Comparing the Impacts of Bus Technology and Fuel Types in the East Bay

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Abbreviations

AC	Alameda-Contra Costa (usually used in reference to AC Transit)
BART	Bay Area Rapid Transit
BEB	Battery Electric Bus
BEV	Battery Electric Vehicle
BIPOC	Black, Indigenous and People of Color
CA	California
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalents
EIO-LCA	Economic Input-Output Life Cycle Assessment
EOL	End of life
EU	European Union
EV	Electric Vehicle
FCEB	Fuel Cell Electric Bus
FCEV	Fuel Cell Electric Vehicle
g	grams
GHG	Greenhouse Gas
GWP	Global Warming Potential
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
ICE	Internal Combustion Engine
kg	kilogram
kWh	kilowatt hour
lbs	pounds
Li-Ion	Lithium Ion
mi	miles
NMC	Lithium Nickel Manganese Cobalt Oxide, type of Li-Ion Battery
PHEB	Plug in hybrid electric bus
SRM	Steam Reforming of Methane
TOD	Transit-Oriented Development
ZEB	Zero-Emissions Bus
US	United States of America

I. Abstract

The transportation sector accounts for 28% of annual greenhouse gas emissions, and thus adoption of zero-emissions vehicles is a crucial component of any decarbonization strategy. While battery electric personal vehicles (BEVs) have seen significant commercial interest, less attention has been paid to similar applications of zero emission technologies to public transportation, most notably buses. This study aims to compare two competing technologies that have emerged as promising solutions for zero emission buses - battery electric (BEB) and hydrogen fuel cell (FCEB), with diesel as a baseline. We specifically analyze the life cycle emissions of these 3 technologies serving AC Transit bus routes within Alameda and Contra Costa Counties, and determine the viability of zero emission technologies as a replacement for diesel powered buses. We found that BEBs generally had the lowest life cycle emissions, but found that emissions of FCEBs depended heavily on the source of hydrogen. Hydrogen obtained from natural gas is associated with significantly more emissions than hydrogen obtained from electrolysis. These findings highlight the importance of comprehensive systemic decarbonization, including zero-emission electricity generation and green hydrogen technology, in order to achieve decarbonization of the transportation sector.

II. Executive Summary

The purpose of this report is to analyze the lifetime greenhouse gas emissions associated with three different options for transit vehicles: battery electric buses, fuel cell buses, and diesel powered buses. Comparing these three different alternatives is important because, in an increasingly sustainability-minded world, understanding the full life cycle impact of a product is vital. Without understanding the full life cycle impact, misleading claims such as “Zero-Emission Vehicle” can be taken as the full truth when really they are only a half truth.

There are two main methods for producing hydrogen: steam reforming methane, which uses natural gas, and electrolysis, which uses electricity. The emissions associated with both methods are vastly different, but hydrogen of both types end up in a vehicle with a sticker that claims “Zero Emissions.” We assessed the lifetime emissions of a vehicle that uses hydrogen from both these processes in order to understand what proportions of SRM and electrolysis that hydrogen is on par with its alternatives (diesel and electric).

III. Introduction

Given the catastrophic ramifications of climate change, there is an urgent need over the next few decades to reduce carbon emissions across every sector of our economy. While the term “greenhouse gases” often evokes an image of a power plant spewing fumes through a smokestack, emissions generated from transportation are equally if not more significant than those from the power sector. The decline of coal and increasing adoption of renewables in the electricity sector have caused the fraction of carbon emissions associated with electricity generation to steadily decline over the past decade. In 2018, transportation narrowly overtook electricity generation as the primary source of CO_2, accounting for roughly 28% of GHG emissions, compared to 27% from the electric power industry (1).

Major strategies for reducing transportation emissions include vehicle efficiency standards (using less fuel), fuel emission standards (using cleaner fuels), and vehicle electrification (2). Public transportation, especially buses, serve as a convenient means for addressing all these areas. Increased bus ridership can theoretically reduce fuel per passenger. While the average consumer may not be financially able to switch to an electric or alternative fuel vehicle, a transportational authority can leverage their economies of scale to their advantage. In addition, transportation authorities are often directly funded by local governments and are thus highly subject to public pressure. Many urban governments have thus already committed to emission reduction goals (3). Compared to the challenge of incentivizing diverse private actors, decarbonizing the transit system under their control makes for a relatively frictionless task.

Transit-oriented development (TOD) is an emerging paradigm in urban planning whereby residential and business developments are centered around transit hubs (56), thus encouraging public transport ridership. Rail-centered TODs have been implemented with great success in many Asian metropolitan areas, notably Tokyo and Hong Kong, where rail ridership, and public transportation ridership more broadly, accounted for 37% and 90% of all trips respectively (67). In comparison, bus ridership in the US is virtually nonexistent, with bus emissions making up just a little over 1% of US transportation emissions. Initiatives in the Bay Area to increase rail ridership through TODs have also been implemented across many BART stations (68). Light-rail centered TODs have recently become very popular due to lower capital costs associated with light-rail infrastructure, and cities in the US such as Seattle and Portland have dedicated significant resources to developing them in recent years (69, 70). Bus-centered TODs have traditionally been overlooked, but bus infrastructure is even less capital intensive than light-rail, and thus has the potential to be even more impactful and quicker to deploy. Between 1990 to 2018, total bus GHG emissions increased by about 158%, which was larger than any other transportation category (1). If similar sociopolitical interest arises for bus-centered TODs, we can expect to see an explosion in bus ridership in the following decades, which makes zero emission bus technologies all the more prescient to solving transportation emissions.

We can understand intuitively that buses generally are more energy-efficient per passenger than a private vehicle that carries only one person. However, there are a number of different energy sources available that could make up a bus's powertrain, which would impact the magnitude of energy savings per passenger. Traditionally, buses run on diesel, but both hydrogen fuel cells and electric batteries are gaining significant traction as alternatives. For example, AC Transit, serving Alameda and Contra Costa Counties in California, is piloting a handful of hydrogen fuel cell vehicles and fuel cell vehicles (4). Washington, DC, is piloting fully electric vehicles in its Circulator routes (5). The remainder of buses in both metropolitan areas, as well as others around the country, still use diesel. Distinguishing between the impacts of these various power sources is complicated. For example, electricity, diesel, and hydrogen all depend on other energy sources for production, so emissions from the tailpipe during day-to-day use is not a sufficient measure.

As we have seen, local governments such as Alameda and Contra Costa Counties and Washington, DC are already choosing bus technologies to prioritize in pilot projects. Many other local governments are following suit and selecting bus technologies to pilot. These decisions made today will affect the makeup of a city's bus fleet for years down the line, as technologies that are proven in deployment first usually become entrenched against challengers. A wrong choice today could mean decades of unnecessary bus emissions!

Notably, GHG emissions are not the only relevant environmental impacts. For example, production of fuel cells, combustion engines, and batteries require raw material sourcing which may introduce toxic byproducts into the water supply. In particular, lithium extraction and purification from lithium brine is an extremely water intensive process, requiring 1.5 million liters of water for every ton of lithium carbonate (71), fueling "water wars" in arid environments such as the Salt Flats in Bolivia or the Atacama Desert in Chile (72). Energy production can emit carcinogenic gases in addition to the kind that heat up the Earth's atmosphere. Global warming potential is the driver for the decision to transition to cleaner buses and to public transit more generally, but any changes to the status quo must consider additional impacts that come along in the backseat. Efforts must be made to retain, reuse, or recycle materials at the end of these buses' useful life in order to avoid further raw material extraction.

In this study, we will compare the life cycle impacts of the electric, hydrogen, and diesel buses in Alameda and Contra Costa Counties. We selected this area based on data availability and policy relevance. Regarding data availability, AC Transit participates in a Department of Energy pilot project on fuel cell buses (6). The community-specific information from that study is easily transferable to this study. Regarding policy relevance, AC Transit has committed to "have a 100% zero-emission[1] fleet in place by 2040" (7). The main strategies considered for creating a ZEB ("Zero-Emission" Buses) fleet are: (a) an all battery electric bus fleet (All-BEB), (b) an all fuel cell electric bus fleet (All-FCEB), or (c) a mixed fleet (BEB-FCEB). An assessment of the comparative impacts of BEB and FCEB could provide useful information for guiding which strategy is selected.

As of 2019, AC Transit already has 5 BEB and 7 FCEB in service from the same manufacturer, New Flyer (22). Detailed factsheets for both models are available on New Flyer's website (23, 24). Schematics showing scale and layout of proposed charging installations also exist (26).

We acknowledge that biofuel is also a viable alternative power source for busing in some areas. However, AC Transit already conducted a study in 2007 testing a 20% biodiesel blend. They found that the blend reduced efficiency, and that local supply was unreliable, so biodiesel is not a viable long-term alternative (8). Indeed, none of AC Transit's ZEB scenarios mentioned above include biodiesel.

IV. Problem Statement

[1] It is unimaginable that the full life cycle of any vehicle has zero emissions, so we assume the plan refers to zero emissions during use.

We found it important to analyze the emissions associated with hydrogen fuel cell electric buses (FCEB), battery electric buses (BEB), and conventional diesel buses. Comparing these three could help to understand the sustainability of each alternative, and particularly the sustainability of FCEB that run on hydrogen produced by steam reforming methane (SRM). SRM is an increasingly popular approach for producing hydrogen, largely by oil and gas companies who have access to vast reserves of natural gas. As the future increasingly favors sustainable fuel options, the oil and gas industry have begun to dip their toes into seemingly "sustainable" energy by producing hydrogen fuel via SRM. Without capturing GHG emissions associated with SRM, however, these emissions may make the impact of FCEBs more similar to conventional diesel buses than anything else. A sensitivity analysis on the mix of hydrogen produced by electrolysis versus SRM can show what mix is comparable to diesel and electric vehicles.

Like FCEVs, battery electric vehicles have also gained traction recently as a low emissions option. While most of the EV traction has been with passenger vehicles, there is still a possibility that electric bus use can continue to grow in cities, especially as battery technology improves. Therefore, electric battery-powered buses are also important to include in comparison. Overall, we analyzed the emissions associated with each of these bus fuel options to see which is the most sustainable, regardless of cost. We focused our analysis on GHG emissions due to policy focus on GHG emissions in transportation.

V. Key Questions

- What are the emissions associated with FCEB that use hydrogen produced by SRM?
- What are the emissions associated with BEB?
- How do these compare to conventional diesel-powered buses?
- As a transit bus fuel, is hydrogen produced by SRM better for the environment than diesel?
- What are the life cycle benefits and drawbacks to BEB?
- Outside hydrogen production, what are the life cycle benefits and drawbacks to FCEB?
- How does power generation mix affect BEB's impact relative to FCEB?
- Is a FCEB still "sustainable" if hydrogen fuel is produced using SRM?
- What mix of electrolysis- and SRM- produced hydrogen makes BEB competitive on GHG emissions with FCEB? Diesel-powered buses?

VI. Background

Battery Electric Bus Technology Maturity and Deployment

A meta-analysis of academic literature on electric buses from 2016-20 indicate a shift in research priorities from battery chemistry to route scheduling and charging infrastructure (9-14). This likely reflects a maturation of battery development and hence a switch in focus to data driven methods of increasing energy and resource efficiency. In other words, this trend indicates that battery technology suitable for electric buses already exists or is close to commercialization. In this case, the greatest hurdles to electric bus adoption today are the lack of institutional knowledge in operating these new technologies, as well as a lack of regulation in governing their development and adoption. The focus is no longer on finding battery technologies with the greatest energy density to cost ratio, but rather on finding a battery best suited to the range and recharge cycles of a given bus network.

Much of the literature suggests that building out an electric charging network would be easier and more cost efficient than building out a hydrogen refueling network, since it only requires minor modifications to an existing distribution network (i.e. the power grid), rather than a complete build out of new pipelines, storage tanks, and trucking routes to support hydrogen distribution. However, AC Transit's ZEB plan suggests the opposite - that hydrogen refueling infrastructure would actually be cheaper than electric chargers (7). AC Transit argues that hydrogen refueling is fundamentally akin to diesel refueling (refueling stations, nozzles), whereas electric charging stations will require a complete redesign of the bus depots to accommodate the more frequent and longer duration charging, which requires significant infrastructure upgrades beyond simple wiring.

Impacts Behind Fuel and Electricity

On the surface, FCEB and BEB may initially appear virtually emissions-free since neither emit GHGs from their tailpipes. However, the production and supply chain of the respective hydrogen fuel and electricity both contribute significantly to the bus's true emissions. Where a FCEB first seems to clearly be more sustainable than a diesel bus, the true winner may be ambiguous when one looks behind the veil of use phase sustainability. For example, this study (15) from the University of Stuttgart found that using hydrogen fuel cell buses in London could only be considered environmentally sustainable if "green" hydrogen was used.

This points to the importance of how hydrogen is produced. One Swedish study considered the tipping point of carbon intensity of the grid, which we will adopt as a framework for determining a similar "tipping point" for hydrogen mixes (18).

The London study also attempts to calculate the bus emissions' indirect cost on human health and climate change. Interestingly, FCEB emissions are said to have no indirect cost to the air quality in London. While there is no negative cost locally, however, limiting the scope to London seems misleading. The people who live near the hydrogen plant, although outside London, will be enduring the consequences of emissions associated with this bus's operation. This highlights a shortcoming in how alternative bus fuels are commonly considered: emissions may be negligible locally, but not absolutely.

Assessments of BEB can also be done through a rose-colored lens. This study (16), which compares diesel buses and BEB across the United States, addresses the impact of electricity production on electric vehicle emissions. Only 8 states were found to have a power generation mix that kept BEB emissions less than diesel buses. Although sometimes neglected by municipal decision-makers, incorporating the carbon intensity of the grid is vital.

Of course, GWP is not the only relevant impact of bus production and use. One study on bus transportation in Perth, Australia comparing diesel, natural gas, and hydrogen fuel cell buses found that FCEB are competitive in terms of GWP and eutrophication to the others (17). However, the FCEB had more higher acidification potential and ozone depletion potential than the others.

The Perth study suggested that switching to sustainable or low-emitting fuels could have a greater effect on transportation emissions than replacing fossil fuel electricity generation with renewables (17). This is based on an assumption that only local emissions reduction are relevant. Conversely, a Swedish study focusing on local emissions found electric propulsion more favorable (18). Given that a focus on local boundaries introduces such inconsistencies, there is no reason to replicate this aspect.

Inventory

Chester and Horvath (2009) emphasized that a life cycle assessment of public transportation should account for infrastructure and the supply chain (55). We used the method presented in that study to approximate the impact of roadway infrastructure needed.

A comparison of Volvo's 7900 bus model series provides a helpful framework for breaking down components within a bus (21). The authors did not have access to specifications for the specific components Volvo used in 4 different vehicle types (BEB, PHEB, FCEB, and conventional). From BEV model data, they extracted baseline specifications for the chassis, frame, and body, which they used for these components in all 4 vehicle types. This idea suggests a useful simplifying assumption: components that would be common between the BEB and the FCEB, as long as they were the same size, would not render a significant difference in impact between the two models. This study also includes a pie chart showing mass-wise split of materials for each of the 4 bus types. It is not generalizable, however, as the BEB version does not necessarily have the most appropriate battery type.

To determine what specific components should be included, we considered bus types that AC Transit already uses. Planning documents indicate that New Flyer BEBs and FCEBs are both currently in use for pilots. Fact sheets for standard models are available on the manufacturer's website (23, 24). Exact make of a few components, like the fuel cell, are listed.

Image 1. Xcelsior Charge by New Flyer, Battery Electric Bus Model Used for Comparison

Image 2. Xcelsior Charge H2 by New Flyer, Battery Electric Bus Model Used for Comparison

Image 3. Gillig 40-foot Commuter Bus

We constructed battery archetypes based on energy storage capacity, known chemistry, and manufacturing partners. The storage capacity is listed on the fact sheets (23, 24), and the chemistry (NMC) and manufacturing partners are described in a 2017 post on the company's blog (27). Technical overviews published by various government agencies provided background information to help us make these approximations (28, 29). Even without detailed vehicle manufacturing knowledge, this is sufficient input for calculating impact using Argonne National Lab's GREET model (36). A working draft from the California Air Resources Board discusses the estimation of life span for different batteries, which is in Table 1 (28).

Figure 1. Chemistry of Lithium Ion Batteries and Common Applications (28)

Battery Chemistries	Specific Energy (Wh/kg)	Life span (cycles)	Applications
Nickel Cobalt Aluminum (NCA)	160	2000+	Used in cars (e.g., Toyota Prius plug-in hybrid, Tesla)
Nickel Manganese Cobalt Oxide (NMC)	150	2000+	Used in consumer goods, cars, and buses(e.g., Nissan Leaf, Chevrolet Bolt, Proterra, New Flyer)
Lithium Manganese Oxide (LMO)	150	1500+	Used in cars; most LMO blends with NMC to improve the specific energy and prolong the life span (e.g. Nissan Leaf)
Lithium Titanate (LTO)	90	5000+	Used in cars and buses (e.g., Honda Fit, Proterra)
Lithium Iron Phosphate (LFP)	140	5000+	Used in cars, buses, and trucks (e.g., BYD, TransPower, Siemens, Nova Bus, Volvo) and stationary energy storage systems

LCAs for Fully Electric Buses and their Batteries

Since FCEB are more mature, we were uncertain whether there would be enough literature available off which to base a BEB battery. However, we were pleasantly surprised.

In addition to studies listed above, Ellingsen of Norway provides a sweeping literature review pointing out papers to reference for different chemistries (30). Reports from the same research group dive into detailed comparisons and discussion (31, 32).

This review (33) indexes a handful of studies focusing on the materials for vehicle batteries, which provide an excellent basis for understanding the end-of-life pathways for these batteries, namely recycling.

Available literature on bus end-of-life decommissioning are scant, and thus we collated studies on steel recycling, Li-ion battery recycling, carbon fiber composite recycling, and lead-acid battery recycling as a means to estimate end-of-life emissions.

VII. Modeling Approach and Data

Overview

In our assessment, we analyzed the kg CO_2e/mi driven by each bus: diesel, hydrogen fuel cell, and battery electric to determine which has the lowest overall life cycle emissions. We analyzed the emissions associated with each part of the lifetime for each vehicle: production/extraction of raw materials, use phase, and end-of-life. We limited our system boundary to California, and assumed the same lifetime for all 3 buses: 12 years, and 500,000 miles, which is 804672 km (35). For the hydrogen fuel cell bus, we compared the use of hydrogen fuel created using natural gas or electrolysis in our sensitivity analysis, in order to understand how this affects the emissions associated with hydrogen fuel cell buses. We used the AC Transit buses manufactured by New Flyer as the model for our assessment (see Images 1,2, & 3).

Outside fuel and electricity production, emissions differences between models are driven by components that vary between bus types, such as hydrogen fuel cells and batteries. The impact of other vehicle components, the weight of the rest of the vehicle, the number of passengers, and the length of the route were all assumed to be the same. This simplification allowed us to focus on the differences between diesel engines, hydrogen fuel cells, and electric propulsion. In practice, this simplification parallels the decision that transit authorities would have to make. The transportation needs of the population do not depend on what makes the vehicle move. The transit authority starts with an estimate of where busing is required and how much busing is required on each route. The difference in impact depends on what type of bus is chosen to fill each predetermined route.

We developed a model (Figure 2, 3) in order to understand the different components we will be calculating emissions for, breaking down the emissions by life stage and distinct components.

Figure 2: Simplified Model Boundary

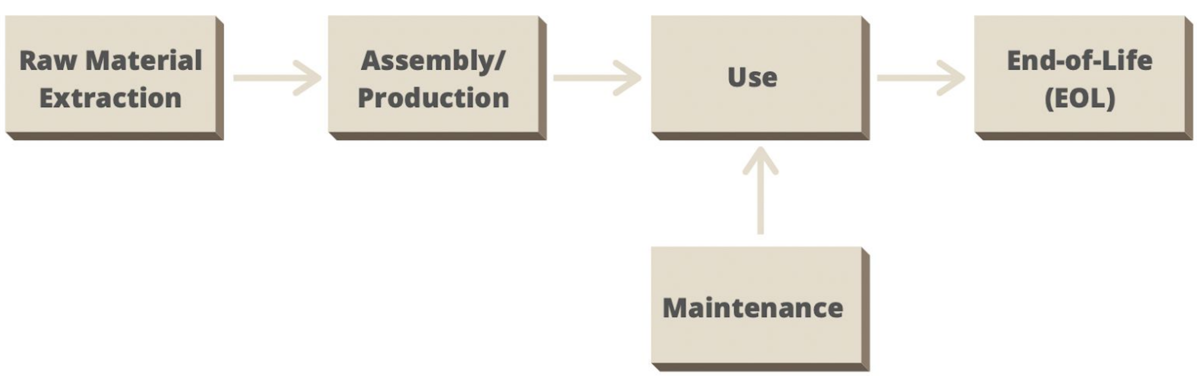
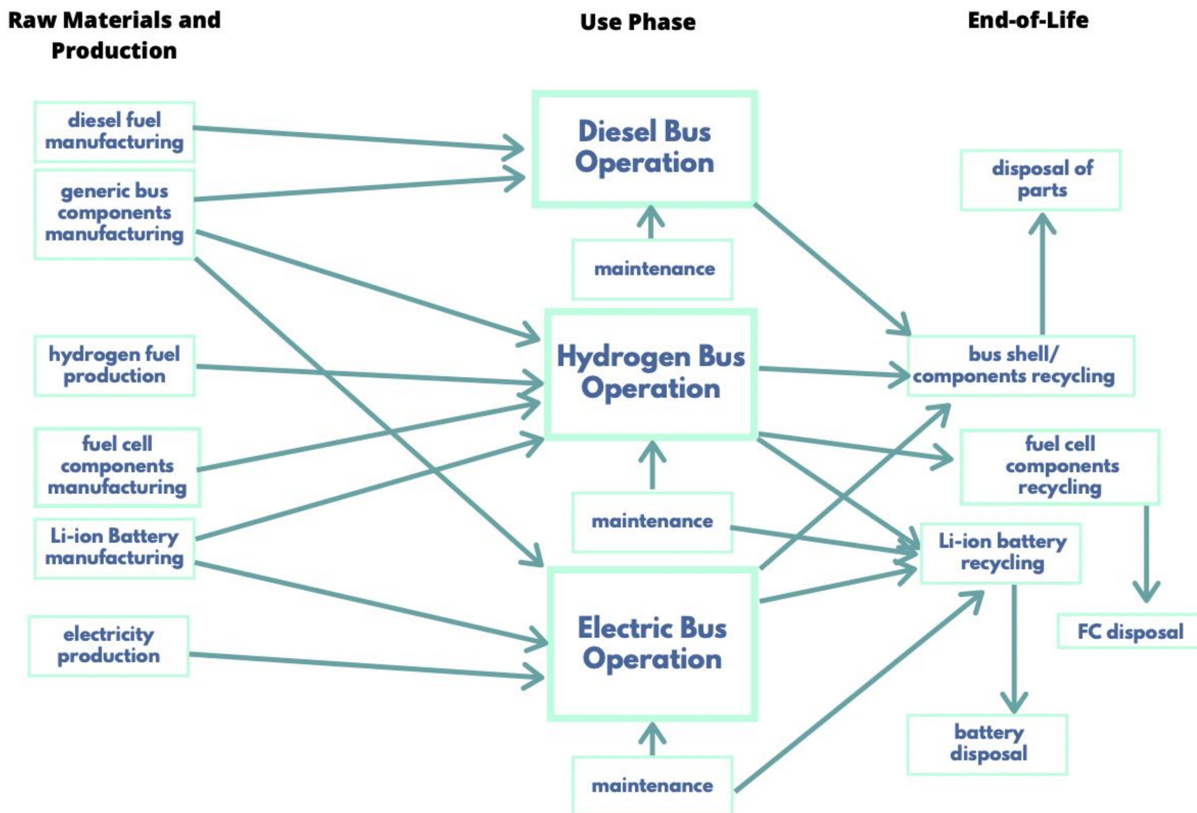


Figure 3: Model of Components Associated with each Bus Type



Data for the emissions associated with these different components came from a number of sources. These included:

- Argonne National Laboratory GREET model (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) (36)
- EIO-LCA (Economic Input-Output Life Cycle Assessment) tool developed by Carnegie Mellon University (37)
- Waste reduction model by the EPA (WARM) (57)
- Various LCA studies, especially for components not explicitly included in the above models

Manufacturing - Generic Bus Components

We found there to be very little current literature available on the emissions associated with manufacturing of transit vehicles. We decided to use the EIO-LCA to estimate emissions associated with generic bus components, which excluded NMC batteries, fuel cell packs, and fuel cell hydrogen tanks. This process was largely inspired by Cooney, et. all 2013 who employed a similar approach for comparing battery electric bus shells and diesel bus shells (86, 87). We converted the costs of each bus (subtracting markup and special components) into 2002 dollars (to align with the year for the EIO-LCA setting). We imported this value into sector 336120 of the EIO-LCA, “Heavy duty truck manufacturing” (37).

Value for the special components, like the Li-ion batteries and the fuel cell components, were subtracted because we estimated the emissions associated with manufacturing these parts separately. These were parts that we expected, and found, to have very high CO_2 emissions since they are specialty components requiring complex manufacturing and relatively immature supply chains. The remaining components in the FCEB and BEB were common parts found in diesel vehicles (drivetrain, motor, tires, interior, chassis, windows, and so on). We felt the EIO-LCA was a fair estimation of manufacturing emissions for these components, given inaccuracies would be shared by all models and thus would not skew any model undeservedly (Figure 4).

Figure 4. Bus Components Summary

Components	**Electric Bus - New Flyer Xcelsior CHARGE (24)**	**Hydrogen Bus - New Flyer Xcelsior CHARGE H2 (23)**	**Diesel Bus - Gillig 40-foot Commuter Bus (58)**
Energy Storage System (Battery)	466 kWh (2,118kg) NCM 12V (23.13 kg) Lead Acid	150 kWh (681 kg) NCM 12V (23.13 kg) Lead Acid	12V (23.13 kg) Lead Acid
Drive Auxiliary System	✓	✓	✓
Power Electronics	✓	✓	X
Motor	Siemens ELFA2 Electric Drive System	Siemens ELFA2 Electric Drive System	Cummins ISL 280 HP
Thermal Management of Motor/Energy Supply	Battery cooling system	Battery thermal management	Engine Cooling System
Electric heating, venting, and air conditioning	✓	✓	✓
Electrical system	✓	✓	✓
Fuel System	X	H_2 Tank Modules + Ballard Fuel Cell	Diesel fuel system
Brake system	✓	✓	✓
Wheels, hubs, suspension	✓	✓	✓
Transmission	X	X	✓
Drivetrain (w/out transmission)	✓	✓	✓
Cabin/Framework	✓	✓	✓
Tires	✓	✓	✓

To estimate the costs of the NMC batteries, we found the average value of a battery to be $209/kWh (60). Then, we multiplied by the known kWh battery capacity specified in the product documents (23, 24). The cost of the BEB and FCEB batteries came out to be approximately $97,400 and $31,400, respectively.

We deducted the price of the fuel cell and class IV tank from the total FCEB cost used as input for the EIO-LCA. This was to prevent double counting, as we used product-specific process data to estimate impacts for both these components. Prices for both the fuel cell and class IV fuel tank were estimated from Dept of Energy manufacturing costs analyses (46, 47). The fuel cell price was scaled by kW rating and averaged between high- and low-volume production scenarios shown in table 10-1 in (46).
The tank price was based off a $/kWh cost projection for the lowest volume production scale in (47).

After estimating these costs, they were subtracted from the total vehicle costs (after subtracting the markup) and converted the cost into 2002 dollars from 2018 dollars (61). The monetary values estimated for EIO-LCA inputs are listed in Figure 5.

Figure 5. Cost of each bus and bus components

	BEB BUS	**FCEB BUS**	**Diesel Bus**
Original Price	$1,134,465.00 (7)	$1,289,838.00 (7)	$425,618.00 (59)
Cost after markup removed	$945,387.50	$1,074,865.00	$354,681.67
Cost of battery	$97,394.00 (60)	$31,350.00 (60)	
Cost of Fuel Cell		$164,603.00 (46, 47)	
Cost of Fuel Cell Tank		$9,268.00 (47)	
Total Cost in 2018 Dollars (2012 for Diesel)	$847,993.50	$869,644.00	$354,681.67
2002 dollars (EIO-LCA Input)	**$607,228.56**	**$622,731.98**	**$277,913.33**

Manufacturing - Batteries

We used data from the Argonne National Laboratory GREET model (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) to calculate the emissions for battery manufacturing and assembly, SRM-produced hydrogen, electrolysis-produced hydrogen, diesel production, and electricity generation mix. In the GREET model, the Lithium-ion NMC111 battery was chosen for modeling, since the New Flyer bus uses NMC batteries (28). We used the WTW (Well-to-wheels) emissions in the GREET model and the US average electricity mixes for the batteries. This accounts for the fact the batteries will be manufactured in the US, while we were unable to find the exact location of the manufacturing for the battery components.

The data in GREET is given in kg CO_2e per kg of battery. The brochure for each bus that listed the energy storage capacity of each battery: 466 kWh and 150 kWh for the BEB and FCEB, respectively (23, 24). Although the BEB model had several options for onboard battery capacity, we chose 466 kWh based on the AC Transit literature, which stated the estimated energy storage capacity for their BEB (7). We then used the energy density that XALT (the battery manufacturer for the New Flyer buses) reported on their website (0.22 kWh/kg) to convert the kWh to kg (62). We found the weights for the BEB and FCEB batteries to be approximately 2118 kg and 682 kg, respectively. From there, we could apply the GREET ratio of kg CO_2e / kg of battery. We found the emissions for the manufacturing of the BEB and FCEB batteries to be approximately 82,600 kg CO_2e and 26,600 kg CO_2e, respectively.

We also assumed that a 12V lead acid battery would be in each vehicle. The GREET model also included manufacturing emissions associated with the lead acid battery in kg CO_2e per kg battery. We found the weight of a common bus battery to be 23.13 kg (51 lbs), through the specs found online for an average bus battery (63). Using the emission factors found through GREET, we found the emissions associated with production of the lead acid battery to be approaximately 19 kg CO_2e. This was equal for each bus model.

Manufacturing - Hydrogen Fuel Cells and Tanks

As discussed above, standard bus manufacturing impacts, estimated using EIO-LCA, can account for most of the components of the FCEB. The only components creating a significant difference are the fuel cell and fuel tank, as discussed in literature analyzing FCEVs (44, 45, 48-50). This contribution is almost entirely due to carbon nanofiber used in production of both the fuel cell and a class IV H_2 fuel tank ().

For a fuel cell, the New Flyer FCEB uses Ballard FCvelocity-HD85, as indicated in the make documentation (23). Ballard, the manufacturer, conducted a study quantifying the GHG impacts of that particular fuel cell make to be 5.6 tons of CO_2 equivalent (42).

The New Flyer FCEB uses a class IV tank (43). This information helps to specify the material makeup and manufacturing process. The supplemental information to Miotti et al estimates the GHG impact for the production of a small class IV fuel tank, capable of holding 5.6 kg H_2 (44). The corresponding study finds that impact of a class IV fuel tank scales almost linearly with tank capacity (45). This allowed us to estimate the impact of the larger fuel tank (37.5 kg) in the New Flyer FCEB, simply by multiplying the smaller tank's impact by the ratio between the two capacities. The impacts calculated in Miotti are from Europe, but no data with sufficient detail for US class IV tank production was available.

Use Phase - Operations

We used the GREET 2020 model (36) to find emissions associated with the use phase. There are no tailpipe emissions associated with hydrogen fuel cell vehicles and electric vehicles. To estimate for the "usage" emissions, we used as input the electricity mix for California, the average kWh/mile for the BEB, and the WTW emissions from GREET for the FCEB and the diesel bus. The amount of energy per mile is given in the AC Transit rollout plan as 2.4 kWh/mi for BEB and 8.5 mi/kg, which is equal to 2.25 mpg for FCEB (7). We used a general estimate of 3.26 mpg for diesel since we could not find values specific to AC Transit specific values (39). The same lifespan for all buses was assumed, as well as the same mileage driven so that the analysis would be consistent across all three buses. We used the default GREET value of 85% for the charging efficiency of the BEB, and the default value of 11.6 average passengers and 0.61 urban share of driving. The latter two default values were acceptable because the passenger value was constant across all the buses, so it affected all three buses in the same way. Values specific to AC Transit for these quantities were not available.

To model the hydrogen fuel, we used the pathway in GREET called: "H_2 Bus (Pathway: Refueling Stations Compressed H_2 from Natural Gas w/o CO_2 sequestration)" This pathway corresponds to SRM, because we determined that the AC Transit fueling stations likely contain H_2 produced using SRM. A personal interview with a former Chevron employee confirmed that Chevron produces H_2 by SRM. Also, we know that Chevron was the original partner for the hydrogen refueling stations according to this press release: "Chevron fuels AC Transit's HyRoad" (64). In our sensitivity analysis, we also analyzed how the lifetime emissions would compare if we used electrolysis to create hydrogen fuel. We assumed the CA average electricity mix would be applicable to this process.

For the electric bus, we used the CA average electricity mix in GREET, which was equal to 203 g/kWh (36). For our sensitivity analysis, we also analyzed the emissions from the US Average Electricity mix in GREET, which has a CO_2e intensity of 432 g/kWh (36). These emissions during the usage phase accounted for the charging efficiency of the docking station, so any losses of the energy are accounted for in this WTW emissions calculation.

For the diesel bus, we used the low-sulfur diesel fuel option for a heavy duty transit bus, and found the emissions associated with diesel fuel created in California, using the default values listed above.

Use Phase - Maintenance

We considered 5 maintenance activities considered to have significant emissions based on existing LCA literature on cars and buses. We listed these important activities and associated emissions in Figure 6.

Figure 6. Vehicle Maintenance Activities

Part Name	**Maintenance Interval [km]**	**CO_2 emission [kg CO_2e/Maintenance]**	**Vehicle**	**Sources**
Tire	200,000	6.7	All	(57)
Lead-Acid Battery	50,000	19	All	(36)
Engine Oil	10,000	29.4	Diesel	(88)
Radiator Coolant	27,000	7.03	Diesel	(88)
Li-Ion Battery	250,000	177/kWh	BEB, FCEB	(36)

We used the EPA waste reduction model, also known as WARM, to calculate the life cycle emissions of the tires, from cradle to grave. This tool calculates the GHG emissions for different waste management practices based on an input weight. Each bus has 4 tires, and we set each tire to weight 145 lbs based on the average weight of Goodyear tires for transit applications (65).

We accounted for the replacement of the NMC batteries in our maintenance emissions, as well. We assumed these batteries would be replaced once over the lifetime of the vehicle, based on estimates of electric vehicle battery lifetimes (18). Estimates from Kawamoto, R., Mochizuki, H., Moriguchi, Y., et. al (2019) provided the basis for the frequency of Lead-Acid battery replacement in vehicles. Replacement was needed every 50,000 km, which resulted in around 16 replacements over the lifetime of the bus. We assumed the emissions associated with maintenance for these items included the WTP emissions from the GREET model for manufacturing these batteries.

We used maintenance interval estimates from the study by Kawamoto, R., Mochizuki, H., Moriguchi, Y., et. al (2019) for radiator coolant and engine oil. We scaled the engine oil estimate by a factor of 32/3.5, since the Kawamoto (2019) study was performed for a sedan, which takes approximately 3.5 quarts of engine oil, while a bus takes approximately 32 quarts of oil (66). Even though the Kawamoto (2019) study was performed for a sedan, the values for maintenance interval would serve as a decent estimate because they are on a per distance basis. This would lead to more maintenance for the bus due to its longer lifetime mileage, which aligns with our assumptions.

Infrastructure - Charging and Fueling

Modeling the charging and fueling stations was difficult, given that little data exists for these. However, existing literature provided a basis for some useful approximations. For charging stations, a Chinese study found that energy losses in the use phase due to charger inefficiencies dominated the contribution to GHG impacts (51). However, the GREET model already accounts for these losses (36).

The story was similar for fueling infrastructure. No existing assessments for fuel pumps were available. We could not use EIO-LCA categories for estimating these, either, since all related categories were too aggregated. An assessment of ICE automobiles relied substantially on EIO-LCA, but dismissed the possibility that fueling stations could be approximated this way (52). The retail service sector, which would be most relevant for a fueling station, simply included too much variety. In the end, however, this study found that the "fuel cycle", which included everything from extraction to fueling, was dominated by extraction and production. These processes were already included in the GREET model's accounting of diesel and hydrogen fuels.

The lack of information on charging and fueling stations, combined with their unimpressive showings in previous studies, suggests that their impacts are negligible. Additionally, any of these stations would likely service dozens if not hundreds of different vehicles over their lifetimes. Our analysis compares only a single bus of each type. Therefore, the impact of these already minor products would be further diluted over the many vehicles that each station services. The magnitude of the fuel, electricity, and bus component impacts make fueling and charging stations of low significance. However, detailed analysis on this equipment remains a significant gap for future transportation LCAs.

Infrastructure - Roadways

Based on the suggestion from Chester and Horvath 2009, we accounted for roadway infrastructure impacts in our environmental assessment. We used the values suggested in Table 20 for urban buses' impact on onroad infrastructure. We used this GHG impact per VMT, and added this into our final calculator of CO_2e/VMT (Figure 7).

Figure 7. Roadway Infrastructure Values per VMT

	Roadway Construction	**Roadway Maintenance**	**Herbicides/ Salting**	**Roadway Lighting**
GHG (g per VMT)	52	11	0.37	4.9

End-of-Life

We broke down each bus model into their constituent components and estimated each component's weight relative to the weight of each bus model, based on previous studies that reported component breakdowns of similar bus models (73). From this itemized list, we individually calculated the energy cost of scrapping and recycling each material or component, and normalized those values to the average carbon intensity of the US electric grid to obtain CO_2e emissions associated with recycling.

The components we analyzed were the steel chassis (all 3 bus types), the steel engine block (diesel only), the Li-ion battery (BEB, FCEB), the carbon fiber composite hydrogen tank (FCEB only), and the lead-acid battery (all 3 bus types).

The exterior dimensions of the New Flyer Xcelsior Charge (BEB) and Charge H2 (FCEB) bus models are identical, and the Charge uses a semi-monocoque steel chassis construction (74). Based on the curb weight of the Charge model, the steel chassis of both the BEB and FCEB models were estimated to be 8600kg. It was not immediately clear which bus model or model types are currently used in the diesel bus fleet operated by AC Transit, and thus an assumption was made that the chassis of the diesel bus would also be identical in weight and material composition to the BEB and FCEB models. We found that the energy cost of recycling steel amounted to 13.4MJ/kg, assuming the use of Electric Arc Furnace (EAF) technology to recycle the various steel components (75).

The battery weights were estimated based on the battery capacities of the BEB and FCEB buses, which were 466kWh and 150kWh respectively; the weights were estimated to be 2120kg and 680kg respectively. Battery recycling technologies are an active area of research and commercial development, and as such, energy costs and efficiency rates vary wildly across different processes and different geographic regions. We based our analysis using the latest available data from 2010 (76), which quoted 34.7MJ/kg as the energy required to recycle Li-ion batteries. Recent papers claim that recycling technologies with a 10-fold decrease in energy consumption compared to technologies from the last decade are becoming commercially available (77, 78), but they do not report an actual value; the 2010 value should, therefore, be treated as a 'worst case scenario' baseline, and we expect the actual energy cost will be much smaller today as newer technologies become available.

The carbon fiber content of the fuel cell stack and hydrogen tank was estimated to be 600kg, based on a previous study on fuel cell systems for personal automobiles (44). We scaled the capacity and power output values from the report to that of a bus fuel cell system. Once again, carbon fiber and fiberglass composites recycling is a relatively new commercial development, and as such, many solutions have not been deployed or tested at scale. Nevertheless, we were able to find a relatively narrow range of values, and we settled on an average energy cost of 10.25MJ/kg to recycle carbon fiber (79).

Finally, we assumed that the lead-acid battery for the starter motor would be identical across all 3 bus models. While no information about lead-acid batteries in buses were found, we found that lead-acid batteries in trucks were typically around 24kg (80); given the absence of better information, we assumed that bus batteries would be of a similar weight. Using GREET data (81) on automotive lead-acid batteries, we estimated the energy cost of recycling lead-acid batteries to be 5.8MJ/kg.

The abovementioned energy costs are based on electricity consumption. Using the EIA database, we found that the average carbon intensity of the US electricity mix is 0.45kg CO_2/kWh (82). While the use phase of the buses will be limited to California (specifically Alameda and Contra Costa counties), we felt that a similarly limited geographic scope would be inappropriate for EOL, since there is little data to suggest that the scrapping and recycling of these buses would take place within California. As such, we used the national average electricity mix rather than the CA average electricity mix when determining carbon intensity of electricity.

Our findings are shown in Figure 8. Using a conversion ratio of 3.6MJ/1kWh, we calculated energy cost in terms of kWh/kg of material recycled in order to more easily multiply that with carbon intensity of electricity. We found that recycling the steel chassis and the Li-ion batteries (especially for the higher capacity BEB battery) accounted for the overwhelming majority of the total emissions associated with EOL processing, owing to the proportion of the total weight of the buses that these components make up.

Figure 8. Energy Cost & Associated Carbon Emissions of End-of-Life Processing

Component / Material	**Mass of Component / Material (kg)**	**Energy Cost (kWh / kg of material)**	**kg CO_2 emitted / kg material**	**Total CO_2 emissions (kg)**
Steel Chassis	8600	3.72	1.675	14400

Steel Engine Block	769	3.72	1.675	1300
Carbon Fiber Composite	600	2.85	1.281	770
Li-ion Battery (BEB)	2120	9.63	4.331	9200
Li-ion Battery (FCEB)	680	9.63	4.331	2950
PbA Battery	24	1.61	0.725	20

VIII. Results and Findings

Our final results indicate that the Battery Electric Bus has the lowest life cycle emissions, and the Fuel Cell Electric Bus has the highest lifetime emissions. We saw the usage phase was especially high for the FCEB, which is due to the WTW emissions associated with the hydrogen fuel produced using steam reforming methane (SRM). The BEB emissions during usage are especially low, owing to the fact that the CA average electricity mix informed the usage phase. We created figures to represent our results as a stacked bar graph showing the total (Figure 9) and a stacked bar graph showing the relative contribution of each stage (Figure 10).

Figure 9. Life Cycle Emissions of Each Bus Type

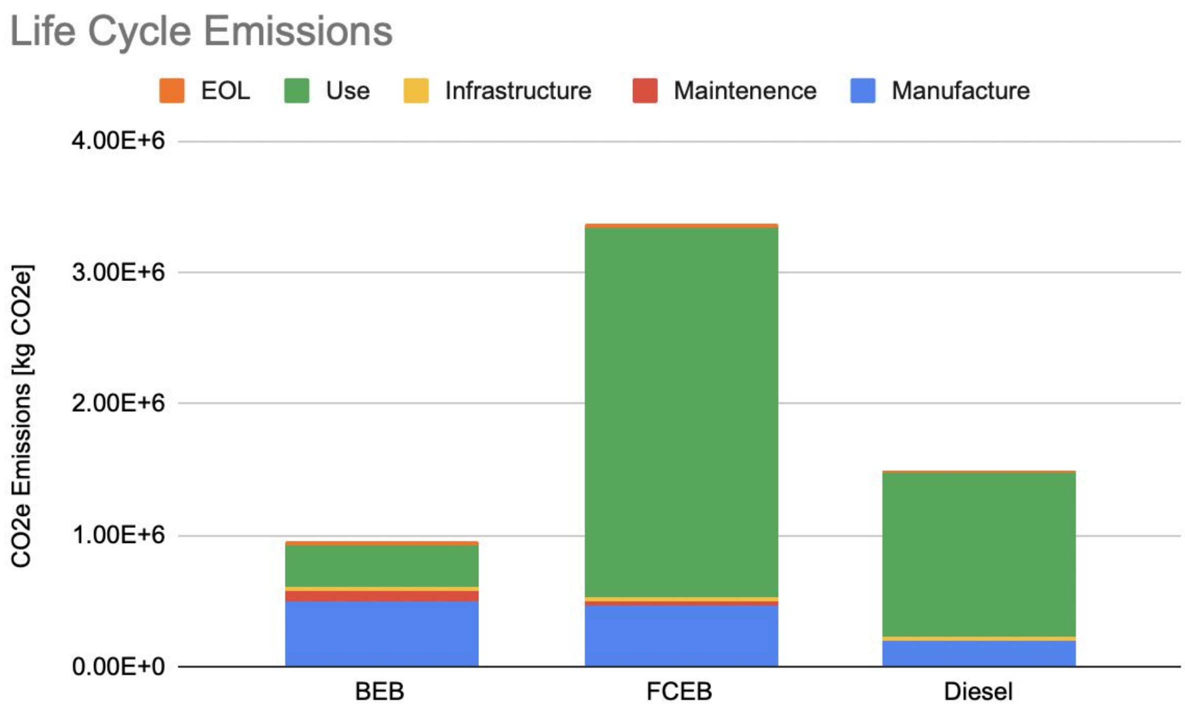


Figure 10. Emissions from each category as a percent of life cycle emissions

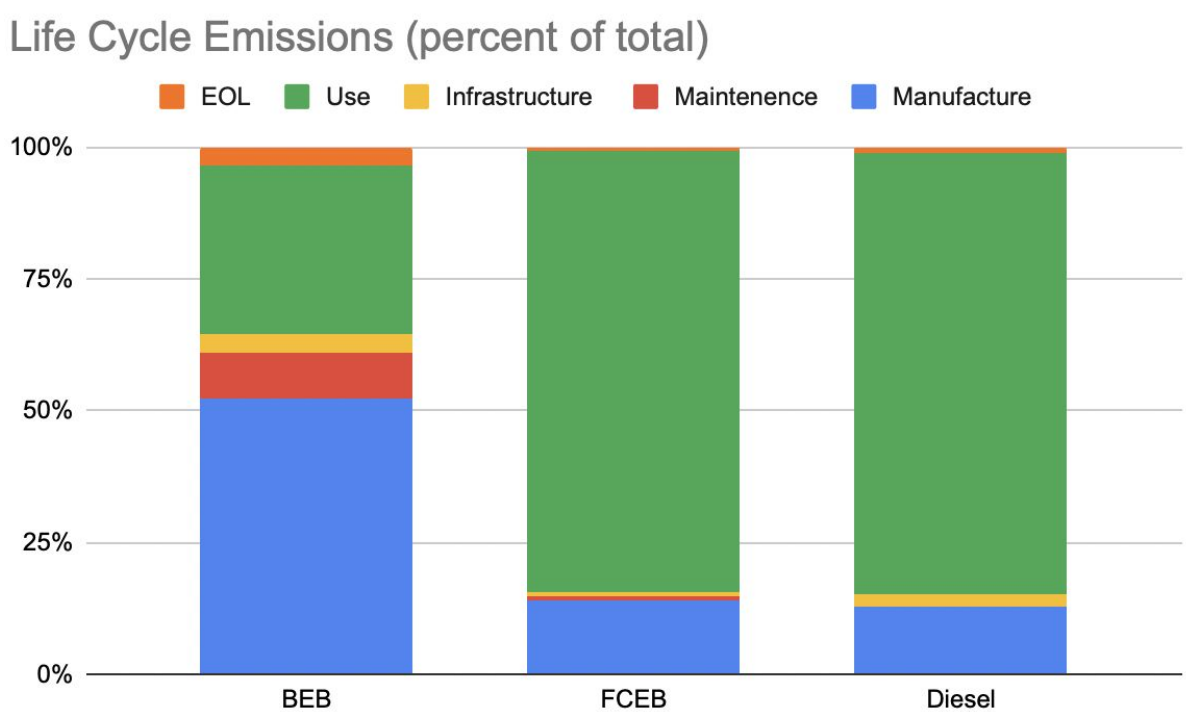


Figure 11. Final results for emissions per vehicle mile traveled for each bus

	BEB	FCEB	Diesel
Emissions [kg CO_2e/VMT]	1.9	6.7	3.0

Our final results indicated that the majority of impacts for FCEB and Diesel Buses come from the usage phase, whereas the majority of impacts for BEB come from the manufacturing phase. We also listed the kg CO_2e per vehicle mile travelled in Figure 11. We chose to analyze our GHG metric in terms of vehicle miles travelled rather than passenger mile travelled, since number passengers riding public transportation is uncertain in the wake of COVID-19. Maintenance in the BEB also poses a significant contribution to overall lifetime emissions, which is due to the replacement of the battery halfway through the lifetime.

IX. Sensitivity Analysis

We performed a sensitivity analysis to determine how the manufacturing phase and usage phase affect our final result. These findings are shown in Figure 12. Figure 13 is a legend for Figure 12. Our final result for this report was based off case "A1", which is a combination of Case A and Case 1. The infrastructure, maintenance, and EOL were constant across all these cases. The listed buses in Figure 12 indicate which bus had the lowest emissions overall for each case.

For Cases A and B, we altered the emissions associated with manufacturing of the main bus components (leaving special components unchanged). We changed the input into the EIO-LCA to an average of the costs of the three buses, which is equal to approximately $950,000. Changing the manufacturing phase emissions for the main bus components to a constant, average value does not have a significant impact on the final result.

For Cases 1-4, we changed the usage phase for the BEB and FCEB, which is detailed in Figure 13. In cases where electrolysis was used, FCEB has the lowest overall emissions, regardless of the electricity grid used to charge the BEB. This indicates that the largest factor affecting our final result is the production of the hydrogen fuel.

Figure 12. Sensitivity analysis of the impacts of manufacturing of main bus components and manufacturing of fuel for usage phase

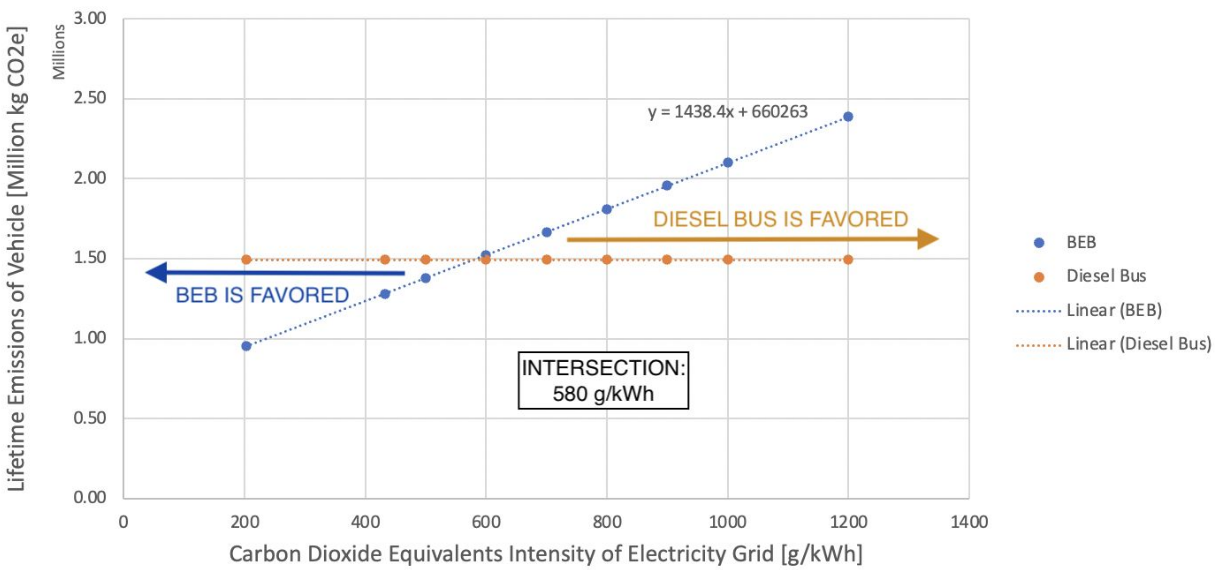
		Manufacturing Phase	
		Case A	**Case B**
Use Phase	**Case 1**	BEB	BEB
	Case 2	FCEB	FCEB
	Case 3	BEB	BEB
	Case 4	FCEB	FCEB

Figure 13. Legend for Figure 12

Case A	EIO-LCA based on cost *(default)*
Case B	Average EIO-LCA emissions from Case A used for all for main bus components
Case 1	CA electricity mix, steam reform methane *(default)*
Case 2	CA electricity mix, electrolysis using electricity from the CA average mix
Case 3	US electricity mix, steam reform methane
Case 4	US electricity mix, electrolysis using electricity from the CA average mix

After performing the first sensitivity analysis, we ran a more detailed analysis on how the production of electricity affected the overall BEB life cycle emissions. We kept the diesel bus emissions constant, and only changed the emissions associated with the electricity used to charge the BEB bus. For a value of 580 g/kWh for the electricity grid, Diesel and BEB are equal in total life cycle emissions. For values above this, the Diesel bus is favored; for values below, the BEB is favored. This is indicated in Figure 14.

Figure 14. Sensitivity Analysis of the lifetime emissions of Diesel Buses and BEB as a function of the GHG intensity of the electricity grid



To understand the sensitivity of the hydrogen fuel on the lifecycle emissions of the FCEB further, we performed a sensitivity analysis to assess what mix of SRM and electrolysis would make the lifecycle emissions of the FCEB equivalent to the BEB lifecycle emissions. We used the FCEB quantities to create an equation that finds what split between H_2 production methods would equal case A1 emissions for the BEB. The equations are:

$$951{,}644.95 = 549{,}9945.93 + 5.64(X) + 0.17(Y)$$
$$X + Y = 500{,}000$$

BEB Emissions = 951,644.95
FCEB Emissions w/out Use Phase = 549,9945.93
kg CO_2e /mi SRM = 5.64
kg CO_2e /mi Electrolysis = 0.17

X = miles run on SRM
Y = miles run on Electrolysis

Results:
X = **57, 897 miles**
Y = **442,103 miles**

This shows that FCEB and BEB are equal in emissions when the FCEB uses a mix of 88% electrolysis and 22% SRM over the course of its lifetime. As the percent of electrolysis increases, it becomes lower in lifecycle emissions than the BEB. As the percentage of SRM increases, it becomes higher in lifecycle emissions compared to BEB.

X. Uncertainty Assessment and Management

Data Quality

As discussed in (53), the pedigree matrix proves a concise, high-level representation of uncertainty surrounding different data inputs (Figure 15). This table provides an overview. Specifics on each data source are discussed in the corresponding section in Section VII, *Modeling Approach and Data*.

Figure 15. Pedigree Matrix (Data Quality Assessment). Each of the 6 quality categories (columns) are rated on a scale of 1 (highest quality) to 5 (lowest quality). For more information on the meaning of each number in the context of a specific category, please refer to (54).

	Acquisition Method	Independence of Data	Representative-ness	Temporal Correlation	Geographical Correlation	Technological Correlation

		Supplier				
Manufacturing						
Generic Bus Components	3	1	1	4	2	4
Li-Ion Batteries	2	1	1	2	2	3
H_2 Fuel Cells	2	2	3	1	1	1
H_2 Tank	3	1	3	2	4	3
Operations						
H_2 Production	3	1	1	1	2	3
Electricity Generation	3	1	1	1	2	3
Diesel Production	3	1	1	1	2	2
Maintenance						
Tire	3	1	1	3	2	3
Lead-Acid Battery	3	1	1	1	2	2
Li-Ion Batteries	3	1	1	1	2	3
Oil and Coolant	3	3	3	3	3	4
Infrastructure						
Charging	4	2	4	1	5	2
Fueling	4	1	4	4	3	4
Roadways	4	3	4	4	3	3
End-of-Life						
Chassis	3	4	2	1	2	1
Engine Block	2	2	2	1	2	1
H_2 Fuel Cell, Tank	3	2	3	1	3	2

Li-Ion Battery	3	2	2	3	2	5
Lead-Acid Battery	1	1	2	3	1	1

XI. Interpretation and Discussion of Results

Our findings show that use phase is the main component in determining GHG emissions for FCEB and diesel buses. We see that the emissions for these bus types are most impacted by the use phase, and altering the use phase results in a large change in the lifetime emissions. The emissions of the BEB are less impacted by the use phase, and more impacted by the manufacturing phase. This indicates that, in order to reduce the overall emissions associated with BEB, the best course of action would be to recycle the materials of the NMC Li-ion batteries.

As the US shifts towards renewable energy, the use phase emissions for many vehicles will fall and the manufacturing emissions will become increasingly important. We found very little available information for the manufacturing of general bus components, which is why we used the EIO-LCA tool. Because the lifecycle emissions of buses run on low-emitting fuels is mainly made up of manufacturing emissions, it is important to increase transparency and accessibility to this type of information. More research and life cycle assessments on buses that capture the manufacturing emissions with more granularity is important in continuing to improve LCA of public transportation. Policy makers may depend on these LCAs to make key decisions, so it is imperative accurate and granular data is used.

Access to databases such as Ecoinvent would have also been helpful in completing our analysis, but we were unable to use these databases due to the cost and time constraints. Free tools like WARM, GREET, and publicly available life cycle assessments were powerful tools for our analysis, and proved vital in coming to our conclusion. Accessibility of information is important for completing life cycle assessment research, whether as a project for a course, thesis work, or even a consumer trying to make well-informed decisions.

Recycling emissions are primarily dependent on the weight of the components, and the various components in our EOL analysis accounts for roughly 72% of the weight of the buses. We acknowledge that the plastic paneling, flooring, seating, windows, and rubber tires that make up the remaining 28% of the weight of the buses may have a noticeable impact on our analysis. However, lack of readily available data made it impossible to make reasonable assumptions both about the material composition as well as disposal or recycling methods, both of which will greatly influence our calculation. We regret the exclusion of the aforementioned components, but since any values associated with those components likely would have been wildly inaccurate due to the lack of information, we ultimately made the decision to omit them from our findings. Furthermore, while we ignored components with negligible weight and emissions, some of these components could become relevant in a cost-based EOL analysis. Including more exotic materials such as platinum from the fuel cell stack could produce greater financial returns from recycling.

XII. Conclusions and Recommendations

In this study, we compared the life cycle impacts from cradle to grave of the electric, hydrogen, and diesel buses in Alameda and Contra Costa Counties. We found that BEB had the lowest GHG emissions, largely due to the significant impact of fuel production. Hydrogen used in East Bay bus fueling stations is produced via steam reforming of methane (SRM), a process carrying significant impact from the eponymous methane. At the simplest level, it appears that BEB are the preferred solution.

In any US state where the GHG intensity of the electricity mix is below 590 g/kWh, we make the recommendation to shift their vehicle fleet to BEB. The shift to FCEB would only be feasible in the case that ~90% of the hydrogen fuel is produced through electrolysis, which would use the electricity from the local grid or renewable energy such as solar and wind. This percentage could change as a function of the electricity grid GHG intensity. We did not analyze other environmental impacts in our assessment, but one in particular to consider for hydrogen fuel produced through electrolysis is the impact on water demand. Electrolysis requires very pure, clean water which is an environmental impact not captured by the GHG intensity measurement. Taking water demand into account could lead to BEB being the more sustainable option even in cases where FCEB has a lower life cycle GHG emissions, due to the water demand of electrolysis. More research would need to be done on this topic in order to make a recommendation on the sustainability of FCEB.

Presenting another opportunity, the BEB and FCEB life cycles, unlike diesel, have the capability to sequester carbon. BEBs and FCEBs have no emissions at the tailpipe, but instead during production at centralized facilities. Here, technologies like scrubbers and other carbon capture and sequestration tools may allow for “dirtier” fuels to be used for the buses so long as the emissions are captured and not just vented to the environment. Unfortunately, capturing carbon and other air pollutants and GHGs before releasing gases to the environment is not always the status quo, which then poses many equity concerns.

In the case of the Bay Area, there are important climate equity challenges related to hydrogen production via SRM. Chevron’s Richmond Refinery in Richmond, CA has undergone a series of expansions to allow for onsite hydrogen production from natural gas since 2011 (83), and it is conceivable that AC Transit will choose to source hydrogen for the FCEB from the Refinery. However, there are ongoing environmental justice issues surrounding the continued operation of Chevron’s Richmond Refinery. It is the largest emitter of GHGs in the entire state (84), has been implicated in numerous toxic spills and chemical releases (85), and has been subject to multiple large scale industrial accidents that released massive amounts of smoke and particulate pollutants into the air. These accidents necessitated shelter-in-place orders for nearby residents, especially for those situated in predominantly BIPOC and low-income communities surrounding the Refinery. Should the Refinery ramp up hydrogen production to meet the increased demand from FCEBs, environmental injustices like these - or worse - will likely be perpetuated.

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