UNIVERSITY OF CALIFORNIA,
IRVINE

# "Technology Mix Optimization for Zero-Emission Fleets Adopting a Multi-Criteria Decision Analysis within a Life Cycle Assessment Framework"

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Environmental Engineering

by

Analy Castillo

Dissertation Committee:
Professor Scott Samuelsen, Chair
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2019

# DEDICATION

The love of Heavenly Father and the unwavering support of my family made this journey possible. To my husband, Shawn, and my sweet baby-girl, Diana Aurora, you both are my inspiration. Para mi abuelita, tu sacrificio y visión nos trajo a este país a cumplir nuestros sueños. Para mis padres, el ejemplo de sacrificio y entrega que dio combustible a mis esfuerzos.

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## NOMENCLATURE

| | |
|---|---|
| APEP | Advanced Power and Energy Program |
| BEB | Battery Electric Bus |
| BEB-LR | Battery Electric Bus Long Range |
| BEB-SR | Battery Electric Bus Short Range |
| BEV | Battery Electric Vehicles |
| CA | California |
| CNG | Compressed Natural Gas |
| D&D | Distribution and Dispensing |
| DGE | Diesel Gallons Equivalent |
| FCEB | Fuel Cell Electric Bus |
| GHG | Green House Gas |
| GREET | Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation |
| GWP | Global Warming Potential |
| $H_2$ | Hydrogen |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |

| | |
|---|---|
| LHV | Lower Heating Value |
| LNG | Liquefied Natural Gas |
| LPG | Liquefied petroleum gas |
| MCDA | Multi-Criteria Decision Analysis |
| MOLP | Multi-Objective Linear Programming |
| OCTA | Orange County Transportation Authority |
| OPV | Open Circuit Voltage |
| PCA | Preferred Combination Assessment |
| PEM | Proton Exchange Membrane |
| PP | Power Plant |
| Rnwb | Renewable |
| SC | Scenarios |
| SMR | Steam Methane Reformation |
| SOC | State of Charge |
| TCO | Total Cost of Ownership |
| WECC | Western Electricity Coordinating Council |
| WTT | Well to Tank |
| WTW | Well to Wheels |

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First, and foremost, I want to thank God for granting me so many blessings during grad school and beyond. I also thank my husband, for his unconditional support, and my sweet daughter; Diana setting an example for you was my inspiration.

I want to thank my family for their love and support; in particular, my parents, their sacrifice has allowed my brothers and me to dream higher. This dissertation is the realization of those dreams that could not have happened if it wasn't for the hard work of my grandmother, Argelia.

I would like to acknowledge Professor Scott Samuelsen, his enthusiasm and passion were my first introduction to APEP and without his guidance and support - along with the one from doctor Brendan Shaffer – this Ph.D. wouldn't have been possible.

Along with the staff at APEP, the following people were instrumental in making this project a success:

• Beth McCormick, Bill Habibe, Gail Cherry and Connie Raya from Orange County Transportation Authority, their time and collaboration were a crucial aspect in understanding transit agencies and made possible having a robust test platform for this research.

• SoCal Gas Company for their interest and support in advancing hydrogen infrastructures in the State of California

- Professor Hedengren and Adam Martin for their guidance regarding optimization concepts and approaches to solve multi-objective linear problems

A special thanks to all my colleagues at the APEP, you all have made the journey through this doctoral degree a wonderful experience.

I also want to thank Professor Stefan Hirschberg and Peter Burgherr for welcoming to their research group during my time as a Fulbright fellow. My year at the Paul Scherrer Institute (PSI) went beyond a successful research collaboration, but it provided me with new friends and experiences. Thank you to all the colleagues at the Technology Assessment Group at (PSI), especially Chris Mutel, Brian Cox, Rebecca Lordan, Karin Treyer, Matteo Spada, and Saverio Calabretta.

Thanks also go to all the students that I had the pleasure to supervise and for their contribution to my research: Kevin Valencia, Alma Santiago, and Pengjie Tian.

Finally, I want to thank the National Science Foundation (NSF) and the Fulbright organization for the great honor of being selected as one of their fellows.

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### EDUCATION

**University of California Irvine –** Irvine, CA June 2019

- Ph.D. Student, Environmental Engineering
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- Emphasis: Sustainable Transportation
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- Advisor: Professor Scott Samuelsen

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- Bachelor of Science, Chemical Engineering
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## RESEARCH INTERESTS

Deployment of zero-emission transportation systems; optimal design of mixed-technology bus fleets; energy resource systems; Life Cycle Assessment of transportation systems comprising of operations, supply-chain and end-of-life; integration of sustainable transportation with energy systems.

## RESEARCH AND PROFESSIONAL EXPERIENCE

**Advanced Power and Energy Program (APEP)**
**University of California, Irvine**

*Graduate Researcher* June 2013 – April 2019

- Created analysis tool for transit agencies to find optimal technology-mix in their bus fleet. The development of the tool included the following task to advise police and strategic decisions to stakeholders:
  - Perform life cycle assessment of hydrogen fuel cell, hybrid, and battery electric buses (on-route and over-night charging)
  - Conduct total cost of ownership for zero-emission buses and fueling infrastructure
  - Collect and analyze electric bus data to understand costumer's operational constraints
- Deployed the first fuel cell bus at the UCI campus as part of a pilot project to test the technology
- Executed pilot project of bringing twenty battery electric buses to UCI by engaging with interdisciplinary groups. Managing the research component for the pilot included:
  - Pilot design and execution, including supervision of scheduling, budgets, and reporting
  - Monitoring of the pilot project by collecting performance data and developed an analytic framework to evaluate the program's goals
  - Provide written and verbal reports to internal and external managing directors
  - Cost estimations for electrification of the bus depot
- Wrote technical portions for grant proposals
- Participated in conferences and public stakeholder meetings to present research results and created research collaborations with transit agencies, industrial partners, and governmental agencies.

**Paul Scherrer Institute (PSI)**
**Federal Institute of Technology (ETHZ), Zürich Switzerland**

*Guest Researcher* September 2016 – August 2017

- Developed a model to quantify lifecycle environmental impacts of various zero-emission bus technologies and their fuel supply chain configurations
- Updated life-cycle inventories of zero-emission drivetrain components and of energy generation portfolio for European countries
- Established a research relationship with fuel cells and electrolyzers OEM's to update life cycle inventories
- Participated in workshops to use a lifecycle model written in python language

**Unit Operations Laboratory**
**Rafael Landivar University, Guatemala**

*Teaching Assistant* January 2011 – June 2011

- Supervised and assisted students in the use of laboratory equipment that included heat exchangers, pilot-plant distiller, cooling towers, etc.
- Shared teaching duties for all discussion sections with the professor
- Actively engaged students in discussions during group work periods aimed at teaching and developing fundamental thermodynamic concepts
- Performed all necessary grading duties

**Chemistry I**
**Rafael Landivar University, Guatemala**

*Teaching Assistant* September 2008 – December 2008

- Planned and implemented discussion lessons that aided in the understanding of Chemistry concepts
- Developed exam and homework questions that effectively tested students' knowledge and comprehension
- Collaborated with the professor and other teaching assistants to ensure cohesion between all lectures and discussion sections
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## CONFERENCE AND OTHER PUBLICATIONS

1. Castillo, A., "*Life Cycle Assessment as a Methodology to Evaluate the Transition to Zero Emission Bus Fleets*," Fuel Cell Seminar and Energy Exposition, Long Beach, CA. November 2017
2. Castillo, A., "*First Hydrogen Fuel Cell Bus at a UC Campus*," Fuel Cell Seminar and Energy Exposition, Los Angeles, CA. November 2015
3. Castillo, A. & Scott, S. & Shaffer, B. (2015). "*Deployment of Fuel Cell Electric Buses in Transit Agencies: Hydrogen Fueling Infrastructure Scenarios*." Paper presented at the ASME 2015 Power and Energy Conversion Conference. San Diego, CA. (http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=2467498)
4. Castillo A, Santizo M. Performance and Efficiency of an Evaporation Tower. Science and Engineering Magazine – Rafael Landivar, 2011.
5. Castillo A., Bances O, Estrada H, Santizo M. Performance and Efficiency of a Tubs and Shell Heat Transfer. Science and Engineering Magazine – Rafael Landivar, 2010.
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President, Association of Energy Engineers (AEE) — 2014
Irvine, CA

Member, Women's Transportation Seminar — 2014
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Outreach & Community Service Coordinator, AEE 2013

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Women's fabrication workshop 2013

Mechanical Engineering Department

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Mentor, Society for Advancement of Chicanos and Native Americans in Science (SACNAS) 2013

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Volunteer, A Roof for My Country 2010 - 2012

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## ABSTRACT OF THE DISSERTATION

“Technology Mix Optimization for Zero-Emission Fleets Adopting a Multi-Criteria Decision Analysis within a Life Cycle Assessment Framework”

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Doctor of Philosophy in Environmental Engineering

University of California, Irvine, 2019

Professor Scott Samuelsen, Chair



Aiming to reduce criteria air pollutant and greenhouse gas emissions, several initiatives have been announced throughout the world to incorporate zero emission buses into public transit agencies within the next 15 years. One example is the California Air Resources Board “Innovative Clean Transit Regulation” with the goal to transform the statewide transit bus fleet by 2040 with zero emission buses. In response, transit authorities face decisions between multiple bus technologies, each with different strengths and weaknesses as well as infrastructure requirements. Furthermore, because the performance of new bus technologies depends on the operating conditions of each transit agency, the results from demonstration projects are not typically applicable to another district.

This dissertation addresses the use of Life Cycle Assessment (LCA) to compare different zero-emission bus (ZEB) technologies for transit districts in the State of California. For LCAs conducted to date, the focus has been on one-on-one bus technology comparisons

rather than a combination of bus technologies integrated into bus fleets (mixed fleet). This dissertation extends the traditional LCA approach by using Multi-Objective Linear Programming (MOLP) to identify the optimal ZEB technology mix.

The novelty of this extended LCA is the use of a consistent framework across multiple powertrain types with the same operating conditions. The fleet optimization incorporates essential aspects of a fleet operation such as operational constraints, route length, required infrastructure, and cost. Additionally, a Multi-Criteria Decision Analysis (MCDA) is incorporated to evaluate parameter weighting in the optimization problem, thereby creating an optimization solution that considers real constraints and priorities from stakeholders, users, and regulatory agencies.

The combination of these capabilities (LCA, MOLP, and MCDA) provides a comprehensive tool, including a variety of energy supply chains, which can inform transit agencies in the design of an electric bus fleet comprised by a mix of available and emerging ZEB technologies.

# CHAPTER 1. INTRODUCTION

## 1.1. Overview

Hydrogen fuel cell electric buses (FCEBs) and different configurations of battery electric buses (BEBs) are being considered today by transit districts as a solution to replace fossil-based fuels with the goal to reduce criteria pollutant and greenhouse gas emissions. However, when selecting a new bus technology, the environmental benefit cannot be quantified solely based on a comparison of tailpipe emissions. Only a detailed study of the entire life of a bus (cradle-to-grave or, ideally, cradle-to-cradle) and resources needed for manufacturing/operation/recycling can allow for a comprehensive comparison between competing technologies.

Because each zero-emission bus technology has different strengths and weaknesses, as well as unique operational requirements, the design of a life-cycle tool that can inform transit agencies about the technology-mix for their bus fleet would be highly valued. To this end, research is required to develop a comprehensive life-cycle tool that can assist transit agencies in California in answering the following question: For a given set of operating conditions, what is the optimal fleet configuration that will reduce costs while minimizing environmental and health impacts?

The answer requires specifics about infrastructure and fuel/energy sources while guarantying to satisfy the transit agency's operational requirements (e.g., route length, passenger demand, route schedule, space requirements).

One strategy is to develop a tool that integrates an extended Life Cycle Assessment (LCA) methodology with a Multi-Criteria Decision Analysis (MCDA) and a Multi-Objective Linear Programming (MOLP) optimization. The extended LCA would then establish a consistent framework across multiple powertrain types with the same operating conditions to assess energy consumption, operating emissions, and operation cost. The (MCDA) would permit weighting the objective functions according to the combined priorities from the operator, manufacturer, and regulatory agencies. Lastly, the MOLP optimization would generate fleet configurations with the optimal number of each zero-emission bus type (Fuel Cell Electric Buses, overnight Battery Electric, and/or on-route charging Battery Electric Buses) and the corresponding source of energy (e.g., electricity, hydrogen).

## 1.2. Goal

The goal of this dissertation is to develop a lifecycle-based optimization tool that can inform transit agencies and other stakeholders (e.g., investors, academic researchers, and decision makers) about the ideal technology mix of zero-emission buses (ZEBs) for public transportation fleets considering operation constraints. To achieve this goal, the following objectives are required:

### 1.3. Objectives

1. Cost and Life Cycle Inventory Databases Development

Collect and create the necessary data to build database inventories of resources and materials relevant for conventional buses and ZEB technologies and the corresponding fuel supply chains.

2. Modeling of Urban Bus Energy Consumption and Operating Emissions

Apply the methodology developed by Cox in [1] for the modeling of energy consumption and operating emissions for the relevant driving cycle for the corresponding transit agency. This requires specific modification to reflect emissions relevant and specific to the State of California.

3. Life Cycle Environmental and Economic Analysis

Apply the principles of a cut-off allocation classification for the Life Cycle Assessment of bus technologies. Obtain the environmental impact from a life-cycle perspective, incorporating a diversity of energy supply pathways for hydrogen and electricity production. Conduct a cost analysis by characterizing the life cycle cost that includes acquisition, operation, and disposal expenses.

4. Multi-Criteria Decision Analysis (MCDA)

Apply the decision support methodology MCDA to address the complex decision problem involving multiple objectives of conflicting nature (e.g., minimizing cost and maximizing environmental benefit opportunities).

5. Technology-Mix Optimization for optimal bus fleet configuration

Apply a Multi-Objective Linear Programming approach to solve the optimization problem of minimizing cost while maximizing environmental benefit opportunities. Incorporate the extended LCA results as part of the objective function criteria and the results from the MCDA to weight the final objective function. Evaluate optimal fleet design under two case scenarios, one for present conditions using the year 2018 as reference and another for future scenarios with projections for the year 2040.

# CHAPTER 2. BACKGROUND

## 2.1. California Transportation Sector

Although public transport by urban bus is generally more environmentally efficient than individual passenger cars, conventional buses are still associated with significant local criteria air pollutant[1] and greenhouse gas emissions[2]. Air pollution associated with criteria pollutants is a significant concern in urban areas such as California's South Coast Air Basin (SCAB) where heavy-duty vehicles and buses are significant contributors to the total emissions of NOx. While progress has been made in reducing criteria air pollutant emissions from light-duty vehicles, medium-duty and heavy-duty vehicles have been more difficult to address due to the diversity of duty cycles and operational needs encompassed by these sectors. Additionally, powertrains in medium-duty and heavy-duty vehicles have typically relied on diesel fuel in order to satisfy their duty cycles, thereby limiting options for emissions reductions.

In addition to criteria air pollutant reductions, many regions of the world have initiated proactive programs to reduce $CO_2$ emissions. California, as an example, has an especially ambitious carbon reduction program. In 2016, total greenhouse gas (GHG) emissions for the State of California were almost 430 million metric tons of $CO_2$ equivalents (MMTCO2e), an overall decrease of 13% from a peak in 2004, and a decrease to 2 MMTCO2e below the 1990

[1] Air pollution contributes to a wide variety of adverse health effects. The U.S. Environmental Protection Agency has established national ambient air quality standards (NAAQS) for six of the most common air pollutants— carbon monoxide, lead, ground-level ozone, particulate matter, nitrogen dioxide, and sulfur dioxide [121].

[2] Gases that absorb infrared radiation and trap heat in the atmosphere are called greenhouse gases[122].

level (the State's 2020 mandated GHG target) [2]. The transportation sector remains the most significant source of GHG emissions in the State, accounting for 41% of the inventory. Figure 1 shows the GHG emission by sector for 2016, and Figure 2 presents trends for the transportation sector from 2000 to 2016. Figure 2 also shows that heavy-duty vehicles are the second largest contributor to (GHG) emissions behind automobiles and that emissions from the heavy-duty sector started decreasing after 2007, even as diesel sales increased.

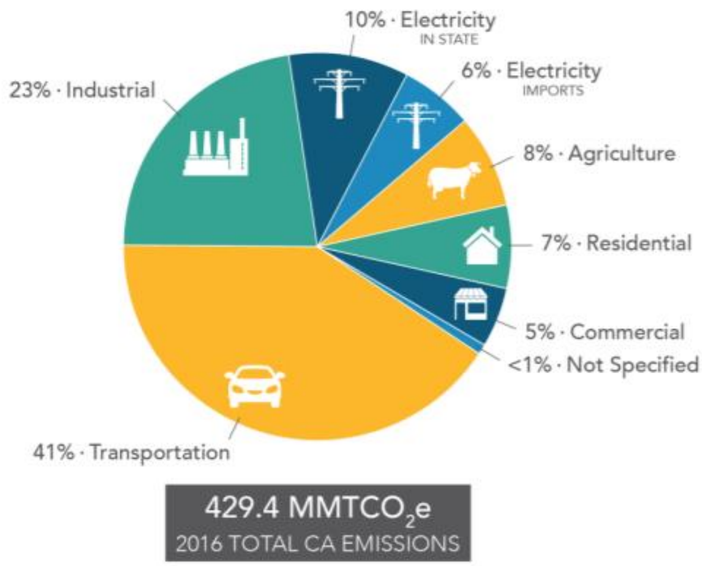



***Figure 1*** ***Greenhouse gas emissions by sector for 2016*** [2]

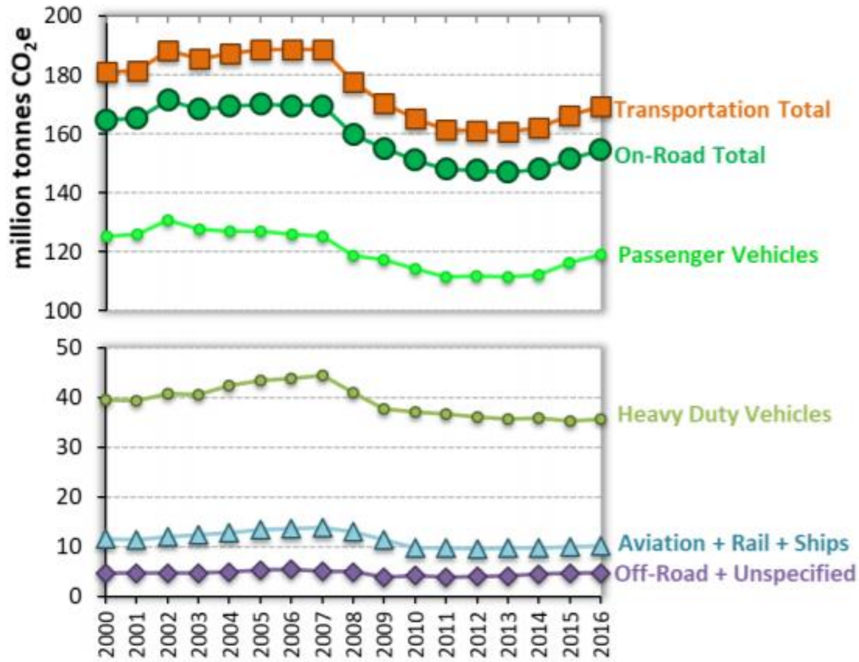



***Figure 2*** ***Greenhouse gas emissions for the transportation sector in California*** [2]

## 2.2. Background Legislation

In recognition of the need for reduction in greenhouse gas and criteria air pollutant emissions from urban buses, initiatives to deploy zero emission buses into public transit agencies have been promulgated by governmental authorities around the world. For example, during the 2016 International Zero Emission Bus Conference in London, over 23 cities presented plans to incorporate 60% of ZEBs in their fleet by 2025 [3]. This includes initiatives such as the C40 Clean Bus Declaration [4], which stipulates the acquisition of over forty thousand clean buses by 2040.

California has been a leader in pollution and GHG emissions reductions for decades. In 2005 Governor Schwarzenegger enacted Executive order S-3-05 which set into motion three GHG emission goals for the State of California in the near and long-term. These goals are to: 1) bring GHG emissions to 2000 levels by 2010, 2) achieve 1990 levels by 2020, and 3) establish GHG emissions levels by 2050 that are 80% below those recorded in 1990. The first two goals were affirmed by the California Legislature in the passage of Assembly Bill 32 (AB 32) in 2016 (the "Global Warming Solutions Act")[5]. While the third goal has not yet been established as a legal mandate, the Legislature passed SB 32 in 2016, which requires by law a 40% reduction from 1990 levels by 2030 [6].

Other legislation, such as Senate Bill 1078, establishes the Renewable Portfolio Standard (RPS), or renewable energy penetration goals for the state. These goals are delineated in Senate Bill 1078 and are updated by Senate Bill 2 with an aim to have a renewable penetration of 20% by 2013, 25% by 2016 and 33% by 2020 [7]. These high penetration objectives, along with future increased load from the electrification of the transportation sector, will have complex and dynamic interactions with the electrical grid. These complex interactions and concurrent complementary technology utilization strategies play a crucial role in energy utilization and price regulation [8], [9]. Therefore, to fully leverage these high renewable penetration rates, a sector-wide, California specific approach must be taken when analyzing the future of California's energy system and build out of complementary infrastructure [10].

To meet the schedule and reduction targets, a substantial effort has been focused on the transportation sector to accelerate fleet modernization and increase the penetration of clean engine technologies and cleaner fuels. Part of this effort is the "Innovative Clean Transit" initiative from the California Air Resource Board, with the goal of transforming the statewide transit bus fleet by 2040 through phasing-in ZEB purchases [11]. Related to this effort, several transport authorities have stated commitments to transition to a zero-emissions fleet within the next 15 years. These transit agencies, however, will be tasked with complying with these initiatives while still being able to satisfy the travel patterns of customers in their service area.

However, no holistic analysis has been conducted to compare the environmental impacts of the overall fuel supply chain needed for the deployment of ZEBs. This type of analysis is essential to: (1) maximize the emission reduction while minimizing resource consumption in the supply chain (e.g., energy and water), and (2) establish criteria that can identify the most effective combination of ZEB technologies based on the characteristics and limitations of the transit agency.

Developing strategies to transition urban bus fleets towards low or zero emissions involves selecting between a wide array of emerging public bus powertrain technologies in the context of operational cycle constraints. However, merely deploying battery electric or fuel cell electric buses do not automatically guarantee significant emissions reductions since many sources of emissions may occur outside of the operating or use phase. Therefore, to gain an accurate assessment of how effective the transition to alternate urban bus powertrain technologies can be, accounting for emissions from the full life cycle of these buses must take place.

### 2.3. Life Cycle Assessment

Life Cycle Assessment (LCA) is a "cradle-to-grave" approach that begins with the gathering of raw materials to create a product or service and ends at the point when all materials are returned to the earth (end-of-life) [12]. LCA allows for the estimation of collective environmental, economic, and energy impacts resulting from the various stages in the product's life cycle. This enables a better understanding of the environmental performance of a product and determines potential areas of improvement while comparing the environmental performance of different products that serve the same purpose.

According to ISO 14040 [13], LCA must be performed in a framework consisting of four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation. A robust iterative component is associated with these four stages. For example, the interpretation of the results from an initial first inventory analysis and impact assessment might lead to refinement of the goal and scope definition resulting in a new impact assessment. Figure 3 is a graphic presentation of the LCA stages and its iterative process.

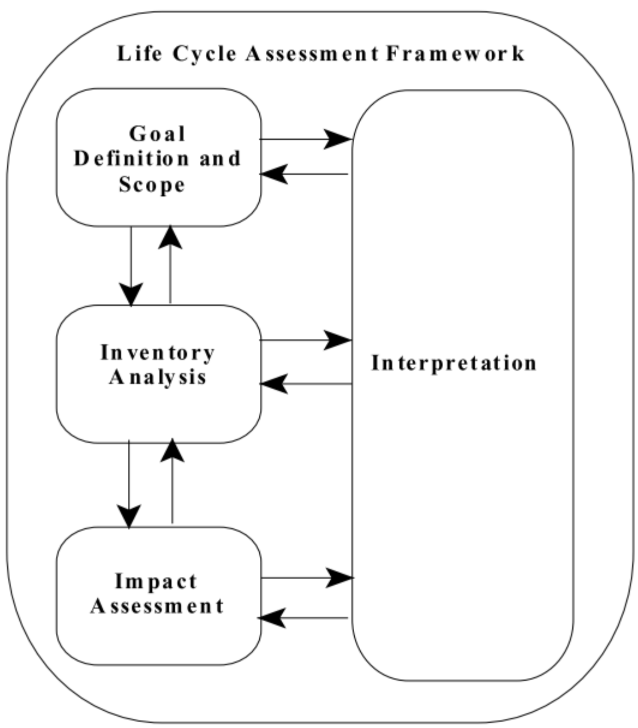



***Figure 3*** ***Stages of Life Cycle Assessment*** [12]

The use of the term "life cycle" in this dissertation encompasses the stages of materials extraction for constructing the buses and fuel supply, manufacturing and assembly of the bus units, the operational lifetime of bus units, and end-of-life disposal or recycling of buses after their operational lifetime.

### 2.4. Multi-Criteria Decision Analysis

Multi-Criteria Decision Analysis, or MCDA, is a valuable tool that can be used to solve complex decisions or to choose from a variety of options. It is most applicable to solving problems that are characterized as a choice among alternatives. The score of an option is calculated based on a set of criteria.

When used for group decision making, MCDA helps groups discuss their decision opportunity in a way that allows them to consider the values that each view as a priority while evaluating complex trade-offs among alternatives. MCDA problems are comprised of five components:

1. Goal
2. Decision maker
3. Decision alternatives
4. Evaluation criteria (interests)
5. Outcomes associated with other options

Several possible mathematical methods could be used to conduct the calculations, examples of which include [14]:

- Complete aggregation (top-down approach): This approach seeks to reduce an undefined number of criteria to a single criterion by aggregating them.
- Partial aggregation (bottom-up approach): seeks to establish outranking relations between potential options/actions by comparing them to each other.
- Local and iterative aggregation: This approach incorporates an iterative search to find a better solution after having a starting solution.

### 2.5. Overview of Hydrogen Supply Chain

Hydrogen is an energy carrier that can be used in fuel cells to generate electric power by means of an electrochemical reaction (rather than combustion), and producing only water and heat as byproducts. Fuel cells are emerging to power vehicles, homes, and office buildings, and potentially power locomotives and ships.

The use of hydrogen in zero-emission fuel cell electric buses with strategic planning of the hydrogen supply chain can provide benefits beyond the elimination of tailpipe criteria air pollutant and carbon emissions. Hydrogen offers a paradigm shift from the current fossil-based fuels due to: (1) the great variety in renewable technologies for the production of hydrogen, and (2) the flexibility to incorporate renewable technologies along the supply chain. The main components of the hydrogen supply chain are presented in Table 1.

*Table 1 Technology components of the hydrogen supply chain* [15]

| Categories of Hydrogen Technologies | Specific Technologies available |
|---|---|
| Production of Hydrogen | Steam methane reformation<br>Electrolyzer<br>Biological systems<br>Gasification<br>Thermo-chemical water splitting<br>Photo-electrochemical systems |
| Storage of Hydrogen | Compressed<br>Liquid<br>Material based / absorption<br>Chemical |
| Transport of Hydrogen | Trucks<br>Pipelines<br>Road-rail tankers (gas or liquid)<br>Ships |
| Transport applications / primary drives | Fuel cell<br>Combustion engine<br>Electric / hybrid drivers<br>Onboard production |

Hydrogen can be produced from a series of renewable sources that are transitioning to commercialization (Figure 4). Hydrogen can also be produced either centralized or distributed (local to the point of use). As a result, the hydrogen supply chain for fuel cell electric buses (FCEBs) has a myriad of options that can be investigated to establish scenarios that best fit the unique characteristics presented by each transit agency.

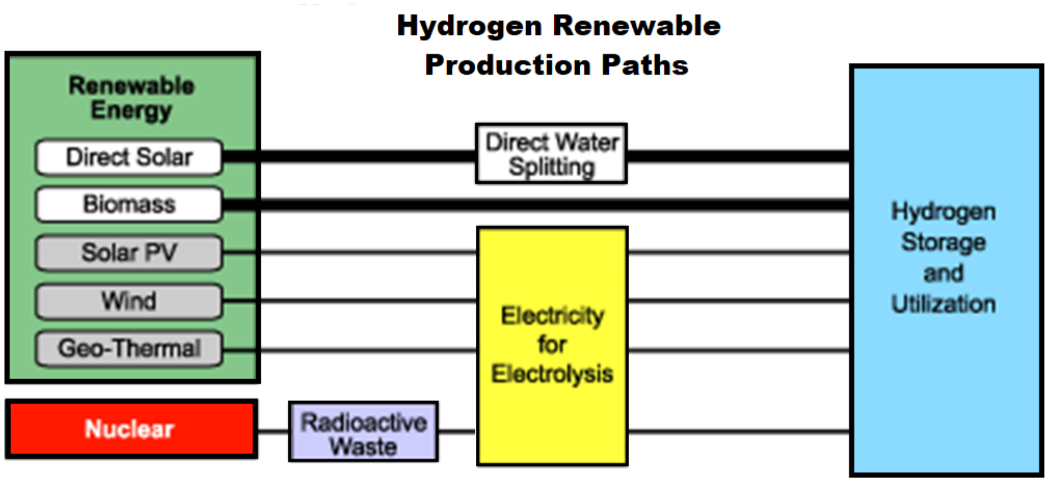



***Figure 4*** ***Hydrogen generation technologies*** [16]

More than 95% of current hydrogen generation in the world relies on some fossil fuel as the feedstock, specifically from natural gas. The United States is rich and abundant in natural gas, having an estimated 27 trillion cubic feet [17] (Figure 5). As a result, the generation of hydrogen from natural gas has the potential to reduce dependency on foreign oil since 87% of the natural gas used in the U.S. is produced domestically.

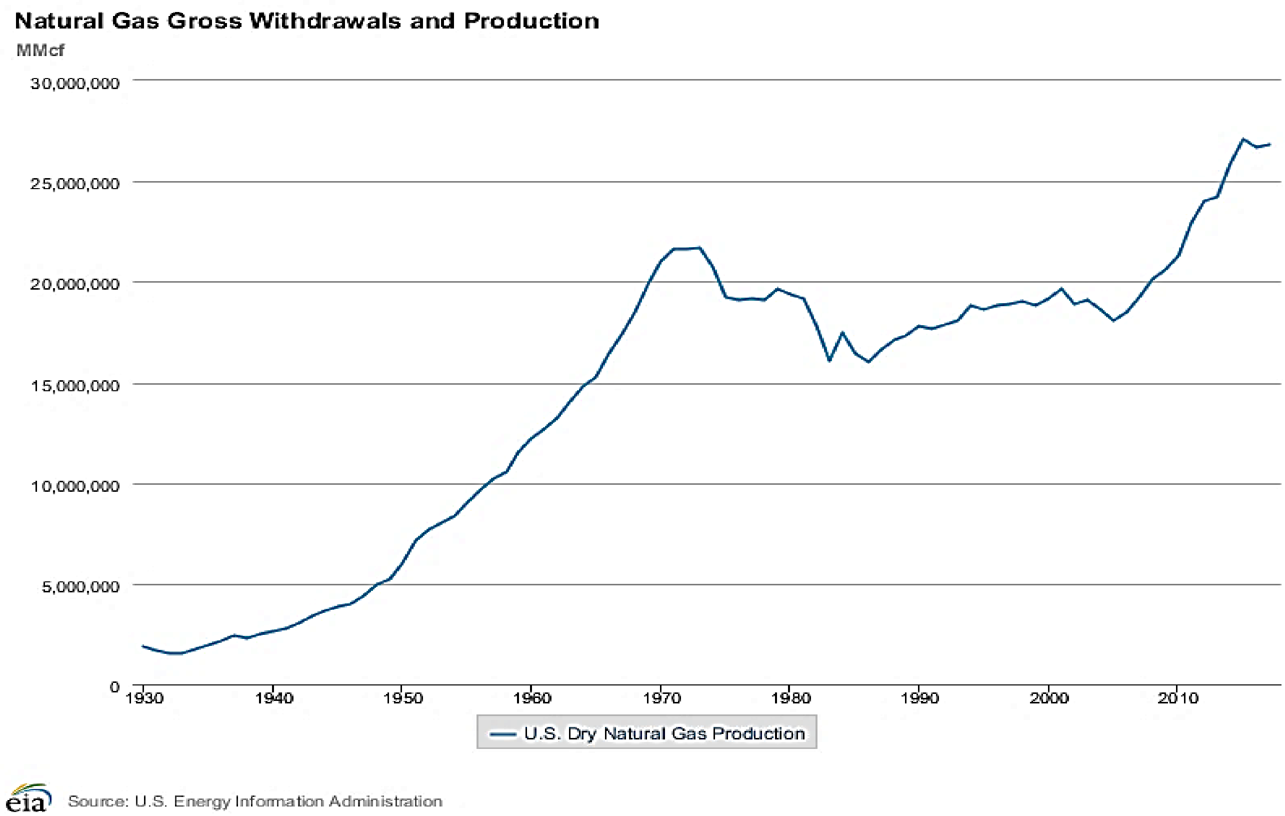



***Figure 5*** ***Natural gas production in the U.S.*** [18]

The two technologies commercially available to produce hydrogen with a neutral or zero emission of carbon are steam methane reformation (SMR) using biogas (carbon-neutral), and electrolysis powered by otherwise curtailed wind (zero-carbon).

### Steam Reformation

Today, most of the hydrogen in the world is generated by SMR as the most cost effective and efficient of all commercial reformation technologies. Efficiencies for centralized natural gas operated SMR plants range from 76 – 81% [19].

SMR operations currently take place mostly on a centralized scale. An example of non-centralized (i.e., "distributed") hydrogen generation is the SunLine Transit station in

Thousand Palms, California. It is likely that more distributed SMR will be introduced into the emerging hydrogen infrastructure since it can take advantage of the existing natural gas infrastructure for wheeling biogas to produce hydrogen on site. Some companies, such as HyRadix, $H_2$Gen, and Ztek, are working on commercializing integrated SMR systems that generate, compress, and dispense hydrogen into vehicles [20].

### Electrolysis

Electrolysis is a method of generating hydrogen from water using an electric current to split water into its two parts: hydrogen and oxygen. The source of the electricity dictates the cost of the process, estimated to be 58% of the price at the pump in one study [21].

Using renewable solar or wind generated electricity that would be otherwise curtailed to power an electrolyzer is an environmentally friendly method to generate zero-carbon hydrogen. Large-scale solar and wind farms can be used for centralized generation of electrolytic hydrogen that can be injected into natural gas pipelines (in the earlier years) and dedicated hydrogen pipelines (in later years), stored from days to seasons, and eventually used to either power fuel cell vehicles or generate electricity through gas turbines or fuel cells [22]. The installation cost of a hydrogen pipeline is 1/3 that of an electrical transmission line that moves the same amount of energy [20]. Hydrogen pipelines are also safer than overhead transmission lines, require less maintenance, and are aesthetically preferred.

Electrolysis using the electrical power grid comes at a higher environmental cost. Some studies show that generating hydrogen from grid electrolysis to fuel automobiles yields a net increase of GHG emissions compared to today's conventional vehicles [23]. However, more recent studies establish that power-to-gas (P2G) technology, which involves the conversion of electrical power into a gaseous energy carrier, is a promising prospect for future energy systems. With P2G, hydrogen can be supplied completely from excess renewable energy, which benefits: 1) balancing the electrical grid with high use of variable, unpredictable renewable power, 2) providing high capacity, long term energy storage for seasonal shifting, and 3) creating a hydrogen supply to promote the use of state-of-art fuel cell vehicles across different transportation sectors, including light, medium, and heavy-duty. Additionally, P2G has also been shown to be the most cost-effective approach for long-term energy storage [24][25].

### 2.6. Overview of Electricity Generation in California

For conventional buses using natural gas or diesel fuel, the primary energy carrier is monolithic. In transitioning to battery electric or fuel cell powered buses, the sources of fuel are significantly more diverse. Electricity can be produced via a wide array of sources and grid mixes, and hydrogen can also be sourced from different energy supply chains. These aspects have a significant effect on life cycle emissions and need to be characterized. The California electric grid mix is considered as one of the options to supply the electric buses and to power electrolyzers when producing hydrogen. In particular, the 2016 California energy generation mix was utilized with an average efficiency of 52% [26], [27] (Figure 6).

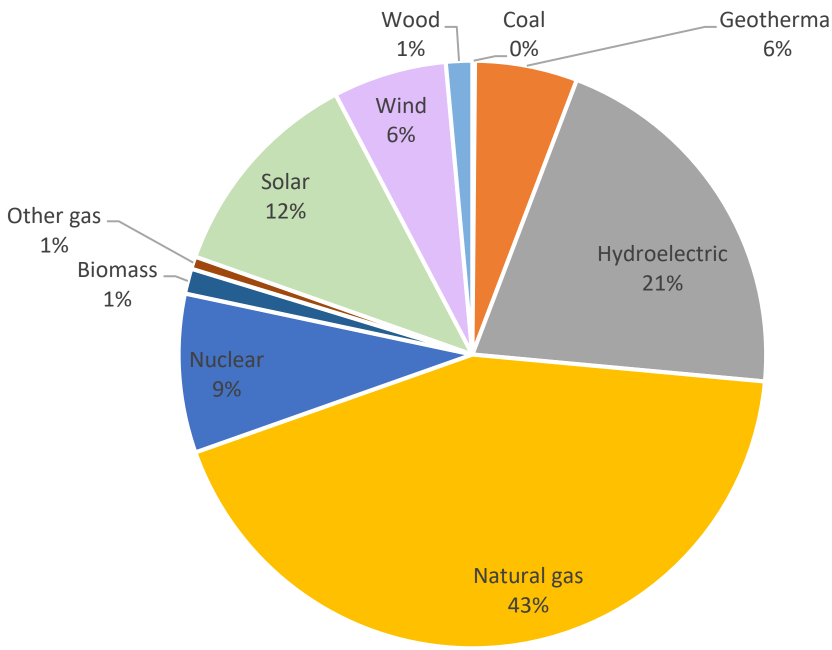



***Figure 6*** ***California Electricity Generation Mix 2017*** [28]

California has started several State initiatives to increase the share of renewables, as required by current legislation. The current grid in California is slowly accommodating more renewables and using less fossil-base fuels. Since no historical data have been collected that could reflect the new grid mix beyond 2016, the snapshot from May 2018 was considered as the best-case scenario for the CA grid mix. Figure 7 shows the grid with considerably more renewable generation, 39% of nonhydroelectric renewables compared to 19% from 2017.

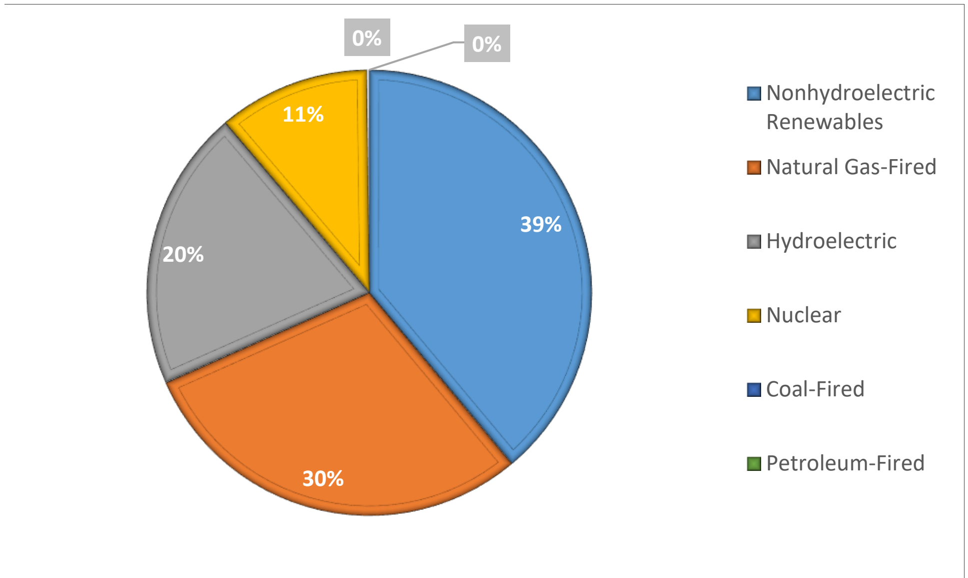



***Figure 7*** ***California Electricity Generation Mix 2018*** [29]

### 2.7. Literature Contribution

The deployment of alternative powertrains for urban buses has been of interest for a long time. Since the late 1990s, test fleets have used ZEBs such as hydrogen fuel cell, plug-in electric, trolley, and on-route charging. In particular, battery electric buses (BEBs) and fuel cell electric buses (FCEBs) are both electric drive vehicles with many common components and have been in demonstration projects across the country [30]–[33]. Data from these demonstration projects have been instrumental in providing transit agencies with information for their decision making. However, when seeking LCAs for these technologies, the information found does not accurately represent the commercially available buses, and the data inventories are often built from theoretical studies. Additionally, the primary energy source mix for hydrogen or electricity are usually limited to local grids and current hydrogen generation pathways, restricting their renewable potential.

Regarding the LCA of one or more of these technologies, several studies have been published for different areas of the world under different conditions. A study for Australia by Ally et al. [34] examined life cycle cost of diesel, natural gas, and hydrogen fuel cell bus systems, but did not analyze environmental metrics nor include battery electric buses. Zicheng performed a life cycle analysis focusing on greenhouse gas emissions for the aggregate United States using averaged electric-grid production data [35] as well as a study for the Ann Arbor, Michigan area [36] for long-range plug-in vs. wirelessly-charged battery electric buses. Lajunen performed studies for Finland, one focusing on cost and greenhouse gas emissions of varied urban bus powertrain types [37] and another focusing on cost-benefit analyses for operation using parallel and series hybrid buses [38]. Cost studies were also undertaken for Singapore by Stempien and Chan [39]. Greenhouse gas emissions impacts from a fleet view of the aggregate U.S. considering mixed fleets of vehicles (cars, buses, vans, trucks), were also examined by Meinrenken [40]. Ercan and Tatari [41] performed a novel assessment of diesel, natural gas, and long-range battery electric buses using input-output (as opposed to process-based) LCA to capture criteria air pollutant and water withdrawal factors. Finally, a tool for assessing alternative powertrains was developed by Xu [42] but is limited to FCEB operations in Atlanta, GA.

These studies span a wide range of specific regions, various bus types, and conditions. The transit characteristics and demands that alternative powertrain buses must satisfy, however, is region dependent. Different areas have different travel patterns, geography, climate, driving cycles, and supporting infrastructure (i.e., electric grid) which may dictate the technologies that are preferred. Moreover, while greenhouse gas emissions are a global issue, the regional importance of different metrics such as air pollutant emissions and water withdrawals vary, and some are more important to account for in one region versus another. For California, however, an LCA of alternative powertrain technologies that are specific to the needs of transit agencies in the State, and in particular the local areas within the South Coast Air Basin, is not available to inform the decision making of local governments and transit agencies.

Additionally, several publications that compared possible ZEBs using LCA have only focused on individual deployment scenarios, without considering diversity in hydrogen distribution pathways or fuel production. The conclusions from these studies do not satisfy the dynamics of real transportation systems or large-scale shifts in supporting infrastructure. In California, for example, significant changes are taking place in the energy mix, which can affect the life cycle emissions of buses due to increased grid dynamics and renewable deployment. Furthermore, because the performance of urban buses depends strongly on operating conditions, the results from different studies and manufacturer information are not always directly comparable.

Based on a comprehensive literature review, only two studies have addressed fleet optimization with alternative powertrains.

1. Ercan et al. utilized a MiniMax function to select the optimal bus fleet combinations LCA and life cycle cost. The study does not incorporate range limitations from BEB, and other operational constraints, that could make their adoption by transit agencies unfeasible. Adding to this limitation, the study does not consider FCEBs or on-route charging of BEB's as technology options, both of which could pose as a

solution for range limitations. Furthermore, the weights for the objective function are only distributed according to the author's judgment, and no optimal solution was found since different fleet results would result depending on the weight distribution.

2. Durango-Cohen and McKenzie [43] created an optimization model to support the design of transit bus fleets while accounting for costs, level-of-service requirements, and environmental impact. However, the linear optimization results are driven by the level-of-service requirements without having a real insight to the necessities of a transit agency (i.e., the need to satisfy a passenger demand during buses on-route is assumed to be equal to a theoretical loading factor). The study considers as a restraint the passenger capacity of each bus technology without a real reference that such limitation would prevail during operating conditions. Similarly to Ercan's research, the considered bus technologies do not include all the available options, and the optimal fleet results are not formed by zero-emission technologies, which is the primary goal of the regulatory bodies in California.

In this context, this dissertation addresses the gap in understanding the life cycle emissions and cost performance of alternative powertrain urban buses by developing and applying a comprehensive tool. The proposed optimization accounts for the specific needs, driving cycles and supporting the infrastructure of California transit agencies while considering metrics that are of importance to the region, such as air quality, fuel supply chain, and water withdrawal.

# CHAPTER 3. Approach

This dissertation develops a life-cycle based optimization tool that can be used to inform transit agencies and other stakeholders (e.g., investors, academic researchers, and decision makers) about the ideal technology mix of zero-emission buses (ZEBs) for transportation fleets while considering operation constraints. The following tasks directly address the established objectives for this work.

### Task 1. Cost and Life Cycle Inventory Databases Development

Collect all data necessary to build a database inventory of resources and materials relevant for fossil-fuel buses (baseline), ZEB technologies, and the corresponding fuel supply chains. Compile the life cycle inventory data derived from a variety of sources, including literature data and the recognized databases such as Ecoinvent. Focus on the following five powertrains for 40-foot long buses: conventional diesel, natural gas, short-range battery-electric with on-road charging, long-range battery electric, and hydrogen fuel cell electric. Build a cost inventory to capture the capital cost, operation, and maintenance expenses, and disposal cost of the vehicles to calculate the total cost of ownership.

### Task 2. Modeling of Urban Bus Energy Consumption and Operating Emissions

Calculate the energy consumption and operating emissions of the different bus powertrains using the methodology developed by Cox in [1]. For each bus, determine the instantaneous power at each second of the driving cycle required to follow the pre-determined velocity-versus-time profile. Include the power requirements to overcome rolling and aerodynamic resistance, acceleration/ deceleration, auxiliary power, and heating and cooling demands, which are all calculated using typical values for urban buses.

Evaluate the following two driving cycles using the model: (1) The Orange County Bus Driving Cycle as developed by West Virginia University and presented by the Society of Automotive Engineers (SAE) [44] that represents the driving patterns of urban transit buses in the Orange County and Los Angeles region of California; and (2) a driving cycle represented by measured data from electric buses deployed by the Anteater Express Fleet at the University of California, Irvine.

### Task 3. Life Cycle Environmental and Economic Analysis

Using LCA and the data bases built for Task 1 and the energy consumption model formulated for Task 2, identify the environmental impacts of the bus technologies.

Formulate several pathways for fuel production, including current hydrogen and electricity generation as well as renewable production from different sources at different penetration levels.

Conduct life cycle calculations using the open-source Brightway2 model [45], which allows for modifications to pre-established databases as well as embedded calculations to link the energy consumption model and optimization all in the same Python language.

Using the cost database built for Task 1, conduct a cost analysis characterizing the life cycle cost that includes acquisition, operation, and disposal expenses of the vehicles, and everything related to their fuel supply.

### Task 4. Multi-Criteria Decision Analysis

Apply the MCDA methodology to address the complex decision problem involving multiple objectives of conflicting nature (e.g., minimizing cost and maximizing environmental benefit opportunities), and formulate a survey for stakeholders in the State in order to yield the informed weight for the optimization parameters.

### Task 5. Technology-Mix Optimization for optimal bus fleet configuration

Use Multi-Objective Linear Programming to solve the optimization problem of minimizing cost while maximizing environmental benefit opportunities, extend the LCA results as part of the objective function criteria, and use the results from the MCDA as weights for the final objective function with the goal to obtain the ideal mix of each bus technology for the fleet under two different scenarios. Design a present case scenario using calculations for the year 2018, and a future scenario with projections for the year 2040.

# CHAPTER 4. Life Cycle Inventory Databases Development

The Life Cycle Inventory (LCI) is the list of all material and energy flows to and from the environment over the product or service's life cycle, which are quantified with the use of a life cycle database. The Ecoinvent database [46] was used as the LCA database in this dissertation. The recycled content approach was used with the "allocation, cut-off by classification" system model for attributional LCA. Where possible, the life cycle inventories for transport technologies were built using datasets directly from the Ecoinvent database. Where the environmental burdens of a life cycle phase were significant, and the Ecoinvent datasets were known to be lacking in some way, datasets were created based on literature review using the Ecoinvent database for the modeling of upstream processes. Datasets were specifically created to reflect the manufacturing process in the US, as well as energy production and operations reflecting activities in California.

Additionally, three main industry manufactures were contacted and agreed to provide proprietary data to validate/update manufacturing requirements and cost for the following components:

1. Proton Exchange Membrane (PEM) Electrolyzer from Proton-on-site
2. PEM Fuel cells from Ballard
3. Hydrogen refueling infrastructure from Air Products

The information was provided under strict confidential agreements and should not be used nor published without the proper authorization. Therefore, some information in the following sections will be redacted. [47]

### 4.1. Life Cycle Inventory for Electrolyzers

Data provided by Proton-on-site contain the list of materials for their M400 proton exchange membrane (PEM) electrolyzer, a 200 MW unit [48], [49]. Based on the information provided by the manufacturer, the list of materials and electrolyzer configuration were updated to create a dataset in combination with the Ecoinvent database for the modeling of upstream processes. The Cell Pack, Hydrogen dryer & deoxidizer unit (HGMS) and Water purifier & feed water tank (WOMS) are the main components specific for a PEM electrolyzer. The list of materials for the additional components from the electrolyzer was leveraged from Simons, Andrew & Bauer, Christian [47]. Table 2 describes the component for the electrolyzer unit, and Table 3 shows the list of materials for three main modules.

***Table 2*** ***Components for one PEM electrolyzer by Proton-on-Site***

| **Component name** | | |
|---|---|---|
| Electrolyzer cell package | 1 | unit |
| Hydrogen dryer and deoxidizer unit (HGMS) | 1 | unit |
| Water purifier and feed water tank (WOMS) | 1 | unit |
| Pumps for electrolyzer | 1 | unit |
| Transformer and rectifier unit, for electrolyzer | 1 | unit |
| Control panel, for electrolyzer | 1 | unit |
| Water purifier and feed water tank, for electrolyzer | 1 | unit |
| Heat exchange module, in the electrolyzer | 1 | unit |
| Tubing and cables, for electrolyzer | 1 | unit |

***Table 3 Material list for electrolyzer cell pack, HGMS, and WOMS modules***

| **Material name** | **Mass (kg)** | **% of the total** | **kg/kW of system** |
|---|---|---|---|
| Stainless steel | [redacted] | [redacted] | [redacted] |
| Carbon steel | [redacted] | [redacted] | [redacted] |
| Aluminum | [redacted] | [redacted] | [redacted] |
| Copper | [redacted] | [redacted] | [redacted] |
| Titanium | [redacted] | [redacted] | [redacted] |
| Polyetherimide | [redacted] | [redacted] | [redacted] |
| Ethylene tetrafluoroethylene | [redacted] | [redacted] | [redacted] |
| Perfluoro sulfonic acid | [redacted] | [redacted] | [redacted] |
| Carbon | [redacted] | [redacted] | [redacted] |
| Styrene | [redacted] | [redacted] | [redacted] |
| Iridium | [redacted] | [redacted] | [redacted] |
| Platinum | [redacted] | [redacted] | [redacted] |
| Nickel | [redacted] | [redacted] | [redacted] |
| Rubber and Fluoropolymer elastomer | [redacted] | [redacted] | [redacted] |
| Silicon | [redacted] | [redacted] | [redacted] |

*Source: Proton-on-Site (confidential)*

### 4.2. Life Cycle Inventory for Fuel Cells

Ballard Power was contacted to obtain proprietary data for their proton exchange membrane (PEM) fuel cell units. Based on the information provided by the manufacturer, the list of materials and configuration were updated to create the fuel cell dataset in combination with the Ecoinvent database for the modeling of upstream processes. The operational specifications for the HD-6 fuel cell module provided by Ballard are presented in Table 4.

***Table 4 Ballard PEM fuel cell operation and cost specifications***

| Description | Unit |
|---|---|
| Product Lifetime | [redacted] hours |
| Preventative and Corrective Maintenance Cost | [redacted] per km |
| Product Cost (Price of Stack and System) | [redacted] $/kW |
| Stack Refurbishment Cost (At End of Stack Lifetime) | [redacted] $/kW |
| Platinum Content | [redacted] $mg/cm^2$ |
| Platinum Content (Kg/Kw) | [redacted] kg/kW |
| Hd-6 Module Power Density | [redacted] $kW/m^3$ |

*Source: Ballard Power (confidential)*

The provided information by the manufacturers was incorporated into the life cycle inventory of PEM fuel cells from Ecoinvent, with the exception of the Platinum content. The platinum load was assigned was 0.0002 kg/kW, as reported in recent publications [50]–[52],[53].

### 4.3. LCI for Batteries

The life cycle inventory developed for batteries focused on lithium-ion technology. Depending on the end application and capacity, a variety of lithium-ion chemistries are being commercialized. Table 5 shows different battery chemistry types with their energy densities and existing applications.

*Table 5* ***Lithium-ion battery chemistry characteristics and applications*** [54]

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

Because of the long-life span and high specific energy, three types of batteries (LFP, LTO, and NMC) are being developed in the application of medium- and heavy-duty vehicles. LFP batteries use graphite as the anode and $LiFePO_4$ as the cathode. The electrolyte is a lithium salt in an organic solvent. Also, the use of phosphate as a positive electrode significantly reduces the potential for thermal runaway [54].

Since LFP has higher discharge current and requires smaller battery size to achieve a given performance target, in addition to a superior thermal and chemical stability, this was the chemistry selected to model the performance of BEBs in this research work.

According to energy storage related patent activity from 1999 through 2008, LFP technology has been the focus of at least twice as much as LTO technology, and four times as much as NMC technology [55]. This battery technology is used in the Transpower battery electric vehicle (BEV) drayage truck, electric school bus demonstrations, and by BYD buses.

The LFP battery configuration used by the twenty BYD buses that arrived at UCI in 2018 is used to define the parameters of the battery in the model. Table 6 shows the battery specifications for the BYD buses at UCI. However, a dynamic function was defined in Python to scale the battery capacity, power, and current to any battery size using the BYD's bus specifications as points to generate the function in combination with bus specifications of other manufacturers (Table 7). The disaggregation of the operational parameter for the battery allows us to explore different bus configurations and sizes without relying on specifications unique to individual manufacturers.

*Table 6 BYD battery specifications for buses at UCI*

| Bus specifications | Units | |
|---|---|---|
| Number of cells per battery system | 384 | |
| Number of modules per battery system | 2 | |
| Number of packs per battery system | 2 | |
| Battery system total energy storage | 324 | kWh |
| Battery power | 300 | kW |
| Nominal battery system voltage (OCV[3] at 50% SOC[4]) | 550 | V |
| Battery capacity | 103680 | Ah |
| Maximum current at full power | 250 | A |
| Recommended State of Charge (SOC) defined by BYD | 20% | |
| Battery specific energy | 134 | kWh/kg |
| Battery configuration (2 packs in parallel, 192 cells in series in a pack) | 270 | Ah cell |
| Battery system voltage | 600 | V |
| Battery capacity | 324 | kWh |

[3] Open Circuit Voltage (OCV)
[4] State of Charge (SOC)

***Table 7 Battery electric bus specifications from various manufacturers***

| | Model | Length (ft) | Battery size (kWh) | Max Power (kW) | Range (miles) | Top Speed (mph) | Battery Chemistry |
|---|---|---|---|---|---|---|---|
| BYD | K9M | 40 | 324 | 300 | 155 | 65 | - |
| Proterra [56] | XR | 40 | 220 | 380 | 153 | 65 | - |
| Proterra [56] | E2 | 40 | 440 | 380 | 270 | 65 | - |
| GreenPower [57] | EV350 | 40 | 320 | 300 | 185 | 60 | $LiFePO_4$ |
| New Flyer [58] | Xcelsior Charge 40 | 40 | 545 | 380 | 260 | - | LiNiMnCb |
| New Flyer [58] | Xcelsior Charge 41 | 40 | 480 | 380 | 234 | - | - |
| New Flyer [58] | Xcelsior Charge 42 | 40 | 200 | 380 | 87 | - | - |
| Nova [59] | LFSE | 40 | - | 230 | - | - | $LiFePO_2$ |

The function in Python uses a correlation between the battery sizes to estimate the range of the specified bus size in the model. Figure 8 shows the correlation.

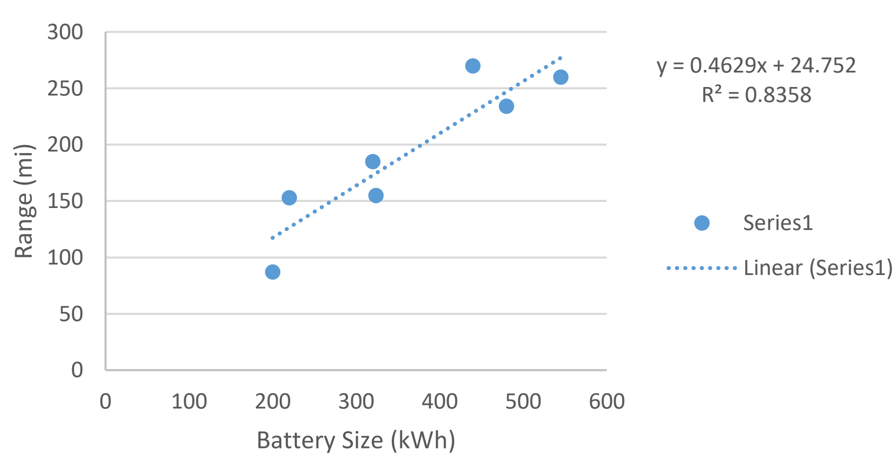



***Figure 8 Correlation between battery size in kWh and bus range***

### 4.4. Energy generation libraries for the US Western region and California

The life cycle inventories for the electricity generation and manufacturing activities were adapted to reflect operations in the Western Electricity Coordinating Council (WECC) region. The main data source for this adaptation came from existing inventories in Ecoinvent using the energy mix corresponding to WECC [28]. An additional electricity generation mix was added, the grid electricity mix for California. The California grid mix was built based on information from the Energy Information Administration (EIA) and from the California Energy Commission for the year 2017 [60] [28]. This generation mix was used in the different scenarios for specific fuel generation in the different LCA scenarios, (e.g., electricity to power electrolysis or energy to charge batteries) and the WECC mix was used for any secondary process for the production of the buses or related components.

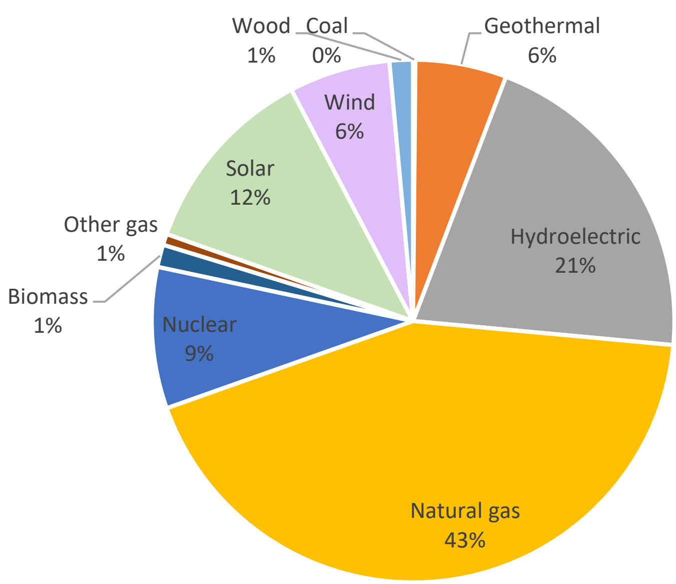



***Figure 9*** ***California Electricity Generation Mix 2017*** [28]

### 4.5. Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) quantifies and groups the environmental burdens due to the LCI into categories associated with known environmental issues. In this dissertation, the ReCiPe 2008 LCIA method was used with the hierarchical perspective [61]. The environmental impact categories most relevant to passenger transport are discussed below.

**Climate Change (CC)** represents the contribution to climate change due to the emission of greenhouse gases such as $CO_2$ and $CH_4$. For this indicator, the most recent global warming potential characterization factors from the IPCC 2013 as implemented by the Ecoinvent Centre were selected [29, 31]. CC was quantified in kg $CO_2$ equivalent.

**Human Toxicity (HT)** represents human exposure to toxic chemicals such as heavy metals and hydrocarbons. HT was quantified in kg 1,4 Dichlorobenzene (DB) equivalent.

**Photochemical Oxidant Formation (POF)** considers the formation of ground-level ozone due to the reaction of $NO_x$ with Non-methane Volatile Organic Compounds (NMVOCs). POF was quantified in kg NMVOC equivalent.

**Particulate Matter Formation (PMF)** considers the human health impacts of fine particles in the air that can enter the lungs. The method takes into account not only the direct emission of particulates, but also the formation of secondary particulates due to emissions such as $SO_x$, $NO_x$, and ammonia ($NH_3$). PMF was quantified in kg PM10 equivalent.

**Mineral Depletion (MD)** represents the impact on society due to the depletion of mineral resources. MD was quantified in units of kg Fe equivalent.

**Cumulative Non-Renewable Energy Demand (CED)** includes all primary energy demand from fossil and nuclear sources. This method was extended to include also renewable energy sources such as solar, wind, and hydro energy. CED was quantified in units of MJ.

### 4.6. Linking Life Cycle Databases with Integrated Assessment Models

One major weakness in performing LCA of future technologies (prospective LCA) is that no background databases are available that represent the current global economy used to produce a foreground system. While prospective LCA studies usually take pains to modify the most important foreground processes (e.g., in the LCA of a future electric bus, the bus efficiency and the electricity grid technology mix used to charge the batteries would be modified for the future), the rest of the system is modeled using the current standard of technology [14, 15, 17, 33, 34]. That is, the future bus is produced using the current electricity system, with current steel production and so on. Some studies, however, have attempted to correct this simplification and include changes to key processes in the background, such as electricity, certain metals, and concrete production [35, 36]. However, the limitation of these studies is that they require significant manual work to create a future database, which makes model updates difficult and changes hard to document. For this reason, the background databases developed in [37] have not been used in future work, and results from the model developed in [38] are still published with the outdated Ecoinvent version 2.2.

The goal of the methodology established here is to create a framework that allows easy, reproducible, and transparent changes to LCA databases based on external data sources. The software is written to enable updating the work for new versions of input data or background databases with minimal effort. Ideally, a single well-accepted source of future technology performance would be used to ensure data consistency. For the scope of this dissertation, it was determined to limit the scope to changes to the global electricity sector. Changes to the electricity sector are relevant as electricity contributes significantly to LCA results for most products, and the electricity sector is expected to change dramatically in the coming decades.

The methodology used to create a modified version of the Ecoinvent database using imported data from a literature review is described in Figure 10. The creation of the modified version of Ecoinvent takes place in five steps as described below.

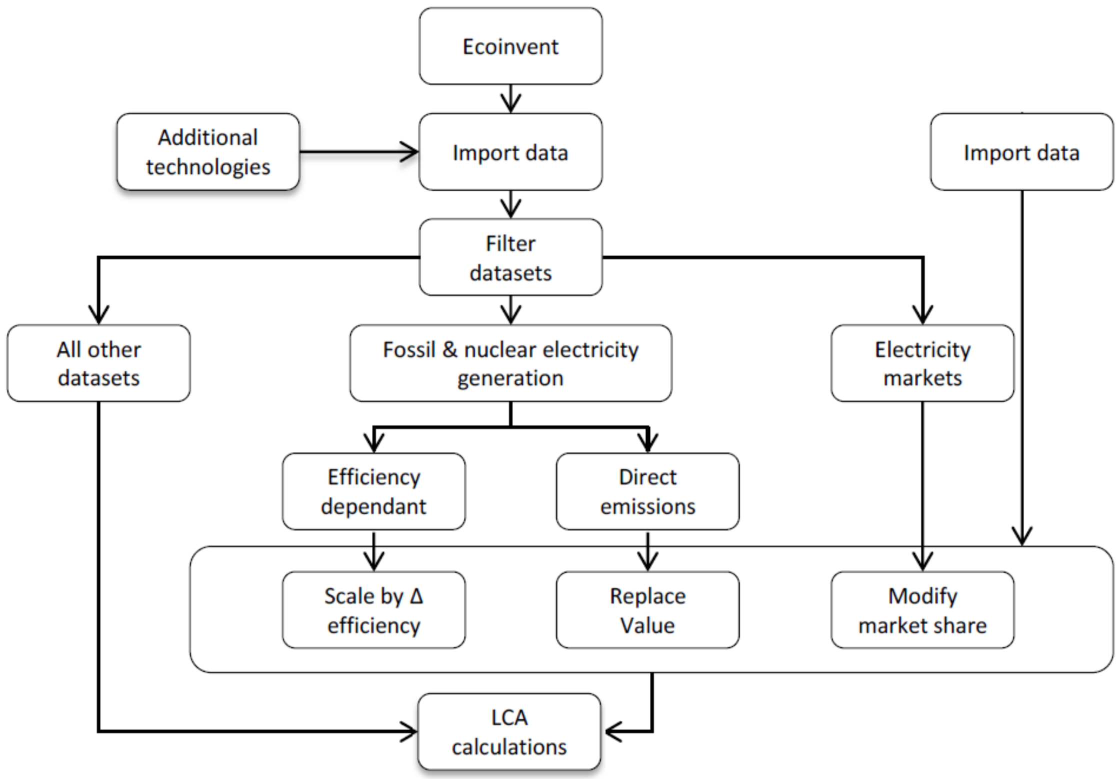



***Figure 10*** ***Schematic of the procedure to modify Ecoinvent using integrated assessment model*** [62]

### Data preparation

In the first step, the allocated Ecoinvent database is imported into a list of single output unit processes that can be modified. Additionally, LCI data for electricity generation with carbon capture and storage from fossil fuels and biomass are imported from Volkart, Bauer [42].

In a parallel step, external data collected from the literature review are imported into the python data analysis library pandas.

### Modifying electricity production datasets

In the next step, electricity generation datasets for all fossil fuels, nuclear and biomass are modified in two ways:

1. Direct emissions of substances such as $NO_x$, $SO_x$, methane, and carbon monoxide are modified directly in Ecoinvent. As no clear relationship between soot and PM emissions could be included, PM emission reductions are included using method 2 described below.
2. All other processes, such as the power plant infrastructure and fuel consumption, are assumed to scale with the changing efficiency of the process. That is, we take the Ecoinvent values as the base, and if the external model results show a 10% efficiency improvement compared to the Ecoinvent value (relative), the value in the Ecoinvent unit process was decreased by 10%.

As the Ecoinvent dataset does not contain explicit assumptions regarding the improved efficiencies of renewable electricity generation technologies, such as wind or solar, these technologies are left unchanged. Capacity factors of all electricity generating technologies are also left unchanged.

### Modifying electricity market datasets

Following this, the average market electricity for each region in Ecoinvent was adapted using WECC and California specific data [29], [63]. First, a list of Ecoinvent unit processes was created for each electricity generation technology. For example, the technology “Coal steam turbine” is matched to two Ecoinvent processes:

- Electricity production, hard coal
- Electricity production, lignite

When matching Ecoinvent datasets to generation technologies, all Ecoinvent datasets have been used that match the generation technology description without judgment of whether that specific technology will be important in the future.

Next, all Ecoinvent high voltage electricity market datasets are modified in turn in the following four steps:

1. All electricity supply exchanges are deleted from the dataset. Exchanges for the transmission grid, transmission losses, supervision, and emissions are not modified.
2. The Ecoinvent location was matched to a region, WECC or California.
3. For each electricity technology to be included in the market, a list of Ecoinvent processes was created. The first choice was to select Ecoinvent processes that match the generation technology and have the same Ecoinvent location as the market dataset. If this was not possible, the second choice was to select all matching technologies in the same region as the market dataset. If more than one technology was matched, the electricity contribution was shared equally between them.

4. The total electricity produced was confirmed to sum to a one-kilowatt hour.

In the last step for electricity market modification, all additional electricity suppliers and electricity imports to medium and low voltage electricity markets are removed, as the simplifying assumption was made that all technologies feed into the high voltage network.

# CHAPTER 5. Cost Inventory Database

For all the bus technologies considered in this dissertation work, the life cycle cost (LCC) was defined as the method to estimate the total cost of ownership. The costs associated with acquiring, operating, maintaining, and disposing of a bus fleet with corresponding refueling infrastructure are organized into the following Table 8.

***Table 8 Life Cycle Cost factors***

| | | |
|---|---|---|
| **Capital Cost** | Bus Purchase | Price for onboard equipment and standard warranty |
| | Fueling Facilities | Cost to build a new fueling station |
| | Staff Training | Not considered in the model |
| | Equipment upgrade | Facility modifications and new tools to service new technologies |
| | New spare parts | Not considered in the model |
| **Operation and Maintenance Cost** | Bus Maintenance | Schedule: Parts and labor cost for regular preventive maintenance<br>Non-schedule: Parts and labor for other failures |
| | Fuel Station O&M | Station's operation and maintenance cost |
| | Fuel Use and Cost | Fuel price was set based on historical data and adjusted due to inflation for 12 years of operation.<br>Fuel economy was calculated based on the methodology that is described in CHAPTER 6.<br>Other operational costs are neglected, like driver's cost, since it will be the same for all technologies |
| | Rehabilitation/ Replacement | Cost of replacement with new or rebuild according to mandated overhauls by the Federal Transit Agency (FTA) or due to technology lifetime |
| | Residual Values | Not considered in model |

Only those costs within each category that are relevant to the decision and significant in amount are considered in the life cycle cost analysis. Costs are relevant when they are different for one alternative compared with another; costs are significant when they are large enough to make a credible difference in the LCC of a bus technology alternative. All costs are entered as base-year amounts in today's dollars; the LCCA method escalates all amounts to their future year of occurrence and discounts them back to the base date to convert them to present values considering 3% inflation [64].

## 5.1. Cost Inventory for Compressed Natural Gas Buses

### 5.1.1. CNG refueling infrastructure

Cost estimations for refueling stations were leveraged from cost reports of stations built for transit agencies that transitioned from diesel to compressed natural gas (CNG), in addition to reports from private consultant firms and research institutions. The following station configurations are what is reflected on the cost estimations.

CNG Station Configuration

A buffer fast-fill station configuration was selected since it is ideal for high fuel use vehicles that require immediate refueling, one after another [65]. Transit buses frequently utilize this configuration due to their need to consecutively refuel and due to overall fuel demand. Buffer systems primarily fuel directly from the compressor into the vehicle, thus requiring less storage. For fast-fill configuration, the demand was set primarily by the hourly flow rate of the compressor(s).

Typical components of a buffer fast-fill CNG system include those for a fast-fill (Figure 11) with the priority panel and sequencing valves replaced by a buffer control panel that routes fuel directly from the compressors to the dispensers using stored fuel only if compressor capacity is exceeded.

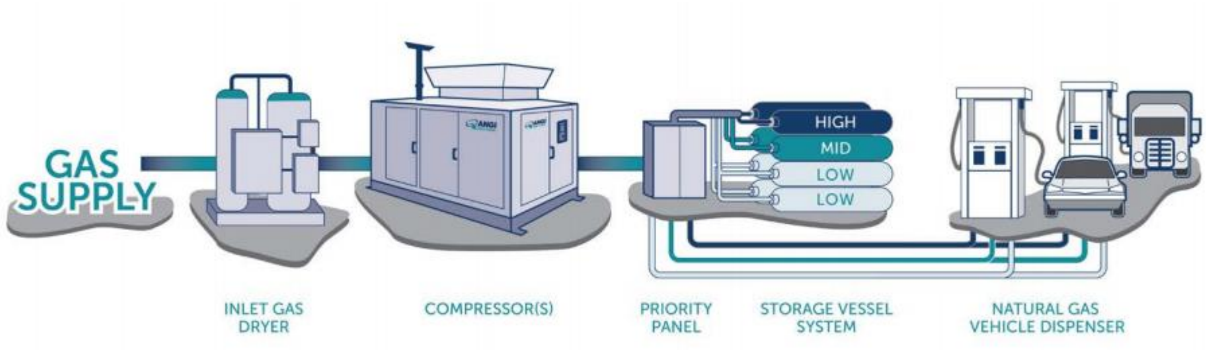



***Figure 11*** ***CNG fast-fill refueling configuration*** [66]

Only the equipment that was identified to drive the total cost of the station according to [67] was considered in the cost calculations; this includes:

- Compressor
- Dispenser
- Storage
- Dryer
- Generator
- Transformer

The price for these components directly depends on the desired capacity, which simultaneously depends on the fuel demand from the transit agency. It was decided to create a dynamic cost model that could provide personalized cost estimations based on the fleet size at each depot of the transit agencies. The first calculation of the cost model is to determine the number of compressors and compressor's capacity based on the filling capacity (FC), also known as flow rate, required at each base. If the filling capacity is not an input for the model, the required number of buses at each base is required, and then the following calculation is considered:

$$\text{FC} = \gamma\ \frac{buses}{base} * \frac{45\ GGE}{bus} * \frac{1}{3\ hr} * \frac{1hr}{60\ min} * \frac{125\ scf}{1\ GGE} = x\ \frac{scfm}{base} \qquad \text{Eq. (1)}$$

Eq. (1) calculates the fill capacity (FC) required at each base, expressed in standard cubic foot per minute (scfm), this capacity directly correlates to the compressor capacity. The following assumptions are considered for Eq. (1):

- The input of buses per depot is presented in the equation as "$\gamma$".
- The average tank capacity for CNG buses is 170 gasoline gallon equivalent (GGE) [67], however, not all buses use the entire mileage range every day. From observations of data provided by OCTA, it was concluded that, on average, at each base, 45 GGE of CNG are filled per bus. Some buses use as much of 95% of its tank capacity, while others are less than 20%; therefore, the 45 GGE/bus represents the average fueling [68].
- Fast filling can be selected in the model for fleets larger than 170 buses/base. It's assumed that a window of 3 hours is the time available to completely refuel the fleet. Even if the fueling window is more than three hours, this number is used as the critical refueling window to calculate the minimum compressor capacity [68].

- Conversion factor: one GGE of CNG is equivalent to 125 standard cubic foot (scf) [69].

The calculated fill capacity (FC) is then used to determine the number of compressors required per depot Eq. (2).

$$n = \frac{FC}{\varepsilon} \qquad \text{Eq. (2)}$$

If $\gamma$ > 170 buses → $\varepsilon$ = 2,000 scfm; Eq. (3)

where

$n$ = number of compressors

$x$ = depot fill capacity (flow rate) in scfm/depot

$\varepsilon$ = compressor capacity in scfm

$\gamma$ = number of buses per depot

The compressor capacity has been set as a depending variable of the number of buses per depot. It also depends on the fueling method; in this case, it's specific for fast filling. In Eq. (3) constraints for the compressor capacity is stablished, and the assumptions are based on compressors installed in real depots [70], [71].

<u>Cost of CNG refueling station</u>

The cost of compressors drives the station cost, and it correlates with the number of dispensers, another primary cost factor. Eq. (4) describes how for the fast filling station, the number of compressors is equal to the number of one-hose dispensers ($\delta$). If the number of hose/dispenser ratio increases, then the filling time would increase, and the three-hour filling window would no longer be part of the configuration assumptions.

$$n = \delta \qquad \text{Eq. (4)}$$

Installation cost is the third main factor that drives the total cost of the refueling station. Since the installation cost can vary depending on bidding and from contractor to contractor, estimations from consulting reports were used. It's assumed that 65% of the total cost of equipment is equal to the cost of installation [72].

A comprehensive literature review was completed to compare the cost and specifications of equipment required at a CNG fueling station. Table 9 presents the compilation of equipment and a range of cost found in the literature.

***Table 9*** ***Compilation of equipment cost used at CNG fueling stations***

| | **Flow Rate (scfm)** | | **Price ($)** | | **Source** |
|---|---|---|---|---|---|
| **Equipment** | **Low** | **High** | **Low** | **High** | |
| Backup Power Generator | | | $ 150,000 | $ 250,000 | [72], [73] |
| Compressors | 1 | 650 | $ 4,000 | $ 550,000 | |
| | 1 | 8 | $ 4,000 | $ 22,000 | |
| | 20 | 40 | $ 5,000 | $ 90,000 | |
| | 50 | 75 | $ 80,000 | $ 150,000 | |
| | 100 | 150 | $ 100,000 | $ 250,000 | |
| | 250 | 650 | $ 200,000 | $ 550,000 | |
| | 1700 | 2000 | $ 500,000 | $ 600,000 | [44], [66], [71] |
| Dispenser fast fill | | | $ 25,000 | $ 60,000 | [72] |
| Dual-hose time-fill post | | | $ 4,000 | $ 7,000 | [67], [72] |
| Storage tank | | | $ 70,000 | $ 130,000 | |
| Card Reader | | | $ 10,000 | $ 30,000 | |
| Gas Dryer | | | $ 10,000 | $ 300,000 | |

Using the values from Table 9 and reports from transit agencies that transitioned from diesel to CNG [71], [74] the following equations were formulated to estimate the cost of equipment, and ultimately, the total cost of investment for a CNG fueling station. It is important to note that all the values for Table 9 were dated before 2012. Therefore, an adjustment for the future value considering inflation was applied [75].

Total cost of CNG compressors:

$$C_{CNGcompr} = n * \$700{,}000 \quad \text{Eq. (5)}$$

Total cost of one-house dispensers in the station:

$$C_{CNGdisp} = \delta * \$70{,}000 \quad \text{Eq. (6)}$$

Cost of backup generator[5]:

$$\text{if } \varepsilon = 2{,}000 \text{ scfm} \rightarrow C_{CNGgen} = \frac{n}{3} * \$200{,}000 \quad \text{Eq. (7)}$$

Cost of storage:

$$C_{CNGstore} = \$550{,}000 \quad \text{Eq. (8)}$$

Cost of gas dryer:

$$\text{if } \varepsilon * n > 6{,}000 \text{ scfm} \rightarrow C_{CNGdryer} = \frac{\varepsilon * \mathrm{n}}{6{,}000} \$80{,}000 \quad \text{Eq. (9)}$$

$\varepsilon$ = compressor capacity in scfm
$n$ = number of compressors

[5] 1,500 kW Ultra-low sulfur diesel generator [123].

The total cost of a CNG filling station was calculated with Eq. (10), where the cost of equipment and installation is included by a factor of 65% of the total cost of equipment [72]. Eq. ( 11) includes the numerical values for each of the factors that contribute to the cost of the CNG station.

$$C_{CNGstation} = [C_{CNGcompr} + C_{CNGdis} + C_{CNGgen} + C_{CNGstore} + C_{CNGdryer} + C_{CNGtransforme}] * 1.65 \quad \text{Eq. (10)}$$

$$C_{CNGstation} = [n * \$616{,}500 + \delta * \$60{,}000 + \$130{,}000 + \$300{,}000 + \$550{,}000 + \$80{,}000] * 1.65 \quad \text{Eq. ( 11)}$$

Maintenance and operation cost for CNG filling station

The estimated annual maintenance and operation (M&O) costs used in the model are 5% of the upfront cost of a large station and 8% of the upfront costs of a small station. This assumption, provided by Rob Adams of Marathon Technical Services [76], was selected because the value averages the M&O estimates received from other sources. The estimates from other sources vary as a result of contractor's reliance on station-specific circumstances that were not available for these general estimates.

#### 5.1.2. Cost of CNG Bus Maintenance

The total cost of maintenance for CNG, including preventive maintenance and unscheduled repairs, was reported by OCTA to be $0.59 per mile [77]. A similar value was reported by NREL for a combination of CNG buses used at Massachusetts Bay Transportation Authority (MBTA), OCTA, and SunLine (Table 10) [78]. Data for the maintenance cost were collected for CNG buses with year models between 2008 and 2013. For the total cost of ownership simulation, the maintenance cost was modeled as a total cost of $0.57 per mile.

***Table 10*** ***Maintenance cost per mile by system component for CNG buses*** [78]

| System | Cost per Mile ($) |
|---|---|
| Car, body, and accessories | 0.26 |
| Propulsion-related | 0.10 |
| Preventive Maintenance Inspection | 0.07 |
| Brakes | 0.03 |
| Frame, steering, and suspension | 0.04 |
| HVAC | 0.03 |
| Lighting | 0.01 |
| Tires | 0.01 |
| **Total** | **0.54** |

### 5.1.3. CNG Bus Purchase Price

A literature review was conducted to investigate the purchase price of CNG buses offered by different manufacturers (see Table 11). The purchase price by ElDorado was adjusted with an inflation rate of 3.5% and then used to estimate the average price for a CNG bus. The total cost used for the model was set to $650,000 per CNG bus.

*Table 11 CNG bus purchase price by different manufacturers*

| Manufacturer | Unit Price ($) | Source |
|---|---|---|
| ElDorado National 2003 | 205,185.33 | [79] |
| NABI | 575,000.00 | [80] |
| MTA | 683,304.35 | [81] |

### 5.1.4. Price of CNG fuel

The default liquid fuel prices used for this dissertation are national commercial retail averages and come from the U.S. Energy Information Administration (EIA) Gasoline and Diesel Fuel Updates [82]. Fuel prices are reported weekly and provide national and regional retail averages for conventional fuels such as gasoline and diesel.

The price of CNG was calculated based on the 6-month California average price of commercially delivered natural gas [83]. This value was then converted from $/ft$^3$ to $/GGE using EIA conversion factors of 1,023 Btu/ft$^3$ and 124,238 Btu/gasoline gallon resulting in an average cost of $1.06 per GGE of CNG.

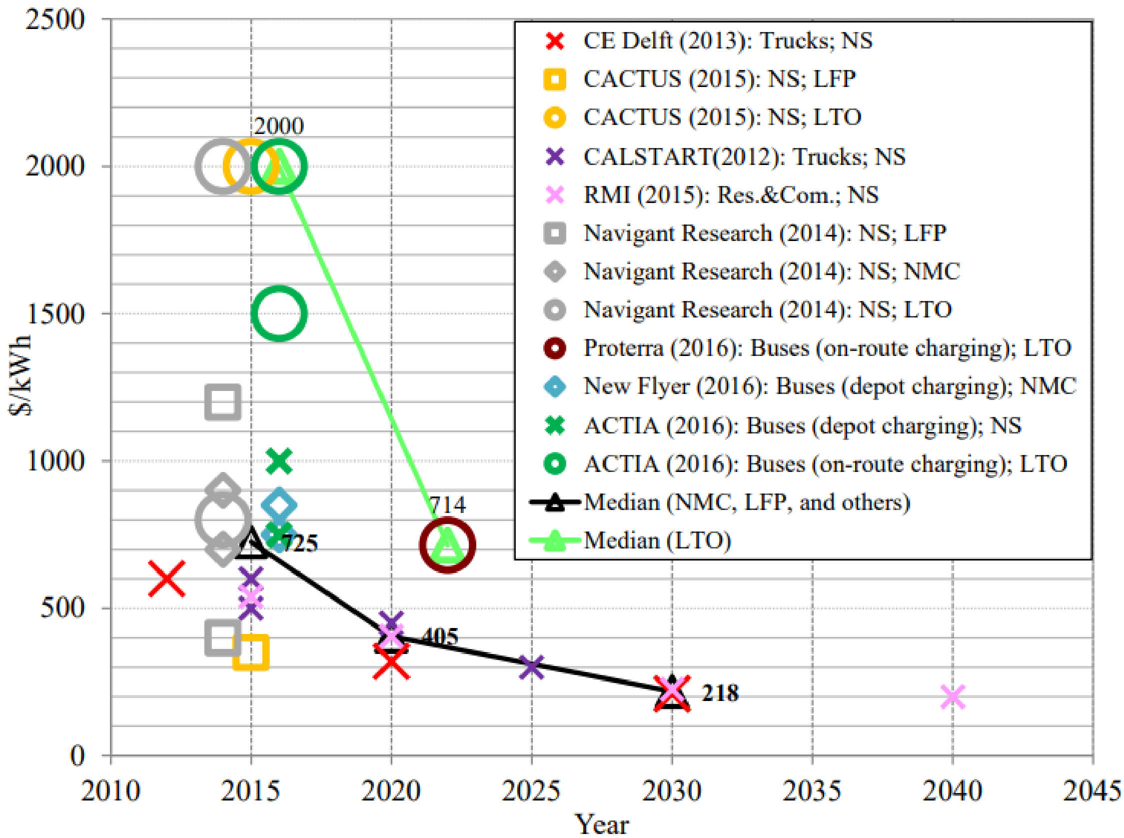
The price of CNG was validated with data collected at Foothill. During 2018, Foothill Transit paid an average of $0.90/GGE for CNG ($0.93/DGE) [84].

## 5.2. Cost Inventory for Battery Electric Buses

### 5.2.1. Cost of Batteries

The Electric Power Research Institute (EPRI) has identified three key cost dependencies: cell size, cell production volume, and standardization of battery components. Studies from Argonne National Laboratory (ANL) noted that estimates of battery costs vary with power to energy (P/E) ratio, production sale, and thermal management systems. To accurately model the cost of batteries, detailed information was required regarding these cost driving factors. Much of the information available concerning cost models of batteries is specific to light-duty batteries and although some batteries used for heavy-duty electric vehicles share similar chemistry as light-duty ones, battery pack costs per kWh for heavy-duty battery electric vehicles (BEVs) are currently higher, mainly because of different packaging, thermal management systems, and lower purchase volumes [85].

It is currently challenging to estimate battery cost for heavy-duty BEVs due to the following three reasons: (1) battery costs vary widely with chemistry, yet most estimates are for all types of lithium-ion batteries lumped into one group; (2) most published estimates are applicable for light-duty BEVs and not for heavy-duty vehicle applications; and (3) a lack of information about explicit relationships between production volume and battery cost for heavy-duty vehicle applications [85]. However, the estimated costs from various studies can be used as a reference to model the battery costs as a function of capacity. A California Air Resource Board (CARB) report [54] contained the most relevant and well-summarized data. Battery cost ranges from different literature sources, evaluated for the report, included studies such as CE Delft (2013), CACTUS (2015), CALSTART (2012), Rocky Mountain Institute (RMI) (2015), Navigant Research (2014), and cost estimates from original equipment manufacturers (OEMs) as summarized in Figure 12.




Sources: CE Delft, 2013; CACTUS, 2015; CALSTART, 2012; RMI, 2015; Navigant Research, 2014; Proterra, 2016; New Flyer, 2016; ACTIA, 2016

***Figure 12*** ***Battery Cost Estimates and Projections from Different Sources*** [54]

Since a disaggregated cost model of the batteries was not possible, the cost was instead designated based on levelized average costs of batteries with the same chemistry and with calculated future values for the year 2018. As described in Section 4.3, lithium iron phosphate (LFP) was selected as the default for the chemistry of the batteries in the model. The calculated cost of this battery was set to $700 per KWh.

#### 5.2.2. Battery Electric Bus Purchase Cost

Ideally, the purchase price for zero-emission buses should be desegregated to have the price per component so that the price of different bus sizes and configurations can be accurately estimated. However, little to no data have been made available by bus manufacturers. Instead, a literature review was conducted to investigate the purchase price of plug-in (versus route-charging) BEBs offered by different manufacturers (see Table 12).

***Table 12 Purchase prices of 40-foot long plug-in BEBs by different manufacturers***

| Manufacturer | Unit Price ($) | Source |
|---|---|---|
| BYD | $ 529,400 | [86] |
| BYD for UCI | $ 824,262 | |
| Proterra | $ 825,000 | [80] |
| | $ 789,000 | |
| | $ 904,490 | |
| Green Power | $ 850,000 | [87] |

Even though the size of the buses is the same for all the buses in Table 12, battery and motor configurations vary across manufacturers. To standardize the bus price for the model, the following approach was applied:

- All the unit prices of the buses from Table 12 were converted from the year of publication to the year 2018 using a future value formula with an annual inflation rate of 3.5% [75].
- For each unit price from the different bus manufacturers, the cost of the battery was subtracted. The battery price was determined following the methodology described in the section above. This yields the cost of chassis, motor (including

cooling system), auxiliary components, and any personalized modifications to the bus.

- Cost of personalized modifications was subtracted when details were available.
- An average of the bus price was calculated to obtain the standardized bus price without the cost of the battery.
- The standardized bus price was then added to the model to a function that adds the cost of the battery based on the desired battery capacity, which was set as an input for the model. Eq. (12) describes the function in the model where $C_{Battery}$ is the cost of the battery in $/kWh as described in the previous section.

$$C_{BEB} = C_{standarBus} + B_{capacity} * C_{Battery} \quad \text{Eq. (12)}$$

Following the described calculations, the unit price calculated by the model for a 40-foot BEB with a 320-kWh battery size is of $780,000. This price excludes the financing cost since that factor was calculated in the total cost of ownership calculations at a 3.44% interest rate and a 3.5% inflation rate.

The bus price for BEBs that charge on-route, however, differs in the motor configuration and other auxiliary systems. Therefore, the price for on-route BEBs was calculated using the same calculations described above but using the data presented in Table 13, obtained from the literature review.

*Table 13 Purchase price of on-route charging BEBs*

| OEM - Operator | Bus Cost | Source |
|---|---|---|
| BYD - AVTA | $ 770,000.00 | [86] |
| Proterra - King county | $ 797,882.00 | [80] |
| Proterra - Foothill | $ 789,000.00 | [80] |

### 5.2.3. Cost of Charging Infrastructure

Modeling the cost of charging infrastructure becomes complex since the level of electric modifications necessary to install equipment can widely vary depending on the depot location and current equipment. Additionally, the different arrangements with the utility company and equipment manufacturer have proven to drastically affect the investment cost.

The conducted literature review regarding the cost of charging infrastructure of different demonstration projects presents combined installation costs without making distinctions between the cost of labor or electric equipment - such as transformers, generators, etc. Furthermore, the data collection shows a lack of reporting on the cost of chargers for operators since often the purchase contract combines the cost of vehicle and cost of chargers.

The twenty plug-in buses delivered to UCI had a well-documented deployment process and data collected during the period of this dissertation and were used as a reference point to average cost values found in the literature. According to reports from UCI Anteater Express, the installation of twenty chargers with individual connector, including connection to the UCI micro-grid and preparation of the lot, cost $1.52 million. However, specific details of the construction process and installed equipment remain confidential for safety reasons.

An average cost per charger was estimated based on literature data presented in Table 14 and Table 15, and it was levelized using information from Anteater Express. For plug-in or depot chargers, the cost of equipment was set to $40,000 for one connector charger with installation costs of $70,000 per bus. For on-route chargers, the equipment cost was set to $500,000 per charger with $250,000 for installation per charger (dual charger).

***Table 14    Cost of depot charging BEBs and charging infrastructure***

| **OEM - Operator** | **Bus Unit Price** | **Equipment Cost per Depot Charger** | **Installation Cost per Depot Charger** |
|---|---|---|---|
| BYD - AVTA | $ 770,000 | $ 19,000 | $ 55,000 |
| BYD - UCI | $ 784,262 | $ 40,000 | $ 76,500 |
| Proterra - King county | $ 797,882 | $ 60,000 | --- |
| Center for Transportation and the Environment (CTE) | $ 887,308 | $ 50,000 | $ 17,050 |

***Table 15    Cost of on-route charging BEBs and charging infrastructure***

| **OEM - Operator** | **Bus Unit Price** | **Equipment Cost per on-route Charger** | **Installation Cost per on-route Charger** |
|---|---|---|---|
| BYD - AVTA | $ 770,000 | $ 350,000 | $ 250,000 |
| Proterra - King county | $ 797,882 | $ 600,000 | $ 241,510 |
| Proterra - Foothill | $ 789,000 | $ 500,000 | $ 200,000 |
| Center for Transportation and the Environment (CTE) | $ 887,308 | $ 495,636 | $ 202,811 |

### 5.2.4. Maintenance Cost of BEBs

The total cost of maintenance for BEB was reported by CTE to be $0.64 per mile [88]; this includes scheduled and unscheduled repairs. A similar value was reported by NREL for the BEB deployed at Foothill [80]. Data for the maintenance cost were collected for BEBs that started service since 2014. Table 16 presents the maintenance cost by system type, but for the total cost of ownership simulation, the maintenance cost was modeled as a total cost of $0.60 per mile.

***Table 16*** ***Maintenance cost per mile by system component in battery electric buses*** [80]

| System | Cost per Mile ($) |
|---|---|
| Cab, body, and accessories | 0.109 |
| Propulsion-related | 0.199 |
| Preventive Maintenance Inspection | 0.085 |
| Brakes | 0.002 |
| Frame, steering, and suspension | 0.022 |
| HVAC | 0.010 |
| Lighting | 0.013 |
| Axles, wheels, and drive shaft | 0.000 |
| Air, general | 0.156 |
| Tires | 0.0.18 |
| **Total** | **0.610** |

In Table 16 the propulsion-related repairs for the BEBs include low-voltage batteries, battery equalizer, cooling system, DC-DC converter.

#### 5.2.5. Electricity Prices

Through collaboration with Anteater Express, it was possible to obtain the electricity invoice of their depot. The electric bill reflects the operations, demand chargers, and corresponding rate. The electric bill was obtained for the summer and winter months of 2018, reflecting the different rates throughout the year. An average of the year 2018 was used to calculate the average electricity price, which resulted in an average of $0.14 per kWh. However, it’s important to note that the Anteater Express charging lot is connected not to a utility company, but rather to the UCI microgrid with an associated rate structure unique from the local utility.

Since transit agencies will be subject to prices of electricity based on different tiers from utilities as well as different electricity rates for summer and winter months, it was necessary to consider such factors in the fuel price estimations. One of the best-documented pilot projects for BEBs is the case of Foothill. The electricity rates have been recorded by NREL since early 2014, but a recent change in rate structure (from TOU-GS-1-A to TOU-EV-4) provides the most relevant information from 2016 to 2018 [84], [89].

Figure 13 shows the monthly electricity cost at Foothill Transit agency under tier TOU-EV-4. Transit pays different electricity rates for the summer and winter months. During the reporting period for Foothill, the average price was $0.16 per kWh for the winter months (October–May) and $0.21 per kWh for the summer months (June–September). The average rate under TOU-EV-4 rate structure is $0.18/kWh, and this was the assumed value for the total cost of ownership simulation [84], [89]. The assumption was that no demand chargers are applied due to charge management strategies and was assumed that the monthly demand is between 20 kW and 500 kW.

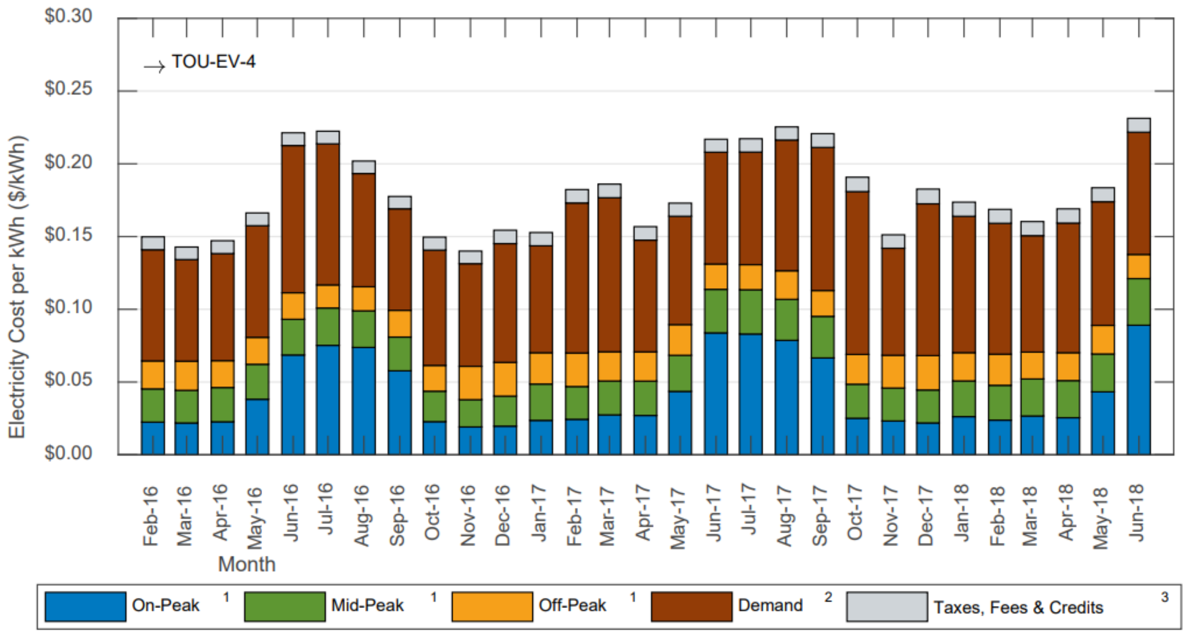



***Figure 13 Monthly Electric Utility Cost at Foothill Transit Agency to Charge BEBs*** [84]

It is anticipated that different cities across southern California will be subject to different electricity rates depending on the operating utility company. Figure 14 presents the electricity cost estimations for different utility companies. Southern California Edison (SCE) customers, that were served on Schedule TOU-EV-4 were transferred to Schedule TOU-EV-8 [90] starting March 1, 2019. The cost model has an internal library with a different electricity rate so that the user can select the electricity price based on the area of service, but for this research work, an average electricity price of $0.18 per kWh was selected as the default input for on-route charging which uses on-demand charges in its majority.

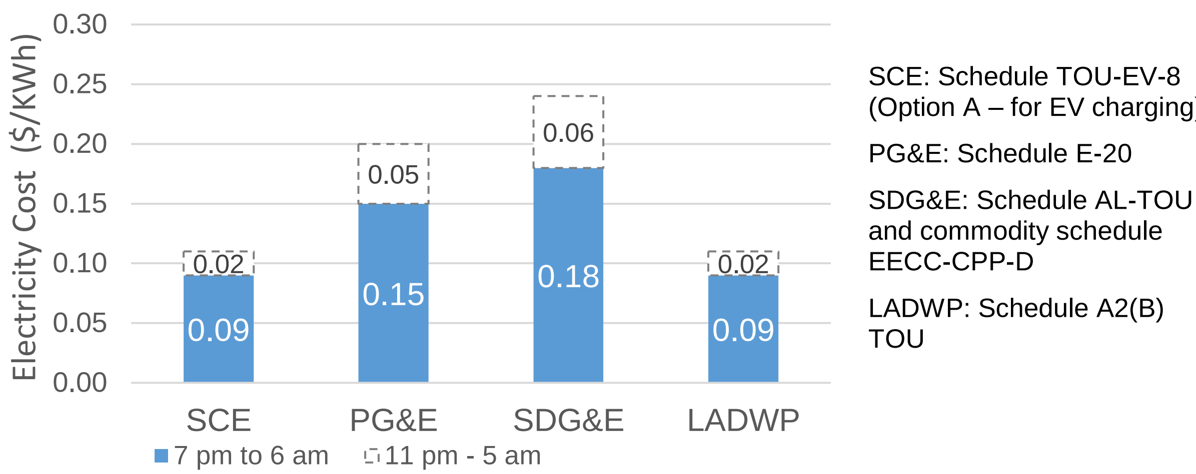



***Figure 14 Charging Electricity Cost for Different Utility Companies*** [88]

#### 5.2.6. Overhaul cost for Battery Electric Buses

The main component that was anticipated to require a mid-life overhaul is the battery pack. For both plug-in and on-route charging BEBs, the cost of battery replacement was set to $700 per kWh.

### 5.3. Cost Inventory for Fuel Cell Electric Buses

#### 5.3.1. Fuel Cell Bus Purchase Price

Anteater Express received its fuel cell electric bus (FCEB) in 2014. At the time, the bus was valued at approximately $1.8 million. Since then, the bus prices have dropped to $1.34 million as reported by New Flyer [91]. Similar to the calculation of the purchase price of BEBs, it would be ideal to have a cost breakdown for the major components of the FCEBs. However, the lack of published data does not make this task possible. The trend in the price drop, in combination with price pledges made by Proterra [56], were used to estimate a purchase price of $1 million for a standard 40-foot long FCEB.

### 5.3.2. Maintenance Cost of FCEBs

The total cost of maintenance for the FCEB was reported by UCI to be $0.64 per mile [88]; this includes scheduled and unscheduled repairs. A similar value was reported by NREL for the 2018 Current Status report of FECBs [78]. Data for the maintenance cost were collected for FCEBs that started service since 2012. Table 17 presents the maintenance cost by system type, but for the total cost of ownership simulation, the maintenance cost was model as a total cost of $0.48 per mile.

***Table 17*** ***Maintenance cost per mile by system in FCEBs*** [78]

| **System** | **FCEB $/mile** |
|---|---|
| Propulsion Related | 0.09 |
| Car, body, and accessories | 0.21 |
| Preventive Maintenance Inspection | 0.09 |
| Brakes | 0.02 |
| Frame, steering, and suspension | 0.04 |
| HVAC | 0.02 |
| Lighting | 0.00 |
| General air system repairs | 0.00 |
| Axles, wheels, and drive shaft | 0.01 |
| **Total** | 0.48 |

### 5.3.3. Hydrogen Refueling Infrastructure

The cost of hydrogen refueling stations will vary largely depending on the hydrogen generation path and installed capacity. The challenge of estimating the infrastructure cost for hydrogen relies on how to scale the costs. Data collection from literature reviews (showed in Table 18) resulted in a max reported-capacity of 350 kg/day while projections for a large transit agency show that it would require at least 4,000 kg/day per depot [92].

***Table 18*** ***Cost of hydrogen refueling stations*** [93]

| Station Type | Installation Year | Cost per Capacity ($/kg/day) | Capacity (kg/day) | Capital Cost ($) |
|---|---|---|---|---|
| *GH2 Truck Delivery* | 2012 | 10,000 | 100 | 1,000,000 |
| | | 6,000 | 250 | 1,500,000 |
| | 2013 | 10,210 | 180 | 1,837,800 |
| | | 12,533 | 180 | 2,255,940 |
| | 2014 | 9,000 | 100 | 900,000 |
| | | 5,600 | 150 | 840,000 |
| | | 12,702 | 180 | 2,286,360 |
| | | 8,000 | 350 | 2,800,000 |
| | 2015 | 5,000 | 100 | 500,000 |
| | | 3,600 | 250 | 900,000 |
| | | 3,750 | 400 | 1,500,000 |
| *LH2 Truck Delivery* | 2013 | 10,889 | 240 | 2,613,360 |
| | | 8,326 | 240 | 1,998,240 |
| | 2014 | 11,111 | 180 | 2,000,000 |
| | | 12,170 | 200 | 2,434,000 |
| | | 7,209 | 350 | 2,523,150 |
| *On-site electrolyzer* | 2010 | 21,240 | 100 | 2,124,000 |
| | 2014 | 43,956 | 105 | 4,615,380 |
| | | 19,801 | 105 | 2,079,105 |
| | | 26667 | 120 | 3,200,000 |

The $H_2$CAT cost model [92] provides a cost analysis to inform the decision-making process by adding information about the economic delivery pathway and estimations about the total cost of hydrogen. This section contains a brief description of the methodology used for this module and how it was adapted for the life cycle cost modeling.

Figure 15 describes what was considered in the cost analysis, and it shows that designed to only evaluate the capital cost and price per kilogram variation of four distribution pathways:

- Liquid Truck
- Gas Truck
- Pipeline
- Distributed generation

For distribution from a centralized location, the module assumes a levelized production cost of hydrogen of $3.42 per kilogram. This assumption was made considering centralized SMR units with natural gas as the feedstock, and it was obtained using the H2A Production Analysis Tool from the Department of Energy [94].

The price of feedstock cost per truck and additional cost assumptions regarding the station and dispensing were adjusted based on literature review and data from other transit agencies with current hydrogen buses demonstrations. Table 19 presents these assumptions and the correspondent reference.

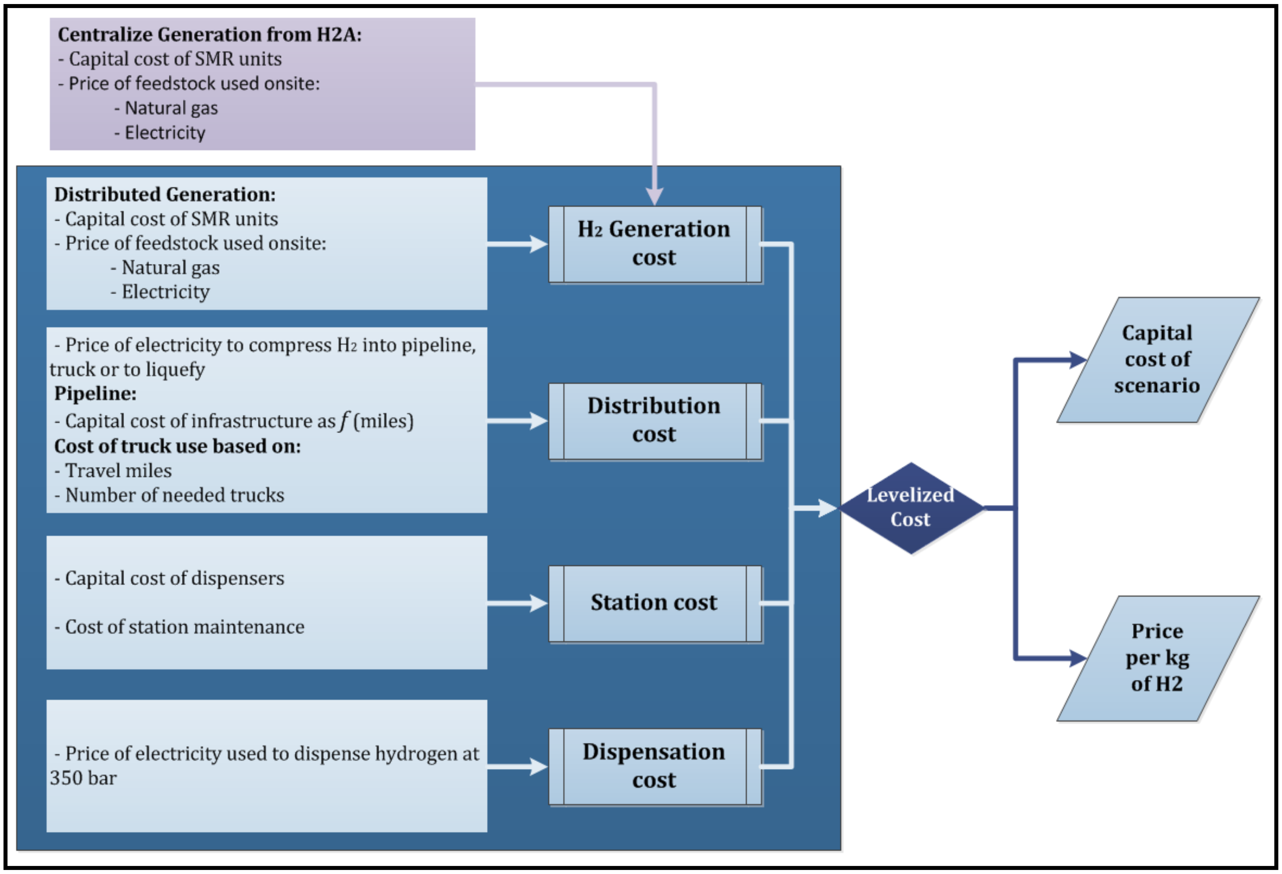



***Figure 15*** ***Considerations of $H_2$CAT Cost-Analysis module*** [92]

*Table 19 Variables for hydrogen stations and distribution pathways*

| Detail | | Units | Reference |
|---|---|---|---|
| Cost of electricity | 0.118 | \$/kWh | [95] |
| Well-to-product cost of Hydrogen | 3.42 | \$/kg of $H_2$ | [94] |
| **Liquid Hydrogen** | | | |
| Liquid truck capacity | 4,500 | kg of $H_2$/truck | [96] |
| Cost of liquefaction equipment | 1.03 | \$/kg of $H_2$ | [61] |
| Cost of travel | 4 | \$/mile traveled per truck | [96] |
| Electricity requirement for liquefaction | 8.27 | kWh/kg of $H_2$ | [97] |
| Gaseous Hydrogen | | | |
| Electricity req. to compress into truck | 2.5 | kWh/kg of $H_2$ | [96] |
| Gas truck capacity | 650 | kg of $H_2$/truck | [94], [96] |
| Cost of travel | 4 | \$/mile traveled per truck | [96] |
| **Pipeline** | | | |
| Capital cost of infrastructure | 358,507 | \$/mi | [94], [96] |
| Electricity req. to compress into pipeline | 0.50 | kWh/kg of $H_2$ | [20], [98] |
| **Distributed generated Hydrogen** | | | |
| Capital Cost of SMR units | 2,862,300 | \$/unit | [96], [99] |
| Storage capacity | 3,000 | kg of $H_2$ | [100] |
| Natural gas req. | 0.172 | MMBTU/kg of $H_2$ | [101] |
| Cost of natural gas | 7.5 | \$/MMBTU | [96] |
| Electricity req. for storage | 2.27 | kWh/kg of $H_2$ | [20] |
| **Dispensing details** | | | |
| Electricity req. for dispensing at 350bar | 3.03 | kWh/kg of $H_2$ | [20], [98] |
| **Station details** | | | |
| Maintenance cost | 142,000 | \$/year | [102] |

**Capital Cost**

Eq. ( 13) is a regression equation designed to adjust the capital cost of light-duty vehicle hydrogen stations to the predicted cost for large fleet stations. The data used to derive this equation were obtained from several reports of station cost, cost of bus stations from demonstration projects, and H2A delivery [94], [96]–[99], [103]. The capital costs that this equation considers include storage, compressors, dispensers, and investment in infrastructure to comply with safety requirements. The required inputs for the model are:

- Travel miles for trucks
- Travel length of pipeline
- Well-to-product cost of hydrogen can be adjusted
- Number of hydrogen fuel cell buses

$$CC_{Hstation} = 101{,}849 * (kg/day)^{0.5516} + (Number\ of\ Dispensers) * 26{,}880$$

Eq. ( 13)

**Price per Kilogram of hydrogen**

With the levelized capital cost with the defined variables from Table 19 and the above inputs, the tool can calculate the levelized capital cost based on the present value of the capital cost for a period of 12 years with an 8% debt rate (Table 20). The cost, in addition to other fixed costs and variant costs presented in Table 21 are used to calculate the breakeven for the hydrogen price.

***Table 20 Financial and operational assumptions for levelized hydrogen cost***

| | |
|---|---|
| **Financial assumptions** | |
| 8% | Debt rate |
| 312 | Days in a year |
| 12 | Years to pay back |
| **Operational assumptions** | |
| 250 | Miles per day for one bus |
| 6.5 | Fuel economy mi/kg |
| **Delivery assumptions** | |
| 35 | Miles travel (one-way) |
| 35 | Miles of pipeline |
| 3.42 | $/kg of $H_2$ well-to-product price |

***Table 21 Fixed and variant cost used for the breakeven cost of hydrogen***

| Fixed Cost | Variant Cost |
|---|---|
| Levelized Capital Cost of the station per year | Cost of transportation per kilogram of hydrogen transported |
| Maintenance cost of $H_2$ station per year | Production of hydrogen (well-to-wheels price) |
| | Cost of electricity for compression into storage and dispensing |

Table 22 shows the prices for electricity, hydrogen, diesel, and CNG calculated from the assumptions described in this section and that are used for the scenarios analyzed in this dissertation work.

*Table 22 Fuel Prices used for life-cycle cost calculations*

| Fuel type | Price |
|---|---|
| Diesel | \$3.80 per gallon |
| CNG | \$1.06 per GGE (\$1.20 per DGE) |
| Electricity | \$0.18 per kWh |
| Hydrogen | $H_2$CAT |

### *Liquid vs. gas delivery trucks*

In the State of California, 33% of the hydrogen dispensed must be sourced from renewable sources. For the purpose of this research, this requirement was assumed to be satisfied by operating the SMR by a combination of natural gas and biogas. Diagrams with the components necessary for liquid truck and gaseous truck delivered are presented in Figure 16 and Figure 17, respectively.

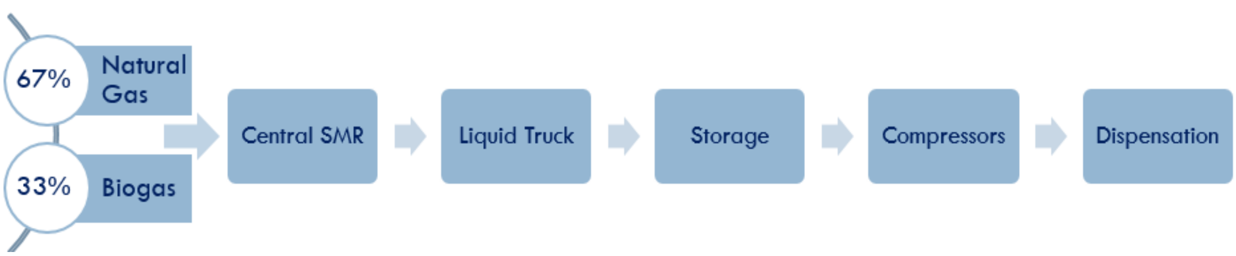



***Figure 16 Components necessary for liquid truck delivery of hydrogen***

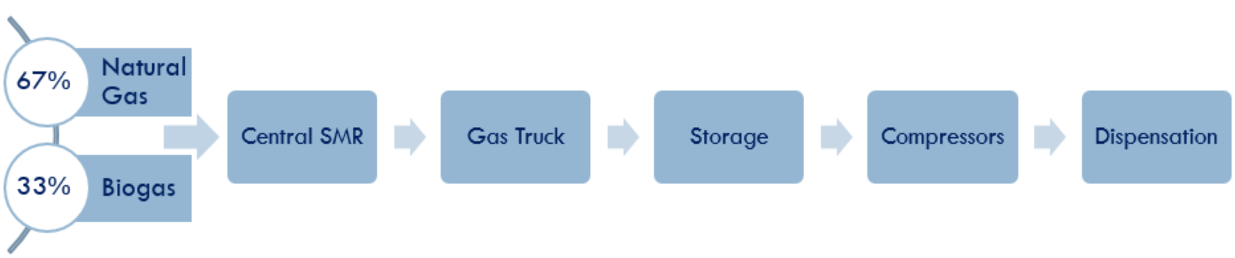



***Figure 17 Components necessary for gaseous truck delivery of hydrogen***

An accurate estimation of the capital cost for the different hydrogen supply chain pathways is a key component of the cost inventory that will be used to calculate the life cycle cost of hydrogen buses. The capital cost calculated using Equation Eq. ( 13) considers:

- Storage
- Compressors
- Dispensers
- Investment in infrastructure to comply with safety requirements
- Vaporizers

The capital cost for hydrogen as a function of the number of buses that can be filled at the station was calculated with the methodology described above and is presented in Figure 18 and Figure 19 for hydrogen delivered as a liquid and in a gaseous state, respectively. The more buses are filled, the more capacity the station will have and the more expensive it will be until reaching a low slope growth.

The capital cost is presented as a function of the number of buses to help identify the capital cost for different penetration percentage of hydrogen buses into a fleet. Figure 18 and Figure 19 show that for 300 buses to be filled by a hydrogen station, an initial capital cost of $21.4 million would be required for liquid hydrogen delivery and $18 million if gaseous hydrogen is delivered.

When hydrogen is delivered as a liquid, the hydrogen first is vaporized and compressed by the main compressor to 54 MPa and stored in storage tubes, when the bus is filled the hydrogen is cascaded directly from the 54 MPa storage tubes to the bus tank. For hydrogen delivered as a gas, no need for vaporizers is necessary, and this is one of the reasons why the capital cost for a station that gets hydrogen delivered as gas is lower than for when it's delivered as a liquid.

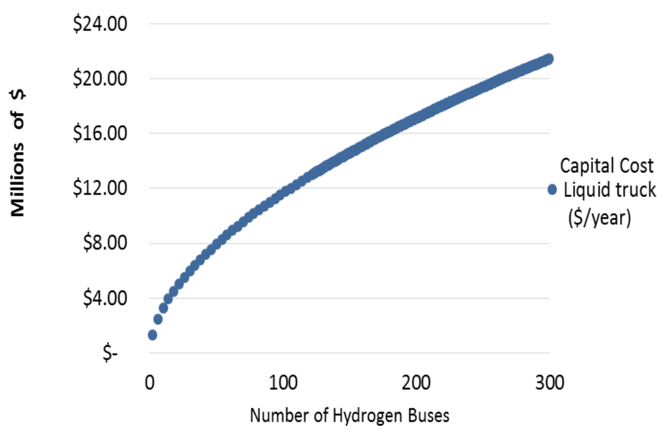



***Figure 18 Capital cost of distribution via liquid trucks***

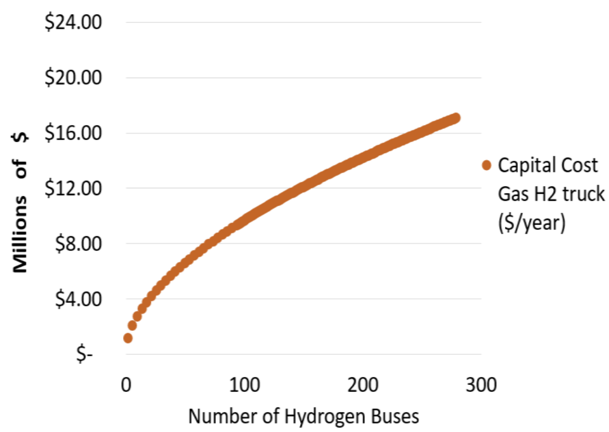



***Figure 19 Capital cost of distribution via gaseous trucks***

The hydrogen demand for 300 buses assuming an average of 250 daily miles is 11,500 kg of hydrogen per day; for such demand, and based on the current market equipment specification, six dispensers will be required to fill 300 buses in a period time of 6 to 8 hours. To store gas hydrogen at 3,190 psi, it would require four sets of eight vessels (8 x 40' ABS skids [100]) with a total area of 1,100 ft$^2$.

The price per kilogram of hydrogen that is generated at a centralized SMR plant and distribution with liquid trucks is presented in Figure 20, and it reflects the well-to-pump price of hydrogen that complies with the 33% renewable hydrogen requirement that some states are implementing. The price of hydrogen can be lower than $7.00 per kilogram of hydrogen when more than 150 buses are deployed and as low as $6.65 per kilogram of hydrogen when 300 buses or more are deployed.

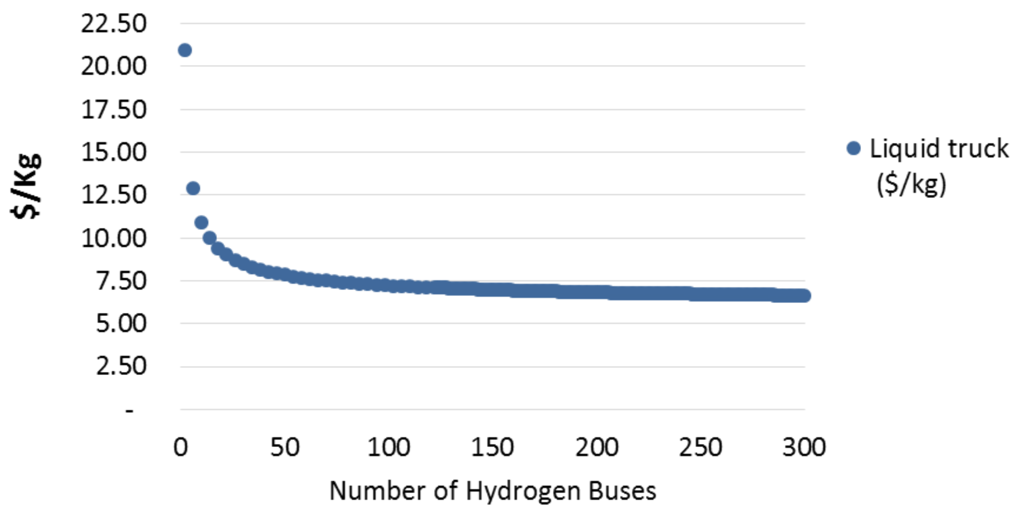



***Figure 20*** ***Cost per kilogram of $H_2$ from central SMR and distribution via liquid trucks***

The price per kilogram of hydrogen produced from centralized SMR and distribution with gas trucks is presented in Figure 21. The price of hydrogen can be lower than $5.20 per kilogram of hydrogen when more than 150 buses are deployed at and as low as $5.00 per kilogram of hydrogen when 300 buses or more are deployed.

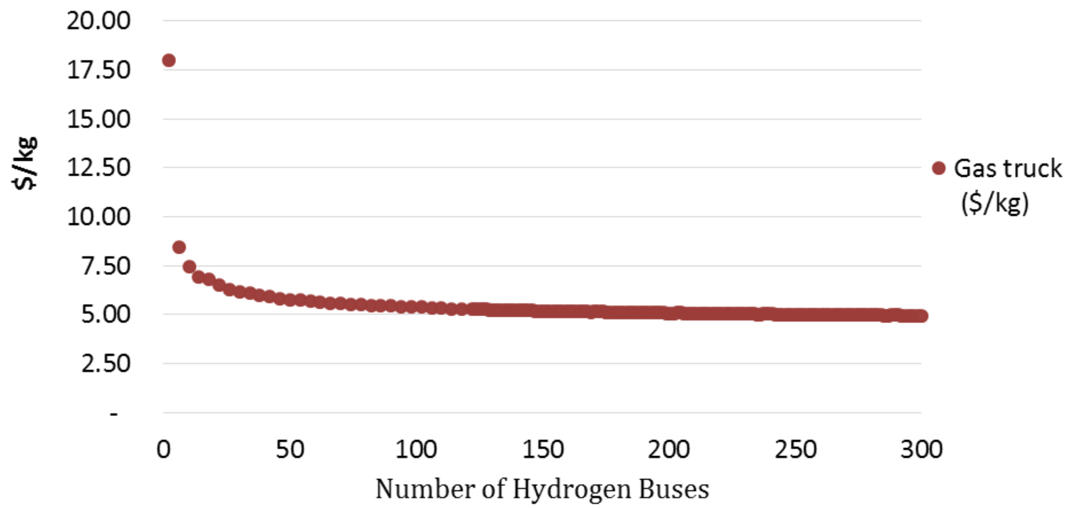



***Figure 21 Cost per kilogram of $H_2$ from central SMR and distribution via gas trucks***

Even when the capital cost of gas delivery trucks is lower than for liquid delivery, the feasibility of the gas distribution pathway has its limitations. One of the outputs of the tool is the number of trucks that will be required for the delivery of hydrogen, for both gas and liquid. Figure 22 compares the hydrogen price for both pathways and shows the number of gas tube trucks that will be required to deliver the hydrogen as a function of the number of buses that are deployed by a transit agency. From this figure, the gas tube trucks are shown to be not feasible since, to supply the demand of 300 buses, 18 tube trucks per day will be needed to supply the three bases. Considering logistics and space available at most transit agencies, delivery using only compressed gas hydrogen is cheaper but not feasible when more than three tube trucks need to arrive per day, which occurs when 35 hydrogen buses are in service.

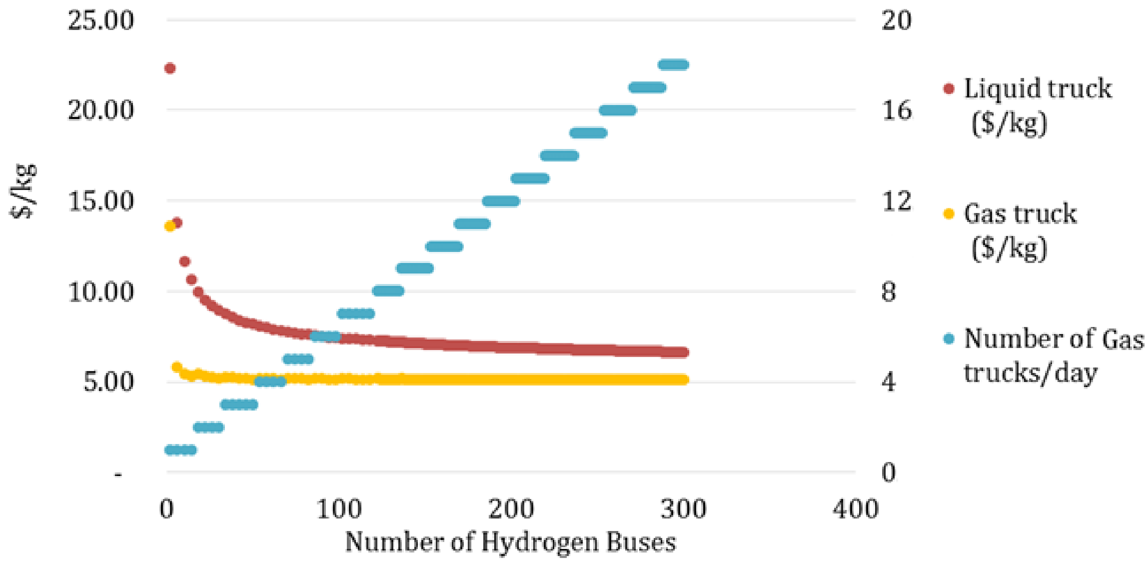



***Figure 22 Comparison of liquid truck and gas truck distribution pathways for centralized SMR generation scenario***

**Pipeline vs. distributed generation**

Specific diagrams with the description of the components necessary to deliver hydrogen using pipelines and for hydrogen produced locally (distributed generation) are presented in Figure 23 and Figure 24.

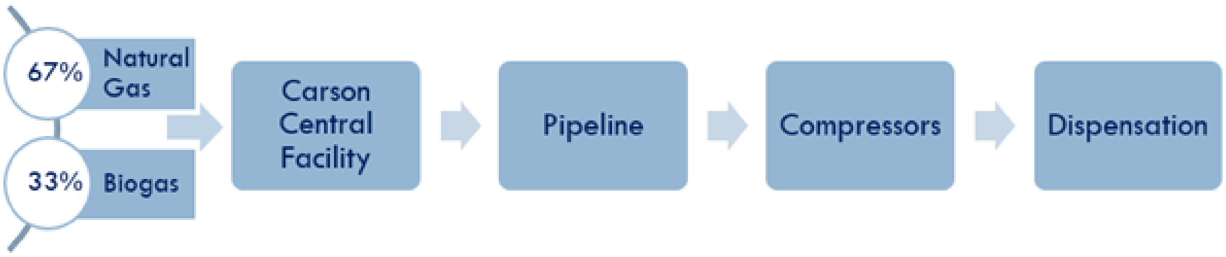



***Figure 23 Components of pipeline delivery hydrogen scenario***

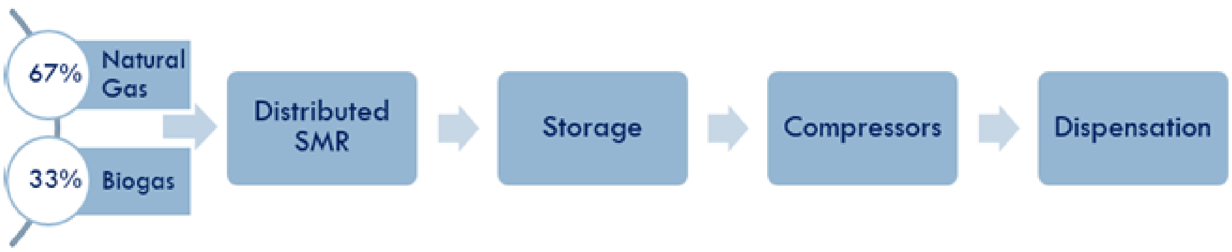



***Figure 24 Components distributed generation hydrogen scenario***

Similar to the comparison between liquid and gas truck delivery, this comparison includes the initial capital cost and the total price of hydrogen per kilogram. The tool used the same inputs and the same financial assumptions described in this section.

The suggested infrastructure for the pipeline (red) was obtained from using $H_2AT$ to identify the nearby resources to the bases of Orange County Transit Authority (OCTA). With the outputs from $H_2AT$ and using the software ArcGIS, the spatial allocation of the preferable refinery and layout of suggested pipeline infrastructure were obtained (Figure 25). The outputs from H2AT utilized the current layout of natural gas pipelines to generate the 35 miles of hydrogen pipelines needed to interconnect a refinery in Carson with the three main bases at OCTA.

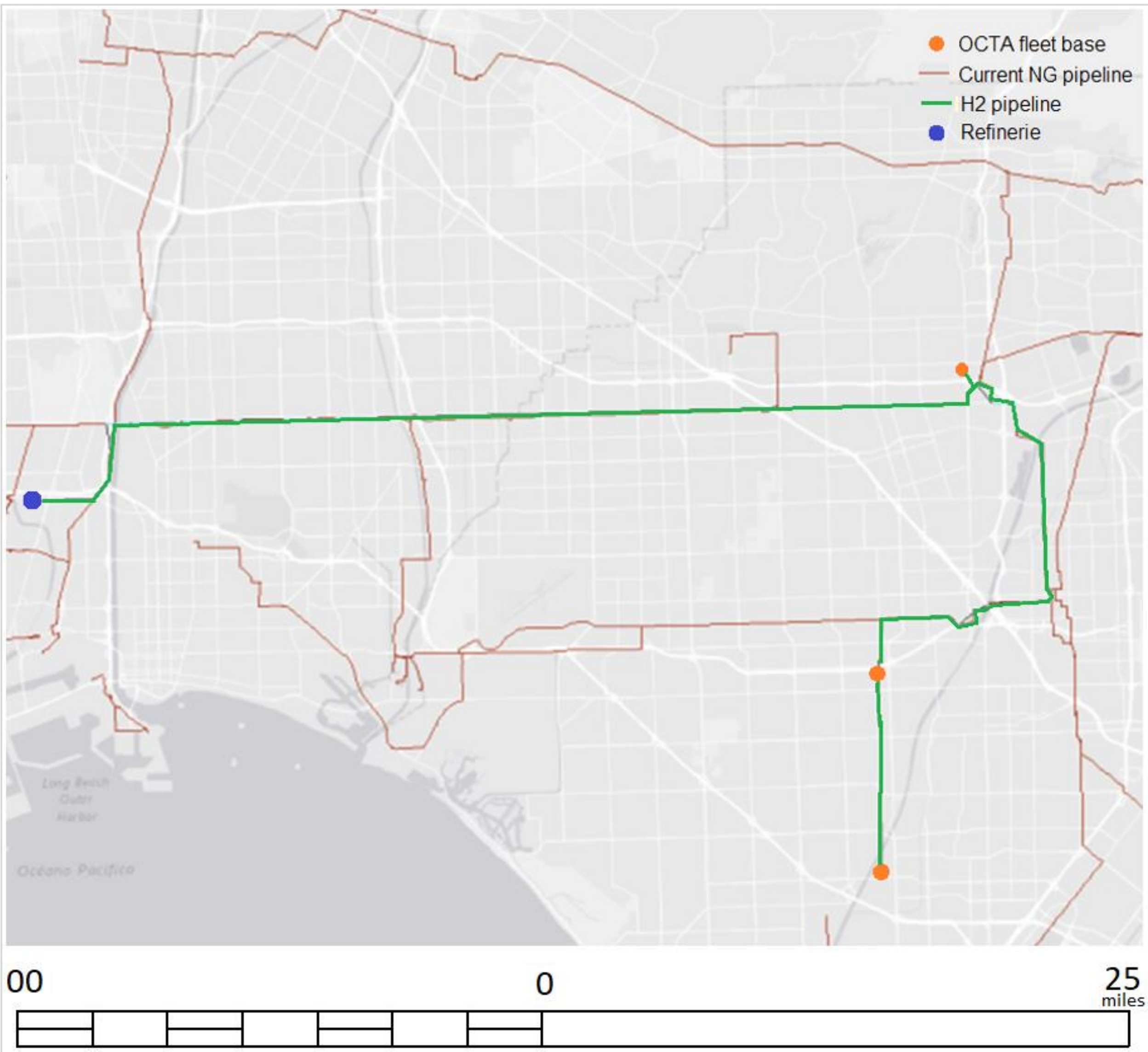



***Figure 25 Spatial allocation of suggested pipeline between Carson refinery and OCTA bases***

The capital cost for hydrogen delivered using pipelines has a similar trend line to the capital cost of the tube truck delivery pathways, namely increasing in a linear tendency after reaching a capacity to serve 100 buses. The capital cost for the pipeline pathway is presented in Figure 26 and includes the cost of:

- Pipeline infrastructure investment
- Dispensers
- Compressors
- Investment of infrastructure to comply with safety requirements

It considers storage only for an emergency which price is almost irrelevant in comparison to the other considerations.

The capital cost for the pipeline infrastructure is $10.8 million, and it remains independent of the hydrogen demand (buses in service). Figure 26 shows that an initial capital cost of $18 million is needed when other equipment is added to service 300 buses at a hydrogen station that receives the fuel via pipeline. The capital cost is lower than for the tube truck delivery because the storage equipment is almost eliminated as well as the vaporizers.

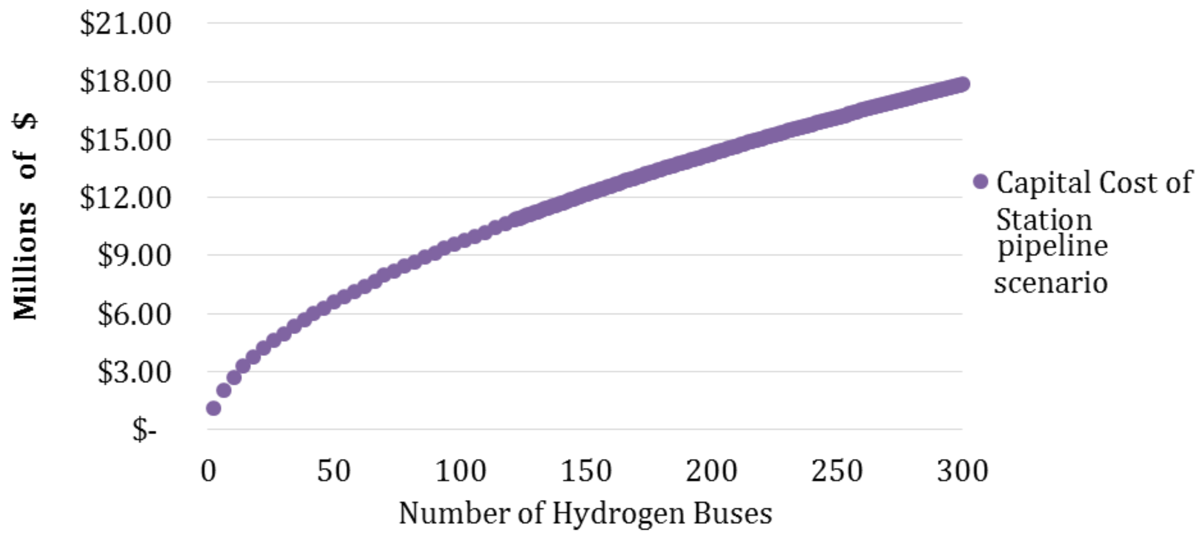



***Figure 26 Capital cost of distribution via hydrogen pipelines.***

The total cost of hydrogen per kilogram was estimated for the pipeline delivery pathway. Figure 27 shows the price of hydrogen as a function of the buses deployed for central SMR distributed via pipelines. If this scenario were to be implemented at OCTA when they have less than 50 buses, then the price for hydrogen would not be lower than $10. Therefore, investing in pipeline infrastructure is not recommended for 12 years, unless more than 50 buses are to be deployed. A positive aspect about this pathway is that the cost of hydrogen can be as low as $4.96 per kilogram if more than 300 buses are deployed at OCTA.

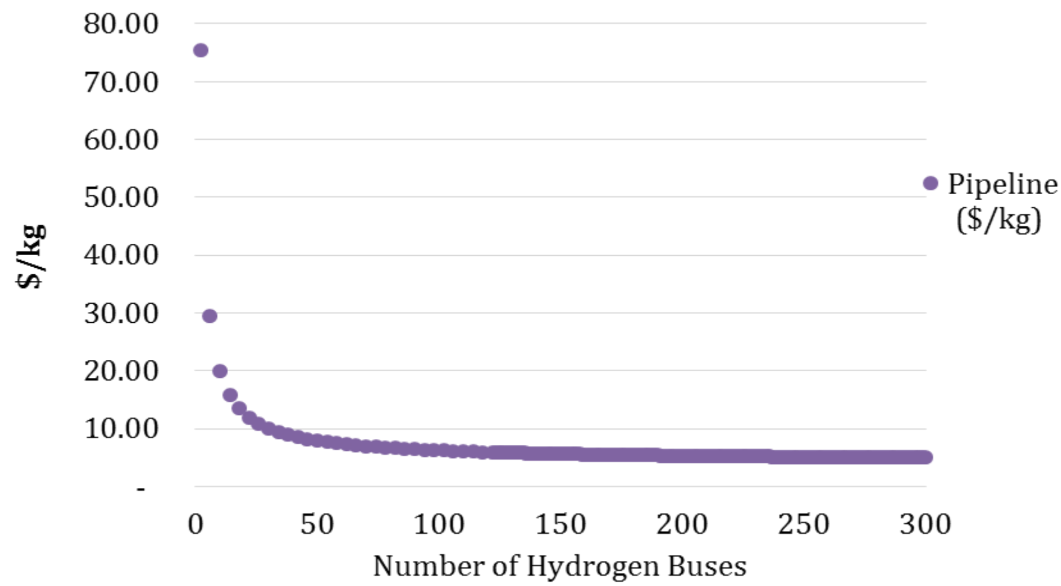



***Figure 27 Cost per kilogram of hydrogen from central SMR and distribution via pipeline***

The capital cost of hydrogen using distributed SMR units has a different tendency than the other distribution pathways. Unlike the other distribution pathways, the capital cost is continuous until a new SMR unit or more storage vessels need to be added because of the hydrogen demand scales up. Figure 28 shows that the capital cost can be as high as $50 million for stations that could accommodate the hydrogen demand of 300 FCEB. The capital cost is significantly higher with respect to the other pathways because it includes the production cost and not just the station itself. The cost of production is levelized in the other scenarios in the well-to-product price of $3.50 per kilogram of hydrogen. Therefore, this should not be a point of comparison between the other scenarios; the comparison can be made concerning the total price of hydrogen per kilogram. But even when the total price per kilogram will be a fair point of comparison, the capital cost for this delivery/production method is critical because it represents an initial investment that the transit agency will need to make in addition to the investment for the refueling station for the deployment of the buses.

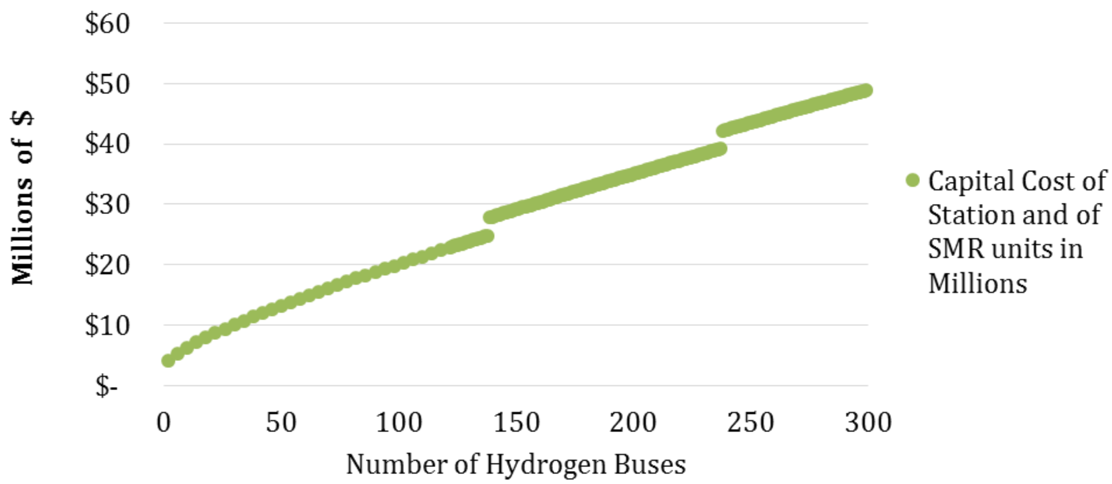



***Figure 28 Capital cost of hydrogen from distributed SMR with natural gas and biogas***

For the distributed SMR pathway, the price per kilogram of hydrogen is dependent on the feedstock prices of the directed biogas from wastewater treatment plants and of the price of the natural gas. But unlike the other pathways, is independent of third parties that could control the well-to-product price of the hydrogen.

Figure 29 shows the total price of hydrogen by kilogram when produced on-site with SMR distributed units. Similar to the pipeline pathway, the price of hydrogen is high if less than 50 FCEB are deployed with the difference that the higher price for this distribution pathway is $37 per kilogram in comparison to $75 for the pipeline case.

The hydrogen price for the distributed generated SMR can be as low as $3.87 if more than 300 are deployed at OCTA.

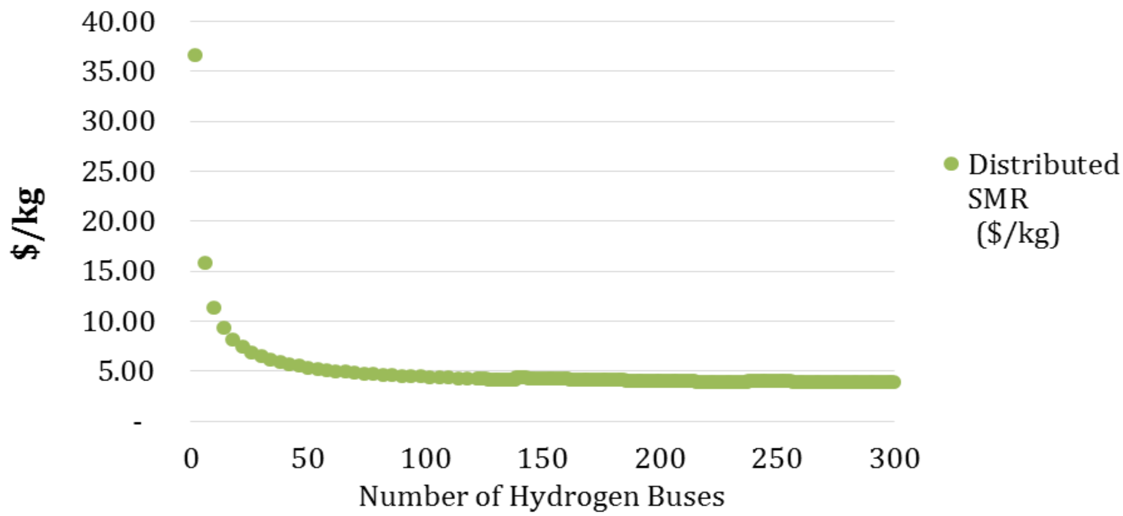



***Figure 29 Cost per kilogram of hydrogen from distributed generation via SMR***

As established in the section above, the distribution pathway involving gas delivery trucks presents restrictions on the number of trucks that can be managed by the bases at OCTA, therefore is not included as a viable scenario for full FCEB deployment.

Figure 30 shows the price per hydrogen for three distribution pathways: 1) delivery by liquid trucks, 2) pipeline infrastructure, and 3) distributed generation via SMR units. The on-site generation scenario is the pathway with a lower total price of hydrogen but also the one with higher investment. It can also be inferred that when 25 or more FCEBs are in service, pipeline infrastructure is preferable over liquid trucks.

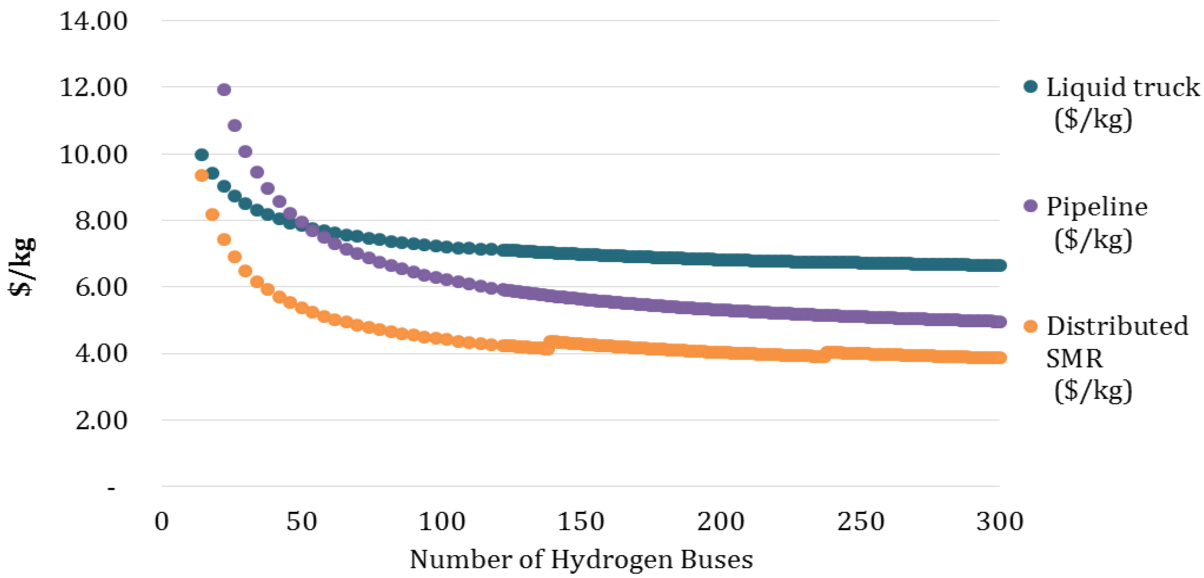



***Figure 30 Cost per kilogram of hydrogen for three different distribution methodologies***

### 5.4. Cost Inventory for Future Scenarios

In order to analyze the influence that cost parameters have in the optimization of bus fleets, a future scenario was designed. The purpose of the cost inventories for future years is not to predict the trend in costs, but to demonstrate the importance of the information that is input into the optimization model and to illustrate the impact of the input information on the results. Table 23 presents the key cost assumptions, projected by the Air Resources Board, for the calculations used to estimate the economic impacts of the Innovative Clean Transit regulation [104]. The price of all bus types, except the FCEB, was projected to decrease and then increase starting in 2023. For the case of the BEB-LR, even though the price is higher than for the 2018 scenario, the range is assumed to be no longer an operational constraint.

*Table 23 Future Cost Assumptions for ZEB for the Year 2040* [104]

| | CNG | BEB-LR | BEB-SR | FCEB |
|---|---|---|---|---|
| **Bus capital cost** | $810,000 | $930,000 | $907,000 | $930,000 |
| **Fuel prices** | $1.95 per DGE | $0.17 per kWh | $0.17 per kWh | $4 per kg |
| **Average Maintenance Cost** | 0.85 $/mile | 0.60 $/mile | 0.60 $/mile | 0.49 $/mile |
| **Infrastructure (Equipment and Installation)** | $6,000,000 | $105,000 per unit | $599,000 per unit | $5,050,000 per 1,500 kg/day |
| **Fueling infrastructure O&M** | $0 | $500 per year | $2,200 per bus/year | $0 |

# CHAPTER 6. Modeling of Urban Bus Energy Consumption

According to the National Renewable Energy Laboratory, FCEB and BEB designs are considered to be at a technology readiness level (TRL) 7 to 8 (e.g., full-scale validation in a relevant environment) [78], [80]. As a result, several manufacturers have emerged in the market, and a wide range of bus configurations are currently available.

This variety has created several opportunities, as well as challenges. For example, the standardization of bus chargers for BEBs concerns transit agencies that might seek to acquire buses from more than one manufacturer (e.g., the difference in fuel cell size and battery capacity can result in different driving ranges). Additionally, the variance among bus manufactures goes beyond drivetrain configuration and includes different bus weight, passenger capacity, auxiliary power demand, and regenerative braking configurations.

The variety in bus configurations adds to the already difficult comparison between technologies that transit agencies need to perform when transitioning to zero-emission fleets. Since the operating duty cycle of a bus has a significant effect on fuel economy, only a comprehensive evaluation of bus technologies can standardize non-drivetrain components and thereby allow end users to examine which technology can truly answer their operative demands. The model presented in this chapter provides the ability to compare different powertrains, given that the driving cycle, vehicle configuration, and auxiliary loads are consistent.

The simulation starts by assessing the mechanical energy demand for a specific bus type and driving cycle. In this context, the bus type will include fuel cell electric, battery electric, compressed natural gas, and diesel powertrains with a defined weight, frontal area, aerodynamic drag, and rolling resistance coefficient.

A driving cycle, represented as speed versus time profile, was used for the simulation of vehicle performance and energy use. In this research work, the Orange County transit bus cycle (OCTA) was the reference driving cycle for the calculation of energy use. The OCTA cycle is based on a chassis dynamometer test cycle for transit buses operated by the Orange County Transit Authority in California that was developed by West Virginia University [44] (see Figure 31).

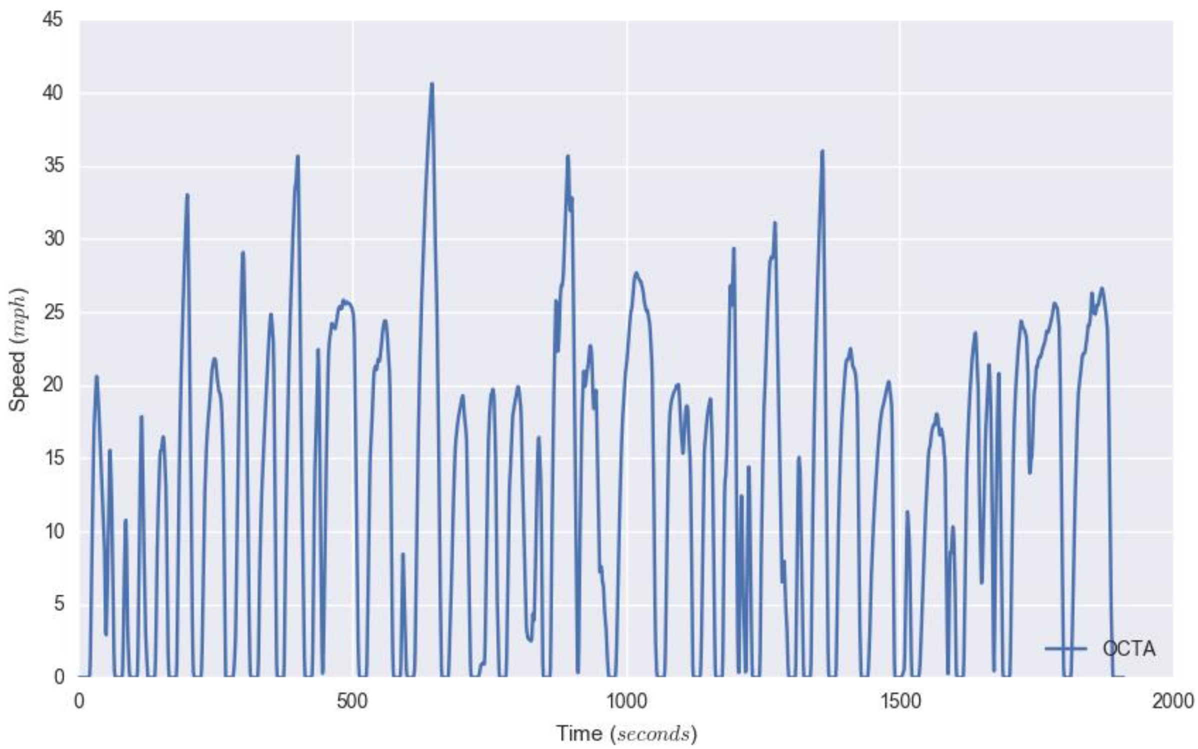



***Figure 31*** ***OCTA driving cycle*** [105]

Based on the parametric calculation of mechanical energy demand, an analytic simulation method was used to calculate conventional and electric vehicle configuration and power requirements [106].

The methodology developed calculates wheel traction power demand given a velocity (v) versus time profile and assumptions about mass, vehicle' frontal area, coefficient of aerodynamic drag ($C_{drag}$), air density ($\rho_{air}$), and rolling resistance ($C_{rolling}$) according to the following equations:

$$F_k = acceleration * mass \quad \text{Eq. (14)}$$

$$F_{rolling} = mass * C_{rolling} * g \quad \text{Eq. (15)}$$

$$F_{air\_res} = \left(v^2 * Af * C_{drag} * \rho_{air}\right) / 2 \quad \text{Eq. (16)}$$

$$F_T = \sum F = F_k + F_{rolling} + F_{air\_res} \quad \text{Eq. (17)}$$

$$Power = F_T * velocity \quad \text{Eq. (18)}$$

$$Power_{wheels} = \left(\frac{v^2 * Area * C_{drag} * \rho_{air}}{2} + 9.8 * m * C_{rolling} + m * \dot{v}\right) v \quad \text{Eq. (19)}$$

Eq. (14) calculates the kinetic force; Eq. (15), and Eq. (16) calculate the force to overcome rolling resistance and air resistance, respectively. In Eq. (17) the sum of all the forces is the total force that is required to move the vehicle and Eq. (18) and Eq. (19) show the total power requirement at the wheels. In addition to propulsive energy use, auxiliary loads for interior climate control (HVAC) and electronic appliances were considered. An analytic expression was used to evaluate vehicle component sizes and energy use as a function of configuration parameters such as range, and technical parameters such as battery specific energy [1], [107].

Integrating the power requirement over the whole cycle and dividing by the total distance traveled yielded energy consumption per mile traveled (Figure 32), which was then used to calibrate the model with measured values found in the literature and from data collected at UCI. The high level of integration between technical assessment and powertrain simulation enabled a consistent comparison of the bus vehicle technologies.

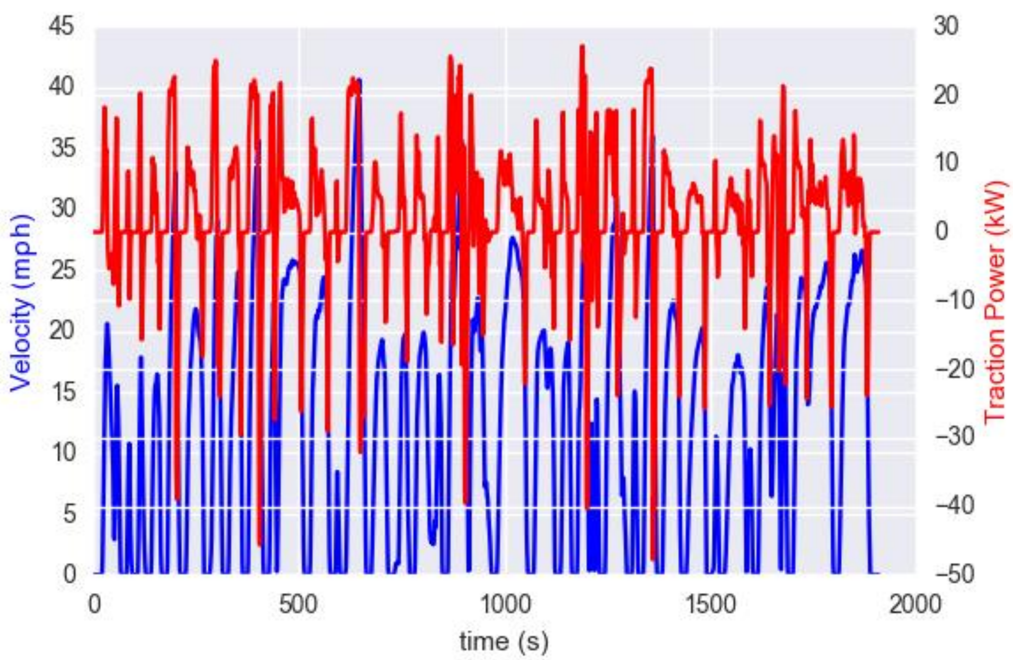



***Figure 32 Power requirement for OCTA driving cycle***

Figure 33 shows the energy consumption for different powertrains including hydrogen fuel cell bus (FCEB), battery electric bus (BEB) that includes short range (SR) and long range (LR), diesel (ICEV-D), compressed natural gas (CNG), and diesel hybrid electric (HEV-D).

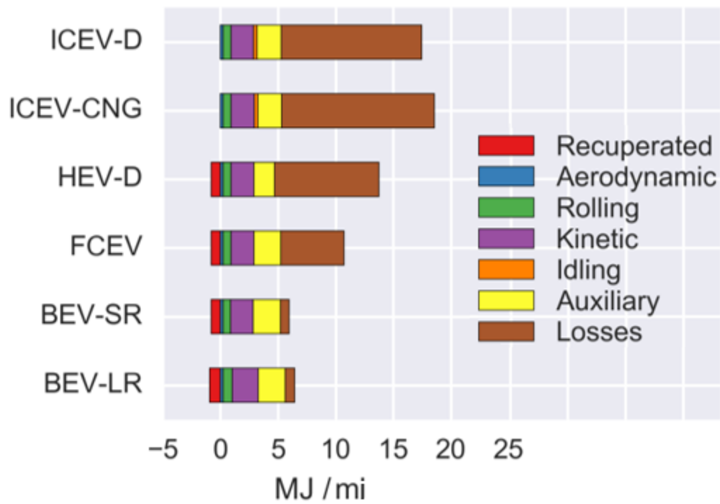



***Figure 33*** ***Tank-to-Wheel energy consumption for different powertrains calculated by Fuel Efficiency Model***

# CHAPTER 7. Life Cycle Assessment of Zero Emission Buses

The long-term transition to zero-emission technologies for California transit agencies is under consideration with the Innovative Clean Transit (ICT) regulation proposal [104]. The regulation proposes to eliminate on-road emissions from buses by 2040 and to eliminate fossil-fuels dependency with the overall goal to minimize impacts on the environment and health effects in communities.

Transport authorities required to adopt a zero-emission fleet are faced with a decision between multiple bus technologies, each with different strengths and weaknesses as well as infrastructure requirements. This decision is made more difficult because the performance of the buses depends strongly on operating conditions which cannot be predicted in advanced from manufacturer information or deployment of similar demonstration projects.

To support transit agencies and decision makers in this transition, an extended LCA framework was developed that allows a consistent comparison of different bus powertrains and energy chain configurations. Furthermore, only a comprehensive life cycle assessment can potentially predict the extend of environmental benefits or hidden risks found in transitioning to zero-emission fleets.

Data inventories described in Chapter 4 are used together with component sizes and vehicle energy consumption to calculate aggregated LCIA results for the complete vehicle life cycle; essentially disaggregating every major bus component to then standardize everything except the different types of powertrains. The model framework allows for the simulation of a wide range of different vehicle size and performance classes. Additionally, the modeling methodology for the fuel energy consumption described in Chapter 6, provides the foundation for a consistent comparison of different bus powertrains and energy chain configurations when utilizing life cycle assessment.

The full simulation using the approach presented here is implemented in an interactive Python tool in which the user can modify scenario assumptions and access the full set of results. For this dissertation, an extensive model is demonstrated by showing the results for the 40-foot 'Maxi' long bus of average performance, and the following powertrain variants were considered in the calculations:

- Diesel (ICEV-D),
- Diesel hybrid (HEV-D),
- Compressed natural gas (ICEV-CNG),
- Fuel cell electric (FCEV),
- Battery electric with short range from opportunity charging (BEV-SR),
- Battery electric with long-range from plug-in charging (BEV-LR).

Though calculations in this section refer to 2018 and 2040 bus construction years, the model has the capability of creating bus specifications for construction years between 1990 and 2050.

The novelty of this modified LCA approach lies in the use of a consistent framework to compare multiple powertrain types under the same operating conditions in order to evaluate energy consumption and operating emissions, as well as health/risk impacts.

### 7.1. Life Cycle Assessment Approach

Life Cycle Assessment of different zero-emission bus technologies was analyzed with regard to several criteria of interest. As illustrated in Figure 34 (adapted from [1], [107]), the modeling framework considered exogenous and endogenous criteria. Exogenous criteria are aspects related to vehicles performance such as size, range, and acceleration. Those exogenous criteria were necessary input parameters to specify a bus, execute the vehicle simulation, and perform the LCA. Endogenous criteria were the simulation results, such as vehicle mass and energy use. The technology options were selected to be independent (i.e., they can be combined in every possible way) to study the range of resulting criteria and to better understand the interdependencies between technology and fuel options, future developments, and environmental impacts [108]. For the LCA calculations reported herein, the technology options were split into powertrain and fuel type, vehicle size, range and performance, primary energy source, and vehicle model year.

The cradle-to-grave life cycle assessment was performed using the Ecoinvent 3.2 database with the cut-off system model [46] and the Brightway2 software [45]; this included the entire bus material cycle, from production to regular maintenance and end-of-life, as well as the entire fuel cycle and operating emissions. The functional unit of the study was vehicle miles traveled (VMT).

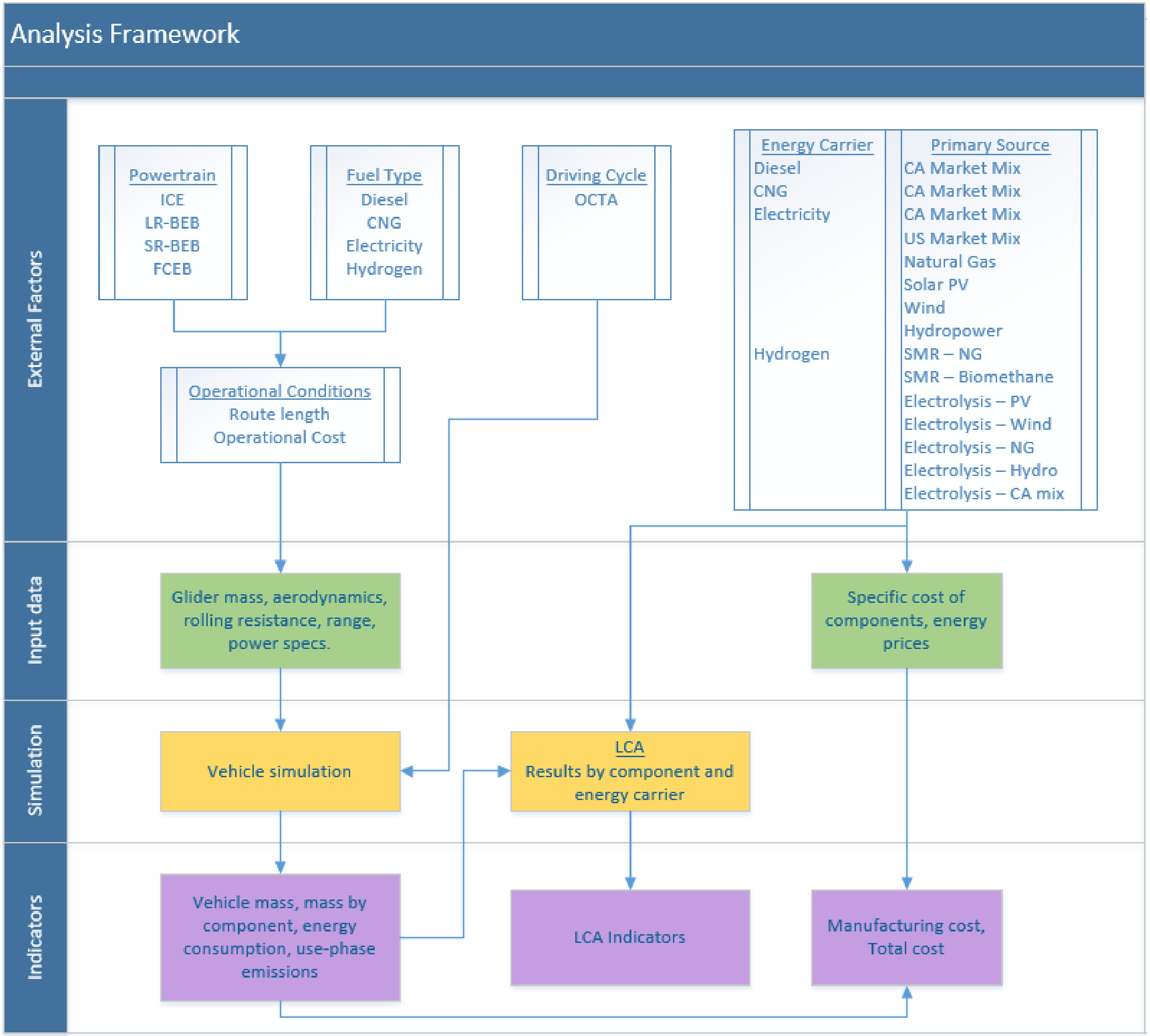



***Figure 34*** ***Modeling of energy consumption and LCA framework (Adapted from*** [1], [107]***)***

Life cycle impact assessment (LCIA) translates emissions and resource extractions into a limited number of environmental impact scores that are calculated by using characterization factors. ReCiPe was selected as the method for the impact assessment (LCIA) in the LCA. The two options to use the ReCiPe characterization factors are at midpoint level and at endpoint level (Figure 35).

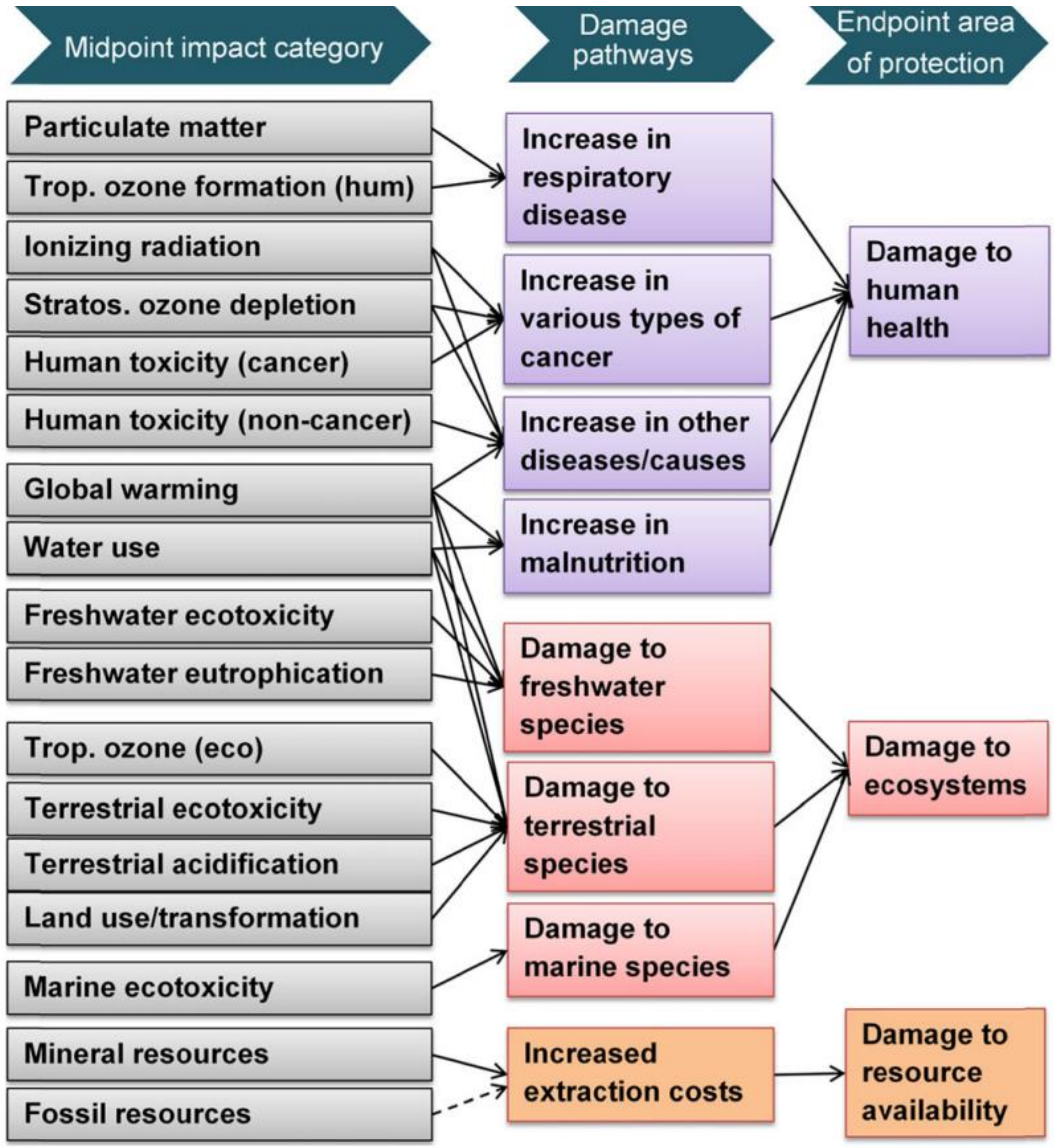



***Figure 35 Overview of the impact categories and their relation to the areas of protection. The dotted line means there is no constant mid-to-endpoint factor for fossil resources***[109][110].

Midpoint indicators focus on single environmental problems, for example, climate change or acidification. Endpoint indicators show the environmental impact on three higher aggregation levels, being the 1) effect on human health, 2) damage to the ecosystem, and 3) resource availability.

Only the following midpoint indicators were selected to be presented in this research to demonstrate the capabilities of the LCA extended methodology described ins this chapter:

#### 7.1.1. Global Warming Potential (GWP)

GWP represents the contribution to climate change due to the emission of greenhouse gases such as $CO_2$ and $CH_4$. The most recent global warming potential characterization factor was selected from the IPCC [31], as implemented by the Ecoinvent center. GWP is quantified in kg $CO_2$ equivalents using a 100-year reference time period.

#### 7.1.2. Particulate Matter Potential Formation (PMPF)

PMFP considers the human health impacts of fine particles in the air. Not only the direct emission of particulates was considered, but also the formation of secondary particulates due to emissions such as $SO_x$, $NO_x$, and ammonia ($NH_3$). PMFP is quantified in kg PM 10 equivalents. This indicator is calculated using the ReCiPe 2008 method with the hierarchical perspective [61]. PMFP is used to represent the urban air quality aspects of bus operation, as $NO_x$ and particulate emissions are among the most important emissions from buses.

#### 7.1.3. Terrestrial Acidification Potential (TAP)

Acidic gases such as Sulphur dioxide ($SO_2$) react with water in the atmosphere to form acid deposition, also known as "acid rain." Acid deposition causes a decrease in plant performance and biodiversity losses [111]. Acidification potential is expressed using the reference unit kg $SO_2$ equivalent, and it accounts only for acidification caused by $SO_2$ and $NO_x$.

#### 7.1.4. Photochemical Oxidant Formation (POFP)

The photochemical oxidants are secondary air pollutants formed by the action of sunlight on nitrogen oxides and reactive hydrocarbons, their precursors. The most important phytotoxic components produced by these atmospheric photochemical reactions are ozone and peroxyacetyl nitrate [112]. POFP are implicated in problems of smog and crop damage. This impact category is quantified in kilograms of Non-Methane Volatile Organic Carbon (NMVOC). The indicator name for this impact category is Photochemical Ozone Concentration.

#### 7.1.5. Metal Depletion Potential (MDP)

MDP refers to the decreasing availability of natural resources, specifically metals. These midpoint factors are given as kg of Fe-equivalents. This indicator is calculated using the ReCiPe 2008 method with the hierarchical perspective [61].

#### 7.1.6. Human Toxicity Potential (HTP)

HTP is used to express the potential harm of a unit of chemical released into the environment. HTP includes both inherent toxicity and generic source-to-dose relationships for pollutant emissions. HTP is calculated by adding the releases, which are toxic to humans, to three different media, i.e., air, water, and soil. The chemical 1,4-dichlorobenzene is used as a reference substance for these midpoint calculations (kg 1,4 DB equivalent).

#### 7.1.7. Freshwater Eutrophication Potential (FEP)

This impact category provides a method for describing fate, exposure, and the effects of phosphate equivalent substances on freshwater bodies. Characterization factors are expressed using the reference unit, kg of phosphate equivalent (P eq.)

**ReCiPe Endpoint**

At the endpoint level, most of the midpoint impact categories are further converted and aggregated into the following three endpoint categories:

- ReCiPe Endpoint Human Health
- ReCiPe Endpoint Ecosystem Quality
- ReCiPe Endpoint Resources Availability

The single-score (ReCiPe Endpoint Total) aims to aggregate and normalize all the end-point categories to present an overall score. However, the single-score calculation method does not account for either the effect of alternatives having high values across all endpoints or the interdependency of the indicators being aggregated. Furthermore, despite the risks of over interpreting or even misinterpreting normalized and weighted results, the Endpoint Total is used as a comparison point among different powertrains.

## 7.2. Bus Modeling

The focus on the vehicle type for the calculations was on standard 40-foot long buses. All buses were assumed to have a lifetime of 12 years and travel a total of 520,000 miles during their lifetime. A description of the 6 different bus powertrain types is presented below:

- **ICEV-D**: Internal Combustion Engine Vehicle – Diesel. This is a standard diesel-powered bus that meets CARB emissions regulation. It has a 230-kW engine.
- **ICEV-CNG**: Internal Combustion Engine Vehicle – Compressed Natural Gas. This is a standard compressed natural gas-powered bus, also with a 230-kW engine.

- **HEV-D**: Hybrid Electric Vehicle – Diesel. Hybrid bus configuration with a 185-kW diesel engine that operates a generator. The wheels are powered by two 75 kW electric motors that are capable of recuperative braking and 150 kW of lithium ion power batteries (15 kWh storage capacity). The bus does not have the ability to recharge batteries from the electricity grid, not a plug-in to charge the vehicle
- **FCEV**: Fuel Cell Electric Vehicle. This is a Proton Exchange Membrane (PEM) fuel cell powered bus that operates on hydrogen. The fuel cell has a net power output of 150 kW, and 80 kW of lithium ion power batteries (11 kWh) are used to balance the load. Two 75 kW electric motors that are capable of recuperative braking are used to power the wheels.
- **BEV-SR**: Battery Electric Vehicle – Short Range. A battery electric bus powered by lithium ion batteries. This bus was assumed to have a range of only 20 miles with regular recharging events along the route with inductive charging. The wheels are powered by two 75 kW electric motors that are capable of recuperative braking.
- **BEV-LR**: Battery Electric Vehicle – Long Range. A battery electric bus powered by lithium ion batteries. This bus is assumed to have a range of 150 miles from a 320-kWh stack of batteries and is assumed to charge once per day. The wheels are powered by two 75 kW electric motors that are capable of recuperative braking.

For all the bus performance modeling, the basic parameters were kept the same. As a result, no constraints due to operational differences were considered. All the buses were assumed to travel the same daily distance, the same number of stops, no difference in route due to charging events, same passenger load, same driving cycle and no changes in the power requirements, the only difference relied on the efficiency of each powertrain and the fuel used to power the bus. Table 24 presents a summary of all the relevant parameters used in the modeling of each powertrain type.

Two scenarios were investigated to analyze the environmental effect of deploying zero-emission buses. The first scenario was specific for the conditions of one of the bases operated by Orange County Transportation Authority (OCTA). The second scenario analyzed the present and future benefits of ZEB without specifics of operation from a given transit agency.

*Table 24 Summary of relevant bus parameters for LCA calculations*

| | | | Diesel | HEV-D | CNG | FCEV | BEB-SR | BEB-LR |
|---|---|---|---|---|---|---|---|---|
| **Bus mass** | lb. | 2018 | 23,958 | 24,112 | 24,310 | 30,310 | 26,584 | 28,896 |
| | lb. | 2040 | 23,606 | 23,672 | 23,958 | 29,254 | 25,726 | 27,102 |
| **Maximum Range** | Mi | 2018 | 400 | 400 | 311 | 340 | 7 | 140 |
| | Mi | 2040 | 400 | 400 | 311 | 340 | 7 | 140 |
| **Traction energy demand** | MJ/mi | 2018 | 8.5 | 6.3 | 8.5 | 7.1 | 7.1 | 7.6 |
| | MJ/mi | 2040 | 7.7 | 5.6 | 7.7 | 6.3 | 6.3 | 6.4 |
| **Onboard Energy Storage** | kWh | 2018 | 2,420 | 1,800 | 2580 | 1480 | 86 | 380 |
| | kWh | 2040 | 2,100 | 1,570 | 2230 | 1230 | 75 | 325 |
| **Auxiliary Power** | kW | 2018 | 7 | 5.3 | 7.00 | 5.30 | 5.30 | 5.30 |
| | kW | 2040 | 5.4 | 4.9 | 5.4 | 4.9 | 4.9 | 4.9 |
| **HVAC Power** | kW | 2018 | 5.3 | 5.3 | 5.3 | 8.5 | 8.5 | 8.5 |
| | kW | 2040 | 4.1 | 4.1 | 4.1 | 6.6 | 6.6 | 6.6 |
| **Tank to Wheel Efficiency** | % | 2018 | 29 | 30 | 35 | 46.1 | 85 | 85 |
| | % | 2040 | 30.2 | 31.2 | 36 | 49.3 | 85.6 | 85.6 |
| **Charging Efficiency** | % | 2018 | - | - | - | - | 85 | 90 |
| | % | 2040 | - | - | - | - | 85 | 90 |
| **Recuperation Efficiency** | % | 2018 | - | 50 | - | 50 | 50 | 50 |
| | % | 2040 | - | 53 | - | 53 | 53 | 53 |
| **Total Energy Consumption** | MJ/mi | 2018 | 28.2 | 20.8 | 35 | 17.1 | 8.2 | 7.9 |
| | MJ/mi | 2040 | 24.3 | 18.2 | 30 | 14.3 | 7.2 | 7.6 |

### 7.3. Results for Orange County Transportation Authority Scenarios

It was necessary to conduct the analysis considering operations per maintenance base hub and not for the entire bus fleet since the refueling infrastructure needs to be specific to each hub. Since the Orange County Transportation Authority (OCTA) has three bases with a similar number of buses at each base, the results from the economic and LCA analysis can be multiplied by 3 to obtain the deployment plant of the transit agency. Additionally, for the optimization section, it was necessary to analyze the route length and scheduling of the buses, which is easier to accomplish if the analysis is done per base and not for the entire fleet. Therefore, the first scenario was conducted per base hub in order to include these LCA results in the objective function of the optimization.

The bus specifications are the same as the ones described in Table 24. Additionally, the operation conditions that were included in the OCTA scenario are reflected in Table 25.

No BEV-SR were considered in the OCTA scenario since the logistics required for the installation of on-route chargers cannot be account for due to the large number of cities that need to be considered.

*Table 25 Specific conditions for OCTA scenario*

| Aspect | Description |
|---|---|
| Buses per base | 150 buses |
| Route length assignment | 24% of fleet above 140 VMT a day |
| Powertrains options | ICEV-NG<br>ICEV-D<br>Hybrid-D<br>BEB (LR)<br>FCEB |
| Fuel generation options | 1. Electricity generation using CA grid mix<br>2. Electricity generation from hydropower<br>3. Electricity generation from natural gas using combined cycle power plant<br>4. Hydrogen generated from electrolyzer using CA grid mix<br>5. Hydrogen generated from an electrolyzer powered by hydropower<br>6. Hydrogen generated from an electrolyzer powered by CA grid mix<br>7. Hydrogen generated from SMR using natural gas |
| Year of calculations | 2018 |

**Error! Reference source not found.** presents the global warming potential results for the OCTA scenarios. For the FCEVs, generating electrolytic hydrogen yields the lowest GWP score (0.4 kg of $CO_2$ eq per mile). The low impact on this category is only improved if BEVs are charged using electricity generated by wind (0.3 kg/VMT). Even when the California grid mix uses less than 45% of fossil-fuels, relying on the grid generates the lowest

GWP score when directly used to charge BEVs or to generate hydrogen using electrolysis. It's important to note that the hydrogen generated via steam methane reformation is considering the 33% renewable required in the State of California. Additionally, for all zero-emission buses with their fuel generation pathway, the GWP score is below the baseline of the CNG buses operated by OCTA.

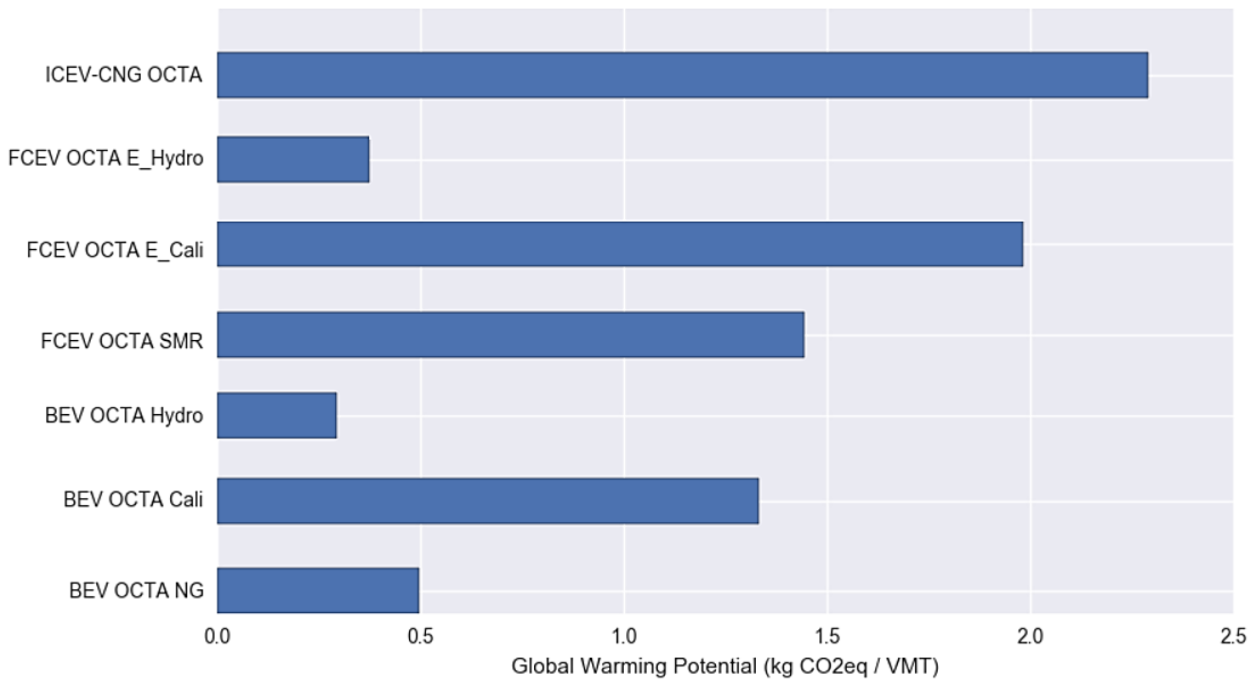



***Figure 36 Global Warming Potential result for OCTA 2018 scenarios***

Results for the terrestrial acidification are found in Figure 37. The scenarios that rely on the California grid mix for fuel generation (electricity or hydrogen) have the highest kilograms of $SO_2$ equivalent per vehicle mile travel. A portion of the emissions can be attributed to the operation of natural gas power plants, and the small share from coal fired Power Plants (PP). A sulfur compound added to natural gas as an odorant in case of leaks, results in the emission of $SO_2$ from power plants powered by natural gas. This is also the case for the scenario that uses natural gas to generate electricity and power BEVs. However, the difference in emissions between the California grid mix and pure NG for electricity generation relies on the small portion of coal and biomass that is used in the CA grid mix. "Sulfur dioxide ($SO_2$) emissions produced in the generation of electricity at power plants in the United States declined by 73% from 2006 to 2015, a much larger reduction than the 32% decrease in coal-fired electricity generation over that period. Nearly all electricity-related $SO_2$ emissions are associated with coal-fired generation" [113].

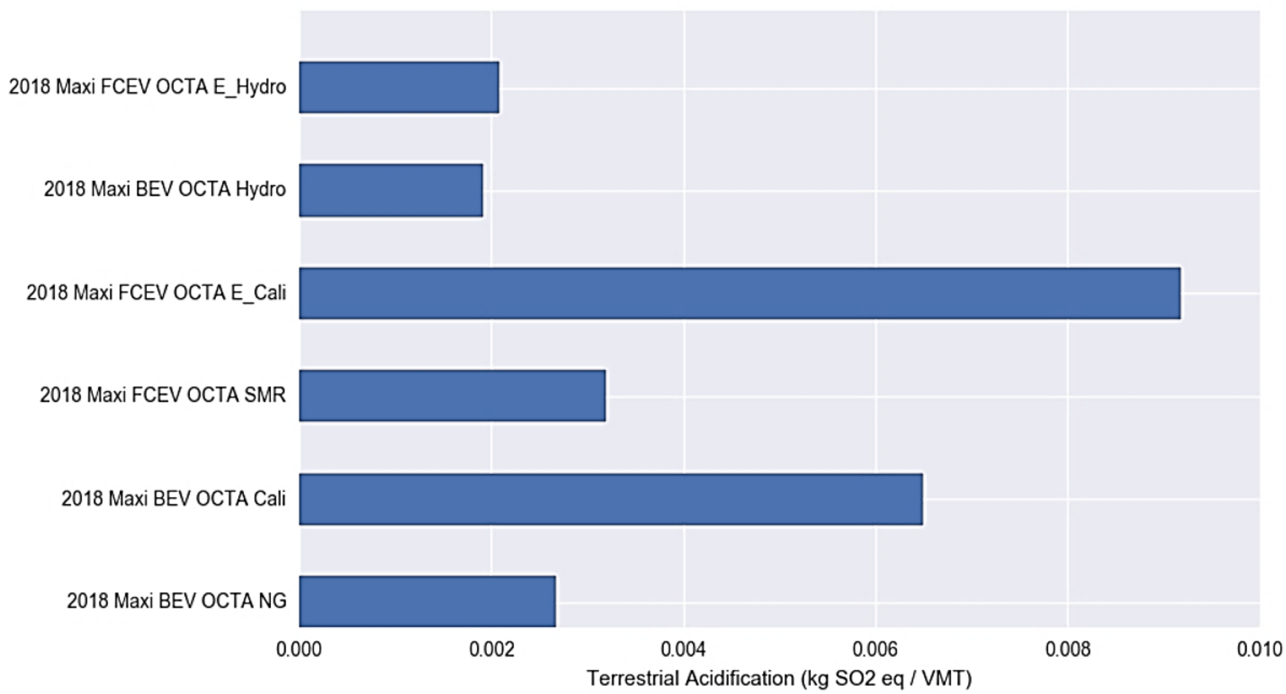



***Figure 37 Terrestrial Acidification Potential for OCTA scenarios***

When analyzing photochemical oxidant formation, the same patterns as for terrestrial acidification were observed, namely scenarios that depend on the California grid mix for fuel generation have higher emission rates than when using hydropower (Figure 38).

Figure 37 and Figure 38 reveal a second pattern related to the difference between using the California grid mix to power electrolyzers or to directly charge BEVs. The difference in $SO_2$ equivalent emissions per vehicle mile travel is a direct reflection of the efficiency in the fuel generation process. The efficiency to generate electricity using the CA grid mix is the same for both scenarios (FCEV E_Cali and BEV NG). However, the efficiency of the hydrogen conversion process via electrolysis is a lot lower than the efficiency to charge the battery electric buses, in addition to efficiency losses due to transportation and storage of hydrogen.

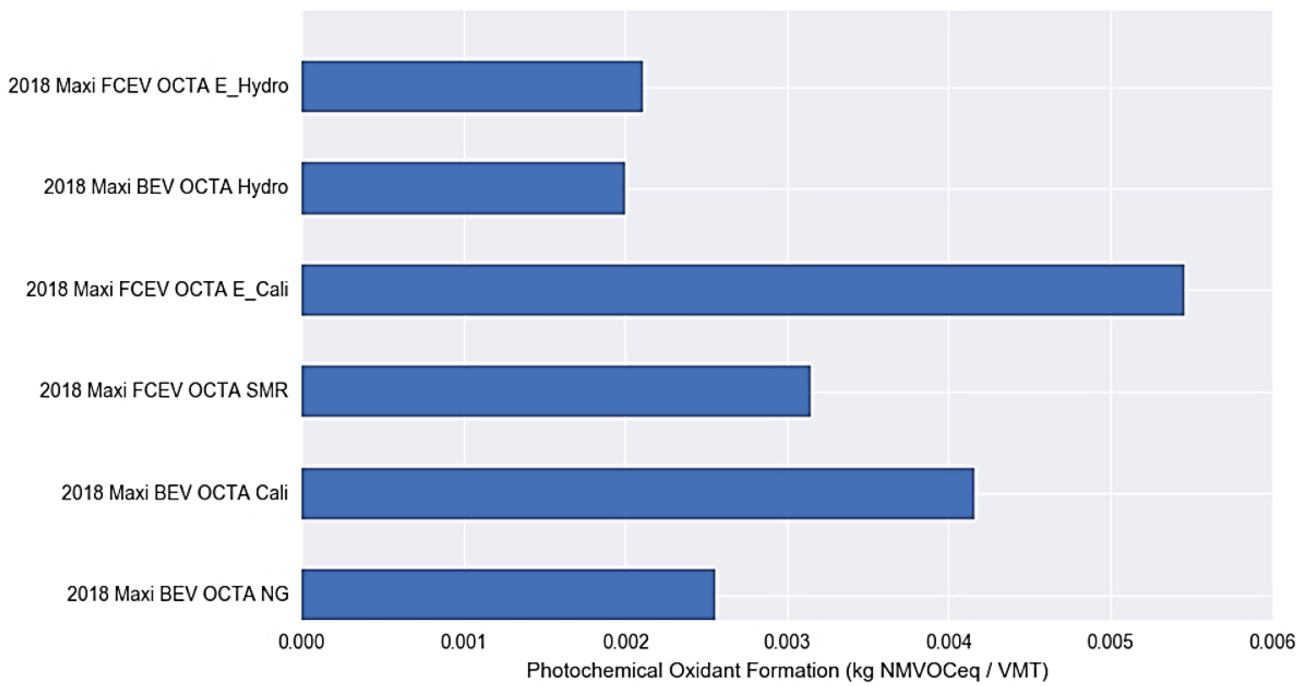



***Figure 38 Photochemical Oxidant Formation results for OCTA Scenarios***

The results for particulate matter formation are presented in Figure 39. Fuel cell and battery electric buses, dependent on hydropower as their feedstock, present the lowest kilograms of PM10 equivalent per vehicle mile traveled. Using natural gas to generate hydrogen via SMR results in lower PMF than using natural gas to generate the electiricy that is used to charge BEVs. Finally, the PMF emissions generated from using the CA grid to generate hydrogen via electrolsyis results in almost three times the emission than if hydropower is the feedstock.

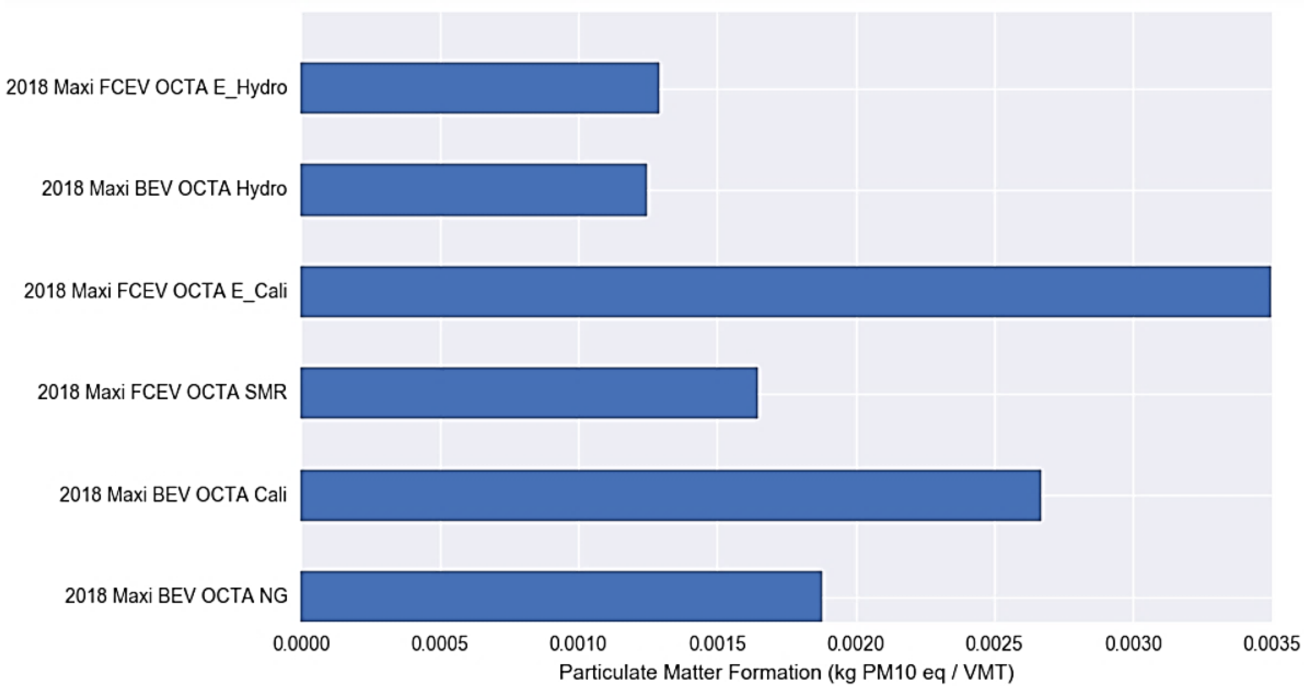



***Figure 39*** ***Particulate Matter Formation results for OCTA scenarios***

Figure 40 shows the ReCiPe Endpoint Total score for zero-emission buses operated at OCTA under different fuel generation scenarios. The Endpoint Total aggregates and normalizes all the mid-point categories to present an overall score. Therefore, under such a definition, producing hydrogen to operate fuel cell electric buses via electrolyzer powered with hydropower has the lowest impact in the environment, human health, and resources depletion; even more than using that hydropower to charge battery electric buses. If considering the Endpoint Total results as the only deployment parameter, using the current

California grid mix results in a higher impact on the environment and human health than the current bus baseline of CNG buses at OCTA. However, this category does not account for either the effect of the alternatives having high values across all endpoints or the interdependency of the indicators being aggregated. Specifically, the categories related to terrestrial acidification, photochemical oxidation, and freshwater ecotoxicity have scores above base-case scores due to the mining of precious metals for the construction of fuel cells and batteries.

In conclusion, the selection of an alternative powertrain and fuel supply chain needs to take into consideration where proper weights/relevance is assigned to each factor. Its recommended, for example, to perform a spatial analysis of such categories to determine the direct impact to communities and, thereby establish the priority of each factor.

When analyzing each factor independently, the fuel cell and battery electric buses with fuel generation derived from hydropower have the lowest score/measurement for the majority of LCIA factors. Analyzing the best-case scenario of fuel generation was beneficial since it revealed that categories with high measurement per mile traveled were independent of the fuel generation and linked to the production of powertrain; as it was the case for Photochemical Oxidant Formation, Terrestrial Acidification, and Freshwater Ecotoxicity.

Furthermore, the analysis of OCTA specific operation conditions in combination with three fuel feedstocks (hydropower, natural gas, California mix grid) documented evidence of the importance to continue incorporating renewables into the CA grid mix and thereby reduce emissions throughout the life cycle of zero-emission buses.

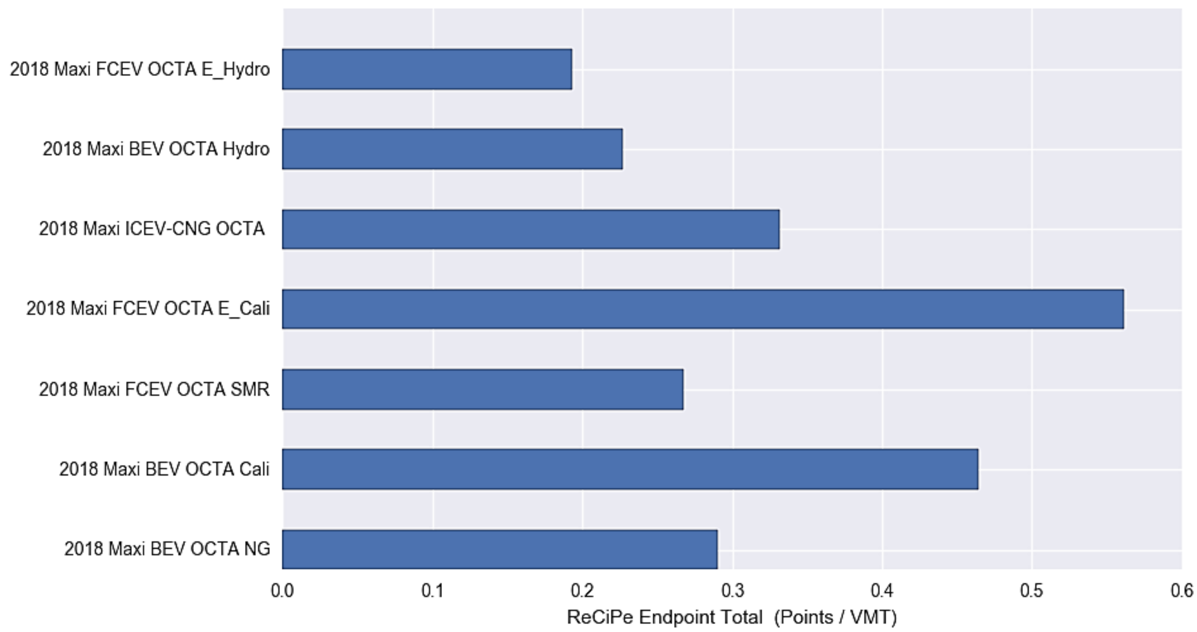



***Figure 40 ReCiPe Endpoint Total results for OCTA 2018 scenarios***

### 7.4. Results for Present and Future Zero Emission Buses

The second set of analyzed scenarios aimed to present the environmental results of current and future buses that can be deployed at any transit agency and is not specific to the operation conditions of OCTA. Additionally, this second scenario considered the two extremes of fuel generation. The best-case scenario for fuel generation, or the cleanest way to generate the fuel, is achieved with electricity generated from wind turbines to power both the BEV and the electrolyzer producing hydrogen. The other fuel generation pathway studied was the use of natural gas to generate electricity or support the generation of hydrogen by SMR. The operation conditions that were included in the present/future scenario are reflected in Table 26.

*Table 26 Specific conditions for present and future bus scenario*

| Aspect | Description |
|---|---|
| Powertrain options | CNG Bus<br>Diesel<br>Hybrid-D<br>BEV-LR<br>BEV-SR<br>FCEV |
| Fuel generation options | 1. Electricity generation from wind to directly charge BEBs and to power electrolysis for hydrogen generated (Wind\|\|BEB, Wind\|\|FCEB)<br>2. Electricity generation from natural gas using combined cycle power plant to charge BEBs directly and to power electrolysis for hydrogen generated (NG\|\|BEB, NG\|\|FCEB)<br>3. Hydrogen generated from an electrolyzer powered by wind (Wind\|\|FCEB)<br>4. Hydrogen generated from SMR using natural gas (NG\|\|FCEB) |
| Year of calculations | 2018<br>2040 |

The results for the global warming potential of present and future scenarios are presented in Figure 41. All zero emissions bus options have lower kilograms of equivalent $CO_2$ per mile than conventional buses, for both present and future scenarios. Additionally, BEB-SRs that are powered by all renewables, in this case wind, have the minimum global warming potential.

Figure 42 shows ReCiPe endpoint total results for the present and future scenarios. For the year 2018, hybrids have a lower impact than any ZEB that relies on natural gas for fuel generation. For the year 2040, the lowest impact is for ZEB that rely on wind to produce fuel, with FCEB and BEB-LR having the same score, and BEB-SR having the best score among all bus technologies. The emissions and score rate for future scenarios are presented in Table 27, the values of the GWP midpoint impact category and endpoint ReCiPe total score are used in the optimization for future scenarios in Chapter 10.

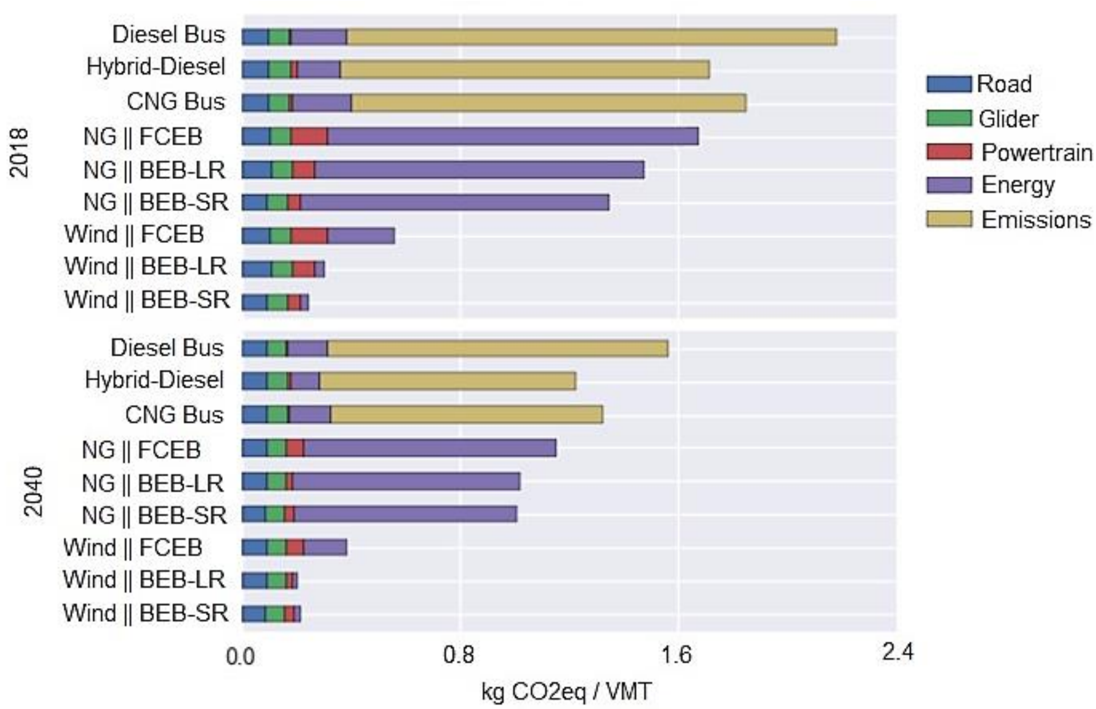



***Figure 41 Global Warming Potential results for present and future scenarios***

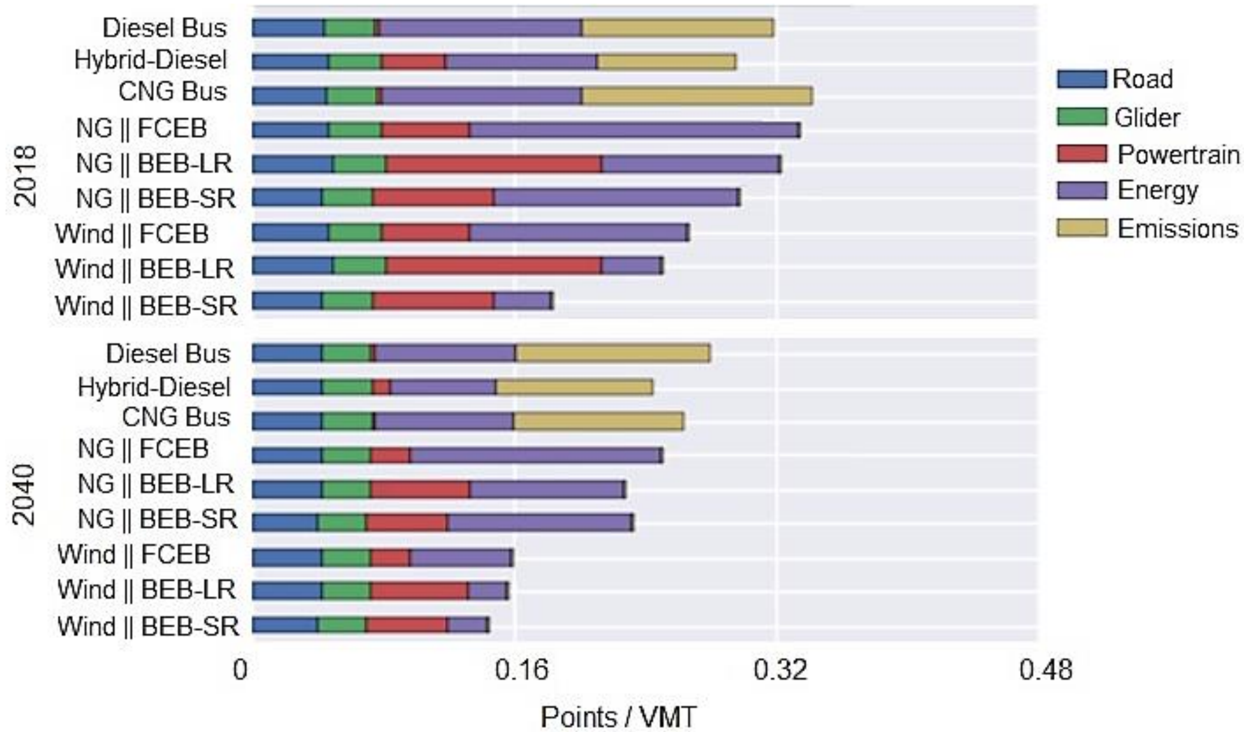



***Figure 42 ReCiPe Endpoint Total results for present and future bus scenarios***

***Table 27 Life Cycle Assessment Results of Selected Indicators for Future Scenario***

| | **Global Warming Potential Year 2040 (kg $CO_2$eq/VMT)** | **ReCiPe Endpoint Total Score Year 2040 (Points)** |
|---|---|---|
| **CNG Bus** | 1.3 | 0.26 |
| **Wind \|\| FCEB** | 0.25 | 0.16 |
| **Wind \|\| BEB-LR** | 0.2 | 0.16 |
| **Wind \|\| BEB-SR** | 0.2 | 0.15 |

Figure 43 presents the metal depletion potential in iron equivalent (Fe eq) per vehicle mile traveled. For all the ZEBs, powertrain production is the category that has the highest emissions production. Among all the ZEBs, the BEB-LR has the highest impact in metal depletion for the present scenarios; however, projected improvements in battery technology for the future scenarios reduce the overall impact of the BEB-LR in relation to the BEB-SR. Since all ZEBs have a standard electric motor design to overcome the same driving conditions, what creates the different level of emissions are the components that deliver power (either fuel cell or batteries). Therefore, the production of the batteries is what drives the level of metal depletion. This trend is the same for human toxicity potential (Figure 44) and for fresh water eutrophication (Figure 45). The design of scenarios with the minimum emissions from fuel generation using wind generation, allowed to identify that emissions for these three indicators are independent of the fuel generation process but are influenced the most by the production of powertrains.

The extended LCA methodology developed in this dissertation has the capability of generating results for any of the 18 midpoint or 3 endpoint ReCiPe indicators. However, for the purpose of the fleet optimization demonstration, only the global warming potential and the total endpoint score are factors considered. Appendix A presents the results for additional midpoint and endpoint indicators for the present and future scenarios.

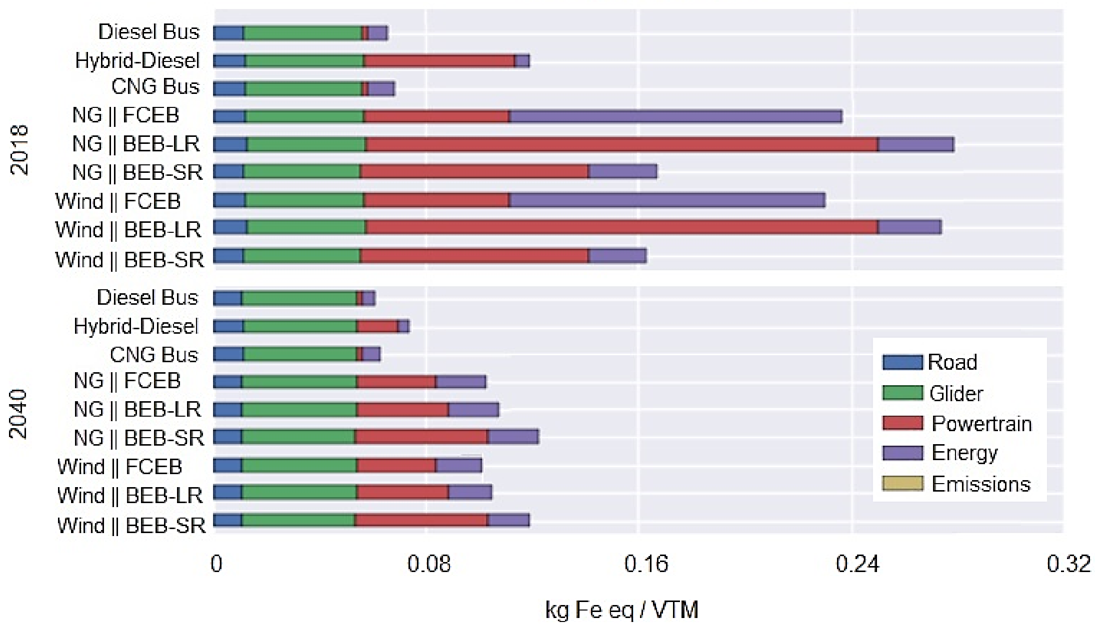



***Figure 43 Metal Depletion Potential results***

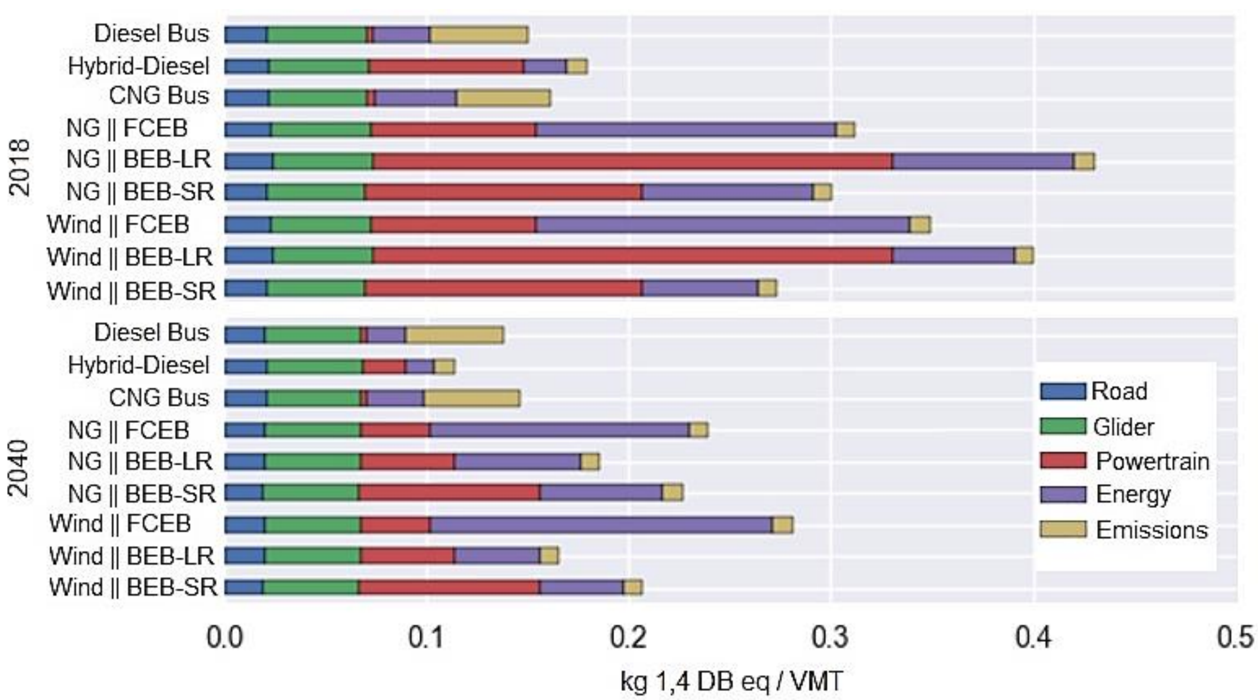



***Figure 44 Human Toxicity Potential results***

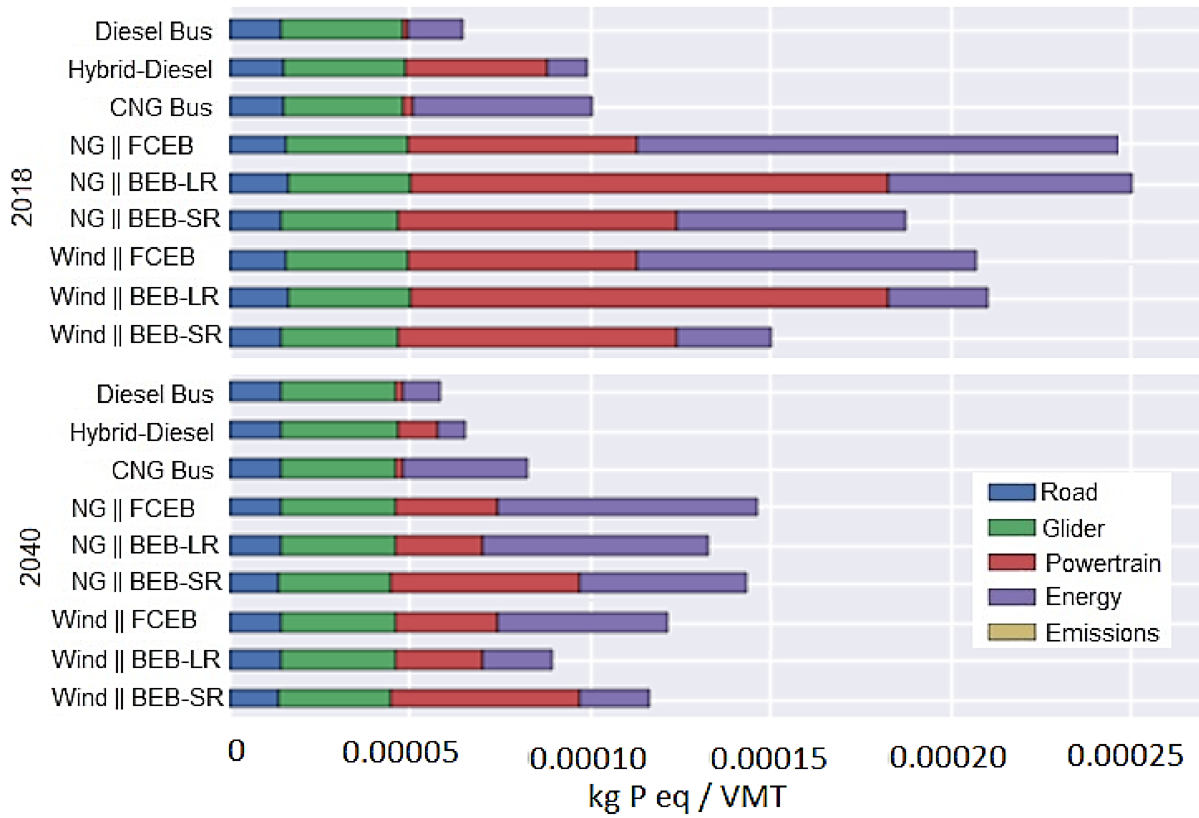



***Figure 45 Fresh Water Eutrophication Total***

# CHAPTER 8. Life Cycle Cost of Zero-Emission Buses

Life Cycle Costing (LCC) is a technique to establish the total cost of ownership; it is a structured approach that can assist in the selection process that transit agencies will be facing in the transition to zero-emission fleets. Total Cost of Ownership (TCO), as defined by Wouters et al. (2005, p. 167), is an application of activity-based costing (ABC) that quantifies the costs that are involved in acquiring and using purchased goods; that could include maintenance, asset disposal, training, cost of upgrades, energy consumption, resources used in manufacture, and cost of operations.

The total cost of ownership was applied in this research work as a philosophy for understanding all relevant supply chain related costs to the acquisition and operation of public transit buses. TCO does not actually require the precise calculation of all costs but looks at major cost issues, and costs that may be relevant to the decision at hand [114]. Price is one element of the total cost of ownership, and often the largest single element, but still only one piece of TCO.

The total life-cycle cost for each of the zero-emission bus technologies studied in this work included the calculation of the total cost of ownership considering the following mayor expenses (Figure 46):

- Bus purchase cost
- Midlife overhaul
- Capital cost of fueling infrastructure
- Operation and maintenance
  - Cost of scheduled maintenance
  - Cost of unscheduled maintenance
- Cost of operation
  - Cost of fuel
  - Driver's wages

Table 28 shows the main parameters for the TCO calculations, and Table 29 summarizes the cost parameters used in the TCO calculations. Detailed explanations, justification, and documentation for each of these assumptions can be found in the "Cost Inventory Database" section.

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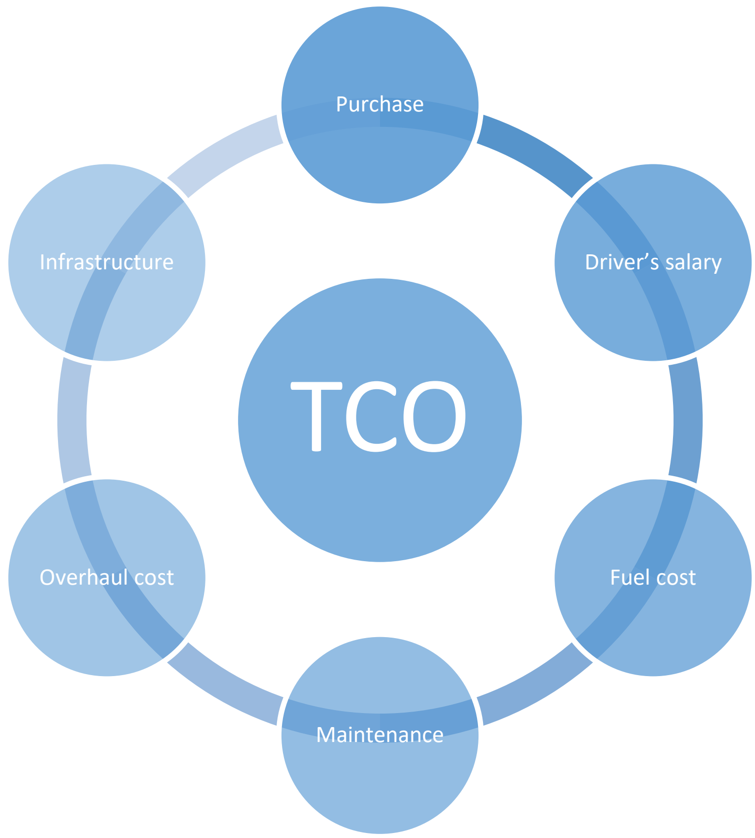



***Figure 46 Factors considered in the total cost of ownership calculations***

***Table 28 Simulation Parameters for TCO calculations***

| **Assumptions** |
| --- |
| 12 years of life span for buses |
| 3.44% interest rate per year |
| 3.5% inflation rate per year |
| Fueling station design for a minimum of 150 buses |
| 520,000 Vehicle Miles Traveled (VMT) |
| Midlife overhaul at 260,000 miles |

*Table 29 Cost parameters for the total cost of ownership calculations of transit buses*

| | BEB-LR | BEB-SR | FCEB | CNG | Diesel |
|---|---|---|---|---|---|
| **Bus Purchase Price** | $780,000 | $800,000 | $1,000,000 | $650,000 | $480,000 |
| **Maintenance Cost** | $0.61 | $0.61 | $0.48 | $0.57 | $0.85 |
| **Fuel Price** | $0.15/KWh<br>$5.66/DGE | $0.18/KWh<br>$6.77/DGE | $H_2$CAT[6] | $0.93/DGE | $2.21/DG |
| **Overhaul Cost** | $700/KWh | $700/KWh | $67,300 | $70,500 | $50,000 |
| **Fueling Equipment cost per charger** | $40,000 | $500,000 | $H_2$CAT | $5,168,000 | $100,000 |
| **Fueling Installation cost per charger** | $70,000 | $250,000 | | | |
| **Driver Hourly Wage** | $27/hr. | $27/hr. | $27/hr. | $27/hr. | $27/hr. |

The fuel efficiency for each bus powertrain used to model the TCO was calculated based on a dynamic model that standardizes the bus operations to have a comprehensive cost comparison, as described in the "Modeling of Urban Bus Energy Consumption" section. This methodology was used instead of reported fuel efficiency values that are affected by operational conditions like different driving speed, diversity of driving terrains, load factor, and bus configurations. By standardizing operation conditions and any other bus component besides the main powertrain, estimated fuel efficiencies were obtained that allows for an apples-to-apples comparison when applying a life cycle cost analysis.

[6] Hydrogen Characterization and Analysis Tool ($H_2$CAT)[92] estimates hydrogen prices according to the methodology described in Figure 15.

### 8.1. Battery Electric Buses Total Cost of Ownership

The two types of battery electric buses considered were over-night charging plug-in buses that have a long range (BEB-LR) and short-range buses (BEB-SR) that can charge on-route. Figure 47 shows the total cost of ownership for these two types of battery electric buses; the TCO presented is per unit vehicle. The main cost difference in the TCO analysis between these buses is the midlife overhaul and infrastructure costs. Since the size of the battery differs around 200 kWh between BEB-LR and BEB-SR, the cost of replacing the batteries at midlife for BEB-LR is higher than for BEB-LR. However, the installation and equipment cost of BEB-SR is higher than for BEB-LR, which makes up for some of the midlife-overhaul cost difference. Furthermore, given that BEB-SR needs to charge while on-route, the purchase of electricity can be subject to demand chargers, resulting in a higher cost of electricity. From the results presented in Figure 47, it can be concluded that the total cost of ownership for battery electric buses deployed in Southern California is approximately $2.84 million for both types of electric buses, plug-in, and on-route charging.

The allocation of on-route charges installed in the service routes of BEB-SR is a complex problem, and it can be subject to extensive simulations to minimize costs. For this research work, the calculations were simplified by assuming that for any route shorter than 50 miles one charger is allocated for each direction of the route (total of two chargers per route). Additionally, if more than eight buses are allocated to the same route, then an additional set of chargers needs to be installed in such route to avoid long waiting periods for charging.

The TCO calculation for plug-in electric buses (BEB-LR) in Figure 47 does not take into consideration the range limitations of the bus to cover the route length. From internal data collected with OCTA, over 44% of the routes covered by this agency are more than 120 miles long. To consider the cost implications that a transit agency needs to incur to accommodate the operational constraints that range limitations causes, an additional scenario was modeled for the TCO of BEBs. It's was assumed that, if a route is more than 140 miles long, one additional BEB-LR needs to be purchased and assigned to such route. While not practical since increasing the number of buses in a fleet is usually not viable for transit agencies due to space limitations, lack of operators, and FTA funds, this additional scenario sought to consider operational constraints and to quantify the economic impact of such limitations. This additional scenario is presented in Figure 47 under the label "BEB w/extra buses."

Incorporating additional buses to a fleet has cost implications. Even when the total cost of ownership is expressed per bus unit, the cost of wages and costs of operations increases the overall life-cycle cost. The total cost of ownership for this scenario is $3.08 million, as shown in Figure 47. The calculations of the extra buses to compensate range limitations was only calculated using plug-in BEBs since the limitation is eliminated with on-route charging. Even when this scenario considers great simplifications to the logistics of increasing the number of buses in a fleet, it's a more accurate reflection of the LCC for BEBs-LR, and the results should be of more relevant to stakeholders than results that do not take into account operational constraints from range limitations.

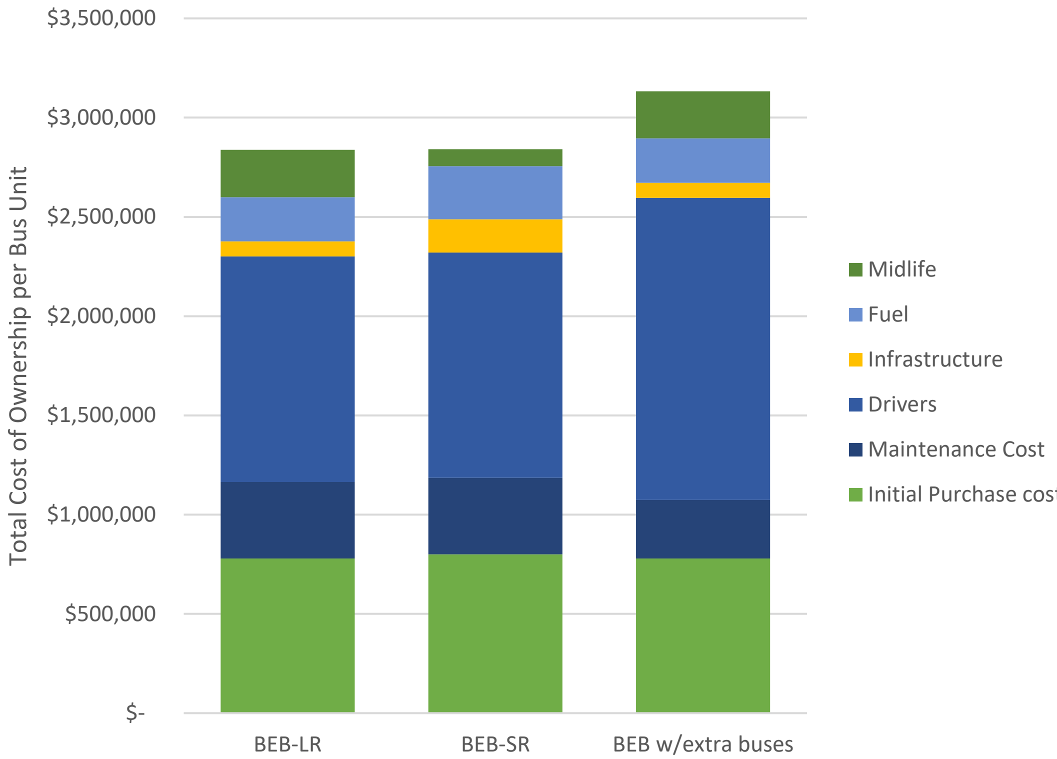



***Figure 47 Total Cost of Ownership of Battery Electric Buses***

The fuel price, one of the driving factors in the TCO calculations, has uncertainty that needs to be considered. In particular, the price assigned per kilowatt-hour can drive the cost estimations in favor of a given bus powertrain and can be the determining factor of adoption for transit agencies. Transit agencies adopting zero-emission fleets find themselves transitioning from simple supply contracts that are only subject to market variations to negotiating long term electricity tariffs with their utility company, state regulatory bodies, and the state utility commission. Because of the (1) large power demand that battery electric buses represent for an agency, and (2) a changing grid mix that is adjusting to an increasing present of renewables, it is a challenge to project long-term electricity costs.

The variation in electricity rate charges and its effect on the total cost of ownership was studied. Figure 48 presents the TCO of BEB-LR under different electricity rates, and Table 30 provides details of the cost assumptions for each scenario.

***Table 30*** ***Electricity Costs Depend on Utility Rate and Charging Pattern***

| Utility Company | Cost of Electricity at Depot charge $/kWh | $/DGE |
|---|---|---|
| SCE | 0.18 | 6.77 |
| PGE | 0.24 | 9.03 |
| SDGE | 0.34 | 12.80 |
| LADWP | 0.20 | 7.53 |
| BEB-SR | 0.18 | 6.77 |

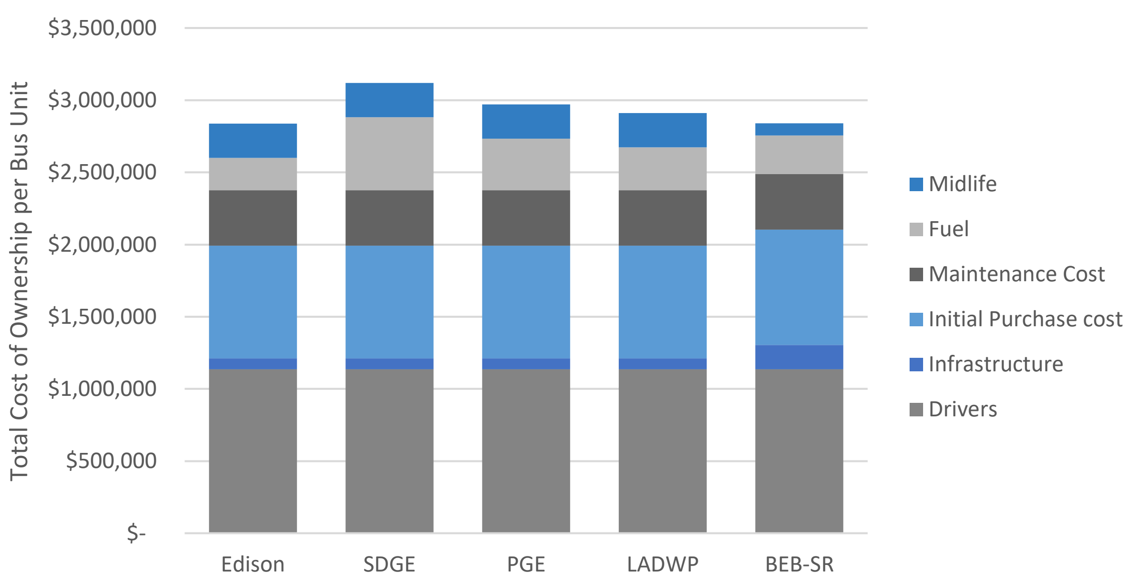



***Figure 48*** ***Total Cost of Ownership for BEBs with different electricity rate charges***

The TCO for a plug-in battery electric bus (BEB-LR) can be as low as $2.84 million per bus or as high as $3.12 million when the electricity price range is between eighteen cents and thirty-four cents per kilowatt-hour. The variation in TCO can be even more drastic for on-route charging buses (BEB-SR) since they can be subject to demand chargers. However, an electricity use model that can capture the effect of demand chargers requires detailed information on the daily schedule for an entire fleet.

### 8.2. Fuel Cell Electric Buses Total Cost of Ownership

When modeling the life cycle cost of fuel cell electric buses, it's necessary to investigate the impact that the different fuel supply pathways have on the total cost. Applying the same methodology used to calculate the TCO of BEBs, the total cost of ownership was estimated for three different hydrogen distribution methods (liquid delivery, distributed SMR, pipeline) and compared to the hydrogen price target stablished by the FTA of $4 per kilogram.

As described in the Cost Inventory Database section, the model $H_2$CAT [92] was used to project the price of hydrogen under different generation and distribution pathways. $H_2$CAT considers the cost of equipment, maintenance, and operation of the station, inflation and interest rate, and all the costs are levelized and integrated to calculate the final price of hydrogen in dollars per kilogram. The cost per kilogram of hydrogen calculated with $H_2$CAT for each distribution scenario is shown in Table 31; the cost of hydrogen was then used to calculate the TCO for the corresponding scenarios.

Figure 49 presents the TCO results for FCEBs. The fuel supply pathways with lower TCO are distributed SMR with $2.86 million per bus and hydrogen delivered via pipeline with

$2.89 million per bus. These two scenarios have the same cost for all the other categories (purchase, maintenance & operation, and midlife overhaul) with the only difference in the levelized price of hydrogen.

Delivery of liquid hydrogen to supply FCEBs resulted in a TCO of $3.02 million per bus, which is $29,000 above the TCO of the FTA target that assumed a hydrogen price of $4 per kilogram.

The cost bars in Figure 49 do not show the cost of infrastructure since the capital cost, and operation cost of the station is already reflected in the price per kilogram of hydrogen for all the scenarios, except for the FTA scenario.

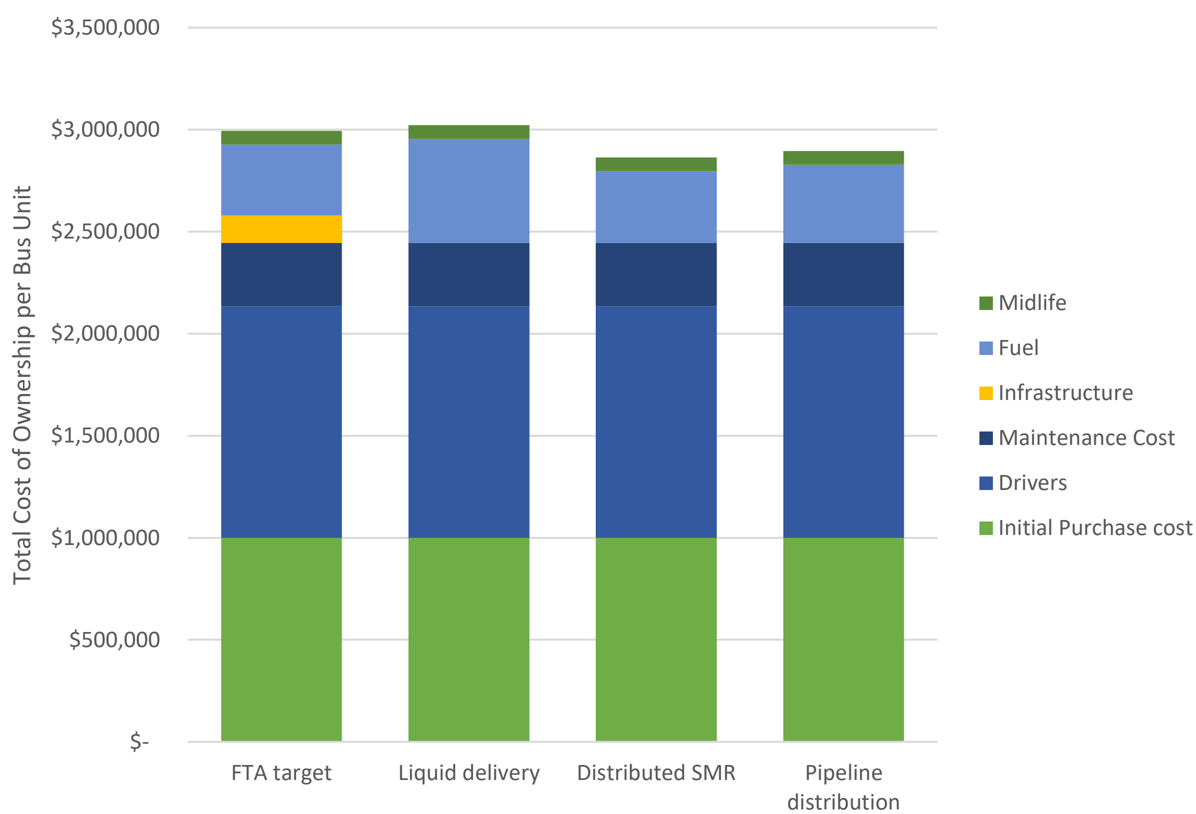



***Figure 49 Total cost of ownership of Fuel Cell Electric Buses with different hydrogen distribution pathways***

*Table 31 Minimum Cost of Hydrogen for different distribution pathways from $H_2$CAT*

| Distribution Pathway | Cost of Hydrogen ($/kg) |
|---|---|
| Pipeline | $ 4.43 |
| Distributed SMR | $ 4.08 |
| Liquid Hydrogen | $ 5.91 |
| FTA goal (without infrastructure) | $ 4.00 |

To further analyze how the variation in fuel price impacts the total cost of ownership, Figure 50 presents the TCO for fuel cell, and battery buses with the mean and variability resulted from different fuel prices. The middle line of the box represents the median, $2.94 million for FCEB and $2.91 for BEBs. The mean for FCEBs is the same value as the median, $2.94 million; and for BEBs, the median TCO value is also $2.94 million. Because the set of information used to calculate TCO of BEBs is based on possible electricity rates and no actual data points from a population, the mean is a better-expected value of TCO for BEBs. Meaning that if we take into consideration variations in the fuel prices for both hydrogen and electricity, the total cost of ownership for FCEBs and BEBs can be expected to be the same, $2.94 million per bus.

The median divides the data set into a bottom half and a top half. The bottom line of the box represents the median of the bottom half or 1st quartile; in millions, $2.87 for FCEB and $2.84 for BEB. The top line of the box represents the median of the top half or 3rd quartile; $3.02 for FCEB and $3.08 for BEB. The whiskers (vertical lines) extend from the ends of the box to the minimum value and maximum value. Therefore, the total cost of ownership for fuel cell electric buses can be expected to be between $2.86 million and $3.02 million per bus; as for battery electric buses, it can be expected to be between $2.84 million and $3.12 million.

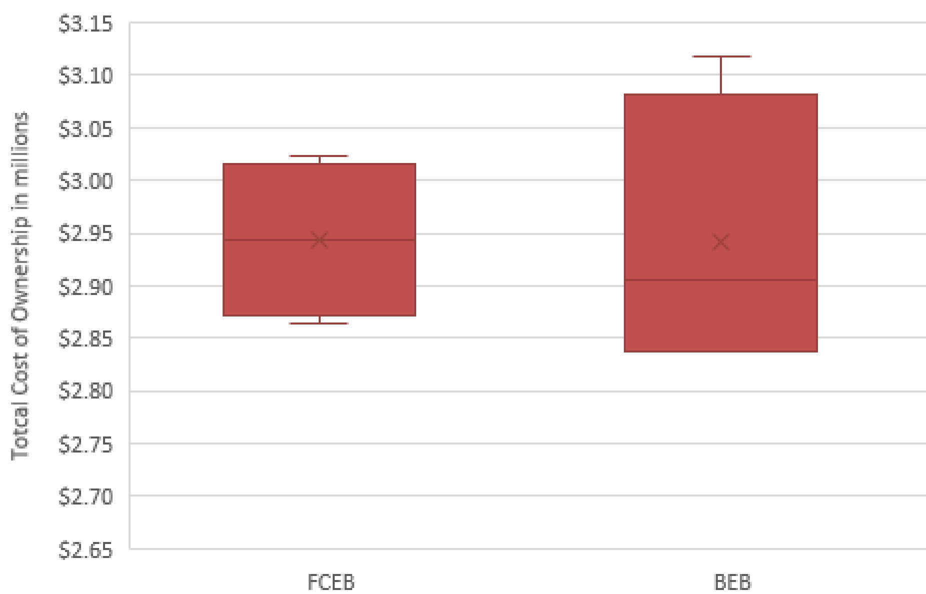



***Figure 50 Total Cost of Ownership of FCEBs and BEBs with mean and variability***

## 8.3. Total Cost of Ownership of Zero-Emission and conventional Fuel Transit Buses

The life cycle cost of conventional-fuel buses was calculated in the form of the total cost of ownership to compare with the cost of zero-emission buses. Figure 51 presents the TCO for all the powertrains considered in this research work. CNG buses have the lowest TCO with $2.46 million per bus; diesel buses follow with a TCO of $2.55 million. Battery electric buses – both LR and SR - have a TCO of $2.84 million, which is an increase of $382 thousand with respect to CNG buses. However, as it was analyzed in prior sections, the TCO of BEB-LR does not take into consideration the range limitations that impose operational constraints. If takin into consideration that additional battery electric buses are required to provide the same service coverage, then the TCO of $2.89 million required by fuel cell buses is lower than for BEBs ($3.08 million).

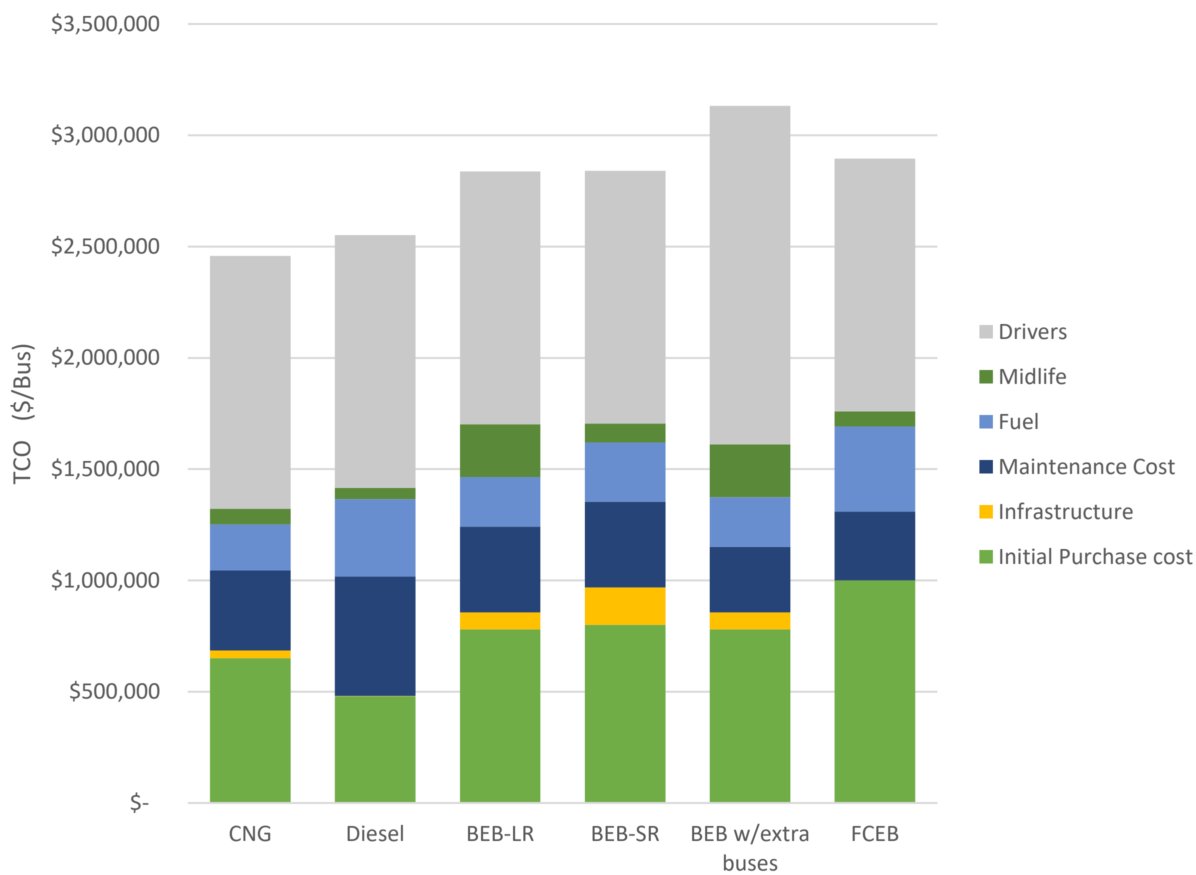



***Figure 51 Total Cost of Ownership of zero-emission and conventional-fuel buses***

Figure 52 compares the TCO of FCEBs. BEBs, CNG buses, and Diesel buses using a box plot. In the figure, the minimum and maximum are displayed with the whiskers; first and third quartile with the ends of the box; the cross represents the mean; a vertical line goes through the box at the median. The FCEB and BEB have the same mean of $2.94 million, but the BEB has a lower median ($2.91 million). Even though the minimum cost calculated for BEBs can be lower than for FCEBs, the max TCO can also be higher for BEBs with respect to any other bus alternative.

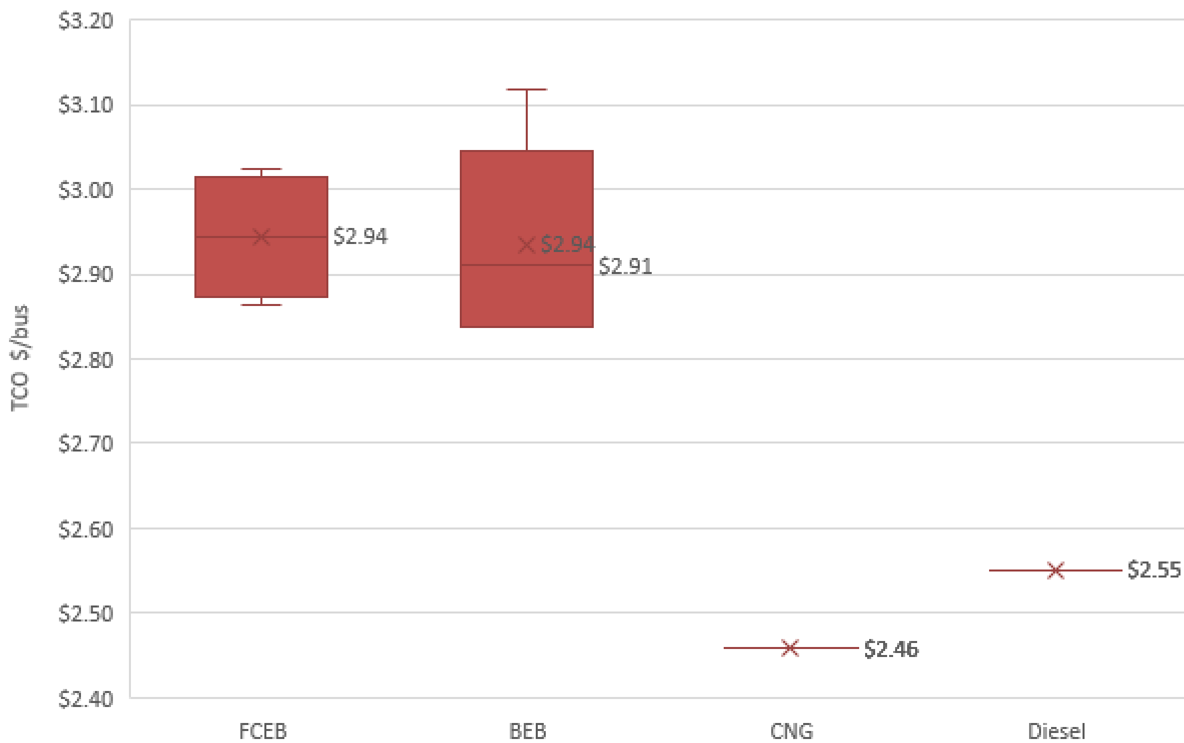



***Figure 52 Total Cost of Ownership of transit buses with mean and variability***

### 8.4. Future Scenario Total Cost of Ownership

In order to analyze the influence that cost parameters have in the optimization of bus fleets, a future scenario was designed. The purpose of the cost inventories for future years is not to predict the trend in costs, but to demonstrate the importance of the information that is input into the optimization model and to illustrate the impact of the input information on the results.

The cost inventories developed in Section 5.4 were used to calculate the total cost of ownership for the ZEBs and CNG buses in the year 2040. The cost assumptions were obtained from the Air Resources Board, and are the calculations used to estimate economic impacts of the Innovative Clean Transit regulation [104]. The future TCO of the different bus technologies is presented in Figure 53.

The purchase price of the BEB-LR and the BEB-SR increased from 2018 to 2040 but decreased for the FCEB. For the year 2040, the price per kWh remained relatively unchanged compared to 2018 since it was projected to follow a decreasing trend from a max price reached in 2030. The fuel economy improvements for the year 2040 were calculated based on the methodology described in Chapter 6.

The TCO for CNG increased from close to $2.4 million per bus in 2018 to $3 million in 2040. The main factor that influenced the increase in TCO was the capital cost of the bus purchase and a projected increase in the cost of natural gas.

In general, the TCO for all the ZEBs show an increase from 2018 to 2040. However, the trend relative to one another changes from 2018 to 2040. For the year 2040, BEB-LRs have the lowest TCO followed by FCEBs. Lastly, for the year 2040, CNG buses have the highest TCO when, in 2018, CNG buses had the lowest cost value.

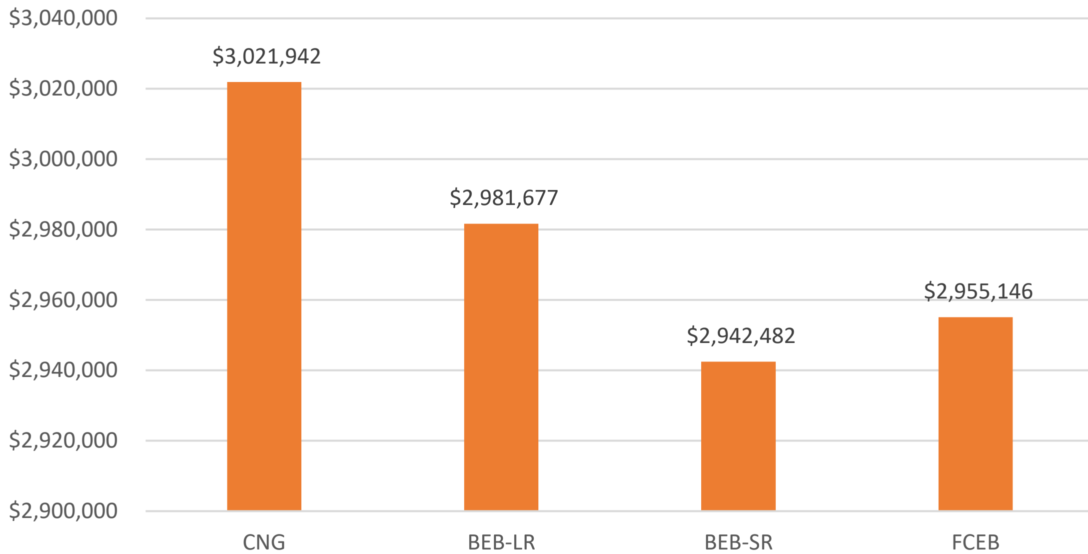



***Figure 53 Total Cost of Ownership for Bus Technologies in 2040***

# CHAPTER 9. Multi-Criteria Decision Analysis

Multi Criteria Decision Analysis (MCDA) is a framework used to support complex decision-making situations with multiple conflicting objectives that decision-makers or stakeholders value differently [115].

Figure 54 shows an illustration of the MCDA process used for this work. The first stage was to identify the problem, followed by problem structuring, creation of a model, application of the model, and development of an action plan. Each stage is further explained in the continuing sections.

## 9.1. Objective

The objective was to define the weighting for the parameters used in the selection of zero-emission bus technology that would satisfy the needs of a given transit agency while accommodating operational constraints. The following aspects were defined to structure the main objective:

- Goal – Define a set of criteria and sub-criteria that are crucial to consider for the selection of zero-emission bus fleets. By evaluating the priorities from stakeholders, users, and regulatory agencies, a consensus on the weighting assigned to each category can be found.
- Key Issues – Cost of investment, maintenance, operational constraints, environmental impact, disruption to the agency, and served communities.

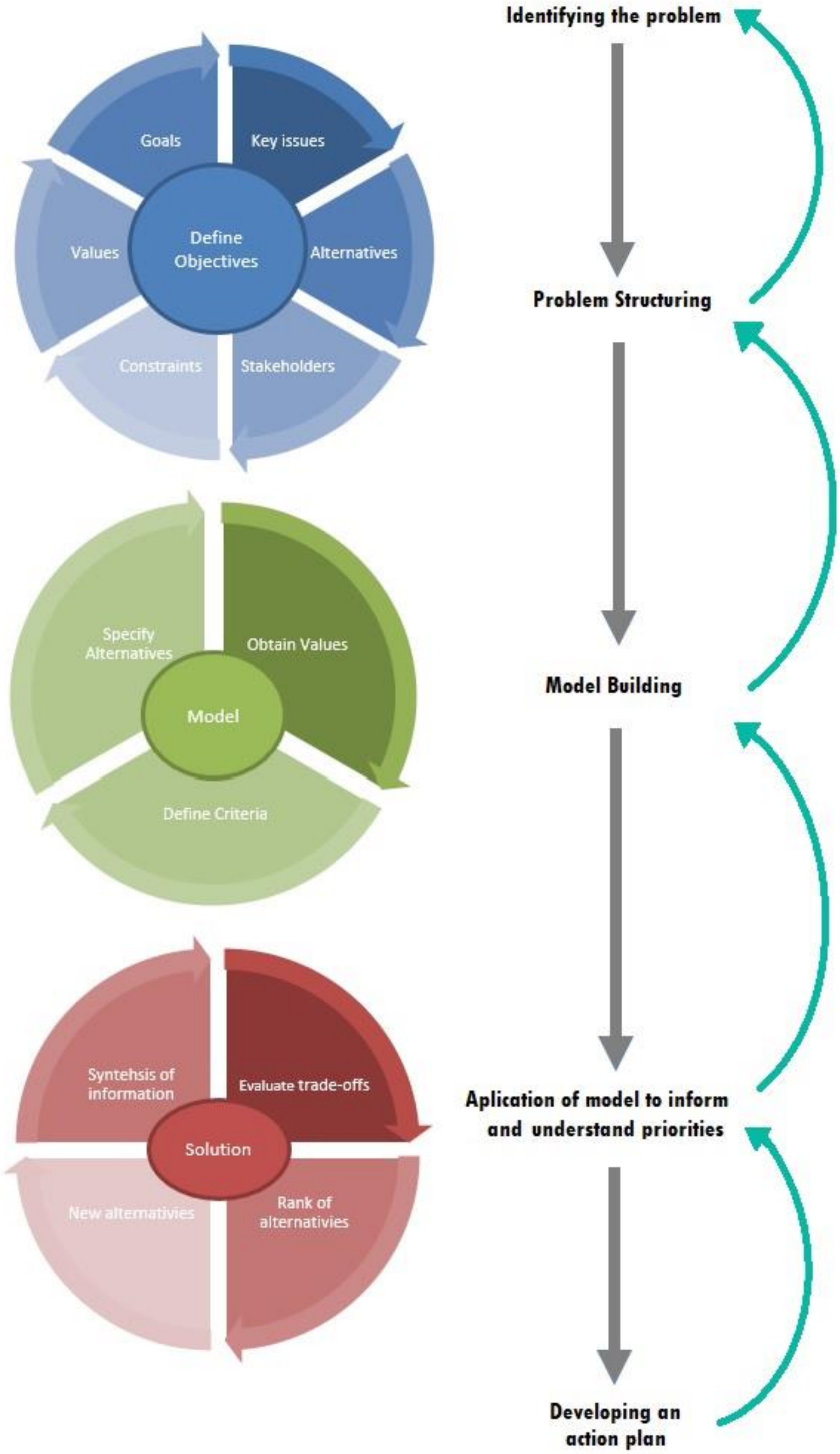



***Figure 54 An illustration of an MCDA process, modified from Belton and Steward (2002)***

- Stakeholders – The following groups were identified as key decision makers for the adoption of zero-emission fleets in California:
    - Transit agencies
    - Manufacturers
    - Stage regulatory agencies
    - Federal agencies
    - Research groups/institutes
    - City representative
    - Utility companies
    - Non-Governmental Organizations.
- Constraints – It was necessary to study the operational constraints transit agencies will face for the deployment of the different zero-emission alternatives. The information was collected from demonstration projects [30] and shared experiences by the Anteater Express bus fleet at UCI which deployed a hydrogen fuel cell bus in 2016. The main constraints related to daily operations that were identified are bus mileage, refueling time, and space availability.
- Values – The State of California is in the final stages of writing a regulation that will require all medium and large transit agencies to transition to zero-emission fleets by 2040 [116]. The regulation reflects a set of values and priorities for the State that needs to be adopted by transit agencies. The core values behind the regulation are environmental impacts, which specifically refers to, reduction of greenhouse gases, elimination of criteria air pollutants to improve air quality, and

human toxicity to reduce health risks. Additionally, the impact to communities that would be receiving service from these fleets was taken into consideration; these impacts can be negative like increased traffic due to infrastructure modifications, or positive such as noise reduction and improved air quality.

## 9.2. Model

The purpose of the model is to define the criteria for deployment, obtain values (scores), and specify potential alternatives to complete the above-defined objectives. The main structure of the model consists of a survey that incorporates all the aspects of the identified problem (Section 9.1). To develop the survey, a set of criteria and sub-criteria were identified. The distributed survey can be found in Appendix B. The survey was then distributed to all the stakeholders for them to provide a weight by following implementing the following three steps.

### 9.2.1. Define Criteria

Using the definition of the problem from Section 9.1, the following criteria and sub-criteria were identified as essential to consider when deploying new bus technologies in transit agencies:

- Impact on community
- Operational constraints
- Environmental impact
- Fuel supply
- Maintenance cost
- Capital cost

Each category had a sub-criterion for the consideration of the stakeholders (Table 32). The selection of the categories and sub-criterion was based on demonstration projects, and experiences gathered from transit agencies that have started deployment of zero-emission buses [78], [80], [117], [118]. Such projects have recorded the bidding and acquisition process, daily operations, maintenance logs, operational challenges, and have had extensive outreach activities to hear back from the communities they serve. Several of the recommendations reflected in the demonstration project reports were used to create the main categories and enquire among stakeholders about their relevance. Another important source of information to define the categories and sub-criterion was the experience of bus acquisition and deployment of Anteater Express (AE), the organization providing transportation services at the UCI campus. In 2016, AE acquired a hydrogen fuel cell bus that was refueled at the UCI hydrogen station; the first station opened to the public in Southern California. Starting January of 2018, six out of twenty battery electric buses joined the fleet. The delivery of BEBs was finalized in May of 2018. Monthly meetings with AE provided a detailed insight into the transition to a zero-emission fleet with combined bus technologies.

*Table 32 Sub-criteria for the deployment of zero-emission bus technologies*

| Category | Sub-criterion |
|---|---|
| **Capital Cost** | Capital cost of buses |
| | Capital cost of station |
| | Adaptation cost of maintenance facilities |
| **Maintenance Cost** | Fuel price |
| | Mid-life overhaul |
| | Routine maintenance |
| | Cost of road calls |
| **Fuel Supply** | On-site generation (hydrogen/electricity) |
| | Third-party vendor/supplier |
| **Environmental Impact** | Greenhouse gases |
| | Regional air quality like criteria pollutants |
| | Human health toxicity |
| **Operational Constraints** | Bus mile range |
| | Refueling time |
| | Space availability for fueling infrastructure |
| **Impact on Community** | Traffic Impact |
| | Noise reduction |
| | Rare-metals mining |

### 9.2.2. Specify Alternative

The alternatives evaluated in the MCDA survey included the bus technologies currently under consideration for the Innovative Clean Act by the California Air Resource Board [116]:

- Hydrogen fuel cell electric bus (HFCEB)
- Battery electric bus (BEB) plug-in
- Battery electric bus (BEB) on-route charging

These zero-emission buses are also considered to be on a readiness level (RL) 9 by the National Renewable Energy Laboratory (NREL) and are commercially available. The survey also included diesel hybrid electric buses as one of the alternatives. Even though hybrid buses are not being considered by CARB in the Innovative Clean Act, since it's not zero-emission, it was included in the survey as a baseline.

### 9.2.3. Obtain Values

The values for the evaluation and ranking of the main categories we assigned by allocating 100 points among the six categories. The more important the criterion, the higher it's weight. The sum of the scores for all categories should add up to 100.

Provide to each sub-criterion its own weight. Weights can take on any value between zero and the maximum of the main category (group weight). For example, if a group weight or category was assigned 25 as the score/value, the sub-criteria in that group can range from 0 to 25. The sum of the sub-criteria does not need to add to the score of the category, and the same value can be assigned repetitively in that group.

## 9.3. Solution

### 9.3.1. Evaluation

Over thirty surveys were distributed to representatives of the stakeholders described in section 9.1; fifteen responses were received. Each representative assigned a score to each category. Results obtained from the survey for the deployment categories are presented in Figure 55.

The category that ranked with the highest score was operational constraints with 26 out of 100. Maintenance cost and capital cost were the two categories that ranked second with almost the same score, 18 and 19 out of 100, respectively. Environmental impact and fuel supply had the same score and ranked third in importance. Finally, the impact on the community was the lowest scored category with 9 of 100.

The scores for each category obtained from the MCDA survey will be used as the weighting for optimization parameters in Chapter 10.

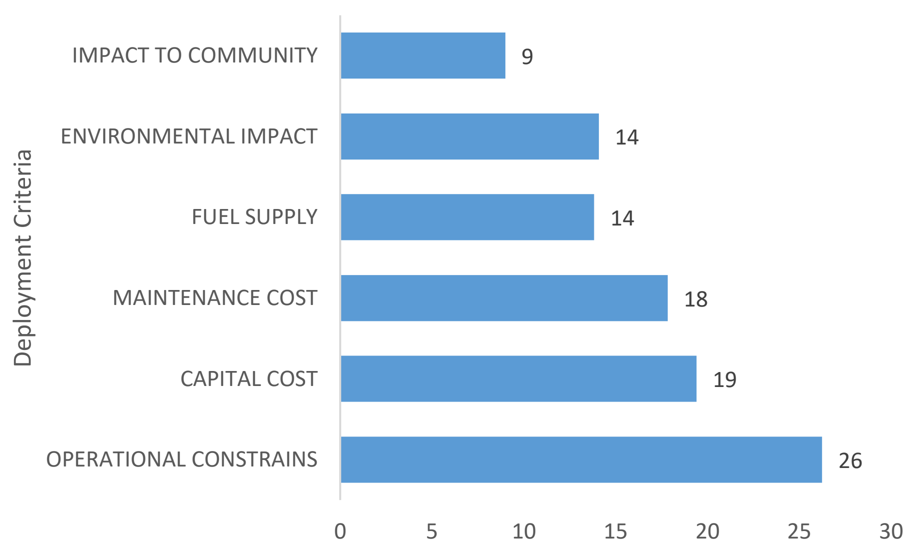



***Figure 55 Results of MCDA survey for deployment categories***

Results for the subcategories gathered from the MCDA survey are presented in Table 33. The sub-criterion could receive any score between zero and the number assigned to the category it belongs to. The category "operational constraints" was the highest ranked and the sub-criterion of major relevance for this category was bus mileage range. In fact, bus mile range was the highest ranked among all the sub-criteria with a score of 16. The sub-criteria with the highest score were the capital cost of the buses and the fuel price. Figure 56 shows a graphic representation of these results.

***Table 33 Average ranking for main zero-emissions deployment criteria and sub-criteria***

| | **Average Ranking for Main Criteria** | **Average Ranking for Sub-criteria** |
|---|---|---|
| **CAPITAL COST** | **19** | |
| Capital cost of buses | | **13** |
| Capital cost of station | | **12** |
| Adaptation cost of maintenance facilities | | **8** |
| **MAINTENANCE COST** | **18** | |
| Fuel price | | 13 |
| Mid-life overhaul | | 7 |
| Routine maintenance | | 7 |
| Cost of road-calls | | 5 |
| **FUEL SUPPLY** | **14** | |
| On-site generation (hydrogen/electricity) | | **11** |
| Third-party vendor/supplier | | **9** |
| **ENVIRONMENTAL IMPACT** | **14** | |
| Greenhouse gases | | **8** |
| Regional air quality like criteria pollutants | | **10** |
| Human health toxicity | | **7** |
| **OPERATIONAL CONSTRAINTS** | **26** | |
| Bus mile range | | **16** |
| Refueling time | | **10** |
| Space availability for fueling infrastructure | | **12** |
| **IMPACT TO COMMUNITY** | **9** | |
| Traffic Impact | | **5** |
| Noise reduction | | **6** |
| Rare-metals mining | | **5** |

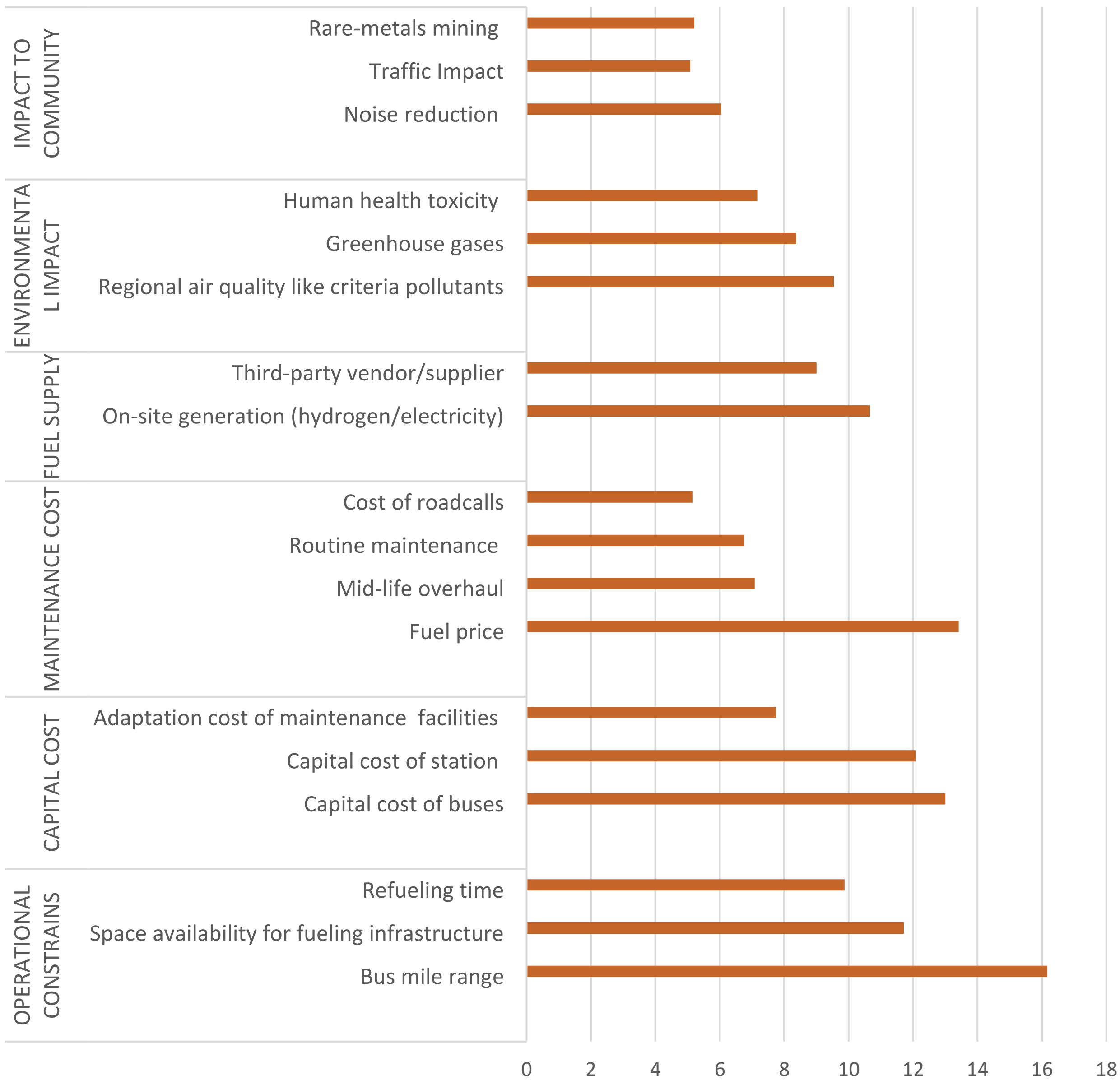



***Figure 56 Graphic representation of scores assigned to deployment criteria and sub-criteria obtained from the MCDA survey***

The capital cost of zero-emission buses and of fueling infrastructure continues to be the main deployment challenge for transit agencies. From Figure 57, it can be observed that besides capital cost constraints, logistics regarding refueling of the buses is a key component for the deployment of clean buses. Space availability for refueling infrastructure ranked fifth among the sub-criteria. The survey revealed a preference of having an on-site generation of fuel (either hydrogen or power generation) over third-party suppliers. Some of the options for on-site generation are electrolyzers powered by the grid or from renewable sources, distributed steam methane reformation (SMR) units to generate hydrogen or solar panels with batteries on-site to charge BEBs.

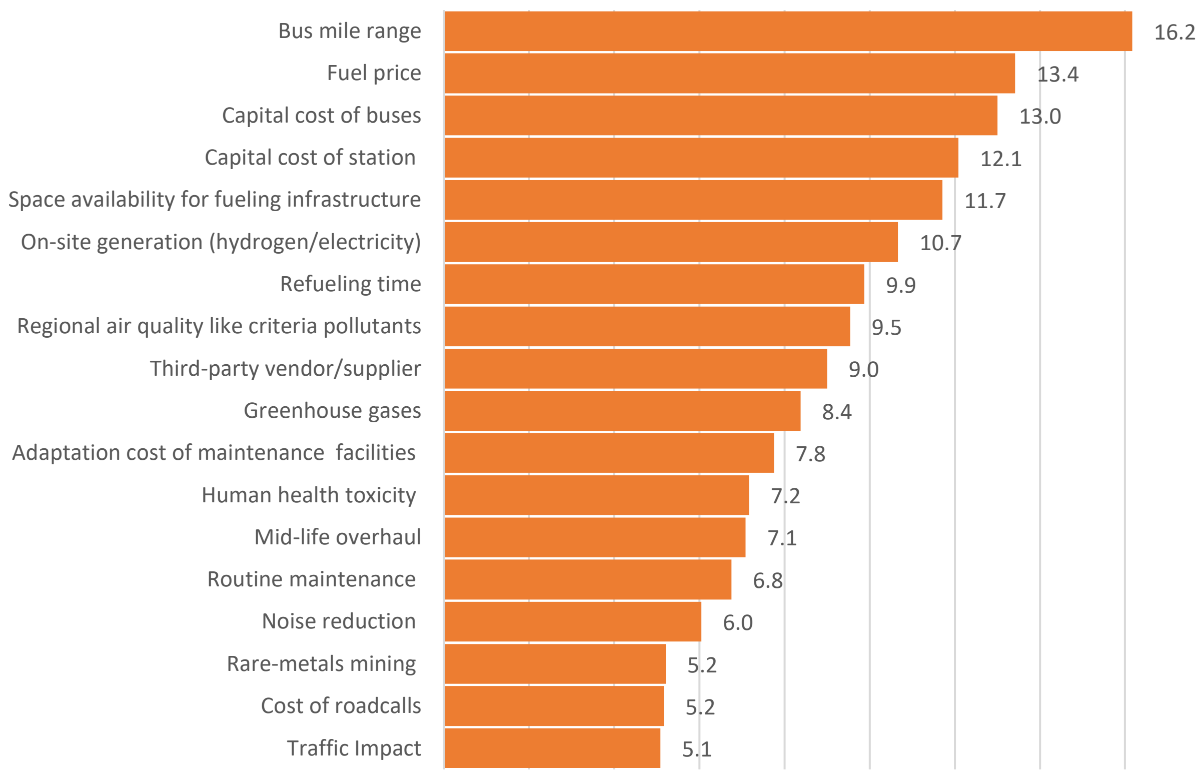



***Figure 57 Scores assigned to deployment sub-criteria obtained from the MCDA survey***

### 9.3.2. Rank of alternatives

In the context of this dissertation, the purpose of applying a Multi-Criteria Decision Analysis to the selection of zero-emission buses was to obtain the weighting parameters for the optimization problem and not to obtain a solution to the problem. However, the survey participants were asked to rank the alternatives; the results are summarized in Figure 58.

According to the fifteen surveys, hybrids received the maximum score of 69% when evaluated over the main categories and sub-criteria. However, since hybrids are not zero-emissions, they do not represent a relevant solution for the future Innovative Clean Transit regulation [104]. FCEBs were the ZEBs with the highest ranking with an overall score of 4,684, or 65%. Plug-in battery electric buses (BEB-LRs) were ranked slightly lower with 4,593 or 64%, and on-route buses were ranked last with only 3,866 points or 54%. However, the sample has a small standard deviation of only 0.0668 and a range of 16%, as summarized in Table 34, indicating a low variability in the scores assigned to each technology.

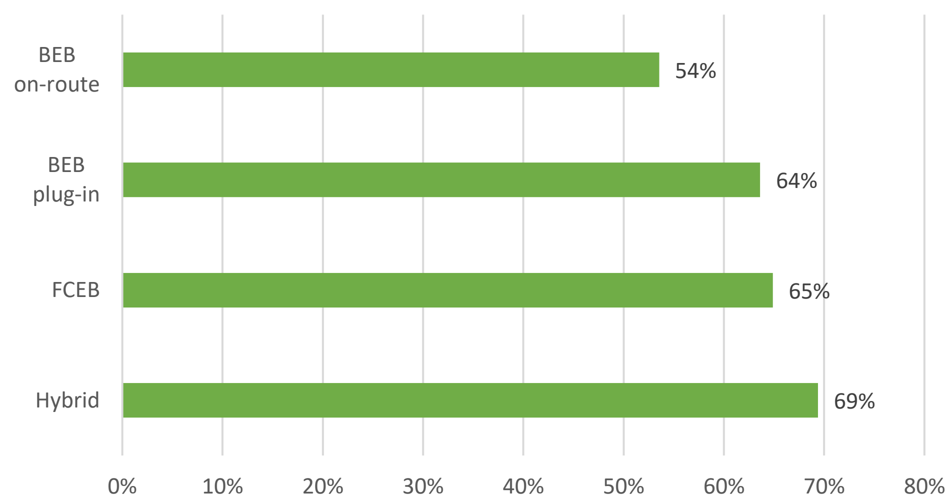



***Figure 58 Rank of Bus Alternatives Results from MCDA. Buses with a higher score are preferable.***

*Table 34 Statistic Analysis of Survey Results*

| Measurement | Value |
|---|---|
| **Mean** | **63%** |
| **Median** | 64% |
| **Range** | 16% |
| **Standard Deviation** | 0.0668 |

# CHAPTER 10. Technology-Mix Optimization for Optimal Bus Fleet Mix

Multi-Objective Linear Programming was implemented to solve the optimization problem of minimizing cost while maximizing environmental benefit opportunities. The results obtained in Chapter 7 from the extended LCA methodology, and the results from Chapter 8 related to life cycle cost were incorporated as part of the objective functions. Additionally, the results from the MCDA study were incorporated in the optimization to prioritize objectives.

Specific conditions need to be met for each objective function; however, the following conditions apply to the optimization problem in general.

$$x + y + z + w - T_{extra} = T_{fleet}$$

Eq. (20)

where:

X = number of BEB-LR
Y = number of BEB-SR
Z = number of FCEB
W = number of CNG buses
$T_{fleet}$ = total number of buses in the fleet
$T_{extra}$ = extra BEB-LR necessary to cover route length

The total number of buses in the fleet, provided by the user, is an input for the equation and cannot be modified. However, because the optimization is incorporating operational constraints, if the driving range of the BEB-LR buses is below the total route length, then the model considers adding extra buses to cover the route ($T_{extra}$). The extra buses required due to range limitations were calculated with the following condition Eq. (21):

$$T_{extra} = x - T_{fleet} * (1 - R_l)$$
Eq. (21)

Route limit ($R_l$) represents the percentage of the fleet that has a route length above 140 miles, which is the assumed driving range limit for BEB-LR with a state of charge (SOC) of 20%. The expression "$T_{fleet} * (1 - R_l)$" is the number of buses that need to be acquired to cover the extra route length.

### 10.1. Cost Objective Function

The life cycle cost results obtained for each powertrain type, as described in Chapter 8, are used in this section to define the cost objective function **Error! Reference source not found.**).

$$C = C_{LR} * x + C_{SR} * y + C_{FCEB} * z + C_{CNG} * w$$
Eq. ( 22)

where:

$C_i$ = Cost of ownership for each type of powertrain expressed in $/bus

LR = Battery electric buses that are long-range

SR = Battery electric buses that are short-range

The goal is to minimize the cost objective function while satisfying the following logical conditions:

$$C_{FCEB} = 3.02; TCO\ using\ liquid\ hydrogen \qquad \text{if} \qquad z < 72$$
Eq. (23)

$$C_{FCEB} = 2.89; TCO\ using\ pipeline\ and\ SMR \qquad \text{if} \qquad z >= 72$$

Eq. (24)

$$C_{LR} = 3.08 * (T_{extra}) \qquad \text{if} \qquad T_{extra} >= 0$$

Eq. (25)

$$C_{LR} = 2.84 \quad \text{if} \qquad T_{extra} < 0$$

Eq. (26)

$$C_{SR} = 2.84 \quad \text{if} \qquad y > 0$$

Eq. (27)

$$C_{CNG} = 2.46 \quad \text{if} \qquad w > 0$$

Eq. (28)

Equation 23 and 24 are conditional statements that determine the cost of ownership based on the number of deployed buses. For Equation 23, if over 72 buses are FCEB in the technology mix, then the TCO is reduced. Similarly, for Equation 24 if the selected BEBs-LR exceed the number of routes that are above 140 miles (which is defined by $T_{extra}$), then one additional bus needs to be added for every BEB-LR assigned to the fleet. The conditional statement stablishes that for every extra electric bus, then a higher TCO is used in the objective function.

### 10.2. Environmental Objective Function

The life cycle results obtained for each powertrain type, as described in Chapter 7, are used in this section to define the environmental objective function Eq. (29):

$$S = S_{LR} * (x + T_{extra}) * \varepsilon + S_{SR} * y * \varepsilon + S_{FCEB} * z * \varepsilon + S_{CNG} * w * \varepsilon$$

Eq. (29)

where:

$S_i$ = Score of LCA category. For this optimization, it represents the sum of GWP and ReCiPe Endpoint total.

X = number of BEB-LR

Y = number of BEB-SR

Z = number of FCEB

W = number of CNG buses

$\varepsilon$ = average mileage per bus

The average mileage per bus ($\varepsilon$) is the key component for the LCA objective functions since it scales the magnitude of the environmental effects for each LCA indicator. Eq. (30) presents the calculation for the average mileage per bus. In a transit agency, each route has a defined number of buses assigned in a given schedule, therefore, each bus has a regular daily mileage that needs to be covered ($n_i$), where "i" is the total number of buses in service, without the reserve/spare buses ($T_{spare}$). Starting the calculation from a daily mileage instead of the monthly traveled mileage by the fleet was selected because it made it possible to identify the percentage of buses that have a daily mileage above the range limit.

$$\varepsilon = \frac{\sum_1^i (n_i)}{T_{fleet}}$$

Eq. (30)

$$T_{fleet} = i + T_{spare}$$

Eq. (31)

### 10.3. Parameter Weighting

A weight was assigned to prioritize objectives. Table 35 presents the results obtained in the MCDA chapter; such rankings are assigned as the weighting in a set point high and a set point low.

***Table 35 Average ranking for main deployment criteria and normalized ranking***

| | **Average Ranking for Main Criteria** | **Normalized Ranking** |
|---|---|---|
| Capital Cost | 19 | 73 |
| Maintenance Cost | 18 | 69 |
| Environmental Impact | 14 | 53 |
| Operational Constraints | 26 | 100 |

The ranking of 26 given to operational constraints is applied as the added cost by assigning 100 to the L-1 norm specifications when defining Eq. (32). L-1 norm error objective is used to prioritize the desired objective, in other words, the solver minimizes the sum of the absolute value of the difference between the control variable and the set point [119].

$$T_{extra} >= x - T_{fleet} * (1 - R_l)$$

Eq. (33)

The normalized ranking of 73 was assigned to the cost function by assigning 73 to the L-1 norm variable specifications. Furthermore, a value of 53 was assigned to the environmental function and a value of 69 to the maintenance function.

### 10.4. Multi Objective Linear Programing

The defined optimization problem has multiple competing objectives, minimizing cost while minimizing environmental impacts. These competing objectives are part of the trade-off that defines the optimal solution. For the optimization problem defined in this dissertation, the competing objectives have separate priorities where one objective should be satisfied before another objective is considered. Additionally, such competing objectives have a ranked hierarchy. The highest-level objective, capital cost, was satisfied first followed by lower ranked objective, environmental impact. For this optimization problem, the L1-norm objective was used. The L1-norm objective is a natural way to explicitly rank objectives and simultaneously optimize multiple priorities with a single optimization problem [120].

### 10.5. Optimal Solution for Present Scenarios

The optimization script for a multi objective linear programing (MOLP) developed by APMonitor and Gekko [120], which is written in Python, was used to run the optimization calculations. The above sections were used to populate the optimization problem with the objective functions, control variables, and control weighting.

The fleet optimization was conducted per bus base and not for the entire OCTA fleet. The results presented in this section allow planning for infrastructure and operational requirements per bus base that can be scaled as many times as desired.

If the environmental impact is not considered in the optimization (i.e., no GWP emissions or ReCiPe scores), then the optimal solution is to acquire only CNG buses, yielding a minimum cost of ownership of $369 million for 150 buses (Figure 59).

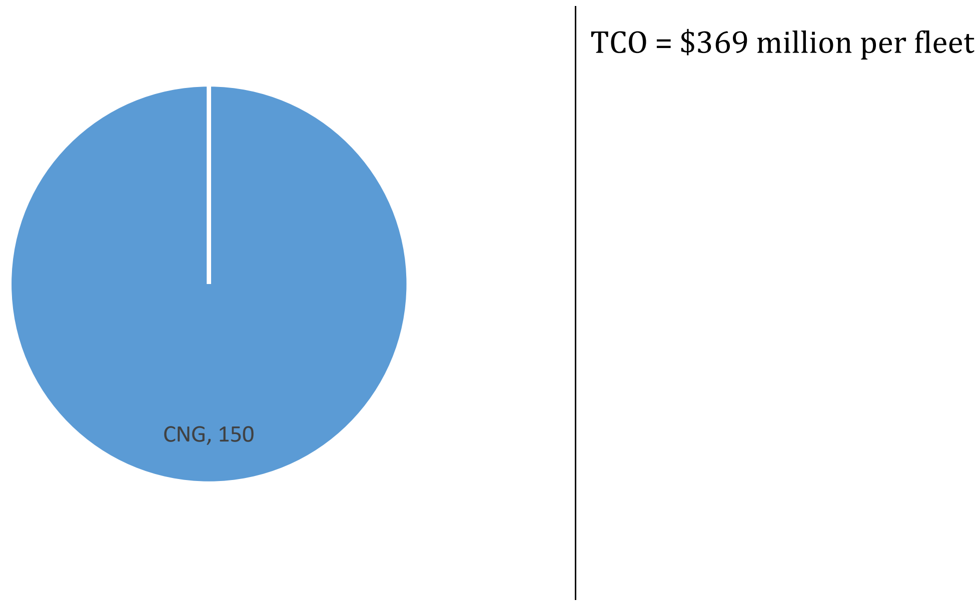
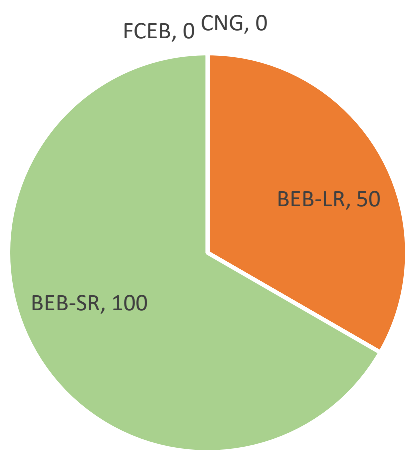



***Figure 59 Results for cost optimization with no environmental considerations***

When two objectives are being optimized, it is necessary to have a weight factor to determine which of the two objective functions has priority over the others. The weight factors derived from the MCDA are then incorporated in the optimization to minimize cost and minimize the environmental impact. Using the GWP emissions calculated in Section 7.3 to define the environmental objective function, the optimal fleet results in 50 BEB-LRs and 100 BEB-SRs as represented in Figure 60.

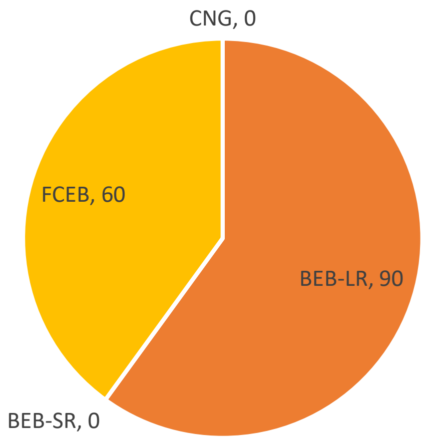



TCO = $426 million

GWP = 7,800,000 kg $CO_2$ eq/year

***Figure 60 Results for fleet optimization considering TCO, GWP and MCDA weighting factors***

Based on results from the MCDA, BEBs-SR received the lowest score when evaluated by stakeholders, which makes them the less likely technology to be deployed by transit agencies. Therefore, a new optimization scenario was studied, also using GWP and TCO, but without considering BEBs-SR. Additionally, current regulation aiming to transition public transit agencies to zero-emission fleets will not allow the purchase of CNG buses after 2019 [104]. To reflect how future fleets can be optimized with these limits, CNG buses and BEBs-SR were eliminated from the problem formulation. The optimal zero-emission fleet was found to include 90 BEBs-LR and 60 FCEBs (Figure 61). The TCO for 150 buses resulted in $436.8 million and the GWP emissions for the fleet per year resulted in 8 million kg of $CO_2$ equivalent.

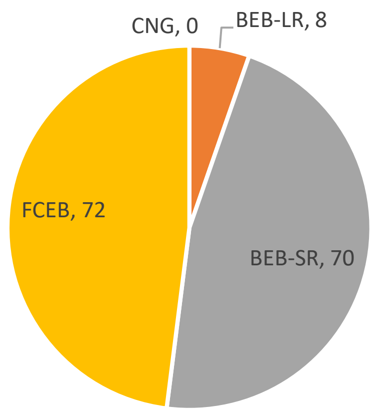



TCO = $436.8 million

GWP = 8,040,000 kg CO2 eq/year

***Figure 61 Results for zero-emission fleet optimization considering GWP and MCDA factors while excluding BEB-SR***

The ReCiPe endpoint total results for FCEBs are the lowest, mostly due to lower environmental impacts in the drivetrain manufacturing process. This environmental advantage, coupled with lower cost of hydrogen when over 72 buses are deployed (after 72 buses using pipelines to distribute hydrogen lower the TCO), are some of the factors why an additional scenario was analyzed using the ReCiPe endpoint as the factor to define the environmental objective function. The ReCiPe scenario results in 72 FCEBs, 70 BEBs-SR, and 8 BEBs-LR if CNG buses are not considered in the optimization; with a minimum cost of $429.9 per fleet and a minimum score of 1,742,400 points per year for the fleet (Figure 62).




TCO = $429.9 million

ReCiPe = 2,238,400 points/year

***Figure 62 Fleet optimization considering TCO, ReCiPe endpoint total score and MCDA factors***

## 10.6. Optimal Solution for Future Scenarios

The TCO results obtained in Section 8.4 and presented in Table 36 are used to define the cost objective function for the year 2040. Additionally, the global warming potential and the ReCiPe endpoint total score for the year 2040 presented in Section 7.4 (Table 37Table 27) are used to define the environmental objective function.

***Table 36 Total Cost of Ownership for Transit Buses in 2040***

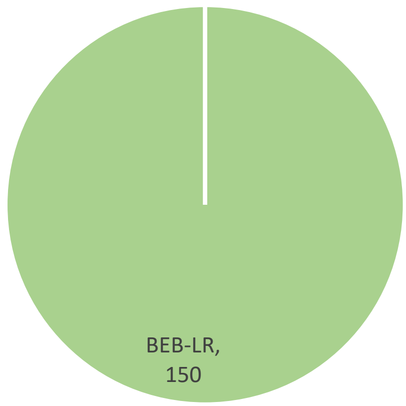
| | Total Cost of Ownership ($/bus) |
|---|---|
| **CNG** | $ 3,021,942 |
| **BEB-LR** | $ 2,981,677 |
| **BEB-SR** | $ 2,942,482 |
| **FCEB** | $ 2,955,146 |
| **FCEB if >50** | $ 2,890,000 |

*Table 37 Life Cycle Assessment Results of Selected Indicators for Future Scenario*

| | **Global Warming Potential Year 2040 (kg $CO_2$eq/VMT)** | **ReCiPe Endpoint Total Score Year 2040 (Points)** |
|---|---|---|
| **CNG Bus** | 1.3 | 0.26 |
| **Wind \|\| FCEB** | 0.25 | 0.16 |
| **Wind \|\| BEB-LR** | 0.2 | 0.16 |
| **Wind \|\| BEB-SR** | 0.2 | 0.15 |

If the GWP indicator is used to define the environmental objective function, then the optimal fleet for the year 2040 would only include BEBs-SR (Figure 63). The TCO of the fleet results in $441 million with 1.2 million kilograms of $CO_2$ equivalent released per year. When the environmental objective function is defined using the ReCiPe endpoint total scores instead of the GWP, the results of the fleet configuration is the same, but the minimized environmental impact is expressed as 900,000 points/year for the 150 BEBs-SR.

The optimization for the future scenario was defined by the low TCO and low environmental values that BEBs-SR were projected to have due to improvements in cost and performance of batteries. Additionally, even when the operational constraints due to the driving range from the BEBs-LR were eliminated, BEBs-SR were still the optimal solution.




TCO: $441 million per fleet

GWP: 1,200,00 kg $CO_2$ eq/year

***Figure 63 Zero-emission Fleet Optimization for the Year 2040***

As observed from the different optimized scenarios, the inputs selected to define the objective function are critical for the design of the optimization. Depending on the selected environmental indicator, a different fleet configuration can result. Global warming potential was selected as one of the midpoint indicators to populate the optimization factor, and a different fleet configuration was obtained when selecting ReCiPe endpoint total as the environmental indicator. Therefore, the optimization of a fleet is sensitive to the environmental factor selected when setting the formulation of the optimization problem, even when all of the factors support the interpretation of the same LCA study. Additionally, by having a present and future scenario that affected the TCO and the results from environmental factors, it was possible to demonstrate that this model and methodology can be applied throughout the changing dynamic that is implied when planning the deployment of ZEBs.

# CHAPTER 11. Conclusions and Recommendations

## Conclusions

The conclusions drawn are divided into general conclusions and those specific to the results from the two scenarios evaluated for 2018, and 2040.

### 11.1 General Conclusions

- **According to the MCDA, Fuel Cell Electric Buses (FCEBs) and Battery Electric Buses-Long Range (BEBs-LR) with plug-in charging are preferred over Battery Electric Buses-Short Range (BEBs-SR) with on-route charging.**

  The deployment criterion for "Operational Constraints" received the highest priority among all stakeholders responding to the MCDA survey, with "bus mileage range" as the second criterion that influenced the score the most. Because FCEBs have a driving range comparable to CNG buses with similar refueling conditions, FCEBs received the highest score in the MCDA study despite having higher capital cost than other zero-emission bus technology. BEBs-LB ranked only slightly lower, and not significantly different. As a result, FCEBs and BEBs-LR are today a favored solution for the transit agencies surveyed, based on all the evaluated criteria.

  BEBs-LR and BEBs-SR revealed a total cost of ownership of $2.84 million per vehicle for both bus types, showing no significant difference from an economic perspective. However, BEBs-LR ranked 16% higher than BEBs-SR in multi-criteria decision analysis (MCDA) conducted among California public transportation stakeholders. The higher ranking suggests that BEBs-LR are more likely to satisfy the deployment criteria established for the adoption of zero-emission buses. The deployment criteria include operational constraints, capital cost, maintenance cost, fuel supply, environmental impacts, and impacts to the community.

- **Stakeholders involved in the deployment of zero-emission buses in California ranked operational constraints as the determining factor for the deployment of alternative powertrains.**

  The multi-criteria decision analysis consisted of a survey distributed to decision makers involved in the advancement of zero-emission buses in the State of California. Each stakeholder assigned a score to a set of deployment criteria, the category that ranked with the highest score was operational constraints with 26 out of 100. Maintenance cost and capital cost were the two categories that ranked second with almost the same score, 18 and 19 out of 100, respectively. Bus mile-range was the sub-criteria with the highest individual score, followed by the capital cost of buses, station capital cost, and space availability at base-hub.

- **FCEBs and BEBs-LR are comparable in some, but not all circumstances.**

  **Where Comparable?**

  - **Total cost of ownership (TCO)**. FCEBs are comparable in cost to BEBs-LR when renewable sources are the feedstock for hydrogen generation, and pipelines are the conveyance of delivered fuel. Despite FCEBs having a higher investment cost, the hidden cost from operational constraints (driving range and battery degradation) for BEBs results in the same median for the total cost of ownership between FCEBs and BEBs-LR.

- **Life Cycle Assessment**. When renewable sources are the feedstock for hydrogen (such as electrolytic hydrogen) and for electricity generation (such as hydropower), the Global Warming Potential emissions, Particulate Matter Formation, and the ReCiPe Endpoint Total score are the same for FCEBs and BEBs-LR.

**Where not Comparable?**

- **Range.** When operational constraints due to range limitations for BEB-LR are considered in the cost analysis as well as in the LCA of environmental benefits, the selection of FCEBs over BEBs-LR represents cost benefits if renewables are the feedstock for fuel generation. The acquisition of extra BEBs necessary to cover the routes that are above the electric range increases the TCO.
- **Infrastructure.** Refueling equipment and operations for FCEB are similar to those of CNG and diesel buses; including working with compressed gases (only for CNG), refueling mechanisms using hose and nozzles, overnight refueling, and comparable fueling times. Contrary, recharging times of BEB-LR impose restrictions on the operator since on average, four hours are needed to charge long-range batteries fully. Additionally, individual plug-in connectors are

required as part of the charging infrastructure to avoid operational changes to rotate buses overnight.

- **Price of fuel**. For all generation pathways, hydrogen prices are projected to go down as demand, or the number of buses deployed increases. However, given uncertainty and variability of electricity rates, the price per kWh is expected to go up. In fact, if the electricity rate applied to BEBs-LR is higher than $0.24 per kWh, then FCEBs have a lower total cost of ownership.

- **The manufacturing of fuel cells and batteries are the processes that contribute most to the emissions associated with the following impact categories: metal depletion potential, human toxicity, and freshwater eutrophication.**

  FCEBs and BEBs with fuel generation derived from hydropower had the lowest score/measurement for the majority of midpoint indicators. The design of scenarios with the minimum emissions from fuel generation allowed to identify that some midpoint indicators were independent of the fuel generation process but were influenced by to the production of powertrains; as it was the case for metal depletion, human toxicity, and freshwater eutrophication.

- **Calculations of the total cost of ownership for BEBs were proven to be directly dependent on the pricing strategies of the utility company.**

  The price assigned per kilowatt-hour by the utility sector can drive the cost estimations in favor of a given bus powertrain and can be the determining factor of adoption for transit agencies. Transit agencies that are transitioning to zero-emission fleets are also transitioning from formalizing supply contracts (that are only subject to market variations) to negotiating long term electricity tariffs with their utility company, state regulatory bodies, and the state utility commission. TOC is highly sensitive to electricity rate charges. A 50% increase in the charged rate can represent an increase of up to 10% in the total cost of ownership; a significant jump when the TCO is in the millions of dollars for any transit agency adopting the technology.

- **The optimization of the ideal technology mix for a fleet of zero-emission buses was successfully demonstrated.**

  An optimization methodology was developed that can be applied to the specific needs of any transit agency or party seeking to transition to a zero-emission fleet bus. The methodology for the optimal solution considers a modified Life Cycle Assessment approach, total cost of ownership calculations, and prioritized optimization objectives established from multi-criteria decision analysis (MCDA).

## 11.2 Conclusions Specific to the Two Optimization Scenarios

The optimization methodology was demonstrated for two years (2018 and 2040) using the Orange County Transit Authority (OCTA) as an example. Using actual operations information from the OCTA as input to the optimization, the following conclusions resulted:

- **While different environmental indictors can be used to formulate the optimization problem, the resulting fleet configuration is affected by the indicator that is minimized.**

  To illustrate this conclusion the environmental indicator was varied for the 2018 scenario. When Global Warming was selected, the optimized fleet configuration was projected to be 50 BEBs-LR, and 100 BEBs-SR with a minimum cost of $426 million per fleet. When the ReCiPe endpoint total was selected as the environmental indicator, the fleet configuration resulted in 8 BEBs-LR, 70 BEBs-SR, and 72 FCEBs for a minimum TOC of $429.9 million for the fleet.

- **The optimization model and the adoption of a multi-criteria decision analysis within a life cycle assessment framework can be applied today and in the future, resulting in potentially different results.**

  To illustrate this conclusion, 2040 was selected for a future year and the results compared to the 2018 scenario using Global Warming as the environmental indicator in both cases. For 2018, the optimal mix was 50 BEBs-LR, and 100 BEBs-SR with a minimum cost of $426 million per fleet. For 2040, the optimal mix resulted in 100% BEBs-SR with a minimum TCO of $$441 million for a fleet of 150 buses. The future scenario results are explained by the low TCO and low environmental values that BEBs-SR were assumed to be achieved as a result of improvements in the performance of batteries.

## Recommendations

- Modeling the total cost of ownership of battery electric buses with short length (BEB-SR) could be improved if an optimization for location and number of on-route chargers is applied to the specific routes and conditions to a transit's agency service map.

- Charging management, or "smart charging" for BEB-LR and BEB-SR needs to be further investigated to determine what effect it can have in the total cost of ownership and overall fleet optimization.

- A spatial analysis of LCI categories should be performed to determine the direct impact to communities to establish a priority or score for each factor when calculating the ReCiPe Endpoint Total.

- The total cost of ownership and LCA results used to define the objective function in the optimization problem were non-dynamic values, i.e., values calculated for specific circumstances such as a define fuel pathway or a fixed electricity rate. A dynamic calculation of the factors linked to the optimization problem should be investigated to increase the accuracy of the optimization problem.

# REFERENCES

[1] S. (Editor) Hirschberg, “Opportunities and challenges for electric mobility: an interdisciplinary assessment of passenger vehicles,” *PSI, EMPA, ETH*, 2016.

[2] California Air Resources Board, “California Greenhouse Gas Emissions for 2000 to 2016,” 2018.

[3] C. Element Energy, “2016 International Zero Emission Bus Conference Report.”

[4] “C40 Clean Bus Declaration.” [Online]. Available: http://www.c40.org/blog_posts/c40-clean-bus-declaration-urges-cities-and-manufacturers-to-adopt-innovative-clean-bus-technologies. [Accessed: 18-May-2017].

[5] A. E. Farrell *et al.*, “A Low-Carbon Fuel Standard for California Part1,” 2007.

[6] California Legislative Senate, “Bill Text - SB 32 California Global Warming Solutions Act of 2006: emissions limit.” [Online]. Available: https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB32. [Accessed: 26-May-2019].

[7] “California Renewables Portfolio Standard (RPS).” .

[8] M. K. Chang, J. D. Eichman, F. Mueller, and S. Samuelsen, “Buffering intermittent renewable power with hydroelectric generation: A case study in California,” *Appl. Energy*, vol. 112, pp. 1–11, Dec. 2013.

[9] L. Zhang, T. Brown, and G. S. Samuelsen, “Fuel reduction and electricity consumption

impact of different charging scenarios for plug-in hybrid electric vehicles," *J. Power Sources*, vol. 196, no. 15, pp. 6559–6566, Aug. 2011.

[10] P. Willette, "A Holistic Analysis of the Energy and Environmental Impact of Hydrogen as an Alternative Fuel in 2050," University of California Irvine, 2014.

[11] California Air Resource Board, "Advanced Clean Transit (ACT) Proposal from the Air Resource Board," 2015.

[12] M. A. Curran, "Life Cycle Assessment: Principles and Practice," 2006.

[13] "ISO 14040 Environmental management — Life cycle assessment — Principles and framework," *ISO 14040*, vol. 14040, no. 2006-07–01, 2006.

[14] Z. I. Batouta, R. Dehbi, M. Talea, and O. Hajoui, "Multi-Criteria Analysis and Advanced Comparative Study Between Automatic Generation Approaches in Software Engineering," *J. Theor. Appl. Inf. Technol.*, vol. 81, no. 3, 2015.

[15] "Safety and Security Assessment - Roads2HyCom Hydrogen and Fuel Cell." [Online]. Available: http://www.ika.rwth-aachen.de/r2h/index.php/Safety_and_Security_Assessment.html. [Accessed: 30-Sep-2015].

[16] Florida Solar Energy Center, "Hydrogen Basics - Production." [Online]. Available: http://www.fsec.ucf.edu/en/consumer/hydrogen/basics/production.htm. [Accessed: 20-May-2019].

[17] EIA, "U.S. Dry Natural Gas Production (Million Cubic Feet)," *EIA*, 2017. [Online]. Available: https://www.eia.gov/dnav/ng/hist/n9070us2A.htm. [Accessed: 17-Aug-

2018].

[18] K. Manliclic, “Advanced Methodologies for Fuel Cell Vehicle Infrastructure Deployment using Geographic Information Systems (GIS) and Vehicle Sales Data,” *Master Sci. Univ. Calif. Irvine*, 2014.

[19] “DOE Hydrogen Analysis Repository: Distributed Hydrogen Production via Steam Methane Reforming.” [Online]. Available: http://www.hydrogen.energy.gov/analysis_repository/project.cfm/PID=215. [Accessed: 08-Dec-2014].

[20] S. D. Stephens-Romero, “Development of a Spatially and Temporally Resolved Planning Tool for Deployment of Hydrogen Infrastructure,” *UCI Diss.*, p. 223, 2011.

[21] “Technology Brief: Analysis of Current-Day Commercial Electrolyzers.” [Online]. Available: http://www.nrel.gov/docs/fy04osti/36705.pdf. [Accessed: 30-Sep-2015].

[22] “Electrolysis: Information and Opportunities for Electric Power Utilities.” [Online]. Available: http://www.nrel.gov/docs/fy06osti/40605.pdf. [Accessed: 21-Aug-2014].

[23] I. Mizuho Information & Research Institute, “Well-to-Wheel Analysis of Greenhouse Gas Emissions of Automotive Fuels in the Japanese Context,” 2004.

[24] California Air Resource Board, “Methods to Find the Cost-Effectiveness of Funding Air Quality Projects.” [Online]. Available: http://www.arb.ca.gov/planning/tsaq/eval/evaltables.pdf. [Accessed: 15-Dec-2014].

[25] A. Saeedmanesh, M. A. Mac Kinnon, and J. Brouwer, “Hydrogen is essential for

sustainability," *Current Opinion in Electrochemistry*. 2018.

[26] U.S. Energy Information Administration, "Annual Electric Utility Data – EIA-906/920/923 Detailed Data." [Online]. Available: http://www.eia.gov/electricity/data/eia923/. [Accessed: 15-Dec-2014].

[27] U. S. E. I. Administration, "EIA Technical Notes & Documentation - Complete 2012." [Online]. Available: http://www.eia.gov/state/seds/seds-technical-notes-complete.cfm. [Accessed: 15-Dec-2014].

[28] "US Energy Mapping System Energy Information Administration (EIA)." [Online]. Available: http://www.eia.gov/state/maps.cfm. [Accessed: 27-Aug-2015].

[29] EIA, "California - State Energy Profile Overview - U.S. Energy Information Administration (EIA)." [Online]. Available: https://www.eia.gov/state/index.php?sid=CA#tabs-4. [Accessed: 06-Sep-2018].

[30] L. Eudy, M. Post, C. Gikakis, L. Eudy, and M. Post, "Fuel Cell Buses in U.S. Transit Fleets: Current Status 2016," *Natl. Renew. Energy Lab.*, no. December, 2016.

[31] L. Eudy *et al.*, "Foothill Transit Battery Electric Bus Demonstration Results: 1st Report," *Natl. Renew. Energy Lab.*, no. January, p. 60, 2015.

[32] A. Kontou and J. Miles, "Electric Buses: Lessons to be Learnt from the Milton Keynes Demonstration Project," *Procedia Eng.*, vol. 118, pp. 1137–1144, 2015.

[33] S. University, "Electric Buses at Stanford, California Higher Education Sustainability Conference (CHESC)," 2014.

[34] J. Ally and T. Pryor, “Life cycle costing of diesel, natural gas, hybrid and hydrogen fuel cell bus systems: An Australian case study,” *Energy Policy*, vol. 94, pp. 285–294, 2016.

[35] N. Resources, “Plug-in vs . Wireless Charging : Life Cycle Energy and Greenhouse Gas Emission Analysis of an Electric Bus System,” vol. 146, no. April, pp. 1–43, 2015.

[36] Z. Bi, R. De Kleine, and G. A. Keoleian, “Integrated Life Cycle Assessment and Life Cycle Cost Model for Comparing Plug-in versus Wireless Charging for an Electric Bus System,” *J. Ind. Ecol.*, vol. 21, no. 2, pp. 344–355, 2017.

[37] A. Lajunen and T. Lipmana, “Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses,” *Energy*, vol. 106, pp. 329–342, 2016.

[38] A. Lajunen, “Energy consumption and cost-benefit analysis of hybrid and electric city buses,” *Transp. Res. Part C Emerg. Technol.*, vol. 38, pp. 1–15, 2014.

[39] J. P. Stempien and S. H. Chan, “Comparative study of fuel cell, battery and hybrid buses for renewable energy constrained areas,” *J. Power Sources*, vol. 340, pp. 347–355, 2016.

[40] C. J. Meinrenken and K. S. Lackner, “Fleet view of electrified transportation reveals smaller potential to reduce GHG emissions,” *Appl. Energy*, vol. 138, pp. 393–403, 2015.

[41] T. Ercan and O. Tatari, “A hybrid life cycle assessment of public transportation buses with alternative fuel options,” *Int. J. Life Cycle Assess.*, vol. 20, no. 9, pp. 1213–1231, 2015.

[42] Y. Xu, F. E. Gbologah, D.-Y. Lee, H. Liu, M. O. Rodgers, and R. L. Guensler, "Assessment of alternative fuel and powertrain transit bus options using real-world operations data: Life-cycle fuel and emissions modeling," *Appl. Energy*, vol. 154, pp. 143–159, 2015.

[43] P. L. Durango-Cohen and E. C. McKenzie, "Trading off costs, environmental impact, and levels of service in the optimal design of transit bus fleets," *Transp. Res. Procedia*, vol. 23, pp. 1020–1032, 2017.

[44] National Renewable Energy Laboratory, "NREL DriveCAT - Chassis Dynamometer OCTA Drive Cycle." [Online]. Available: https://www.nrel.gov/transportation/drive-cycle-tool/. [Accessed: 19-May-2017].

[45] C. Mutel, "Brightway2 Advanced life cycle assessment framework." [Online]. Available: https://brightwaylca.org/. [Accessed: 19-May-2017].

[46] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema, "The ecoinvent database version 3 (part I): overview and methodology," *Int. J. Life Cycle Assess.*, vol. 21, no. 9, pp. 1218–1230, Sep. 2016.

[47] A. Simons and C. Bauer, "A life-cycle perspective on automotive fuel cells," *Appl. Energy*, vol. 157, pp. 884–896, 2015.

[48] O. Information, "M Series," *Orient*, pp. 4–5, 2011.

[49] "M Series Hydrogen Generation Systems MODEL M100 M200 M400," 2011.

[50] F. C. Today, "The Fuel Cell Industry Review 2013," *FuelCellToday*, 2013.

[51] J. Spendelow, J. Marcinkoski, and D. Fuel Cell Technologies Office, “DOE Hydrogen and Fuel Cells Program Record Title: Fuel Cell System Cost -2014,” 2014.

[52] J. Devaal, A. Niroumand, P. Fellow, F. Golnaraghi, and P. Description, “Heavy Duty Fuel Cell System Improvements.”

[53] B. L. Cox and C. L. Mutel, “Environmental and economic life cycle assessment of current and future motorcycles,” pp. 1–18.

[54] California Air Resources Board, “Advanced Clean Transit Battery Cost for Heavy-Duty Electric Vehicles,” 2016.

[55] Boston Consulting Group, “Batteries for Electric Cars: Challenges, Opportunities, and the Outlook to 2020,” 2012.

[56] “Proterra Battery Electric Bus 40 foot Specs.”

[57] “GreenPower Battery Electric Bus EV350 Specs.”

[58] “New Flyer Electric Bus XCelsior Specs.” [Online]. Available: https://www.newflyer.com/site-content/uploads/2018/09/One-Pager-Tech-Spec_XE40_2018_NF.pdf. [Accessed: 10-Oct-2018].

[59] “Nova Electric Bus LFSE Specs.”

[60] “California - State Energy Profile Data - U.S. Energy Information Administration (EIA).” [Online]. Available: http://www.eia.gov/state/data.cfm?sid=CA#ReservesSupply. [Accessed: 19-Sep-2015].

[61] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. Van Zelm, “ReCiPe 2008 A Life Cycle Assessment Method. Report I: Characterisation,” 2013.

[62] B. L. Cox and C. L. Mutel, “The environmental and cost performance of current and future motorcycles,” *Appl. Energy*, vol. 212, pp. 1013–1024, 2018.

[63] “Eia.gov - Data - U.S. Energy Information Administration (EIA) Energy Consumption by Sector.” [Online]. Available: http://www.eia.gov/beta/MER/?tbl=T02.01#/?f=A.

[64] H. G. (Holger G. Thuesen, W. J. (Wolter J. . Fabrycky, and G. J. Thuesen, *Engineering economy*. Prentice-Hall, 1977.

[65] Drive Natural Gas Initiative, ANGA, and AGA, “CNG Infrastructure Guide for the Prospective CNG Developer.”

[66] Clean Cities, “Clean Cities CNG Infrastructure Cost Webinar,” 2014.

[67] G. Mitchell, “Building a Business Case for Compressed Natural Gas in Fleet Applications,” 2015.

[68] Octa, “OCTA Operational Data,” 2014.

[69] “Nat G CNG Solutions - CNG Units Explained.” [Online]. Available: http://www.nat-g.com/why-cng/cng-units-explained/. [Accessed: 16-Jan-2019].

[70] Air Pollution Reduction Review Committee for the Clean Transportation Funding, “Construct CNG Refueling Station and Maintenance Facility Modifications | Mobile Source Air Pollution Reduction Review Committee,” 2005. [Online]. Available: http://www.cleantransportationfunding.org/projects/2005/construct-cng-

refueling-station-maintenance-facility-modifications. [Accessed: 15-Jan-2019].

[71] Air Pollution Reduction Review Committee for the Clean Transportation Funding, "Construction of New Compressed CNG Refueling Station at OCTA." [Online]. Available: http://www.cleantransportationfunding.org/projects/2008/construction-new-compressed-natural-gas-refueling-station. [Accessed: 15-Jan-2019].

[72] M. Smith and J. Gonzales, "Costs Associated With Compressed Natural Gas Vehicle Fueling Infrastructure," 2014.

[73] J. De Tapia *et al.*, "Trillium CNG Program for Miami-DADE Transit."

[74] Clean Transportation Funding, "Construction of New Compressed Natural Gas Refueling Station | Mobile Source Air Pollution Reduction Review Committee." [Online]. Available: http://www.cleantransportationfunding.org/projects/2008/construction-new-compressed-natural-gas-refueling-station. [Accessed: 13-Jan-2019].

[75] "CPI Inflation Calculator." [Online]. Available: https://data.bls.gov/cgi-bin/cpicalc.pl?cost1=616%2C000.00&year1=200801&year2=201701. [Accessed: 19-Jan-2019].

[76] R. Adams, "Upgrading a Facility for CNG," *Marathon Corp.*, 2014.

[77] Orange County Transportation Authority, "Orange County Transportation Authority Operational Data," 2016.

[78] L. Eudy and M. Post, "Fuel Cell Buses in U.S. Transit Fleets: Current Status 2018,"

2018.

[79] OCTA, “Transit Division Performance Measurements Report Fiscal Year 2011-2012 Third Quarter,” pp. 1–33, 2012.

[80] L. Eudy and M. Jeffers, “Foothill Transit Battery Electric Bus Demonstration Results: Second Report,” 2015.

[81] MTA, “MTA Capital Dashboard | Home Page.” [Online]. Available: http://web.mta.info/capitaldashboard/CPDHome.html. [Accessed: 04-May-2019].

[82] EIA, “Gasoline and Diesel Fuel Update - Energy Information Administration.” [Online]. Available: https://www.eia.gov/petroleum/gasdiesel/. [Accessed: 19-Jan-2019].

[83] EIA, “Natural Gas Commercial Price.” [Online]. Available: https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PCS_DMcf_m.htm. [Accessed: 19-Jan-2019].

[84] L. Eudy and M. Jeffers, “Foothill Transit Agency Battery Electric Bus Progress Report, Data Period Focus: Jan. 2018 through Jun. 2018,” 2018.

[85] California Air Resources Board, “Advanced Clean Transit Battery Cost for Heavy-Duty Electric Vehicles,” 2016.

[86] Anaheim Resort Transportation, “Anaheim Transportation Network Electric Bus Purchase.”

[87] Your Central Valley, “Porterville goes green with electric buses.” [Online]. Available:

https://www.yourcentralvalley.com/news/porterville-goes-green-with-electric-buses/1340640054. [Accessed: 25-Apr-2019].

[88] Matt Boothe - CTE, “Critical Answers for Smart Deployments.”

[89] Southern California Edison, “Schedule TOU-EV-4,” 2019. [Online]. Available: https://www1.sce.com/NR/sc3/tm2/pdf/ce141-12.pdf. [Accessed: 05-May-2019].

[90] Southern California Edison, “Schedule TOU-EV-8,” 2019. [Online]. Available: https://www1.sce.com/NR/sc3/tm2/pdf/ce401.pdf. [Accessed: 05-May-2019].

[91] M. A. Hursh, “Alameda-Contra Costa Transit District Staff Report,” 2017.

[92] A. Castillo-Munoz, “Deployment of Fuel Cell Electric Buses in Transit Agencies : Hydrogen Demand Allocation and Preferable Hydrogen Infrastructure Rollout Scenarios,” University of California Irvine, 2016.

[93] “Hydrogen Station Cost Estimates - NREL.” [Online]. Available: http://www.nrel.gov/docs/fy13osti/56412.pdf. [Accessed: 11-Oct-2015].

[94] M. Mintz, J. Gillette, and A. Elgowainy, “H2A DELIVERY SCENARIO ANALYSIS MODEL VERSION 1 . 0 * USER ’ S MANUAL,” no. March, pp. 1–32, 2006.

[95] “Santa Ana, CA Electricity Rates | Electricity Local.” [Online]. Available: http://www.electricitylocal.com/states/california/santa-ana/. [Accessed: 27-Sep-2015].

[96] T. Brown, L. Smith, S. Stephens-romero, and S. Samuelsen, “Economic analysis of near-term California hydrogen infrastructure,” *Int. J. Hydrogen Energy*.

[97] S. Shayegan, D. Hart, P. Pearson, and D. Joffe, "Analysis of the cost of hydrogen infrastructure for buses in London," *J. Power Sources*, vol. 157, no. 2, pp. 862–874, Jul. 2006.

[98] T. Brown, S. Stephens-Romero, and G. Scott Samuelsen, "Quantitative analysis of a successful public hydrogen station," *Int. J. Hydrogen Energy*, vol. 37, no. 17, pp. 12731–12740, Sep. 2012.

[99] L. Eudy and K. Chandler, "SunLine Transit Agency Advanced Technology Fuel Cell Bus Evaluation : Fourth Results Report," *Natl. Renew. Energy Lab.*, no. January, 2013.

[100] F. Canning, "FIBA Canning Hydrogen Storage and Delivery." [Online]. Available: http://www.fibacanning.com/pdf/Compressed Gas Equipment.pdf. [Accessed: 29-Jul-2015].

[101] California Air Resource Board, "Detailed California-Modified GREET Pathway for Compressed Natural Gas (CNG) from Landfill Gas." .

[102] L. Eudy, "Zero Emission Bay Area ( ZEBA ) Fuel Cell Bus Demonstration : First Results Report," *NREL Tech. Rep.*, no. August, 2011.

[103] L. Eudy and M. Post, "Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration Results : Third Report," *Natl. Renew. Energy Lab.*, no. May, 2014.

[104] California Air Resource Board, "Innovative Clean Transit | California Air Resources Board." [Online]. Available: https://www.arb.ca.gov/msprog/ict/ict.htm. [Accessed: 21-Mar-2019].

[105] A. Duran, "DRIVE Analysis Tool Generates Custom Vehicle Drive Cycles Based on

Real-World Data (Fact Sheet), NREL (National Renewable Energy Laboratory)."

[106] B. Wipke KB, Cuddy MR, "A user-friendly advanced powertrain simulation using a combined backward/forward approach," *IEEE Trans Veh Technol*, vol. 48, no. 6, pp. 1751–61, 1999.

[107] M. Miotti, J. Hofer, and C. Bauer, "Integrated environmental and economic assessment of current and future fuel cell vehicles," *Int. J. Life Cycle Assess.*, no. NOVEMBER, 2015.

[108] B. L. Cox, "MOBILITY AND THE ENERGY TRANSITION: A LIFE CYCLE ASSESSMENT OF SWISS PASSENGER TRANSPORT TECHNOLOGIES INCLUDING DEVELOPMENTS UNTIL 2050," ETH Zurich, 2018.

[109] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. Van Zelm, "ReCiPe 2008 First edition (revised) Report I: Characterisation," 2013.

[110] M. A. J. Huijbregts *et al.*, "ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level," *Int. J. Life Cycle Assess.*, vol. 22, no. 2, pp. 138–147, Feb. 2017.

[111] A. P. Acero, C. Rodríguez, and A. C. Changelog, "LCIA methods Impact assessment methods in Life Cycle Assessment and their impact categories," 2017.

[112] O. of R. & Development, "EFFECTS OF PHOTOCHEMICAL OXIDANTS ON PLANTS."

[113] EIA, "Sulfur dioxide emissions from U.S. power plants have fallen faster than coal generation - Today in Energy - U.S. Energy Information Administration (EIA)." [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=29812. [Accessed: 19-May-2019].

[114] L. M. Ellram, "Total Cost of Ownership," in *Handbuch Industrielles Beschaffungsmanagement*, Wiesbaden: Gabler Verlag, 1999, pp. 595–607.

[115] H. Saarikoski, D. Barton, J. Mustajoki, H. Keune, E. Gomez-Baggethun, and J. Langemeyer, "Multi-Criteria Decision Analysis | Openness Project." [Online]. Available: http://www.openness-project.eu/library/reference-book/sp-MCDA. [Accessed: 20-Dec-2018].

[116] California Air Resources Board, "Proposed Amendments to the Innovative Clean Transit Regulation, a Replacement of the Fleet Rule for Transit Agencies."

[117] L. Eudy and M. Post, "Zero Emission Bay Area ( ZEBA ) Fuel Cell Bus Demonstration Results : Fourth Report Zero Emission Bay Area ( ZEBA ) Fuel Cell Bus Demonstration Results : Fourth Report," *NREL*, no. July, 2015.

[118] H. Messe and P. Kr, "CHIC : Clean Hydrogen In European Cities - demonstration of 52 FC hydrogen buses -," 2014.

[119] L. Beal and J. Hedengren, "GEKKO Documentation Release 0.0.3b1," 2019.

[120] AP Monitor, "Multi-Objective Optimization." [Online]. Available: http://apmonitor.com/do/index.php/Main/MultiObjectiveOptimization. [Accessed: 21-May-2019].

[121] Environmental Protection Agency, "Criteria Air Pollutants," 2015.

[122] US EPA, "Overview of Greenhouse Gases."

[123] Capitol Equipment, "Generac 1500kW Diesel Generator SD1500 for sale in

Manchester, CT. Capitol Equipment Manchester, CT (860) 643-7958.” [Online]. Available: https://www.capitolequipmentandmarine.com/new-models/2018-generac-1500kw-diesel-generator-sd1500-26621783b. [Accessed: 19-Jan-2019].

## APPENDIX

### Appendix A: Midpoint and Endpoint ReCiPe Indicators for Zero Emissions and Conventional fuel Transit Buses

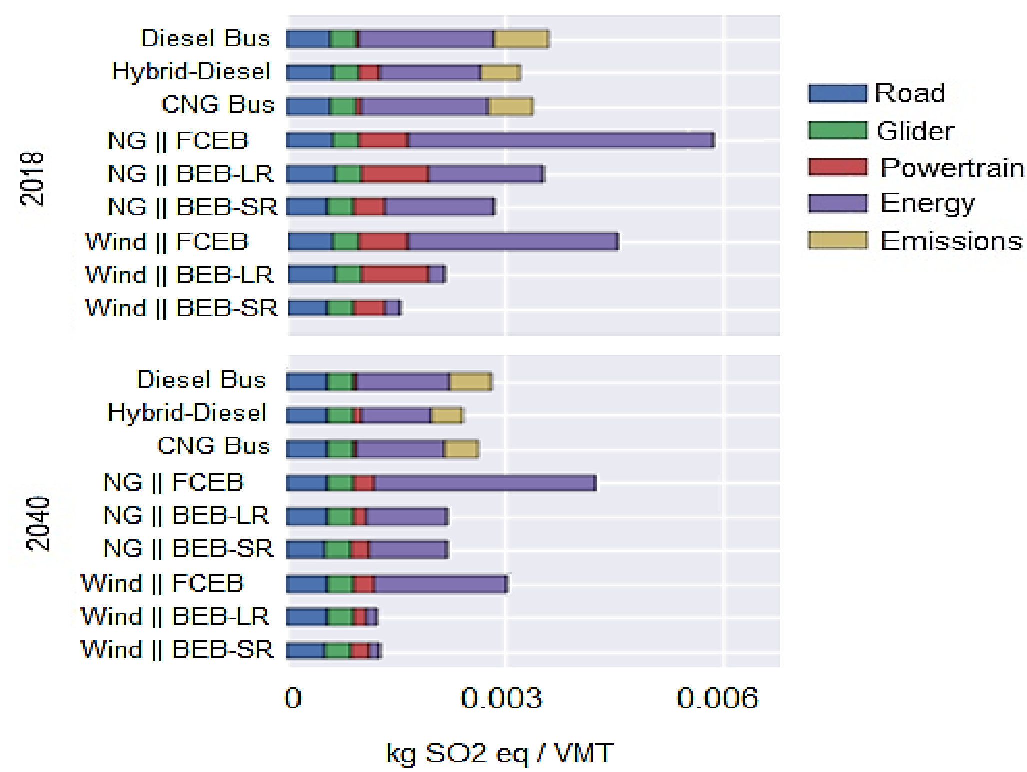



*Figure 64 Terrestrial Acidification Potential results for present and future scenarios*

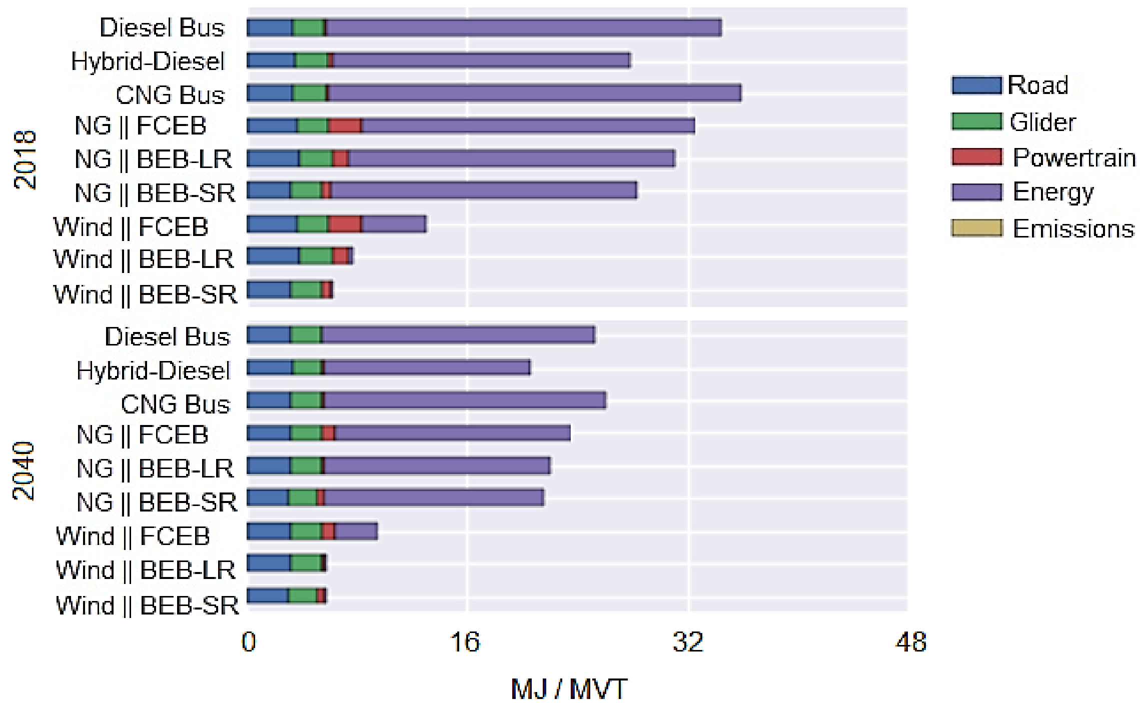



***Figure 65 Results for present and future scenarios of Cumulative Energy Demand of Non-Renewable***

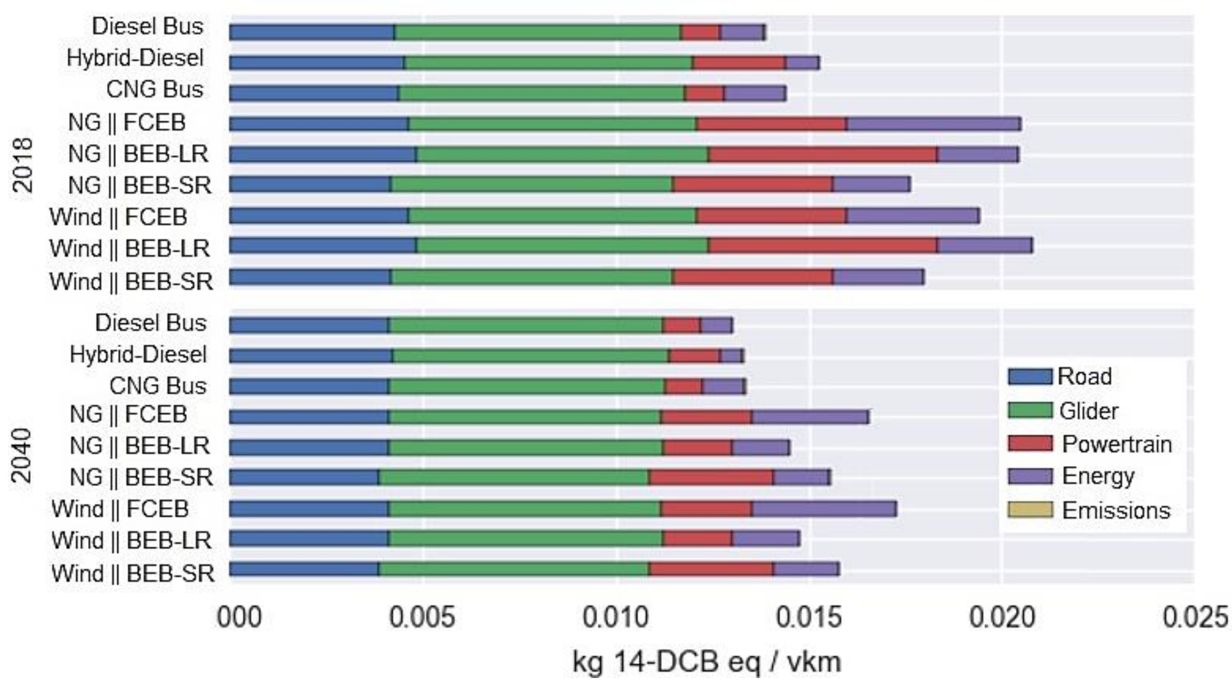



***Figure 66 Freshwater Ecotoxicity Potential results for present and future bus scenarios***

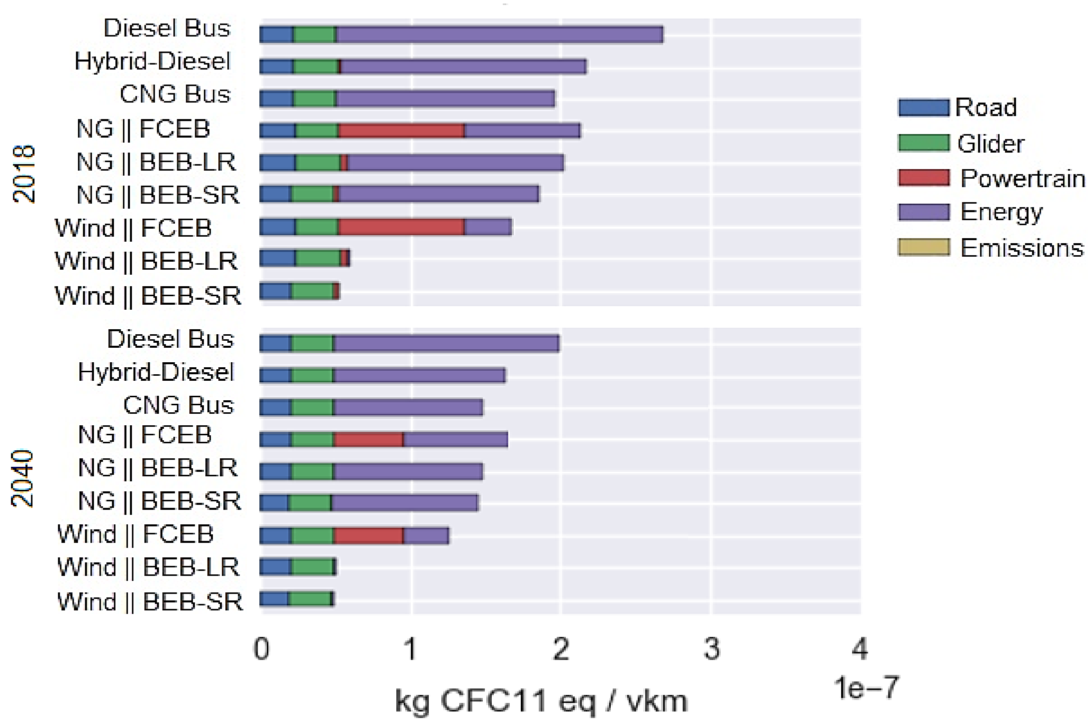



***Figure 67 Ozone Depletion Potential results for present and future bus scenarios***

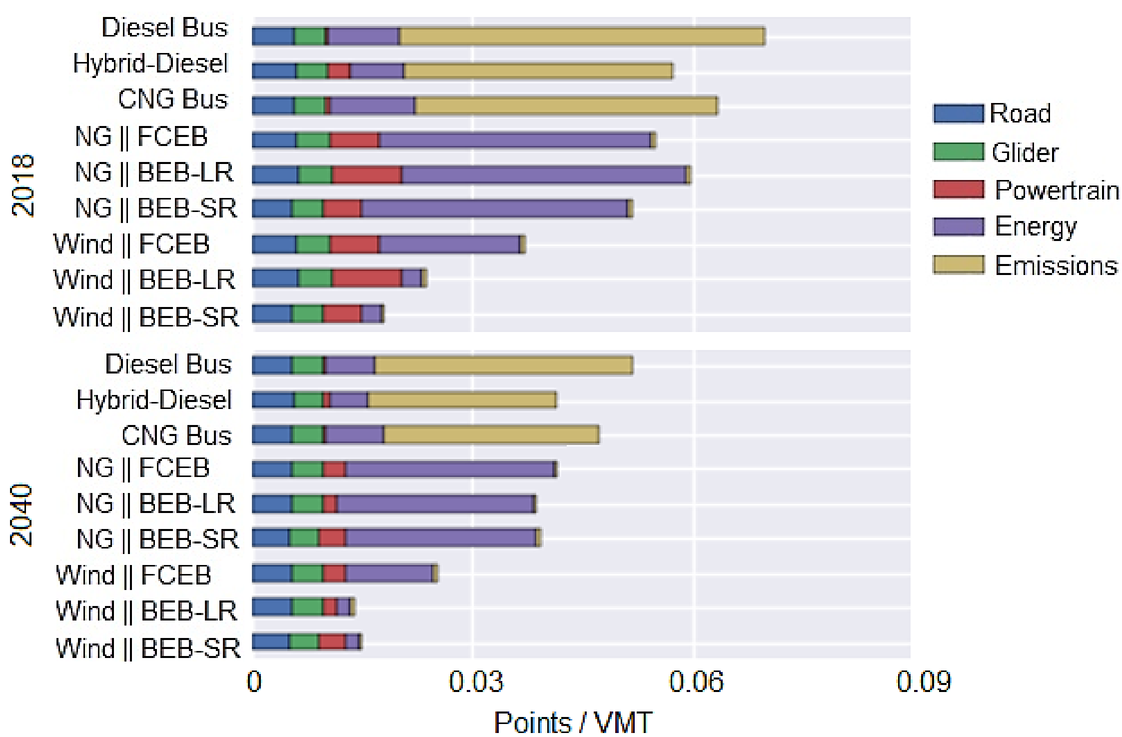



***Figure 68 ReCiPe Endpoint Human Health Results for present and future bus scenarios***

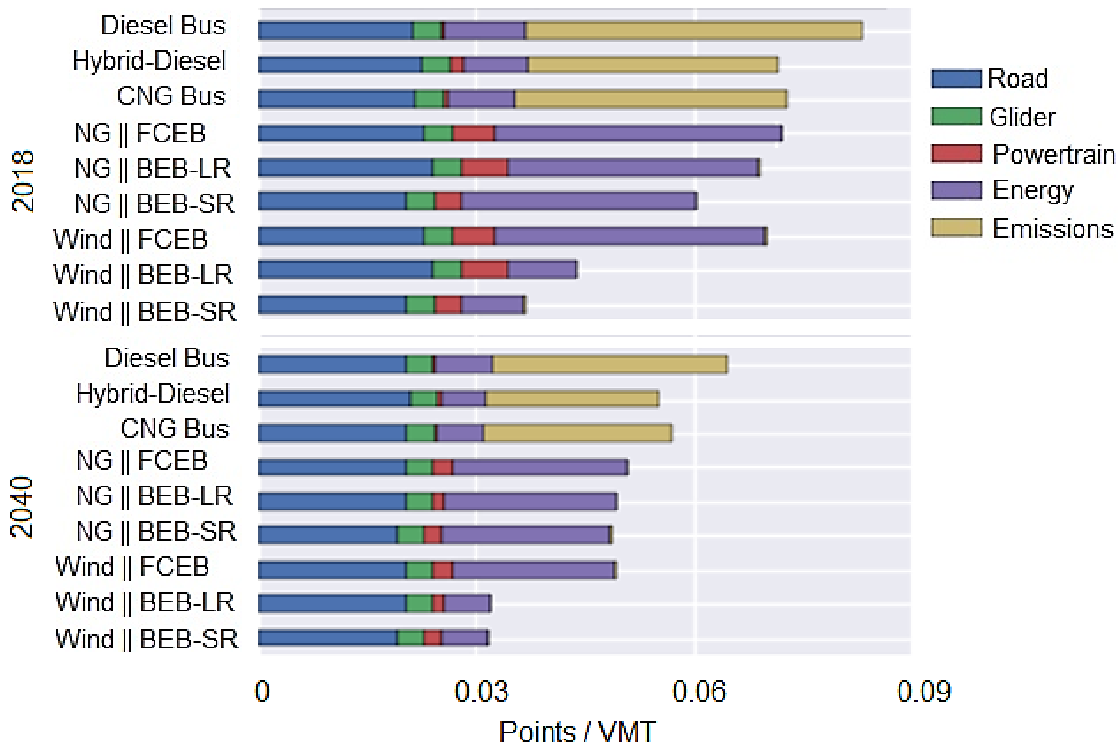



***Figure 69 ReCiPe Endpoint Ecosystem Quality results for present and future bus scenarios***

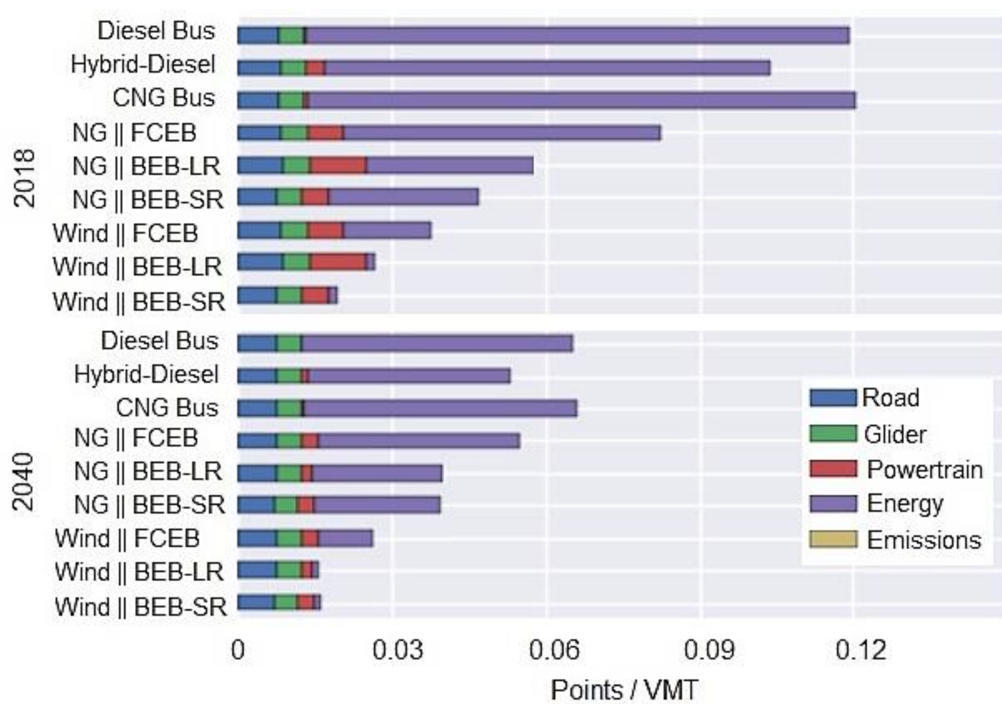



***Figure 70 ReCiPe Endpoint Resources results for present and future bus scenarios***

# Appendix B: Survey distributed for the Multi-Criteria Decision Assessment

## ZERO-EMISSION BUS TECHNOLOGY EVALUATION

NAME (optional) ____________________ Date ____________

Organization Type: ☐ Transit Agency ☐ Manufacturer ☐ State Agency ☐ Federal Agency ☐ Research ☐ City Rep. ☐ Utility Company ☐ NGO ☐ Other

The criteria and subcriteria below are designed to help evaluate each bus technology. Please fill up the survey following Steps 1, 2, and 3. The "Criteria 1 Example" (yellow section) presents an example of how to fill out the survey.
If there is a criteria or subcritera that you are not familiar with, just assign the lowest possible

**Step #1:** Assign each category a group weight by allocating 100 points among the 6 categories. The more important the criterion, the higher it's weight. The sum of the scores for all categories should add up to 100.

**Step #2:** Provide to each subcriterion its own weight. Weights can take on any value between zero and the maximum of the **group weight**. For example, if you assigned a group weight of 25 to a category, the subcriteria in that group can range from 0 to 25. You can assign all subcriteria in that group a 25, or some a 20, one an 5, one a zero, and so on.

**Step #3:** Rate each bus technology relative to the others in satisfying each subcriteria. For example, if you think a Hybrid bus provides the best capital cost, you would give to that bus a score of 4 for that subcriteria
The best bus option for the subcriteria = 4
The worst bus option for the subcriteria = 1

| Criteria Categories and Subcriteria | Group Weight | Subcriteria Weight | Rating: HFCEB[1] | Rating: BEB[2] plug-in | Rating: BEB on-route | Rating: Hybrid |
|---|---|---|---|---|---|---|
| **CRITERIA 1 EXAMPLE** | Step 1 – 25 | | | | Step 3 | |
| Subcriteria 1 | | 5 | 1 | 2 | 3 | 4 |
| Subcriteria 2 | | Step 2 – 20 | 4 | 2 | 1 | 3 |
| Subcriteria 3 | | 25 | 2 | 4 | 3 | 1 |
| **CAPITAL COST** | | | | | | |
| Capital cost of buses | | | | | | |
| Capital cost of station | | | | | | |
| Adaptation cost of maintenance facilities | | | | | | |
| **MAINTENANCE COST** | | | | | | |
| Fuel price | | | | | | |
| Mid-life overhaul | | | | | | |
| Routine maintenance | | | | | | |
| Cost of roadcalls | | | | | | |
| **FUEL SUPPLY** | | | | | | |
| On-site generation (hydrogen/electricity) | | | | | | |
| Third-party vendor/supplier | | | | | | |
| **ENVIRONMENTAL IMPACT** | | | | | | |
| Greenhouse gases | | | | | | |
| Regional air quality like criteria pollutants | | | | | | |
| Human health toxicity | | | | | | |
| **OPERATIONAL CONSTRAINS** | | | | | | |
| Bus mile range | | | | | | |
| Refueling time | | | | | | |
| Space availability for fueling infrastructure | | | | | | |
| **IMPACT TO COMMUNITY** | | | | | | |
| Traffic Impact | | | | | | |
| Noise reduction | | | | | | |
| Rare-metals mining | | | | | | |

EXAMPLE EXAMPLE EXAMPLE

[1]HFCEB: Hydrogen fuel cell electric bus [2] BEB: Battery electric bus