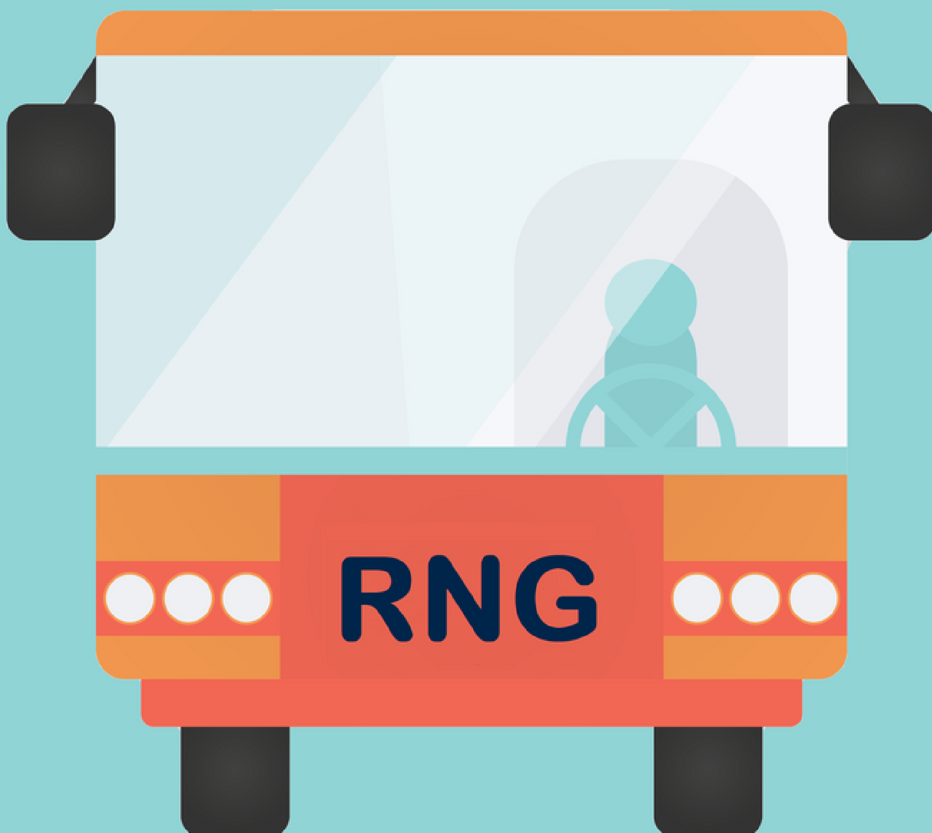
Renewable natural gas as a complementary solution to decarbonizing transit



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List of Acronyms

BC Transit	British Columbia Transit
BEB	Battery electric bus
CARB	California Air Resources Board
CI	Carbon intensity
CNG	Compressed natural gas
CUTRIC	Canadian Urban Transit Research and Innovation Consortium
DLE	Diesel litre equivalent
DGE	Diesel gallon equivalent
FCEB	Fuel cell electric bus
GHG	Greenhouse gas
HFC	Hydrogen fuel cell
HSR	Hamilton Street Railway (City of Hamilton Transit Division)
LCA	Lifecycle analysis
LCFS	Low Carbon Fuel Standard
LNG	Liquefied natural gas
MBRC	Mileage between road calls
MMBTU	Metric million British thermal unit
NGV	Natural gas vehicle
NREL	National Renewable Energy Laboratory
NYCT	New York City Transit
RNG	Renewable natural gas
RTA	Riverside Transit Agency
UPS	United Parcel Service

Executive Summary

Eliminating the emission of pollutants to the atmosphere is of utmost importance given the imminent climate crisis and increasing health issues faced across the globe. Taking transit is one of the most common modes of transportation in big cities, and these vehicles are predominantly powered by fossil fuels, most often diesel. Diesel is one of the fossil fuels that pollutes the most with the entire fuel supply chain being carbon intensive.

To counter the pollution of fossil fuel powered vehicles, significant attention has been given to electric vehicles (EVs) in recent years. This is because they do not emit harmful gases from their tail pipes. In this sense, CUTRIC regularly advocates for cleaner transit with the adoption of battery-electric buses (BEBs) and fuel cell electric buses (FCEBs). However, a less explored option that can outperform BEBs and FCEBs exists. Compressed natural gas (CNG) buses operating using renewable natural gas (RNG) can be cleaner and cheaper to operate than BEBs and FCEBs.

Transit electrification is challenging in many aspects. BEBs are only as clean as the electricity grid utilized to produce the energy consumed by the vehicles. Therefore, the deployment of BEBs in jurisdictions that use fossil fuels to produce its electrical energy does not make sense. Additionally, the typical range of BEBs is significantly lower than the fossil fuel counterpart. Operational challenges might require a replacement ratio between fossil fuel vehicles and BEBs to be higher than one. In other words, it is generally necessary to deploy a higher number of BEBs to deliver the same service of a lower number of fossil fuel vehicles. Moreover, transit electrification using BEBs requires installation of expensive charging infrastructure in addition to procuring vehicles that are more expensive.

The implementation of FCEB technology also introduces significant challenges due to high costs associated with the production of hydrogen fuel. While the cost of fuel production has been decreasing in recent years, fleet electrification with FCEBs requires large capital investments with hydrogen storage capabilities, hydrogen refuelling stations and vehicle costs that are higher than BEBs.

CNG buses, however, have already been disseminated in the transit industry using fossil fuel natural gas. If these buses are powered with RNG, transit can be simultaneously cleaner and cheaper. The RNG fuel has the potential of being zero-carbon or carbon-negative depending on the methods of production. Its production can offset both the tailpipe emissions and the emissions of other human activities as explained in this report. No vehicle modifications or additional infrastructure are necessary because RNG is chemically identical to the fossil fuel natural gas. This translates to increased flexibility in the fuel supply chain as CNG buses can be powered with blends of RNG/CNG at any proportion.

CUTRIC has worked in collaboration with five transit agencies that are leaders in transit decarbonization and are instrumental in the development of the present report. This study considers three years of operational data (2018-2020) provided by three Canadian agencies and two American agencies: Calgary Transit in Alberta, an innovative transit agency in California, Riverside Transit Agency (RTA) in California, HSR || Hamilton Street Railway (City of Hamilton Transit Division) in Ontario and TransLink in British Columbia. Each of the agencies provided data describing distances travelled, the quantity of fuel consumed, the cost of fuel and the cost of maintaining vehicles for diesel and CNG. The data collected are used alongside RNG price points and carbon intensity (CI) factors obtained from a literature scan to predict the potential environmental impacts and cost associated with using RNG to power CNG buses in Canada. Only aggregated and anonymized results from the five transit agencies participating in the study are presented in this report.

Depending on the method of RNG production, a direct comparison between diesel and RNG shows that it is possible to power CNG buses with a blend ratio between 20 and 60 per cent of RNG/CNG to achieve carbon neutrality. The data also show the possibility of operational savings with fuel and maintenance in relation to diesel buses while operating carbon neutral CNG buses. Alternatively, CNG buses can become carbon negative if powered with RNG at higher blend ratios, operating at cost parity, or at slightly higher costs in relation to diesel buses.

The RNG/CNG knowledge gathered through the transit industry experience should be transferable to other applications as well. Heavy-duty transportation in general and specific markets such as refuse trucks could reinforce the strength of the industry, contributing to a further improvement of the business case of RNG as a carbon-neutral solution.

CUTRIC has actively advocated for RNG to be identified as zero-emission technology solution. The increasing use of Canada's low-carbon RNG supplies should be considered eligible for ZEB feasibility studies, as well as permanent federal transit funding in the future, because they offer reductions of emissions over diesel and diesel-hybrid comparative vehicles.

1 Literature Review

The utilization of natural gas as a fuel in the transportation industry can contribute to the reduction of greenhouse gas (GHG) emissions and help address the problem of climate change. The carbon intensity of natural gas, that is, the emission rate of pollutants generated in its production, distribution and consumption, in relation to the activity intensity, is relatively low. Natural gas CI values can even reach negative values [1] if the fuel is produced by renewable means as explained in more detail below.

According to Clean Energy Fuels [2], natural gas buses present some unique characteristics:

1. Natural gas buses, even when using fossil-based natural gas, produce less GHG emissions and tailpipe exhaust than diesel buses.
2. Natural gas buses are approximately C$50,000 more expensive than diesel buses but C$25,000 cheaper than diesel-electric hybrid buses.
3. Switching from diesel to natural gas can introduce savings of more than C$250,000 per

vehicle over the 16 years of a vehicle's lifetime due to lower fuel and maintenance costs in Canada.

4. Natural gas buses can bring savings on maintenance as they are free from problematic diesel particulate filters.
5. Natural gas buses can be 10 decibels quieter (i.e., ten times quieter than diesel buses on average).
6. Natural gas buses do not suffer from performance issues in terms of power, acceleration or cruise speed. They also do not introduce range anxiety as many battery-electric buses do.

1.1 Background and landscape of CNG

The history of using natural gas to power vehicles traces back to the early 1930s in Italy [3]. However, scalable efforts of converting gasoline vehicles to natural gas vehicles (NGVs) did not start until after the oil crisis in the 1970s [4]. By the end of 2019, the top three global leaders of NGV adopters were China, Iran and India [5]. Table 1 shows the number of NGVs and natural gas fuelling stations around the world [5], clearly indicating that the number of NGVs in North America is the lowest among other regions, and possibly indicating the existence of great potential for increasing the adoption of NGVs.

Table 1: Number of NGVs and natural gas fuelling stations around the world

Regions	No. of NGVs	No. of fuelling stations
Asia-Pacific	~20,500,000	20,300
Latin America	~5,500,000	5,800
Europe	~2,100,000	5,200
Africa	~300,000	200
North America	~200,000	1,900

In the 1980s and 1990s, the number of NGVs in Canada increased to over 35,000 with the assistance of Canadian federal and provincial research programs, demonstration projects and NGV deployment programs [6]. After 1995, the Canadian NGV market started to decline due to drops in gasoline and diesel prices, lack of R&D support, higher up-front cost of NGVs and lack of fuelling stations [6]. Eventually, the overall number of NGVs decreased to about 12,500 in 2016 [7]. Regardless of this significant decline occurring predominantly in the light-duty application sector, strong growth in the number of medium and heavy-duty NGVs was observed from 2010 to 2013 [7].

According to the Government of California, CNG and liquefied natural gas (LNG) have lower carbon intensities than gasoline and diesel fuel [8]. California has been using natural gas in transportation for more than two decades and multiple types of vehicles, including passenger cars, trucks, transit buses, school buses, package delivery vehicles and refuse and recycling trucks [8]. One recent study reveals that over one billion dollars is being invested in California to expand the RNG production [9, 10]. The key findings from this study include:

1. By January 2024, 119 million DGE of RNG will be produced from 160 RNG production facilities. This is enough to power 13,731 natural gas trucks annually. The primary source of RNG is from dairy farms and landfills.
2. 77 per cent of the investment is from private investors.
3. The carbon intensity for the RNG produced by January 2024 will reach the value of negative 101.74 gCO_2eq/MJ.
4. Using this RNG in NGVs will result in more than 3.4 million tons of GHG emission reduction annually.
5. If California's Heavy-Duty Vehicle Incentive Program can provide a US$45,000 voucher to purchase NGVs that could be fuelled by the RNG produced in California, such hypothetical new fleets could result in 51.4MtCO_2eq (million tonnes of carbon dioxide equivalent) and 20,800 tons of nitrogen oxides (NOx) reductions with the cost of $12.03/Mt$CO_2$eq and US$29,702 per ton of NOx over the period of 15 years.

Currently, more than 150,000 NGVs are running in America, of which approximately 88 per cent are medium and heavy-duty vehicles [8]. In general, the use of natural gas as a fuel has several advantages over diesel and gasoline for powering vehicles:

1. CNG is widely available as Canada has an abundant supply of this resource [7].
2. Generally, NGVs emit less carbon dioxide (CO_2) than vehicles powered by other fossil fuels. Compared with diesel trucks, this difference is in the range of 13-15 per cent [11].
3. Studies have shown that NGVs can significantly reduce air pollutants such as carbon monoxide (CO), NOx, sulfur dioxide (SO_2) and particulate matter (PM) compared with diesel and gasoline counterparts [4].
4. Natural gas is compatible with conventional engines [4]. Moreover, this fuel has a relatively high-octane rating, which allows for high compression ratios in the engine. As a result, NGVs can achieve a thermal efficiency of approximately 10 per cent higher than that of gasoline-powered vehicles [4].
5. Using natural gas can lead to significant operational cost savings due to the stable low commodity pricing of natural gas in Canada [4, 7].

1.2 Renewable Natural Gas

Typically, the term "compressed natural gas" and its acronym CNG refers to the fossil-based, naturally occurring, hydrocarbon gas mixture extracted from underground rock formations or associated with other hydrocarbon reservoirs. In contrast, the term “renewable natural gas” or RNG refers to the product extracted from the decomposition of organic matter resulting from other human activities (e.g., agriculture and waste management). Even though RNG is chemically identical to CNG, the RNG/CNG terminology is used in this report to differentiate between the fossil-fuel-based and the human-produced natural gases.

Huge amounts of organic matter are continuously discarded in Canada. According to the National Zero Waste Council, edible food waste contributes to more than two million tonnes each year [12]. Animal manure, agricultural and forest residues are other examples of organic matter that may end up decomposing in the environment or in landfills. As Figure 1 illustrates, the process of decomposing organic matter produces biogas which can be used to produce RNG.

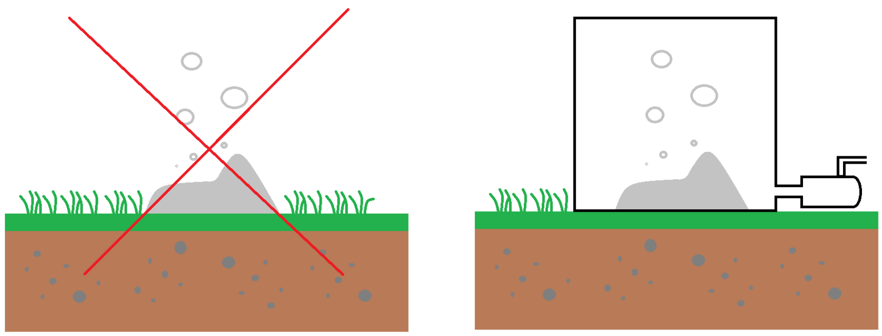

Figure 1: RNG production concept scheme

RNG is produced from biogas, a product from bacterial decomposition of organic matter under anaerobic conditions. Anaerobic digesters are often used to process organic wastes such as food wastes, manure and other biodegradable materials to produce biogas. Raw biogas can contain up to 60 per cent methane, about 40 per cent CO_2 and an additional small number of impurities [13]. After filtering out the CO_2 and impurities from biogas, the remaining methane becomes the RNG and can be used to power NGVs [13].

Less conspicuous methods such as thermal gasification are available for producing RNG. This technique consists of heating the organic matter to break the molecules into the biogas that can then be purified. Thermal gasification, however, is more expensive and generally more carbon intensive.

Not only is the burning of natural gas generally less carbon-intensive than other fossil fuels but the production of RNG also captures methane which would otherwise be released into the atmosphere because of non-transit related human activities. Since methane has a global warming potential approximately 25 times higher than CO_2, releasing methane is significantly worse than releasing CO_2 [14]. By capturing this methane gas and burning it into NGVs as a means of propulsion, the global warming potential of tailpipe emissions is far lower than the corresponding emissions of the human activity that generates methane in the first place. In this sense, the energy and transportation sectors can contribute significantly to offset the human carbon footprint from other sectors. For this reason, the use of RNG-rich natural gas mixtures or pure RNG in NGVs can reach neutral or even negative carbon intensity values.

The research literature lacks extensive research on carbon intensity factors for RNG production in the Canadian context due to the incipient character of this activity in the country. The marketplace of RNG in the United States is more developed, with California as one of the leaders. This study considers the carbon intensity factors achieved in the US as a reference as explained in detail in the next sections. The CI factors depend heavily on the method of production and source of biomass which can include agricultural residues, forestry and forest residues, municipal solid waste, landfills, wastewater and animal manure.

1.3 RNG is getting traction

With rising public and governmental concerns about GHG emissions, RNG is attracting attention as a promising fuel that can be blended with fossil-based CNG, or even completely replace the fossil-based CNG for fuelling NGVs.

Multinational corporations in the private sector are promising to make the transition to clean energy by setting emission reduction goals. Amazon invests in a diversified matrix of clean energy with electric vehicles. The company goal is to reach full renewable energy sources by 2025 with the use of renewable power generation with solar, wind and RNG. Amazon intends to fuel a portion of its fleet with low- and negative-carbon RNG [15].

According to NGVAmerica and the Coalition for Renewable Natural Gas (RNG Coalition), approximately 53 per cent of all on-road fuel used in NGVs in 2020 was RNG. Those institutions evaluated that RNG grew as a transportation fuel by 25 per cent in 2019, an increase of 267 per cent over the last five years [16].

The Canadian RNG market might soon reach the same level of maturity as the United States. Currently, 279 Canadian biogas projects are capturing methane from community and agricultural waste with the production of approximately six petajoules per year of RNG [17]. If this amount of energy could be converted into electricity without losses, it would be the equivalent of installing almost 200MW of clean electricity. To put this quantity in perspective, achieving this power level by adding additional hydroelectric reservoirs would require the construction of more than 10 large hydroelectric power plants [17]. If all this RNG is used to power CNG buses, more than 4,000 vehicles could rely on the clean fuel.

Overall, only approximately 16 per cent of the biogas production in Canada is upgraded into RNG, with approximately 41 per cent being flared, 14 per cent used for heating or direct use and 29 per cent for electricity generation [17]. These numbers point to an enormous opportunity. By only upgrading the flared portion to RNG, the availability of this clean fuel would more than double.

Canada, moreover, is only accessing approximately 13 per cent of its potential to obtain easily available biogas [17]. A study by TorchLight Bioresources estimates that approximately 155 petajoules of RNG, which could power more than 100,000 CNG buses, is realistically available [18].

One of the leaders in the RNG space in Ontario is the city of Hamilton as it has been producing RNG from wastewater and converting it to electricity for more than 15 years [19]. More recently, this RNG has been powering a 60-foot CNG bus that displaces the emissions of 36,000 litres of diesel per year [20].

1.4 Case studies of non-transit NGVs

Arteconi et al. performed a life-cycle analysis (LCA) of GHG emissions of heavy-duty vehicles that use LNG as fuel in Europe and compared the results with those of diesel-powered vehicles [21]. The study assumed a heavy-duty truck running in a duty-cycle that includes both highways and out-of-town and in-town roads. Using LNG can reduce up to 10 per cent GHG emissions compared with diesel fuel in this case.

Using the modelling tool GHGenius, Rose et al. performed an LCA study of GHG emissions from refusal collection vehicles powered by diesel and CNG in Surrey, British Columbia [22]. The authors collected real-time operational data from the city of Surrey for analysis. The study concluded that although replacing diesel refuse collection vehicles with CNG powered vehicles does not improve energy usage, the amount of GHG emissions is about 24 per cent lower and the emission of pollutants is significantly reduced. Furthermore, fuel cost comparisons show that CNG costs less than half of diesel fuel. This is based on the prices of both fuels in 2011 and a five-year lifetime of refuse collection vehicles.

Alex Lawson Associates Inc. and Red River College conducted a study to evaluate the winter performance of CNG refuse trucks [23]. The primary data source is from a fleet of 18 CNG refuse trucks operating in Montreal, Quebec, and the secondary data source is from 58 CNG refuse trucks operating in Winnipeg, Manitoba. The 18 CNG refuse trucks in Montreal had a minimum downtime of over two years of operation with 10 hours of operation each day, per truck, with an estimated 40,000 km annual distance travelled per truck. These 18 CNG buses experienced few operational issues with minimal cold weather aids during the two years of operation even when temperatures dropped to -16℃ [23]. However, the 58 CNG refuse trucks that operated in Winnipeg experienced multiple operational issues such as ice buildup in the air intake and frozen fuel filters in their first winter when the temperatures reached below -25℃. As these CNG refuse trucks are not designed for arctic conditions, they require extensive cold weather aids and vehicle modifications to allow the vehicles to function normally in extremely cold weather. These aids and modifications would also have been required for gasoline and diesel-powered vehicles [23]. Thus, the study shows that CNG refuse trucks can function properly in the Canadian cold winter once appropriate modifications are made.

The Argonne National Laboratory conducted a case study that explored the production and use of RNG from the anaerobic digestion of cow manure at Fair Oaks Farm, which is involved in the largest operational digester-to-RNG vehicle fuel project in the U.S. [13]. Among the gases coming out of the anaerobic digesters, methane accounts for 55-60 per cent, followed by 35-40 per cent CO_2, and less than one per cent trace constituents. The outcome after a gas purification process is a 98 per cent or higher methane-rich gas (RNG) that can be used as a vehicle fuel. Fair Oaks Farm has converted 42 heavy-duty milk tanker diesel trucks to CNG trucks and fuels the truck fleet with the RNG, saving 1.5 million gallons of diesel fuel annually. The study shows that Fair Oaks Farm has achieved a 43 per cent GHG emissions reduction associated with producing and delivering a gallon of its milk. Furthermore, Fair Oaks Farm uses extra RNG as fuel to power a one-megawatt generator to save its electricity bill.

The Argonne National Laboratory conducted another case study by using anaerobic digestion to convert food waste to RNG as a transportation fuel in Sacramento, California [24]. In this study, the food wastes that are fed into the anaerobic digester are collected from commercial enterprises such as supermarkets, restaurants, food manufacturers and processors. The generated RNG is used to power 28 heavy-duty natural gas refuse trucks. The study shows that with full capacity, the anaerobic digester is capable of processing 40,000 tons of organic waste annually and generating a natural gas equivalent to more than 500,000 gallons of diesel fuel. The byproducts from the digester include soil enhancers and fertilizer products for agricultural purposes. The authors also found that on a lifecycle basis, the RNG produced is a net-carbon-negative fuel.

In another case, the United Parcel Service (UPS) tested NGVs in 1989 [25]. In 2002, UPS became the owner of the largest private CNG vehicle fleet in the U.S. with more than 1,000 delivery vehicles. In 2019, UPS started a $450 million investment to purchase 6,000 natural gas-powered delivery trucks from the year 2020 to 2022 [26]. Since its agreement to purchase 230 million gallons equivalent of RNG for seven years, UPS has become the largest consumer of RNG in the transportation industry. [26]. The company operates more than 11,000 low-emission vehicles and RNG is an important part of its strategy to increase alternative fuel consumption by 40 per cent of its total fuel purchases by 2025 [27].

1.5 Case studies of transit NGVs

Starting in 1985, in the province of Ontario, the City of Hamilton was the first to operate CNG buses in Canada by converting four diesel buses to CNG [28]. From 1991 to 2003, new buses ordered by the City of Hamilton were nearly all CNG-powered buses [28]. By the end of 2019, HSR operated 137 CNG buses comprising more than 50 per cent of the fleet at the time [29], and more recently started operating one of its CNG buses fuelled with RNG [20].

British Columbia Transit (BC Transit) has been adding CNG buses across the province since the initial introduction of CNG buses in the Regional District of Nanaimo and City of Kamloops in 2014 [30]. By the year 2019, BC Transit had added 128 CNG buses to three regional transit systems (i.e., Whistler, Nanaimo and Kamloops) [31]. According to BC Transit, these vehicles have successfully demonstrated their best-in-class technology in terms of providing dependable and sustainable transportation solutions, encouraging BC Transit to continue adding CNG buses, and fulfilling BC Transit's commitment to reduce GHG emissions [31]. In 2020, 60 CNG buses, 25 medium-duty and 35 heavy-duty vehicles were added to Victoria Regional Transit System's fleet within BC Transit [32]. These CNG buses fall under BC Transit's Low Carbon Fleet Program, supporting the province's targets for GHG emission reduction and aligning with the CleanBC plan. The benefits of these vehicles are both environmental and economic (i.e., cutting GHG emissions and operational costs) [32].

In the province of Alberta, the City of Red Deer received 17 new CNG buses to replace retired diesel vehicles in 2017. The remainder of the fleet is expected to be gradually replaced by CNG buses as diesel vehicles begin to phase out [33, 34]. Red Deer's decision to transition to CNG buses is based on extensive environmental and economic analysis that shows CNG buses produce fewer harmful emissions and noise and are more efficient than their diesel counterparts [34].

Medicine Hat, another city in Alberta, recently added six CNG buses that account for 14 CNG buses out of a total of 19 buses owned by the city [35]. Medicine Hat is planning to transition its entire fleet to CNG since the vehicles are much quieter, can reduce GHG emissions, and require less engine maintenance [35].

The City of Calgary and Calgary Transit introduced CNG powered buses in the year 2013 as a part of a pilot project to test the performance of these vehicles under the local diverse weather conditions [36]. According to the agency, a total of 62 new CNG buses entered service with Calgary Transit in 2019. An additional 48 buses entered service in 2020, bringing the total number of CNG buses currently in service at Calgary Transit to 114. Orders have been placed for an additional 57 CNG buses to be delivered in 2022. Calgary Transit has also planned to add an additional 150 CNG buses by 2025 [37]. To prepare for the arrival of a large number of CNG buses, Calgary Transit recently opened the industry-leading Stoney CNG Bus Storage and Transit Facility. It has enough storage space for approximately 450 buses and is capable of supporting the maintenance, operation and fuelling of CNG buses. Six buses can be fuelled at the same time within almost four minutes [37].

In summary, according to industry reviews and literature, NGV technology is mature and has a similar performance to diesel vehicle technologies in terms of range, operating conditions and fuelling time. Operating NGVs also cost less, reduce emissions and are quieter in comparison to diesel vehicles. Moreover, as RNG enters the transportation fuel industry and scales up, a higher content of RNG in the fuel mixture can help NGVs achieve carbon neutrality or potentially a negative carbon intensity. This can result in NGVs reducing more GHG emissions than battery-electric buses. Considering all the benefits of NGVs, it is no longer practical for transit agencies to purchase diesel buses.

2 Data Analysis

CUTRIC tracked more than 450 million kilometres travelled by diesel and CNG buses in this study. In addition to distance travelled, the quantity of fuel consumed, the fuel cost and maintenance costs were also monitored for more than 2,500 40-foot buses from transit agencies participating in the study. This includes: Calgary Transit, HSR, an innovative transit agency in California, RTA and TransLink. The data refers to an operational period of three years from 2018 to 2020. Approximately 70 per cent of the vehicles are powered by diesel and approximately 30 per cent use CNG as fuel.

Data from vehicles of the same size and technology were aggregated. A particular vehicle configuration was only included in the analysis if at least three of the five agencies operate and provide data. For example, one of the agencies operates BEBs and another operates FCEBs, but these vehicle configurations were not included because the data could not be properly aggregated and anonymized. As a result, the analysis was only carried out for 40-foot diesel buses and 40-foot CNG buses.

The cost savings predicted in this report are based on average RNG price points as observed in the American market, this is explained in the next few sections. However, the estimations are conservative in the sense that credits potentially resulting from the Clean Fuel Standard were not included in the analysis [38]. It is important to note that some jurisdictions have had RNG subsidized under rate agreements with their respective utility regulators (e.g. BC).

2.1 Aggregated and anonymized data

A breakdown of the distance travelled, average fuel efficiency, fuel cost and maintenance cost for diesel and CNG buses can be seen in Table 2. No single price points were utilized in the analysis. Instead, short term fluctuations in fuel prices were all captured by tracking the actual expenditure of the transit agency. The fuel efficiency of CNG is expressed in kilometres per diesel litre equivalent (km/DLE).

The maintenance costs in Table 2 include both costs with parts and labour.

Table 2: Aggregated data of five transit agencies

Vehicle Technology	Distance (km)	Avg fuel efficiency	Fuel cost (C$)	Maintenance cost (C$)
Diesel	316,040,969	1.746km/L	181,418,603	262,286,979
CNG	142,490,572	1.549km/DLE	40,483,020	97,880,302

For the Californian agency and RTA, the average annual exchange rates to convert the expenditures to Canadian currency between the Canadian and American dollar for 2018-2020 were applied after adding the annual costs of those agencies. The resulting costs were then aggregated to other agencies.

All cost figures in Table 2 exclude taxes, and the fuel cost for CNG excludes the cost of fuel compression. The transit agencies did not provide detailed data for the cost of compressing CNG in their refuelling operations. Most of the compression costs come from electricity to operate electrical compressors. In some cases, there is no dedicated electricity meter for the refuelling stations. Therefore, separating the contribution of fuel compression from the total electricity bill of the transit facilities is not obvious. This difficulty increases when one considers that the electricity bill contains components that do not scale with the amount of energy used such as power demand charges and fixed costs.

Instead of trying to isolate fuel compression costs, a conservative estimate for the average cost of CNG compression was obtained by directly asking transit agencies personnel to provide CUTRIC with the data for this study. CUTRIC also checked the figures provided informally, considering the typical amount of energy required to compress CNG and the typical electricity rates available in the local jurisdictions of the transit agencies. The figures were all consistent. The resulting average is C$0.20/DLE, which is then added to the aggregated fuel cost of Table 2 to provide the average cost per distance as described below.

Table 3 displays the average cost per distance travelled with the breakdown of the fuel and maintenance components. For the case of diesel, the values were obtained by taking the ratios of the appropriate figures in Table 1. For the average fuel cost of CNG, the cost of compression described in the previous paragraph was added. The compression contribution per distance is obtained by dividing the average CNG compression cost by the average fuel economy of CNG (C$0.20/DLE / 1.549km/DLE ≈ C$0.129/km). As a result, the average cost of fuel for CNG is C$0.284/km (Table 2) plus C$0.129/km to account for compression. Estimated compression costs are all inclusive of (electricity, maintenance, and labor).

Table 3: Average cost per distance

Vehicle Technology	Avg. fuel cost (C$/km)	Avg. maintenance cost (C$/km)	Total cost (C$/km)
Diesel	0.574	0.830	**1.404**
CNG	0.413	0.687	**1.100**

Table 3 shows that the average operational cost for CNG buses is approximately 78 per cent of the diesel counterpart. This operational cost excludes the labour required to operate the vehicles.

2.2 CI factors for diesel and CNG

This section provides an estimation of the average GHG emissions of the vehicles analyzed in this report. Recent studies placed the average diesel carbon intensity factor for Canada at approximately 96gCO_2/MJ, while placing the carbon intensity factor of CNG at approximately 62 gCO_2/MJ [39]. Moreover, the energy content of these two fuels are approximately 38.7MJ/L for diesel and 36.1MJ/DLE for CNG [39, 40]. CI factors on a per litre basis are 3.7 kgCO_2/L for diesel as opposed to 2.2 kgCO_2/DLE for CNG.

Considering the different energy efficiencies displayed in Table 2, the emissions per distance are approximately 2.1 kgCO_2/km for diesel and 1.4 kgCO_2/km for CNG. Thus, fossil-fuel CNG is one-third less carbon intensive than the diesel counterpart. Factoring in the difference between these emission factors and the total distance travelled by CNG buses, a total of approximately 100,000 tonnes of CO_2 was saved in three years of operation analyzed in this study.

2.3 Assumptions for RNG

This section provides a set of assumptions used to extrapolate the data presented in the previous section to predict environmental and cost impacts of introducing RNG to CNG bus operations.

Due to the extensive research available, the reference adopted in this study for CI factors and cost of production is the United States. In 2020, data from the California Air Resources Board (CARB) demonstrated that the energy weighted CI value of California's NGV portfolio in the Low Carbon Fuel Standard (LCFS) program was below zero at -0.85 gCO_2/MJ [41]. Moreover, it has been determined that 160 California-based RNG production facilities will be supplying more than 15.8 million metric million British thermal unit (MMBTU), or nearly 119 million diesel gallon equivalents (DGE) to transportation end users by 2024. With a significant proportion of growth in local production coming from California dairies, the energy weighted CI value of the projected instate supply of RNG is predicted to be approximately -101.74 gCO_2/MJ [42].

The "*Study on the Use of Biofuels (Renewable Natural Gas)"* by ICF International provides a comprehensive analysis of both the CI factors and the production costs in the United States [43]. This section focuses on the results of the ICF by considering averages of the CI and production cost results for the anaerobic digestion method of production utilizing a few different sources of organic matter. Table 4 displays the results of this averaging process along with two additional columns: the required concentration of RNG to make the RNG/CNG blend carbon neutral and the price at carbon neutrality.

Table 4: Assumed CI factors and production cost of RNG

Method of production / organic matter source		Pure RNG (C$/DLE)	CI (kgCO_2/DLE)	Carbon neutrality	Price at carbon neutrality (C$/DLE)
Anaerobic digestion	Landfill gas	0.784	0.92	-	-
	Animal manure	1.264	-7.81	22%	0.629
	WRRF	0.899	0.92	-	-
	Food waste	1.195	-1.45	61%	0.904

Table 4 considers an average exchange rate between Canadian and American dollars for the year of publication of that study (C$/US$~0.82) It also includes the cost of compression as discussed in section 2.1.

As noted in Table 4, the anaerobic digestion method can produce negative CI factors when the organic matter source is animal manure or food waste. For these two cases, it is possible to achieve an RNG/CNG blend that is carbon neutral. Assuming the CI factors for pure CNG as described in the previous section, the required fraction of RNG for carbon neutrality is 22 per cent if the source of organic matter is animal manure. Food waste RNG, however, displays a less negative CI factor, thus requiring a larger fraction of 61 per cent to make the blend with CNG carbon neutral.

The last column assumes the average price point of CNG experienced by the three agencies during the period of data analysis. Figure 2 displays an interpolation of the CI factors for the different organic matter sources.

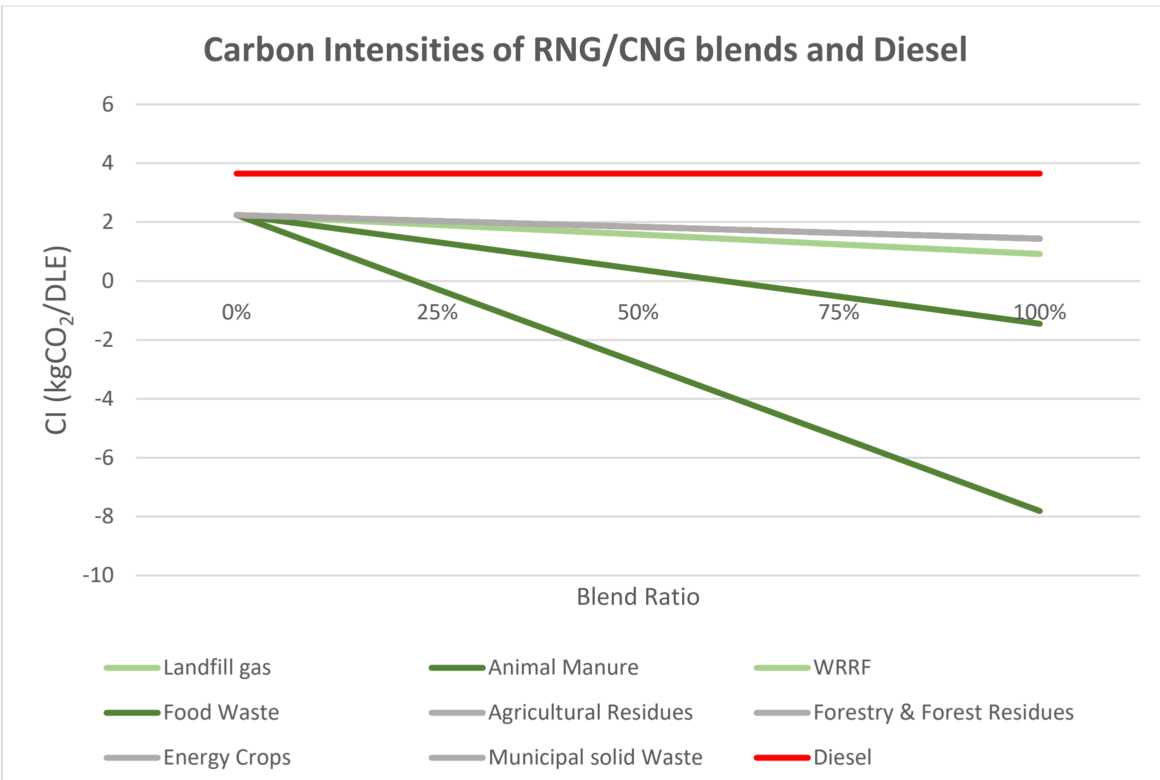

Figure 2: CI factors for RNG/CNG blends

As illustrated in Figure 2, an increase in the concentration of RNG in the RNG/CNG blend reduces the resulting CI factor of the CNG fuel, which already starts below diesel at zero RNG concentration. The animal manure and food waste curves cross the horizontal axis to the region of negative CI values. Energy crops, agricultural residues, municipal solid waste and forestry are represented by the same gray line, for those RNG sources portray very similar carbon intensity values.

2.4 RNG at carbon neutrality versus diesel

Combining the results of the last sections, it is possible to compare the operational cost of diesel, CNG and RNG/CNG blends at several instances of carbon neutrality. The carbon neutrality scenarios in this analysis include using an animal manure RNG/CNG blend, food waste RNG/CNG blend and landfill with animal manure RNG/CNG blend. Table 5 provides a breakdown of the fuel and maintenance costs of the carbon intensive and carbon neutral configurations.

Table 5: RNG/CNG operational costs at carbon neutrality

Fuel	Fuel cost (C$/km)	Maint. cost (C$/km)	Total (C$/km)	CI ($kgCO_2$/km)
Diesel	0.574	0.830	**1.404**	**2.1**
CNG	0.413	0.687	**1.100**	**1.4**
22% RNG/CNG animal manure (CI = 0)	0.421	0.687	**1.108**	**0**
61% RNG/CNG food waste (CI = 0)	0.591	0.687	**1.278**	**0**
89% Landfill – 11% animal manure RNG/RNG (CI = 0)	0.540	0.687	**1.227**	**0**

The diesel fuel cost presented in Table 5 reflects the average for all agencies and the time frame ranging from 2018 to 2020. Since then, diesel price points have risen significantly and large fluctuations are observed more recently due to the war in Ukraine. In reference to the wholesale prices in Toronto, a conservative estimate for diesel prior to the Ukraine invasion is approximately C$1.60/L [44]. This value was then used and labeled as “current” diesel price for comparison. Even though a direct comparison of price points in different periods might not be perfectly accurate, it would still provide some valuable insight into the fuel cost trend.

Figure 3 provides a graphic visualization of the total cost data contained in Table 5 along with the estimated cost with diesel fuel considering the current average price point.

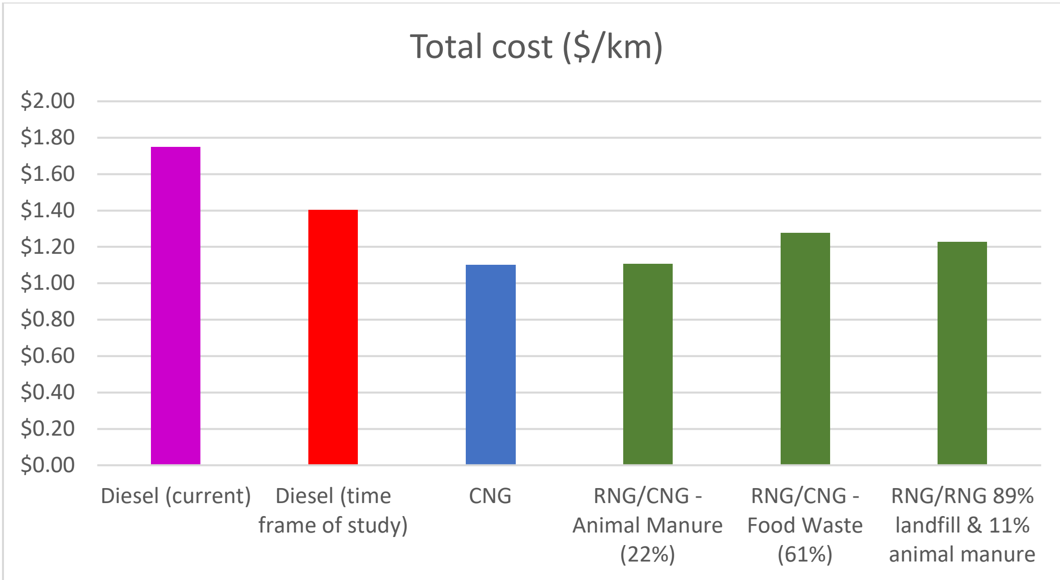

Figure 3: RNG/CNG operational costs at carbon neutrality

The results of this section show that it is possible to operate CNG buses with RNG achieving carbon neutrality while maintaining a lower operational cost in relation to diesel. This can be accomplished for all sources of RNG if current diesel prices are considered. Even if the lower average diesel price experienced during the timeframe of the study is considered, operational savings are still possible if animal manure is the source of organic matter. If food waste is the sole source of organic matter at carbon neutrality, the operational costs are still lower than diesel. However, there is almost price parity considering the price point of the study timeframe. The results also show that it is possible to achieve carbon neutrality if the availability of biogas is concentrated in landfills as a source or organic matter. In that case, a 90/10 ratio between landfill RNG and animal manure RNG is sufficient to bring carbon neutrality and realize operational savings compared to diesel.

2.5 Cost and CI factors for vehicles fuelled with full RNG

The cost and CI factors are extrapolated for the case in which the vehicles are fuelled with 100 per cent RNG to investigate the full potential of this renewable fuel. The case of RNG produced with landfills as a source of organic matter is included as another scenario in this section. Table 6 summarizes the numerical results while Figure 4 and Figure 5 provide a graphic visualization of the costs and CI factors, respectively.

Table 6: Full RNG operational costs and carbon intensities

Fuel	Fuel cost (C$/km)	Maint. cost (C$/km)	Total cost (C$/km)	CI ($kgCO_2/km$)
Diesel	0.574	0.830	**1.404**	**2.1**
CNG	0.413	0.687	**1.100**	**1.4**
100% RNG - Landfill	0.506	0.687	**1.193**	**0.9**
100% RNG - Animal manure	0.816	0.687	**1.503**	**-7.8**
100% RNG - Food waste	0.771	0.687	**1.458**	**-1.5**

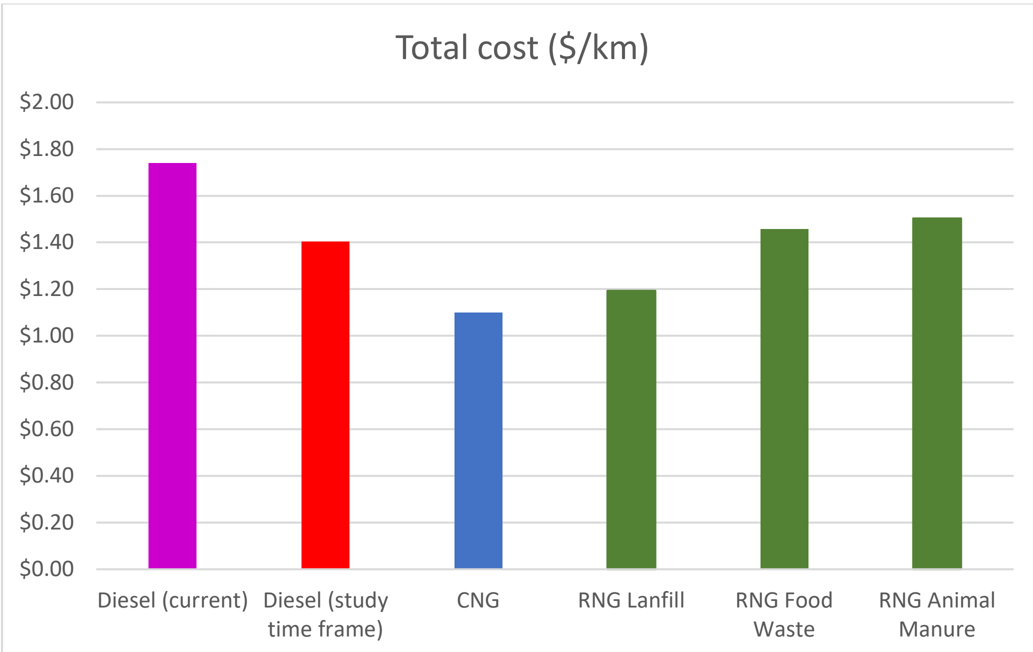

Figure 4: Full RNG operational costs

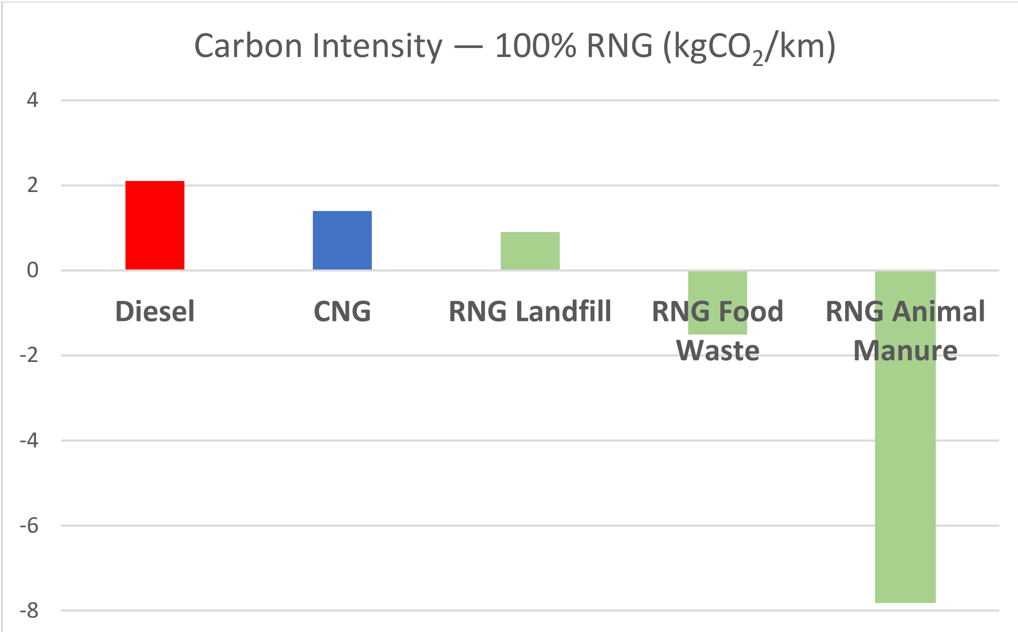

Figure 5: Full RNG carbon intensities

Overall, operating CNG buses with pure RNG is slightly more costly than operating diesel buses. However, the carbon intensities can be significantly lower or reach negative values with a larger magnitude. The lower cost increment occurs when the source of organic matter is landfills, for which higher GHG emission savings are incurred. Operating CNG buses with 100 per cent RNG from landfills is approximately eight per cent more costly than operating them with pure CNG. However, there is almost 36 per cent GHG reduction in relation to CNG and 57 per cent reduction in relation to diesel.

If the source of organic matter is animal manure, the cost of operating the vehicles is approximately seven per cent higher than operating diesel vehicles, although the vehicle would effectively remove almost eight kilograms of carbon dioxide from the atmosphere for each kilometre travelled.

2.6 Summary of observed and assumed fuel price points and CIs

The previous sections provided cost comparisons in terms of cost per distance travelled for each kind of fuel considered in this study. This section, however, provides a summary of the volumetric price points observed for diesel and CNG and also the extrapolated volumetric price points of the different RNG/CNG fuel blends considered in the previous sections.

Table 7 displays the fuel price points and the corresponding CIs in $kgCO_2/DLE$.

Table 7: Observed and extrapolated volumetric price points of fuels

Fuel	Fuel price (C$/DLE)	CI ($kgCO_2$/DLE)
Diesel	1.00	3.7
CNG	0.64	2.2
100% RNG – landfill	0.78	1.4
100% RNG – animal manure	1.26	-12.1
100% RNG – food waste	1.19	-2.3
22% RNG/CNG – animal manure	0.65	0
61% RNG/CNG – food waste	0.92	0
89%/11% landfill/animal manure RNG/RNG	0.84	0

As seen in Table 7, the average diesel price point experienced by the transit agencies during the data collection period is approximately C$1.00/L. Using the assumed value for the current diesel price point (C$1.60/L), the differential cost per kilometre would be at least an additional C$0.34/km. This brings diesel cost higher than any of the options presented in this study, including fuelling with 100 per cent RNG.

2.7 RNG and other clean transit technologies

This section provides a comparison of the environmental benefits of different transit technologies including BEBs, FCEBs and CNG buses powered with RNG in terms of GHG emissions. CUTRIC closely follows the empirical performance data of vehicles deployed in Canada within the scope of the Pan-Canadian Battery Electric Bus Demonstration and Integration trial. One of the results of this project is that the typical energy efficiency of BEBs in Canada is approximately 1.3 kWh/km. This number is used as a reference in the estimation of BEB emissions in this work.

BEB emissions are heavily dependent on how clean the energy grid is to generate the electricity consumed by the vehicle. Canada is significantly heterogeneous in this aspect, with some provinces presenting an extremely clean electricity grid and other provinces with carbon intensive grids. According to the latest National Inventory Report, the electricity consumption intensity - including generation, transmission and consumption - for Manitoba is 1.3 gCO_2/kWh whereas the same parameter for Nunavut has a numerical value of 890 gCO_2/kWh [45].

In order to include the performance of FCEBs in the environmental comparison established in this section, CUTRIC considered a combination of predictive modelling work results and empirical data from FCEBs. The resulting average fuel efficiency is approximately 0.1 kgH_2/km, with only electrolytic hydrogen included in the comparison. A typical large-scale electrolysis unit can reach 70 to 75 per cent efficiency while smaller systems can reach 80 to 85 per cent efficiency [46]. In this analysis, 80 per cent efficiency is considered as a reference, requiring approximately 50kWh to produce each kg of hydrogen fuel. This result is combined with the electricity CI factors of the different provinces to estimate local operational emissions of FCEBs.

Figure 6 identifies the carbon intensities of diesel, CNG, 100 per cent RNG for selected organic matter sources, BEBs and FCEBs considering the average energy/fuel efficiencies described above and the local electricity CI factors.

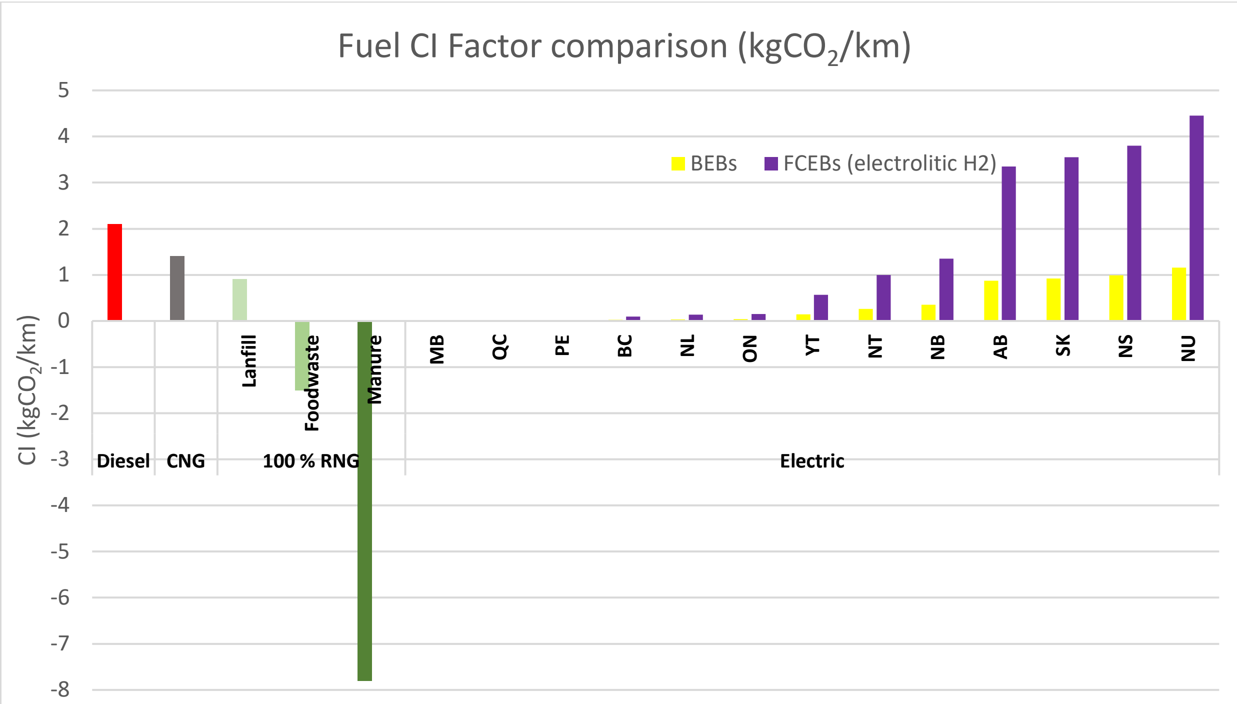

Figure 6: Fuel CI factors

Figure 6 shows that operating CNG buses with RNG can outperform BEBs and FCEBs in any jurisdiction depending on the concentration of RNG and the source of organic matter used to produce that fuel. For some provinces, RNG would be the only viable solution to reduce GHG emissions because the electricity grid is carbon intensive.

3 Conclusions

This study shows that RNG is a viable option in transit decarbonising efforts because the fuel can dramatically reduce GHG emissions, while maintaining the operational costs comparable with diesel and CNG. Depending on specific operating conditions and source of organic matter for RNG production, it is possible to realize operational savings in comparison to diesel. These savings are possible without the massive infrastructure investments that would be required if BEBs or FCEBs are chosen to clean transit. RNG can be directly injected in CNG pipelines, leveraging already installed refuelling infrastructure.

Moreover, the introduction of RNG does not require a paradigm shift in technology or operations because CNG buses are already an established technology. The fact that approximately 30 per cent of more than 450,000,000 km tracked in this study was covered with CNG buses is proof that CNG technology is mature. Both in range and refuelling time, CNG buses are comparable to diesel, which is another advantage over BEBs. Compared to diesel buses, CNG buses are quieter and emit a lower amount of particulate matter.

CNG buses powered with RNG might be the only viable option to reduce the carbon intensity of transit in jurisdictions where the electricity grid is carbon intense. Even in locations with a clean electricity grid, RNG availability should be leveraged as much as possible and integrated in the energy matrix and utilized as a means of propulsion.

With the increasing diesel fuel prices, operating buses with RNG is more economical and less dependent on RNG sources and blend ratio.

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