Clean Ride to School:

Viability and Opportunities of School Bus Electrification in Massachusetts

by

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Abstract

The iconic Yellow Bus system is the largest form of mass transit in the United States, comprising 480,000 buses that carry 25 million children to school every day. And it mostly runs on diesel. Due to the recognized toxicity of diesel exhaust, there have been substantial efforts to deploy cleaner forms of transportation for school children. Over the last 20 years, diesel engine retrofits have significantly reduced air pollutant emissions from heavy-duty vehicles, and alternative fuels such as liquified petroleum gas (LPG) promise to cut such emissions even further. However, none of these technologies eliminates air pollution or the greenhouse gases (GHG) that drive climate change, the greatest global environmental, economic and social threat of our times. Electric school buses offer a solution to address both climate and air quality concerns by eliminating tailpipe emissions, with the additional promise of long-term economic returns due to fuel savings and low maintenance costs. Electric school buses are being deployed at increasing pace, but they are still considered an emerging technology. This project seeks to validate the claims of lifetime cost competitiveness of electric school buses *vis a vis* the more conventional diesel and LPG vehicles. A total cost of ownership (TCO) model is created to assess under which conditions electric school buses are a favorable technology. The TCO shows that despite the fuel and maintenance savings, the upfront price of an electric school bus is too high to provide lifetime economic returns especially when compared to LPG, unless significant purchase incentives are provided. Incorporating the health, environmental and social costs only marginally improves the economic argument for an electric school bus. The cost-benefit analysis (CBA) suggests that the use of the school bus battery as an energy storage asset through vehicle-to-grid (V2G) becomes almost a necessary strategy to recuperate costs, but its applicability and effectiveness depend on case-specific factors and policies that needs to be created. Yet, the sensitivity analysis shows that specific use cases that are cost-effective for electric school buses already exist and can be leveraged immediately to accelerate the deployment of electric school buses in Massachusetts. This work also proposes policy and regulatory interventions that can help break down adoption barriers and achieve beneficial electrification while delivering on environmental justice and smart grid management. The analysis underscores the urgent need to incorporate a long-term, multi-solution approach to allow transition to a sustainable and equitable school bus fleet in the Commonwealth.

Acknowledgements

There are many individuals who have shaped my personal and professional path and to whom I am deeply grateful. I am especially grateful to the individuals who have provided ideas and guidance throughout the convoluted months that have led to the completion of this capstone project. I sincerely thank you for the support and encouragement.

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I dedicate this work to the ones who believe that a different world is possible, and to my mother, the finest example of strength, patience and empathy.

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Abbreviations

AFLEET	Alternative Fuel Life Cycle Environmental and Economic Transportation
CBA	Cost-Benefit Analysis
COBRA	CO-Benefits Risk Assessment
DALYs	Disability Adjusted Life Years
DERA	Diesel Emission Reduction Act
DPF	Diesel Particulate Filter
EIA	Energy Information Agency
EPA	Environmental Protection Agency
ESCO	Energy Service Company
GHG	Greenhouse Gases
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GWSA	Global Warming Solution Act
IEA	International Energy Agency
IPCC	International Panel on Climate Change
ISO-NE	Independent System Operator New England
LCFS	Low Carbon Fuel Standard
LPG	Liquified Petroleum Gas
METCO	Metropolitan Council for Educational Opportunities
TCI	Transportation and Climate Initiative
TCO	Total Cost of Ownership
TOU	Time Of Use
V2G	Vehicle-To-Grid
VSL	Value of Statistical Life
WHO	World Health Organization
ZEV	Zero Emission Vehicle

1. Introduction

This section discusses the environmental issues associated with the transportation sector and heavy-duty vehicles. It highlights the progress made in reducing emissions from diesel school buses, and the coming to market of alternative fuels and zero-emission options. An overview of the Massachusetts school bus fleet is provided, and the research questions are defined.

1.1 Transportation at the Nexus of Climate Change, Air Quality, and Public Health

Transportation is the fastest growing source of climate change-inducing greenhouse gas (GHG) emissions worldwide, and it represents 24 % of the global carbon dioxide (CO_2) output from fuel combustion (International Energy Agency, IEA, 2019). Scientific consensus indicates that in order to decelerate the climate change crisis, transportation emissions need to be heavily reduced through 'aggressive and sustained mitigation policies', including fuel change, efficiency measures and modal shift (International Panel on Climate Change, IPCC, 2018). Transportation is also a major contributor to air pollution, which causes 5 million of premature deaths worldwide due to respiratory and cardiovascular diseases, and it is considered a threat for sustainable development (World Health Organization, WHO, 2019). Air pollution has also been linked to neurological conditions such as dementia and Alzheimer's disease (Underwood, 2017).

While light-duty vehicles are responsible for the majority of transportation-related GHG emissions, heavy-duty diesel powered vehicles – e.g., trucks and buses - are disproportionately responsible for the emissions of primary particulate matter (particles smaller than 2.5 micron in diameter, or $PM_{2.5}$) and gases such as nitrogen dioxide (NO_2), hydrocarbons (HC), and volatile organic compounds (VOCs) that lead to the formation of secondary $PM_{2.5}$ and ground-level ozone (O_3). The combined adverse health effects of O_3, NO_2 and $PM_{2.5}$ have been documented extensively (Lelieveld et al., 2015). More recently, epidemiologists are turning their attention to understanding the health impacts of vehicle exhaust particles with diameter smaller than 0.1 micron (ultrafine particles) which can enter the blood stream due to their extremely small size. There is now direct evidence that ultrafine particles inflame the body and weaken the immune system, making it more prone to diseases (Lane et al., 2016). The specific health dangers of exposure to diesel fumes are also well documented (California Office of Environmental Health Hazard Assessment, 2001; U.S. Environmental Protection Agency, EPA, 2002). The primary $PM_{2.5}$ from diesel exhaust is indeed made of soot, a cancer-causing material, and of other substances with negative health effects (Brook et al., 2004; National Toxicology Program, 2016). Diesel-related NO_2 emissions are particularly worrisome as exposure to NO_2 can aggravate respiratory diseases, particularly asthma (Guarnieri and Balmes, 2014; U.S. EPA, 2016a).

In the U.S., the transportation sector contributed about 29% - 1900 million metric tons of carbon dioxide equivalent (MT CO_2 e) – to the GHG budget already in 2017 (U.S. EPA, 2020a), and its share is projected to grow in the coming years. It is also estimated that the U.S. transportation sector is responsible for $150 billion in health costs annually, with most of the damage caused by asthma-inducing NOx emissions (Tschofen et al., 2019). In 2018 the Center for Disease Control (CDC) put the economic burden of asthma at more than $80 billion in combined medical expenses, deaths, and days missed from work and school, with the most affected population segments being poor and low-income communities, women, children and people of color (Nurmagambetov et al., 2018). Meanwhile, the estimated social cost of carbon – that is, the cost of damage inflicted by GHG emissions to the global climate – is also growing as the climate crisis intensifies. In the U.S., for example, climate-related disasters have increased dramatically since 2000: 2019 was the fifth consecutive year in which 10 or more billion-dollar events have impacted the United States (National Oceanic Atmospheric Administration, 2020). As such, the real price of CO_2 emissions is estimated to be at least a few hundred (Ricke et al., 2017) and likely thousands of dollars per metric ton (Archer et al., 2020). In this context, widespread vehicle electrification is accepted as a critical strategy to achieve the recommended 2050 GHG reduction targets (Williams et al., 2015), while reducing the health burden of vehicle pollution. Additional co-benefits of vehicle electrification - energy security, creation of manufacturing jobs, industry competitiveness - are also now recognized (Gao et al., 2018).

The electrification of vehicles with short daily mileage, regular neighborhood routes, low fuel economy and tendency to idling is particularly attractive to minimize emissions in urban centers (International Council on Clean Transportation, 2016). School buses fit this use case, and they are considered perfect for electrification. In fact, the average school bus travels less than 100 miles per day on neighborhood routes and spends 30% of its travel time in zero-speed or idling mode. In addition, school buses have a unique midday and summer break that make them particularly suitable as battery storage units for innovative vehicle-to-grid (V2G) applications, which can include a variety of services such as grid stabilization and revenue generation (Steward, 2017; Electric Power Research Institute, 2019). Therefore, the electrification of the school bus transportation sector has been presented by many as a no-brainer for climate change, air quality, public health and economic reasons.

But is it?

1.2 Old problems and Emerging Solutions

The effort to 'clean up' diesel emissions from heavy-duty vehicles has been underway for almost two decades through a combination of policies and technological innovations, including the mandatory use of ultra-low sulfur diesel (ULSD) fuel and of exhaust retrofits with particulate filters (DPFs) and oxidation catalysts (DOCs). In 2008, the U.S. EPA Diesel Emission Reduction Act (DERA) set to mitigate the negative effects of diesel exhaust through a program that between 2009 and 2013 has replaced or retrofitted almost 60,000 diesel engines. According to the Fourth Report to Congress, this program resulted in $11 billion in total health benefits from reduced air pollutant emissions (U.S. EPA, 2019a).

About half of these engine retrofits were performed on school buses to directly address the concerns regarding the health effects of diesel on children (see Appendix A for a summary of peer-reviewed literature on the topic). Throughout the retrofit programs, studies showed that reducing children's exposure to diesel exhaust reduced hospital visits by 23%-37% (Beatty and Shimshack, 2011), and lowered the incidence of pulmonary inflammation (Adar et al., 2015). However, retrofit systems do not eliminate emissions completely, and the emission reductions can vary anywhere between 35 and 95% depending on the type of retrofit and engine maintenance (Zhang and Zhu, 2011). Furthermore, it has been found that in-cabin pollution from the diesel engine crankcase – the largest source of pollution for children riding school buses (Ireson, 2011) - can only be eliminated by dedicated filters that also require special maintenance (Zhu and Lee, 2015). Despite the remaining open questions about the effectiveness of diesel retrofits, the DERA program was authorized up to $100 million annually through FY2016, and it has been highly praised by the National School Transportation Association (NTSA) for its role in improving children's health (NSTA, 2014; 2018).

Meanwhile, cleaner fuels including biodiesel, methane and propane have been coming to market. In the school bus industry, propane – technically sold as liquefied petroleum gas or LPG - has increasingly gained popularity. In 2014, the U.S. Department of Energy (DoE) found LPG school buses to be a promising alternative to diesel due to low maintenance costs (Laughlin, 2014). While emission reductions are considered a secondary for fuel switching, LPG school buses are also praised for reducing NOx emissions compared to diesel (Gas Technology Institute, 2017; Taylor, 2018). However, proponents of 'clean diesel' counteract that while LPG buses may have lower NOx emissions, LPG combustion produces air pollutants in similar or even larger quantity than the cleanest diesel engine on the market (Thomas Built Buses, 2018).

Electric school buses – which eliminate tailpipe emissions – are the newest innovation in the alternative fuel market, and a growing number of school districts across the U.S. is deploying electric school buses to reduce the pollution burden on communities and to lower operational costs (Kahn, 217; School Transportation News, 2019). Since the delivery of the first all-electric school bus in 2014 (Figure 1), over 400 electric school buses are in use across the U.S., with positive results (Descant, 2018). The Twin River District in Sacramento, CA, operates the largest electric school bus fleet (30 units), but every state is now operating or piloting smaller fleets while experimenting with V2G. The White Plain school district in upper NY state, for example, started a V2G pilot with 5 buses in fall 2019 (Clukey, 2019). A deployment of 50 units all V2G capable is planned in Virginia starting late 2020 (Shahan, 2020). According to a report from April 2020, the global electric school bus market is expected to grow from $9.4 to $32 million by the end of 2025 at an annual rate of 19%, based on indicators such as product innovation, market development and diversification, and manufacturing capabilities (Reportlinker, 2020).

However, despite the encouraging numbers, the current price of an electric school bus is still 3.5 times higher than a regular diesel or LPG.

And that is a problem.

Figure 1: The first ever all-electric school bus outside the California capitol building in Sacramento, 2014 (Dechert, 2014).

1.3 Massachusetts's Electrification Goals and The Current School Bus Fleet

Massachusetts is one of thirteen U.S. Zero Emission Vehicle (ZEV) states (Multistate ZEV Task Force, n.d) and has a goal to convert 300,000 vehicles to electric by 2025; however, as of early 2020, only 16,000 electric vehicles – mostly passenger cars – have been sold. As public officials and concerned residents seek ways to expedite vehicle electrification, the attention is rapidly turning to medium- and heavy-duty vehicles. On July 14, 2020, following the groundbreaking California's mandate to electrify nearly all its trucks by 2045, Massachusetts and other 13 states signed a non-binding memorandum of understanding pledging to electrify 30% of the medium and heavy-duty vehicles operating in each state by 2030 (Shepardson, 2020).

As of 2018, 9,000 school buses were operating in Massachusetts according to the Pupil Transportation Statistics (School Bus Fleet, 2019) to serve the 289 districts and approximately 500,000 students daily. Out of these buses, only three are electric. In 2016, the cities of Amherst, Cambridge and Concord were part of an early-adopter pilot that delivered three electric school buses, entirely paid for by the state (VEIC, 2018). Despite some technical difficulties, the pilot was successful. However, the adoption of electric school buses in the state has stalled, and as of early 2020, virtually all school buses operating in the state today are fossil fuel powered.

To the best of my knowledge, there has not been a systematic analysis of both the viability, opportunities and net benefits of a potential transition to a fully zero-emission school bus fleet in Massachusetts. Furthermore, informal conversations have revealed that the knowledge about electric school buses that is available to the general public is scattered and often anecdotal. This situation creates an environment of uncertainty which can lead to both high expectations and excessive fears about electric school bus adoption. There is therefore a need to fill this knowledge gap through a cost-benefit analysis that can elucidate the possible pathways of a sustainable transition of the school bus fleet in the Commonwealth.

1.4 Purpose of the Study and Research Questions

The underlying objective of this project is to evaluate the feasibility and benefits of the decarbonization of school transportation in Massachusetts. The research aims at providing tools that can enable fleet owners to approach the vehicle purchase decision-making process with information that can be tailored to a specific use case. Another goal of the study is to educate decision makers about the importance to integrate elements of long-term thinking such as lifecycle costs, health benefits of electrification and environmental justice into the vehicle procurement process. The research developed around the following questions:

1) Is school bus electrification viable from a total cost of ownership (TCO) standpoint?
2) What are the social benefits that can and should be considered?
3) What are the existing barriers and opportunities for school bus fleet electrification?
4) How can the transition be made equitable towards disadvantaged communities?
5) What are the opportunities for beneficial electrification?

Short- and long-term policy interventions that can overcome existing barriers to school bus electrification are also proposed. Once completed, this project is intended to be an important information resource to guide the electrification of the school bus fleet in Massachusetts, thereby extending the useful life and broadening the significance of this research.

2. Methods

This section gives an overview of the qualitative and quantitative methods used in this study, along with assumptions and limitations. Additional information about quantitative methods is reported in Appendix B.

2.1. Qualitative Methods

Qualitative methods were used at the initial phase of the research project to gather information about school bus electrification at the national and state level. Methods included literature reviews, analysis of reports and public documents, and informal conversations with acquaintances and professionals in the field. These professionals included fleet operators, local representatives of school bus original equipment manufacturers (OEMs) and private individuals who have experience with school bus operation and could either provide or validate data obtained through publicly available resources. A literature search provided an overview of the capital and operational parameters that are relevant to asses vehicle costs (Aber, 2016; Eudy and Jeffers, 2017; National Renewable Energy Laboratory, 2017). While the capital and operational costs of diesel school buses are easy to obtain, very limited data exists for electric and LPG school buses, especially for fuel and maintenance costs. For example, in Massachusetts only Boston Public Schools owns LPG buses, and their operational data are not public. Furthermore, the state doesn't keep a publicly available database of bus contractors. While some information could be found on the transportation webpages of the major school districts, very few companies have their own website, and only in rare occasions do the websites have information about the number and type of school buses that are operated. Therefore, a detailed bus inventory reflecting the exact number and types of school buses distributed across the Commonwealth could not be created. While such data gap didn't affect this research, it would certainly represent an obstacle for a state agency deciding to undertake school bus electrification in a systematic manner.

2.2 Quantitative Methods

The core method of this capstone is a total cost of ownership (TCO) model that compares the lifetime costs of three commercially available school bus fuel types: diesel, LPG, and battery electric. The capital and operational cost parameters for the TCO were obtained as described in section 2.1. Appendix B describes more in detail the TCO parameters and the calculations performed to obtain the input values for the model. The TCO was performed over 10 years (the average life of a school bus in Massachusetts) and total costs were discounted at a rate of 3%, consistent with the historical cost of capital for a 10-year high rated municipal bond (WM Financial Strategies, 2020). The TCO does not include vehicle depreciation and additional costs such as insurance and taxes, which are assumed identical in all cases. Further, the analysis does not include midlife overhauls (typically not performed for school buses) and end-of-life costs (data not available). In the case of electric vehicles, battery recycling and/or disposal has been a topic of growing concern, but recent applications are opening to the possibility of a second life for batteries as energy storage units in buildings (Engel et al., 2019).

Other quantitative methods were used to estimate vehicle emissions and externalities that were combined with the TCO to perform a full cost-benefit analyses (CBA). The U.S. EPA's Simplified GHG Emissions Calculator, v5 (U.S. EPA, n.d.) was used to calculate GHG in metric tons of CO_2 equivalent (MT CO_2e). The GHG equivalencies were calculated with the EPA GHG Equivalency Calculator (U.S EPA, 2018).

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model (Argonne National Laboratory, 2020a) was used to extract the tailpipe emission factors (EF) of typical vehicle pollutants for the diesel and LPG school bus; EF values were available for particulate matter (PM_{10} and $PM_{2.5}$), sulfur oxides (SO_x), nitrogen oxides (NO_X), ammonia (NH_3), methane (CH_4), carbon monoxide (CO), black carbon (BC), and volatile organic compounds (VOC). The AFLEET model – a subset of GREET (Argonne National Laboratory, 2020b) – was used to extract the monetized costs of petroleum use.

The tailpipe pollution quantities (in tons per year) calculated for the entire Massachusetts fleet were then used as inputs for the U.S. EPA CO-Benefits Risk Assessment (COBRA) Health Impacts Screening and Mapping Tool (U.S. EPA, 2020b). COBRA calculates the health impacts resulting from changes in secondary ambient $PM_{2.5}$ there are driven from changes in primary pollution, i.e., $PM_{2.5}$, SO_2, NO_X, NH_3, and VOC. The changes in $PM_{2.5}$ are calculated against a 'pollution' baseline preloaded in the model for year 2017 or 2025. The year 2025 was used in this study as pollution baseline. COBRA uses a simplified air quality dispersion model, the Source-Receptor (S–R) matrix, to determine the effect of emission changes at the county, state, or national levels. The COBRA model is a screening tool, and as per EPA, "does not replace regulatory quality analyses." However, it is granular enough to make detailed estimates of the costs associated with 12 specific health endpoints ranging from premature death to days of missed work. COBRA has been extensively used, including in studies that have looked at the benefits of transitioning bus fleets from diesel to cleaner fuels (Olawepo et al., 2019).

The Disability Adjusted Life Years (DALYs) was used as an additional estimate of the health benefits associated with vehicle emission reduction according to the formula:

$$DALYs = Emissions \times Intake\ fraction \times Effect\ factor$$

where the emission factors are the same used in the COBRA model, intake fractions indicate the amount of $PM_{2.5}$ (in milligrams) inhaled for each kilogram of emissions of primary $PM_{2.5}$ or precursor pollutants, and the effect factors indicate the number of disability-adjusted life years associated with each kilogram of inhaled $PM_{2.5}$. Intake fractions and effect factors specific for the U.S. were obtained from Fantke et al. (2019) and Humbert et al. (2011), respectively. The number of avoidable premature deaths was calculated by dividing estimated DALYs by the average severity factor as used in Fantke et al. (2019), or 26.3 DALYs per death. The value of avoided health damages was obtained by multiplying the number of premature deaths by the value of a statistical life (VSL). A U.S. EPA-recommended VSL of $10 million was used, also consistent with the COBRA model.

Finally, a sensitivity analysis was performed to understand how key variables (e.g., mileage, fuel cost, electricity rates, etc.) affect the TCO and the CBA, and to determine under which conditions electric school buses are cost effective compared to diesel and LPG.

2.3 Assumptions and Limitations

This study relies on a series of assumptions and limitations that are reported below.

Assumptions:

a) *The TCO model includes all the relevant cost parameters, and such costs are representative of real-world numbers*. As described earlier, the TCO didn't include costs such as taxes, insurance, and the monetary value of each vehicle type at the end of life, which are unknown. While it is unlikely that these represent major cost or revenue factors, they should be included in future models when possible. Additionally, the TCO relies on a limited pool of operational cost data, given the scarcity of publicly available information from fleet operators. However, a cross-comparison with data published for transit buses and conversations with experts in the field indicate that the operational cost numbers used in the TCO are representative.

b) *The number of school buses used in this study (9,000) reflects the real number of vehicles operating in the state.* The Massachusetts school bus numbers fleet size was obtained from an official school bus industry publication, but it may not be accurate given the lack of a database of both public and private school bus providers. Further, it is assumed that all buses, except for the 400 LPG units owned by Boston Public Schools, are diesel powered as opposed to e.g., gasoline powered (the number of gasoline powered school buses is unknown). However, given that the per-mile emissions of fossil fuel school buses are similar, the possible error introduced by this assumption is minimal.

Limitations:

a) *The CBA does not consider the full lifecycle externalities associated with vehicle manufacturing and disposal.* Only the 'fuel cycle' emissions (also called pump-to-wheel) are incorporated in the CBA, as a full life-cycle analysis is beyond the scope of this project.

b) *The CBA does not include all possible health and environmental costs of pollution.* Tailpipe exhaust includes hundreds of different compounds that are not routinely measured and monetized. Consequently, the true environmental externalities of tailpipe exhaust are likely underestimated. Additionally, the externality prices may not represent their true value, as prices are assigned based on economic theories and rarely on true health effects, which are difficult to estimate and parse out from other factors. Nonetheless, pricing externalities is still considered a useful and necessary exercise to guide and optimize the decision-making process.

3. Results

This section presents the results from the TCO model, CBA and sensitivity analysis. All data refer to a Type C school bus model (see Appendix A, Table A1), which is the most common bus type and the only vehicle that exists in the diesel, LPG, and electric versions Additional results pertaining to this section are reported in Appendix C.

3.1 Capital and Operational Costs

The TCO analysis was performed using an iterative process. Initially, only capital and operational costs of the three vehicle technologies were considered. A 'base case' was constructed using average conditions, e.g., bus mileage of 12,000 miles per year and travel speed of 12 mph. Table 1 summarizes the input cost parameters for the base case TCO.

Table 1: Summary of input parameters for the base case TCO. For the electric bus, the electricity price (\$0.17/kWh, or \$0.25/mile) reflects the Massachusetts average cost of energy production (\$0.12/kWh) plus delivery (\$0.05/kWh) for commercial entities. See Appendix B for more details.

CAPITAL	**Diesel**	**LPG**	**Electric (155 kWh)**
Bus cost	\$100,000	\$110,000	\$370,000
Fueling Equipment	\$5000	\$5000	-
Charging Equipment	-	-	\$2000 (Level II)
Charging Infrastructure	-	-	\$28,000 (trenching & wiring)
Total Capital Costs	\$105,000	\$115,000	\$400,000
OPERATIONAL	**Diesel**	**LPG**	**Electric (155 kWh)**
Annual Miles	12,000		
Vehicle Speed	12mph		
Fuel Economy (mpdge)	7.1	4.7	25
Fuel (\$/mile)	\$0.35	\$0.21	\$0.25 (\$0.12/kWh, supply \$0.05/kWh, delivery \$10.00/kW, demand)
Maintenance (\$/mile)	\$0.55	\$0.32	\$0.17

As the Table shows, the electric school bus has a much greater total capital cost. However, it also has a much greater fuel economy (reported in miles per diesel gallon equivalent, or mpdge) compared to the two fossil fuel counterparts.

While at average speed a diesel school bus can only travel 7 miles and the LPG bus can travel less than 5 miles on a gallon, the electric school bus can go 25 miles with a gallon equivalent of electricity, due to the much greater efficiency of a battery compared to a combustion engine (as explained in Appendix C, the 25 mpdge already includes the battery range losses in cold weather). The maintenance costs of the electric bus are also much lower than the other two technologies, suggesting significant operational savings.

Figure 2 shows the results of the base case scenario of the TCO including capital, fuel, and maintenance costs. The data are displayed as annual costs (not discounted) incremented over the vehicle lifetime (Fig. 2a) as well as total discounted costs for each category (Fig. 2b; see Appendix C, Table C1, for the actual numbers). The fuel costs are incremented annually following the Energy Information Agency's (EIA) Annual Energy Outlook 2020 'reference scenario' projections for diesel, LPG, and electricity prices for the transportation sector, which predicts an annual fuel price change of +0.8% for diesel, +1.2% for LPG, and +0.1% for electricity (see Appendix B, Table B4). The maintenance costs are incremented annually by 10% for the LPG and electric bus, and by 12% for the diesel bus to account for the extra maintenance of the diesel exhaust fluid (DEF), which is part of the DPF in modern diesel engines.

According to the TCO, the discounted cost of the electric school bus is still ~$252,000 higher than LPG, and ~$194,000 higher than diesel at the end of the 10th year. This is due to the high upfront capital cost of the electric school bus, which cannot be recuperated with the fuel and maintenance savings over the lifetime of the vehicle. In fact, the electric school bus purchased in 2020 for $370,000 has a payback of 25 years. The LPG bus is therefore the most cost-effective choice due to both low capital and operational costs.

To what extent might including environmental and other social costs improve, comparatively, the economics of the electric school bus?

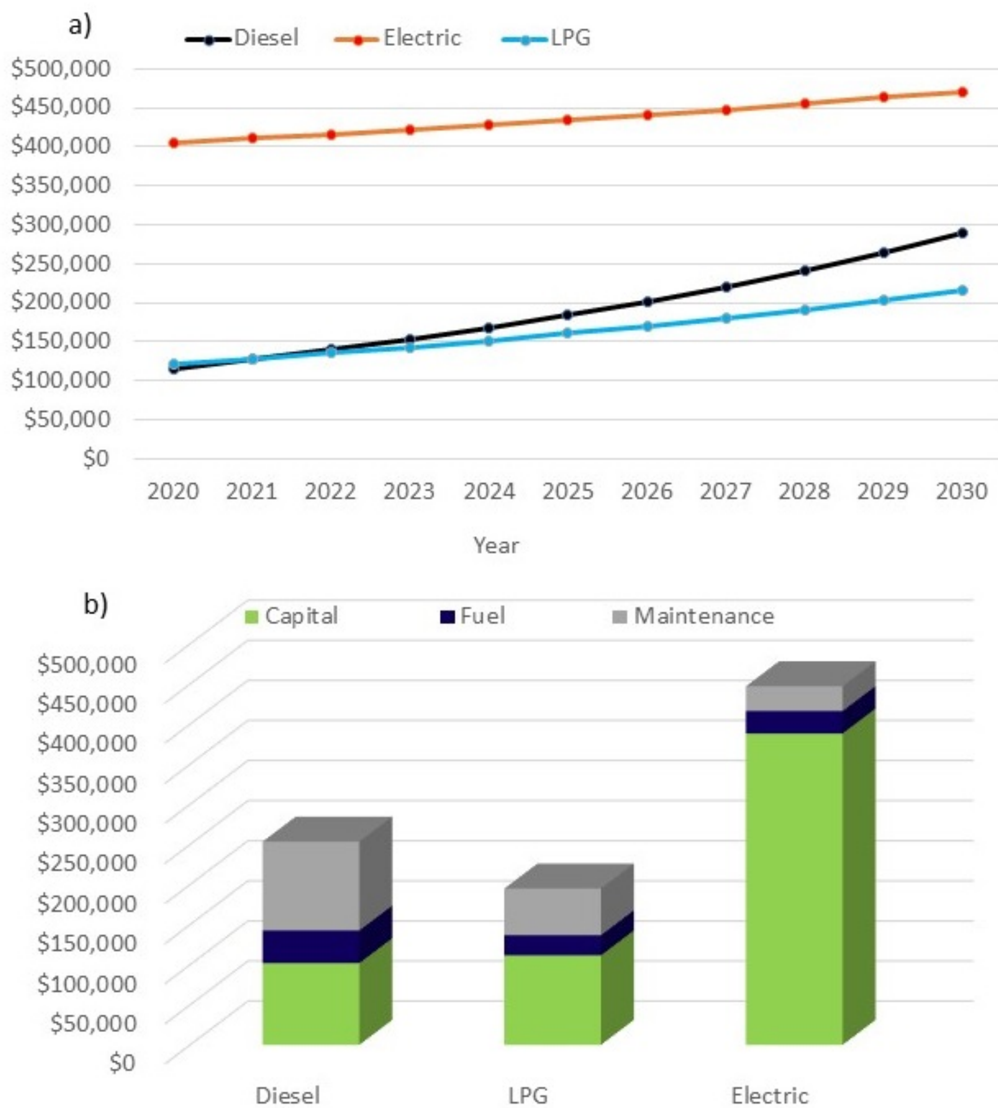

Figure 2: Panel a) Time series of the incremental cost of ownership (not discounted) for each bus technology, 2020 through 2030. The TCO includes the capital and operational costs. Panel b) Stacked histogram of the same costs, discounted at 3%, with cost categories individually shown.

3.2 Environmental and Social Costs

Quantifying the cost of pollution caused by human activities is becoming common practice in the field of sustainability, due to the recognized increasing costs of climate disruption and air pollution (World Bank, 2016) to which the transportation sector is a major contributor (Caiazzo et al., 2015). Incorporating the full cost of externalities in policy and decision making is also becoming more popular, even if valuation methods are not perfect and prices do not capture the true cost of damage (Helbling, 2020). Nonetheless, adding the environmental and social costs of pollution to the TCO model is a logical step to build a more complete CBA.

The first externalities considered are the GHG emissions. The electric school bus does not have tailpipe GHG emissions, but charging a vehicle requires electricity, which is largely generated from fossil fuels. While the emissions associated with electricity generation reduce the net benefits of electric vehicles, studies have demonstrated that the fuel cycle emissions of electric vehicles across all classes are always lower than those from combustion engines on a per mile basis (O'Dea, 2019; Knobloch, 2020). This is because of the greater efficiency of an electric battery to convert energy in miles driven, as indicated by the fuel economies in Table 1.

In this study, the fuel-cycle emissions for each vehicle were calculated using New England-specific CO_2 emission coefficients for electricity generation (0.56 lbs of CO_2 per kWh of generated power for the region), as well as diesel and LPG fuel (22.4 and 13 lbs of CO_2 per gallon of fuel burned, respectively). As shown in Figure 3, an electric school bus charged in New England emits 380 grams per mile (g/mi) of CO_2e from electricity generation, a ~72% reduction compared to the tailpipe GHG emissions from the diesel or the LPG counterparts.

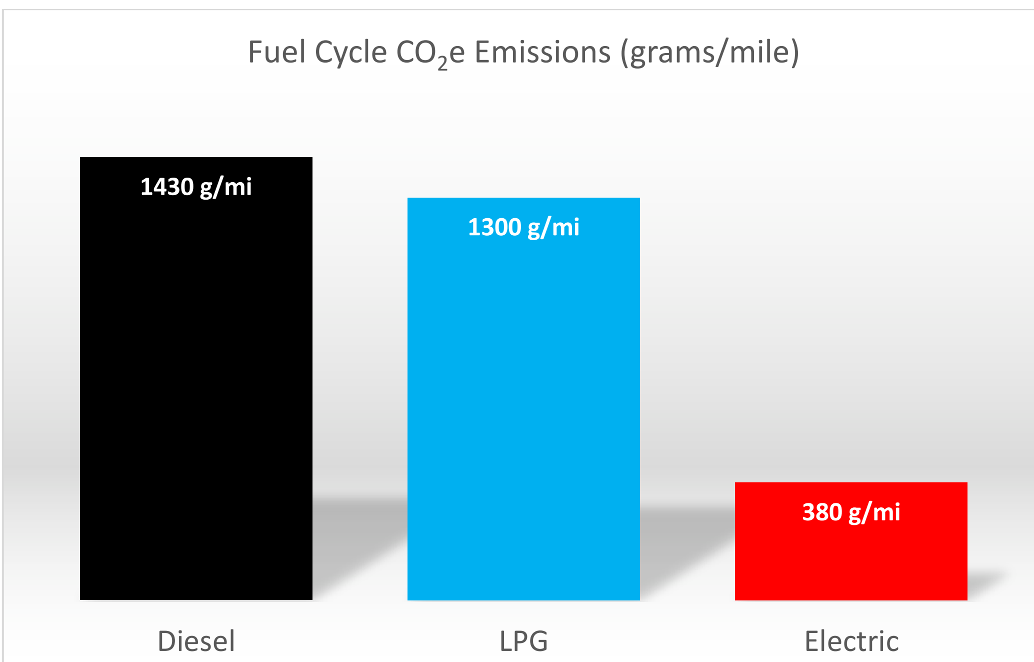

Figure 3: GHG fuel cycle emissions (g/mi) of a diesel, LPG and electric school bus calculated for average fuel economy of 7.1, 4.7 and 25 mpgde respectively, and 12,000 miles/year ('base case').

Tailpipe pollutants for the diesel and LPG school bus were calculated using he GREET emission factors EF (g/mi), which have been recently updated to reflect the modern vehicle technologies. The EF values used here refer to a diesel school bus burning ULSD and to an LPG bus with a low NOx emission engine. The GREET EF values are shown in Figure 4. The highest emission for the diesel school bus is for NOx (0.84 g/mile) while CO emissions are the largest source of tailpipe pollution for the LPG bus, reaching 9 g/mi (the EF for CO are shown on a separate scale because they are one order magnitude higher than the other EF values). While it is known that lighter fuels such as LPG produce more CO and VOCs than diesel when burned, LPG is still advertised as a clean fuel because of the low NOx content. However, both CO and VOCs, like NOx, are chemical precursor of ground-level O_3, and in addition, CO is highly toxic to humans (Levy, 2015; U.S. EPA, 2016b).

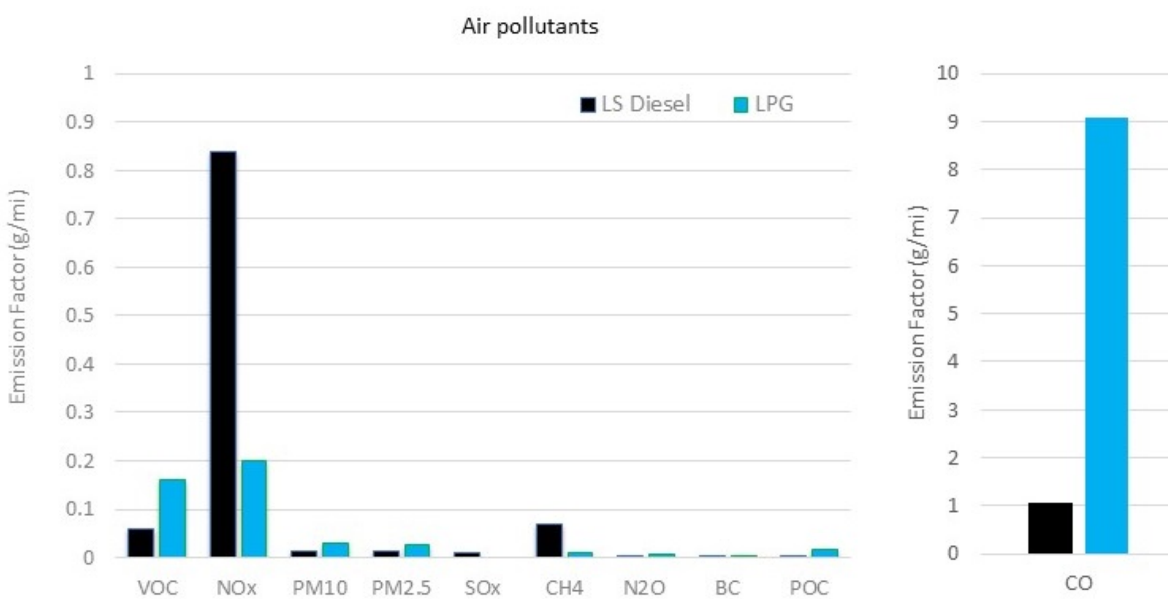

Figure 4: Emission factors (EF) of tailpipe pollutants from the GREET database, reported in grams per mile (g/mi). NOx is the highest pollutant for the diesel bus, while CO is the highest pollutant for the LPG bus on a per mile basis.

An extensive literature search was performed to gather cost values of each pollutant shown in Figure 4. The King County Metro electric bus feasibility study (King County Metro Transit, 2017) reports monetary values for NOx ($ 8,010/t), GHG ($45/t), PM_{10} ($336,400/t) in 2015 dollars per ton as well as noise as cost per vehicle mile traveled, VMT, ranging from $0.076/mi for a diesel bus to $0.046/mi for the electric bus (VTPI, 2015). The U.K. Government also produced economy-wide 2020 damage values for SO_2 ($16,500/t), VOC ($128/t), NH_3 ($9,900/t), and traffic emission-specific values for NOx ($40,000/t) and $PM_{2.5}$ ($360,000/t) (U.K. Department for Environment Food & Rural Affairs, 2020). These values are consistent with the ones produced by more sophisticated models (Michalek, et al., 2011; Heo, et al. 2016), even though the price assigned to VOC emissions in both studies seems low. For the GHG costs, $45/t of CO_2e was used for consistency with other studies even though expert consensus calls for higher price to reflect the true damage of climate change (Howard, 2015).

Table 2 shows the price for each ton of pollutant ($/ton) taken from the studies mentioned above, and the calculated annual cost of each pollutant for the diesel and LPG school bus obtained for the base case scenario.

Table 2: Summary of annual (year 1) environmental and social costs for a diesel, LPG, and electric school bus for the base case (in 2015 dollars). The cost of petroleum use is from the AFLEET model. The cost of CO is from Michalek et al. 2011, adjusted to 2015 dollars for consistency.

Environmental, Social Costs	Cost ($/ton)	Diesel ($/year)	LPG ($/year)	Electric ($/year)
GHG (fuel cycle)	$45	$765	$700	$202
NO_X (urban)	$40,000	$403	$96	$0
SO_2	$16,500	$2	$0	$0
VOC	$128	$0.1	$0.25	$0
$PM_{2.5}$	$360,000	$57	$114	$0
PM_{10}	$366,000	$63	$131	$0
CO	$968	$12	$105	$0
Noise	$0.076 (diesel) $0.066 (LPG) $0.046 (electric)	$910	$790	$550
Petroleum Use		$650	$250	$3

Figure 5 shows the TCO with the added environmental and social costs. Because $PM_{2.5}$ is a subset of PM_{10}, only the cost of PM_{10} is used in the TCO to avoid double counting. While the gap between the lifetime costs of the three technologies narrows in favor of the electric bus, there is still a difference of ~$173,000 with diesel and ~$239,000 with LPG. Appendix C, Table C2, reports the detailed discounted costs from the histogram in Figure 5b.

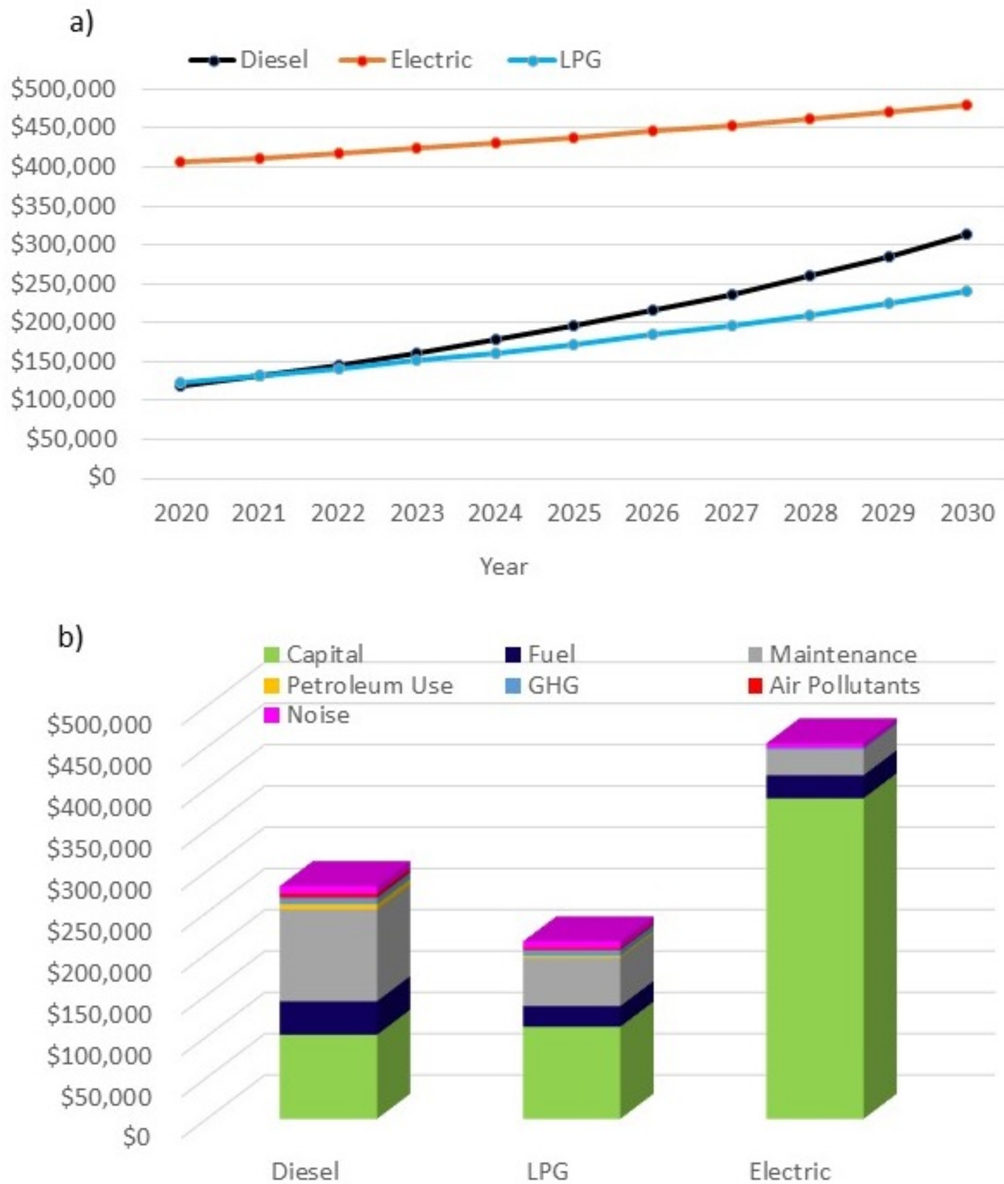

Figure 5: Panel a) Time series of the incremental cost of ownership (not discounted) for each bus technology, 2020 through 2030. The TCO includes the capital, operational and externality costs. Panel b) Stacked histogram of the costs, discounted at 3%, with cost categories individually shown.

3.3 Vehicle-To-Grid (V2G)

It is said that electric school buses have a potentially ‘secret’ card: vehicle-to-grid, or V2G. The concept of V2G is not new (Kempton and Tomic, 2005a, 2005b). As the name suggests, V2G allows the bi-directional flow of energy between the vehicle’s electric battery and the grid using special charging equipment and a dedicated energy management software.

Essentially, the battery of the vehicle becomes an energy storage asset that can be used as a distributed-energy resource (DER) for purposes ranging from building resiliency during power outages to grid stability at times of high energy demand. Further, V2G can generate revenue for the vehicle owner who can monetize the value of reselling energy to the grid. While residential applications of V2G with light-duty electric vehicles are becoming common in Europe, V2G is still at the piloting stage in the U.S., and it has focused on electric school buses. Electric school buses are indeed particularly suited for V2G because they are parked 60% of the time during the typical school day and sit virtually unused in summertime. Current pilots show that V2G can generate annual revenues up to $12,000 per bus with favorable electricity prices (Matthews, 2016). The net V2G revenue also depends on the application chosen by the vehicle owner: if V2G is used for dynamic pricing, it might be preferable to have fast, but expensive, level III chargers to exchange high amount of power over short time (typically minutes) to maximize revenue. If the goal is to stabilize the grid during 'peak-times' (typically over 3-4 hours), cheaper level II chargers can be used to exchange power at lower rates. For this study, V2G revenue was modeled for the 155kWh electric bus battery discharging in 'peak shaving' mode for ~3 hours per day, yielding a total revenue of ~ $9,000 per year with current electricity prices in New England (see Appendix B for details on V2G calculations and price assumptions).

Figure 6 shows the TCO with V2G included as a revenue stream for the electric bus. Adding the V2G revenue makes a more compelling economic case for the electric school bus, as about $91,000 cab be recuperated over the vehicle lifetime. However, a purchase incentive of $100,000 would still be needed for the electric school bus to reach cost parity with the diesel bus at year 8; the incentive would have to be $150,000 to get cost parity with the LPG bus by year 9. Appendix C, Table C3, reports the detailed discounted costs from the histogram in Figure 6b.

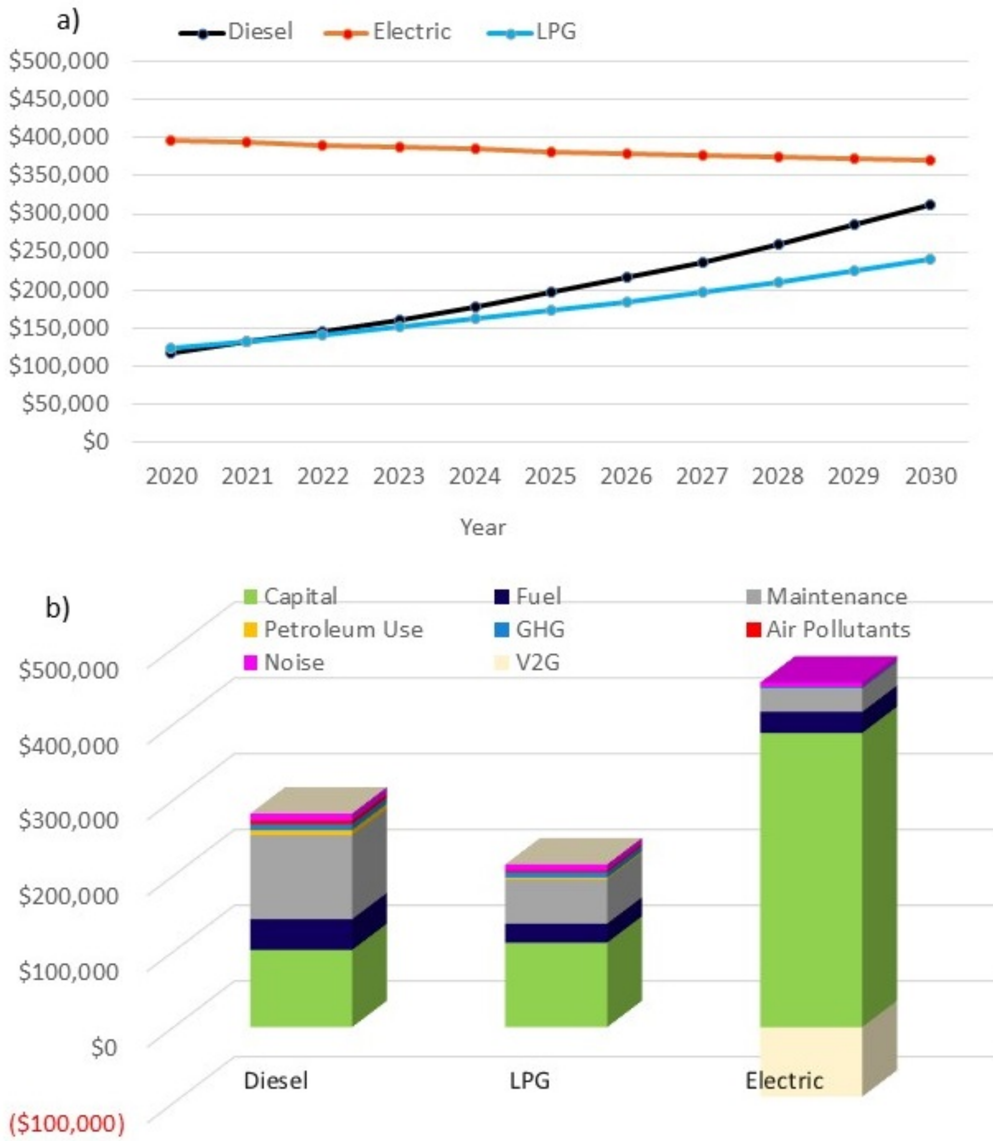

Figure 6: Panel a) Time series of the incremental cost of ownership (not discounted) for each bus technology, 2020 through 2030. The TCO includes the capital, operational and externality costs, as well V2G revenue for the electric bus. Panel b) Stacked histogram of the costs and revenues, discounted at 3%, with categories individually shown.

3.4 Sensitivity Analysis

The CBA results so far indicate that without upfront incentives, battery electric school buses are not financially cost-effective even after including the environmental and social externalities and potential V2G revenue streams. However, it is useful to perform a sensitivity analysis to explore the effect that user-dependent parameters have on the TCO of each

technology and on the CBA. The aim is to understand if there are conditions that are more economically favorable to an electric school bus. Table 3 shows the parameter investigated in the sensitivity analysis, with minimum and maximum values representative of typical operational conditions. Time-of-Use (TOU) electricity rates are also explored. The idea behind TOU rates is to incentivize consumers to use electricity when demand is low and power generation is less expensive (usually overnight, between 8pm and 8am) by rewarding them with low off-peak prices. Conversely, electricity use during daytime hours (usually between 11 am and 6 pm) is discouraged by higher on-peak prices. TOU rates are being implemented by utilities as one of the many managed charging strategies that can help better distribute grid loads, with benefits for the entire electricity marketplace including both costs and emission reductions (Myers, 2019).
For this sensitivity analysis, a scenario where the bus charges off-peak and performs V2G services on-peak is considered. However, the different V2G strategies (slow vs. fast battery discharge) are not explored because the results would be too speculative.

Table 3: Summary of key operational parameters investigated for the sensitivity analysis.

PARAMETERS	**Low**	**Base case**	**High**
Miles per year	8,000	12,000	20,000
Speed (mph)	5	12	20
Fuel Price (% change/yr)			
Diesel	-0.5%	+0.8%	+2.1%
LPG	-0.4%	+1.2%	+2.4%
Electricity	+0.1%	+0.1%	+0.1%
Electricity Rates ($/kWh) with Time of Use (TOU)	off-peak, 0.07 $/kWh (supply only) on-peak, 0.20 $/kWh (supply only)		

First, the effect of mileage is explored. Intuitively, lower mileage reduces fuel consumption and fuel costs. Emissions also change with fuel usage and so do the related externalities. For the 20,000 miles per year use case, the electric bus is the most favorable technology due to proportionately higher savings in fuel and maintenance, as well as lower externalities compared to diesel and LPG. As indeed shown in Figure 7, the electric school bus reaches cost parity with diesel by year 9, if V2G is included, and without upfront incentives. Still, the LPG bus remains the most cost-effective choice.

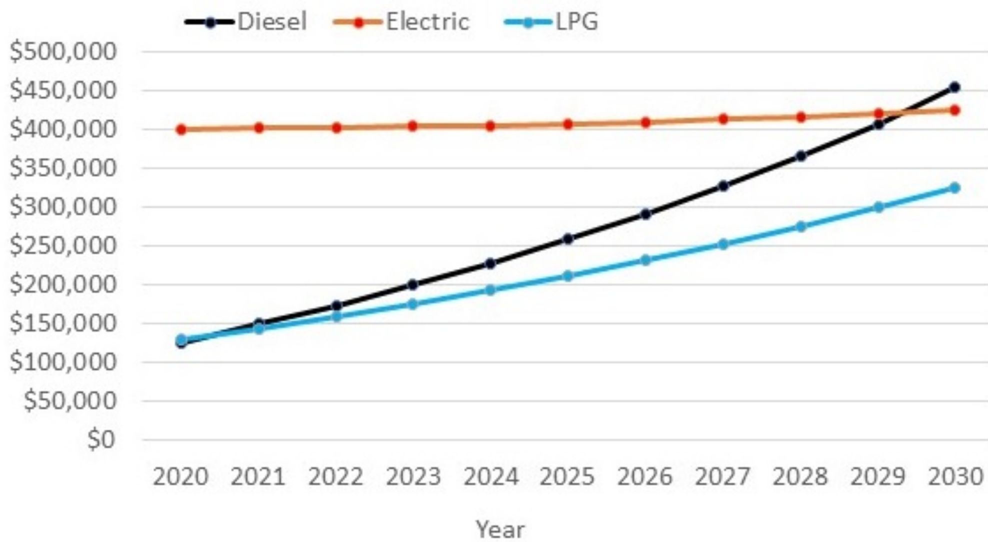

Figure 7: Incremental cost of ownership (not discounted) for the 20,000 miles per year use-case. The TCO includes the capital, operational and externality costs, as well V2G revenue for the electric bus. Under this scenario, the electric school bus reaches cost-parity with diesel by year 9.

Appendix C, Table C4, reports the percentage differences between the discounted costs of the electric school bus and the two fossil fuel counterparts for annual mileages of 8,000, 12,000 and 20,000 miles, with and without V2G revenue. The savings offered by the electric school bus would be even higher for annual mileage above 20,000 and could reach cost parity with LPG as well for mileage of 40,000 or more. However, school bus models currently on the market have a maximum battery range limited to 150 miles per day on a single charge, limiting their applicability to ~30,000 miles annually (assuming that buses are charged only once per day).

Next, the effect of vehicle speed is tested. In combustion engines, vehicle speed changes fuel economy, and therefore fuel consumption and costs; at low travel speed fuel usage goes up, and viceversa. However, the relationship is not linear, as fuel economy drops drastically below 10 mph (see Appendix B, Figure B2). Such non-linearity is reflected in the GHG emissions of the diesel and LPG bus as shown in Figure 8. The CO_2e emissions of a diesel and LPG bus increase by 60% with speed dropping from 12 to 5 mph, but only decrease 20% with speed increasing from 12 to 20 mph. Meanwhile, the GHG fuel-cycle emissions remain constant for the electric school bus because its fuel economy does not vary with speed.

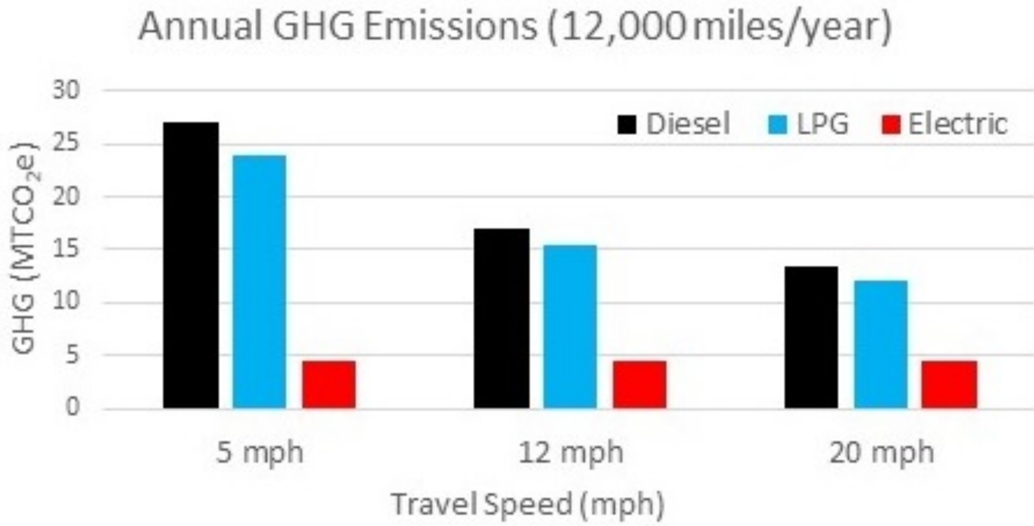

Figure 8: Fuel cycle GHG emissions (MT CO_2e) of diesel, LPG, and electric bus at three different travel speeds. The GHG emissions of the electric school bus are from the electricity used to charge the battery and do not change with travel speed.

Low travel speed can also affect the EF of other tailpipe pollutants; studies on transit buses (Bradley, M.J. & A., 2013) reported that the EF of NOx and CO doubles when the bus speed drops from 12 to 6 mph because engines become less efficient at low speeds and pollution control technologies are less effective (Yang et al., 2016). Therefore, the EF of NOx and CO are doubled at low speed in this study, and the cost of pollution is increased accordingly.

Figure 9 shows the result of the sensitivity analysis performed for the use case of 5 mph. After 10 years, the lifetime cost of the electric school bus is close to the one of diesel, confirming that low travel speeds (typical of congested urban routes) are more favorable for the deployment of an electric school bus. However, the electric school bus is still 13% more expensive than diesel and 34% more expensive that LPG at 5 mph, even with V2G revenue included. Appendix C, Table C5, reports the percentage differences between the discounted costs of the electric school bus and the two fossil fuel counterparts for travel speeds of 5, 12, and 20 mph, with and without V2G revenue.

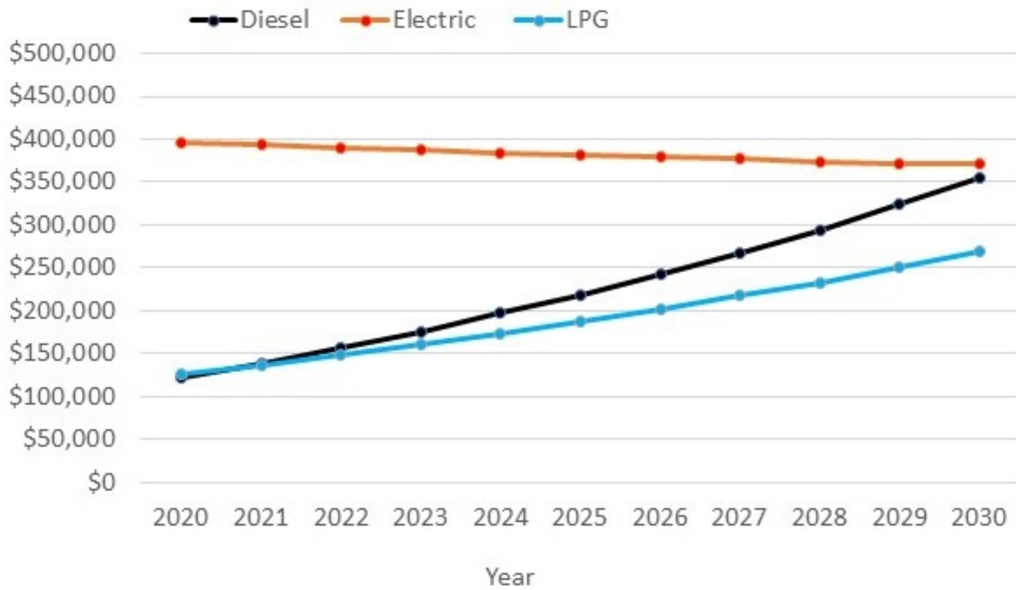

Figure 9: Incremental cost of ownership (not discounted) for each bus technology for the 5-mph travel speed use-case. The TCO includes the capital, operational and externality costs, as well V2G revenue for the electric bus.

The effects of oil price changes projected by the EIA 2020 Outlook are explored next. Appendix C, Table C6, reports the percentage differences between the discounted costs of the electric school bus and the two fossil fuel counterparts for different fuel costs based on oil price projections, using average annual mileage and vehicle speed, with and without V2G. As expected, the electric school bus is slightly more favorable with high oil prices, but the differences between low and high oil prices are minimal and do not translate into substantial differences in TCO. However, while the absolute prices of diesel and LPG fuels matter for the TCO, transit agencies operating electric bus fleets have reported that the historically stable electricity prices always represent an advantage over the volatile oil price and make the electric bus an easier asset to manage in terms of budgeting fuel costs over the vehicle lifetime.

Finally, the effect of TOU rates on the TCO of the electric school bus is explored. Using the rates in Table 4, the fuel costs and revenues are calculated assuming that the electric school bus charges the battery at night (off peak) and performs V2G services during the midday (on-peak). Under these optimal conditions applied to the base case, charging costs go down (from $3,000 to $2150 on year 1) and the V2G revenues go up (from $9,000 to $11,400 on year 1). At the end of the lifetime, there would be additional net savings for the electric school bus, and its final lifetime cost would be reduced by 7% compared to the base case shown in Figure 6. The electric school bus would still be more expensive over the lifetime, but the upfront incentive needed to reach cost parity by year 9 with diesel would be $50,000, and $100,000 with LPG (these incentives are about ~$50,000 lower than what would be needed without TOU rates).

In summary, the CBA shows that despite the lifetime operational savings, the current upfront cost of a Type C electric school bus is too high for the vehicle to pay back for itself during its lifetime under most explored conditions, unless substantial purchase incentives are provided. On the other hand, the sensitivity analysis indicates that the electric school bus offers substantial fuel savings at low travel speeds and for high annual mileage, suggesting that there are cases for targeted electrification projects that could be already cost-effective.

The possibility of using the school bus battery for V2G services – currently at the pilot stage in California and New York state - would further reduce the financial pressure and the size of the upfront purchase incentive, while providing additional services. Unfortunately, these services currently are not monetized. Likewise, the social and environmental costs that are included in the CBA are not currently internalized, rather they are passed to the Massachusetts residents. To this date, California is the only state that is pricing carbon pollution from transportation through the cap-and-trade Western Climate Initiative (WCI, 2020), and is reusing the revenues to finance vehicle electrification, while exploring V2G and enabling TOU rates.

In the current circumstances, can Massachusetts enable school bus electrification at scale?

4. Discussion

This chapter identifies opportunities, explores barriers, and suggests short and long-term policy interventions to spearhead a strategic electrification of the Massachusetts school bus fleet. These recommendations leverage the know-how generated over the years by other clean energy sectors such as the solar industry and more recently, by the electrification of public transit buses.

4.1 Opportunities

The term beneficial electrification is widely used to indicate the practice of electrifying energy end-uses to reduce operational costs and achieve other benefits such as GHG emission reduction (Lisowski, 2019). The TCO indicated that while an electric school bus has a large upfront sticker price, the operational costs are low over time, and that beneficial electrification could be possible for specific use cases. Furthermore, significantly reducing GHGs and air pollutants has enormous benefits even if carbon pollution is not currently priced. The next three paragraphs discuss specific opportunities to advance beneficial electrification in Massachusetts through the hypothetical conversion of the school bus fleet.

4.1.1 Climate Compliance

The 2008 Global Warming Solution Act (GWSA) requires Massachusetts to reduce GHG emissions of 80% by 2050, and it is known that the electrification of the heavy-duty sector offers a unique opportunity to cut both GHGs and harmful air pollutants. In this context, it is useful to estimate the GHG elimination potential of school bus fleet electrification.

Assuming a fleet of 8,600 diesel and 400 LPG buses each traveling 12,000 miles per year, the annual GHG emissions generated by the Massachusetts school bus fleet amount to ~152,000 MT CO_2e (Figure 10, panel a). Note that this number is twice the GHG emissions of the entire public transit fleet operating in the state, which comprises ~2,700 buses - a mix of diesel, diesel-hybrids, and compressed natural gas, or CNG. A simple GHG equivalency exercise reveals that such estimated school bus emissions equate to those of ~33,000 cars, and that it would take ~33 wind turbines to offset them (Figure 10, panel b). Because an electric school bus charged in New England reduces GHG emissions by 70% on a per mile basis compared to a combustion engine bus (see Figure 3), the electrification of the entire Massachusetts fleet would eliminate ~111,500 $MTCO_2e$ of tailpipe GHG emissions, and would help advance the state's ZEV and GWSA goals.

If carbon pollution would be internalized through carbon pricing Massachusetts would save \$5 million in GHG-related damages alone, at the conservative price of \$45 per $MTCO_2e$. Adding the other environmental externalities calculated using the prices reported in Table 2 would bring the total savings to about \$347.5 million.

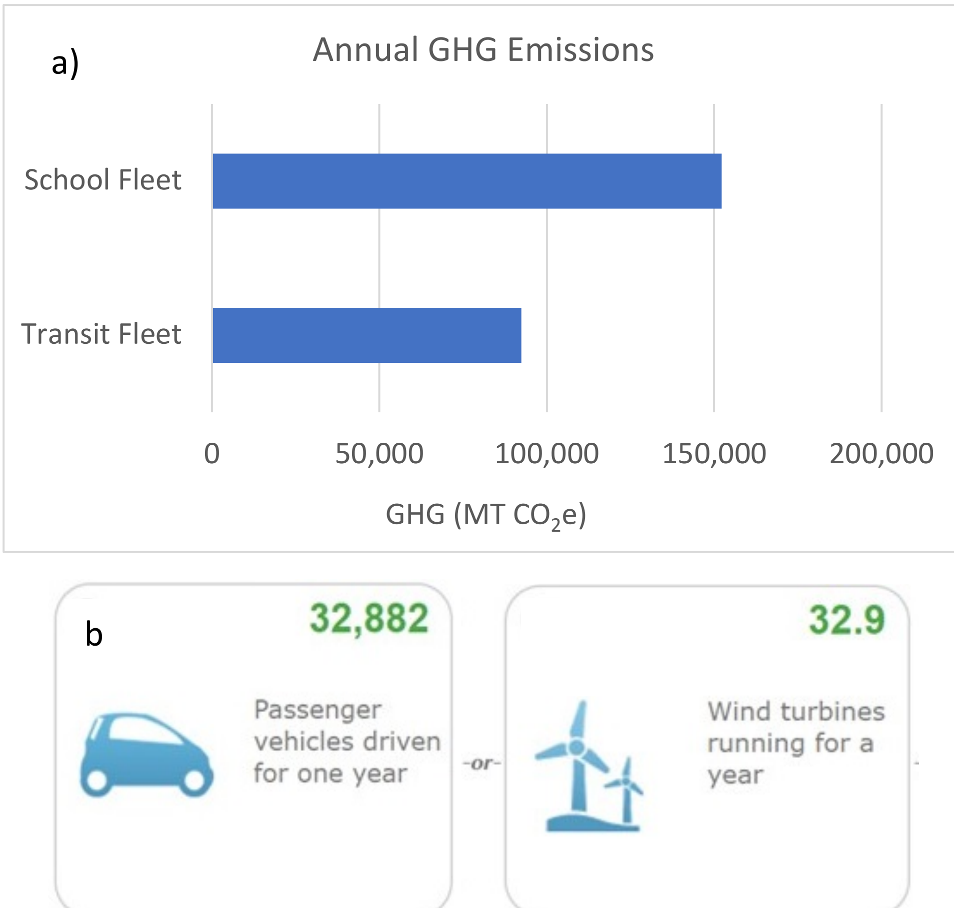

Figure 10: Panel a) Annual GHG emissions ($MTCO_2e$) of the school and transit bus fleets in Massachusetts, calculated assuming mileages of 12,000 per year and 35,000 per year, respectively. Panel b) GHG equivalencies of the Massachusetts school bus fleet.

The health benefit of the hypothetical fleet-wide transition to electric school buses should be also valuated, given that tailpipe exhaust -especially from diesel- is linked to negative health outcomes. The health savings of the eliminated VOC, NOx, SOx, and $PM_{2.5}$ emissions were calculated using the COBRA model as described in Section 2.2, and assuming 2025 as baseline year. Unfortunately, the COBRA model does not allow including the contribution of tailpipe CO emissions from the school bus fleet (150 tons annually).

Table 4 summarizes the state-wide health cost savings resulting from the electrification of the school bus fleet as calculated by the COBRA model, reported for a series of health effects including annual non-fatal cardiovascular and respiratory illnesses, asthma, hospitalization, and mortality incidence. The results suggest that eliminating the school bus fleet tailpipe emissions would result in \$1.58 million (low estimate) to \$3.56 million (high estimate) of total health benefits. These savings are mostly represented by avoided premature deaths over the 20 years following exposure (U.S. EPA, 2006). All the other health effects (or benefits) occur instantaneously on year 1.

Table 4: Results of the COBRA model run for the base case scenario. The number of cases is expressed as fractions because COBRA calculates small statistical risk reductions aggregated over the state's population.

Health Effects	Number of Cases	Costs
Total Benefits (over 20 years)		\$1,578,644.0 \$3,565,071.0
Mortality (over 20 years)	0.1566 (low) 0.3538 (high)	\$1,557,552.0 \$3,519,989.0
Non-Fatal Heart Attack	0.022 (low) 0.2041 (high)	\$2,893 \$26,883
Hospital Admissions, Respiratory	0.05 (all) 0.0364 (direct) 0.0046 (asthma) 0.009 (chronic lung disease)	\$ 1,577
Hospital Admissions, Cardiovascular	0.055	\$2,383.6
Acute Bronchitis	0.2	\$109
Upper Respiratory Symptoms	3.65	\$138
Lower Respiratory Symptoms	2.55	\$61
Minor Restricted Activity Days	112	\$8,659
Work Loss Days	19	\$3,390
Asthma Exacerbation	3.8 (all) 0.86 (cough) 1.16 (shortness of breath) 1.78 (wheeze)	\$ 250

Because these incidences and costs seem low, a second assessment was obtained using the Disabled Adjusted Life Years (DALYs) method. Based on this method, transitioning the fleet to electric would save 15 cumulative years of life lost, corresponding to 0.57 premature deaths and a cost of $ 5.7 million (using the EPA recommended value of statistical life of $10 million). This is twice as much as what obtained by COBRA. While a more sophisticated model would provide ore accurate data, the consistency of the results obtained by the COBRA model and the DALY method suggest that the order of magnitude of these estimates is most likely correct.

With health costs included, the total net benefits of eliminating tailpipe emissions from the Massachusetts school bus fleet are valued at $350 million. Taking this number at face value, the $350 million saved in pollution and health damage would be enough to pay for the conversion of 1,400 school buses receiving an incentive of $250,000, or 2,300 school buses receiving an incentive of $150,000. In other words, the electrification of the first ~2,000 school buses could be made economically viable *IF* the cost of externalities would be fully internalized. This would put Massachusetts on a reasonable path to climate compliance while avoiding further delaying the transition to electric school buses.

4.1.2 Environmental Justice

One of the most common criticism of the current clean energy trend is that only the wealthiest segments of society are benefitting from clean technologies because they have economic means and the power to attract investments in their communities (Golden, 2020). Consistently, adoption and deployment of clean vehicles to date has occurred in the wealthiest households and most affluent communities (U.S. EIA, 2018).

To address these disparities, both governmental agencies and non-governmental organizations have shaped policies and created programs to address the inequities of clean energy access (Greenlining Institute, 2020). In the case of school buses, the state of California has prioritized the replacement and electrification of old diesel buses serving low-income communities that are disproportionately affected by pollution and have higher rates of childhood asthma (California Energy Commission, 2020).

While not plagued by the same pollution levels as California, Massachusetts is not exempt from environmental justice issues that only recently have begun to be fully recognized with the creation of environmental justice policies (Mass.gov., 2017). Massachusetts is also one of the few remaining recipients of a school desegregation program, the Metropolitan Council for Educational Opportunities, or METCO. As of 2019, the METCO program included 190 schools and 33 school districts, enabling ~3,100 students - mostly African American and Latino living in Boston's disadvantaged neighborhoods - to attend schools in wealthier and mostly white suburban areas, with the intent to promote diversity and address the entrenched inequalities in educational opportunities (METCO, 2020).

The map in Figure 11 shows the location of the participating METCO districts in the greater Boston metro area. The colored in gray indicates the Boston neighborhoods of Hyde Park, Dorchester and Mattapan that are recipients of the METCO program. The travel distance from these areas to the hosting districts (color-coded by the number of enrolled METCO students) can reach 25-30 miles and has an average travel time of over two hours each way. In fact, the METCO bus schedules of Newton, which is rather close to Boston, indicate that children are picked up in Boston starting at 6 am, and dropped off at the elementary school in Newton at 815 am. That means that kids participating in the METCO program spend at least 4.5 hours per day on a fossil fuel school bus.

As the TCO indicated, the most suitable routes for electrification in terms of operational cost savings are the ones with the highest mileage and the ones that spend time in traffic traveling at low speed or idling. While the exact mileage and depot location of the buses serving the METCO program is not known, the METCO routes could be good candidates for electrification to reduce fuel and operational costs, in addition to reducing emissions for the school children and the impacted communities. Based on the number of students enrolled, the METCO fleet should consist of approximately 60 buses – a modest-size fleet that could be electrified relatively easily, both financially and logistically. More importantly, by serving disadvantaged children, the electrification of METCO would directly address pernicious environmental justice problems that have never been resolved fully, while providing an opportunity to elevate a program that has been consistently underfunded (Samuels, 2019).
In other words, the intentional and targeted electrification of the METCO routes would directly fulfill the environmental justice commitment of the Commonwealth.

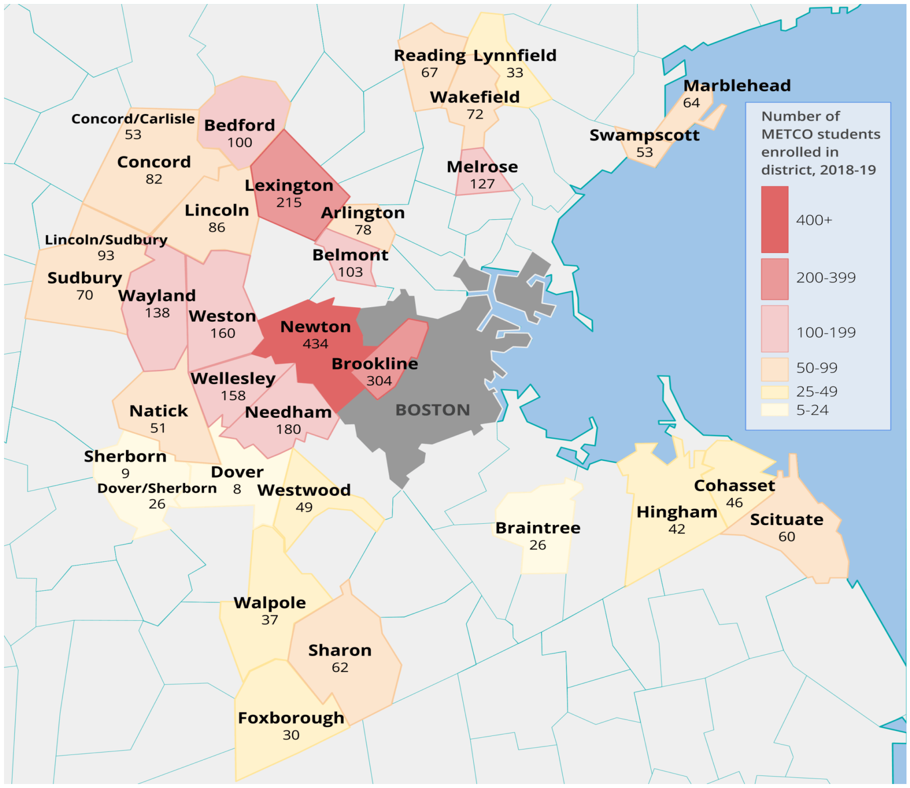

Figure 11: Map of the districts participating in the METCO program. The average distances between the Boston locations (in gray) and recipient districts is 22 miles each way.

4.1.3. Peak Demand Management

On June 9, 2020, the Massachusetts Department of Energy Resources (DoER) filed the Clean Peak Energy Portfolio Standard Regulation, a new initiative aiming to 'establish a pathway to reduce emissions and the costs associated with electricity generation during times of seasonal peak demand' (Mass.gov., 2020). In the New England Independent System Operator (ISO-NE), peak generation can reach 25,000 MW on hot summer days and 20,000 MW on cold winter days, typically in the afternoon hours when people ramp-up air conditioning use or heat-up their homes. During these times, ISO-NE meets the additional energy demands with old, inefficient and polluting oil and coal power plants – also called 'peaker-plants'. These plants are expensive to maintain and contribute to high electricity prices that are passed to consumers. In New York City alone for example, ratepayers paid an estimated $4.5 billion between 2009 and 2019 mostly to keep the city's peaker-plants in standby; in fact, these facilities are in use only for 100 hours per year (Clean Energy Group, 2020).

A recent study by Physicians, Scientists and Engineers (PSE) for Health Energy looked at this issue in several states including Massachusetts, where there are 23 individual peaker-plants and peak units able to provide ~2800 MW of generation capacity, when needed. Like in New York, many of these plants burn oil and are in low-income and minority communities (PSE, 2020). Half of them have less than 25 MW capacity and run less than 4 hours per day, when used. The largest one in the state, the Mystic Generation Plant located in Everett, has a 630 MW oil unit that has been allowed to continue operating through 2024, a decision that has generated concern among the nearby residents suffering high rates of asthma (Abel, 2020). Given that the DoER's Clean Peak Energy Portfolio Standard initiative allows electric vehicle charging infrastructure to participate in the program and receive clean peak credits, could electric school buses play a role through V2G, and supply energy when needed?

For example, the Framingham, MA peaker-plant has a peak generation capacity of 85MW (Figure 12). Given that an electric school bus with a 155kWh battery discharging energy in slow mode for 3.5 hours can input about 50kW into the grid, approximately 1,700 electric school buses would be needed to displace those 85 MW through V2G.

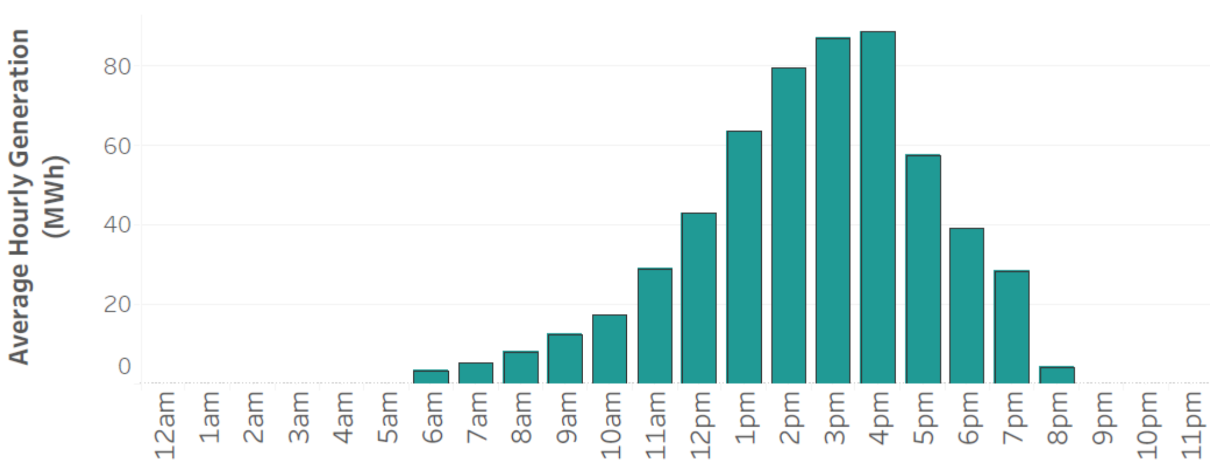

Figure 12: Average hourly generation from the Framingham, MA peaker-plant, adapted from 'Massachusetts peaker power plants: Energy storage replacement opportunities' (PSE, 2020).

On August 10, 2020, ISO-NE used oil and coal plants to generate 150MW of energy at peak from 5 to 6 pm (the entire peak period was just over 4 hours, from 3 to 730 pm). Assuming the same discharge rate of 50kW per bus in 3 hours, it would have taken ~3,500 electric school buses to replace the oil usage over those 4 hours of peak-demand. Given that there are approximately 28,600 school buses in New England, there is an enormous potential for creating a large amount of storage capacity that could actively be managed to displace peak generation, thereby reducing emissions and consumer costs, while addressing environmental justice.

Despite the enormous progress in technology and software necessary to integrate distributed energy resources into the grid, this type of application is not available today due to the lack of electric school buses to be integrated at large scale, and the unclear regulatory pathway for vehicle integration. The next section addresses these and other barriers that are specific to Massachusetts.

4.2 Barriers

4.2.1 Financial Context

In their comprehensive review of the financial options to pay for electric buses, the Public Interest Research Group identifies several avenues that are available to school districts to pay for electric buses. These include municipal bonds, federal rebates from the U.S. EPA DERA program, grants from the Volkswagen (VW) Settlement Fund (U.S. EPA, 2019b), and other state, regional and local programs such as option transportation taxes levied through ballot initiatives (U.S PIRG, 2018). Unfortunately, only a handful of those are available in Massachusetts, or are applicable to the current school bus fleets.

The VW Settlement Fund has been a popular source of grants for low or zero emission vehicles. However, the VW fund is limited, and of the $75 million awarded to Massachusetts, $25 million has been already spent; to this date, only four school buses have received grants ($250,000 per bus). The biggest drawback of the VW settlement is that funds can only be used to replace diesel engines model 2009 and older. Similar, the EPA DERA program only applies to vehicles with engine model 2006 or older. While these programs are useful to remove the oldest and most polluting vehicles, the number of qualifying school buses in Massachusetts is likely small, as buses don't stay in service for more than 12 years. Further, many private bus contractors in Massachusetts are cut off from accessing the grants because schools require contracted buses to be not older than 5-6 years.

At the regional level, the Regional Greenhouse Gas Initiative (RGGI) has generated hundreds of millions of dollars over the last decade by pricing the emissions of the power sector in the Northeast and Mid-Atlantic states (RGGI, 2020). RGGI was used to fund the first three electric school buses that were delivered to Massachusetts in 2016. Since then, the RGGI funds in Massachusetts have dwindled. However, a similar cap-and-trade program specifically aiming at pricing transportation fuels - the Transportation and Climate Initiative, TCI (TCI, 2020) – is now being created on the model of RGGI. According to a report by the Climate XChange, cap-and-trade programs generate health and climate benefits that greatly outweigh their costs (Breslow and Wincele, 2020). It is estimated that TCI could generate $400 million per year in Massachusetts alone, and some of the funds would go towards electric school buses. However, TCI implementation will occur in 2022 at the earliest.

At the state level, Green Banks have demonstrated to be a sustainable source of funding, and an effective way to deploy low risk capital to cover the upfront cost of clean energy projects (NREL, n.d.). Massachusetts is one of the few New England states not to have created a Green Bank, but it runs a similar initiative called Clean Energy Investment Program (CEIP), a low-cost financing system that was originally designed for state agencies to finance energy efficiency and clean energy projects. The program has never been used for electric vehicles and it is not clear if it could be used by school districts, without a modification of its statute; it certainly could not be used by private contractors, as it is designed for state projects only.

At the municipal level, the Green Communities Act (GCA) of 2008 (S.B. 2768, 'An Act Relative to Green Communities') mandates the deployment of energy efficiency strategies and renewable energy deployments, and could be used to finance electric school buses in designated Green Communities on two legal grounds: improving vehicle efficiency, and fulfilling the GHG emission reduction targets of individual municipalities that have developed Climate Action Plans. However, legislative action would be required to increase the funds available through the GCA, and likely only municipally owned school fleets could access such funds.

Finally, the General Law's Chapter 71 on Public Schools has provisions under sections 7A, 7B, and 7C to reimburse qualifying school districts 'for expenses approved by the commissioner of education, incurred by any town for the transportation of pupils.' This program applies to both owned and contracted buses and could be used to cover the higher contracting costs of electric school buses ($2,000/day vs $600/day for a regular diesel). However, the program is underfunded, and rumors have indicated that it may end (personal communication).

4.2.2 Logistical, Regulatory and Educational Context

Even with enough funding available, converting thousands of buses would be an enormous feat, with several challenges to be addressed. Logistically, school fleets have an advantage over transit fleets because of the summer break that allows more time to integrate new vehicles. However, building the necessary charging infrastructure can be a lengthy process. To the best of my knowledge, only two school districts in the entire U.S., Twin River in Sacramento and Torrance in Los Angeles, CA, are deploying sizeable electric school bus fleets (Twin River has now 30 electric school buses). In both cases, advanced electrification policies and collaboration with local utilities have been key to enable such transition. First, California has a mandate for 'widespread transportation electrification' that requires all major California utilities to create comprehensive 'make-ready' program to cover the cost of infrastructure and power upgrades for fleets through incentives such as the Low Carbon Fuel Standards (California Public Utility Commission, 2016; PG&E, 2020; ACT News 2020; SCE, 2020). With these programs, the utility constructs, owns and maintains all electrical infrastructure up to the meter and in some instances, it pays for behind-the-meter infrastructure as well (Figure 13). Additionally, low electricity prices and innovative rate strategies such as subscription charges (Trabish, 2019) guarantee low operational prices to fleet operators, on top of incentives for the vehicle and charging infrastructure ($4,000 per bus and $15,000 for a Level III 50 kW charger).

Utilities in Massachusetts have also established 'make-ready' programs, but their scope is limited, and it only applies to private light duty vehicles or public charging stations, even though some fleet advisory services are provided. Unfortunately, electricity rates in Massachusetts are among the highest in the country and the regulatory procedures to modify rates and create new programs are very lengthy. Massachusetts is also home of 41 Municipal Light Plants (MLP), public electricity providers owned and controlled by municipalities, typically located in suburban and rural areas. Because of their independence from private utility companies, MPLs are uniquely positioned to implement renewable energy programs and set rates, including TOU that are favorable for electric vehicles. The Concord MLP, for instance, has committed to 100% carbon free electricity and, after receiving its first electric school bus in 2016 through the RGGI funds, has been negotiating TOU rates to favor electric school bus charging, and plans to electrify its entire fleet of 42 units (Fucci, 2019).

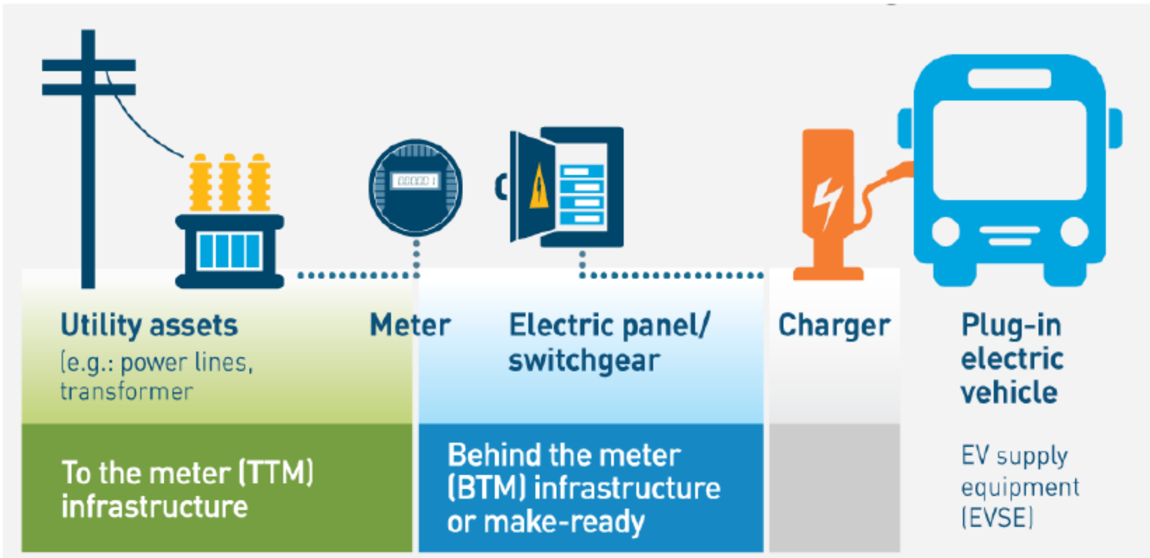

Figure 13: Pacific Gas & Electric (PG&E) schematic of their Make Ready program.

Education about electric bus technology is also critical. Informal conversations with the public revealed both understandable worries that the technology is only deployed at scale in a few areas, and misconceptions based on outdated information. For example, while fleet operators across the country have publicly stated that electric school buses are reliable and perform well, the narrative among the general public is that electric school buses are riddled with issues because of the bad reputation of the early electric school bus models. Some people are also worried about the source of electricity and its emissions. Range anxiety, the need for auxiliary heat in winter and other technical questions can also become an impeding factor if not addressed properly with the adequate technical and educational tools. The geographically scattered nature of the school bus fleets, and the different needs of each community are also a challenge for both stakeholder engagement and electric school bus adoption model. For example, some school districts may decide to rely on the electric battery for heating the buses in cold weather to avoid the emissions from the diesel-fired auxiliary heater, while others may accept running auxiliary heating: these two different operational approaches would determine different infrastructure needs, charging schedules and possibly V2G models. The necessity to understand the implications of different vehicle choices and operational strategies is therefore key for a successful deployment of electric vehicles.

Table 6 summarizes the factors that can represent real and perceived barriers discussed so far, grouped by category (financial, logistical, institutional, and educational).

Table 6: Factors that can be perceived as barriers to electrification.

Financial	Logistical	Regulatory/Institutional	Educational
Capital Costs	Power Availability	Electricity rates	Technology Readiness
Grant Availability	Fleet Turnover	V2G Revenue	Environmental and Social Benefits
Electricity Costs	Fleet Management	Stakeholder Support	Training and Support

4.3 Policy Recommendations

There are several complementary interventions that the Commonwealth of Massachusetts can put in place to initiate and facilitate the transition of the electric school bus fleet, even without federal financial support. Most actions would benefit the clean energy transition of other fleets, and unless specified, could be implemented in the short term.

Legislative and Financial Actions:

a) *Establish an Electrification Mandate*: The state should develop fleet electrification targets and mandates, given that current non-binding vehicle electrification pledges have been demonstrated to be ineffective. As shown by California and pointed out by industry experts, legislative mandates create a stable policy environment and stimulate the industry which in turn lowers costs through manufacturing at scale, while creating jobs.

b) *Expedite the Implementation of TCI*: A legislative mandate is only effective if the state can provide financial incentives, especially while upfront costs are still a challenge. That is why Massachusetts should expedite the implementation of TCI, the cap-and-trade program that would price fuels and generate the needed revenue to fund transportation projects.

c) *Create a Low Carbon Fuel Standard*: The California Low Carbon Fuel Standard (LCFS) is a market-based program designed to incentivize fuel switching by pricing the carbon intensity of transportation fuels. This program has proven to be instrumental to create a market for zero-emission vehicles, generating credits of $2 billion in 2018 only (currently pricing carbon at $200 per ton of CO_2 eliminated). LCFS credits help utilities financing the make-ready programs that can accrue total savings of least $50,000 per school bus. Unfortunately, TCI doesn't include a LCFS complementary policy, but the growing adoption of the LCFS by the Pacific states may push the TCI states to follow suit.

d) *Establish a Green Bank*: Green Banks are among the most sustainable and safest form of financing. The OECD defines a Green Bank as a "public, quasi-public or non-profit entity established specifically to facilitate private investment into domestic low-carbon, climate-resilient infrastructure." Green Banks can implement different programs including demand aggregation and group-buying deals. While largely used for solar projects, specific programs funded by Green Banks could be created for electric vehicles.

Regulatory Actions:

a) *Establish Make Ready Programs and Subscription Rates for Fleets*: Fleet specific utility programs should be created to avoid penalizing fleet owners with high electricity bills. Time of Use (TOU) and/or subscription rates should be offered with the intent to phase out demand charges (a charge applied to the maximum consumption in kW during a month) that can affect the TCO of fleets. These solutions are already being implemented by major private utilities in California and are being recognized as one of the key parameters to incentivize and support fleet transition projects. The Massachusetts Department of Public Utilities should work together with the Governor's Office and the legislature to expedite the implementation of strategies favorable to electric vehicles.

b) *Reform Utility Revenue Model (long-term)*: Utilities in Massachusetts rely on rate increases and consumer surcharges to finance their energy efficiency and electrification projects. These rate increases face opposition because they are not accompanied by transparent spending plans and standardized evaluation metrics, causing ruling delays and often project downsizing. Jenkins and Perez (2017) have proposed a new regulatory process that would set revenue schemes over a multi-year regulatory period (e.g. 5 years) without burdening the ratepayer with charges *ex-ante*. Given the conflictual nature of recent rate increase proposals in Massachusetts, these alternate, low-conflict models should be explored by the DPU.

Educational and Institutional Actions:

a) *Create an Electric School Bus Task Force*: The state should leverage the existing ZEV Commission to establish a dedicated Bus Electrification Taskforce that can address the issues related to the electrification of school buses in the state. The task force would have the ability to: convene key stakeholders or stakeholder group representatives; create an electrification roadmap with guidelines, goals and milestones; and organize financial resources efficiently. Furthermore, the task force could: address the possibility to electrify the METCO fleet or other fleets serving environmental justice communities; identify the oldest vehicles that are still eligible for the VW settlement grants; coordinate with existing and planned energy retrofit projects in schools; and identify opportunities for regional coordination among districts, bus contractors and third parties. For example, there could be opportunities to build charging hubs that could serve both school bus fleets and other medium-duty electric vehicles such as delivery vans (this type of regional approach would reduce costs for the participating entities by avoiding redundant infrastructure). More importantly, the Taskforce could facilitate peer-to-peer learning and the sharing of best-practices. Finally, it could be an opportunity to engage with large contracting companies that have a national presence on subjects such as workforce retraining programs and federal advocacy to create dedicated grants for school buses.

Other financial solutions:

a) *Tariffed on-bill finance systems*: On-bill financing is a promising avenue that leverages partnership with utilities and third-party financing providers through program such as PAYS (Pay As You Save®) for Clean Transport, where the utility pays for the upfront cost of the vehicle and the recipient (school district or private contractor) pays a fixed amount over time. In Massachusetts, a system like PAYS could work well with private contractors. Recently the concept of PAYS was successfully demonstrated for a large purchase of electric transit buses in Lima, Peru (Clean Energy Works, 2020).

b) *Energy Service Companies (ESCOs)*: ESCOs provide energy services through an energy saving performance contract, or ESPC, that has the goal to reduce operation and maintenance costs. ESCOs use a performance based contracting methodology, with compensations linked to energy cost savings. DOE maintains a list of qualified ESCOs based on their technical and financial capabilities (Department of Energy, 2017). The efficiency of electric vehicles makes a compelling case for applying the ESPC concept to fleets, to replace low efficiency combustion engines with high efficiency electric vehicles (Nigro et al., 2015). For instance, the Vermont Energy Investment Corporation (VEIC) launched their T-ESCO initiative in 2015 to access sustainable financing options for transportation efficiency projects (VEIC, 2015). Given the experience of ESCOs with building retrofit projects, school upgrades and energy retrofits could be combined with fleet transition projects, including solar canopy installations at the bus depot. In Massachusetts, this system could work with school districts that undergo building energy retrofits, a practice that recently has led to the creation of several net-zero or al electric schools (New England Energy Efficiency Project, 2020).

c) *Purchasing Collaborative*: The Climate Mayors Purchasing Collaborative is a partnership created to facilitate the purchase of electric vehicles through a one-stop-shop approach and help local governments achieve their vehicle electrification target (Climate Mayors, 2018). Electric school buses are now included in the Collaborative, and school districts could lease electric school buses directly via the site platform, possibly with a discount for larger quantities. However, it is not clear that the charging infrastructure could also be leased and who would pay for the installation costs and needed upgrades.

Table 7 summarizes the most relevant policy interventions mentioned so far. Given the complexity of the issues at hand, school bus electrification at scale will only occur if a combination of these strategies can be enacted together in a complementary fashion.

Table 7: Summary of main policy interventions to address for each barrier category

Financial	**Operational**	**Educational**
Grants and Vouchers	Charge Management	Stakeholder Engagement
Leases On-Bill Financing	Time-of-Use and subscription rates	Community Education
CEIP / ESCOs	Make Ready programs	Utility Assistance

5. Conclusions

A cost-benefit analysis was conducted to assess the economic viability and the environmental benefits of electric school buses compared to diesel and propane (LPG). To the best of the author's knowledge, this is the first such comparative study applied to school bus electrification. Capital and operational variables were gathered and combined to create a total cost of ownership model and sensitivity analysis that also considered the dependence of costs and emissions on vehicle speed and mileage, as well as fuel prices. While high mileage and low travel speed are favorable conditions for the deployment of electric school buses compared to diesel and LPG, the high upfront cost remain an impediment. Surprisingly, factoring in environmental and social costs only slightly improves the case for electric school buses. In almost all cases, substantial financial incentives are still needed under the current Massachusetts policy scenario, suggesting the need for both utilities and public entities to implement strategic interventions at multiple levels to reduce both the capital and the operational costs of electric fleets, and to support their implementation with dedicated programs.

The cost analysis may suggest that large scale implementation of school bus electrification is unlikely anytime soon. Yet, the scenario-building exercise is useful to reduce the uncertainties associated with lifetime costs and uncovers already existing opportunities for beneficial electrification. Future research should include additional cost parameters and perform more detailed analyses for better cost forecasting, using, for example, real route data.

Furthermore, some fleet owners or state agencies may evaluate project feasibility with other metrics beyond costs. For example, one might argue that the importance of clean rides for school children or the value of electric school buses as battery storage assets for vehicle to grid has more value than what can be reasonably estimated and modeled. Similarly, it can be argued that the price of continuing burning fossil fuels is too high, and that the $45 per ton of CO_2 used in this study cannot possibly account for the true damage of climate change. Given that a school bus stays in service for 10 years, further delaying electrification will keep locking-in additional fossil fuel usage, and only worsen the climate, air quality and environmental justice crises.

Electric school buses cannot solve these crises alone, but they have the potential to start creating win-win-win solutions to can put us on the right path for more sustainable and equitable future.

References

Abel, D. (2020, June 14). Effort to keep states largest power plant open fuels concern about climate, public health. Retrieved July 1, 2020 from https://www.bostonglobe.com/2020/06/14/metro/effort-keep-states-largest-power-plant-open-fuels-concern-about-climate-public-health/

Aber, J. (2016). Electric bus analysis for New York City transit. Retrieved May 20, 2020 from http://www.columbia.edu/~ja3041/Electric%20Bus%20Analysis%20for%20NYC%20Transit%20by%20J%20Aber%20Columbia%20University%20-%20May%202016.pdf

ACT News (2020, July 16). SDG & E launches new EV incentives powering San Diego fleets. Retrieved July 18, 2020 from https://www.act-news.com/news/sdge-launches-new-ev-incentives-powering-san-diego-fleets/

Adar, S.D., D'Souza, J., Sheppard, L., Kaufman JD, Hallstrand, T.S., Davey, M.E., et al. (2015). Adopting clean fuels and technologies on school buses pollution and health impacts in children. *American Journal of Respiratory and Critical Care Medicine*, 191(12),1413-1421.

Archer, D., Kite, E., and Lusk, G. (2020, July 15). The ultimate cost of carbon. *Climatic Change*, Retrieved July 20, 2020 from https://doi.org/10.1007/s10584-020-02785-4

Argonne National Laboratory, ANL (2020a). Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model. Retrieved April 28, 2020 from https://greet.es.anl.gov/index.php

Argonne National Laboratory, ANL (2020b). Alternative Fuel Life Cycle Environmental and Economic Transportation (AFLEET) Tool. Retrieved April 28, 2020 from https://greet.es.anl.gov/afleet

Beatty, T. and Shimshack, J. (2011). School buses, diesel emissions, and respiratory health. *Journal of Health Economics*, 30(5), 987-999.

Bradley, M.J., & Associates. (2013). Comparison of modern CNG, diesel and hybrid-electric transit buses. Efficiency and environmental performance. Retrieved May 3, 2020 from https://mjbradley.com/sites/default/files/CNG%20Diesel%20Hybrid%20Comparison%20FINAL%2005nov13.pdf

Breslow, M., and Wincele., R. (2020). Cap and trade in California: Health and climate benefits greatly outweigh costs. Retrieved July 17, 2020 from https://climate-xchange.org/wp-content/uploads/2018/08/California_Cap_and_Trade-3-13-2020-spreads.pdf

Brook R. D., Franklin, W., Cascio., B., et al. (2004). Air pollution and cardiovascular disease. A statement for healthcare professionals from the expert panel on population and prevention Science of the American Heart Association. *Epidemiology*, 109 (21), 2655-2671, doi: 10.1161/01.CIR.0000128587.30041.C8

California Energy Commission (2020). School bus replacement program. Retrieved April 20, 2020 from https://www.energy.ca.gov/programs-and-topics/programs/school-bus-replacement-program

California Office of Environmental Health Hazard Assessment, OEHHA. (2001, May 21). Health effects of diesel exhaust. Retrieved April 29, 2020 from https://oehha.ca.gov/air/health-effects-diesel-exhaust

Caiazzo, F., Ashok, A., Waite, I.A., et al. (2013). Air pollution and early deaths in the United States. Part I. Quantifying the impact of major sectors in 2005. *Atmospheric Environment,* 79, 198-208, https://doi.org/10.1016/j.atmosenv.2013.05.081

Clean Energy Group (2020). Dirt Energy, Big Money. PEAK Coalition. Retrieved July 24, 2020 from https://www.cleanegroup.org/ceg-resources/resource/dirty-energy-big-money/

Clean Energy Works (2020). Tariffed on-bill finance to accelerate clean transport. Retrieved July 28, 2020 https://www.cleanenergyworks.org/clean-transit/

Climate Mayors. (2018). Climate Mayors electric vehicles purchasing collaborative. Retrieved July 20, 2020 from https://driveevfleets.org/

Clukey, K. (2019, September 25). New York Electric School Buses to Feed the Power Grid. Retrieved July 6, 2020 from https://news.bloomberglaw.com/environment-and-energy/new-york-electric-school-buses-to-feed-power-grid

Dechert, S. (2014, March 5). New all-electric school bus saves California district 10,000 per year. Retrieved May 5, 2020 from https://cleantechnica.com/2014/03/05/new-electric-school-bus-saves-california-district-10000-per-year/

Descant, S. (2018, December 4). Electric buses are not only clean but less costly to run. Retrieved June 20, 2020 from https://www.govtech.com/workforce/Electric-Buses-Are-Not-Only-Clean-But-Less-Costly-to-Run.html

Department of Energy, DoE (2017). Energy Service Companies. Retrieved July 24, 2020 from https://www.energy.gov/eere/femp/energy-service-companies-0

Electric Power Research Institute (2019). Vehicle to grid: $1 Billion in annual grid benefits? Retrieved June 15, 2020 from https://eprijournal.com/vehicle-to-grid-1-billion-in-annual-grid-benefits/

Engel, H., Hertzke, P., and Siccardo. G. (2019, April 30) Second-life EV batteries: The newest value pool in energy storage. Retrieved June 3, 2020 from https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage

Eudy, L., and Jeffers, M. (2017). Foothill transit battery electric bus demonstration results: Second report. National Renewable Energy Laboratory. NREL/TP-5400-67698. Retrieved May 12, 2020 from https://www.nrel.gov/docs/fy17osti/67698.pdf

Fantke, P., Jolliet, O., Apte, J. S., Hodas, N., Evans, J., Weschler, C. J., and McKone, T. E. (2017). Characterizing aggregated exposure to primary particulate matter: Recommended intake fractions for indoor and outdoor sources. *Environmental Science & Technology,* 51(16), 9089–9100. https://doi.org/10.1021/acs.est.7b02589

Fantke, P., McKone, T. E., Tainio, M., Jolliet, O., Apte, J. S., Stylianou, K. S., Evans, J. S. (2019). Correction to "Global effect factors for exposure to fine particulate matter." *Environmental Science & Technology,* 53(17), 10534–10534. https://doi.org/10.1021/acs.est.9b04486

Federal Transit Administration, FTA. (n.d.). Grant programs. Retrieved July 17, 2020 https://www.transit.dot.gov/grants

Fucci, R. (July 25, 2019). Clean energy report highlights Concord school bus program. Retrieved May 13, 2020 from https://concord.wickedlocal.com/news/20190724/clean-energy-report-highlights-concords-electric-school-bus-program

Gao, Z., Z. Lin, S. Davis, and A. Birky. (2018). Quantitative evaluation of MD/HD vehicle electrification using statistical data. *Transportation Research Record*, 2672 (24), 109–121. journals.sagepub.com/doi/abs/10.1177/0361198118792329

Gas Technology Institute, GTI (2017). GHG and criteria pollutant emissions analysis report. PERC DOCKET 20890 / GTI PROJECT NUMBER 22061. Retrieved June 3, 2020 from https://propane.com/wp-content/uploads/2019/06/20890-GTI-GHG-Emissions-Analysis-Final-Report.pdf

Golden, S. (2020, June 5). How racism manifest in clean energy. Retrieved July 11, 2020 from https://www.greenbiz.com/article/how-racism-manifests-clean-energy

Greenlining Institute (2020). Environmental equity. Electric vehicles. Retrieved July 12, 2020 from https://greenlining.org/our-work/environmental-equity/electric-vehicles/

Guarnieri, M., and Balmes, J.R. (2014). Outdoor air pollution and asthma. *Lancet*, 383(9928):1581-1592. doi: https://doi.org/10.1016/S0140-6736(14)60617-6

Helbling, T. (2020, February 24). Externalities: Prices do not capture all costs. *International Monetary Fund*. Retrieved July 16, 2020 from https://www.imf.org/external/pubs/ft/fandd/basics/external.htm

Heo, J., Adams, P.J., and Gao, H. O. (2016). Public health costs of primary $PM_{2.5}$ and inorganic $PM_{2.5}$ precursor emissions in the United States. *Environmental Science & Technology,* 50 (11), 6061–6070. https://doi.org/10.1021/acs.est.5b06125

Howard, P., and Sylvan, D. (2015). Expert consensus on the economics of climate change. Retrieved May 2, 2020 from https://www.edf.org/sites/default/files/expertconsensusreport.pdf

Humbert, S., Marshall, J. D., Shaked, S., Spadaro, J. V., Nishioka, Y., Preiss, P., Jolliet, O. (2011). Intake fraction for particulate matter: Recommendations for life cycle impact assessment. *Environmental Science & Technology*, 45(11), 4808–4816. https://doi.org/10.1021/es103563z

International Council on Clean Transportation (2016). United States efficiency and greenhouse gas emission regulations for model year 2018-2027 heavy-duty vehicles, engines, and trailers. Retrieved July 3, 2020 from https://theicct.org/sites/default/files/publications/US%20HDV%20Phase%202%20FRM_policy-update_08252016_vF.pdf

International Energy Agency, IEA. (2019). Tracking transport 2019. Retrieved May 8, 2020 from https://www.iea.org/reports/tracking-transport-2019

International Panel on Climate Change, IPCC. (2018). Summary for Policymakers. In: Global Warming of 1.5°C. Retrieved May 12, 2020 from https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter8.pdf

Ireson, R.G., et al. (2011). Measuring in-cabin school bus tailpipe and crankcase PM2.5: A new dual tracer method. *Journal of the Air & Waste Management Association*, 61:5, 494-503. https://doi.org/10.3155/1047-3289.61.5.494

Jenkins, J.D., and Perez-Arriaga. I. (2017). Improved regulatory approaches for the remuneration of electricity distribution utilities with high penetrations of distributed energy resources. *The Energy Journal*, 38(3). http://dx.doi.org/10.5547/01956574.38.3.jjen

Kahn, M. (2017, July 6). The big yellow electric school bus. Retrieved June 11, 2020 from https://www.electric.coop/electric-school-bus-minnesota-co-ops/

Kempton, W. and Tomic, J. (2005a). Vehicle-to-grid power fundamentals: calculating capacity and net revenue, *Journal of Power Sources*, 144, 268–279, doi:10.1016/j.jpowsour.2004.12.025

Kempton, W. and Tomic, J. (2005b). Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy, *Journal of Power Sources*, 144, 280–294, doi:10.1016/j.jpowsour.2004.12.022

King County Metro Transit (2017). Feasibility of achieving a carbon-neutral or zero-emissions fleet. Retrieved June 9, 2020 https://kingcounty.gov/~/media/elected/executive/constantine/news/documents/Zero_Emission_Fleet.ashx?

Knobloch, F., Hanssen, S., Lam, A., et al. (2020). Net emission reductions from electric cars and heat pumps in 59 world regions over time. *Nature Sustainability,* 3**,** 437–447 https://doi.org/10.1038/s41893-020-0488-7

Lane, K.J., et al. (2016). Association of modeled long-term personal exposure to ultrafine particles with inflammatory and coagulation biomarkers. *Environment International,* 92-93:173-182, doi: 10.1016/j.envint.2016.03.013

Laughlin, M., Burnham, A. (2014). Case study: Propane school bus fleets, Clean Cities, U.S. Department of Energy, ANL Contract No. 2F-32321, Retrieved May 12, 2020 from http://www.afdc.energy.gov/publications/

Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., and Pozzer., A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature,* 525(7569), 367–371, doi:10.1038/nature15371

Levy, R. (2015). Carbon monoxide pollution and neurodevelopment: A public health concern. *Neurotoxicol Teratol*., 49: 31–40. doi: 10.1016/j.ntt.2015.03.001

Lisowski, R. (2018, August 21). Beneficial electrification: What and why? Retrieved June 1, 2020 from https://slipstreaminc.org/blog/beneficial-electrification-what-and-why

Mass.gov. (2017). Environmental justice policy of the executive Office of Energy and Environmental Affairs. Retrieved July20, 2020 from https://www.mass.gov/files/documents/2017/11/29/2017-environmental-justice-policy_0.pdf

Mass.gov (2020). Clean peak energy standard notices and updates. Retrieved July 20, 2020 from https://www.mass.gov/service-details/clean-peak-energy-standard

Matthews, K. et al. (2016). ZEV school buses: They're here and possibly free. Retrieved June 17, 2002 from https://greentechnology.org/gcsummit16/images/35-ZEV-School-Buses.pdf.

Metropolitan Council for Economic Opportunities, METCO. (2020). Metropolitan Council for Economic Opportunities. Retrieved July 13, 2020 from https://metcoinc.org/

Michalek, J.J., Chester, M., Jaramillo, P., Samaras, C., Shiau, C.S.N., Lave, L.B. (2011). Valuation of plug-in vehicle life-cycle air emissions and oil displacement benefits. *Proc. Natl. Acad. Sci.*, *108*, 16554–16558, https://doi.org/10.1073/pnas.1104473108

Multistate ZEV Task Force (n.d.). Retrieved May 19, 2020 from https://www.zevstates.us/

Myers, E.H. (2019). A comprehensive guide to electric vehicle managed charging. Smart Electric Power Alliance. Retrieved July 5, 2020 from https://sepapower.org/resource/a-comprehensive-guide-to-electric-vehicle-managed-charging/

National Renewable Energy Lab (n.d.). State, local and tribal governments. Green banks. Retrieved July 25, 2020 from https://www.nrel.gov/state-local-tribal/basics-green-banks.html

National Renewable Energy Laboratory, NREL (2017). King County Metro battery electric bus demonstration. Preliminary results. Retrieved June 5, 2020 from https://afdc.energy.gov/files/u/publication/king_county_be_bus_preliminary.pdf

National School Transportation Association, NSTA. (2014). Celebration of clean diesel technology in 2014. Retrieved June 13, 2020 from https://s3-us-west-2.amazonaws.com/nsta/6867/Green-Fleet-Certification-Press-Release.pdf

National School Transportation Association, NSTA. (2018). Celebration of DERA in 2018 at Children's Health Day. Retrieved June 13, 2020 from https://s3-us-west-2.amazonaws.com/nsta/61955/EPA-Event-Press-Release-2018-10-02.pdf)

National Toxicology Program, NTP. (2016). Report on carcinogens, fourteenth edition: Diesel exhaust particles. Retrieved June 9, 2020 from https://ntp.niehs.nih.gov/ntp/roc/content/profiles/dieselexhaustparticulates.pdf

New England Energy Efficiency Project, NEEP (2020). Massachusetts net-zero energy schools toolkit. Retrieved July 27, 2020 from https://neep.org/sites/default/files/resources/Zero%20Energy%20Schools%20Toolkit%20FINAL.pdf

Nigro, N., Welch, D., Park, J.E. (2015). Strategic planning to enable ESCOs to accelerate NGV fleet deployment: A guide for businesses and policymakers. Retrieved July 17, 2020 from https://www.c2es.org/site/assets/uploads/2015/11/strategic-planning-enable-escos-accelerate-ngv-fleet-deployment-guide-businesses-policy.pdf

National Oceanic Atmospheric Administration, Center for Environmental Information, NCEI. (2020). U.S. billion-dollar weather and climate disasters. Retrieved May 13, 2020 from https://www.ncdc.noaa.gov/billions/, doi: 10.25921/stkw-7w73

Nurmagambetov, T., Kuwahara, R, Garbe, P. (2018). The economic burden of asthma in the United States, 2008-2013, *Annals of the American Thoracic Society*. Retrieved June 22, 2020 from https://www.thoracic.org/about/newsroom/press-releases/resources/asthma-costs-in-us.pdf

O'Dea, J. (2019, December 18). Ready for Work. Now it is the time for heavy-duty electric vehicles. Retrieved April 4, 2020 from https://www.ucsusa.org/sites/default/files/2019-12/ReadyforWorkFullReport.pdf

Olawepo, J.O., and Chen, L.W. (2019). A health benefits from upgrading public buses for cleaner air: A case study of Clark County, Nevada and the United States, *Int. J. Environ. Res. Public Health*, 16(5), 720, doi: 10.3390/ijerph16050720

Pacific Gas & Electric, PG&E. (2020). EV Fleet Program. Retrieved June 10, 2020 from https://www.pge.com/en_US/large-business/solar-and-vehicles/clean-vehicles/ev-fleet-program/ev-fleet-program.page

Physicians, Scientists and Engineers for Healthy Energy, PSE (2020). Energy storage peaker plant replacement project. Retrieved July 10, 2020 https://www.psehealthyenergy.org/our-work/energy-storage-peaker-plant-replacement-project/

Regional Greenhouse Gas Initiative, RGGI (2020). Elements of RGGI. Retrieved July 7, 2020 from https://www.rggi.org/program-overview-and-design/elements

Reportlinker. (2020). Electric school bus market research report by type - global forecast to 2025. Retrieved July 12, 2020 https://www.reportlinker.com/p05912170/Electric-School-Bus-Market-Research-Report-by-Type-Global-Forecast-to-Cumulative-Impact-of-COVID-19.html

Ricke, K., Drouet, L., Caldeira, K. et al. (2018). Country-level social cost of carbon. *Nature Climate Change*, 8**,** 895–900, https://doi.org/10.1038/s41558-018-0282-y

Samuels, A. (2019, April 11). The utter inadequacy of America's efforts to desegregate schools. Retrieved July 16, 2020 https://www.theatlantic.com/education/archive/2019/04/boston-metco-program-school-desegregation/584224/

School Transportation News (2019, May 1). School buses going 100% electric?: just common sense. Retrieved May 21, 2020 from https://stnonline.com/partner-updates/school-buses-going-100-electric-just-common-sense/

School Bus Fleet. (2019). School Transportation: 2017-2018 school year. Retrieved May 2, 2020 from https://files.schoolbusfleet.com/stats/SBF-StateTransportationStats2017-18.pdf

Shahan, C. (2020, January 12). Largest electric school bus program in United States launching in Virginia Retrieved February 2, 2020 https://cleantechnica.com/2020/01/12/largest-electric-school-bus-program-in-united-states-launching-in-virginia/

Shepardson, D. (2020 July 14). 15 U.S. states to jointly work to advance electric heavy-duty trucks. Retrieved July 15, 2020 from https://www.reuters.com/article/us-autos-emissions-trucks-idUSKCN24F1EC

Southern California Edison, SCE. (2020). Charge ready transport. Retrieved July 23, 2020 from https://www.sce.com/business/electric-cars/charge-ready-transport

Steward, D. (2017). Critical elements of vehicle-to-grid (V2G) economics. National Renewable Energy Laboratory, NREL/TP-5400-69017. Retrieved July 12, 2020 from https://www.nrel.gov/docs/fy17osti/69017.pdf

Taylor, M. (2018, Jan 31). 5 lesser-known propane benefits for school buses. Retrieved April 30, 2020 from https://www.schoolbusfleet.com/blogpost/sbfblog/728302/5-more-propane-benefits-for-school-buses

Thomas Built Buses (2018, April 6). There is more to school bus emissions than NOx. Retrieved April 23, 2020 https://thomasbuiltbuses.com/bus-advisor/articles/there-is-more-to-school-bus-emissions-than-nox/

Trabish, H., K. (2019, January 23). PG&E, SCE, SDG&E pursue subscriptions, time-of-use rates to drive more California EVs. Retrieved July 17, 2020 from https://www.utilitydive.com/news/pge-sce-sdge-pursue-subscriptions-time-of-use-rates-to-drive-more-cali/545907/

Transportation and Climate Initiative, TCI (2020). Transportation and Climate Initiative of the Northeast and Mid-Atlantic States. Retrieved July 2, 2020 from https://www.transportationandclimate.org/

Tschofen, P., Azevedo, I. L., and Muller, N. Z. (2019). Fine particulate matter damages and value added in the US economy, *Proc Natl. Acad. Sci*. 116 (40) 19857-19862; https://doi.org/10.1073/pnas.1905030116

U.K. Department for Environment Food & Rural Affairs. (2020). Air quality appraisal: damage cost guidance. Retrieved July 18 2020 from https://www.gov.uk/government/publications/assess-the-impact-of-air-quality/air-quality-appraisal-damage-cost-guidance

Underwood, E. (2017, January 26). The Polluted Brain. Evidence builds that dirty air causes Alzheimer's, dementia. *Science,* Retrieved May 16, 2020 from http://www.sciencemag.org/news/2017/01/brain-pollution-evidence-builds-dirty-air-causes-alzheimer-s-dementia

U.S. Energy Information Administration (2018, May 22). Electrified vehicles continue to see slow growth and less use than conventional vehicles. Retrieved June 8, 2020 from https://www.eia.gov/todayinenergy/detail.php?id=36312&src=email

U.S. Environmental Protection Agency, EPA. (n.d.). Center for Corporate Climate Leadership. Simplified GHG emissions calculator. Retrieved March 12, 2020 from https://www.epa.gov/climateleadership/center-corporate-climate-leadership-simplified-ghg-emissions-calculator

U.S. Environmental Protection Agency, EPA. (2002). Health assessment document for diesel exhaust, National Center for Environmental Assessment, Office of Research and Development, EPA/600/8-90/057F.

U.S. EPA. (2006). Final Regulatory Impact Analysis: PM2.5 NAAQS. Research Triangle Park, NC: Office of Air and Radiation, Office of Air Quality Planning and Standards

U.S. Environmental Protection Agency, EPA. (2016a, September 8). NO_2 pollution. Basic information about NO_2. Retrieved June 3, 2020 from https://www.epa.gov/no2-pollution/basic-information-about-no2

U.S. Environmental Protection Agency, EPA (2016b, September 8). Carbon Monoxide (CO) Pollution in Outdoor Air. Retrieved June 17, 2020 from https://www.epa.gov/co-pollution/basic-information-about-carbon-monoxide-co-outdoor-air-pollution

U.S. Environmental Protection Agency, EPA. (2018, October 15). EPA GHG equivalency calculator tool. Retrieved May 26, 2020 from https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

U.S. Environmental Protection Agency, EPA. (2019a). DERA Fourth Report to Congress. Highlights of the diesel emission reduction program. Office of Transportation and Air Quality (OTAQ). EPA-420-R-19-005. Retrieved June 23, 2020 from https://www.epa.gov/sites/production/files/2019-07/documents/420r19005.pdf

U.S. Environmental Protection Agency, EPA. (2019b, October 31). Volkswagen Clean Air Act civil settlement. Retrieved June 5, 2020 from https://www.epa.gov/enforcement/volkswagen-clean-air-act-civil-settlement

U.S. Environmental Protection Agency, EPA. (2020a, April 11). Inventory of U.S. Greenhouse Gas emissions and sinks: 1990–2018. Retrieved April 28, 2020 from https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions#transportation

U.S. Environmental Protection Agency, EPA. (2020b). Energy Resources for State and Local Governments. CO-Benefits Risk Assessment (COBRA) Health Impacts Screening and Mapping Tool. Retrieved June 27, 2020 from https://www.epa.gov/statelocalenergy/co-benefits-risk-assessment-cobra-health-impacts-screening-and-mapping-tool

U.S PIRG (2018, October 30). Paying for electric buses. Retrieved June 4, 2019 from https://uspirg.org/sites/pirg/files/reports/National%20-%20Paying%20for%20Electric%20Buses.pdf

Vermont Electric Investment Corporation, VEIC (2015, March 20). VEIC launches pilot project to increase transportation efficiency for businesses. Retrieved July 13, 2020 from https://www.veic.org/news/veic-launches-pilot-project-to-increase-transportation-efficiency-for-businesses

Vermont Electric Investment Corporation, VEIC (2018, April 20). Electric school bus pilot project evaluation. Retrieved May 5, 2020 from https://www.veic.org/documents/default-source/resources/reports/veic-ma-doer-electric-school-bus-pilot-project.pdf?sfvrsn=2

Victoria Transport Policy Institute, VTPI. (2015). Transportation Cost and Benefit Analysis II. Retrieved June 7, 2020 from www.vtpi.org/tca/tca0511.pdf

Western Climate Initiative, WCI. (2020). Greenhouse gas emissions trading: a cost-effective solution to climate change. Retrieved June 5, 2020 from https://wci-inc.org

Williams, D.J.H., Haley, B., Kahrl, D.F., Morre, J., Jones, D.A.D., Torn, D.M.S., and McJeon, D.H. (2015). Pathways to deep carbonization in the United States: Technical Report. *Lawrence Berkeley National Laboratory, Energy and Environmental Economics Inc. (E3).*

World Bank, Institute for Health Metrics and Evaluation. (2016). The cost of air pollution: Strengthening the economic case for action. World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/25013 License: CC BY 3.0 IGO.

World Health Organization, WHO. (2019). Health and sustainable development. Air pollution. Retrieved April 8, 2020 from https://www.who.int/sustainable-development/transport/health-risks/air-pollution/en/

WM Financial Strategies. (June 2020). The bond buyer 20-Bond GO index. Retrieved April 6, 2020 from http://www.munibondadvisor.com/market.htm

Yang, L., et al. (2016). Evaluating real-world CO_2 and NO_X emissions for public transit buses using a remote wireless on-board diagnostic (OBD) approach. *Environmental Pollution*, 218, 453-462, https://doi.org/10.1016/j.envpol.2016.07.025

Zhang, Q., and Zhu, Y. (2011). Performance of school bus retrofit systems: ultrafine particles and other vehicular pollutants, *Environmental Science & Technology*, 45, 6475-6482, https://pubs.acs.org/doi/10.1021/es201070t

Zhu., Y. and Lee., E. (2015, April 10). Reducing air pollution exposure in passenger vehicles and school buses. Report prepared for the California Air Resources Board and the California Environmental Protection Agency. Contract Number 11-310. Retrieved May 4, 2020 from https://ww2.arb.ca.gov/sites/default/files/classic//research/apr/past/11-310.pdf

Appendices

Appendix A: Health effects of diesel exhaust on children: a literature review.

This section lists the main peer reviewed research the health effects of diesel exhaust and traffic pollution on children's health. Much of this research, initially spearheaded by the California Air Resources Board in the early 2000s, has been critical to inform policy making on the need to reduce diesel emission exposure in school children and eventually led to the creation of the U.S. EPA Diesel Emission Reduction Act (DERA) of 2005, a landmark legislation that established several diesel emission reduction programs that still exist today. As a result, modern diesel engines are 10-15 times cleaner than in the early 2000s.

Table A1: Summary of research studies on the health effects of diesel-related pollutants on children

Author	Main Finding
Wargo et al (2002)[1]	Showed that students inside school buses are exposed to levels of $PM_{2.5}$ that are 5-15 times higher than background levels, and to levels of NO_2 exceeding federal standards
California Air Quality Board, 2003[2]	Found that the mean $PM_{2.5}$ levels inside the cabin due to self-pollution are between 50 and 200 times greater than those for the loading/unloading areas, and 20–40 times higher than those recorded at bus stops. Self-pollution was higher in older buses, and when windows were closed.
Behrentz et al., 2005[3]	Quantified the exposure to general traffic during school commuting, a likely risk factor for asthma
Beatty, Shimshack, 2011[4]	Researched the role of diesel exhaust in inducing asthma in healthy children
Bienkowski, et al., 2013[5]	Linked the increase of autism in children with the chronic exposure to toxic substances contained in diesel fumes
Hime, 2018[6]	Showed that children are more susceptible to air pollution than adults because they have higher breathing rates and developing lungs
Garcia, 2019[7]	Demonstrated that lower levels of NO_2 exposure were associated with lower rates of asthma incidence in children

Section Endnotes

[1] Wargo, J., and Brown, D. (2002). Children's exposure to diesel exhaust on school buses. *Yale University and Environment & Human Health*, Inc., New Haven, CT. Retrieved June 2, 2020 from www.ehhi.org/reports/diesel/diesel.pdf

[2] California Air Resources Board, CARB (2003). Characterizing the range of children's pollutant exposure during school bus commutes. Contract No. 00-322.

[3] Behrentz, E, Sabin, L.D., Winer, A.M., Fitz, D.R., Pankratz, D.V., Colome, S.D. and Fruin, S.A. (2005). Relative importance of school bus-related microenvironments to children's pollutant exposure. *Journal of the Air & Waste Management Association*, 55:10, 1418-1430.

[4] Beatty, T. and Shimshack, J. (2011). School buses, diesel emissions, and respiratory health. *Journal of Health Economics*, 30 (5), 987-999.

[5] Bienkowski, B. (2013, June 18). U.S. kids born in polluted areas more likely to have autism, *Environmental Health News, Sustainability*, Scientific American. Retrieved June 2, 2020 from https://www.scientificamerican.com/article/us-kids-born-in-polluted-areas-more-likely-to-have-autism/

[6] Hime, N.J., Marks, G.B., and Cowie, C.T. (2018). A comparison of the health effects of ambient particulate matter air pollution from five emission sources. *Int J Environ Res Public Health*, 15(6):1206. doi:10.3390/ijerph15061206

[7] Garcia, E., Berhane, K.T., Islam, T. et al. (2019). Association of changes in air quality with incident asthma in children in California, 1993-2014. *Journal of the Air & Waste Management Association*, 321(19):1875-1877. doi:10.1001/jama.2019.5343

Appendix B: Building a Total Cost of Ownership Model

The Total Cost of Ownership (TCO) model uses the Type C school bus because it is the most common vehicle type and it exists in the diesel, LPG, and electric version. Several manufacturers of electric buses are now active in the market and Table B1 shows models, makes and characteristics of the types currently offered. The Type C electric vehicle with a 155kWh battery and 120 miles of nominal range was considered for the analysis.

The TCO 'base case' used an average annual mileage of 12,000 miles[1] and a bus lifetime of 10 years, which reflects the average school bus lifetimes in Massachusetts. The base case uses an average travel speed of 12 miles per hour (mph), consistent with previous studies.[2] At 12 mph, the average fuel economy for a diesel school bus is ~7 miles per diesel gallon equivalent (mpdge)[3] whereas LPG buses have 35% lower fuel economy than diesel[4], e.g., ~4.5 mpdge at 12 mph. Because fuel economy and vehicle speed in combustion engines are tightly correlated, data previously published for diesel transit buses[2,5] were used to construct a relationship of fuel economy vs. speed for the diesel school bus. The LPG fuel economy values at different speeds were then obtained by lowering all diesel fuel economy values by 35%. The parameterization results (Figure B1) show a dramatic drop in fuel economy at travel speed lower than 10 mph for diesel and LPG. The fuel economy of the electric school bus remains constant with speed, but it is sensitive to external temperature.[6] Auxiliary heating and cooling can be used to condition the vehicle instead of drawing power from the battery. If auxiliary heating and cooling is not used, the battery must be conditioned before unplugging the vehicle, and such practice can lead to additional electricity consumption and energy costs. Without temperature related losses, the fuel economy of the 155-kWh battery bus would be ~29 mpgde (obtained as 155 kWh ÷ 120 mi = 1.3 kWh/mi, and then converted to mpdge using the formula mpdge = 37.65 ÷ kWh/mi). To reflect the typical weather conditions in Massachusetts, a 15% yearly loss in battery range was applied to the electric school bus, leading to 25 mpdge, which is used in this study. Even so, the battery school bus remains ~3.5 times more efficient than diesel and ~5.5 times more efficient than LPG, at 12 mph. Table B2 summarizes the fuel economies of the three vehicle technologies at various speeds (slow city, fast city, suburban, and the 12 mph national average extrapolated from the parameterization of Figure B1 for diesel and LPG).

Vehicle costs were obtained from publicly available data but were double checked with manufacturers and bus owners. The average cost for a Type C diesel bus is around $100,000, the LPG version is around $110,000, and the electric version is quoted around $370,000 (for 2019). While the price of batteries - the most expensive component of an electric vehicle – has been falling dramatically and it is expected to keep falling at a rate of 3-4% per year[7], the lack of manufacturing at scale for electric school buses makes them expensive. Charging infrastructure can also be a significant cost for heavy duty electric vehicles, and costs vary depending on the needs for power upgrades. Fleet managers and utilities have stated that infrastructure costs for a fleet of 15 electric buses range from $15,000 to $30,000 per bus depending on the need for trenching and conduit installation. This TCO assumes an infrastructure cost of $28,000 per bus, and a charging strategy relying on high-power level II charging ($2,000 per charger). Fast charging requires more expensive infrastructure (a level III charger costs $40,000) and it is typically not required for school buses. The fueling infrastructure for diesel and LPG is much cheaper and conservatively estimated to be around $5000 per bus based on the quoted price of fueling pumps and fuel tanks for a fleet of 30 buses. For context, King Metro Transit[8] reported infrastructure costs of $10,000 for a diesel transit bus.

Manufacturers of both electric and LPG school buses claim significantly lower operational costs compared to diesel: in the case of LPG, OEMs and fleet operators claim average savings of $0.35 per mile ($/mi) compared to diesel because the cleaner LPG fuel requires less engine maintenance, less frequent oil changes and creates less operational downtime. Transit and school bus operators alike have indeed stated – both privately and in official settings – that the operating costs of modern diesel engines have increased since the introduction of pollution control technologies that need to be maintained regularly, especially if buses spend a significant amount of time traveling at low speed. The diesel school bus was therefore assigned $0.55/mi in maintenance costs and $0.35/mi of fuel costs (at 12 mph), and the LPG school buses was assigned $0.32/mi in maintenance costs and $0.21/mi of fuel costs (at 12 mph). Operators of electric buses also claim substantial maintenance savings compared to diesel due to lack of mechanical parts and less brake wear thanks to regenerative breaking technology in electric vehicles. OEM websites report up to 60% fuel savings and 80% maintenance savings for an electric school bus compared to diesel. Upon confirming such information with two fleet operators, the maintenance cost for an electric school bus was priced at $ 0.17/mi.

Electricity costs are much more stable than oil prices, even though they can vary substantially across U.S regions (from \$0.05/kWh to \$0.2/kWh).[9] In Massachusetts, the average electricity generation price is \$0.12/kWh, which translates into \$0.18/mi for 1.5 kWh/mi. However, the full cost of electricity to the consumers also includes delivery, which in Massachusetts are around \$ 0.05/kWh for commercial customers. Therefore, the total cost of electricity used in this analysis is \$0.17/kWh, or \$0.25/mi. Demand charges can also affect the final electricity prices, as demonstrated by early deployment of transit buses[10], but they are not included in this analysis. For diesel and LPG, fuel costs are calculated at the three travel speeds by varying the fuel consumption as a function of fuel economy; the reference fuel costs (in diesel gallon equivalent, DGE, of \$2.5/DGE for diesel and \$1/DGE for commercial LPG) are taken by the Alternative Fuel Data Center of the Department of Energy.[11]. Table B3 summarizes the average maintenance and fuel costs at different speeds for the three technologies.

Changes in fuel prices over time were also considered. This analysis uses the Energy Information Agency's Annual Energy Outlook 2020 projections for diesel, LPG, and electricity prices for the transportation sector through 2050.[12] The EIA projects that average diesel fuel prices will increase 0.8% per year through 2050; LPG is projected to increase 1.2%, whereas electricity is projected to go up 0.1% per year. These reference fuel price projections were applied to the base TCO case over the lifetime of the buses. The EIA low and high fuel price scenarios were instead used in the sensitivity analysis. Table B4 summarizes the EIA fuel price projections (low, high and reference) through 2050.

Finally, Table B5 reports the electricity rates used in the modeling of revenue from vehicle-to-grid (V2G) with and without time-of-use (TOU) rates. V2G revenue was modeled for the 155kWh electric bus battery discharging in 'slow mode' for 3 hours per day. Total revenue was calculated by adding both energy payment and capacity payments. Energy payments are based on the exchanged electricity (retail electricity price in \$/kWh multiplied by the total dispatched electricity in kWh), while capacity payments are measured by the grid operator and rely on the vehicle's available time for providing V2G services as well as available power capacity.[13] In this case, capacity payments are based on the ISO-New England average regional network service (RNS) price of \$10/kW. Note that the V2G estimates performed here are only a first approximation and do not account for seasonal variations and other pricing factors that may be included in more sophisticated V2G models.

Table B1: Summary and Characteristics of Available Electric School Bus Models in the U.S.

Make	Model (Type)	Weight (lbs)	Battery Capacity (kWh)	Range (miles)
Motiv[a]	Epic E450 (A)	14,500	106	85
	Epic F-59 (C)	22,000	127	100
BlueBird[b]	Microbird (A)	14,500	100	100
	Vision (C)	33,000	155	120
	All American (D)	36,000	155	120
Thomas Built & Proterra[c]	Jouley (C)	35,000	220	135
eLion[d]	eLion (A)	~15,000	80; 160	75; 150
	e Lion (C)	~33,000	88 - 220	65 -155
Greenpower[e]	Synapse 72 (D)	~36,000	100 - 200	75-140

[a] Motiv Power Systems, Inc https://www.motivps.com/application/school-bus/

[b] BlueBird Corporation, Inc https://www.blue-bird.com/buses/vision

[c] Proterra, Inc https://www.proterra.com/vehicles/proterra-powered-vehicles/school-bus/

[d] Lion Electric, Inc https://thelionelectric.com/en/products/electric

[e] Greenpower Motor Company https://www.greenpowerbus.com/product-line/

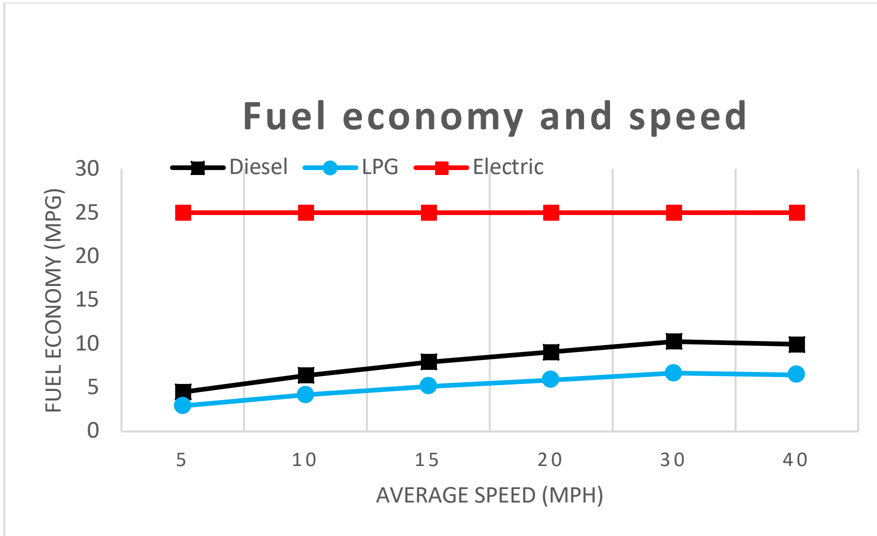

Figure B1: Relationship between vehicle speed and fuel economy for diesel, LPG, and electric school bus. The parameterization for diesel and LPG is based on the model of Clark et al., 2009. For electric buses, there is no dependence of fuel economy on vehicle speed.

Table B2: Summary of fuel economies for diesel, LPG, and electric school bus calculated at different speeds using the parameterization of Figure B1. The national average of 12 mph is the 'base case'.

Duty Cycle	Speed (mph)	Diesel (mpdge)	LPG (mpdge)	Electric (mpdge)
Slow Urban	5	4.5	2.9	25
Urban	10	6.4	4.1	25
National Avg	**12**	**7.1**	**4.7**	**25**
Suburban	20	9.1	5.9	25

Table B3: Summary of operational costs for diesel, LPG, and electric school buses, in $/mile. Fuel prices are reported as a function of vehicle speed as well.

Fuel Type	Maintenance ($/mi)	Fuel, 5 mph ($/mi)	Fuel, 12 mph ($/mi)	Fuel, 20 mph ($/mi)
Diesel	0.55	0.55	**0.35**	0.27
LPG	0.32	0.34	**0.21**	0.17
Electric	0.17	0.25	**0.25**	0.25

Table B4: Fuel price variation based on three oil price scenarios (low, reference and high) as projected by the EIA. The reference fuel price values are applied to the base case scenario.

Fuel Price Scenario	Diesel (% change)	LPG (% change)	Electric (% change)
Reference	**0.80%**	**1.20%**	**0.10%**
High	2.10%	2.40%	0.10%
Low	-0.50%	-0.40%	0.10%

Table B5: Electricity rates (supply only) used in the modeling of revenue from vehicle-to-grid (V2G) with and without time-of-use (TOU) rates. Both tariffs ($/kWh) and costs ($/mile) are shown.

V2G Revenue	kWh/mile	$/kWh	$/mile
Base Case (no TOU)	1.5	0.12	0.18
Smart Case (TOU)	1.5	Off-peak 0.07 On-peak 0.20	Off-peak 0.1 On-peak 0.3

Section Endnotes

[1] U.S. Department of Energy, DoE. (2020). Average annual vehicle miles traveled by major vehicle category. Retrieved June 10, 2020 from https://afdc.energy.gov/data/widgets/10309

[2] M J B&A. (2013). Comparison of modern CNG, diesel and diesel hybrid-electric transit buses. Efficiency and environmental performance. Retrieved June 10, 2020 from https://mjbradley.com/sites/default/files/CNG%20Diesel%20Hybrid%20Comparison%20FINAL%2005nov13.pdf

[3] U.S. Department of Transportation, DOT. (2011). Bus lifecycle cost model for federal land management agencies. National Transportation Library. Retrieved June 12, 2020 from https://rosap.ntl.bts.gov/view/dot/9548

[4] U.S. Department of Energy, DoE. (n.d.). Fuel conversion factors to gasoline gallon equivalents. Retrieved June 12, 2020 from https://epact.energy.gov/fuel-conversion-factors

[5] Clark, N. N., Zhen, F., & Wayne, W. S. (2009). TCRP Report 132: Assessment of hybrid-electric transit bus technology. *Transit Cooperative Research Program*. Retrieved June 12, 2020 http://www.reconnectingamerica.org/assets/Uploads/hybridelectricbustechnology2009.pdf

[6] Lajunen, A. (2014). Energy consumption and cost-benefit analysis of hybrid and electric city buses. *Transportation Research Part C: Emerging Technologies*, *38*, 1–15. http://doi.org/10.1016/j.trc.2013.10.008

[7] Bloomberg NEF (2019). A Behind the scenes take on lithium-ion battery prices. Retrieved July 3, 2020 from https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

[8] King County Metro Transit (2017). Feasibility of achieving a carbon-neutral or zero-emissions fleet. Retrieved June 22, 2020 from https://kingcounty.gov/~/media/elected/executive/constantine/news/documents/Zero_Emission_Fleet.ashx?

[9] Stinson, J. (2020, May 27). EV shows savings compared to diesel trucks, but not in every U.S. city. Retrieved May 29, 2020 from https://www.transportdive.com/news/Electric-Trucks-Amply-MPGs-study/578610/

[10] National Renewable Energy Laboratory, NREL (2017). King County Metro battery electric bus demonstration. Preliminary results. Retrieved May 7, 2020 from https://afdc.energy.gov/files/u/publication/king_county_be_bus_preliminary.pdf

[11] U.S Department of Energy (n.d.). Alternative Fuel Data Center. Maps and data. Retrieved June 9, 2020 from https://afdc.energy.gov/data/

[12] Energy Information Agency, EIA. (2020). Annual Energy Outlook 2020. Retrieved June 19, 2020 from https://www.eia.gov/outlooks/aeo/tables_ref.php

[13] Ercan, T., Noori, M., Zhao, Y., and Tatari, O. (2016). On the front lines of a sustainable transportation fleet: applications of vehicle-to-grid technology for transit and school buses. *Energies, 9*, 230; doi:10.3390/en9040230

Appendix C: Additional TCO Results

This Appendix reports the discounted cost elements (in Net Present Value, or NPV) of the TCO model discussed in Section 3.

Table C1: Summary of the discounted capital, fuel and maintenance lifetime costs (reported as NPV) from the histogram in Figure 2.

NPV	Diesel	LPG	Electric
Capital	$101,942	$111,650	$388,350
Fuel	$40,602	$25,000	$27,889
Maintenance	$110,952	$58,212	$30,925
Total	$253,496	$194,862	$447,164

Table C2: Summary of the discounted capital, fuel and maintenance lifetime costs plus externalities (reported as NPV) from the histogram in Figure 5.

NPV	Diesel	LPG	Electric
Capital	$101,942	$111,650	$388,350
Fuel	$40,602	$25,000	$27,889
Maintenance	$110,952	$58,212	$30,925
Externalities	$28,544	$21,085	$7,683
Total	$282,040	$215,947	$454,847

Table C3: Summary of the discounted capital, fuel and maintenance lifetime costs plus externalities and V2G revenue of the electric school bus (reported as NPV) from the histogram in Figure 6.

NPV Values	Diesel	LPG	Electric
Capital	$101,942	$111,650	$388,350
Fuel	$40,602	$25,000	$27,889
Maintenance	$110,952	$58,212	$30,925
Externalities	$28,544	$21,085	$7,683
V2G	$0	$0	($91,548)
Total	$282,040	$215,947	$363,300

Table C4: Results of the sensitivity analysis performed on bus mileage, using average fuel economy values (for a travel speed of 12 mph) with and without V2G. Purchase incentives are not applied. The most favorable cases for the electric bus (high mileage) are highlighted in bold.

Mileage / Costs	Low (8,000 mi)	Medium (12,000 mi)	High (20,000 mi)
NPV w/out V2G	+48% (vs. diesel) +58% (vs. LPG)	+38% (vs. diesel) +52% (vs. LPG)	**+19% (vs. diesel)** **+43% (vs. LPG)**
NPV w/ V2G	+35% (vs. diesel) +47% (vs. LPG)	+22% (vs. diesel) +41% (vs. LPG)	**+1% (vs. diesel)** **+30% (vs. LPG)**

Table C5: Results of the sensitivity analysis performed on bus speed using average annual mileage (12,000 miles per year), with and without V2G. Purchase incentives are not applied. The most favorable cases for the electric bus (low speed) are highlighted in bold.

Speed / Costs	Low (5 mph)	Medium (12 mph)	High (20 mph)
NPV w/out V2G	**+30% (vs. diesel)** **+47% (vs. LPG)**	+38% (vs. diesel) +52% (vs. LPG)	+41% (vs. diesel) +54% (vs. LPG)
NPV w/ V2G	**+13% (vs. diesel)** **+34% (vs. LPG)**	+22% (vs. diesel) +41% (vs. LPG)	+26% (vs. diesel) +43% (vs. LPG)

Table C6: Results of the sensitivity analysis performed on oil price projections, using average ('base case') annual mileage and vehicle speed, with and without V2G. Purchase incentives are not applied. The most favorable case for the electric bus (high oil price) is highlighted in bold.

Oil Price / Costs	Low	Reference	High
NPV w/out V2G	+39% (vs. diesel) +53% (vs. LPG)	+38% (vs. diesel) +52% (vs. LPG)	**+37% (vs. diesel)** **+52% (vs. LPG)**
NPV w/ V2G	+23% (vs. diesel) +42% (vs. LPG)	+22% (vs. diesel) +41% (vs. LPG)	**+21% (vs. diesel)** **+40% (vs. LPG)**