36th International Electric Vehicle Symposium and Exhibition (EVS36)
Sacramento, California, USA, June 11-14, 2023

Zero emission fleet composition optimization model

Anaïssia Franca[1], Andrew Clarry[1], Shervin Bakthiari[1], Julian Fernandez-Orjuela[1], Brian Cheung [1], Gheorghe Munteanu [2]

[1] *WSP, Canada*

[2] *Société de transport de Laval, Québec, Canada*

Executive Summary

Several technology alternatives are available to fleet owners that are looking to transition to zero emission vehicles, including battery electric, hydrogen fuel cells and ultracapacitor powered drivetrains. Each technology and related infrastructure has its own set of operational, financial, and physical characteristics that need to be taken into account to make an informed choice about the trajectory of the fleet transition. This paper explores the development of a strategic fleet composition optimization tool, applied to a transit bus fleet, that takes into account hundreds of inputs and defines a set of operational and spatial constraints to optimize the bus fleet composition between 2021 and 2037. One of the key conclusions based on the assumptions made for this application was the critical role in hydrogen fuel cell buses when it comes to simplifying operations and reducing operational expenditure in Québec in the long run. The results of the tools were validated using a traditional detailed engineering feasibility study that came to the same recommendation for the fleet transition.

Keywords: Zero emission vehicles, optimization, cost predictions, hydrogen, battery

1 Introduction

The government of Québec in Canada has set ambitious targets to reduce greenhouse gas (GHG) emissions by over 37.5% by 2030. To achieve this goal, the public transportation sector can play a critical role by transitioning to zero-emission technologies powered by clean electricity, such as hydro-power. The Société de Transport de Laval (STL), the public transit authority of Laval in Québec, is committed to replacing its diesel-powered fleet with zero-emission vehicles over the next 25 years. A crucial step towards this objective is to plan for the procurement of the appropriate zero-emission vehicles and associated infrastructure while maintaining flexibility to adapt to technological advancements in the long-term.

To help guide this transition, WSP was tasked with developing a model that calculates the optimal technology mix for the bus fleet from 2021 to 2045. The model is designed to be flexible, allowing users to update assumptions and databases to account for changes in technology, operations, and infrastructure, including the introduction of autonomous driving and new bus models for two different bus sizes (12 m and 18 m). The three technologies evaluated in the model are battery electric buses, hydrogen fuel cell buses, and ultracapacitor buses.

To input data into the model, a detailed feasibility study was conducted to assess the spatial requirements for each bus type at an existing garage and at a future garage that is set to be built. This study evaluated the space required for fueling and charging, as well as for the electrical distribution system at each site. The model also accounted for additional costs associated with operating two zero-emission technologies concurrently due to additional fire suppression and safety measures.

To plan the evolution of the vehicle fleet, the developed algorithm solves a future vehicle allocation problem over a set period of time to minimize costs while meeting operational constraints. This paper reviews the methodology developed by WSP to define the algorithm of the tool, the inputs, constraints, and lessons learned from the results of the model through a case study. By transitioning to zero-emission technologies and implementing optimized vehicle allocation strategies, fleet operators can provide cleaner and more sustainable services without compromising on efficiency.

2 Methodology

2.1 Objectives and criteria

The main goal of the model is to identify the most economical solution that satisfies all operational constraints applicable to the fleet. This involves taking into account the dimensional and technological characteristics of each propulsion mode (battery, hydrogen, and ultracapacitors) studied, while also ensuring operational needs are met, including usage and operational limitations. The solution must be both practical and achievable, with physical and temporal constraints factored in. The optimization process is primarily based on cost calculations, and the solution chosen is the most feasible, meeting all criteria while being the least expensive. The specific criteria considered in the model are detailed in Table 1.

Table 1: Criteria that the optimal solution has to meet

Criteria	Solution
Dimensional and technological characteristics of each technology considered	The solution takes into account different vehicle sizes, all technical characteristics of the three evaluated technologies, and their infrastructures.
Operational needs of the fleet	The solution meets the operational requirements of the network and complies with conditions of use, operation, and maintenance.
Meet the operational needs of the fleet in case of an emergency	The solution allows to meet the minimum service requirements in case of an emergency
Technical feasibility	The solution meets the physical and time constraints generated by the needs for infrastructure and garage conversion.

The following four constraints defined to narrow down the number of solutions considered:

- Resiliency: This constraint evaluates whether at any given time at least one technology that uses fuel to operate is sufficiently deployed to maintain minimum service level in case of emergency.
- Technology Availability: This constraint evaluates the availability of each technology at a given date based on a detailed review of the work reported in [1, 2, 3, 4].
- Operational and Bus Network Evolution Constraints: This constraint ensures that there are enough buses to: 1) meet STL's growing demand for each vehicle size and 2) offer the service level required for STL’s customers, meeting daily mileage requirements.

- Space Constraint: The optimal solution must be able to operate in the limited space of the current garage, especially with the addition of battery and hydrogen technologies and vehicle size characteristics.

2.2 Algorithm

To achieve the most cost-effective solution, the methodology involves comparing the results of numerous simulations to identify the solution with the lowest net present value (NPV). Rather than defining an optimization function with numerous constraints, the algorithm simulates multiple solutions, assesses whether they satisfy the criteria specified in Table 1, and calculates the final cost. The optimal solution, X_n, is the one that satisfies all constraints and has the lowest cost (see Figure 1).

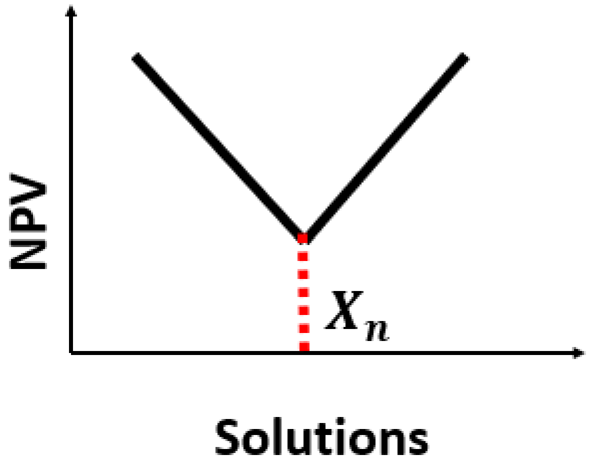

Figure 1: Illustration of the optimisation by simulation comparison

As shown in Figure 2, the overall calculation process is managed through different stages. First, different fleet composition "targets" at the end of the timeframe are created from a mesh spanning 0-100% for each technology. A composition target is the number of vehicles of each technology as a % of the total. For each fleet composition target considered, the algorithm generates a fleet which follows that target by evolving the fleet year-by-year via procurement and retirement. During this step, it also considers the operational and resilience constraints, ensuring all solutions satisfy those constraints. It then determines the energy infrastructure (the number of chargers and fueling stations) and facility configuration (parking space) required to support that fleet for each year.

Using this plan, costs are calculated for that composition target. For vehicles, these costs include capital expenditure - CAPEX (purchase cost, midlife overhaul, battery replacement, fuel cell replacement), and operational expenditure – OPEX (drivers, maintenance, cleaning, fuel, etc.). For infrastructure, costs are also divided into CAPEX (purchase and installation cost) and OPEX (maintenance). For the facilities, CAPEX is calculated from necessary building retrofits to accommodate changes in bus technology as well as costs to build new facility space. These costs were estimated in the parallel engineering study, and account for additional costs related to safety when multiple technologies are present in the same facility. OPEX costs related to operating and maintaining existing space are also included. The NPV is then calculated by aggregating these unit costs across all years considered.

The algorithm sorts all the solutions by NPV, and finally selects the scenario with the lowest total cost as the optimum solution.

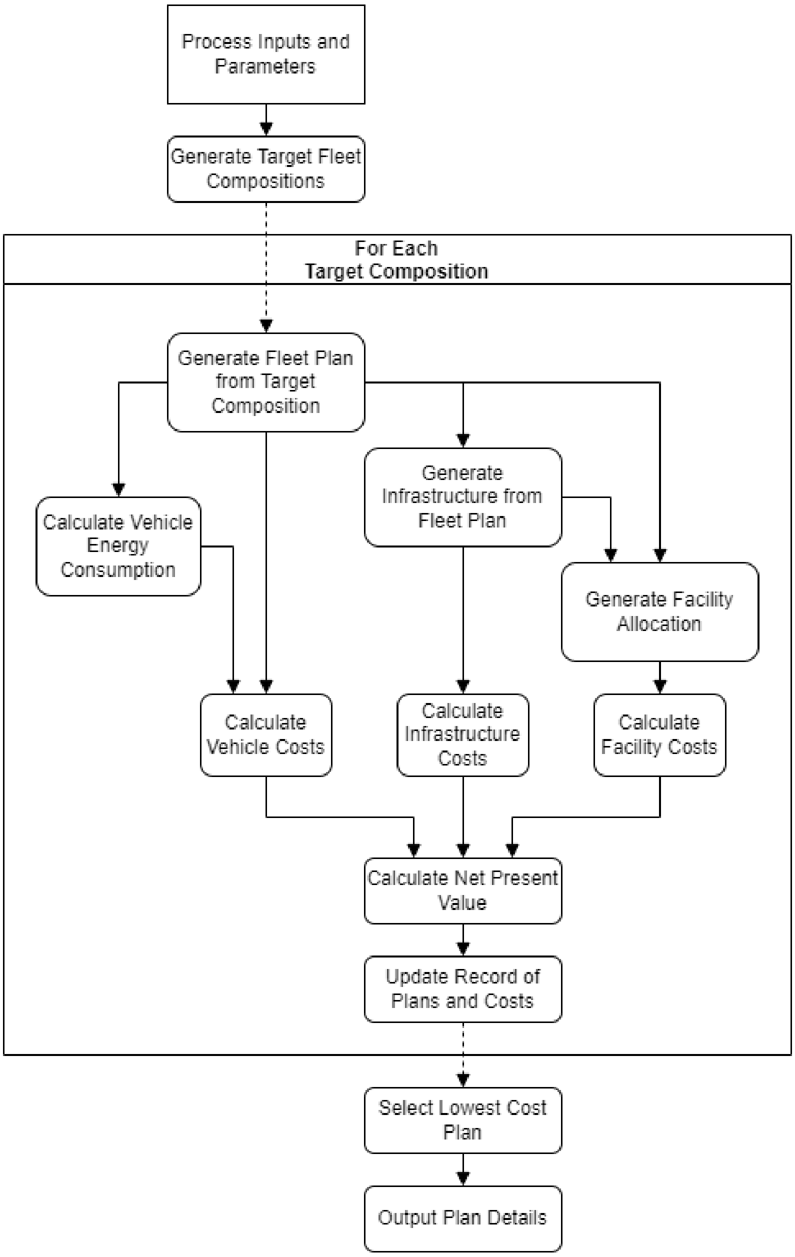

Figure 2: Calculation process overview

2.3 Inputs

There are four types of inputs: the ones that relate to the network and operations, infrastructures and buildings, technology and associated software and charging/fuelling, and costs.

The inputs vary by technology and timeframe studied. As an example, the model considers a gradual increase of the battery available capacity including the state-of-charge (SOC) buffer, starting close to 450 kWh in 2021 to reach close to 700 kWh in 2035. Once an electric bus model reaches a similar range as a diesel bus, the battery capacity remains stable. Inputs relate to the number of chargers and dispensers per bus, capacity and pressure of the hydrogen fuelling station, peak demand of the equipment, use of auxiliary heating in the winter, energy consumption of new models, and related CAPEX and OPEX.

Vehicles in the fleet are categorized by size (12m or 18m) and energy storage and propulsion technology (i.e., slow charge at the garage, fuel cells, ultracapacitors, and diesel for hybrids or diesel buses). Choices can be made about the number of vehicles of each type and the energy distribution infrastructure required for the selected technology. Table 2 below provides a review of selected inputs used to model 12 m electric buses between 2021-2035. A similar format is used for fuel cell buses and supercapacitor buses, as well as 18m buses. In this table, when a valuechanges depending on the timeline, it means that every new vehicle purchased within the defined time horizon will have the associated values. A bus that is purchased between 2021-2025 will have the same characteristics until it reaches its end-of-life. Note that the inputs were obtained through a review of the literature available, and discussions with ten North American manufacturers, however futuristic assumptions represent the authors best educated guests and should be cited with careful consideration.

Table 2: Selected inputs for the model for 12 m electric buses only. All costs expressed in Canadian dollars

Input	Type	Value (2021 – 2025)	Value (2025-2030)	Value (2031-2035)
Vehicle lifecycle	Operations	16 years	16 years	16 years
Age for battery replacement	Technology	5 years	10 years	10 years
Percentage of auxiliary heating use (day per year)	Technology	38 %	0%	0%
Electricity cost	Operations	0.07 $/kWh	Increased inflation of 2% yearly	Increased inflation of 2% yearly
Demand costs	Operations	94.05 $/kW	Increased inflation of 2% yearly	Increased inflation of 2% yearly
Bus purchase	Technology	1,200,000	1,000,000	900,000
Usable battery capacity	Technology	414 kWh	460 kWh	626 kWh
Winter auxiliary heating consumption	Technology	10.4 L/100 km	8.3 L/100 km	6.2 L/100 km
Electricity consumption in the winter	Technology	2.4 kWh/km	2 kWh/km	1.8 kWh/km
Chargers' costs	Technology	$833 $/kW	Increased inflation of 2% yearly	Increased inflation of 2% yearly
Equivalent electric bus to diesel replacement ratio	Technology	1.6	1.3	1.15
Vehicle maintenance cost	Operation	0.5 $/km	Increased inflation of 2% yearly	Increased inflation of 2% yearly

Charger maintenance cost	Operation	$18,000/charger/year	Increased inflation of 2% yearly	Increased inflation of 2% yearly
Charger per bus	Operation	1	0.75	0.75
Software costs	Operation	$1000/bus	$2 500/bus	$2 500/bus
Peak demand optimisation	Operation	0%	25%	25%
Bus residual value	Technology	10% of purchase value	10% of purchase value	10% of purchase value
Space used per electric vehicle (garage retrofit)	Building	73 m2/electric bus (compared to 50 m2/bus for diesel and hybrid)		
Garage retrofit cost	Building	$100,000/electric bus		
Garage new build cost	Building	$850,000/electric bus		

The user is offered to choose different options in the graphical user interface, including the start and end year of the simulation, when the new garage build will be available, the minimum frequency of operation in case of emergency, which technology should be considered and when are they ready to be in operation. In this simulation, the battery electric buses were assumed to be deployed as early as 2022, while the fuel cell vehicles were set to be deployed in 2025.

3 Results and sensitivity analysis

3.1 Results with set inputs

For the set of inputs introduced above, the optimal solution consists of a combination of two technologies: hydrogen fuel cell buses and slow-charging battery buses, which is illustrated in Figure 3 below. To protect confidentiality of operating and planning information, the following results are from scenarios with modified fleet size and operational inputs. The exact values differ from the results which were provided to STL, but the overall pattern and the conclusions reached are similar.

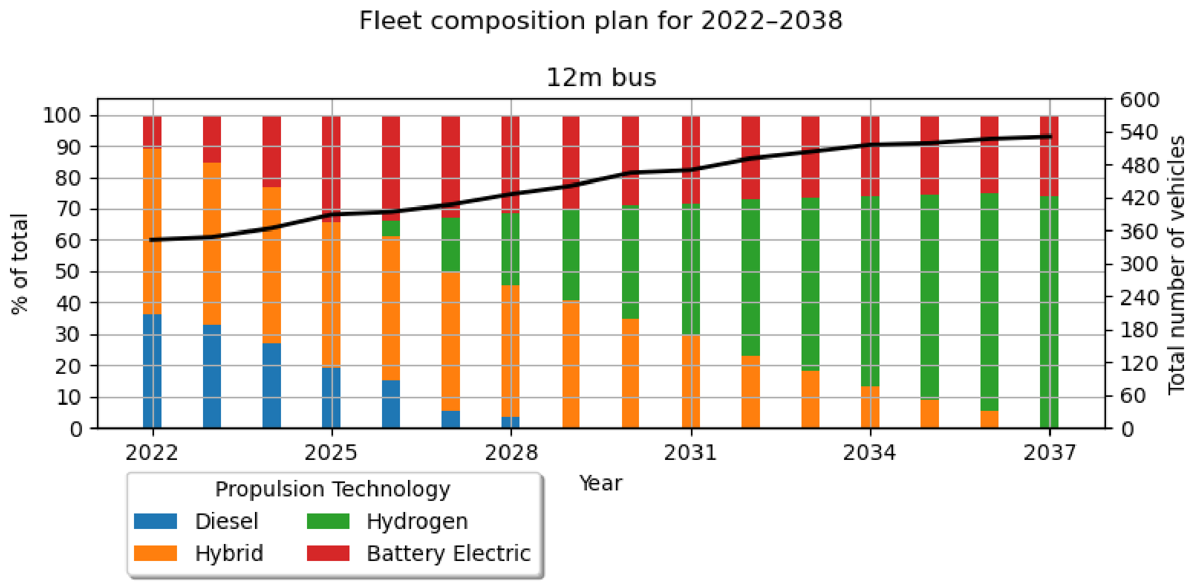

Figure 3: Results of the model with the set inputs

Figure 4 shows the total transition cost to achieve different composition targets using fuel cell and slow-charging electric technologies for the 12-meter buses between 2021-2045. These results demonstrate that the optimal distribution of these two technologies is in the middle range, between 70% and 50% for fuel cell buses, or between 30% and 50% for battery buses. Note that this cost includes all transition elements between 2021 and 2045, including the cost of the required workforce which make up the majority of the OPEX costs. The more battery electric buses are adopted, the higher the costs, as demonstrated by the yellow points.

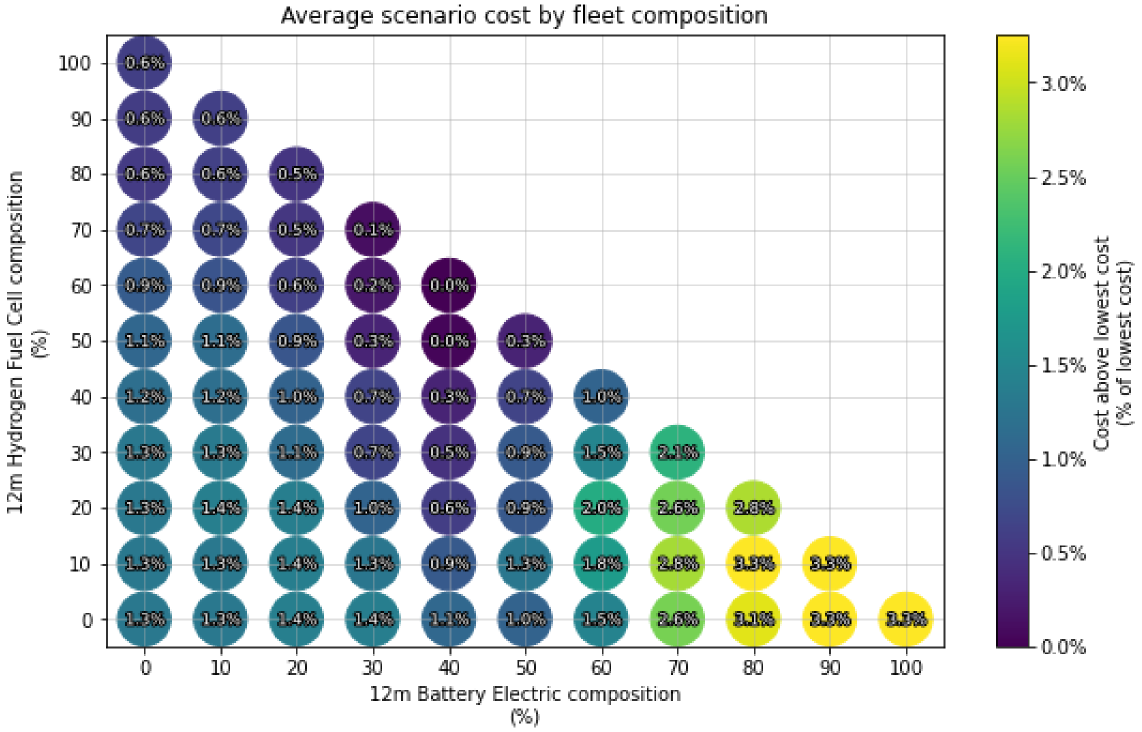

Figure 4: Total project transition cost comparison for different adoption targets with battery electric bus and fuel cell buses (12 m buses)

3.2 Selected sensitivity analysis

A sensitivity analysis was performed by varying the technologies' integration dates, fuel and electricity costs, vehicle and infrastructure procurement cost, as well as the technology improvement assumptions separately. As expected, it was found that increasing the cost of hydrogen fuel would reduce the optimal number of 12m hydrogen buses. The following paragraphs describe the three scenarios considered. The results of the sensitivity analysis are summarized in Table 3.

3.2.1 Increased cost of hydrogen, electricity and diesel (scenario 1)

In this scenario, the cost of all energy sources is increased compared to the baseline scenario. This increases the operating costs of all propulsion types, but the competitiveness of hydrogen buses is hurt relatively more, causing the algorithm to choose fewer hydrogen buses.

3.2.2 Increased cost of hydrogen (scenario 2)

This scenario models a future where the cost of hydrogen fuel remains high, due to factors such as difficulties in scaling up zero-emissions hydrogen production. This increases the operating costs of hydrogen fuel cell buses significantly, lowering the amount of hydrogen buses in the fleet similar to scenario 1.

3.2.3 Increased battery performance growth (scenario 3)

In this scenario, battery capacity and lifetime for battery electric vehicles grows at a faster than expected rate. This increases the competitiveness of battery-electric buses, mainly by reducing the number of additional buses required in the fleet to accommodate vehicle charging in longer schedules in the system. Under this scenario, the algorithm acquires as many battery electric buses as it can while maintaining the operating resiliency requirement.

Table 3: Comparison of the sensitivity tests compared to the baseline simulation

	Scenario 1	**Scenario 2**	**Scenario 3**
Vehicle and operating costs (% of baseline)	111.0%	108.4%	92.5%
Electrical and fuel infrastructure costs (% of baseline)	120.2%	105.6%	99.6%
Garage construction and renovation costs (% of baseline)	110.7%	121.1%	102.9%
Total cost (% of baseline)	111.6%	109.1%	93.7%
Fleet size in 2037	544	544	519
% Hydrogen vehicles in 2037	54%	54%	35%
% Battery electric vehicles in 2037	46%	46%	65%

4 Conclusion

The results of the tool were coherent with a technical feasibility study that analysed over 28 technology adoption scenarios between 2021 and 2045. This methodology can be applied to any mixt fleet in the process of transitioning to zero emission technology, including various vehicles and fleet types (delivery, freight, transit, and others). Different technology mixes should be considered to optimize the fleet composition.

While these results are based on a public transit operator in Québec (Canada) and so limited in their generalizability, they clearly demonstrate the advantages of incorporating hydrogen fuel cell vehicles into the fleet mix. Contrary to some belief, the study found that the fuel cell vehicle option could potentially be more cost-effective than other alternatives in the long run. Therefore, the findings suggest that deploying hydrogen fuel cell vehicles could be a promising strategy for achieving sustainable and efficient public transportation in Québec, and potentially in other regions as well.

In this version of the tool, the optimization is performed by simulating a large number of possible solutions meeting the defined constraints and selecting the least expensive one. This process has been chosen because it is certain to arrive at a feasible solution. However, this process can be time consuming depending on the computing power of the computer and the size of the search grid. The other option would be to develop a mixed linear optimization approach; the risk being the complexity of formulating such a problem, as it requires a large set of constraints and decision variables.

5 Acknowledgement

The authors would like to express their gratitude to the Société de Transport de Laval for their invaluable support in enabling this work, providing the necessary structure, and offering continuous feedback throughout the year and a half long collaboration.

References

[1] V. Kumaravel, J.Bartlette and S. Pillai, "Solid Electrolytes for High-Temperature Stable Batteries and Supercapacitors," *Advanced Energy Materials,* p. 2002869, 2021.

[2] C. H. D. Grey, "Prospects for lithium-ion batteries and beyond—a 2030 vision," *Nature Communications ,* vol. 6279, no. 11, 2020.

[3] Y. Manoharan, S. Hosseini, B. Butler, H. Alzhahrani, B. Senior, T. Ashuri and J. Krohn, "Hydrogen Fuel Cell Vehicles; Current Status and Future Prospect," *Appl. Sci.,* vol. 2296, no. 9, 2019.

[4] P. Poonam, K.Sharma, A.Arora and S. Tripathi, "Review of supercapacitors: Materials and devices," *Journal of Energy Storage,* vol. 21, pp. 801-825, 2019.

(1)

Presenter Biography

Anaïssia Franca is the Director of the Centre of Excellence in Sustainable Mobility at WSP, a global engineering consulting firm. She leads projects aimed at promoting the adoption of Zero Emissions Vehicles and related infrastructures. Anaïssia holds a Master's degree in Applied Science in Mechanical Engineering and is a Professional Engineer in Canada. Her expertise in zero emission vehicle charging and fueling requirements, along with peak demand calculations, helps to size charging and electrical infrastructure to meet the energy needs of fleets. Anaïssia has provided her expert knowledge and support for electrification projects for agencies and municipalities across Canada, USA, New Zealand, Australia, Israel, and Sénégal.