Alternative Fuel Buses

What's The Best Option For Your Transit Agency? (Vol. 1)

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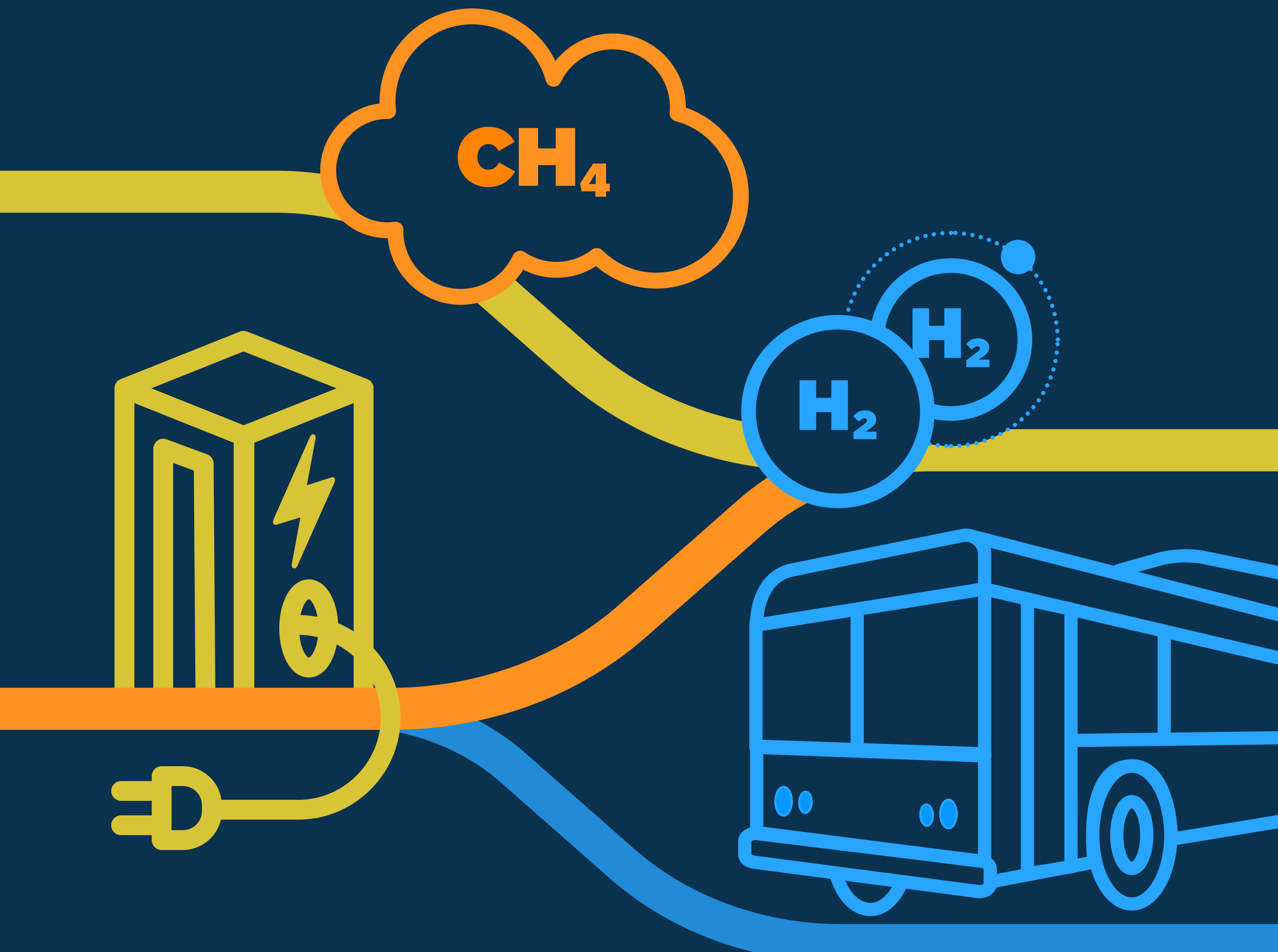

Alternative Fuel Buses

Executive Summary

This report is an assessment of the three leading alternative fuels for transit buses: Compressed Natural Gas, Battery Electric Buses, and Fuel Cell Electric Buses. Our comprehensive analysis focused on three key topics: (1) Expenditures and Technological Capacities, (2) Air Pollution, Greenhouse Gas Emissions, and Other Considerations, and (3) Market Trends.

By qualitatively comparing the three technologies, we concluded that Battery Electric Buses are the leading technology. In the nine categories that our analysis considered, it simultaneously had the most outstanding scores and the fewest subpar ones. Once Battery Electric Buses were identified as the leading technology, we interviewed leading transit agencies whose combined fleets represent 12% of all the transit Battery Electric Buses operating in the United States, as of 2021, to better understand how well the transition can be implemented.

The choice of a transit agency bus fuel has far-reaching consequences, as it locks municipalities into a long-term trajectory over multiple decades. Transitioning off of fossil fuels, such as natural gas, is imperative for achieving climate goals while eliminating tailpipe emissions, improving local health, and advancing environmental justice.

Based on our comprehensive analysis and survey results, **we strongly recommend the implementation of Battery Electric Buses as the primary choice for transit agencies aiming to shift to alternative fuels**, closely followed by Fuel Cell Electric Buses as another promising alternative. While this report's original focus was specific on Charlottesville Area Transit (CAT), its insights and findings have applicability to other localities, with the caveat that other agencies consider any unique local factors.

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Finally, we want to extend heartfelt gratitude to designer Sara Boyer whose designs continue to exceed all expectations. Sara's quick work, creativity, and willingness to help are so appreciated. Her help was made possible through the Charlottesville Area Community Foundation's donation to the Catchafire, Inc. platform.

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Glossary

Battery Electric Bus (BEB): Buses powered solely by electric batteries.

Compressed Natural Gas (CNG): Natural gas stored under pressure.

Cryogenic storage: Storing gases at ultra-low temperatures, typically below -150°C, for industrial purposes.

Electrolysis: Process using electricity to split water into hydrogen and oxygen gases.

Eminent domain: Government's legal authority to acquire private property for public use, often with compensation.

Fast Chargers: High-capacity chargers for electric vehicles, enabling rapid battery replenishment.

Fuel Cell Electric Buses (FCEB): Buses that use hydrogen fuel cells for electric propulsion.

Greenhouse Gases (GHG): Gases like CO2 and methane trap heat and contribute to global warming.

Ground-level (tropospheric) Ozone: Harmful air pollutants formed when pollutants react in sunlight.

Hydrogen by production processes: Brown hydrogen is from coal gasification, Black hydrogen relies on fossil fuels without carbon capture, Blue hydrogen uses natural gas with carbon capture, Green hydrogen is produced from renewable energy sources, Purple hydrogen employs nuclear power, Turquoise hydrogen explores methane pyrolysis, White hydrogen is generated from biomass, and Yellow hydrogen uses partial natural gas oxidation.

Internal Combustion Engine (ICE): Conventional vehicle engines that burn fuel inside for power.

Light-duty vehicles (LDV): Smaller vehicles designed for personal and light commercial use.

Managed charging: Strategically controlling electric vehicle charging to optimize grid stability and reduce costs.

Nitrogen Oxides (NOx): Pollutants from combustion processes affecting air quality.

On-Route Charging: Electric vehicle charging infrastructure placed along travel routes for extended journeys.

PM2.5: Fine particulate matter under 2.5 micrometers in diameter.

PM10: Particulate matter with a diameter under 10 micrometers.

Power grid: A network for generating, transmitting, and distributing electrical energy to homes and businesses.

Renewable Energy (or "Renewables"): Energy sources that do not rely on the combustion of minerals.

Renewable Natural Gas (RNG): Biogas produced from organic waste sources.

Tailpipe Emissions: Pollutants released from vehicle exhaust pipes, impact air quality and climate.

Tire and brake wear (TBW): Particulate matter released due to tire and brake usage, impacting air quality.

Volatile Organic Compounds (VOC): Evaporating organic chemicals contributing to air pollution.

1. Introduction

This report serves as a resource for municipalities contemplating the transition of their diesel bus transit fleets to alternative fuels, particularly those dedicated to climate action and carbon neutrality. It covers economic, social, and environmental aspects and allows for comparisons between three alternative fuel choices: Battery Electric Buses, Compressed Natural Gas buses, and hydrogen Fuel Cell Electric Buses.

The genesis of this report stemmed from Charlottesville, Virginia's forward-thinking decision to transition its transit fleet to alternative fuels. With this report, the Community Climate Collaborative (C3) aimed to provide guidance to Charlottesville Area Transit (CAT) to align its operations with the Charlottesville 2050 carbon neutrality goals. Over time, this report has grown in scope, aiming to inform fuel-transition strategies for transit agencies across the state and nation, fostering a collective journey toward a climate-just future. For instance, Arlington County, Virginia, faces a similar situation to Charlottesville. Both municipalities are expected to make a decision in fall 2023.

The report starts with an analysis of each alternative fuel through economic, environmental, and technological dimensions. It next highlights the recent market performance of each technology. When combined, these insights allowed us to compare the technologies and conclude through a qualitative assessment that Battery Electric Buses appear to be the best choice. In an attempt to verify the validity of that conclusion, C3 conducted a series of surveys and interviews with transit agencies leading the transition to Battery Electric Buses. The agencies' insights pointed out an encouraging future for Battery Electric Buses.

Problem-solving and directing resources toward comprehensive solutions to address climate change are core values at C3. We emphasize proactive change over catastrophic narratives that could hinder progress. While we acknowledge the complexity of public transportation solutions and the evolving nature of the ideal remedy, we hold zero-emission buses in high regard.

When making local policy choices, it is also crucial to not lose sight of important global data, such as the World Health Organization's estimation of 5 million climate-related deaths between 2030-2050[1], the Institute for Economics and Peace's prediction of over 1.2 billion people facing climate-based displacement by 2050[2], and the Inter-American Development Bank's projection of up to 30 million Central American-to-U.S. migrants by 2050, primarily driven by climate-induced food insecurity.[3] As we pursue solutions rooted in justice, equity, sustainability, and fiscal prudence at the local level, we must recognize the ripple effects of our decisions across the globe. Our local choices hold the potential to mitigate or exacerbate the far-reaching impacts of climate change.

2. Alternative Fuels

This section of the report walks through the considerations and opportunities associated with alternative fuel technologies for transit fleets including service reliability, on-route charging, infrastructure and other expenses specifically associated with each technology, expected technological advancements, local health and climate impacts, and "flow-on" impacts.[4]

The three alternative fuels dissected in this section are Battery Electric Buses (BEBs), Compressed Natural Gas (CNG) buses, and hydrogen Fuel Cell Electric Buses (FCEBs). These three technologies are being considered across transit agencies in the United States as local communities work to reduce their greenhouse gas (GHG) emissions in the most equitable, reliable, and socially conscious manner.

The three technologies are reviewed alphabetically and several tables that are referred to throughout the report are placed in the BEB section, simply because that technology is ordered first alphabetically. Please refer back to the BEB section for tables cited in later parts of the report.

2.1 Battery Electric Bus (BEB)

- On-route charging could effectively extend the range of BEBs and give them a replacement rate of nearly 1:1 with mainstream diesel transit buses.
- As the number of BEBs operated by a transit agency increases, so will their combined cost-effectiveness.
- BEBs are zero-emission vehicles, which means that their operations eliminate all tailpipe pollution.
- BEBs cut GHG emissions today and have the potential to lead to carbon neutrality in the future.
- BEBs also present the most cost-effective operational expenses encompassing fuel and maintenance.

What Is It?

Battery Electric Buses (BEBs) solely run on electricity, recharging from external sources. BEBs have long-/extended-range or fast-charge categories, defined by battery size. Long-/extended-range BEBs charge once or twice daily, while fast-charge BEBs have smaller packs and frequent high-powered charges.[5]

Expenditures and Technological Capabilities

Service Reliability

Ensuring that passengers can arrive at their destinations as expected is one of the primary responsibilities of a transit agency. C3 deeply explored the question of reliability and ultimately concluded that under several scenarios BEB buses are fully reliable.

Preliminary information from CAT's "Feasibility of Alternative-Fuel Buses Study"[6] observed that: "*The operational analysis results show that the commercially available Battery Electric Buses (BEBs) are capable of reliably serving only 38% of CAT's operational blocks under the system optimization plan.*" After seeking additional clarification, C3 discovered that this BEB coverage pertains solely to a scenario without the implementation of fast-charging infrastructure. Therefore, even though practical challenges would have to be addressed (such as schedule adjustments for extended layovers at charging stations), the limitations on service coverage highlighted by the experts are not applicable if fast chargers are available.[7]

63

For CAT, experts estimate that "the long-term BEB fleet size requirement stands at 63 buses, marginally surpassing the diesel requirement of 58"

In addition, preliminary information from CAT's "Feasibility of Alternative-Fuel Buses Study" highlights that BEBs' manufacturers' stated range (averaging 150-350 miles) would be affected by factors like weather, elevation, driver behavior, battery health, and occupancy. However, while subtly, the study notes that on-route charging could effectively extend the range and thus give BEBs an almost 1:1 replacement rate with diesel buses. The consultant's presentation also observes that the long-term BEB fleet size requirement stands at 63 buses, marginally surpassing the diesel's requirement of 58[8], an expectation of nearly 1:1 replacement ratio that reaffirms the dependability of the BEB technology. Building on this line of reasoning, it is fair to conclude that BEBs, especially if supported by fast chargers, can adeptly serve all CAT routes.[9]

In order to keep a safe and reliable estimate, CAT's "Feasibility of Alternative-Fuel Buses Study" uses the assumption of a 40% operating range reduction for BEBs (compared to the manufacturer's stated 225-mile range). After requesting further clarification, C3's policy team learned that the 40% operation range reduction is based on a 30% reduction that is based on an "average" from other cities and transit agencies where BEBs are in use. The 40% operation range reduction (an additional 10% to the 30% assumption) also accounts for all above-average (atypical) risks that could reduce the BEBs' performance under challenging conditions like extreme weather, passenger loads, or hilly

10-12 MW

LA Metro initially estimated a 20 MW electrical capacity requirement for depot charging but managed charging strategies helped lower it to 10-12 MW.

terrain. In other words, by using the 40% operating range reduction, the study considers a very conservative scenario for BEBs.

Finally, it must be pointed out that CAT's system optimization plan, used to inform the subsequent alternative fuels study, might carry potential critical deficiencies. It is a concern of C3 that the optimization study's timeframe, capturing ridership between the second half of 2020 and the first half of 2021 (amidst the peak of the COVID pandemic), might have influenced the study's outcomes. Furthermore, the system optimization study, presented to the Charlottesville City Council in May 2021, was followed by a CAT's leadership statement that characterized it as simply a "stopgap measure", rather than a comprehensive overhaul that would have fully optimized the system.

On-route Charging

According to experts, on-route charging can incur "high expenses due to peak rate electrical costs and maintenance."[10] It's worth noting, however, that the aggregated electrical "peak demand rate" associated with each on-route charger would remain relatively steady for chargers serving single or multiple buses, reducing the per unit cost burden of each bus and alleviating concerns for transit agencies with plans to expand their BEB fleet.[11]

Managed charging can significantly further cut charger capacity needs, enabling fewer power cabinets to serve more buses. This not only reduces utility service upgrades but also results in substantial cost savings and quicker deployment of charging infrastructure. For instance, LA Metro initially estimated a 20 MW electrical capacity requirement for depot charging but managed charging strategies helped lower it to 10-12 MW.[12]

Battery Replacement Costs

Battery lifespan, estimated up to 12 years based on a recent BEB study [13], aligns with 12-year warranties from BYD[14] and Proterra[15]. New Flyer offers a 6-year warranty, extendable to 12 years. BEB manufacturers also facilitate battery longevity via lease options[16], ensuring alignment with the bus's lifecycle.[17]

Infrastructure (Facility + Vehicles)

The vehicle costs of BEBs are between the cost of CNG buses and FCEBs, per unit. Even though installing and maintaining the necessary charging stations and a larger fast-charging facility will incur costs[18], as the number of BEBs operated by a transit agency increases, so will their combined cost-effectiveness.[19] In the more expensive scenario, the facility costs for BEBs are the highest of the three options (Table 1). However, under optimistic conditions (defined in Table 1) BEBs are less expensive than FCEBs and only slightly more expensive than CNG facility costs when considering federal funding for both (Table 1).

	BEB	CNG	FCEB
Vehicle Cost per unit	$889,000 ($845,000)**	$552,000	$1.1 M
Vehicle Cost per unit (With Federal Grants Covering 85%)* **	$133,350 ($126,750)**	$82,800	$165,000
Facility Cost	$6.3 M (or $3.7 M)**	$2.3 M	$5.7 M
Facility Cost (With Federal Grants)	$945,000 (or $555,000)**	$345,000	$855,000

* Data from a Kimley-Horn presentation to Charlottesville City Council (2023a).
** Low-estimate presented by Kimley-Horn (2023a), which assumes an optimistic scenario for BEBs.
*** Assuming 85% of Federal Transit Administration (FTA) contributions and 15% of local match, as in the "Low or No Emission Vehicle Program - 5339(c)".

Table 1. Comparing infrastructure costs (vehicle and facility) per unit across three alternative fuel options: BEBs, CNG buses, and FCEBs.*

Operating Costs

A life-cycle cost analysis from the National Renewable Energy Laboratory (NREL) found that BEBs are more cost-effective than natural gas-based alternatives.[20] BEBs also present the most cost-effective operational expenses encompassing fuel and maintenance. BEB buses demonstrate an equivalent fleet fuel economy of almost 20 mpg equivalent (at 2.15 kWh/mile), which corresponds to an average cost of 17.372 ¢/mi (assuming an average cost of 8.08 ¢/kWh).[21]

In contrast, CNG buses exhibit less than 5 mpg equivalent, and as highlighted by NREL,[22] their fuel cost is approximately $0.32/mile. This further confirms BEBs' efficiency and economic viability in comparison to the CNG alternative (Table 2).

	BEB (C3)	CNG (C3)	BEB (Kimley-Horn)	CNG (Kimley-Horn)	FCEB (Kimley-Horn)
Fuel Economy ("miles per diesel gallon equivalent", or mpdge)	20 mpdge	5 mpdge	17.35 mpdge	2.59 mpdge	8.93 mpdge
Cost ($/mi)	$ 0.17 per mi	$ 0.32 per mi	$0.43 per mile[23]	$0.44 per mile	$0.72 per mile

Table 2. Comparing the fuel economy, GHG emissions, and Cost of different fuel alternatives using calculations from C3 and Kimley-Horn.

BEBs

BEBs cut GHG emissions today and have the potential to lead to carbon nuetrality in the future.

Air Pollution, Greenhouse Gas Emissions, and Other Considerations

Community Health and Air Pollution

BEBs are zero-emission vehicles[24] with opperations that eliminate all tailpipe pollution, including carbon monoxide emissions –which are harmful to human health– as well as nitrogen oxides (NOx), particulate matter (PM), volatile organic compounds (VOC), and sulfur oxides (SOx) emissions.[25] As such, zero-emission buses (ZEBs) combat climate change and prioritize justice for those disproportionately affected by pollution, especially lower-income households, and Black, Brown, and immigrant communities.

Climate Goals and Reduced Greenhouse Gases (GHG) Emissions

BEBs cut GHG emissions today and have the potential to lead to carbon neutrality in the future due to their inherent energy efficiency, and as power grids shift toward cleaner sources.[26] Ongoing advancements in energy storage and integration with renewables enhance their sustainability. Despite today's grid, BEBs remain a key step in reducing urban transportation emissions and fostering a greener future.

When assessing near-term emission reductions, preliminary materials from CAT's "Feasibility of Alternative-Fuel Buses Study" calculated fleet-wide emissions reductions by 2030, with the assumption that CAT would have a total of 5 alternative buses by that year. In that near-term analysis, consultants assumed all scenarios would include CAT's 2 planned BEBs, plus 3 additional alternative fuel buses of a specific fuel source (BEBs, CNG, or hydrogen) for each possible scenario. Consequently, the study's near-term alternative fuels emissions comparison does not offer a "pure technology vs. technology" comparison, as it assumes that BEBs represent at least 40% of CAT's alternative fleet in all scenarios. Additionally, while the consultants acknowledged BEBs emit only 22% of CNG buses emissions, the results displayed in their presentation can be misleading, as they compare the entire fleet's performance rather than a one-on-one comparison. Despite that, BEBs are still shown to emit far lower GHG emissions than the other options presented using both C3's and the consultant's analyses (Table 3).

	BEB (C3)	CNG (C3)	BEB (Kimley-Horn)	CNG (Kimley-Horn)	FCEB (Kimley-Horn)
GHG emissions (lbs of CO_2e/mile)[27]	1.38 lbs	3.04 lbs[28]	1.29 lbs	5.77 lbs	3.35 lbs

Table 3. Fuel economy, GHG emissions, and cost of different fuel alternatives. C3 calculations and Kimley-Horn data.

Safety Risks

While lithium-ion battery-powered vehicles face many of the same flammable risks as diesel-powered vehicles, the risk of fire has been found to be reduced. Recent statistics show that electric vehicles are involved in 25 fire incidents per every 100,000 vehicles, compared to 1,530 incidents for gasoline vehicles.[29] Similarly, EV FireSafe found that 18 e-bus high-voltage battery fires have been verified since 2010, in a context where there is a stock of 110,000 such vehicles globally. One potential cause of these incidents is the occurrence of thermal runaway, which refers to an event where exothermic processes continually build on one another until temperatures reach uncontrollable levels. Batteries in electric buses are sometimes mounted on the roof, which exacerbates this issue as solar energy directly heats the batteries.[30] Electrical faults during charging may also be the cause of some of these incidents, and the close proximity of fleets when charging can cause fires to spread from one vehicle to another.

100,000

Recent statistics show that electric vehicles are involved in 25 fire incidents per every 100,000 vehicles, compared to 1,530 incidents for gasoline vehicles.[29]

Because of these factors, it can be deemed very unlikely that there is a significant risk of spontaneous or explosive fire, but rather that overheating, either from high surrounding temperatures or overcharging, is the primary concern. Reducing opportunities for batteries to overheat, either through changes in charging location or duration, is an important mitigation technique that can help reduce battery-related fires. Increasing education focused on these lithium-ion battery-related incidents will also help ensure firefighters and first responders are better prepared to combat any incidents that do occur.[31]

Flow-on Impacts

Critics of electric vehicles (EVs) largely point to the flow-on impacts of EVs and concern about their environmental and social consequences. Understanding the extent of these impacts and the projected future mitigation strategies is key for realizing the full potential of EVs in the transition away from Internal Combustion Engine (ICE) vehicles. The consequences of EVs may be less extreme than the narrative suggests:

Greenhouse Gas Emissions (GHG) from Electricity Generation:

- The specific carbon footprint of an EV heavily depends on the electricity grid mix, however, EVs still have a lower carbon footprint to charge than new ICE vehicles.[32] Given that the carbon intensity of Virginia's power grid is lower than the national average[33], EVs can have an especially smaller carbon footprint here compared to traditional ICE vehicles.
- Over their lifetime, BEBs have lower GHG emissions than hydrogen-powered buses (FCEBs).[34]

Embedded GHGs in Manufacturing:

- EVs have more embedded carbon than ICE vehicles. The process of creating an EV battery and the car itself is associated with a high carbon footprint –roughly twice as high as an ICE vehicle– but the emissions even out after a short period of time.[35] That carbon footprint "break-even" is particularly faster for heavily used vehicles (such as transit buses).

Battery Production and Retirement:

- Lithium mining, often cited as a concern, accounts for a very small fraction (0.06%) of global mining by weight.[36] Even if lithium mining were to increase substantially to meet the demand for EVs, upcoming advancements in efficiency and recycling technologies are expected to mitigate these environmental impacts.
- As a critical mass of EVs reach the end of their life, recycling elements from the existing batteries can significantly reduce the amount of new Lithium needed to create an EV battery.[37, 28]
- Battery waste at the end of a vehicle's life is one of the downstream considerations of BEBs. Currently, only 5% of EV materials are recycled[39], but as technology continues to advance, that waste can be diverted from landfills and used in new battery creation (see above).

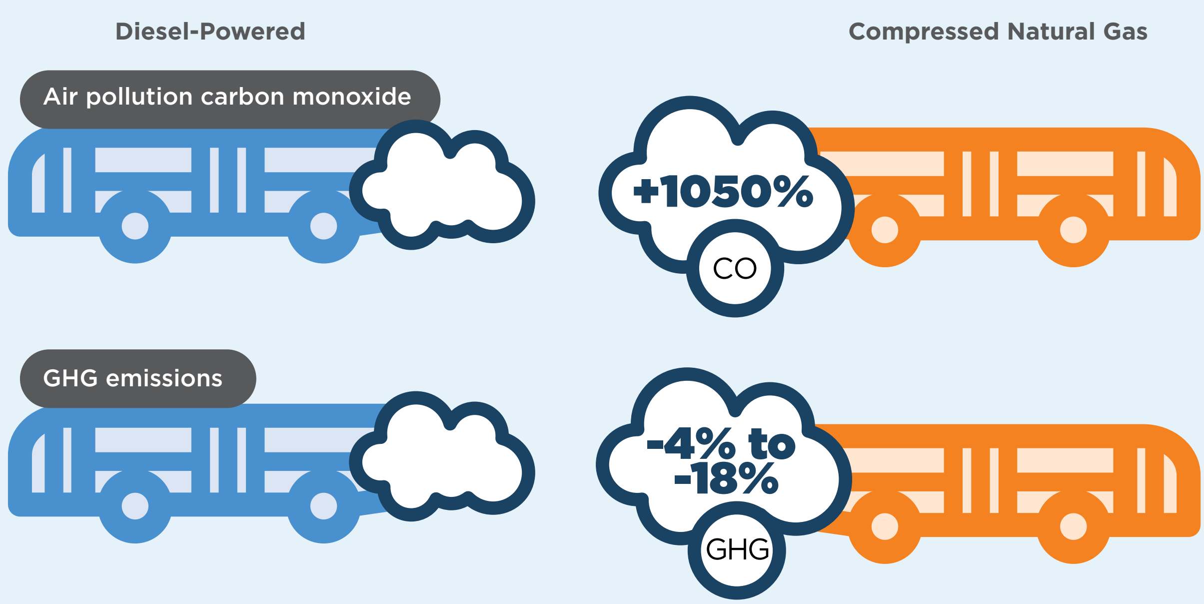
Utility Grid Overextension:

- The notion that the U.S. utility grid will be overextended by widespread EV adoption is over-exaggerated. EVs can be charged at off-peak times to even out the power demanded at any given time, and some EV chargers are bidirectional so that they can charge during off-peak hours and then supply power back to the grid during peak hours.
- Grid resiliency should increase in the coming years. The Bipartisan Infrastructure Act committed $13 billion to improving grid resiliency, which can further reduce the likelihood of grid collapse.[40]

2.2 Compressed Natural Gas (CNG) Today and Renewable Natural Gas (RNG) Tomorrow: A "Cheap" Bargain That Could Prove Costly

- CNG holds the longest service range of all three alternative buses, being capable of effectively achieving a 1:1 replacement ratio with mainstream diesel buses.
- Switching purely to CNG may not be congruent with the goal of becoming carbon neutral by 2050. To achieve said goal, transit agencies would have to purchase RNG buses as fuel for their future buses.
- Even in its full potential, RNG sources are likely too limited to supply adequate demand and much more costly than the other alternatives studied.
- Tailpipe emissions associated with CNG are associated with a 1,050% increase in Carbon Monoxide from the current mainstream transit diesel bus emissions.
- Carbon emissions and environmental injustices are prevalent throughout the process of natural gas production and distribution.

CNG Buses: Another Fossil Fuel With The Same Old Issues



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What Is It?

Compressed Natural Gas (CNG) is a commercially available vehicle fuel formed by compressing natural gas. Stored under high pressure, CNG vehicles offer fuel efficiency similar to conventional gasoline vehicles.[41]

Renewable natural gas (RNG) is a form of biogas that mirrors conventional natural gas. It is a byproduct of biomass sources through anaerobic digestion or gasification that is purified for vehicle applications, meeting pipeline standards. Its usage as compressed or liquefied natural gas highlights its potential as an advanced biofuel for sustainable transportation.[42]

Expenditures and Technological Capabilities

Service Reliability

The range of a CNG bus can be 350–400 miles.[43] CNG buses have existed for significantly longer than either BEBs or FCEBs and the greater maturity of their technology adds to their service reliability.[44] Several transit agencies in the vicinity of Charlottesville, including the Greater Richmond Transit Company and Arlington County Transit, have utilized CNG buses.

Infrastructure (Facility + Vehicles)

The infrastructure costs for CNG buses are projected to be the lowest of the fuel choices studied by CAT's "Alternative Fuels Study." Both the price per bus and the facility costs are lower than any of the other fuel alternatives considered in this report (Table 1).

Operating Costs

The operational costs (fuel + maintenance) are slightly higher but still comparable to those of BEBs (Table 2).[45] The City's ownership and operation of its own natural gas utility could be a benefit, however, its plan to decarbonize could limit its ability to further increase operations. While conventional CNG is relatively a low-cost fuel to operate, it could face a sizeable surge in fueling costs if a switch to RNG takes place (see more in Section 3).

Air Pollution, Greenhouse Gas Emissions, And Other Considerations

Community Health and Air Pollution

In the near term, CNG would have a mixed impact on local air pollution when compared to mainstream diesel transit buses. NOx emissions would be significantly reduced, but preliminary information from CAT's "Feasibility of Alternative-Fuel Buses Study" indicates that a switch to natural gas [CNG] would lead to an increase of 1,050% in the emission of carbon monoxide, a harmful air pollutant.[46] The social implications

2.7

(…) Neighborhoods with majority-nonwhite residents had NO2 levels that were 2.7 times higher in majority-nonwhite neighborhoods than majority-white ones.

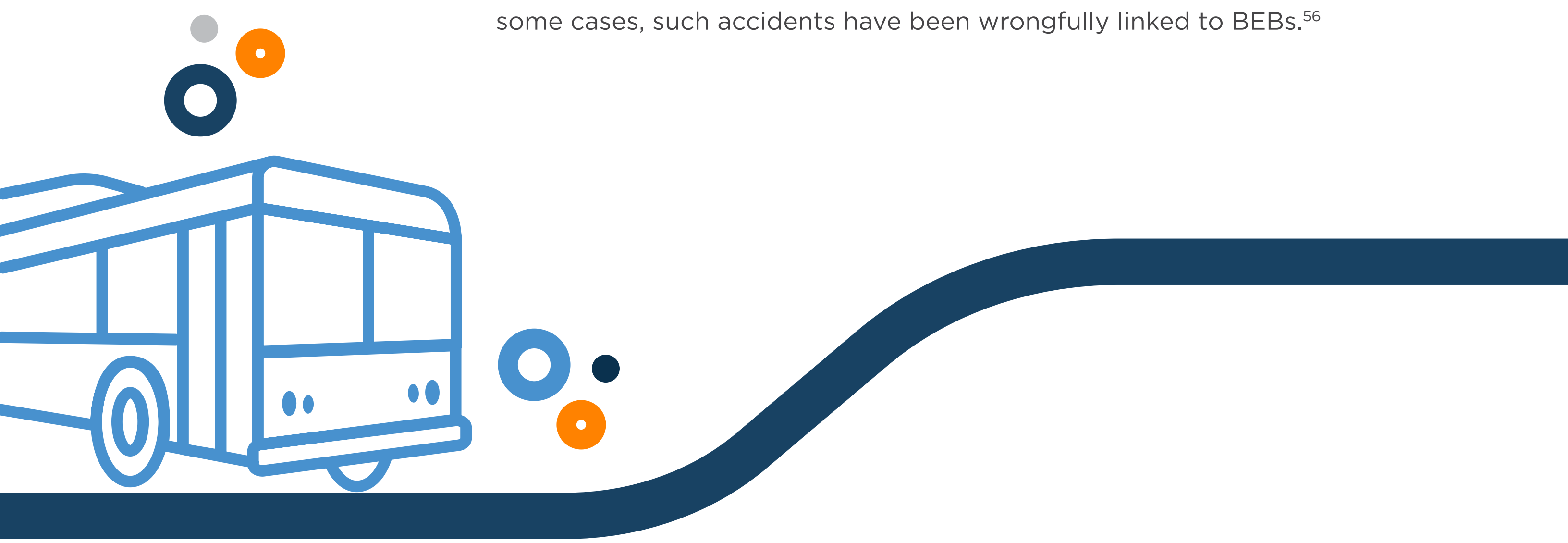
are clearly adverse and not equitable, disproportionately impacting community members who rely heavily, if not solely, on public transit for their transportation needs.

Both RNG and CNG buses produce NOx, VOC, and other pollutants that diesel buses do.[47] This traffic-related air pollution has been associated with many health issues, including asthma, heart problems, and even premature death.[48] These effects have also been shown to disproportionately impact communities of color. One national study found that neighborhoods with majority-nonwhite residents had NO2 levels that were 2.7 times higher in majority-nonwhite neighborhoods than in majority-white ones.[49]

Climate Goals and Reduced Greenhouse Gases (GHG) Emissions
Even though preliminary information from CAT's "Feasibility of Alternative-Fuel Buses Study's indicates that *"switching purely to natural gas would [CNG] not be congruent with the (…) carbon emissions reduction goal of becoming carbon neutral by 2050,"*[50] it also states that the "purchase of renewable natural gas [RNG] provides a further reduction in carbon emissions."[51] Furthermore, it goes on to say that "a switch to natural gas [CNG] would provide a reduction in CAT's carbon emissions."[52]

However, it has been shown that both CNG and RNG buses exhibit comparable adverse tailpipe GHG emissions as conventional fossil fuel gas.[53] Moreover, the International Council on Clean Transportation (ICCT) notes that natural gas buses provide modest GHG reductions (4% to 18%) when compared to diesel.[54]

Safety Risks
CNG buses pose explosion risks due to the highly flammable nature of natural gas. In the event of a gas leak and ignition source, CNG can combust rapidly, leading to explosions such as one that took place in April 2022[55], in Italy. Although safety measures are in place, such as pressure relief devices and strict maintenance protocols, these risks underline the importance of diligent safety practices and monitoring to mitigate potential hazards associated with CNG buses. Unfortunately, in some cases, such accidents have been wrongfully linked to BEBs.[56]



Flow-on Impacts

Gas pipelines:

Pipelines are expected to be used for both the transportation of the natural gas that fuels CNG buses and RNG buses. The construction of gas pipelines for natural gas often involves the use of eminent domain, a matter of significant social justice consideration that may also have negative environmental impacts, disturbing the vegetation and wildlife around pipelines, as well as risking pipeline leakage and thus contamination and pollution.[57, 58] The transportation of RNG can carry equivalent hazards to that of fossil fuels, encompassing the potential for pipeline ruptures, particularly in cold conditions.

Fracking:

Hydraulic fracturing (fracking), a common practice used to collect oil and natural gas, can lead to many adverse health effects, even causing small earthquakes and contaminating nearby drinking water with chemicals.[59] Communities of color are among the most likely to face these effects, as they live disproportionately closer to fracking wells.[60]

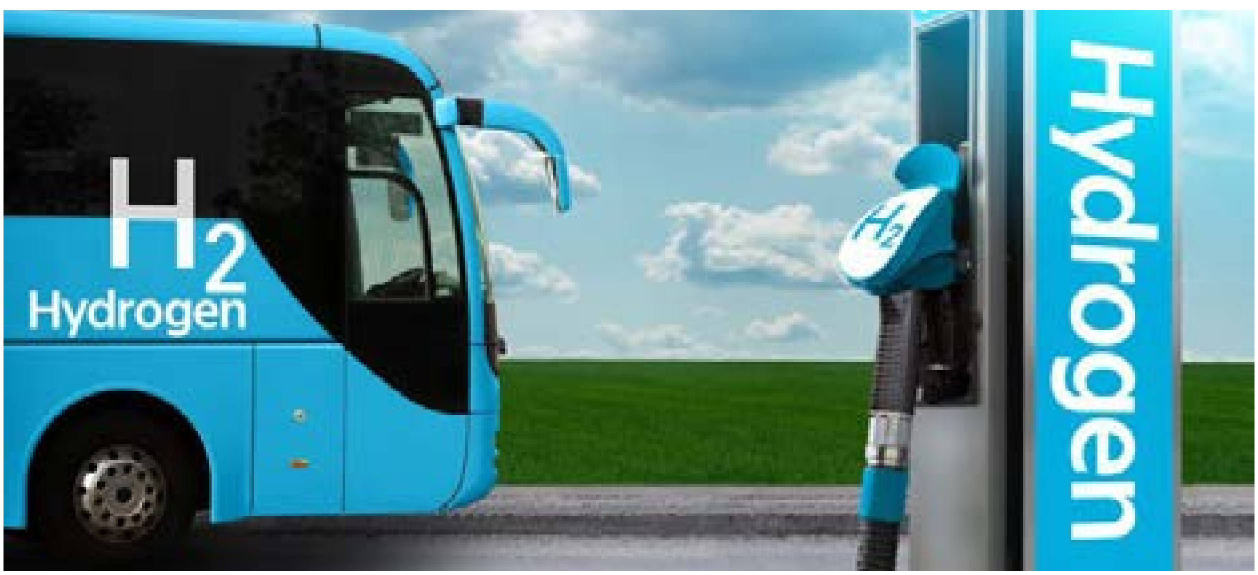
Gas Leaks:

Exposure to air pollutants caused by natural gas leaks can lead to respiratory symptoms, cancer, and cardiovascular disease.[61] People living close to oil and gas wells experience higher rates of these symptoms, in addition to poor pregnancy outcomes such as birth defects, premature births, or fetal fatalities.[62] Children living with high pollution levels are also more likely to have lower academic skills.[63]

The negative downstream impacts of CNG usage include decreased air quality and increased GHG emissions, which in this report are considered under their specific sections.

2.3 Hydrogen-Powered Fuel-Cell Electric Buses (FCEB): The Advantages and Challenges of Running Only on Electricity and Water

- FCEBs' long range and quick refueling hint at a seamless transition from conventional diesel buses.
- FCEBs are an incipient technology, which contributes to their relatively high upfront and fuel costs along with uncertain maintenance costs.
- There are zero tailpipe emissions associated with FCEBs, and their overall GHG reductions will be mainly determined by how the hydrogen is produced.
- In the near term, FCEBs would create 2.6x more GHG emissions than those of BEBs.
- Generating, storing, and accessing electricity from hydrogen, results in significant energy losses.
- Attaining carbon neutrality in the transportation sector via FCEBs would demand a 2- to 5-fold greater rise in electrical power demand when compared to what would have been the increase demanded by BEBs.
- Powering a bus for one day using hydrogen would take approximately 224–510 local gallons of water, which is equivalent to the daily consumption of 2 to 5 local single-family households daily.



What Is It?

Hydrogen-fueled vehicles, also known as fuel-cell electric vehicles or buses (FCEVs or FCEBs, respectively), use electricity from a fuel cell powered by hydrogen to drive an electric motor. Unlike battery electric vehicles, FCEVs generate their electricity onboard, eliminating the need for charging. The hydrogen fuel tank determines energy storage, while a battery assists during acceleration and braking.[64]

Expenditures and Technological Capabilities

Service Reliability

The long-range and relatively rapid refueling capabilities of FCEBs suggest their potential for a seamless transition, mirroring the performance of conventional diesel buses in mainstream transit. The range for hydrogen buses is 260-350 miles, which makes this technology's range both bigger and less variable than BEBs.[65] It only takes 6-10 minutes to refuel FCEBs, meaning operations can run similarly to the current diesel fleet.[66]

2x

The cost of an FCEB vehicle is about twice that of a CNG bus and around 30% more than a BEB

Infrastructure (Facility + Vehicles)

According to experts, the infrastructure costs for FCEBs are the highest of the three options considered in this study. The cost of an FCEB vehicle is about twice that of a CNG bus and around 30% more than a BEB (Table 1). The facility costs for FCEB are higher than for CNG. Depending on which BEB scenario comes to fruition, it could be that FCEBs have a higher or a lower facility cost than BEBs.

Much like the cost scalability of BEBs, FCEBs also experience efficiency gains as the fleet expands, especially concerning the expected costs and complexity of hydrogen fueling infrastructure expansion.[67]

Operating Costs

The operations costs for the transition to FCEBs are also estimated to be the most expensive (Table 2). Additionally, this fuel technology could require a new cryogenic storage and fueling facility to be built.[68]

Due to its expensive costs, FCEB adoption has been slow as transit agencies often favor BEBs instead. Famously, in 2022, the City of Montpellier (France) scrapped its plan for 50 hydrogen buses in favor of battery electric ones due to significantly lower operating costs, calculating that the costs per mile of running hydrogen buses would be more than 6x higher than those of BEBs. The decision came under new city management, which realized the initial plan over-emphasized upfront investment costs while downplaying operational expenses. Acknowledging that hydrogen remains promising, Montpellier will revisit the technology in 2030.[69]

Air Pollution, Greenhouse Gas Emissions, And Other Considerations

Community Health and Air Pollution

Just like with BEBs, fueling FCEBs produces zero tailpipe emissions, ensuring that their operations result in the elimination of all harmful tailpipe pollutants, including carbon monoxide, which poses health risks to humans, as well as NOx, PM, VOC, and SOx emissions.[70] Consequently, these ZEBs play a critical role in addressing climate change and promoting environmental justice, particularly for marginalized communities, such as lower-income households, and communities of color, who are disproportionately affected by pollution.

Climate Goals and Reduced Greenhouse Gases (GHG) Emissions
FCEBs contribute to GHG emission reduction and long-term carbon neutrality goals similar to BEBs by producing zero tailpipe emissions and relying on electric motors. FCEBs reduce GHG emissions as they can be powered by hydrogen produced through electrolysis using renewable energy sources.

According to experts, the estimated long-term GHG emissions reduction of the hydrogen transition is 99%.[71] However, the actual emissions reduction will be closely linked to how the hydrogen is sourced. Today, hydrogen is mostly produced from natural gas and only 5% is created without using fossil fuels.[72] If hydrogen is obtained through electrolysis processes using a carbon-neutral power grid, then emissions would be significantly reduced.[73] As such, the effectiveness of both FCEBs and BEBs hinges on a decarbonized power grid.

44%

A conservative estimate suggests that 44% of energy is retained throughout the [Hydrogen energy production] process.

Noteworthy, while it's premature to definitively label hydrogen as a greenhouse gas, it's crucial to emphasize the growing concerns surrounding hydrogen leaks and their potential as a more significant source of global warming than previously anticipated.[74]

Inevitable and Significant Impact on Our Power Grid's Generation Capacity

Efficiently generating, storing, and accessing electricity from hydrogen involves notable energy losses and inefficiencies[75, 76, 77]. To enable the production of hydrogen for FCEBs through electrolysis, the power grid must be able to produce a considerably greater amount of energy compared to what would have sufficed for charging BEBs. As such, while the grid is not carbon neutral, hydrogen would create much more GHG emissions than those of BEBs (approximately 2.6x more, see Table 3).

Even within a climate-friendly grid context, massive hydrogen fuel cell deployment in the transportation sector would bring about a considerable increase in electricity demand. The process of generating, storing, and accessing electricity from hydrogen, results in significant energy losses. The grid would need to supply significantly more clean energy to create through electrolysis all the hydrogen required to power FCEBs than what would have been necessary to charge BEBs. In the meantime, on top of the bigger electricity demand, GHG emissions from hydrogen will be much higher than for electric buses.

Efficiencies in hydrogen production:

- **Electrolysis:** Energy splits water into hydrogen and oxygen (~70% efficient)
- **Storing hydrogen:** hydrogen must be stored as a liquid or under high pressure (90% efficient)
- **Converting hydrogen into electricity:** hydrogen must be converted back to electricity (60–70% efficient)[78]

Based on the presented data, a conservative estimate suggests that 44% of energy is retained throughout the process (calculated as 0.70 x 0.90 x 0.70 = 44%). However, various sources [78, 79, 80], indicate a range of 18–46% of energy being preserved. This implies a significant energy loss: between 54% and 82%.

In comparison, the energy loss in powering BEBs is approximately 5%. Put simply, attaining carbon neutrality in the transportation sector via FCEVs would demand a 2 to 5-fold greater rise in power demand when compared to what would have been the increase demanded by battery electric vehicles. In light of this, C3 recommends that adopting hydrogen fuel cells should be prioritized for transportation modes where battery electric options are less viable and face limitations, such as commercial and cargo air transportation.

Safety Risks

FCEB safety concerns are two-fold: there is the risk of hydrogen leaks or battery fires. Neither is an issue of great concern. Hydrogen, a flammable gas, most commonly leaks when there are pipe or valve failures,[83] however, because hydrogen is so light, it tends to quickly dissipate, which limits the concern of fire.[84] For more information on battery safety, please check for BEB safety risks on Section 2.1.

Flow-on Impacts

GHG from Hydrogen Production: A study developed in 2022 observed that most environmental concerns regarding hydrogen encompass the emissions associated with its production. The predominant method of hydrogen production is gray hydrogen, generated through steam methane reforming (SMR) without carbon capture. While gray hydrogen has lower GHG emissions compared to diesel or compressed natural gas (CNG), it still has environmental impacts. Green hydrogen, produced via electrolysis using carbon-neutral electricity, holds promise for substantial GHG reductions. The consultants concluded that, in the interim, transitioning to hydrogen would necessitate some reliance on gray hydrogen as technology and supply chains evolve.[85]

Battery Production and Retirement: In order to increase their energy efficiency and range, it is common for FCEBs to capture energy from braking and other processes and store it in onboard batteries (in a similar way to conventional hybrid vehicles). The FCEBs considered by CAT's consultants use this hydrogen plus battery storage model.[86] Please refer to Section 2.1 for more information about the flow-on impacts of battery production.

Water Consumption and Potential Impact on the Local Water Supply

In addition to electricity, local water resources are needed to create energy from hydrogen (the hydrogen molecule is isolated from water molecules in the electrolysis process).[87] Currently, it takes 10 – 11 liters of water to create 1 kilogram of hydrogen commercially.[88, 89]

To put into perspective, the fuel required to power a hydrogen bus for 150 miles (approximately the daily travel range of a transit bus in Charlottesville), assuming between 3.23 and 6.71 mi/kg[90], is 46.4–22.4 kg (150 mi ÷ 3.23 mi/kg = 46.4 kg and 150 mi ÷ 6.71 mi/kg = 22.4 kg, respectively). Therefore, powering a bus for one day using hydrogen would take 224–510 local gallons of water, which is equivalent to the daily consumption of 2-5 local single-family households per day. When considering a fleet of 60 buses, that is equivalent to the water needs of 120–300 single-family households.[91]

This could potentially strain the local water supply if the electrolysis process is conducted locally, especially during severe drought years. This aspect should be carefully contemplated in view of present-day local draughts warmings that encourage water conservation and the projection of more intense naturally occurring droughts, both in the Charlottesville Area specifically[92] and across Virginia.[93] While still in their early stages, pioneering projects worldwide are investigating the utilization of treated wastewater in hydrogen electrolysis to reduce the strain on local water resources.[94]

3. Beyond Fuel Type: What Else to Consider?

To provide community members and decision-makers with a comprehensive perspective on technology choices, it's crucial not only to analyze the current state of each technology individually but also to assess their historical performance and future market and technological trends in relation to one another.

This section begins by examining the broader market trends within the alternative fuel industry, shedding light on the current landscape and anticipated shifts. This dual perspective enables us to identify technologies poised for ongoing advancements and those at risk of stagnation.

Furthermore, we delve into a common environmental concern spanning all vehicle technologies: the emission of particulate matter from brakes and tires. By amalgamating insights about individual technologies, their market interactions, and shared environmental challenges, we are better equipped to compare these technologies and make informed preferences.

- BEBs are increasingly favored by agencies in the alternative fuel bus market over CNG and FCEB options.
- From 2011 to 2021, the average EV range grew from 86 miles to 217 miles.
- Of the few FCEB transit buses in operation in the U.S., 85% are in California.
- Between 2015 to 2019, within the alternative fuel bus market, the share of BEBs has been growing and the share of CNG buses has been shrinking.
- RNG's full-scale deployment may only substitute around 3-7% of current natural gas consumption.
- The cost of RNG is reported to be 3 to 18 times higher than traditional natural gas.
- The maintenance costs for hydrogen fuel cell vehicles are not well-established.
- Bankruptcies are common even in mainstream industries and can provide key insight into the future development of clean transportation manufacturers.
- Transitioning to ZEBs will improve transit justice by reducing air pollution in underserved communities.

The Big Picture: Navigating Market Trends

Despite CNG buses being a technology far more mature than BEBs, with nearly 15x as many CNG buses in operation as BEBs, there are only 1.5x as many agencies using CNG buses (Table 4). Together, this information suggests that (i) agencies are beginning to adopt BEBs but have not fully transitioned their fleets, and that (ii) CNG buses have failed to achieve widespread adoption even though they have been in operation for nearly 40 years longer than BEBs.

Of the few FCEB transit buses in operation, a number that represents only 5% of the number of BEBs in operation, 85% are in California, where there are a significant number of hydrogen-refueling stations. In Virginia, establishing dedicated infrastructure for FCEBs could pose a unique challenge, despite the producer's financial support. With a lack of local expertise to service the refueling stations and buses, reliability could be significantly diminished when maintenance to the FCEB system is required. Challenges faced by agencies in Virginia may differ significantly from those in California, which makes it challenging to anticipate issues and could mean a steep learning curve for agencies in the Commonwealth.

	BEB	CNG	H2 (FCEB)
Agencies	120	191	5
Vehicles	1,072	16,654	54
Manufacturers	13	32	4

Table 4. The table shows the total number of BEB, CNG, and FCEB buses as well as the number of transit agencies operating each type of bus and the number of manufacturers for each fuel type.

While there are more CNG buses in operation than BEBs and FCEBs (Figure 1), the current growth rate of CNG bus purchase is increasingly slower than that of BEBs. Over a three-year period, from 2017 to 2019, BEB purchases grew 45%, 79%, and 52%, respectively. Comparatively, CNG buses only grew 15%, 15%, and 12% in the same period.[95] Consistently, preliminary information from CAT's "Feasibility of Alternative-Fuel Buses Study" stated that "Market and industry trends are moving towards low- and zero-emission vehicles."[96]

Accordingly, regarding the market share of each alternative fuel technology (BEB, CNG, and FCEB) in the five-year period from 2015 to 2019, we found that the share of BEBs has been growing and the share of CNG buses has been shrinking (Figure 2). This change indicates that among those interested in transitioning away from gasoline and diesel buses, BEBs are rapidly emerging as the preferred choice. This growth will continue to secure more investments, technology improvements, and collaborative problem-solving for current shortcomings. All these benefits have the potential to enhance reliability and quality of service.

In addition to BEBs, FCEB is often talked about as a rapidly growing technology, however, the lagged adoption of hydrogen technologies translated into fewer FTA-approved providers for FCEBs. Comparatively, there are more than a dozen manufacturers of BEBs. Even if the FCEB technology were assumed to be growing rapidly, its adoption is comparatively so far behind that it could be challenging to have buses serviced, which can negatively impact reliability.

Underscoring this trend, an estimated 5,480 ZEBs were in operation, awarded, or on order in the United States as of 2022. Notably, 96% of these were BEBs, with FCEBs only accounting for 211 buses. Nearly two-thirds of these FCEBs are associated with operators located in California.[97]

To get a better sense of how these technologies are changing the market, we considered how both BEBs and CNG buses, the two most mature technologies, have grown from 2015 to 2019. BEBS have grown between 45 and ~90% each year since 2016, but CNG buses have only grown between 12 and ~25% in the same period (Figure 3). Even though CNG buses might currently occupy a larger market share than BEBs, their growth has stagnated over the past half a decade, whereas BEBs have continued to increase in popularity.

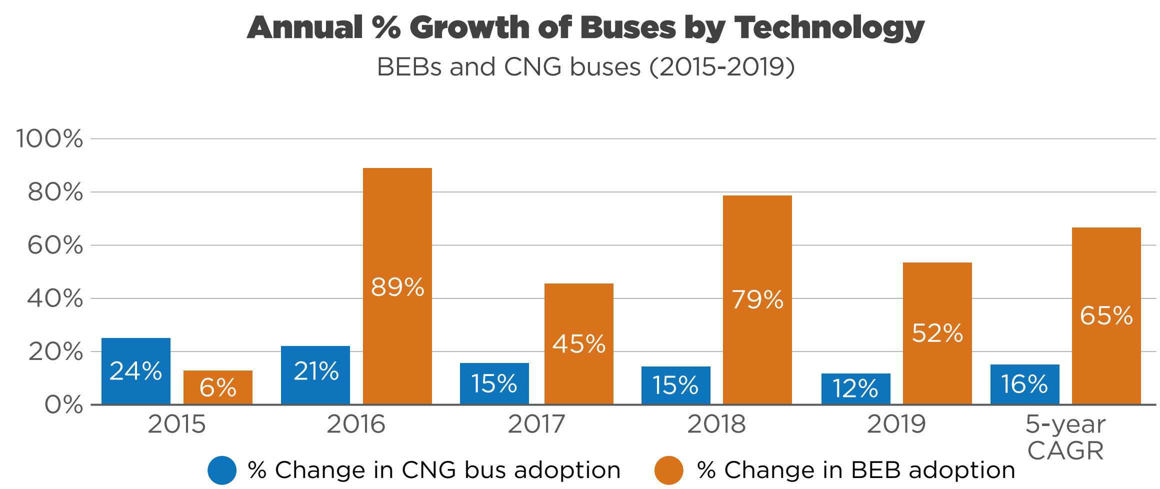


Figure 3. Change in the adoption for the two leading alternative fuel bus types (BEBs and CNG buses). Data shown for 2015 to 2019 as well as the Compound Annual Growth Rate for the five pre-pandemic years. Graph made with data from the DOT 2021.

Technology Trends

Related to how each technology is growing in the marketplace is how rapidly the underlying technology of each is advancing. This section seeks to understand what the future of the technologies is expected to be.

Battery Technology

BEBs stand to benefit from the upcoming wave of next-gen batteries, particularly solid-state lithium batteries[98], anticipated to provide twice the energy storage capacity and 5x longer lifespans. These advanced batteries are projected to hit the market by 2030.[99] Furthermore, the cost per unit of storage in lithium batteries has already dropped by 97% in the past three decades, with further reductions expected as technology matures. By 2025, research firm Fastmarkets predicts that lithium-ion battery pack prices, including lithium iron phosphate (LFP) cells and nickel manganese cobalt (NMC), will reach the $100/kWh threshold[100], making BEBs a more cost-effective and attractive option for the future.

Observing the recent evolution of the driving range of light-duty EVs due to advancements in battery technology can serve as a valuable proxy for understanding the potential trajectory of battery electric buses. From 2011 to 2021, the average EV range grew from 86 miles to 217 miles (Figure 4).[101] Light-duty EVs and BEBs share a common reliance on battery technology for power storage, and improvements in this technology are likely to benefit both segments. As batteries become more energy-dense and cost-effective, the driving range of light-duty EVs has been expanding, and similar advancements could translate to battery electric buses, enabling them to cover longer distances on a single charge. Moreover, the adoption of better batteries in light-duty EVs often precedes their integration into larger vehicles like buses, making it a relevant precursor to gauge the future capabilities of electric buses in terms of range, efficiency, and overall performance.

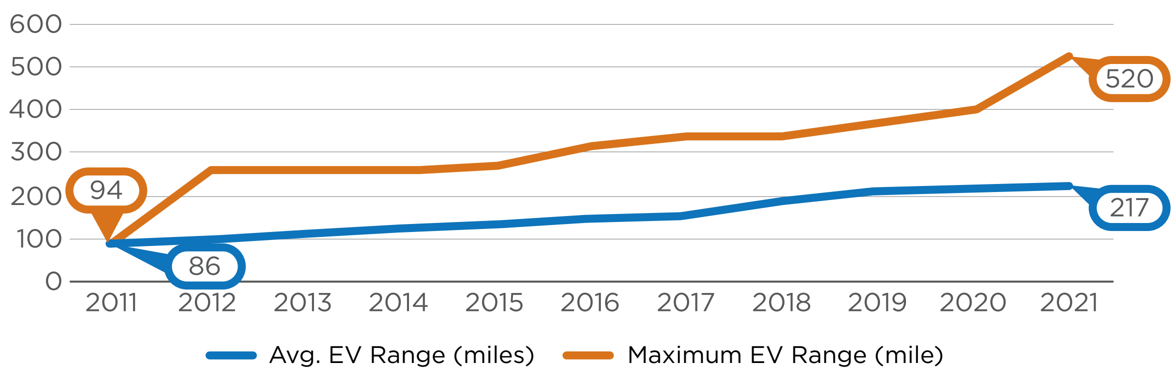


Figure 4. Evolution of Light-Duty Electric Vehicle range between 2011-2021.[102]

Renewable Natural Gas Technology

According to preliminary information from CAT's "Feasibility of Alternative-Fuel Buses Study": "(...) establishing a reliable and direct RNG source is likely to be challenging."[103] Addressing the quest for a dependable RNG source, it is noteworthy to point out that future RNG's full-scale deployment may only substitute around 3-7% of current natural gas consumption.[104] Even an otherwise favorable report by the World Resources Institute (WRI)[105] identifies three key barriers to RNG production: uncertainties tied to (i) feedstock availability, (ii) regulatory factors, (iii) market and operational risks, and (iv) project economics. Furthermore, the cost of RNG is reported to be 3 to 18 times higher than traditional natural gas – an aspect sometimes overlooked in presentations led by alternative fuel experts.[106, 107]

It should also be noted that establishing a reliable and efficient RNG source will be challenging, and a new fueling facility will have to be built.[108] Additionally, during cold weather seasons, when natural gas consumption is the highest, RNG necessitates higher energy consumption for its production.[109]

Since the scarce nature of RNG, C3 recommends that its allocation should be carefully assessed in conjunction with key local stakeholders, particularly municipally-owned natural gas utilities like Charlottesville Gas in the case of Charlottesville. This consideration gains even greater significance for municipalities with carbon-neutrality goals, as prioritizing the use of RNG to replace existing natural gas consumption may take precedence over considering the use of it for entirely new purposes.

Hydrogen Technology

According to a study developed in 2022,[110] the market generally recognizes that maintenance costs for hydrogen fuel cell vehicles are not well-established. Research outcomes so far varied significantly, with Ballard Power suggesting that adding $0.20 per mile to the maintenance costs of a battery electric bus is appropriate for hydrogen fuel cell buses, whereas UC Davis reports a 50% reduction in maintenance costs for hydrogen fuel cell vehicles compared to their diesel counterparts. Said study further elaborates on the obstacles facing hydrogen fuel, which encompass the pricing and accessibility of hydrogen fuel cell vehicles. Hydrogen fuel technology is still in its developmental stages and has limited adoption for municipal applications beyond California. In the case of Charlottesville, the nearest industrial hydrogen production facilities are situated more than 300 miles away.[111]

Bankruptcy Across Industries

Bankruptcies are not uncommon in several well-established and critical United States industries, including car manufacturing, aviation (airlines), and oil and gas. Iconic companies like General Motors and Chrysler famously filed for bankruptcy during the late aughts financial crisis.[112, 113] In fact, car manufacturing often grapples with economic cycles and shifting consumer preferences, leading to challenges faced by even industry giants.

The latest automotive bankruptcy to take over headlines has been the Proterra Inc. bankruptcy in August of 2023. Proterra, the largest BEB manufacturer in the U.S., filed for Chapter 11 bankruptcy[114], a process used to re-organize a business that is able to continue operating while paying creditors back. It does not mean that its production of new or that its maintenance of existing products will cease. Proterra intends to continue its operations.

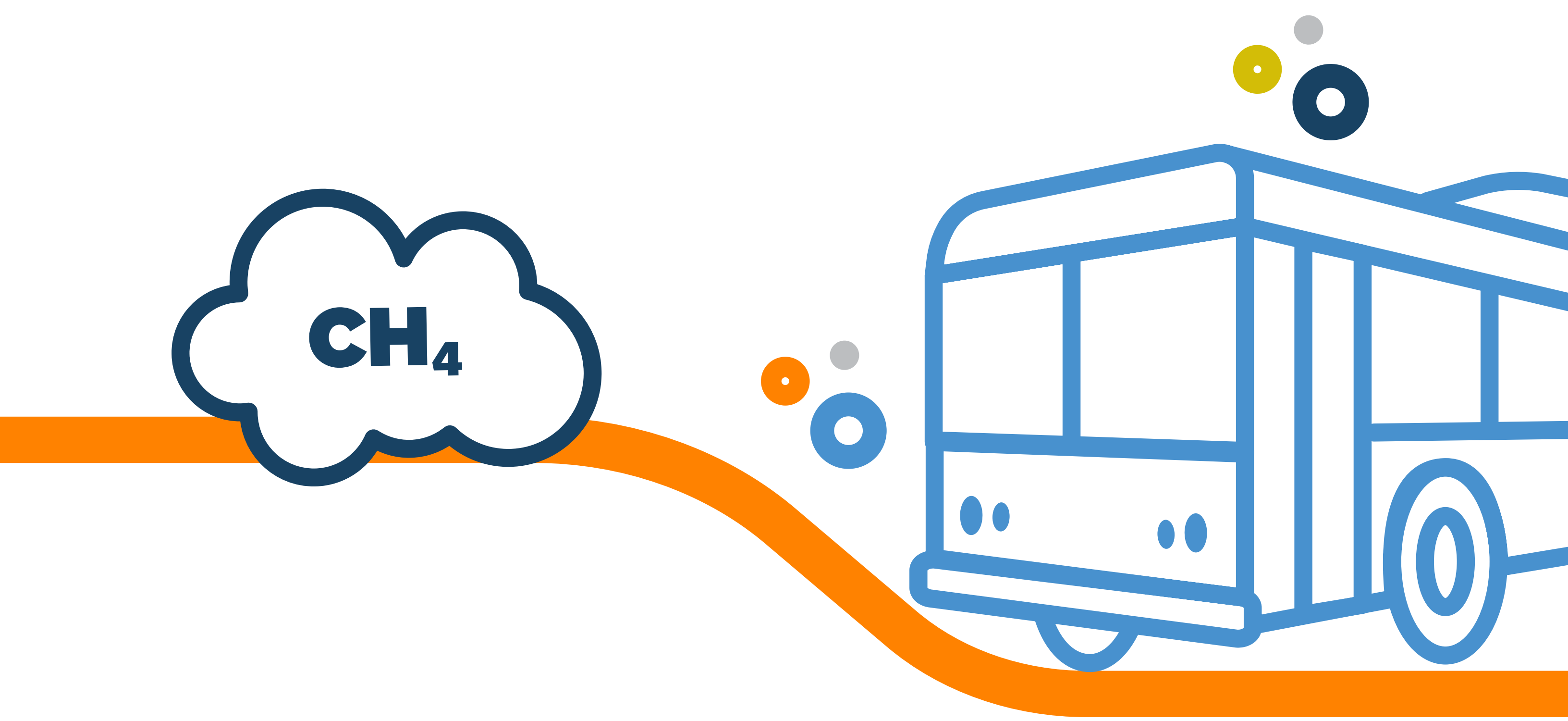
Air Pollution Inherently to Buses, Not Their Fuel Type

Reducing bus pollution plays a pivotal role in promoting transportation equity by minimizing pollution exposure for both riders and community members residing along bus routes. This focus on equity is essential as it directly addresses the disparities in health and environmental quality that often burden underserved populations. The EPA identifies several “criteria pollutants” for which it has established pollution regulations, including ground-level ozone, carbon monoxide, SOx, NOx, and PM, many of which are found in gasoline and diesel vehicle exhaust.[115]

Particulate matter, or PM, is of particular concern due to its adverse health effects. The two primary categories of PM are PM2.5 and PM10, distinguished by their particle size. PM2.5 particles have a diameter of 2.5 micrometers or smaller, while PM10 particles are larger, with a diameter of 10 micrometers or smaller. Because of their smaller size, PM2.5 particles are more harmful as they can penetrate deep into the respiratory system, leading to various health issues, including respiratory and cardiovascular problems.[116] On the other hand, PM10 particles, being larger, are generally less harmful because they can be filtered by the nose and upper respiratory tract.

At first glance, experts' assessment that BEBs have relatively similar air pollution as other fuel sources might appear surprising,[116] especially considering that BEBs produce no tailpipe emissions.[117] However, increasingly, non-tailpipe emissions are being recognized as a source of vehicle pollution, specifically tires. Sometimes where the rubber meets the road, it stays there. Larger chunks of rubber and smaller, particulate matter largely wash off the road without respiratory consequences.

According to the AFLEET Tool data on PM2.5 emissions from tire and brake wear, only 3% of vehicle PM2.5 emissions are the result of tire and brake wear for CNG and diesel buses with no significant difference between the two technologies. Assuming that similar levels of TBW would be associated with the use of BEBs or FCEBs, it can be expected that eliminating tailpipe pollution would still considerably reduce PM pollution from current diesel buses.[119] This distinction is crucial, as it underscores the importance of prioritizing ZEBs to safeguard the health of both passengers and the communities living closest to bus routes, ultimately contributing to transportation equity.



4. A Holistic Comparison of All Three Alternative Fuel Technologies

This section offers a comprehensive and holistic analysis of alternative fuel options for transit fleets, considering factors such as costs, environmental impact, community health, safety, and market trends. It evaluates CNG buses, BEBs, and FCEBs across these categories. The analysis reveals that CNG buses have the lowest ratings due to their negative impacts on climate, health, and market relevance. Zero-emission buses (BEBs and FCEBs) are strong contenders, with BEBs emerging as the preferred choice. This analysis recommends BEBs as the ideal choice for transitioning to cleaner transit fuels, with the following section delving into their feasibility further.

- BEBs performed the best out of the three technologies studied, and they scored “moderate” or “good” in every category.
- FCEBs scored well overall but fell behind BEBs in terms of operating costs, short-term GHG reductions, and market/technology trends.
- CNG buses scored the lowest, largely due to their negative health and environmental impacts, and were recommended to not be a future transit option.

Transportation is a intersectional issue. Determining the best path forward for a transit fleet requires analysis of not only the performance of the technology, but also its impact on the local environment, community health, and flow-on impacts. To understand how each technology compares across this spread of topics, we created the scoring card below that considers three major topics and categories within those larger topics. For each category, the technologies can be rated with symbols to indicate what is “good,” “moderate,” or “bad” based on the information provided in sections 2 and 3 (above). The green checks represent the best rating (or “good”), the yellow dash indicates an average rate (or “moderate”), and the red “x” is the lowest rating (or “bad”).

	BEB	CNG	FCEB
Expenditures and Technological Capabilities			
Service Reliability	⊖	✓	✓
Infrastructure (Facility + Vehicles)	⊖	✓	⊖
Operating Costs	✓	✓	⊗
Air Pollution, Greenhouse Gas Emissions, And Other Considerations			
Community Health and Air Pollution	✓	⊗	✓
Reduced Greenhouse Gases (GHG) Emission 2030	✓	⊗	⊖
Reduced Greenhouse Gases (GHG) Emission 2050	✓	⊖	✓
Safety Risks:	⊖	⊖	⊖
Flow-on Impacts	⊖	⊗	⊖
Market and Technology Trends	✓	⊗	⊖

Table 6. Holistic assessment of the three technologies studied based on leading factors.

Expenditures and Technology Capabilities

The first aspect we considered was "Expenditures and Technological Capabilities" (as detailed in section 2). Within this category, we focused on "service reliability," a critical factor for community members who depend on transit systems for daily needs like work, appointments, and grocery shopping. Ensuring reliability is fundamental to its role in our lives. FCEBs and CNG buses are expected to offer service reliability similar to the current diesel fleet. However, the service reliability of BEBs depends on their implementation. Experts suggest that, without on-route fast charging, BEBs may be limited to specific routes or peak transit hours. On-route charging resolves this issue, but due to mixed results, we rated BEBs as moderate in this regard.

Air Pollution, Greenhouse Gas Emissions, and Other Considerations

Next, we delved into the "Infrastructure (Facility + Vehicles)" category, emphasizing cost considerations. Among the options, CNG buses emerge as the most cost-effective, earning a good rating. Meanwhile, BEBs exhibit variable facility costs depending on specific scenarios, potentially falling higher or lower than those for FCEBs. However, in terms of unit costs, BEBs prove to be more economical. Once we factor in the weight reduction and the availability of substantial Federal funding, both FCEBs and BEBs are deemed moderate in cost-effectiveness.

An additional cost consideration was "Operating Costs." Both BEBs and CNG buses boast low operating expenses, with electricity and natural gas being cost-effective fuel sources. In contrast, the cost of hydrogen stands significantly higher when averaged per mile compared to the other alternatives.

The second topic of the analysis was "Air Pollution, Greenhouse Gas Emissions, And Other Considerations" (as explored in section 2). Within this category, "Community Health and Air Pollution" was studied. Addressing the uneven distribution of pollution in our communities underscores the importance of pursuing a zero-emissions future as a matter of social justice. Local governments bear the responsibility of mitigating past social and environmental inequalities by transitioning away from fossil-fuel-based vehicles, especially those used for public transport. Both BEBs and FCEBs, producing zero tailpipe emissions, merited a "good" rating in this category. In stark contrast, CNG buses, notorious for their significantly higher pollution levels, particularly carbon monoxide emissions, were assigned the lowest ranking in the Community Health and Air Pollution category.

The share of BEBs has been growing and the share of CNG buses has been shrinking.

Additionally, "Climate Goals and Reduced Greenhouse Gases (GHG) Emissions" contributed to the analysis. Numerous U.S. cities, including Charlottesville, have set ambitious climate change targets. Achieving these targets requires comprehensive GHG reduction strategies across all city operations. When considering transit vehicles, the potential for emissions reduction lies at the city level. To account for evolving technological advancements, we divided this category into two ratings: 2030 and 2050.

First, let's examine the 2030 perspective: BEBs, operating on increasingly clean electricity, already exhibit a significantly smaller carbon footprint than traditional gas-powered cars, a trend anticipated to continue throughout the decade. In contrast, CNG vehicles, primarily powered by methane, contribute to a substantial carbon footprint during production and release carbon dioxide, a major climate change contributor, upon combustion. FCEBs rely on hydrogen, often produced using fossil fuels on a national scale. While local hydrogen production could reduce associated GHG emissions, the increased strain on the electrical grid compared to BEBs led to a "moderate" rating for FCEBs in this context.

Market and Technology Trends

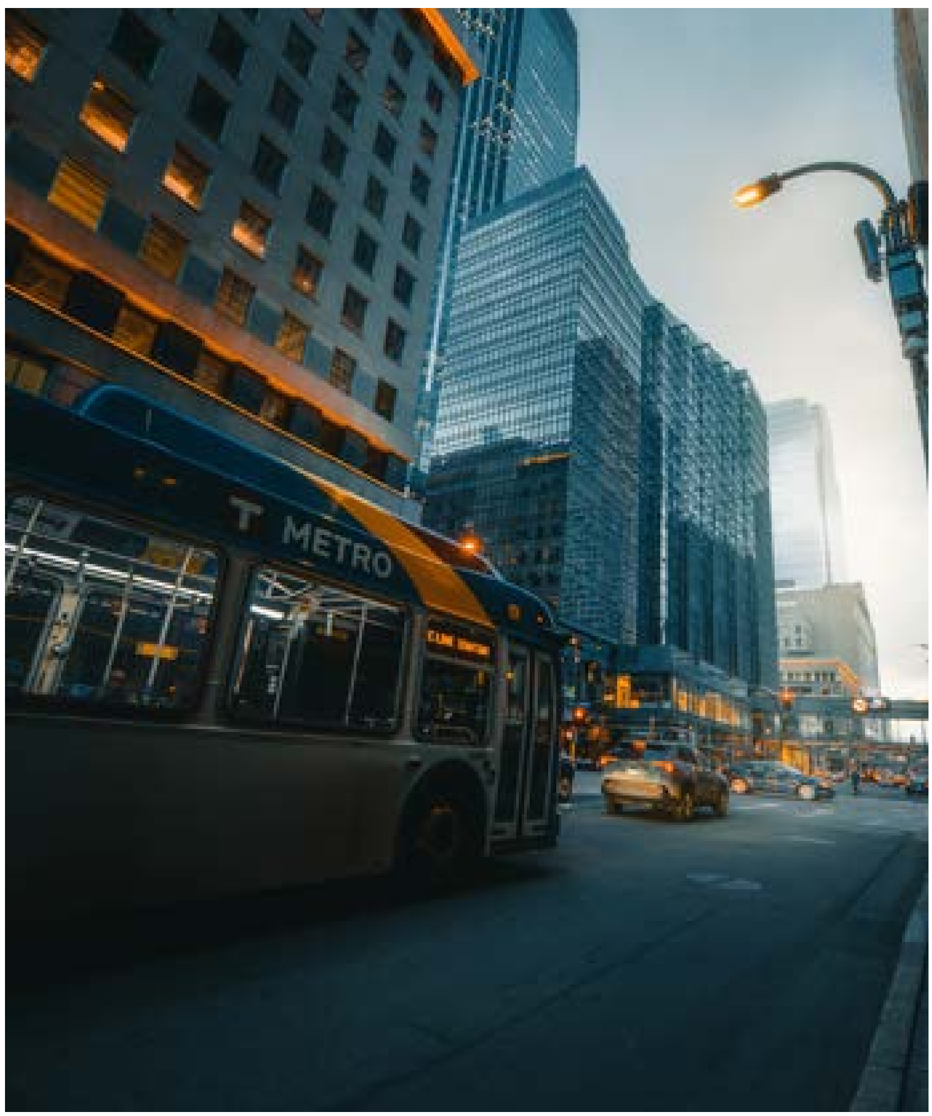
Now, let's shift our focus to 2050: By this time, BEBs are expected to further enhance their environmental credentials, while CNG buses might harness RNG, potentially reducing GHG emissions. Hydrogen fuel is also anticipated to derive from increasingly clean energy sources. Given these evolving scenarios, both CNG buses and FCEBs receive better ratings in the 2050 projection.

The final aspects under consideration encompassed "Safety Risks" and "Flow-On Impacts." Safety is paramount in ensuring the quality of

ZEBs, which have no tailpipe emissions, exhibit strong performance and warrant serious consideration as the leading choice.

transit services, and all three technologies explored exhibited minor safety concerns comparable to those associated with conventional diesel. These concerns were rated as “moderate.” Turning to flow-on impacts, CNG buses stood out as having the most substantial adverse effects. The upstream climate consequences stemming from methane leaks during drilling, coupled with air and water pollution throughout the transmission system and the associated environmental injustices, led to the lowest possible rating for CNG buses in terms of flow-on impacts. In contrast, both BEBs and FCEBs received “moderate” ratings due to up- and downstream impacts associated with lithium mining and waste, albeit with the potential for mitigation as battery recycling practices improve. Notably, while FCEBs feature smaller batteries than BEBs, the use of hydrogen raises energy consumption concerns, contributing to a lower FCEB rating.

The third and final focus was on “Market and Technology Trends” (as explored in section 3). The landscape of alternative fuel buses has undergone significant changes in recent years, and past market trends offer valuable insights into ongoing technological advancements and



their appeal to customers and investors. This evaluation blends market trends with technological developments to assess each technology. Both BEBs and FCEBs have seen market share expansion, although the limited number of FCEBs and the nascent nature of the technology results in a "moderate" rating. In contrast, CNG buses, which have witnessed a decline in market share, are rated poorly.

Based on the research presented in sections 2 and 3, and summarized in the table above, it is evident that CNG buses are the least favorable option. In half of the evaluated categories, CNG buses received unfavorable ratings. Their adverse effects on global climate, local health, and dwindling market relevance render them unsuitable for the future of transit. Conversely, ZEBs, which have no tailpipe emissions, exhibit strong performance and warrant serious consideration as the leading choice. Among ZEBs, BEBs stand out as the optimal selection for the fleet's transition to cleaner fuel. BEBs earned the highest number of positive ratings (five out of eight) and had no unfavorable ratings. In our analysis, FCEBs performed similarly to BEBs in terms of reliability but lagged in 2030 GHG emissions and market trends. Additionally, FCEBs incurred notably higher costs. Considering the findings in this report, which draw from existing literature and data, BEBs emerge as the preferred choice. The subsequent section of this report delves into the feasibility of implementing BEBs, incorporating real-world experiences from transit operators across the nation.

5. The Expert Perspective: Battery Electric Buses in Leading Transit Systems

After understanding that BEBs seemed to be the most promising alternative fuel technology, we decided to delve into the technical and logistical aspects of implementing BEBs. The findings summarized in this section draw from a series of interviews and surveys conducted by C3 with nine transit agency/authority leaders across the United States, whose collective expertise governs ~12% of the operational BEBs in the nation, as of 2021.[120] All transit agencies (agency and authority are used interchangeably in this report) in the US operating cities of 500,000 people or fewer, with at least 10% of their fleet electric, and who have been operating electric buses for at least four years were contacted for the opportunity to be a part of this study. In total, 22 agencies were contacted, representing 33% of all BEBs in operation. The responses from agency responses are included here. In the first stage of the research, we engaged with nine transit agencies to answer six questions each (Phase I). With this enhanced understanding of BEB implementation, we followed up with all nine transit agencies with a second set of questions (Phase II). Any agencies that are represented in Phase I but not Phase It is simply the result of who responded in advance of this report's publication. This original research helps uncover valuable insights into the challenges and opportunities associated with the electrification of public transit fleets.

- There is a high level of satisfaction with BEB fleets.
- Despite some challenges, operators seemed generally satisfied with the reliability and cost of BEBs.
- Agencies seemed to believe that the challenges were worth BEB's environmental and ride quality advantages. Additional benefits include community morale being high during the launch of the all-electric buses, something that operators consider would not have happened during the launch of diesel buses.
- Agencies observed satisfactory feedback regarding the buses being extremely quiet and clean, reducing complaints of them circulating through more residential areas.

Background

Of the transit agencies engaged by C3, the earliest adopter, introduced their first BEB over 30 years ago[121], and the most recent adopter introduced BEBs in 2019 (Table 7). The share of BEBs in their fleets ranged from 11% of the total fleet to 70% and the two most common BEB manufacturers for the transit agencies that we engaged with were Build Your Dreams, Inc. and Proterra Inc. (Figure 5). Two transit agencies mentioned Gillig LLC favorably, although they were not specifically asked about specific manufacturers, and according to the most recent data available, only one of the agencies we engaged with operates a Gillig bus.

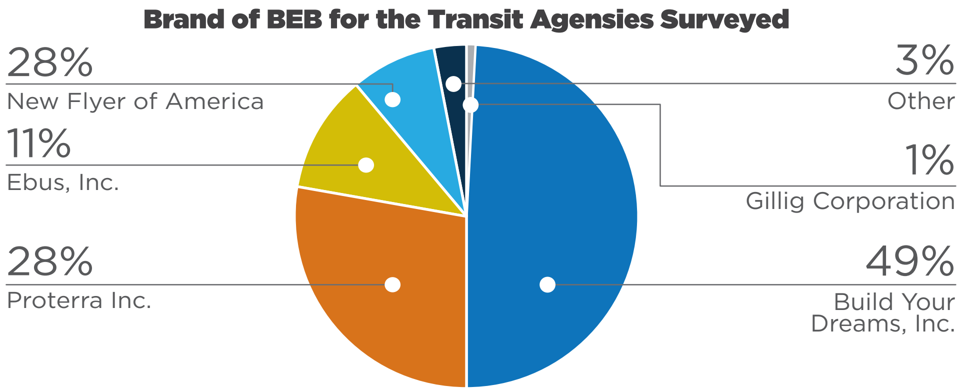


Figure 5. The graph above shows how many buses of each manufacturer are used by the transit agencies that C3 engaged with.

The cities surveyed have comparable, or smaller, populations and surface areas to Richmond, Virginia, but they are larger than Charlottesville. Charlottesville, however, operates a comparable number of buses to several of the cities surveyed. According to C3's VA Transit Tool[122], elaborated together with the Center for Neighborhood Technology (CNT), the population served by the Charlottesville Area Transit is 78,722 and the population served by the Greater Richmond Transit Company is 358,873.[123] Population and areas of the metro areas were not included in the table.

Agencies were usually funded with "Urbanized Area Formula Grants - 5307"[124] or "Low or No Emission Vehicle Program - 5339(c)"[125] (with the battery warranty not being a part of the grants).

	Chattanooga Area Regional Transp. Authority	Missoula Urban Transp. District	City of Everett	Greenville Transit Authority	City of Ashville	City of Lincoln	City of Rock Hill	Frederick County, MD	Antelope Valley Transit Authority
Year Implemented	1988	2019	2018	2019	2019	2019	2019	2016	2014[126]
Total Fleet Size	110	43	69	35	31	94	10	48	110
Total BEBs	17	6	9	4	5	10	7	9	62
Share of B EBs in Fleet	23%	14%	13%	11%	16%	11%	70%	19%	56%
Population of City	182,113	74,822	110,812	72,095	94,067	292,657	74,102	279,835	173,516
City Size (mi^2)	143.2	34.9	47.9	30.0	45.9	100.4	43.9	667.0	94.5
Population Density per mi^2	1272	2144	2313	2402	2051	2915	1690	420	1845
Residents per bus	1656	1740	1606	2060	3034	3113	7410	5830	1577

Table 7. Background information on transit agencies surveyed by C3 in 2023 and 2021 data from the FTC.

C3's Survey: Phase 1

C3 contacted the 22 agencies that had the biggest share of their fleet being BEBs, among transit agencies in the United States, as listed by the FTC as of 2021. The information below represents the information collected through engagements with the eight agencies who responded. Responses were collected by phone, email, or video call.

"Our newest electric buses are proving to be just as reliable, if not more, than the diesel buses"

- SURVEYED BEBS OPERATOR

C3 asked transit agency operators to rate their experiences with the reliability and the cost of BEBs. Almost all transit operators felt like BEBs were reliable (Table 8). One agency was categorical in stating that while it used to take two BEBs for every diesel bus (even as soon as five years ago), the replacement ratio is now much closer to one-to-one. Another agency added that due to their early adoption, their "first generation" of BEBs (acquired in 2016) are among the most unreliable buses in their fleet, however, they stated that due to the rapid advancement of the technology, their newest BEBs (manufactured by BYD in 2019-2020) "are proving to be just as reliable, if not more, than the diesel buses". Another operator also remarked that while reliability was a challenge in the beginning, they are now prepared for issues that arise and rate their reliability as a 4. Conversely, one operator said that [when getting a BEB] "you don't get a [full] bus, but rather 60-70% of a bus," while only one transit operator felt like the buses were extremely unreliable. The survey results support experts' analysis that weather and terrain most impact how far a bus can travel on one charge. According to survey respondents, the weather had the most consistent and largest negative impact on the range, and driver style was another important factor contributing to the range. They suggested that it is possible that BEBs' driving style could be improved with training to increase BEBs' range.

"The public was very excited at the all-electric aspect of our fleet"

- SURVEYED BEBS OPERATOR

Almost all the operators interviewed felt that maintenance costs were similar to a diesel bus or only slightly more expensive (Table 8). When it comes to capital expenditures, one operator mentioned that because of existing federal grants, they were able to save "up to 85% of the cost. Most agencies shared the experience that, in terms of time, the maintenance on the BEBs takes much longer than with diesel buses because of proprietary information kept by the bus companies. That's mainly due to the proprietary nature of electric bus propulsion parts and the rapid obsolescence of the related parts. The increased maintenance times seemed to bother one transit operator significantly but seemed to not be a major concern to other operators.

	Chattanooga, TN	Missoula, MT	Everett, WA	Greenville, SC	Ashville, NC	Lincoln, NE	Rockhill, SC	Frederick County, MD	Lancaster, CA
Reliability	4.5	4, 2	3.5	4[127]	1	2	n/a or 5	1 (early) 4 (current)	4
Cost/ Affordability	3	2	~3[128]	3	1	2	n/a	1 (early) 3 (current)	4

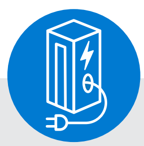
Table 8. C3 survey results about the reliability and cost of BEBs for transit agencies (Both scales compare the performance of BEBs to those of diesel buses, assuming that "3" would be equal to a diesel bus. For reliability, the scale goes from 1 to 5, with 1 being extremely unreliable and 5 being extremely reliable. For costs, the scale goes from 1 to 5, with 1 being much more costly and 5 being much more affordable.)

As noted in a previous section, battery warranties vary by manufacturer and plan. Among all respondents who purchased buses since 2019, only one had to fully replace the battery of a bus. There was another respondent who noted that because each battery is made up of several different cells, there have been roughly 6 instances, across five buses in the last 10 years, when one or more cells within a bus's battery have failed. When this happens, the specific cells affected are replaced. To reduce concerns related to battery reliability, some agencies purchased an extended battery warranty at the time of the original purchase of vehicles for $75,000 per bus that will cover the full replacement of batteries for the Federal Transit Administration (FTA)'s expected service period of the buses. According to one agency, replacing a full battery pack today costs approximately $150,000, even though it stated that most manufacturers will warrant the battery packs through the FTA useful life of the bus.

C3's Survey: Phase 2

Incorporating BEBs into a transit system invites creativity and innovation. That was evidenced by the transit agencies who responded to the second phase of our survey, who created custom approaches for successful implementation in their localities.

Scheduling:
Of the agencies that did not use on-route charging, 40% used their BEBs to supplement existing routes during peak transit times. One agency specified that they use the BEBs for six hours in the morning and six in the evening then allow the buses to charge during times of lower activity.



On-Route Charging:
One of the five agencies who responded to the Phase II questions uses on-route fast charging. The on-route charging allows this agency to use the BEBs on all routes (the longest of which is 290 miles) and stay out all day. The bus schedule incorporates fast charging throughout the day.

Routing:
Most agencies (60% of respondents) used their BEBs only on specific routes. Route constraints were due to either range limitations (one agency commented that they typically get around 120 miles per charge, so that influences which routes the BEBs run) or due to the size of city streets not being conducive to large buses.

Our discussions with transit agencies during Phase II of the survey gave us further insights into BEB implementation. Many agencies employ BEBs during peak hours, tapping into their ability to provide extra capacity during morning and evening rush times. By deploying these electric buses during high-demand times and charging them during downtime, agencies can effectively optimize their resources and reduce emissions, all while maintaining reliability. As one transit official noted, "Our newest electric buses are proving to be just as reliable, if not more, than the diesel buses," dispelling concerns about the dependability of BEBs.

"Our buses are extremely quiet, so people don't mind them coming through more residential areas."

\- SURVEYED BEBS OPERATOR

Of the agencies who responded to Phase II, 60% customized BEB schedules to accommodate these vehicles' charging requirements. This should not be seen as a limitation, but rather an opportunity for innovation. The adaptability of BEBs offers the chance to reimagine transit strategies, schedules, and fleet management to align better with

290

"We have two BEBs that stay out all day through on-route charging and run about 290 miles each."

- SURVEYED BEBS OPERATOR

people's daily lives. It's an exciting prospect that opens the door to greater efficiency, creative solutions, improved environmental health, and, ultimately, attracting more passengers to public transit. "During the initial launch, the public was very excited at the all-electric aspect of our fleet," remarked one transit operator. "This would have been absent if we had diesel vehicles." Even residents who might not use the transit system can benefit from the transition to BEBs because of the reduction in air and noise pollution. Another operator commented, "Our buses are extremely quiet, so people don't mind them coming through more residential areas."

Not all agencies needed to adapt their routes or schedules to accommodate BEBs. In fact, two of the five agencies we talked to for Phase II were able to run their BEBs on all routes –both with and without on-route charging. As one example demonstrates, "We have two BEBs that stay out all day through on-route charging and run about 290 miles each," showcasing the feasibility of integrating BEBs into daily operations. With strategic deployment during peak hours, creative adaptation for route coverage, and utilizing on-route charging, agencies have the opportunity to design transit systems that serve community needs while maintaining necessary reliability and frequency.

The path ahead promises not only greater efficiency but also a chance to craft transit solutions that truly align with the needs and rhythms of people's lives, ultimately leading to healthier, more accessible, and more appealing public transportation systems. Across the nine agencies surveyed in Phase I, transit agencies seemed pleased with the reliability, cost, and overall experience of their BEB fleets. To quote one transit operator, "[The BEBs have] no harmful emissions coming from the unit, better ride quality, and noise pollution [is] minimal."

6. Conclusion

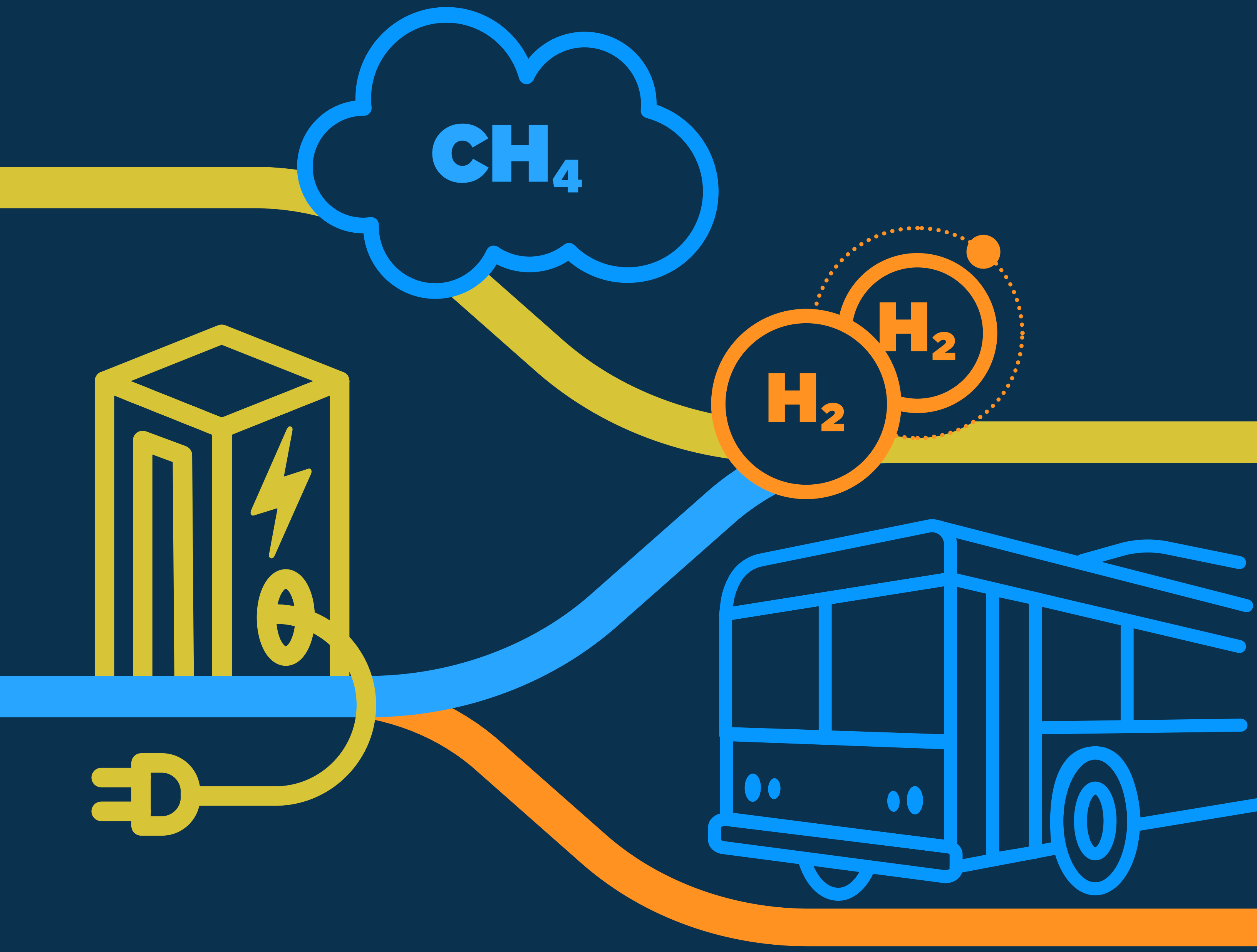
This report underscores the significance of adopting Zero-Emission Buses as a transformative and sustainable solution for Charlottesville and other municipalities throughout Virginia and the United States. Our comprehensive analysis, which amalgamates insights from Kimley-Horn Consultants, additional findings from peer-reviewed and gray literature, and original research through a transit survey, unequivocally positions Battery Electric Buses as the preeminent choice among the three alternative fuel technologies considered.

Acknowledging the absence of flawless technology, it is compelling to note that Battery Electric Buses have excelled in a multitude of categories when compared to Compressed Natural Gas buses and Fuel Cell Electric Buses. This distinct performance elevates Battery Electric Buses as the logical preference for a forward-looking, environmentally-conscious transit system. These buses elevate the overall service quality, while being capable of offering frequency and reliability on par with traditional buses. Furthermore, they have the capacity to instill excitement and satisfaction in public transit, as demonstrated by other leading transit agencies across the nation. As such, the transition to Battery Electric Buses opens doors to increased ridership, granting access to economic opportunities and diverse destinations.

It is paramount to recognize that a robust, eco-friendly transit system serves as the lifeblood of any community. Buses transcend mere transportation; they become community hubs, uniting people from diverse backgrounds in shared spaces for living, working, and recreation. A thriving transit system not only enhances convenience but also plays a pivotal role in reducing pollution within communities. Battery Electric Buses present a promising solution to maintain communal spaces free from pollution, thereby elevating the quality of life for all residents. Moreover, the adoption of these buses propels communities towards their climate goals, as an efficient transit system reduces carbon emissions citywide by replacing private vehicles with zero-emission alternatives.

The insights gleaned from interviews with transit agency leaders, who have successfully integrated Battery Electric Buses into their fleets, validate the positive trajectory of this technology. The high satisfaction levels among these operators underscore the reliability and potential of these clean buses as a formidable alternative fuel source. Communities have experienced a surge in morale during the transition to all-electric buses, an occurrence unlikely with diesel buses. Residents appreciate the quiet and clean operation of Battery Electric Buses, resulting in fewer complaints, particularly in residential areas, and potentially facilitating route expansion. Innovative charging strategies, including on-route charging, ensure the seamless and efficient operation of these zero-emission buses.

In conclusion, the decision to embrace Battery Electric Buses emerges as a clear and compelling choice for the development of a sustainable and just transit system in Charlottesville and other municipalities around the country. By designating Battery Electric Buses as a cornerstone of their future transit strategy, these communities are poised to enhance the quality of life for their residents, diminish their carbon footprint, and nurture a cleaner and healthier community. The road ahead is not only transformative but also inspiring, as we embark on this journey towards a brighter and more sustainable transit future.



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127 This transit agent said that reliability was "pretty high," which we later ascribed a 4 to.

128 This transit agent said that costs were "roughly the same," which we later ascribed a 3 to.

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