Comparative Life Cycle Assessment of Electric Battery and Natural Gas Busses: A case-study for Unitrans in Davis, California

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Abstract: In this study, Compressed Natural Gas (CNG) and Battery Electric (BE) buses (BEBs) manufacturing, transportation, operation, and BEB battery replacement flows are compared to inform decisions for ASUCD-Davis Unitrans, the public transit operator in Davis, CA. Life cycle inventory flows (LCI) are sourced from GaBi Professional, EcoInvent 3.5, and California Air Resources Board CA-GREET3.0 model and Ambrose et al., 2016. Operational data is sourced from Unitrans, Argonne National Laboratory's BatPac 3.1 model, equipment manufacturers, and various literature. Impacts include global warming potential (GWP_{20}), primary energy demand (PED), ecotoxicity, cancerous and noncancerous human toxicity, particulate matter ($PM_{2.5}$), and photochemical smog formation (Smog). A scenario analysis of various BEB fuel efficiencies is developed using both literature and equipment manufacturer data. From the scenario analysis, it can be seen that BEB, regardless of scenario, led to 50%-73% reduction in GWP_{20}. However, the study also shows large increases in PED, ecotoxicity, human toxicity, $PM_{2.5}$, and smog formation potential impacts with values varying depending on the efficiency, electricity mix, and battery replacement rate selected. Future increases in battery recycling rates could lead to a reduction in these impacts, however for the time being the potential GWP_{20} reductions should be considered in tandem with other impacts when prioritizing impact reduction strategies.

***Key Words**: Battery Electric Buses, LCA, Case-study, Transit, CNG Bus*

1.0 Introduction

The rail, road, air and marine transportation sector accounted for 29% of US greenhouse gas (GHG) emissions in 2017 (Environmental Protection Agency, 2019). In terms of road transportation modes, cars, buses, and trucks are the major contributors to GHG emissions (Environmental Protection Agency, 2019). To reduce transportation emissions various actions have been proposed. These include the use of clean fuels, improvement in vehicle efficiency, increased use of public transport, and increased use of electric vehicles (Wang and Ge 2019). Electric vehicles (EVs) are a promising technology for greenhouse gas reductions and are often considered in governmental policies (Archsmith et al., 2015). California has implemented a number of policies and projects related to decreasing transportation-related emissions including the zero-emission vehicle program, clean vehicle rebate project, and other clean transit regulation ("Plug-in electric vehicles," 2020). According to Innovative Clean Transit Regulation by California Air Resources Board (CARB) all public transit agencies have to adopt 100% zero-emission bus fleets by 2040. There are 200 public transit agencies operating 12,000 buses in California. Transit agencies can adopt zero-emission technologies to decrease pollution and noise (Gao et al., 2017). The transit buses typically drive at slow speeds in stop-and-go traffic which, for a conventional bus, results in fuel wastage. Transit agencies have central bus depots which makes it easier to install and access the charging infrastructure (California Air Resources Board, 2018). Buses also have extra space for placing batteries and offer additional advantages such as higher energy efficiency and lower maintenance requirements (Hugh, 2018).

Unitrans is a public transit system jointly operated by the Associated Student Body of UC Davis (ASUCD) and the City of Davis in California. In all, the system operates 46 buses of which 40 use compressed natural gas (CNG), 4 use diesel, and 2 use gasoline (Flynn, 2020). New CARB regulations will require California transit agencies, like Unitrans, to transition to an all-electric fuel-based system in the future (California Air Resources Board, 2018). Previously, Kornbluth et al.

conducted a study for Unitrans to study replacing the current fleet with battery-electric (BE) buses. They report viable BE options, estimated GHG emissions, and provide an economic analysis of potential bus models. However, only natural gas combustion emissions for CNG bus and emissions for electricity production required for charging BE buses in the use phase were considered (Kornbluth et al., 2016). Considering the very narrow scope within this study, a more holistic life cycle assessment (LCA) is needed for Unitrans to understand the environmental impact of fleet electrification. The goal of this paper is to help fill this void of understanding by expanding the system beyond the operational phase. Unitrans is used as a case study, but results may be applicable to entities beyond Unitrans.

1.1 Literature Review

Electric vehicles are generally perceived as being environmentally friendly, but a broader life-cycle perspective is needed to better quantify the impact. In a comparative life cycle assessment (LCA) between conventional vehicles and electric vehicles, including the production and end of life phase, Hawkins et al. find that human toxicity, mineral depletion, and freshwater ecotoxicity impacts are largely driven by the production phase while global warming, terrestrial ecotoxicity, and fossil depletion are dependent on the use phase of the vehicle. This attributional analysis showed that the BE production phase has higher impacts than an internal combustion engine vehicle, with the exception of terrestrial acidification (Hawkins et al., 2013). Additionally, most of the global warming impacts are from vehicle usage. Moreover, in areas where electricity is produced from fossil fuels, increased use of EVs does not reduce emissions (Hawkins et al., 2013; Bauer et al., 2015). An expansion of system scope and environmental indicators will generally lead to a greater understanding of the environmental impact of EVs (e.g. Hawkins et al., 2013; Archsmith et al., 2015; Bauer et al., 2015).

A major source of uncertainty for electric vehicles is their fuel efficiency, as it can vary with terrain and temperature (Archsmith et a., 2015). The National Renewable Energy Laboratory (NREL) has performed trial studies in numerous locations with various electric bus technologies (Eudy et al., 2016). In a technical report, researchers from NREL and CARB study the real-world use of 12 Proterra BEBs by the Foothill Transit Agency which operates in the San Gabriel and Pomona Valley regions of Los Angeles County. The results from the BEBs are compared to CNG buses also operated by the Foothill Transit Agency. From this study, BEBs perform with an average efficiency of 2.15 kWh/mile over 399,663 miles of use with an average per bus runtime of 13.2 hours per day. The miles per equivalent gallon of diesel for BEBs is 17.48 and for CNG buses is 4.51, representing a 387% improvement from the BEBs over the test period. Additionally, maintenance costs decreased by $0.02 per mile when the BEBs are used. However, CNG buses have a better availability rating (94%) than BEBs (90%). In Kornbluth et al. the bus efficiency for a different BE model, New Flyer's XE 40, is found to be 1.8 kWh/mile. This value takes into account ADVISOR output modeling Unitrans Column 50 route and other literature values (Kornbluth et al., 2016). Specifications from Proterra report a high and low efficiency of 1.53 kWh/ mile and 2.19 kWh/ mile (Proterra, 2020).

The electricity generation mix used for charging is crucial to understanding the operational impact of EVs (Archsmith et al., 2015). A study by Archsmith et al. suggests that the level of GHG emissions from EVs depends on the electricity source and temperature of the area where the EV is charged. As would be expected, a cleaner grid mix, with more renewables, has lower emissions compared to the grid with more fossil fuels (Archsmith et al., 2015). Similarly, Doucette and McCulloch found that EVs in countries with higher carbon electricity, such as China and India, do not lead to decreased GHG emissions and can increase overall carbon emissions (Doucette and

McCulloch 2011). In the case of UC Davis, the electricity mix has comparatively high amounts of renewable energy sources (Kornbluth, 2016; UC Davis Facilities Management, n.d.).

Assessing impacts and material demands from different battery chemistries is an important part of EV LCAs as certain constituents within the battery may have highly localized effects. Specifically, Dai et al. point out that aluminum production in North America has a much lower impact concerning Global Warming Potential (GWP), but high water consumption because of the high hydropower penetration in that region (Dai et al., 2019). Another particular problem in representing impacts from different EVs is the lack of LCI data encompassing multiple chemistries. According to a review conducted by Peters et al. of 79 EV LCAs, only 9 authors published LCI results (Peters et al., 2017). In addition to the dearth of chemistry dependent LCIs, many battery LCIs lack harmonization with other databases (Cusenza et al., 2019). Argonne National Laboratory's (ANL) GREET inventory has a wide range of lithium-ion chemistries but lacks granularity in the bill of materials and amount of environmental indicators (Dai et al., 2018). Despite the issues with representing battery chemistry within LCAs, their consideration is important as they can have variable effects on environmental impacts (Ambrose et al., 2016).

2.0 Methods

2.1 Functional Unit, Goal, and Scope

The function of a Unitrans bus is to move riders from location to location across the city of Davis, CA; thus, the functional unit modeled is passenger-kilometer-travelled (PKT). An inherent assumption within the function is that BE buses will perform identically to CNG buses. This assumption is valid given the daily route requirements of Unitrans and range capability of chosen BE bus (Flynn, 2020; Proterra, 2020). The goal of this study is to provide a comparative and process-based LCA, adhering to ISO 14040 and 14044 standards, between the incumbent fuel pathway for the Unitrans fleet, CNG and a new fuel pathway, BE (ISO, 2006). The primary goal is very localized, and this localization is manifest in many of the scoping and parameter assumptions. Despite this, a secondary goal is to present general trends and comparisons for other transit agencies, especially those with similar characteristics to Unitrans, to ultimately guide decision-making. Two different midpoint impact assessment methods are used: IPCC AR5 global warming potential for a 20 year time horizon (GWP_{20}) and Environmental Protection Agency's (EPA) Tool For Reduction and Assessment of Chemical and other Impacts (TRACI 2.1) for remaining environmental indicators (IPCC, 2014; Bare et al., 2011).

The scope of this study includes the manufacturing phase, natural gas extraction phase, transportation phase, and operation phase. For the manufacturing stage, all upstream impacts are considered to be the background system (e.g. material and energy inputs). Explicitly, the manufacturing stage includes CNG bus, BEB, battery, and charger production (Figure 1). Likewise, in the natural gas extraction phase, upstream impacts of natural gas extraction, transport and distribution are in the background system (Figure 1). The transport stage includes delivery of battery to BEB manufacturer, delivery of battery to Davis for replacements and delivery of charger to Davis via truck. Both CNG and BE bus deliveries are modeled as the operational stage as if they are driven from the factory to Davis, CA after manufacturing, however; this distance traveled is excluded from the functional unit calculations. The operational phase includes impacts from electricity generation, CNG combustion, and battery replacement. Other capital investments, such as the natural gas refueling infrastructure or maintenance and storage infrastructure, are already in place and thus excluded from the scope. Impacts past the operation stage are not in the scope of the study, for example, end of life flows are outside of the scope.

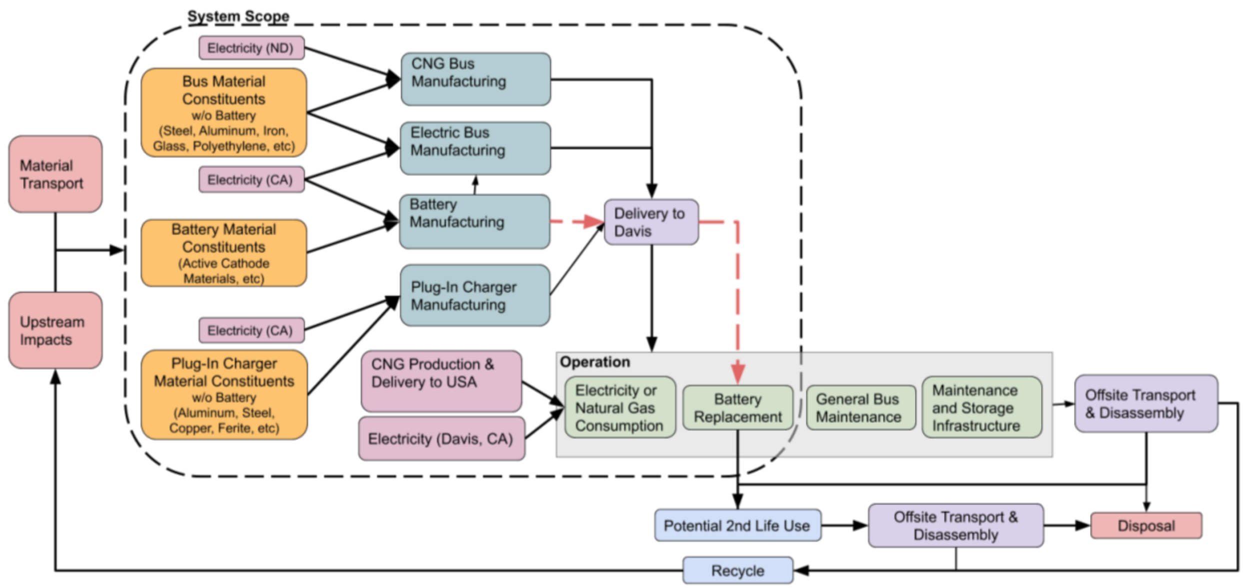

Figure 1: System Flows Diagram with study boundary shown by dashed line

Many scoping assumptions are made to simplify this comparative assessment. The natural gas processes in this study are simplified because of the available LCI used and the uncertainty of compatibility between Unitrans' situation and the assumptions in the LCI. The exclusion of CNG infrastructure is because this study is meant to represent future decisions, not retroactively represent the holistic footprint of the CNG bus system. That is to say, emissions related to CNG infrastructure have already occurred whether Unitrans adopts BE buses or stays with CNG buses. While the manufacturing of the electric charger is considered, the onsite installation of the charger is excluded and is considered negligible over the 15 years lifespan. Two key operational assumptions are excluding maintenance-related impacts, except for battery production and transportation, and tire-surface interactions. Tire-surface interaction impacts should be almost identical, as we model both the bus weights to be very similar. Thus, maintenance is similar enough in scale for the two buses that exclusion is appropriate. The exclusion of the end of life phase is likely the assumption with the largest potential variability and uncertainty. Current battery collection rates are as low as 5% in the United States (Department of Energy, 2019). While the inclusion of recycling could actually credit the BE buses for avoiding future virgin material extraction (Ambrose et al., 2020), the uncertainty of future collection and recycling is uncertain and could greatly skew the results of the study.

To model this system, primary and secondary data is collected for the manufacturing, transportation and operation phases. A major source of primary data for the manufacturing phase is our correspondence with the Unitrans general manager (Flynn, 2020), this motivated our choice for CNG bus model, BE bus model and BE charger. These three products represent very realistic options for Unitrans within this study period. The CNG bus considered is New Flyer's 40' Excelsior model, manufacturing weight is provided by the company (New Flyer, 2020). The BE bus considered is Proterra's 40' Catalyst E2, manufacturing weight is provided by the company (Proterra, 2020). The BE charger considered is Siemens' CPC 150 kW charger, manufacturing weight provided by the company (Siemens, 2020). Importantly, 0.5 chargers are manufactured per bus, given the ability of CPC-150 charger to provide dual-port charging (Siemens, 2020). The weight of the BE bus battery is provided by the company; however, the components of the battery were not. To account for this, the battery is modeled using other publicly available characteristics of the battery with ANL BatPac 3.1 model (Dai et al., 2018). Specifically, the battery is modeled to represent the material needs of NMC-622 in BatPac (Proterra, 2017). BatPac model output provides weight percentages of generic portions of the battery pack. Due to LCI limitations, the cathode material is represented as LMO in all scenarios except one. To account for this discrepancy one scenario explicitly adds aggregate flows from nickel and cobalt separately. Their weight is calculated from BatPac and proportionately displaces weight attributed to the LMO cathode material. Explicitly, the cathode material is modeled as 27.7% of the batteries weight, but when cobalt and nickel (~20% of battery pack weight) are added cathode material goes down to 7.7% in tandem with environmental flows from cobalt and nickel The total gravimetric production of natural gas is calculated from lower heating values of real fuel consumption data from Unitrans' CNG bus operation in 2019 (Alternative Fuels Data Center, 2014; Flynn, 2020). Modeling the transportation phase involves referencing manufacturing weights and calculating distances from manufacturer to destination (Proterra, 2017; New Flyer, 2020; Siemens, 2020). Operational data, again, comes from primary data from Unitrans. Daily route distances, frequencies and ridership are provided for every bus route, this study excluded any bus that was not 40' (Flynn, 2020). From daily route information, total lifetime vehicle kilometers traveled is extrapolated (15 years of operation) for every relevant route and then averaged. CNG bus thermal fuel efficiency is provided by Unitrans from 2019 (Flynn, 2020). Contrastingly, BE bus efficiencies aren't explicitly provided by Unitrans; thus, efficiencies are selected from manufacturer specifications (Proterra, 2020) and relevant literature (Eudy et al., 2016; Kornbluth et al., 2016). Fuel use is calculated from lifetime distance and fuel efficiencies.

2.2 LCI Development

Life Cycle Inventory (LCI) information is provided from three databases and one journal LCI. Ecoinvent 3.5 provides aggregate manufacturing data on a transit bus, passenger vehicle charger and subcomponents within the BE battery (nickel and cobalt). Ecoinvent also provides electricity LCI for both California mix and average WECC mix and inventory for freight transport (Wernet et al., 2015). Gabi Professional + Extension provides aggregate LCI for natural gas at consumer (PE International, 2020). The operational inventory for CNG bus tailpipe emissions is taken from CA-GREET3.0 Model, this inventory is notably more limited than the rest of this paper's inventories. LCIs for various components of BE battery are provided by Ambrose and Kendall, 2016. Table 1A, in Appendix A, provides information on the cumulative LCI of this paper (Table 1A, Appendix A).

2.3 Impact Assessment

Electric vehicles (EVs) are often suggested as a great alternative to reduce GHG emissions (Archsmith et al., 2015). In relation to the goal of climate neutrality for University of California, Davis (UC Davis Environmental Stewardship and Sustainability, n.d.), the GWP of CNG and BE buses was determined using AR5 GWP_{20} (IPCC, 2014). GWP_{20} is selected over GWP_{100}, because the lifetime of the BE bus fleet is assumed to be 15 years.

Hawkins et al. provides a comparative LCA of conventional and EV and suggest that EV production is a huge contributor to a number of other indicators beyond GWP (Hawkins et al., 2013). To consider impacts beyond GWP, the EPA's TRACI 2.1 assessment method is used. The remaining impacts within TRACI are broadly defined as human health criteria (Bare, 2011). These methods are chosen to provide decision-makers with ample information on how a change in bus fuel type could potentially affect both human and ecosystem health. Human toxicity and ecotoxicity is modeled according to the collaborative effort USEtox (Bare, 2011). Photochemical smog formation (Smog) and particulate matter under 2.5 micrometers ($PM_{2.5}$) are also considered. The inclusion of the latter two impacts is in consideration of the large impact both motor vehicle operations and electric utilities have in these categories (Bare, 2011). A potential shortcoming of this assessment of photochemical smog formation and $PM_{2.5}$ is the truncated inventory used in modeling CNG bus tailpipe emissions (CARB, 2019). Due to incomplete combustion, the actual combustion of CNG will likely involve emissions beyond the 3 gases reported in the LCI.

2.4 Scenarios Considered

There are seven scenarios considered in this study which include one natural gas scenario and six electric bus scenarios. The electric bus scenarios were built to examine the environmental impact brought on by changing the efficiency of the electric vehicle, the electricity mix, the number of battery replacements, and the material of the battery.

Scenario Name	***Model***	***Efficiency (kWh/km)***	***Efficiency Source***
CNG	Standard Model	5.87 (21.15 MJ/km)	(Flynn, 2020)
EVS1	Standard Model	0.975	(Prottera, n.d.)
EVS2	Standard Model	1.119	(Kornbluth et al., 2016)
EVS3	Standard Model	1.336	(Eudy et al., 2016)
EVS4	Standard Model	1.535	(Prottera, n.d.)
EVS5	WECC Electricity Mix	1.119	(Kornbluth et al., 2016)
EVS6	2 Battery Replacements (vs. 1 in standard)	1.119	(Kornbluth et al., 2016)
EVS7	Ni and Co as Battery Cathode Material	1.119	(Kornbluth et al., 2016)

Table 1: Scenarios evaluated for this analysis

3.0 Results and Discussion

All seven scenarios were used to compare how different decisions change the seven considered impact categories. As is shown in Figure 2, the natural gas bus scenario has a higher GWP_{20} compared to all other electric vehicle scenarios. However, the electric bus scenario is more impact intensive than that of the natural gas bus scenario for all other impact categories considered.

The natural gas bus scenario has the highest GWP_{20}. When only comparing the electric bus scenarios, the GWP_{20} increases with the decrease of electric bus efficiency. EVS6 has the highest GWP_{20} among all the electric bus scenarios (0.02 kg CO_2e / PKT), because it involves two battery replacements even though the efficiency of EVS6 is the same as EVS2. Comparing EVS2 and EVS7, both with 1.119 kWh/km efficiency, the study shows that modeling nickel and cobalt in the cathode material leads to 70% increased GWP_{20} production per PKT.

Primary energy demand (PED) stands out as a potentially significant category for problem-shifting associated with a transition from natural gas bus to electric bus. The different electric bus fleet scenarios have 257% to 338% greater energy demand compared to the natural gas bus fleet. When only the electric bus scenarios (EVSX) are compared, the PED increases slightly with the decrease of the efficiency of electric buses. Both EVS6 and EVS7 also show 23% higher energy demands due to battery production. Intuitively, changing from WECC and CAMX electricity generation only changes PED slightly.

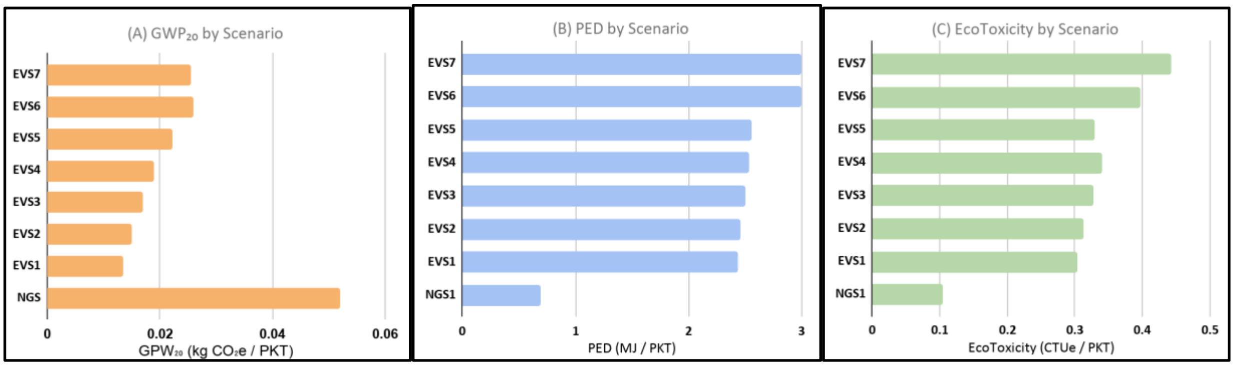

Figure 2: Quantified (A) GWP_{20}, (B) PED, and (C) EcoToxicity impacts for each of the seven scenarios considered

Figure 2(C) shows the quantified impacts for EcoToxicity. All electric bus scenarios display higher ecotoxicity impacts than the CNG fleet, with increases ranging from 191% to 326%. Similar to PED, EVS6 and EVS7 show higher (26% and 41%, respectively) ecotoxicity potential even though they share the same efficiency with EVS2, implying that battery replacement contributes greatly to the EcoToxicity. Human Toxicity displayed in Figure 3, non-cancerous (A) and cancerous (B), shares a similar pattern to EcoToxicity impacts.

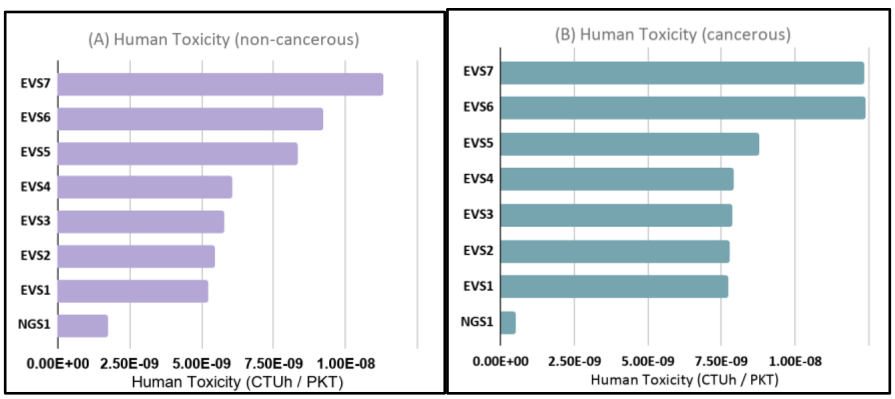

Figure 3: (A) Non-Cancerous and (B) Cancerous Human Toxicity Impact Across Scenarios

Just as above, smog formation increases as the vehicle efficiency decreases, driven by the increase in electricity demand. When the electricity mix changes from CAMX to WECC mix, the change leads to an additional 0.002 kg O_3e per PKT. Similarly, battery production changes are also tied to increased smog formation potential.

All electric bus scenarios also led to increased $PM_{2.5}$e impacts compared to the CNG scenario. Like the other scenarios, $PM_{2.5}$e formation increases with the decrease of electric bus efficiency showing a relationship between $PM_{2.5}$e impacts and electricity generation. The change in energy mix from CAMX to WECC (EVS5) as well as changes to battery production (EVS6 and EVS7) suggests that particulate matter is closely tied to the electricity generation, WECC has lower renewable energy concentrations, and battery production, doubling production and transportation doubles $PM_{2.5}$e impacts.

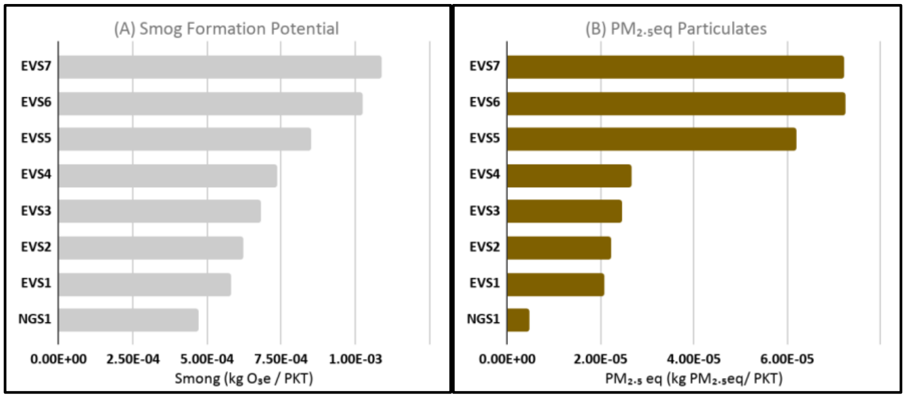

Figure 4: (A) Smog Formation Potential and (B) PM2.5 Equivalent Particulate Matter Impacts by Scenario

There are several parameters that could alter the results significantly. To help Unitrans to reach the goal of electrifying their bus fleets, protecting human health and carbon emission reduction, a sensitivity analysis is conducted specific to BEBs to identify areas where small changes lead to big impact for three environmental impacts. Figure 5 shows the maximum and minimum numerical value of four parameters in terms of seven environmental impacts. The results demonstrate the changing assumptions regarding battery material, electricity mix, battery replacement, and vehicle efficiency could potentially change the environmental impacts.

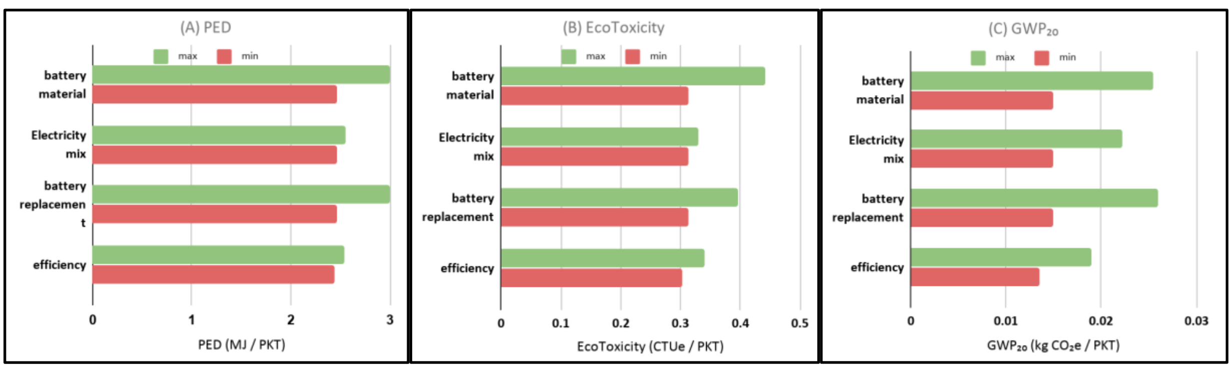

Figure 5: Maximum and Minimum (A) PED, (B) EcoToxicity, and (C) GWP_{20} Values by Scenario Variables

Battery replacement, battery material, and electricity mix can alter GWP_{20} results significantly. Two battery replacements lead to an increase of approximately 0.01kg CO_2e per PKT in its 15 years lifetime. With additional nickel and cobalt, the GWP_{20} is 1.7 times than the baseline scenario (same efficiency). After the WECC mix replaces the CAMX, the GWP_{20} increases by 0.007 kg CO_2e emissions per PKT. The vehicle efficiency has the lowest potential to increase GWP_{20} in our scenarios. When electric vehicle efficiency increases from 1.119kwh/km to 1.535kwh/km, the GWP_{20} increases 0.005 kg CO_2e per PKT.

With regard to primary energy demand, battery material and battery replacement are two dominated parameters. The GWP_{20} increases 0.53 kg CO_2e per PKT with additional nickel and cobalt. The two battery replacement scenario has a similar result.

Previous results show that electric buses have a higher EcoToxicity impact compared to natural gas buses. Therefore, it is essential to identify which parameter influences the EcoToxicity the most if Unitrans intend to electrify the bus fleet in the future. As shown in Figure 5(B), battery material influences the EcoToxicity the most. A second battery replacement leads to an additional

0.08 CTUe/PKT for the electric bus fleet in its fifteen years lifetime compared to one battery replacement scenario.

4.0 Conclusion

In this study CNG and BE buses for the ASUCD-Davis Unitrans fleet operating in Davis, California were compared and select impacts from LCI flows were quantified. The study uses a LCA methodology to model LCI flows from the manufacturing of the buses and BEB charging device, delivery of the buses and BEB batteries to Davis, CA, operation of the bus lines in Davis (with current routes and ridership staying the same), fuel production, and replacement of BEB batteries. Other infrastructures for CNG refueling and general bus storage are not considered since they are already in place. Additionally, given large uncertainties in the battery recycling rates, the end of life is not considered in this study. Assessments were made using a "standard model" assumption for the BEB of a single battery replacement per lifetime and the average 2018 California Electric Mix as the electricity source. For CNG, the "standard model" uses the average real-world fleet fuel economy. A scenario analysis was used to study the results of variable electricity fuel economy, from values reported in literature, a different electricity mix (WECC), more frequent battery replacement, and a battery chemistry with increased Ni and Co levels. From these scenarios the key takeaways are:

- A purely BEB fleet led to reduced GWP_{20} compared to the CNG fleet, regardless of scenario considered.
- BEB vehicles increased PED, EcoToxicity, Human Toxicity, Smog formation potential and $PM_{2.5}$ impacts compared to CNG buses.
- Improvements in battery recycling could lead to decreased impacts from initial BEB production and battery replacement and reduce these impacts.

In all, this study shows that battery electric vehicles have a strong potential to decrease GWP_{20} impacts associated with a public transit bus fleet across many potential vehicle efficiencies. However, a fully electric fleet can lead to increases in other impacts depending on the electricity fuel mixture, electricity efficiency, battery replacement rate, though these impacts could be smaller if increased battery recycling rates leads to a decreasing impact for battery production.

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Appendix A: Tables 1A and 1B (LCI Data and Modeling Values Sources)

Table 1A: LCI Data Sources

Data Type	Source	Data Type	Source
Manufacturing		***Cathode Materials***	
Bus (Agg, GLO)	EcoInvent 3.5	*Aluminum*	EcoInvent 3.5

Charger, electric passenger car (Agg, GLO)	EcoInvent 3.5	*Graphite*	EcoInvent 3.5
CNG at Consumer (Agg, US)	GaBi Professional (V.9)	*Binder*	EcoInvent 3.5
Battery Components (Agg, GLO)	EcoInvent 3.5 & Ambrose and Kendall, 2016	*Copper*	EcoInvent 3.5
Transport		*Steel*	EcoInvent 3.5
Freight Transport, Truck	EcoInvent 3.5	*Electrolyte (less Li)*	EcoInvent 3.5
Operation		*Coolant*	
Electricity (CAMX)	EcoInvent 3.5; Nymberg, 2019	*Cobalt*	EcoInvent 3.5
Electricity (WECC)	EcoInvent 3.5	*Nickel*	EcoInvent 3.5
CNG Tailpipe Emissions	CA-GREET3 Tier 1		

Table 2A: Modeling Values Sources		
Data Type	Source	Primary/ Secondary (1 / 2)
Manufacturing		
New Flyer 40’ Excelsior Curb Weight	(New Flyer, 2020)	1
Proterra Catalyst E2 40’ Excelsior Curb Weight	(Proterra, 2020)	1
Catalyst E2 40’ Excelsior Battery Pack Total Weight	(Montalban, 2020)	1
Battery Component % Composition	BatPac 3.1	2
Charger Weight	(Siemens, 2020)	1
Natural Gas Total use, gravimetric	(Alternative Fuel Data Center, 2014)	2
Transport		
Transport Distances		2
CNG bus,Minnesota to Davis(3016 km)	(Newflyer, 2020)	2
Electric bus and Bus battery, Los Angeles to Davis(682.36km)	(Proterra, 2017)	2
Bus battery, Burlingame to Davis (136.79km)	(Proterra, 2017)	2
Bus battery, Burlingame to Los Angeles(648.58km)	(Proterra, 2017)	2

Operation		
Daily Route Requirements (40’)	(Flynn, 2020)	2
Lifetime distance travelled (15 years, 40’)	(Flynn, 2020)	2
Avg Ridership (40’)	(Flynn, 2020)	1
Natural Gas Total use, thermal	(Flynn, 2020)	1
BE Efficiency (S1)	(Proterra, 2020)	1
BE Efficiency (S2)	(Kornbluth et al., 2016)	2
BE Efficiency (S3)	(Eudy et al., 2016)	2
BE Efficiency (S4)	(Proterra, 2020)	1