Transportation Consortium of South-Central States

Tran-SET

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Life Cycle Environmental Impact of Houston METRO System – Evaluation of Electric Alternatives

Project No. 19PPPVU01

Lead University: Prairie View A&M University

Final Report

August 2020

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16. Abstract

In the Greater Houston Area, mobile sources (on- and off-road vehicles) contribute the highest share of nitrogen oxide (NOx) emissions and second-highest share of volatile organic (VOC) emissions. The Houston METRO system is a key element in Houston's infrastructure that can be expanded to lower emissions of criteria air pollutants (CAPs) and greenhouse gases (GHGs) and improve regional air quality. Currently, there is no comparative study for relative emissions and environmental impacts between passenger automobiles and METRO routes in Houston. Our research addressed this critical gap and developed environmental life cycle assessment for conventional diesel buses, diesel hybrid buses, and alternative electric buses in Houston using the GREET model. The life cycle GHG emissions of electric buses are slightly lower than the other two types of buses. However, all the other major emissions such as CO, NO_x, PM_{10}, $PM_{2.5}$, VOCs, SO_x, N_2O, CH_4, black carbon and primary organic carbon associated with electric buses are higher than diesel buses, thus causing higher environmental cost of electric buses than diesel buses. The life cycle costs of buses are very sensitive to future diesel and electricity prices. The results from this project would serve as a guiding framework to evaluate the effects of the decision to expand the METRO system and estimate the contribution of the METRO system in realizing the Greater Houston Area's environmental objectives.

17. Key Words

Electric bus, Life cycle assessment, greenhouse gas emissions

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

CAPs	criteria air pollutants
GHG	greenhouse gases
LCA	life cycle assessment
LCC	life cycle cost
VOC	volatile organic carbon

EXECUTIVE SUMMARY

Public transportation systems reduce the total emissions of criteria air pollutants (CAPs) from urban centers and form an integral part of environmental strategies to combat climate change. A comprehensive energy and environmental life cycle assessment (LCA) study is vital to quantify the improvements and identify any potential systemic modifications that could further lower environmental impact. As per EPA's 2014 National Emission Inventory, mobile sources (on- and off-road vehicles) contributed the highest share (67%) of nitrogen oxide (NOx) emissions and the second-highest share (23%) of volatile organic carbon (VOC) emissions in the Greater Houston Area. This region has historically been affected by severe summer ozone episodes that impact public health and welfare.

The Houston METRO system is a key element in Houston's infrastructure that can be expanded to lower emissions of CAPs and GHGs, and improve regional air quality. Currently, there is no comparative study for relative emissions and environmental impacts between passenger automobiles and METRO routes in Houston. Our research addressed this critical gap and developed environmental life cycle assessment (LCA) for conventional diesel buses, diesel hybrid buses, and alternative electric buses using the GREET model. This research provided quantitative estimates for energy and water use, life cycle emissions of greenhouse gas (GHG) CAP, black carbon and primary organic carbon, environmental cost, and life cycle cost when switching the fleet of conventional diesel buses and diesel hybrid buses to electric vehicles.

Our study of LCA shows that electric buses have a slightly lower life cycle GHG emissions than conventional diesel buses, but higher than diesel hybrid buses. All the other major emissions such as CO, NOx, PM_{10}, $PM_{2.5}$, VOCs, SO_x, N_2O, methane, black carbon, and primary organic carbon associated with electric buses are higher than both types of diesel buses. In the life cycle cost analysis, at the end of the 24th year, the electric bus system has the lowest costs among the three types of buses. However, their life cycle costs are very sensitive to the prices of diesel and electricity in the future. Also, the environmental cost analyses are performed for the suggested transportation options. The results show that annual environmental cost saving can be over $1.0M by choosing the transportation options with fewer emissions in the Greater Houston Area. The results from this project would serve as a guiding framework to evaluate the effects of the decision to expand the METRO system, and estimate the contribution of the METRO system in realizing the environmental objectives of the Greater Houston Area.

1. INTRODUCTION

Urban mass transit systems are a valuable infrastructure component that alleviates road traffic congestion and reduces environmental impacts from passenger transportation. The Greater Houston area comprising 9 counties has a population of 6.9 million and is served by the Metropolitan Transit Authority of Harris County (METRO). Houston METRO operates buses along 86 routes, categorized as red (28 routes), blue (21 routes), green (30 routes), and other networks (*1; 2*). Three light rail lines, red (13 miles, 51,039 passengers/day), purple (6.6 miles), and green lines, have an average daily ridership of 61,000 passengers collectively as of June 2018 (*2*). Public transportation systems reduce the total emissions of greenhouse gases (GHGs) and criteria air pollutants (CAPs) from urban centers and form an integral part of environmental strategies to combat climate change (*3*). However, a comprehensive energy and environmental life cycle assessment (LCA) study is vital to quantify these improvements and identify any potential systemic modifications that could further lower the environmental impact of transportation infrastructure. As per EPA's 2014 National Emission Inventory, mobile sources (on- and off-road vehicles) contributed to the highest share (67%) of nitrogen oxide (NOx) emissions and second-highest share (23%) of volatile organic (VOC) emissions in the Houston-Galveston-Brazoria (HGB) Area (*4*).

This region has historically been affected by severe summer ozone episodes that impact public health and welfare (*5*). Currently, the Houston-Galveston-Brazoria Area is classified as a marginal nonattainment region for the 2015 ozone standard of 0.07 ppm, as of August 3, 2018 (*5*). The METRO system is a critical element in 'Houston's infrastructure that can be expanded to lower emissions of CAPs and GHGs, and improve regional air quality. However, any expansion of the METRO system includes upfront infrastructure and supply chain processes that need to be considered when evaluating environmental impact. Currently, there is a lack of quality data on the comprehensive energy and environmental impacts of the METRO system. Also, comparative studies for relative emissions and environmental impacts between passenger automobiles and METRO routes in Houston are non-existent. Our research addressed this critical gap., We developed environmental life cycle assessment and cost analysis for the buses operated by METRO, and provided quantitative estimates for GHG and CAP emissions when considering the fleet modification to electric vehicles. The results would serve as a guiding framework to evaluate the effects of the decision to expand the METRO system and estimate the contribution of the METRO system in realizing the environmental objectives of the Greater Houston Area.

2. OBJECTIVES

The overall goal of this study is to provide an estimate of the energy and environmental impacts from the total life cycle of the Houston METRO system and provide a cost-benefit analysis for an electrification alternative. The following are the primary objectives that constitute in realizing the overall goal:

1) Estimate the total GHG and CAP emissions from the current operational routes of the diesel buses of the Houston METRO system;
2) Quantify the total energy and environmental impact resulting from Houston METRO;
3) Evaluate the net change in energy, environmental impact, and cost due to transitioning of the METRO fleet to electric vehicles;
4) Determine the impact of electrification and expansion of the Houston METRO system on regional air quality and global warming potential;
5) Compare the improvements in sustainability resulting from varying degrees of traffic migration/passenger adoption from automobiles;
6) Provide guidance to stakeholders, community leaders within Houston on the adoption of electric vehicles, and the expansion of METRO ridership.

3. LITERATURE REVIEW

Vehicles using diesel and gasoline fossil fuels are the second largest contributor of GHG emission in the U.S., contributing about 27% of the total GHGs. Not only the GHG emissions, vehicles also significantly emit other air pollutants from their tailpipes, such as VOCs, CO, NOx, PM10, PM2.5, etc. To reduce and control air pollution in metropolitan areas, many cities worldwide have promoted or planned to promote to replace conventional public transportation buses with electric buses. To assess the comprehensive environmental impact from alternative modes of transport, indirect effects and supply chains need to be considered, in addition to tailpipe emissions.

Life cycle assessment (LCA) is a valuable tool that provides decision-makers with information needed to evaluate the direct and indirect impacts of transportation systems. Chester et al. (2013) conducted near-term and long-term life cycle impact assessments for the new bus rapid transit and light rail lines in Los Angeles (*6*). Chester et al. (2013) considered Orange Line Bus Rapid Transit (BRT), which is an 18-mile right-of-way in the San Fernando Valley, and Gold Light Rail Transit (LRT), which is 19.7 miles and 21 stations. This study considered reduced automobile travel as a case scenario and estimated reductions in energy and emissions of GHGs and CAPs, also conducted assessments for potential smog and respiratory impacts. Results from this study indicate that infrastructure construction and energy production stages significantly increase the environmental footprint of transit systems by 48-100% in energy and GHG emissions. The most likely scenarios for reducing impacts from transit systems were identified as the adoption of emerging technologies and renewable sources for electricity production. The minimum migration ratios of passengers from existing modes of transport to new mass transit systems to achieve environmental equivalence were calculated to be 20–30% of full capacity. Although this study indicates a significant GHG emissions reduction from the transit system, $PM_{2.5}$ emissions have the potential to increase, thereby increasing the stress on achieving air quality compliance. The Gold LRT line had a higher impact potential in respiratory inorganics due to the electricity generation from coal in the source mix.

Chester et al. (2012) developed a report to guide researchers and decision-makers through the process of identifying sources, inventorying impacts, and interpreting the results of LCA for transportation projects (*7*). This report identifies primary effects of LCA analysis as mode-shift, reduction in fuel consumption and reduction in auto-ownership, and secondary effects as ridership time, increased densification, and ancillary modes of transport such as biking. Recently, Correa et al. (2016) compare energy demands and environmental impacts of diesel, hybrid, hydrogen, and electric urban buses in Argentina, Chile, and Brazil. They found that electric buses are markedly superior in the tank-to-wheel step and that the focus should be on the production of clean energy within the electricity mix (*8*).

Life cycle cost (LCC) is an estimate of the total purchasing, operating, maintenance, and salvage cost of an alternative over the life span. The environmental impacts and life cycle cost of electric buses have widely been investigated, including technology exploration (*8-17*), case studies in both developed and developing counties (*18-26*), and its cost analysis and replacement strategies (*12; 19; 21; 24; 27-30*). In a case study of public electric buses in Macau, it was reported that electric buses in Macau hardly reduced the greenhouse gas emissions with the current electricity mix and that the emissions could be improved with the use of more natural gas and solar power (*22*). Bi et al. firstly studied the life cycle greenhouse gas emissions of plug-in electric buses versus wireless-charged electric buses in the Ann Arbor–Ypsilanti metro area in Michigan (*31*), and integrated life cycle cost analysis with the previous LCA for both types of electric buses later (*29*). They found that wireless-chared buses have a lower cost of US$0.99 per bus-kilometer among the four bus systems of conventional diesel, diesel hybrid, plug-in electric, and wireless-charged electric bus systems.

After we contacted the administrator of Houston Metro, they kindly provided the bus information of route (Local and Park & Ride) and daily mileage (Local and Park & Ride) by route.

- The total number of diesel buses operated by METRO is 1127.
- The seating capacity of each bus type is:
    - i. New Flyer 40 foot – 34
    - ii. Orion 40 foot – 39
    - iii. NABI 40 foot – 36
    - iv. Nova 60 foot – 55
    - v. MCI 45 foot – 55
    - vi. Nova 40 foot - 35
- The total amount of diesel used by local buses daily, monthly, and yearly:
    - In FY19 was approximately 8,800,000 gallons, 24,110 daily, 733,330 monthly.
- The total amount of diesel used by buses running in the Park & Ride routes daily, monthly, and yearly:
    - In FY19 was approximately 2,934,000 gallons, 11,285 daily, 244,500 monthly.

4. METHODOLOGY

4.1 Define Goal & Scope

This study aims to evaluate environmental impacts and life cycle cost resulting from replacing conventional diesel buses with electric buses in the Houston METRO system. This study's geographic scope is limited to 9 counties comprising the Greater Houston metropolitan statistical area (MSA). This project's environmental scope incorporates air pollutants emitted from bus tailpipes and other significant pollutants to air, water, and soil associated with diesel use and electricity generation. The life cycle cost will be evaluated from replacing a single diesel bus to bulk bus replacement.

4.2 Set System boundary & Functional unit

The system boundary of a diesel bus and electric bus covers the three major components: manufacture of vehicles, fuel use (including diesel production, electricity generation and charging infrastructure), and vehicle maintenance. The integrated life cycle environmental and cost analysis is to both diesel and electric bus systems. The function units of environmental impacts are various life cycle emissions per mile, e.g., CO_2 in kg/mi, NO_x in g/mi, $PM_{10,}$ and $PM_{2.5}$ in mg/mi. The life cycle cost of a conventional diesel bus, diesel hybrid bus, and electric bus is estimated for 24 years, i.e., two life cycles of vehicles or three life cycles of electric bus batteries, in U.S. dollars.

4.3 Build the Life-Cycle Inventory

The initial life cycle inventories of low-sulfur diesel and electric transit bus operations were built from GREET 2019 model, as shown in Appendix Tables A-1 and A-2. GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) was developed and maintained by Argonne National Laboratory. It allows researchers and analysts to evaluate the various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis. GREET includes more than 80 vehicle/fuel systems covering various vehicle technologies: conventional spark-ignition engine vehicles; spark-ignition, direct-injection engine vehicles; compression-ignition, direct-injection engine vehicles; hybrid electric vehicles; plug-in hybrid electric vehicles; spark-ignition engines; compression-ignition engines; spark-ignition engines; compression-ignition engines; battery-powered electric vehicles; fuel-cell vehicles. Since the first version of GREET was released in 1996, it has widely been used to conduct LCA of various vehicles, including electric vehicles all over the world *(32-38)*. Specifically, it has been used for the environmental evaluation of different bus systems, including conventional buses, plug-in electric buses, and fuel-cell buses (*30; 39-43*). In SimaPro, life cycle emission inventories of major vehicles were taken from the GREET model. Although it was proposed to use SimaPro to conduct LCA of electric buses in our project proposal. After a thorough review of the literature and realizing the advantages of the GREET model for fuel vehicle evaluation compared to SimaPro, we decided to use the GREET Model instead of SimaPro as proposed. Our electric bus model has been determined as BYD K9 40′ Electric Transit Bus, and its technological specific data is listed in Table 1.

Table 1. Technological specification of electric bus

Dimension		**Performance**		**Powertrain**	
Length	40.2 ft	Top Speed	62.5 mph	Motor Type	.C.A.C. Synchronous
Width	101.6 in	Max. Grade ability	⩾17%	Max Power	150 kW×2
Height	134 in	Range	Up to 157 miles / Up to 177 miles (high capacity)	Max Torque	550 N·m×2
Wheelbase	246.1 in	Turning Radius	<44 ft.	Battery Type	Iron Phosphate
Curb Weight	30,975 lbs	Approach/Departure Angle	⩾8.6° / ⩾8.6°	Battery Capacity	352 kWh
Gross Weight	43,431 lbs			Charging Capacity	80 kW
Seats	37+1			Charging Time	4.5-5 hrs
Wheelchair Positions	2 ADA compliant				

In the GREET 2019, municipal buses are modeled as a transit bus, which is typically 40-45 feet long. When low sulfur diesel is used for a conventional transit bus, the fuel efficiency is 4.4 mi/gal, and the efficiency of a diesel hybrid transit bus is 5.3 mi/gal. In the GREET model, the simulation of electric buses was developed from the baseline of a conventional diesel bus by changing the power source and adapting a bus battery pack with some necessary adjustments for bus electrification. According to the LCA research of electric buses conducted for the Ann Arbor and Ypsilanti area in Michigan, a reasonable battery weight is 3525 kg, equivalent to 458 kWh. (*31*). The battery-to-wheel energy consumption rate of a plug-in electric bus is 2.35 kWh/mile. The input parameters of the electric bus system are demonstrated in Table 2. In the table, SOC (state of charge) is the level of charge of an electric battery relative to its capacity.

Table 2. Life cycle input parameters of lug-in electric buses (per bus)

Life cycle input parameter	**Value**	**Unit**
Life of bus	12	years
Life of plug-in charger	24	years
Days of operation/year	365	days/year
Curb weight of plug-in charged bus	14,000	kg
Average weight of passengers, driver, and cargo	1,000	kg
Battery-to-wheel energy consumption rate of plug-in bus	2.35	kWh/mi
SOC Range (*SOCR*)	60%	percent
Lithium iron phosphate battery specific energy	0.13	kWh/kg
Plug-in charging efficiency	90%	percent
Plug-in charging power	60	kW
Lightweighting correlation: % energy reduction/10% electric bus mass reduction	4.50%	percent
Battery cycle life	3000	cycles
battery: cycle/day	1	cycle/day
Battery charge/discharge efficiency	90%	percent

Life cycle cost (LCC) analyses of electric buses, conventional diesel buses, and diesel hybrid buses used in Houston were conducted by Integrating with LCA. The integration is demonstrated in Figure 1. The production of electric buses (excluding the batteries), use-phase maintenance, and battery recycling are only relevant to the LCC analysis. Some results from previous LCA were used as input parameters in the LCC analysis. The time horizon for the LCC analysis is 24 years, which is twice the life of a bus and the same as the techno-economic life of chargers. Common cost parameters shared by the three systems are summarized in Table 3, and specific cost parameters for each system are listed in Table 4and classified as capital and operation costs (*29*). The night electricity rate of $0.0773 is used in the cost calculations because we assume that it is enough for the electric buses to be charged for one time at night. In Table 3, a negative inflation rate means the price is deflating.

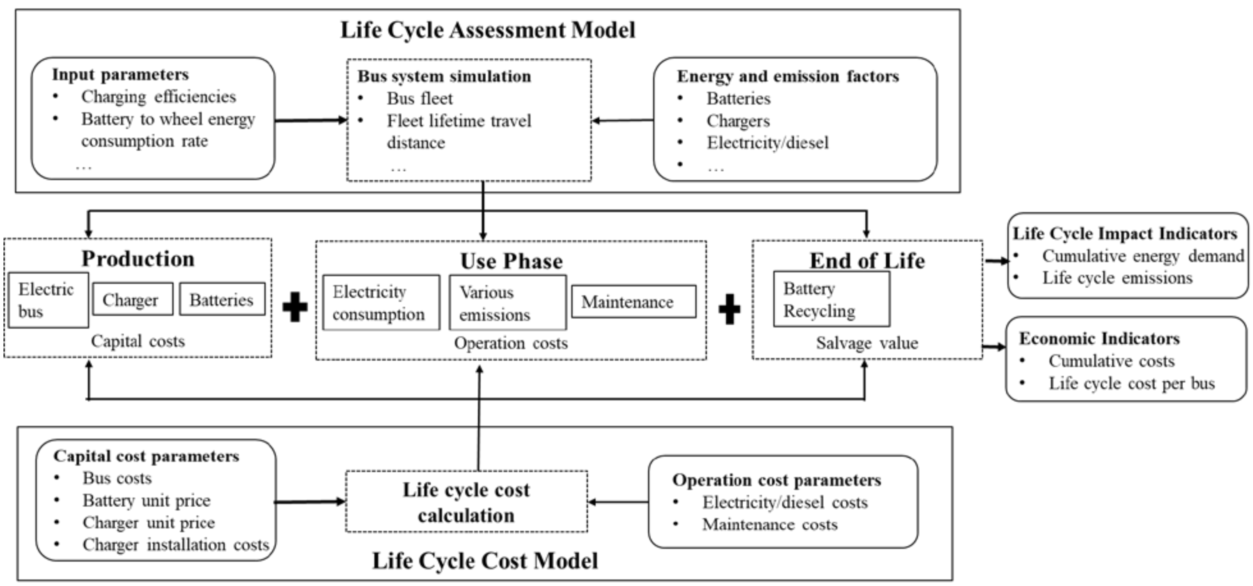

Figure 1. Integration of life cycle assessment and life cycle cost analysis of three bus systems in Houston

Table 3. General cost parameters for the life cycle cost analysis

Name	Value	Unit
Unit price of a battery pack	500	$/kWh
Average Houston commercial electricity rate	0.0766	$/kWh
Diesel price	3.14	$/gal
Fuel economy of a conventional diesel bus	4.4	miles/gal
Fuel economy of a hybrid bus	5.3	miles/gal
Discount rate (20-year, nominal)	3.60%	percent
Annual inflation rate of lithium-ion battery	-9%	percent
Annual inflation rate of electricity rate	2%	percent
Annual inflation rate of diesel	5.84%	percent

Capital costs include bus and battery procurement, charger procurement, and chargers' installation in the bus night-parking areas of Houston Metro. Batteries were assumed to be replaced every 8 years, and buses (excluding the batteries) were assumed to be replaced every 12 years. Operation costs include energy costs and maintenance costs. Operation costs were assumed to be paid at the end of each year. Other use-phase costs, including driver wages and vehicle insurance/warranty, were assumed to be the same for the three bus systems, thus not included in the comparison. Annual maintenance costs cover two parts: maintenance of facilities and infrastructure and maintenance of vehicle propulsion or powertrain systems. Subsidies provided by the Federal, the state of Texas, and the Houston council for purchasing electric buses were not considered. Because there are about 1,200 diesel buses operated in Houston Metro, and 40% of diesel buses have been updated to hybrid buses. Houston Metro can't replace all the diesel buses with electric buses at one time. In our cost analysis, we assumed that 500 electric buses would be purchased in 2020, and the calculations were compared with the same number of conventional and diesel hybrid buses.

Table 4. Cost parameters and intermediate calculated values for life cycle cost analysis

Name	**Unit**	**Electric**	**Conventional**	**Hybrid**
Capital costs				
Procurement of a bus	$	500,000	455,298	615,763
Procurement of a battery pack (average)	$	229,125	-	35,000
Procurement of a plug-in charger (60 kW)	$	8,000	-	-
Installation of a charger	$	1,000	-	-
Operation costs				
Energy: electricity (overnight)	$/fleet/year	6,245,410	-	-
Energy: diesel	$/fleet/year	-	14,345,925	11,639,149
Maintenance of facility & infrastructure	$/fleet/year	500,000	856,313	725,067
Maintenance of propulsion	$/fleet/year	2,631,627	2,703,239	2,631,627

For the plug-in electric bus system, use-phase electricity consumption E was calculated as Equation (1). Similarly, for conventional diesel and diesel hybrid buses, diesel consumption was calculated by dividing fleet travel distance by fuel economy. The electric and hybrid powertrains have better energy efficiencies compared to conventional diesel powertrains.

$$E = k * D/\eta_b/\eta_c \quad (1)$$

Where k is battery-to-wheel energy consumption rate in kWh/mile, η_c is charging efficiency of the charger (%), η_b is charge/discharge efficiency of battery (%), and D is fleet travel distance in miles.

5. ANALYSIS AND FINDINGS

5.1 Life cycle assessment of electric buses, conventional diesel buses, and diesel hybrid buses in Houston

The resource share distribution of electricity generated in Texas (TRE) in 2020 is shown in Figure 2 according to the information of the Year 2019 from the U.S. Energy Information Administration (www.eia.gov). It is predicted to have the changing trend demonstrated in Figure 3, and it is available in the GREET 2019 model. In GREET 2019, the electric bus was build based on the conventional diesel bus, and the modeling details are demonstrated in Figure 3. The energy source is set up as TRE-distributed, which means the electricity mix in Texas. From 2020 to 2040, natural gas in the resource share of electricity generation in Texas would increase from 49.66% to 59.70%, and the coal use will decrease from 19.54% to 12.83%.

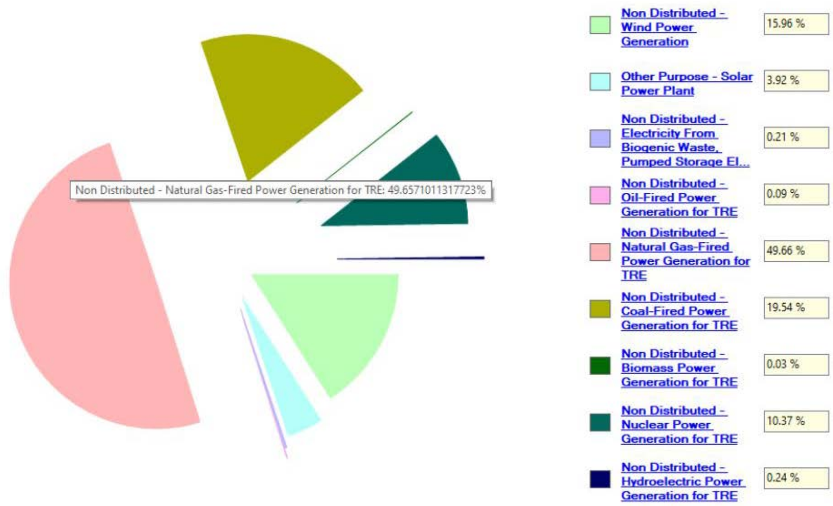

Figure 2. Resource share of electricity generation in Texas in 2020

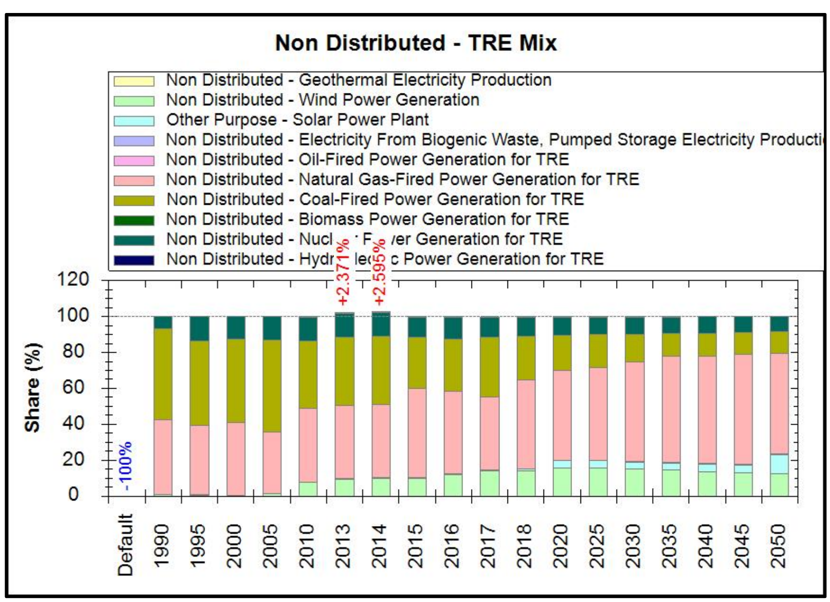

Figure 3. Time series of resource share of electricity generation in Texas

During the production of fuel, electricity, batteries, and vehicles, water as another necessary natural resource is consumed. In the GREET model, the water use is categorized as water reservoir evaporation, water used for cooling, water used for mining, and water used for material/product process. In our specific case of bus evaluation, the functional unit of cm^3/mi is used for the water use. For the different buses simulated in Houston, electric bus, conventional diesel bus, and diesel hybrid bus take the water use of 22,123, 2,537, and 2,106 cm^3/mi, respectively. We can see that electric buses use water 7.7-9.5 times than the other two types of diesel buses since the industry of electricity generation consumes much more water than diesel production. The percentage distribution of categorized water use for the three types of buses is shown in Figure 4. For the buses simulated for 2020, water reservoir evaluation takes most water use for electric buses, and water used in mining is the primary for both types of diesel buses.

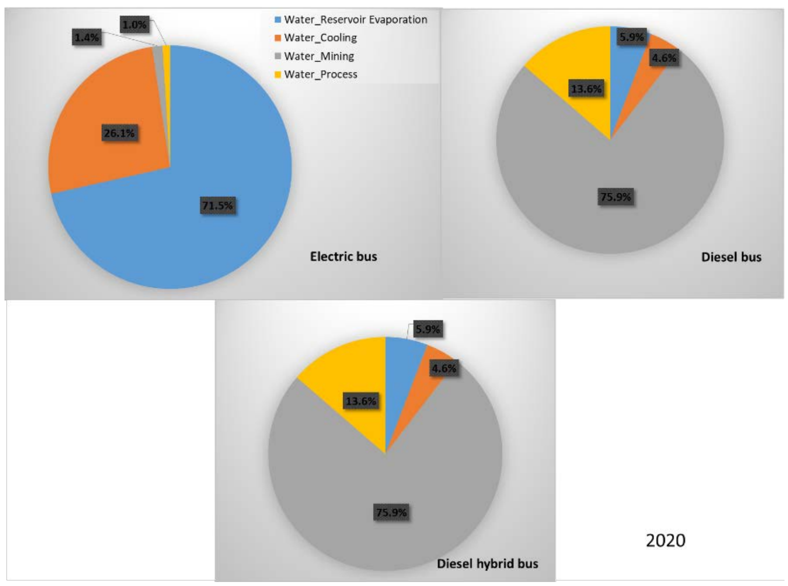

Figure 4. Percentage distribution of water use in categories for three types of buses in 2020

After running the simulations of conventional diesel, diesel hybrid, and electric buses operated in Houston with the GREET 2019 model, their life cycle emissions, including WTP, WTW, and total LCA, are obtained, where WTP means well to pump, WTW is well to wheel, and total LCA means the simulations include electric battery packs and plug-in charges used for electric buses. The emissions and differences of total LCA between the three types of buses in 2020 are shown in Figure 4, and the emission units are present as emissions per mile. The energy consumption in the use phase, i.e., vehicle operation, was computed in LCA based on the fleet travel distance (*29*).

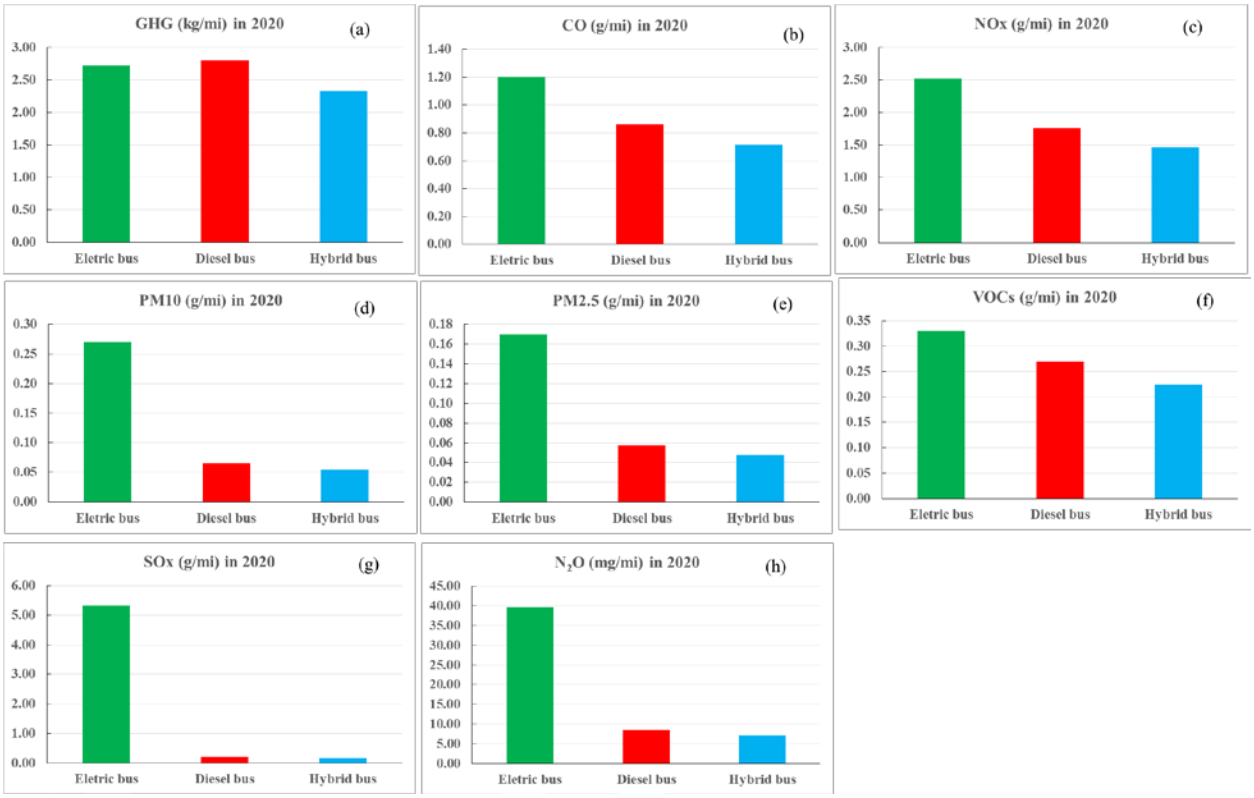

Figure 5. Life cycle emissions of conventional diesel, diesel hybrid, and electric buses of Houston in 2020

Concerning GHG emissions, there is a slightly lower for electric buses than conventional diesel buses, but higher than diesel hybrid buses. Our simulation results of GHG emissions are comparable to a recent study of bus electrification in Macau in which the GHG emissions of electric buses with the support of the current electricity mix are even higher than the conventional diesel buses (*22*). In our study, all the other major emissions such as CO, NOx, PM_{10}, $PM_{2.5}$, VOCs, SO_x, and N_2O associated with electric buses are higher than both types of diesel buses. It is well-known that the major emissions of conventional and diesel hybrid buses are from vehicle operation. For electric buses, although it is zero-emission during bus operation except for TBW (tire & brake wear) emissions, the life cycle emissions are mostly associated with electricity production. When conventional fossil fuels such as coal and natural gas are dominated in electricity supply, e.g., Texas (Figure 1), it is very difficult to reduce overall emissions. In 2020, natural gas takes almost 50% of the resource share in the power generation, and coal is about 20%. It looks like that the use of electric buses will transfer conventional bus emissions in the urban areas to the point-source emissions of power plants. In the case of power plants are located in the rural area, bus electrification will reduce the level of air pollution in cities. For Houston, the majority of electricity is provided by the biggest U.S. power plant, i.e., the W.A. Parish power plant, which is on the border of the megacity. Power fuels are almost 50% of coal and 50% of natural gas in the power plant. When only considering the electricity generated in the W.A. Parish power plant, the life cycle emissions of electric buses would be even worse compared to the scenario of the Texas electricity mix. In the future, electric buses would benefit the entire environment if more clean electricity is produced from wind and solar power.

Methane is estimated to have a global warming potential of 28–36 times that of CO_2 over 100 years. Black carbon forms through the incomplete combustion of fossil fuel, biofuel, and biomass, and it can cause human morbidity and premature mortality. Primary organic carbon refers specifically to the mass of carbon in the particulate matter (PM). Black carbon and Primary organic carbon are two major organic species in the composition of PM. The life cycle emissions of methane, black carbon, and primary organic carbon in 2020 are shown in Figure 5. Similar to the analysis of PM_{10} and $PM_{2.5}$, electric buses contribute to more emissions of methane, black carbon, and primary organic carbon relative to both types of diesel buses.

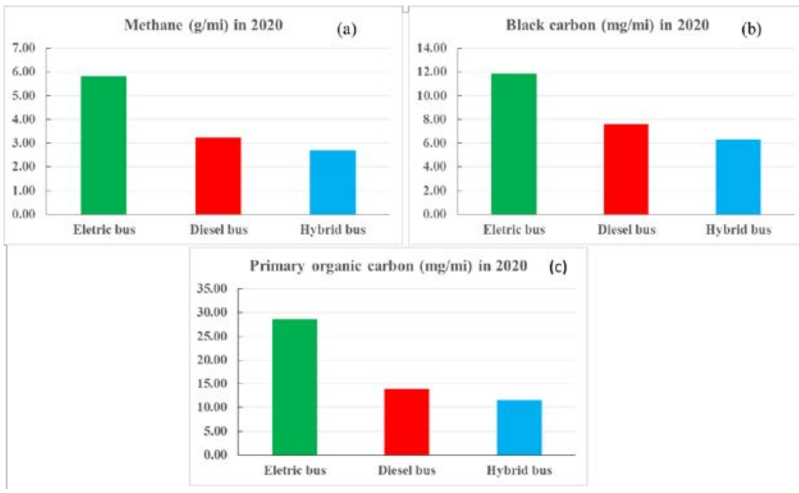

Figure 6. Life cycle emissions of methane, black carbon, and primary organic carbon in 2020

To explore what the life cycle emissions of electric buses will be in the future, LCA simulations of the three types of buses were also conducted for 2040. The categorized distribution of water use for the three types of buses in 2040 is demonstrated in Figure 7. Similar to the analysis for 2020, water reservoir evaporation will take the primary in the categorized water use for electric buses, and water used in mining will be the most for diesel buses in 2040. Compared to water use in 2020, electric buses will save 10.5%, and both types of diesel buses will save 3.1% in 2040.

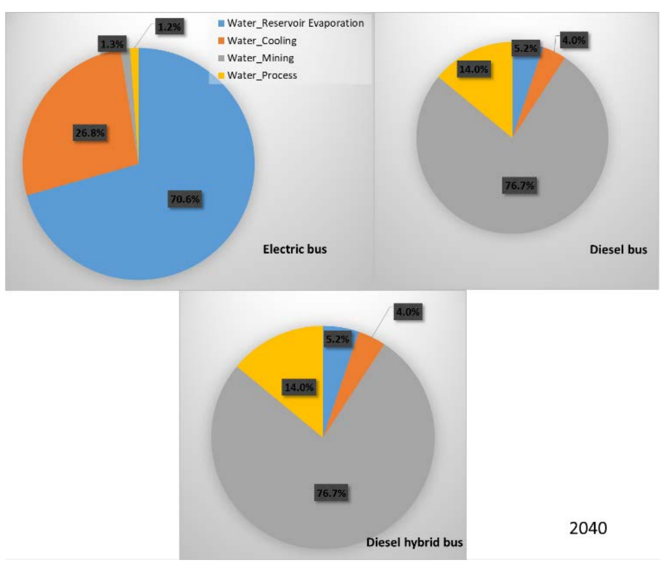

Figure 7. Percentage distribution of water use in categories for three types of buses in 2040

Figure 6 shows various life cycle emissions of buses in 2040. Compared to the emissions in 2020, all the emissions would keep the similar trends, i.e., GHG emissions of electric buses would be slightly lower than those of the other two types, and all the other emissions of electric buses would be higher than the corresponding items of the other two types. However, it would show some improvement in the emissions of electric buses in 2040. Compared to the emissions in 2020, SOx emissions would be lower by 31.5%, PM_{10} emissions would be lower by 25.9%, $PM_{2.5}$ emissions would be lower by 23.5%, and GHG emissions would be lower by 4.0%. It would be caused by almost 10% more natural gas used in electricity generation in Texas in the 2040s and the keeping decrease of coal use for electricity generation.

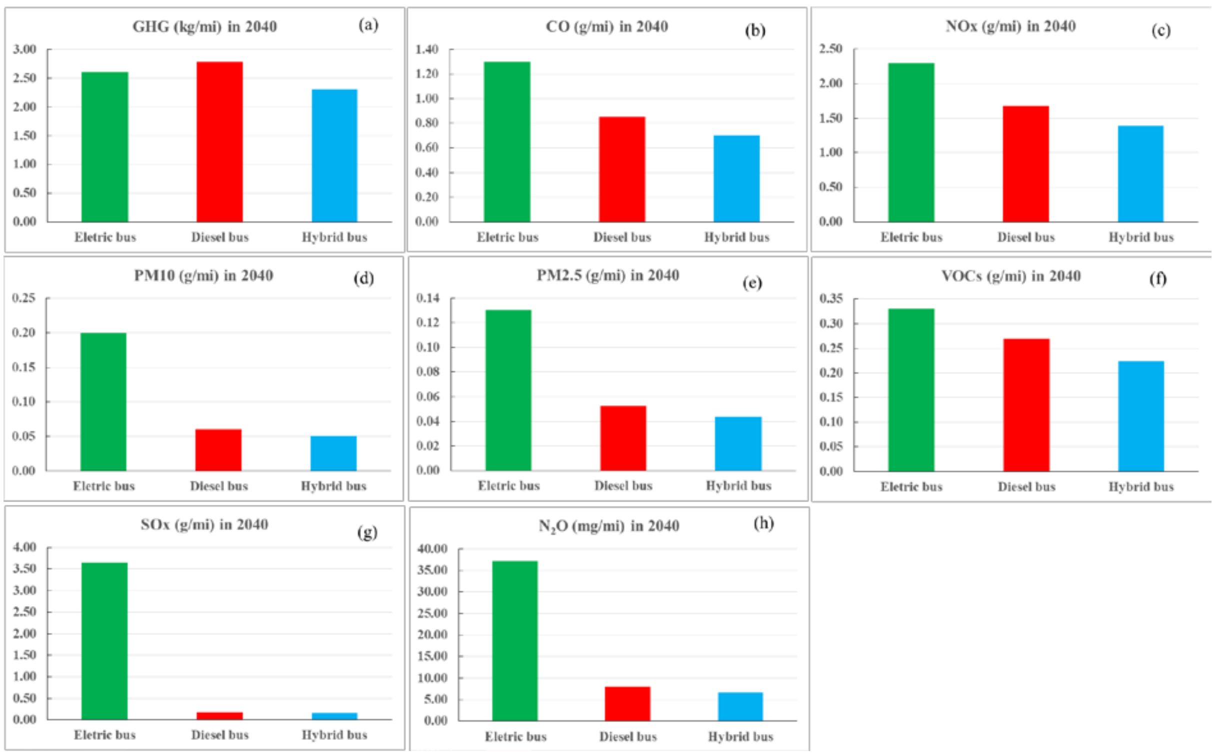

Figure 8. Life cycle emissions of conventional diesel, diesel hybrid, and electric buses of Houston in 2040

Figure 9 shows the life cycle emissions of methane, black carbon, and primary organic carbon for the three types of buses in 2040. Compared to the corresponding emissions of electric buses in 2020, the emissions of black carbon and primary organic carbon in 2040 would decrease by 8.2% and 8.3%, respectively. However, methane emissions will increase by 4.0% since about 10% more natural gas is used for power generation in 2040. With the technological improvement of diesel buses in the future, the emissions of methane, black carbon, and primary organic carbon in 2040 will decrease by 2.5%, 8.5%, and 14.8%, respectively.

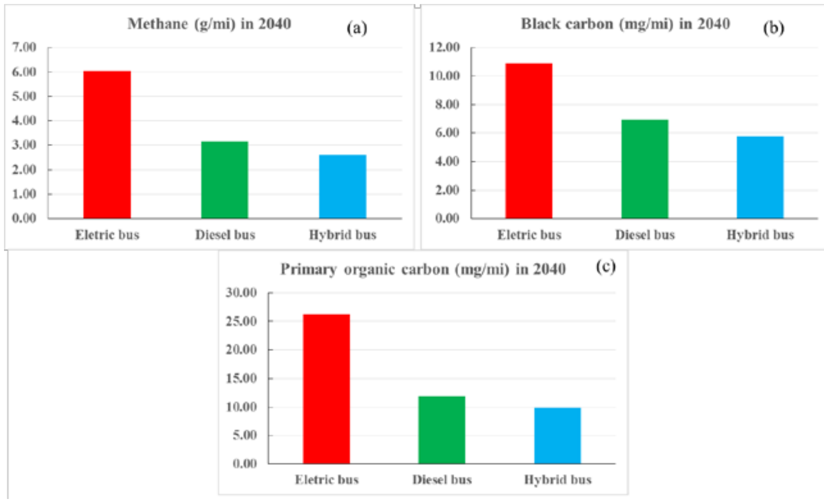

Figure 9. Life cycle emissions of methane, black carbon, and primary organic carbon in 2040

5.2 Life cycle cost analysis of electric buses, conventional diesel buses, and diesel hybrid buses used in Houston

Figure 6 shows the cumulative costs of plug-in electric, conventional diesel, and hybrid bus systems. In 2020 (Year 0, the beginning of the time horizon), the electric bus system has the highest capital cost, and the conventional pure diesel system has the lowest capital cost. We can see that the cost of a bus battery pack is almost half the price of an electric bus without a battery, and the annual inflation rate of lithium-ion batteries is -9%. It is surprising that at the end of the 24th year, the electric bus system has the lowest costs over the period with an entire life cycle cost of US$714.2 million, and that the diesel hybrid bus has the highest costs of US$889.9 million, and the second is the conventional diesel bus system at US$852.3 million. The differences in the fuel economy and annual inflation of electricity and diesel result in different fueling cost increases per year, reflected in the slopes of the curves. In the 8^{th} and 16^{th} years, battery replacements with battery installation costs occur for electric and hybrid buses, and in the 12th year, bus replacement is scheduled for all three types of buses by keeping the same batteries for electric and hybrid buses.

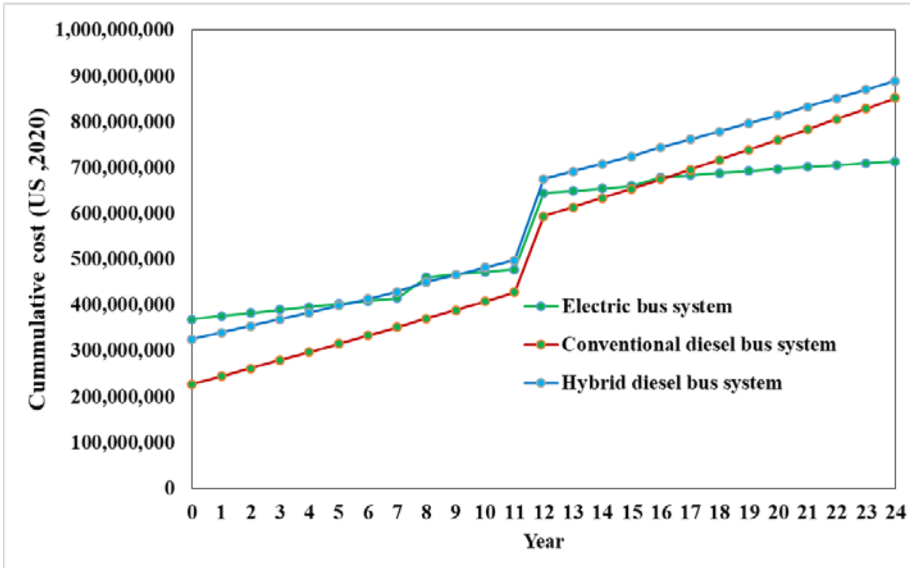

Figure 10. Cumulative costs of plug-in electric, conventional diesel, and diesel hybrid bus systems

The costs of electricity and diesel take the top priority in the LCC analysis. The final results are sensitive to the starting prices of diesel and electricity. In the past several decades, the price of electricity has steadily increased at an annual rate of about 2%. However, gas and diesel prices are more influenced by global economic conditions and some serious global events. Under the co-occurrence of the COVID-19 pandemic and the reduction of oil price prompted by OPEC (OPEC (Organization of the Petroleum Exporting Countries) in March 2020, gas and diesel prices have been running at a historic low price. Although the has diesel price climbed up since the end of March 2020, the average diesel price is about $2.10/gal in Houston, and it is about 33% lower than the pre-built model (*29*). When $2.10/gal is used in the LCC analysis by keeping other input parameters, the final life cycle cost of the conventional diesel bus system changes to the lowest. Figure 7 shows the cumulative costs of plug-in electric, conventional diesel, and diesel hybrid bus systems with the starting diesel price of $2.10/gal. The electric and conventional diesel bus systems have lower final costs than the diesel hybrid bus system similarly.

In the previous two cost evaluations, electricity and diesel have annual inflation rates of 2% and 5.84%, which also influence the final costs of the three bus systems significantly. Although U.S.EIA provides the annual inflation rates of electricity and diesel based on the statistical data in past decades, it is still very difficult to predict the annual inflation rate of diesel if the crude oil price drop happens again like March 2020 in the future. To remove the influence of both annual inflation rates, we also calculated the final costs by setting both as zero. We can see that there is no change in the order of the cumulative costs for the three bus systems starting from 2020 (Figure 8). From the beginning to the end, the conventional diesel bus system has the lowest cost, and the diesel hybrid bus system is the second lower.

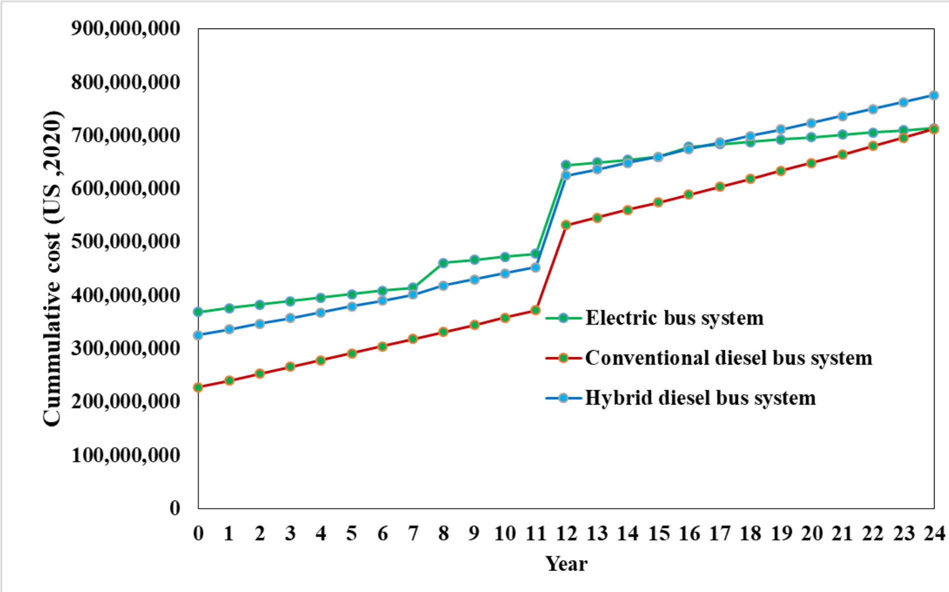

Figure 11 Cumulative costs of plug-in electric, conventional diesel, and diesel hybrid bus systems with the starting diesel price of $2.10/gal

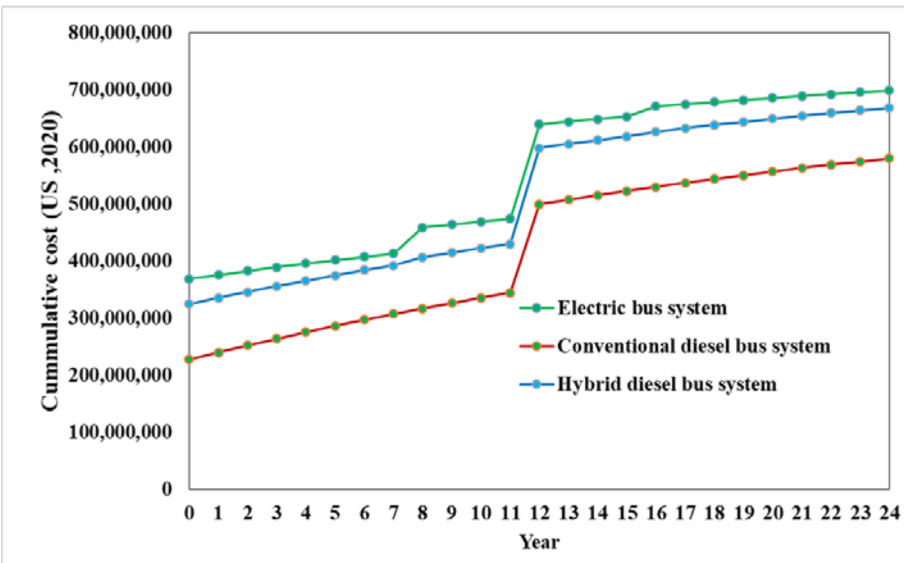

Figure 12 Cumulative costs of plug-in electric, conventional diesel, and diesel hybrid bus systems with the starting diesel price of $2.10/gal without considering the annual inflation of electricity and diesel

5.3 Environmental Cost Analysis

The environmental cost is calculated based on the P2 program developed by the Pacific Northwest Pollution Prevention Research Center (PPRC). P2 program stands for Pollution Prevention (P2) and is available through EPA (the United States Environmental Protection Agency) (*44*). The cost is a conversion of the various types of pollutants to financial values. P2 program originally covers a broad scope of cost savings related to water use, fuel use, soil waste, and air emissions. In this report, we investigated only the cost associated with air emissions as the goal of the project is to define the environmental impacts of alternative transportations. The calculated rate is an average of Texas state rates from a compilation of sources provided to Abt Associates by EPA. Sources include direct conversations between EPA and state Environmental Protection offices, and individual states' department website documents (*44*).

In this section, we estimated the annual net cost realized from emitting regulated air emissions for three different transportation options. Per P2 cost calculation, the environmental cost is calculated based on the total amount of Clean Air Act Title V air pollutants (*45*), which includes nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter of 10 micrometers or less (PM_{10}), volatile organic compounds (VOCs). The environmental cost can also be calculated based on hazardous air pollutants (HAPs) per P2, however, are out of the scope in this research. The cost estimation is estimated and displayed in Figures 13 and 14. It is estimated based on the annual miles per driver 13,476 miles (*46*) and the assumption of 22 passengers per bus. The assumption of the transportation population is 6.9 million in 2020 as discussed in Section 1 of this report and 9.6 million in 2040.

For example, the annual total emission of Clean Air Act Title V air pollutants in 2020 for the electric bus is estimated as 8.45 g/person-miles for the electric bus option based on Figure 5. The total emission per commuter is calculated as 13,476 miles×6.9 million×8.45 g/person-miles/22 (passenger per bus) = 35714.46 ton. Based on the annual emission amounts of 35714.46 tons, the environmental cost is calculated as $1,639,873.05 for the electric buses, as shown in Figure 13. Similarly, the environmental costs of diesel buses and diesel hybrid buses are calculated in 2020 and 2040 as displayed in Figures 13 and 14.

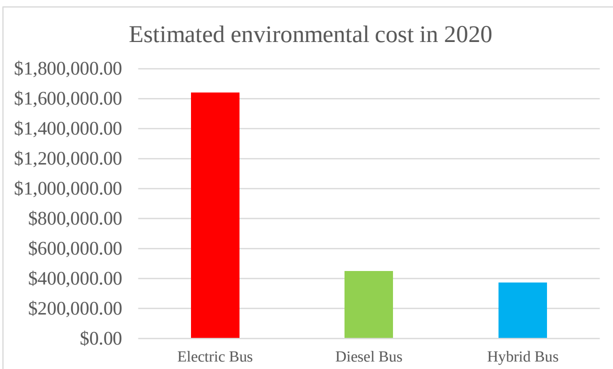

Figure 13 Annual environmental cost based on Clean Air Act Title V Air pollutants emissions in 2020

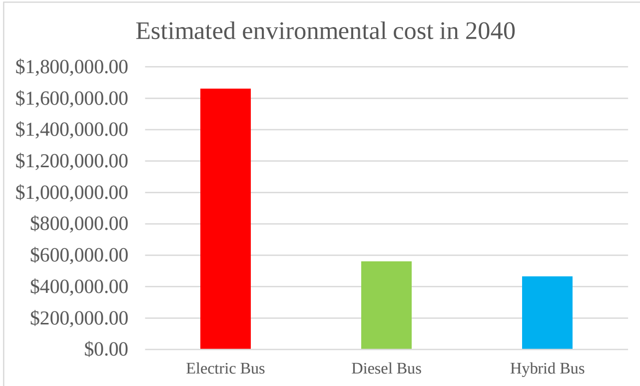

Figure 14 Annual environmental cost based on Clean Air Act Title V air pollutants emissions in 2040

Figures 15 and 16 show the annual environmental cost saving in both 2020 and 2040 compared to the electric bus, which produces the most amount of emissions. The estimated annual cost savings of diesel buses and diesel hybrid buses due to the fewer emissions in 2020 are $1,190,429.45 and $1,266,750.07, respectively. Similarly, the estimated environmental cost savings of diesel buses and diesel hybrid buses in 2040 are $1,097,927.73 and $1,193,122.72 respectively.

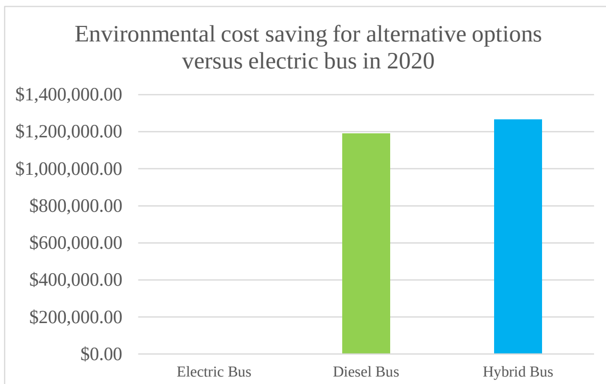

Figure 15 Annual environmental cost saving compared to electric bus in 2020

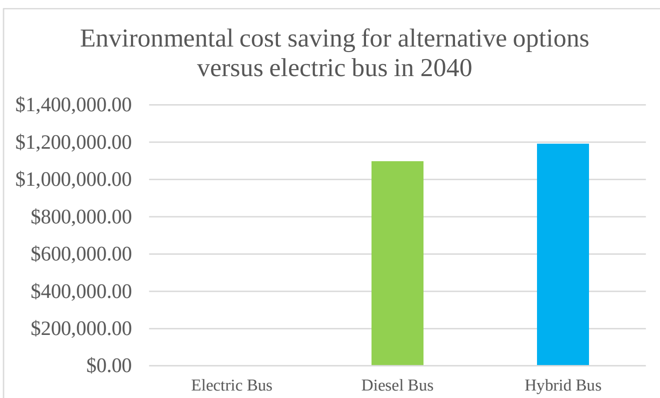

Figure 16 Annual environmental cost saving compared to the electric bus in 2040

6. CONCLUSIONS

We evaluated life cycle environmental impact and economic analysis for switching diesel buses to electric buses in the Greater Houston area. In the search for possible analyses of electric buses, this work developed a comparative study between conventional diesel bus, diesel hybrid bus, and electric bus, taking life cycle emissions as the environmental impact and life cycle cost as economic analysis to perform the evaluation. Life cycle greenhouse gas emissions of electric buses are slightly lower than conventional diesel buses but higher than diesel hybrid buses in 2020. All the other major emissions such as CO, NO_x, PM_{10}, $PM_{2.5}$, VOCs, SO_x, N_2O, methane, black carbon and primary organic carbon associated with electric buses are higher than conventional diesel buses and diesel hybrid buses. The emissions are primarily determined by the resource share of electricity generation in Texas, where natural gas, coal, and nuclear power take about 50%, 20%, and 10%, respectively, with other renewable energies. All the life cycle emissions would be improved in 2040 since more natural gas and less coal will be used in the electricity generation in Texas in the future.

With the application assumption of electric buses starting from 2020, our base-case study demonstrated that the life cycle cost of electric buses would be the lowest at the end of 24 years. In the starting year, the capital cost of electric buses, including batteries and charging station installation, is the highest. The accumulative costs of the three types of buses are primarily determined by the costs of diesel and electricity consumption during vehicle operation. However, the life cycle costs of buses are very sensitive to the prices of diesel and electricity in the future. Different annual inflation rates applied to electricity and diesel in the 24 years would cause significantly different trends in the estimate of life cycle costs. The oil price drop or fluctuation induced by some worldwide events, such as the COVID-19 pandemic and the reduction of oil price prompted by OPEC, would put uncertainties onto the life cycle cost analysis to some degree. The environmental cost analysis demonstrates that conventional diesel buses and diesel hybrid buses can save more than electric buses in Houston when considering the life cycle emissions rather than the tailpipe emissions of vehicles.

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APPENDIX A:

Table A-1. Life cycle inventory of low-sulfur diesel transit bus

Name	WTP	Mode - Regular	Non-Exhaust Emissions	Operation Only
Fossil Fuel	36 MJ/mi	0 J/mi		0 J/mi
Coal Fuel	296.34 kJ/mi	0 J/mi		0 J/mi
Natural Gas Fuel	3583 kJ/mi	0 J/mi		0 J/mi
Petroleum Fuel	33 MJ/mi	0 J/mi		0 J/mi
Renewable	88.05 kJ/mi	0 J/mi		0 J/mi
Biomass	6403.58 J/mi	0 J/mi		0 J/mi
Nuclear	87.26 kJ/mi	0 J/mi		0 J/mi
Non Fossil Fuel	175.32 kJ/mi	0 J/mi		0 J/mi
Water_Reservoir Evaporation	148.64 cm^3/mi			
Water_Cooling	115.68 cm^3/mi			
Water_Mining	1926.88 cm^3/mi			
Water_Process	346.18 cm^3/mi			
VOC	0.22 g/mi	48.17 mg/mi		48.17 mg/mi
CO	0.34 g/mi	0.52 g/mi		0.52 g/mi
NOx	0.59 g/mi	1.17 g/mi		1.17 g/mi
PM10	42.94 mg/mi	22.97 mg/mi		22.97 mg/mi
PM2.5	36.24 mg/mi	21.13 mg/mi		21.13 mg/mi
SOx	0.20 g/mi	16.03 mg/mi		16.03 mg/mi
CH4	3.19 g/mi	51.91 mg/mi		51.91 mg/mi
CO2	0.38 kg/mi	2.33 kg/mi		2.33 kg/mi
N2O	6.18 mg/mi	2.38 mg/mi		2.38 mg/mi
BC	5.72 mg/mi	1.89 mg/mi		1.89 mg/mi
POC	10.64 mg/mi	3.29 mg/mi		3.29 mg/mi
CO2_Biogenic	-5.87e-4 kg/mi	0 kg/mi		0 kg/mi
GHG-100	0.47 kg/mi	2.33 kg/mi		2.33 kg/mi
VOC Urban	81.97 mg/mi	48.17 mg/mi		48.17 mg/mi
CO Urban	51.55 mg/mi	0.52 g/mi		0.52 g/mi
NOx Urban	86.00 mg/mi	1.17 g/mi		1.17 g/mi
PM10 Urban	14.29 mg/mi	22.97 mg/mi		22.97 mg/mi
PM2.5 Urban	12.35 mg/mi	21.13 mg/mi		21.13 mg/mi
SOx Urban	41.68 mg/mi	16.03 mg/mi		16.03 mg/mi
CH4 Urban	76.72 mg/mi	51.91 mg/mi		51.91 mg/mi
CO2 Urban	0.15 kg/mi	2.33 kg/mi		2.33 kg/mi
N2O Urban	1.61 mg/mi	2.38 mg/mi		2.38 mg/mi
BC Urban	1.63 mg/mi	1.89 mg/mi		1.89 mg/mi
POC Urban	2.23 mg/mi	3.29 mg/mi		3.29 mg/mi
CO2_Biogenic Urban	-7.64e-6 kg/mi	0 kg/mi		0 kg/mi
BC_TBW			1.58 mg/mi	1.58 mg/mi
POC_TBW			2.10 mg/mi	2.10 mg/mi

Name	WTP	Mode - Regular	Non-Exhaust Emissions	Operation Only
PM10_TBW			48.20 mg/mi	48.20 mg/mi
PM2.5_TBW			12.40 mg/mi	12.40 mg/mi
VOC_evap			43.69 mg/mi	43.69 mg/mi
BC_TBW Urban				1.58 mg/mi
POC_TBW Urban				2.10 mg/mi
PM10_TBW Urban				48.20 mg/mi
PM2.5_TBW Urban				12.40 mg/mi
VOC_evap Urban				43.69 mg/mi

Table A-2. Life cycle inventory of electric transit bus

Name	WTP	Mode - Regular	Non-Exhaust Emissions	Operation Only
Fossil Fuel	34 MJ/mi	0 J/mi		0 J/mi
Coal Fuel	11 MJ/mi	0 J/mi		0 J/mi
Natural Gas Fuel	23 MJ/mi	0 J/mi		0 J/mi
Petroleum Fuel	314.57 kJ/mi	0 J/mi		0 J/mi
Renewable	4017 kJ/mi	0 J/mi		0 J/mi
Biomass	12.94 kJ/mi	0 J/mi		0 J/mi
Nuclear	2051 kJ/mi	0 J/mi		0 J/mi
Non Fossil Fuel	6067 kJ/mi	0 J/mi		0 J/mi
Water_Reservoir Evaporation	15416.02 cm^3/mi			
Water_Cooling	5476.33 cm^3/mi			
Water_Mining	282.47 cm^3/mi			
Water_Process	200.27 cm^3/mi			
VOC	0.30 g/mi	0 kg/mi		0 kg/mi
CO	1.11 g/mi	0 kg/mi		0 kg/mi
NOx	2.40 g/mi	0 kg/mi		0 kg/mi
PM10	0.26 g/mi	0 kg/mi		0 kg/mi
PM2.5	0.16 g/mi	0 kg/mi		0 kg/mi
SOx	5.18 g/mi	0 kg/mi		0 kg/mi
CH4	5.41 g/mi	0 kg/mi		0 kg/mi
CO2	2.36 kg/mi	0 kg/mi		0 kg/mi
N2O	36.12 mg/mi	0 kg/mi		0 kg/mi
BC	11.03 mg/mi	0 kg/mi		0 kg/mi
POC	26.41 mg/mi	0 kg/mi		0 kg/mi
CO2_Biogenic	0.00 kg/mi	0 kg/mi		0 kg/mi
GHG-100	2.53 kg/mi	0 kg/mi		0 kg/mi
VOC Urban	26.25 mg/mi	0 kg/mi		0 kg/mi
CO Urban	0.25 g/mi	0 kg/mi		0 kg/mi

Name	WTP	Mode - Regular	Non-Exhaust Emissions	Operation Only
NOx Urban	0.66 g/mi	0 kg/mi		0 kg/mi
PM10 Urban	58.43 mg/mi	0 kg/mi		0 kg/mi
PM2.5 Urban	52.72 mg/mi	0 kg/mi		0 kg/mi
SOx Urban	1.85 g/mi	0 kg/mi		0 kg/mi
CH4 Urban	67.06 mg/mi	0 kg/mi		0 kg/mi
CO2 Urban	0.78 kg/mi	0 kg/mi		0 kg/mi
N2O Urban	9.53 mg/mi	0 kg/mi		0 kg/mi
BC Urban	3.12 mg/mi	0 kg/mi		0 kg/mi
POC Urban	7.53 mg/mi	0 kg/mi		0 kg/mi
CO2_Biogenic Urban	-1.54e-5 kg/mi	0 kg/mi		0 kg/mi
BC_TBW			1.58 mg/mi	1.58 mg/mi
POC_TBW			2.10 mg/mi	2.10 mg/mi
PM10_TBW			48.20 mg/mi	48.20 mg/mi
PM2.5_TBW			12.40 mg/mi	12.40 mg/mi
BC_TBW Urban				1.58 mg/mi
POC_TBW Urban				2.10 mg/mi
PM10_TBW Urban				48.20 mg/mi
PM2.5_TBW Urban				12.40 mg/mi