35th International Electric Vehicle Symposium and Exhibition (EVS35)
Oslo, Norway, June 11-15, 2022

Get Fired-Up with Fuel-Fired Heaters in Battery Electric Transit Buses

Katrina Sutton[1,2], Kristian Jokinen[2], Fred Silver[2]

[1]*Corresponding Author, ksutton@calstart.org*

[2]*CALSTART, 48 S Chester Ave, Pasadena, CA, 91106, USA*

Summary

Transit agencies may opt to install diesel fuel-fired heaters (FFHs) in zero-emission buses to maximize passenger comfort and bus performance in cold weather. FFHs produce emissions, which reduce environmental and health benefits of electrification. This paper reviews the current state of FFH regulations and standards, concluding comparability across regulating bodies is a crucial step to reducing FFH emissions. This paper discusses results from a study of FFH energy consumption in an eight transit bus fleet operating in cold climates, finding that sometimes, the total energy required to heat buses was two to three times that used by the traction motor.

Keywords: bus, heating, auxiliary units, public transport, research

1 Introduction & Background

As of September 2021, there are 3,533 full-sized transit battery electric buses (BEBs) in the United States [1]. An increasing number of states and transit agencies are making a commitment to zero-emission buses (ZEBs) across the country. Cold climate regions, such as the Midwest or Northeast, that adopt BEBs may experience significant range limitations in cold weather due to the energy needed to keep the cabin heated throughout the day.

Fuel-fired heaters (FFHs) are traditionally used to provide engine preheat, supplemental heating for passenger comfort in buses, and heating for a Class 8 truck's sleeper cab (e.g., to keep a driver warm while resting). These burners have a combustion chamber that transfers heat to the coolant loop, or alternatively function as direct air heaters depending on the application. Figure 1 illustrates a coolant heater that supplies heat in a water-to-air configuration (i.e., water circuit with a glycol mixture is connected to heat exchangers). In California, the California Air Resources Board (CARB) defines an FFH as "a fuel burning device that creates heat for the purpose of warming the passenger compartment of a vehicle but does not contribute to the propulsion of the vehicle."

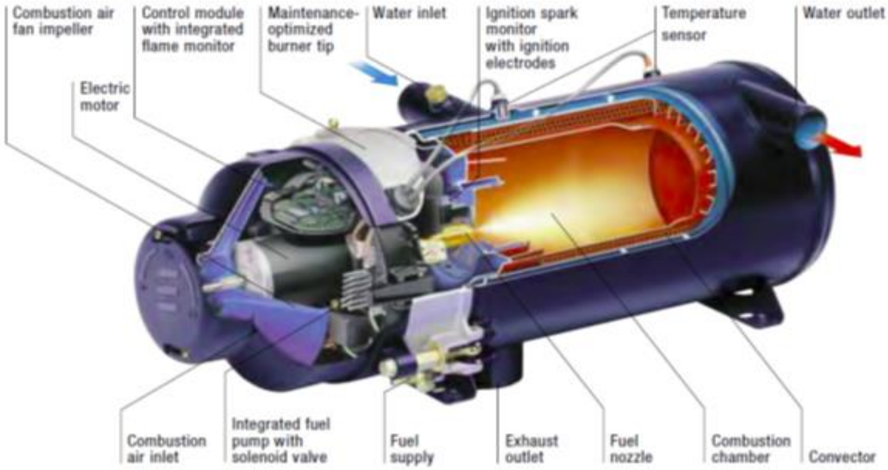

Figure 1: Hydronic L-II Coolant Heater. Image Credit: Eberspaecher North America

Using an FFH in a Class 8 truck mitigates the necessity of idling the main engine for heat. FFHs are generally diesel-powered but use only about one-twentieth of the amount of fuel compared to idling the main diesel truck engine, thus reducing diesel emissions and saving fuel [2]. In California, Class 8 berth trucks are not allowed to run an FFH unless the ambient temperature is 40 degrees Fahrenheit (4.4 degrees Celsius) or below. California's Advanced Clean Truck rule, which requires all new truck sales to be zero-emission starting in 2045, will allow the installation of FFHs in vehicles if they comply with the current FFH emissions regulations [3]. The U.S. Environmental Protection Agency (EPA) does not have specific runtime requirements; however, the EPA does classify FFHs as non-road engines and has a voluntary verification process to assure FFHs use less fuel compared to idling the main diesel engine [4].

BEB manufacturers have caught on to the benefits of installing FFHs to improve vehicle range. One company, Valeo, states on their website that they have installed over 450,000 FFHs into buses after more than 40 years in business [5]. FFHs are a proven product for Class 8 trucks and diesel and compressed natural gas (CNG) buses that may need supplemental heating or engine preheating. Due to increased efficiencies in diesel engines, many diesel buses in cold weather locations are also outfitted with FFHs as there is less waste heat from the engine to repurpose for cabin heating. Cold weather operation can be incredibly detrimental for a BEB due to the limited battery capacity and heating energy requirements. Additionally, transit buses have relatively poor insulation and are prone to lose heat quickly due to frequent stops for on- and off-boarding passengers. To help combat this, a 30 kW (on average) diesel heater is available as an add-on when purchasing a BEB. Having an FFH installed reduces the energy demand for heating required of the traction battery, but the main issue with this solution is the inevitable diesel emissions.

Per California's Innovative Clean Transit (ICT) regulation, buses with FFHs do not qualify as ZEBs. Sixteen states and the District of Colombia are following California's leadership by signing an agreement to sell only ZEBs by 2050 [6], [7]. The states adopting similar ICT regulations may have to allow FFHs in their ZEBs to meet transit agency range demands due to cold climates and harsh winters. Without CARB or other federal guidance, these states could have difficulties setting an appropriate emission limit and test procedure for existing FFH solutions.

To assist in the transition to zero-emission vehicles, California has created the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) to reduce the cost of innovative clean trucks and buses. Transit agencies can receive funding for ZEBs through HVIP, but fleets cannot receive funding for a bus from this program if the bus has an FFH installed [8]. On the other hand, the similar New York Truck Voucher Incentive Program (NYTVIP) allows FFH buses with a caveat: NYTVIP funding cannot be used to purchase or install an FFH, but the funds can be used to purchase a bus with a pre-installed FFH [9]. The EPA's two programs that include approximately $17 million in funding for electric school buses (Diesel Emissions Reduction Act and

2021 American Rescue Plan Electric School Bus Rebates) do not mention FFHs in the vehicle requirements; the omission of FFHs in the guidelines can be interpreted to mean FFHs are allowed in vehicles purchased with funds from these programs [10],[11],[12]. With funding from the Infrastructure Investment and Jobs Act (IIJA), the EPA will provide $5 billion over five years to replace existing school buses with clean and zero-emission vehicles; the program information is forthcoming, and there is currently no information on whether vehicles with FFHs can qualify for funding through IIJA [13], [14].

Presently, CARB's FFH emission regulations do not apply to ZEBs; ZEBs cannot have FFHs installed to qualify under the ICT regulation. Since CARB's ICT regulation is being adopted by other states operating transit buses in colder climates, CARB could consider changing this regulation to allow FFHs under specific and harsh cold climate conditions. Just as new zero-emission heating solutions should be developed, more research should also be conducted to understand the annual or seasonal FFH emissions and emissions variations per route and driver preferences. This research would not only help California accurately account for their transportation emissions but may also help other states make an informed decision about FFHs and ZEB deployments.

The following section of this paper provides context around FFH usage, the relationship between FFH manufacturers and bus original equipment manufacturers (OEMs). Section 3 then evaluates the current policy landscape and emissions standards from California, the United States, and the European Union. Finally, Section 4 illustrates specific transit agency examples and highlights future research, technology, and policy recommendations.

2 Emissions Data and Analysis

To understand how ambient temperature and weather conditions impact FFH emissions, real-world vehicle data should be collected and analyzed. Looking at how transit agencies operate and use their bus fleet can lead to informed policy decisions. Quantifying FFH emissions can help regulatory agencies understand how these emissions are impacting climate goals.

The EPA classifies an FFH as an idle reduction technology. The goal of the EPA's SmartWay program is to reduce fuel use when idling a main engine [4]. The SmartWay program verifies that the emissions of the idle reduction technology are less than idling the diesel engine and confirms the technology can operate properly as needed. The program's list currently includes FFHs for school buses only, not transit buses.

Fuel consumption data for FFHs are readily available and listed on manufacturers' respective factsheets (

Table *1*). On average, a 30 kW FFH can consume around one gallon of diesel per hour. The total consumption is heavily dependent on ambient temperature, heat losses, and temperature setpoints for the heater. Furthermore, the direct emissions associated with the heaters are dependent on usage. The transit agencies listed rely on FFHs to offboard the heating demand to complete routes and maintain passenger comfort. Without the FFH, the vehicles may otherwise be unable to complete a route in the winter months and thus do not represent a feasible option for the transit agency.

Table 1: Example of FFH Manufacturers

FFH Heater Manufacturer	Valeo	Proheat	Eberspaecher
Bus OEM(s)	BYD, New Flyer; Nova Bus	New Flyer	Proterra
Model(s)	Spheros Thermo (230/300/350)	Proheat X30	Hydronic L30
Example of Transit Agency Usage	• Link Transit – Washington State • Metro Transit – Minneapolis/St. Paul • Utah Transit Authority (UTA) – Salt Lake City (Electric buses)	Utah Transit Authority (UTA) – Salt Lake City (Diesel buses)	Chicago Transit Authority (CTA) – Chicago
Fuel Consumption	• Thermo 230: .79 g/h • Thermo 300: 1.05 g/h • Thermo 350: 1.18 g/h	0.1 – 0.31 gal/hr	0.96 gal/hr
Heat Output	• Thermo 230: 23 kW • Thermo 300: 30 kW • Thermo 350: 35 kW	2.9 – 9.1 kW	30 kW

3 Policy Landscape

California's ICT regulation requires transit agencies in the state to transition to a 100 percent ZEB fleet by 2040. The regulation includes a provision for granting exemptions for transit agencies with routes that a BEB cannot service due to daily mileage or gradeability needs [8]. CARB requires extensive supporting documentation such as monthly mileage reports, ZEB requests for procurement, topography information, conventional vehicle performance information, and energy use data (if available) for an exemption. Upon approval, the transit agency may purchase a fossil fuel-powered bus [15]. Because the ICT regulation requires large agencies to begin purchasing ZEBs in 2023 and therefore purchase requirements have not yet taken effect, it is unknown how many agencies will apply for and have their exemption approved. Currently, an auxiliary heating source such as a FFH will, in many cases, be needed for a BEB to complete its route in cold climates. On-route BEB charging can add additional range and partially mitigate the increase in energy needed to maintain cabin heat; the charging infrastructure and electricity demand charges, however, can be detrimentally expensive. Fuel cell electric buses can add additional hydrogen storage tanks to account for the increase in heating energy. It should be noted, though, that from a system approach, a ZEB with a FFH that operates during the cold weather months may still generate fewer emissions compared to an alternative fossil fuel-powered bus in operation year-round and may itself be equipped with a supplementary heater.

Another factor impacting the use of FFHs is the pull-up heater requirement for transit buses in cold conditions. The American Public Transit Association states that the transit bus heater must warm the bus up to 70 degrees Fahrenheit (21 degrees Celsius) from an ambient temperature of -20 degrees Fahrenheit (-29 degrees Celsius) within 70 minutes [16]. More heat than an electric heater can provide may be necessary to warm a bus within 70 minutes. A BEB could also deplete too much of its battery to warm the bus and render it unable to complete its prescribed duty cycle.

Due to California's climate, barring FFHs from ZEBs is not often detrimental, but transit agencies and bus manufacturers have noted cabin heating is a non-trivial issue that they should be aware of when purchasing and designing ZEBs. Transit agencies in the Midwest and Northeast are in colder climates and would benefit from offboarding their heating demand to help with passenger comfort and conserve the battery for the bus route. There have been some instances of the HVAC heater using more of the battery pack energy than the traction motor in cold conditions [17].

The EPA has yet to issue definitive FFH emissions regulations. This technology could be regulated by the EPA nonroad compression ignition engine standards or spark ignition standards [18], [19]. However, the heat output from an FFH comes from a combustion chamber that is connected to a heat exchanger and thus does not directly resemble the mechanics of a compression ignition engine; FFHs could also be treated as a small turbine or open flame device, but none of the EPA's standards completely encompass the FFH. Depending on the rated power output (kW), varying exhaust regulations exist (Table 2). Some of the exhaust standards have not been updated for more than 10 years. When an FFH is installed on a battery electric vehicle, the emissions are not accounted for in the vehicle's performance credits.

Table 2: EPA Nonroad Compression Ignition Engine Emission Standards

Rated Power	Model Year	NMHC + NOx (g/kW-hr)	PM (g/kW-hr)	CO (g/kW-hr)
kW < 8	2008+	7.5	0.40	8.0
8 ⩽ kW < 19	2008+	7.5	0.40	6.6
19 ⩽ kW < 37	2013+	4.7	0.03	5.5

CARB currently regulates FFHs under the Low Emissions Vehicle (LEV) II regulations (Table 3). CARB's 13 CCR 1956.8(a)(6)(D) regulates the emissions of FFHs to be installed and operated on all heavy-duty diesel-fuelled vehicles with a gross vehicle weight rating (GVWR) over 14,000 pounds and all diesel-fuelled commercial motor vehicles with a GVWR over 10,000 pounds. This regulation states "the fuel-fired heater must meet LEVII ULEV (ultra-low-emission vehicle) standards for passenger cars and light-duty trucks less than 8,500 pounds GVWR." Common vehicles that fall under this regulation are diesel-powered school buses, transit buses, and long-haul trucks. Notably, most FFHs are diesel powered, but there is no requirement for particulate matter (PM) testing. The regulation as written applies only to diesel-powered vehicles (i.e., FFHs installed on other alternatively powered vehicles are not regulated). All units in Table 3 below are grams per mile (g/mi).

Table 3: CARB FFH Emission Standards

(g/mi)	NOx	CO	Formaldehyde	Non-Methane Organic Gas
LEV II ULEV	0.050	1.70	0.0080	0.0400

CALSTART received FFH emissions data from FFH manufacturers to understand how BEB FFH emissions compare with CARB's standard. An average of FFH nitrogen oxide (NOx) and carbon monoxide (CO) emissions data (Figure 2) show that FFHs are far below the standard CARB has set in LEVII. The FFH emission standard is the same as passenger vehicle engines, even though FFHs are small, only produce heat, and are not responsible for vehicle movement.

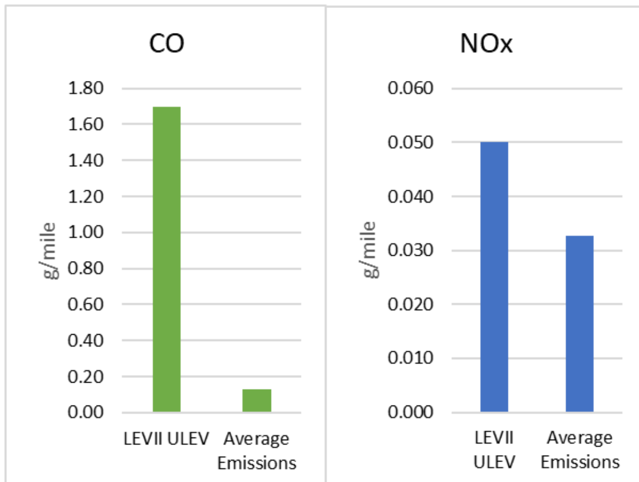

Figure 2: LEVII ULEV Standard vs. Average Emissions of FFH

As the regulation dictates, FFHs must be emissions tested only if installed in diesel vehicles. For example, if a medium- or heavy-duty vehicle is battery-powered, the installed FFH would not have to be tested under CARB's regulation. This is a loophole that could be exploited as alternative fuel vehicles become more common. Creating more stringent FFH regulations based on fuel type can steer manufacturers away from diesel FFHs and toward other fuels such as CNG, propane, biofuels, or hydrogen.

Another CARB regulation is the Heavy-Duty Low NOx Omnibus Regulation, which is intended to reduce NOx emissions in heavy-duty diesel vehicles [20],[21]. Using a few logical assumptions for a transit bus route and heating demands, a comparison was made between the Low NOx standard and the current FFH standard (Table 4). The ULEV standard, per its design for smaller engines, is more stringent than the Low NOx standard; as Figure 2 demonstrated previously, the emissions from FFHs are still far below the standard.

Table 4: Low NOx Standard Compared to FFH LEVII Standard

	Current	2024-26	2027+
Low NOx Standard (g/bhp-hr)	0.200	0.050	0.020
Low NOx Standard (g/mi)*	0.483	0.121	0.048
FFH NOx Standard (LEVII ULEV)	0.050	-	-
% Difference	162%	83%	4%

*Assuming 30 kW heater running for 6 hours on a 100-mile route.

The European Union has enacted specific testing and emissions requirements for FFHs in all passenger vehicles, transit vehicles, trucks, and semi-trucks [22]. In the R122 standard, units are reported in parts per million (ppm) and Bacharach, an optic unit measuring exhaust color (Table 5). One manufacturer's results show that their FFH emissions are well below the standard.

Table 5: R122 Standard Compared to Company A FFH Emissions

	CO (ppm)	NOx (ppm)	Hydrocarbons (ppm)	PM (Bacharach)
R122 Standard	1000	200	100	4
Company A	35	98	1	1
% Difference	186%	68%	196%	120%

CARB and the European Union have set standards for FFH emissions in g/mi and ppm, respectively. Due to current recording, collecting, and reporting methods, it is unfortunately not possible to compare the standards' stringency. The ability to compare these standards would allow for a more holistic view of the policy landscape for FFHs. In addition, CARB's unit to measure emissions is g/mi; by definition, an FFH "does not contribute to the propulsion of the vehicle." Furthermore, the EPA measures emissions in g/kWh, adding another unit that is difficult to compare to the g/mi and ppm values mentioned above.

4 Technology Demonstration

Cold weather has not stopped some transit agencies from adding BEBs into their fleets. By reviewing operational data for BEBs, it has been possible to better understand how heating the bus impacts efficiency. The transit agencies have been made anonymous to ensure the integrity of the data provided.

With funds from the Federal Transit Authority, CALSTART collected BEB data in collaboration with a large Midwestern transit agency in a cold-weather climate. Charging and vehicle usage data from their fleet of 60-foot BEBs produced by a legacy OEM was collected over 12 months of service. The BEB fleet consumed an average of 235 gallons of diesel per month for their FFHs; this is about 30 gallons per bus per winter month. Assuming the FFHs are 80 percent efficient, this is equivalent to almost 1,800 kWh per bus per month needed to run the heaters while the buses are in service. The FFH reduced the energy draw of the bus by 0.71 kWh/mi. Without the diesel heater, it is estimated that the electric heater would have to draw an additional 0.71 kWh/mi to satisfy the heating needs of the bus. One bus would need approximately 60 kWh additional battery pack energy to compensate for the additional heating energy required on the route without the auxiliary heater. The larger, heavier battery pack would lead to a longer charge time and lower overall bus efficiency throughout the year, while the additional stored energy would be required only during the winter months.

To support and extend the buses' battery ranges, the 60-foot BEBs have a switch on the dashboard to activate the FFH as needed. The transit agency configured their heaters to run the electric heater first and then use the diesel FFH when necessary. Depending on the heating needs and setpoint, a transit agency can configure the FFH as the primary source of heat, which would maximize the battery's energy to be used for the electric motor. It is unclear how much control the transit agency and driver have to change the FFH settings after the bus has been delivered, such as if the agency or OEM decided to make the electric heater the secondary source of heat at a later date.

CALSTART was able to look at two days of BEB usage from another transit agency in a cold climate region: one day with the FFH (ambient temperature below 32 degrees Fahrenheit/0 degrees Celsius) and one solely relying on the electric heater (ambient temperature in the mid-50 degrees Fahrenheit/10 degrees Celsius). On average per trip, only about 3 percent of the battery energy went to heating when the FFH was active. When using only the electric heater, 25 percent of the battery energy was dedicated to heating. Seventy-seven percent of the trips on the warmer day utilized the electric heater. The colder day had the electric heater running for only 50 percent of the trips and at a very low energy use; the remaining heating demand was made up by the FFH. There could be additional factors impacting the heating demand on the energy breakdown, such as driver and route characteristics or the cabin temperature setpoint, that were not reported. As such, any heating energy needs by the battery has a significant impact on the vehicle's range.

An on-road energy efficiency demonstration in Germany tested and compared seven 40-foot BEBs in near freezing temperatures [23]. The results found that buses without FFHs had an average efficiency of 3.78 kWh/mi. With a FFH installed, the buses' average efficiency was 1.61-2.17 kWh/mi. The heater reduced the energy draw of the bus by 1.53-2.17 kWh/mi, meaning the savings in traction battery energy allowed the bus to remain on the road longer. Significant block redesign to account for winter range loss would therefore be considered a resource burden.

4.1 Current Technology

Information from one OEM's operating manual explains that the BEB's diesel heater has been programmed to operate only at temperatures less than 40 degrees Fahrenheit (4 degrees Celsius) and to shut off when the ambient temperature is above 45 degrees Fahrenheit (7 degrees Celsius). It also states the diesel FFH is used to condition the battery and for cabin heat. Conversely, a different BEB OEM has programmed their FFH to be solely used for passenger cabin heating. Inconsistent FFH usage and variable cabin temperature setpoints can make it more difficult to understand the use frequency, range impact, and overall emissions impact of FFHs. It is unclear how the heating energy is split between cabin heating and battery thermal management. An additional BEB OEM has an option to prevent the FFH from activating until the bus had travelled a certain distance from ignition, but it was unclear if the FFH was also used for battery thermal management.

A study conducted in Finland compared the emissions from FFHs and the vehicle engine [24]. Although these were FFHs installed on passenger vehicles, the paper concluded that the FFH emissions were higher than the idling vehicle emissions.

Göhlich et al's study found that heating a BEB from an ambient temperature of 14 degrees Fahrenheit (-10 degrees Celsius) to a cabin temperature of 63 degrees Fahrenheit (17 degrees Celsius) can increase energy consumption by 2.09-3.22 kWh/mi depending on the prescribed driving cycle [17]. Using 1.93 kWh/mi as the energy demand for traction and other non-HVAC auxiliaries, heating in cold weather can total to 4.02-5.15 kWh/mi energy demand. Anecdotally, it has been witnessed that in some extremely cold regions, heating and traction energy demand can reach 6 kWh/mi or more, with the total heating energy having two to three times the impact compared to energy used by the traction motor.

4.2 Technology Development

While diesel FFHs are prominent technology, potential alternative zero-emission heating technologies for buses include heat pumps, fuel cell heating, and heating methods utilizing renewable fuel sources.

Valeo has created a CNG-powered FFH that is most often installed into CNG buses. This product is reportedly not a high seller in the US market, but it has seen some success in Canada. There are gasoline-powered FFHs that have been installed in gasoline vehicles in cold climates [25],[24]; full sized transit buses do not use gasoline, so gasoline powered FFH were not explored.

CALSTART has been working with a company that developed an ethanol powered heater. It is a catalytic heater, and the fuel cell generates heat without NOx, CO, PM, sulfur dioxide, or hydrocarbon emissions. It has roughly one-third the heat output as traditional FFHs (12 kW vs. 30 kW), but it is intended as a modular solution for bus and truck applications. CALSTART is actively seeking transit agency demonstration partners and funding resources to validate the bench testing data. In the transit application, it can be directly tied into the current water-glycol loop to simplify integration into the bus HVAC system. Reliably sourcing and storing ethanol at transit facilities to refuel the heater is a concern, though. However, ethanol is mixed into gasoline and is regularly stocked at wholesale fuel distribution points. Depending on how the ethanol is produced, there is potential for the fuel to be carbon neutral or carbon negative.

With improving battery capacities and prices, it could be argued that the heating load can be satisfied with larger battery capacities in the future. However, taking into consideration the highly variable heating needs that can easily require a 50 to 100 percent battery increase, the current estimated price improvements would still result in significant increases in total cost [26]. Additionally, larger battery capacities that can satisfy these heating needs would require longer charging times. Despite projected improvements in energy densities, doubling battery capacity would still impact the design and weight of transit buses.

5 Conclusion and Future Developments

Diesel FFHs have become more prominent as BEBs are deployed in cold climate areas. Using the Midwestern cold climate transit agency as an example, cabin heating in cold weather could lead to an increase in energy of 37 percent in order to maintain service. BEBs cannot have FFHs installed to qualify under California's ICT regulations, but FFHs and other technologies can help maintain passenger comfort in cold climates. The ICT regulation could consider an exception to allow FFHs under specific conditions, such as in cold or hilly regions. To reduce the heating demand of BEBs and thus the need for FFHs, other technologies could be implemented, such as air curtains, heat-pumps, heated passenger seats, increased insulation, and/or driver climate zones.

Zero-emission FFH technology needs to be explored so more regions of the United States can easily add BEBs to their fleet. Off-boarding the heating demand means buses can devote the maximum amount of energy to completing a route. Three potential technologies that can provide heating for a bus with zero emissions are heat pumps, fuel cell heating, and ethanol catalytic heating; however, zero-emission FFH technologies have not been thoroughly explored and are not commercially available seemingly due to the predominance of the tried-and-true diesel FFH. Hydrogen FFHs are near zero-emission and seem feasible; burning hydrogen to produce heat has been used in industrial practices and would require industry engagement, funding, testing, and moderate modifications to function in a BEB. Hydrogen FFHs would produce a small amount of NOx but zero carbon emissions. Ethanol-powered catalytic heating is currently in the developmental stage. It emits no criteria pollutants which could be an appealing choice after additional on-road testing and validation is completed.

Heating load may be satisfied with larger battery capacities as prices fall and capacities improve. However, since highly variable heating needs may also require up to a 100 percent increase in battery capacity (i.e., 200 kWh - 400 kWh), the current estimated price improvements from \$156/kWh to \$80/kWh would still result in a significant increase of the total vehicle cost [26].

Despite projected improvements in gravimetric (Wh/kg) and volumetric (Wh/l) energy densities, doubling battery capacity would still have a substantial impact on the design and weight of a transit bus. The U.S. Advanced Battery Consortium has, in March of 2021, set new lithium electrode cell goals of 450 Wh/kg and \$50/kWh. Current lithium-ion chemistries can achieve around 350 Wh/kg on the cell level as measured at the beginning of life [27]. However, overall end system gravimetric efficiencies are between 0.484-0.742 of the cell values depending on the cell type used (i.e., pouch, prismatic, or cylindrical) [28]. Despite the steady improvements in battery capacities and the introduction of new disruptive technologies such as solid-state batteries, it is difficult to project when it would be feasible to cover the heating demand with a battery both from a technical and financial standpoint.

Larger battery capacities that can satisfy heating needs would also require significantly longer charging times with currently available charging power levels. With limited information and real-world performance data of new storage technologies, such as solid-state batteries, it is difficult to project what the total weight and design implications could be when accounting for total propulsion and heating loads of a bus operating in severe cold climates.

5.1 Recommendations

This research demonstrates a need to explore alternative heating research and testing and reporting standardization when considering the future development and implementation of FFH technology.

5.1.1 Alternative Heating Research

The emissions implications and use frequency of FFHs, as well as alternative heating techniques, should be more thoroughly evaluated and researched. It is important to understand annual or seasonal FFH emissions to try to obtain an accurate account of emissions coming from the transit sector. Phasing out diesel FFHs should be considered, and alternatives need to be explored and tested to fully divest transit buses from fossil fuels. A growing number of transit agencies that operate in cold climates have or will install diesel FFHs to overcome adverse weather. In the future, other transit agencies should have zero-emission heating options when purchasing BEBs for their fleet. FFHs are currently a necessity for many transit agencies, but this legacy technology's emissions need to be mitigated to allow ZEBs to be truly zero-emission. New zero-emission heating solutions can also be broadly adopted in other segments of the industry, such as in heavy-duty sleeper cabins. The feasibility for alternative zero-emission heating solutions, such as ethanol catalytic heaters or hydrogen FFHs, should be further evaluated.

CALSTART recognizes alternative BEB heating is a pressing issue and is actively seeking demonstration transit agencies, technology partners, and funding sources to quantify the emissions and energy implications of a new ethanol-powered auxiliary heater.

5.1.2 Testing and Reporting Standardization

FFH testing and reporting should be comparable across regulating bodies. The current mismatch has made it difficult to compare emission stringencies and does not allow for a comprehensive view of the FFH policy landscape. The regulatory agencies should work together to understand the relative strengths of their standards; FFHs are an international product that could become more prominent as ZEBs continue to increase market share.

Acknowledgments

The authors would like to thank John Jackson for his initial work on this project, members of CARB, U.S. EPA, and FFH manufacturers for their critical review on an earlier version of this report. The authors would also like to thank the transit agencies that shared the heating data, as well as key CALSTART staff for their critical review of and additions to this report, including Kevin Leong, Derek Ichien, Emily Varnell, and Dan Welch.

References

[1] H. Hamilton, R. Chard, B. Lee, F. Silver, and J. Slosky, "Zeroing in on ZEBs - The Advanced Technology Transit Bus Index: A North American ZEB Inventory Report," Dec. 2021. Accessed: Apr. 07, 2022. [Online]. Available: www.calstart.org.

[2] B. Roy and P. Windover, "Idle Reduction Assessment for the New York State Department of Transportation Region 4 Fleet," *New York State Dep. Transp.*, no. 30899, 2015.

[3] California Air Resources Board, "California takes bold step to reduce truck pollution | California Air Resources Board," 2020. https://ww2.arb.ca.gov/news/california-takes-bold-step-reduce-truck-pollution (accessed Mar. 26, 2021).

[4] US EPA, "Learn About Idling Reduction Technologies (IRTs) for Trucks and School Buses | Verified Technologies for SmartWay and Clean Diesel | US EPA." https://www.epa.gov/verified-diesel-tech/learn-about-idling-reduction-technologies-irts-trucks-and-school-buses (accessed Feb. 05, 2021).

[5] “Valeo Thermal Bus.” https://www.valeo-thermalbus.com/us_en/Products/Fuel-fired-Heaters (accessed Feb. 05, 2021).

[6] California Air Resources Board, “15 states and the District of Columbia join forces to accelerate bus and truck electrification,” 2020. https://ww2.arb.ca.gov/news/15-states-and-district-columbia-join-forces-accelerate-bus-and-truck-electrification (accessed Jan. 28, 2021).

[7] M. Lewis, “Nevada pledges to electrify all new trucks and buses by 2050 - Electrek,” *Electrek*, Apr. 01, 2022.

[8] C. Air Resources Board- Mobile Sources Control Division, “Fleet Rule for Innovative Transit - Final Regulation Order,” 2020. Accessed: Jan. 28, 2021. [Online]. Available: https://ww2.arb.ca.gov/sites/default/files/2020-06/Final Reg Order 08132019.pdf.

[9] NYSERDA, “How to Participate in NYTVIP: Vehicle Manufacturers.” https://www.nyserda.ny.gov/All-Programs/Programs/Truck-Voucher-Program/For-Vehicle-Manufacturers (accessed Feb. 05, 2021).

[10] US EPA, “2021 American Rescue Plan (ARP) Electric School Bus Rebates | US EPA.” https://www.epa.gov/dera/2021-american-rescue-plan-arp-electric-school-bus-rebates (accessed Apr. 10, 2022).

[11] US EPA, “School Bus Rebates: Diesel Emissions Reduction Act (DERA) | US EPA.” https://www.epa.gov/dera/rebates (accessed Apr. 10, 2022).

[12] S. Calvina, “EPA Awards $980,000 for Cleaner School Buses in California | US EPA,” Mar. 15, 2022. https://www.epa.gov/newsreleases/epa-awards-980000-cleaner-school-buses-california (accessed Apr. 10, 2022).

[13] US EPA, “Clean School Bus Program Funding | US EPA.” https://www.epa.gov/cleanschoolbus (accessed Apr. 12, 2022).

[14] Thomas Build Buses, “The Clean School Bus Program: What the New Infrastructure Law Means for Your Fleet - Thomas Built Buses,” Mar. 04, 2022. https://thomasbuiltbuses.com/resources/articles/the-clean-school-bus-program-what-the-new-infrastructure-law-means-for-your-fleet/ (accessed Apr. 12, 2022).

[15] California Air Resources Board, “Diesel - Fueled Bus and Engine Exemption Request for Transit Agencies,” 2022, Accessed: Apr. 10, 2022. [Online]. Available: https://ww2.arb.ca.gov/sites/default/files/2022-.

[16] American Public Transportation Association, “APTA BTS-BPG-GL-001-13 - American Public Transportation Association,” 2013. https://www.apta.com/research-technical-resources/standards/procurement/apta-bts-bpg-gl-001-13/ (accessed Feb. 05, 2021).

[17] D. Göhlich, T. A. Fay, D. Jefferies, E. Lauth, A. Kunith, and X. Zhang, “Design of urban electric bus systems,” *Des. Sci.*, vol. 4, pp. 1–28, 2018, doi: 10.1017/dsj.2018.10.

[18] US EPA, “Nonroad Compression-Ignition Engines: Exhaust Emission Standards (EPA-420-B-16-022, March 2016),” Mar. 2016. Accessed: Feb. 05, 2021. [Online]. Available: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100OA05.pdf.

[19] US EPA, “Nonroad Spark-Ignition Engines 19 Kilowatts and Below: Exhaust Emission Standards,” no. March, pp. 1–2, 2016, [Online]. Available: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100OA0J.pdf.

[20] K. Caesar and S. Young, “California adopts strong new regulation to further reduce smog-forming pollution from heavy-duty diesel trucks | California Air Resources Board,” Aug. 28, 2022. https://ww2.arb.ca.gov/news/california-adopts-strong-new-regulation-further-reduce-smog-forming-pollution-heavy-duty (accessed Apr. 20, 2022).

[21] E. Miller, “CARB Formally Adopts Low-NOx Omnibus Rule,” *Transport Topics*, 2020. https://www.ttnews.com/articles/carb-formally-adopts-low-nox-omnibus-rule# (accessed Jan. 28, 2021).

[22] Economic Commission for Europe of the United Nations, “Regulation No 122 of the Economic Commission for Europe of the United Nations (UN/ECE) — Uniform technical prescriptions concerning the approval of vehicles of categories M, N and O with regard to their heating systems,” Jun. 2010. Accessed: Jan. 28, 2021. [Online]. Available: http://www.unece.org/trans/main/wp29/wp29wgs/wp29gen/wp29fdocstts.html.

[23] “Electric bus range, focus on electricity consumption. A sum-up -,” *Sustainable Bus*, Mar. 20, 2020. https://www.sustainable-bus.com/news/electric-bus-range-focus-on-electricity-consumption-a-sum-up/ (accessed Apr. 14, 2022).

[24] P. Karjalainen *et al.*, "Fuel-operated auxiliary heaters are a major additional source of vehicular particulate emissions in cold regions," *Atmosphere (Basel).*, vol. 12, no. 9, pp. 1–8, 2021, doi: 10.3390/atmos12091105.

[25] Valeo, "THERMO G 300 CNG HIGHLIGHTS," Accessed: Apr. 10, 2022. [Online]. Available: www.valeo-thermalbus.com/us.

[26] DNV GL, "Energy Transition Outlook 2020 - A global and regional forecast to 2050," *Dnv Gl Energy Transit. Outlook*, p. 306, 2020, [Online]. Available: https://eto.dnvgl.com/2020/index.html.

[27] A. Masias, J. Marcicki, and W. A. Paxton, "Opportunities and Challenges of Lithium Ion Batteries in Automotive Applications," 2021, doi: 10.1021/acsenergylett.0c02584.

[28] H. Löbberding *et al.*, "From Cell to Battery System in BEVs: Analysis of System Packing Efficiency and Cell Types," *World Electr. Veh. J.*, vol. 11, no. 4, p. 77, Dec. 2020, doi: 10.3390/wevj11040077.

Authors

Katrina Sutton is a project manager at CALSTART specializing in zero-emission bus technologies and infrastructure. She received an M.S. in Transportation Technology and Policy at UC Davis in 2020 and a B.S. in Environmental Science and Management from UC Davis in 2015. Her research interests include electric buses, barriers to EV adoption, EV education, charging management strategies, charging etiquette, and climate change mitigation. Proud owner of one 2011 Chevrolet Volt, one cat, and ten PV solar modules.