While improving the HVAC auxiliary system on the bus can greatly improve performance, buses will also need general improvements to energy efficiency to improve their performance. One method for achieving this will be to introduce new technologies to make better use of energy on the bus. Ultracapacitors are the best technology for absorbing energy that would ordinarily be lost during braking and for quickly absorbing or delivering large amounts of power. Developing and adopting improved power electronics would also improve the energy efficiency of the bus and reduce the amount of energy consumed by major components like the electric motor. Adopting these technologies would help towards maximizing use of the energy that is available on a bus. To encourage adoption of these technologies, the price of these components would likely need to fall.

Lastly, improvements to existing energy storage technologies are needed to increase the amount of energy that can be stored on the bus. While advances in the energy density of lithium-ion batteries has started to plateau, other battery chemistries might be able to provide better energy densities. Likewise, the development of higher-pressure hydrogen fuelling would increase the range of hydrogen fuel cell buses. These advancements will help to improve the performance of ZEBs, increase user acceptance, and encourage further deployments of ZEBs.

ZEBs are rapidly changing the landscape of public transportation. Nationwide, transit agencies are making the switch from low-emission to zero-emission vehicles slowly but surely. Many agencies are waiting for the technology to develop before making the purchase. In addition to this, the cost of ZEBs are a lot higher than hybrid or CNG buses, which means funding for these vehicles must come from other sources than just local ones. Forward thinking and technological milestones will be two of the aspects that will be heavily looked when agencies in colder climates look toward purchasing ZEBs. This combined with electric vehicle infrastructure upgrades and more funding at state and federal levels can help to facilitate the transition to ZEBs.

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