Energy Policy 115 (2018) 109–118

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Electrification of road freight transport: Policy implications in British Columbia

Hoda Talebian, Omar E. Herrera, Martino Tran, Walter Mérida*

Clean Energy Research Centre, The University of British Columbia, 2360 East Mall, Vancouver, BC, Canada V6T 1Z3

ARTICLE INFO

Keywords:
Road freight transport
Electrification
Well-to-Wheels GHG emissions
Energy resource assessment

ABSTRACT

Road transportation accounts for 25% of total greenhouse gas (GHG) emissions in British Columbia (B.C.) and more than half of these emissions originate from road freight transport. We examined the potential of all-electric freight trucks to achieve 64% GHG emissions reduction by 2040. The results suggest that even the stringent regulations on fuel efficiency of conventional trucks will fail to steadily decrease the emissions. More than 65% of freight trucks would have to run on all-electric powertrains which translates into 100% sector penetration as early as 2025. We assessed the available local energy resources for mass market penetration of all-electric trucks. The results suggest that every 1% of GHG emissions reduction from road freight transport would require 1.5–3.8% additional hydroelectric generation by 2040. Correspondingly, a 64% reduction requires 12–33 TWh of electricity. That is 2.5–6.5 times the projected generation of the B.C.'s largest hydroelectric project in decades (Site C). Hence, new policies are required to support diversified renewable electricity generation and low-carbon pathways. For example, carbon capture and sequestration coupled with provincial reserves of natural gas can enable low-carbon hydrogen production and decrease the electricity requirements for zero-emission vehicles in B.C.

1. Introduction

The transportation sector accounts for the largest portion of total Greenhouse Gas (GHG) emissions in British Columbia (B.C.), and two thirds of these emissions originate from on-road vehicles (Fig. 1). The trucking industry has been a leading contributor to the road transportation sector with a 13.5% GHG emissions increase from 2007. Freight trucks are also significant sources of criteria air contaminants (CAC), like Particulate Matter (PM 10, PM 2.5), Nitrogen Oxides (NOx), Carbon Monoxide (CO) Sulphur Oxides (SOx) and Volatile Organic Compounds (VOC), which adversely affect air quality and human health.

In B.C., the provincial government's Climate Action Plan targets 80% GHG emissions reduction in 2050 compared to 2007 (Government of B.C, 2005). If we assume an 80% GHG emissions reduction for road freight transport, this would require GHG emissions below 1.88 $MtCO_2eq$ by 2050. The total Well-to-Wheels (WTW) GHG emissions of freight trucks was 10.56 $MtCO_2eq$ in 2014, and the per capita Gross Domestic Product (GDP) is projected to grow in B.C. by 20% in the next 20 years (NEB, 2016). Due to the direct correlation between the number of freight trucks and GDP, it may be difficult to reduce emissions in this sector while simultaneously ensuring economic growth (OECD, 2011).

Several options are suggested for reducing GHG emissions from freight trucks. The non-technical options consider the efficiency improvement of freight logistics such as load-matching and maximizing capacity, a modal shift to more energy-efficient means of transportation (e.g., rail) and the standardization of logistics-related facilities and equipment (CalSTA, 2014). The technical improvements deal with the efficiency of internal combustion engine (ICE) trucks. In 2013, Canada began regulating on-road GHG emissions from ICE freight trucks with Gross Vehicle Weight Rating (GVWR) above 3856 kg. Under the Canadian Environmental Protection Act, two phases of regulations have been proposed for the deployment of advanced cost-effective technologies to increase the fuel efficiency and GHG emissions standards for new freight trucks. The first phase applies to 2014 and newer model vehicles, which reach full stringency with model year 2018 (Canada Gazette Part II, 2013). The second phase is built upon the first phase and reach full stringency with model year 2027 (Canada Gazette Part II, 2017). It is projected that the full deployment of this legislation will decrease the GHG emissions by 15–50% from freight trucks with model year 2027 compared to the 2010 counterparts depending on the vehicle's duty cycle.

While the legislation targets the fuel efficiency of conventional gasoline or diesel trucks, some attempts have been focused on alternative

* Corresponding author.
E-mail address: walter.merida@ubc.ca (W. Mérida).

https://doi.org/10.1016/j.enpol.2018.01.004
Received 6 September 2017; Received in revised form 20 December 2017; Accepted 3 January 2018
Available online 10 January 2018
0301-4215/ © 2018 Elsevier Ltd. All rights reserved.

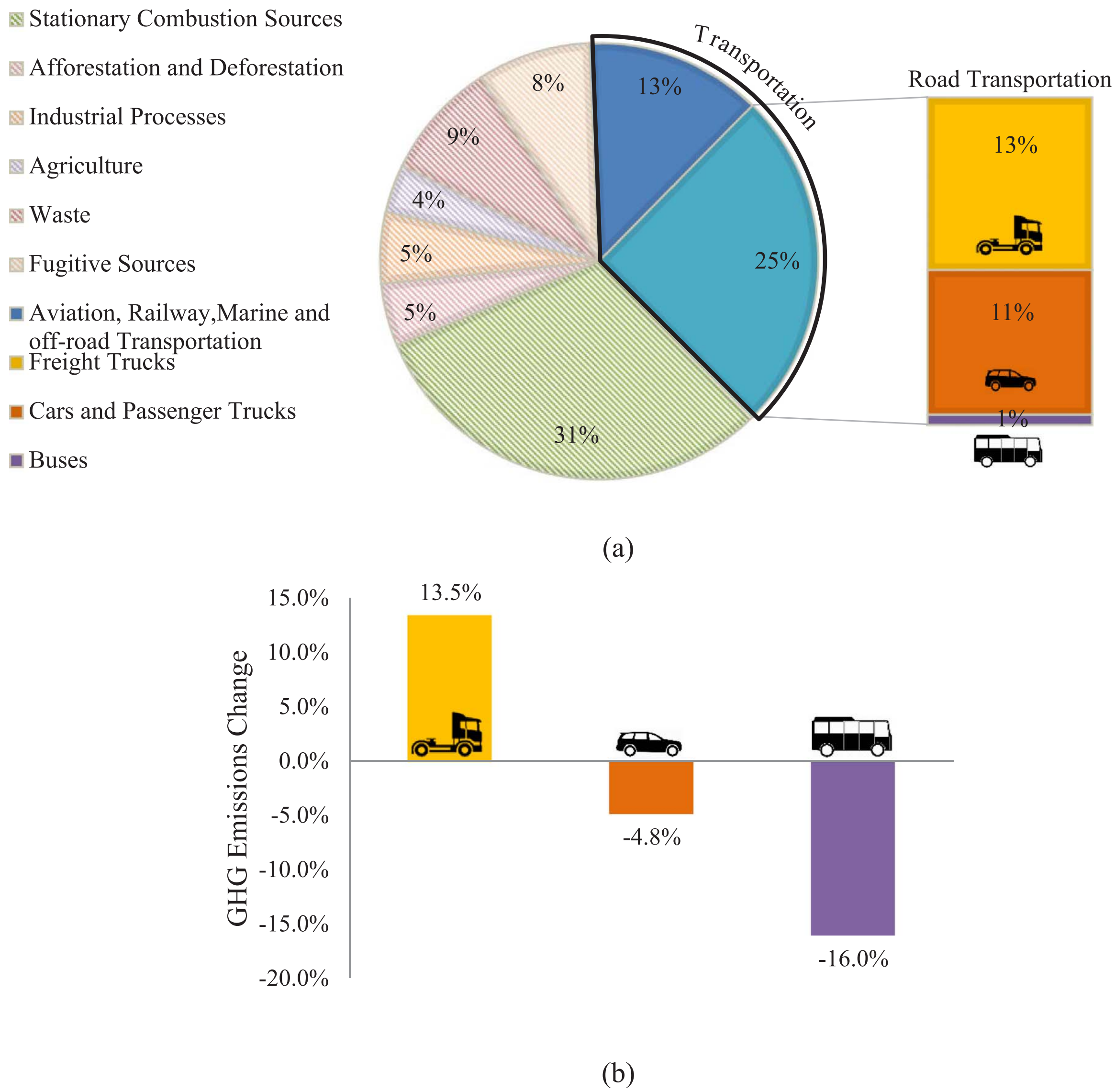

Fig. 1. 2014 GHG emissions in B.C.: (a) GHG emissions by sector (b) GHG emissions from road transport: change from 2007(NRC, 2016).

fuels. The deep-carbon reduction scenarios for road freight transport often rely on significant amounts of biofuels. The B.C. Low Carbon Fuels Regulations states that by 2020 the life-cycle GHG intensity of all transportation fuels must be reduced by 10% from 2013 levels (Government of B.C, 2008a). This requirement is expected to be met using first generation biofuels in the fuel blends, ethanol from corn and grain, and biodiesel from canola. Ethanol and biodiesel are already being blended into refined petroleum fuels in B.C. and the blending percentage is rising steadily. The Ethanol content increased in the gasoline pool from 5% in 2010 to 6.3% in 2014, and the biodiesel blend reached 5.6% in 2014 (Wolinetz and Moorhouse, 2016). One of the important challenges associated with biofuels is the indirect land use change, which can result in additional GHG emissions and raises concerns around food security and biodiversity maintenance (Tomes et al., 2011). Moreover, the amount of sustainable biofuels which will be available beyond 2020 is uncertain (Girvan and Hall, 2008). Given the uncertainties and difficulties with biofuels, this option is not likely to result in significant GHG emissions reductions of road freight transport required by 2050 in B.C. (BC Hydro, 2011). The non-renewable low-carbon fuels such as CNG, LNG and propane are now being considered as transition fuels that could serve as cost-competitive, near-term solutions. The greenhouse gas reduction regulation under the Clean Energy Act offers incentives to diversify and grow the market for natural gas in B.C.'s transportation sector (Government of B.C, 2012). The incentives target medium- and heavy-duty trucks switching from diesel to natural gas, and decrease the fuel costs on a per kilometer basis (Natural Gas Use in Transportation Roundtable, 2010). Natural gas trucks can reduce tailpipe greenhouse gas emissions by as much as 20% over gasoline or diesel trucks (McJeon et al., 2014). However, climate benefits of natural gas heavily depend on the lifecycle emissions of methane (Howarth, 2014; Venkatesh et al., 2011). The hydrogen enriched natural gas (HCNG) engine is another promising technology to enhance fuel economy and decrease emissions compared with CNG counterparts. However, implementing the perfect methane/hydrogen mixture with the current CNG infrastructure and on-board storage are the major challenges facing the adaptation of this technology. Also, mitigating the NOx increase as a result of hydrogen enrichment is challenging and needs to be addressed effectively (Mehra et al., 2017).

The large-scale GHG emissions reduction in B.C. requires that the long-term fuel portfolio shifts toward renewable or carbon-neutral fuels. The electrification of road transportation offers zero-tailpipe emission potential. Electrification could result in large-scale GHG emissions reductions if the energy carrier is generated from renewable resources or the production facilities are equipped with carbon capturing technologies. All-Electric vehicles are classified into battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). To date, electrification has primarily targeted the passenger vehicle market. Commercial all-electric heavy-duty vehicles are limited to urban delivery trucks and buses at the moment (den Boer et al., 2013; Eudy et al., 2015; HSU, 2017; Hua et al., 2014; Lambert, 2017a, 2017b; NREL, 2013; O'Dell, 2017).

The BEVs use electricity sourced from the electrical grid to recharge on-board batteries. Current battery electric trucks, using lithium-ion batteries, have a range of 150–400 km, depending on the mass of the battery. These trucks are being developed worldwide for daily based travel on defined routes with low average speeds, high idle times and high frequency of stops and starts (den Boer et al., 2013; NREL, 2013). This duty-cycle makes the overnight stationary charging and battery swapping suitable for short-haul battery electric trucks. There are a number of demonstration projects for battery electric semi-tractors that target captive truck fleets within the companies' distribution network (Lambert, 2017a, 2017b). For long-haul applications, the low energy density of batteries is a barrier, as significant weight and volumes are required to address the short vehicle range and long recharging times. Even if the energy density is improved by factors of 5–10, the weight increase of a 40 t GVWR truck would be approximately 2 −4 t. (den Boer et al., 2013). Moreover, an overnight plug-in charging unit of 19 kW can regenerate the 200 kWh battery within 10-h, which is far beyond the acceptable idle times for long-haul trucks. To make the charging time compatible with the refueling time of a conventional truck (less than 30 min), a 400 kW DC charger and upgrades to the transmission network would be required. However, battery electric long-haul trucks are still part of long-term vehicle portfolio when combined with on-the-road charging technology, e.g., overhead catenary wires or dynamic inductive charging (den Boer et al., 2013).

Unlike BEVs, FCEVs are comparable to conventional ICE vehicles in terms of range and fueling time. The toxicity and fire hazard properties of hydrogen rank it as the safest fuel with a safety factor of 1, while the safety factors of methane and gasoline are 0.8 and 0.53, respectively (Veziroğlu and Şahin, 2008). Fuel cell technology has been deployed with fuel cell buses (Eudy et al., 2015) and it has successfully penetrated the forklift market (U.S. Department of Energy, 2013). Demonstrations for fuel cell freight trucks such as package delivery vans and semi-tractors used in refuse or drayage service are in early stages (ARB, 2015; HSU, 2017; O'Dell, 2017). Fuel cell durability and the volume and weight of the onboard hydrogen storage system are the key technical challenges to the adoption of Fuel cell technology in heavy-duty vehicles. Also, hydrogen fueling stations need to be distributed and available for heavy-duty fuel cell vehicles with suitable fueling protocols. The California Fuel Cell Partnership provided an Action Plan to support the implementation of fuel cell technology in medium-duty and heavy-duty trucks in California (CaFCP, 2016).

British Columbia (B.C.) has several competitive advantages including energy resources, technologies deployments, and policies to pursue opportunities in zero-emission heavy-duty powertrains. First, B.C. has a wide access to renewable and low cost hydroelectricity, as well as abundant potential electricity generation capacity from other renewable resources, like wind, biomass and geothermal energy (BC Hydro, 2013). B.C. is also Canada's second largest natural gas producer (NRCan, 2017). If combined with carbon capture and storage (CCS) technology, natural gas could be one of the main energy resources to produce hydrogen in the province. Moreover, B.C. possesses the largest share of hydrogen and fuel cell developers in the world from fuel cell stack manufacturers to several hydrogen infrastructure-supply companies (CHFCA, 2016). B.C. also has a leading position in smart grid infrastructure deployment which is critical for developing smart charging technology for electric vehicles (Hiscock, 2015). B.C. has progressive environmental legislation and climate leadership to support the development of zero emission transportation, e.g., the North America's first carbon tax (Government of B.C, 2008b), Clean Energy Act (Government of B.C, 2010), Climate Action Plan (Government of B.C, 2005) and Low Carbon Fuel Regulation (Government of B.C, 2008a). The municipal climate policies are also in place, helping to promote alternative fuel vehicles and infrastructure. For example, the alternative fuel bylaw by Surrey City Council requires all new gas stations to include low-carbon fuel infrastructure, and Vancouver Greenest City Action Plan targets for a 100% renewably-powered city by 2050 (MNP, 2016).

In this paper, the 2040 fuel-side WTW GHG emissions from B.C. trucking sector was projected for two scenarios; named as the business as usual (BAU) and the current legislation fulfillment (CLF). The BAU scenario considers no technology improvement in ICE trucks, while the CLF considers the full deployment of current legislation targeting freight transportation. The potential of battery electric and fuel cell trucks to meet the mid-term GHG emissions reduction targets for 2040 was investigated for both scenarios. Also, the total WTW energy requirement for all-electric trucking was quantified and the availability of different energy resources in B.C. to support zero emission trucking was assessed.

2. Methodology

In this study, the target year for the vehicle stock projections, GHG emissions calculations and resource assessment was 2040. The analysis was based on GDP projections, and forecasts of electricity and natural gas production and demand in B.C. (NEB, 2016), which were only available until 2040, at the time of the study. It was also assumed that the mid-term target for reducing GHG emissions from freight road transportation is 64% by 2040 from the level of 2007.

2.1. Freight Trucks stock forecasting

The first step to project the GHG emissions from road freight transport is to project the stock of freight vehicles. Natural Resources Canada (NRCan) has classified the freight trucks to Light Duty (LD), Medium Duty (MD) and Heavy Duty (HD) based on the GVWR as shown in Table 1. For each truck class, the NRCan comprehensive energy use database for transportation sector in B.C. (NRCan, 2016) provided the average vehicle use-intensity (kilometers traveled per vehicle annually), number of new vehicles and the vehicle stock from 2000 to 2014. These historical trends were used to project the stock of each

Table 1
Freight truck classification (NRCan, 2016).

Truck Class	GVWR Category/kg	Class Range	Icon
Light Duty Truck (LDT)	≤ 3855	1-2	
Medium Duty Truck (MDT)	3856 to 14969	3-7	
Heavy Duty Truck (HDT)	≥ 14970	8	

truck class by 2040.

The historical data on the average vehicle use-intensity (NRCan, 2016) show a decreasing trend for all three truck classes. Since there are no projections available in the literature for B.C, the vehicle use-intensity was fitted with a quadratic polynomial regression with the minimum mileage value extending over the studied time frame. The quadratic regression provides a conservative projection for this study. Linear and exponential regressions produce near zero vehicle use-intensity for year 2030 onward which is unrealistic for a freight vehicle.

The number of new freight vehicles has been projected based on historic trends and the real GDP per capita (Eom et al., 2012; Hao et al., 2015; Limanond et al., 2011). For B.C., the annual increase rate of new trucks per real GDP per capita was calculated from the historic data on the number of new trucks and the real GDP per capita between years 2000–2014 (NRCan, 2016). As this historic annual increase rate did not follow a traceable path, the average increase rate ($\overline{X}$) is used for the projection. Having the average increase rate of new trucks and the projections on the real GDP per capita to 2040 (NEB, 2016), the new vehicles of each truck class (*NewT*) were projected to 2040 as follows:

$$\overline{X} = \frac{\sum_{i}^{n} \frac{(NewT_{i+1} - NewT_i)}{(GDP_{i+1} - GDP_i)}}{n - i}$$
$$NewT_k = \overline{X} \times (GDP_k - GDP_{k-1}) + NewT_{k-1}$$
$$i = 2000, \quad n = 2013, \quad N = 2040$$
$$k = n + 2, \ldots, N \tag{1}$$

The stock of each truck class was projected using the average truck lifetime in B.C., either in years (Y) or total kilometers (K) (Table 2), and the projections on the number of new trucks and the average vehicle use-intensity (U), as follows:

$$Stock_j = Stock_{j-1} + New\ vehicle_j - New\ vehicle_{j-i} \times \left\{ i|0 \le i \le Y, \sum_{k=i}^{j} U_k \ge K||j - i \ge Y \right\} \tag{2}$$

It is worth mentioning that there are several constraints for the future growth of freight movements, such as the congestion and capacity of road networks, sudden change in fuel prices and economic indicators and the availability of trucks and drivers. However, the analysis of those factors was beyond the scope of this study.

2.2. GHG emissions projections from road freight transport: BAU and CLF scenarios

The fuel-side WTW GHG emissions are analyzed from the primary energy source extraction to the point of fuel utilization. It should be noted that the life-cycle effects of vehicle manufacturing and infrastructure construction/decommissioning were not covered in the fuel-side GHG emission analysis. For the historical WTW GHG emissions calculation, the tank-to-wheel (TTW) GHG emissions for different truck classes were extracted from the NRCan database (NRCan, 2016). The fuel average TTW GHG emissions rate was considered as 2370 and 2734 gCO_2eq/lit for gasoline and diesel, respectively (NRCan, 2016). The GHG emissions associated with fuel production (Well-to-Tank (WTT)), were also considered as 690 and 617 gCO_2eq/lit for gasoline and diesel, respectively (NRCan, 2013). Two scenarios were considered for the projections, with no alternative fuel or powertrain being added to the market, as follows:

2.2.1. Business as usual (BAU) scenario

This scenario gives a conservative projection, considering the current technology (Year 2014) remains unchanged. Thus, constant average fuel efficiency (Table 2) was used for the entire projection period. The annual WTW GHG emissions were calculated for each ICE truck class using the fuel average WTW GHG emissions rate, average fuel efficiency (Table 2), and the forecast results on the stock and vehicle use-intensity:

$$[GHG\ emissions(gCO_2eq)]_{j,truck\ class} = average\ fuel\ WTW\ GHG\ emissions\ rate(gCO_2eq/lit) \times [average\ fuel\ efficiency(lit/km)]_{truck\ class} \times [vehicle\ stock]_{j,truck\ class} \times [vehicle - use\ \mathrm{int}\ ensity(km)]_{j,truck\ class}\ j = 2015, \ldots, 2040 \tag{3}$$

2.2.2. Current legislation fulfillment (CLF) scenario

This scenario gives a favorable projection on the efficiency of ICE trucks. It reflects the full deployment of the proposed federal regulations for the GHG emissions reductions from medium and heavy-duty vehicles (Canada Gazette Part II, 2017, 2013). These regulations mandate the fuel efficiency improvement of the trucks by considering a combination of engine efficiency improvements, lower rolling resistance tires, aerodynamic drag improvements, mass reduction, axle and transmission efficiency improvements and workday idle reduction systems. The regulatory standards were grouped into 8 categories based on gross vehicle weight, which include combination tractors (class 7 and 8), vocational vehicles (class 2b-8) and heavy-duty pick-ups and vans (class 2b-3). The standards for tractor trucks are classified under 9 subcategories based on weight, roof height and cab configuration. There are also separate standards targeting the engines of these vehicles. However, the available B.C.'s truck statistics are solely based on three weight categories (NRCan, 2016) as shown in Table 1. In order to use these standards with the available B.C.'s statistics, fuel efficiency improvement of trucks was averaged for three weight categories as shown in Table 3. Also, as the aforementioned regulations do not cover the GVWR below 3855 kg, the legislation amending the passenger automobiles and light truck GHG emissions (Canada Gazette Part II, 2014, 2010) was used to represent the light-duty freight trucks.

The annual WTW GHG emissions of freight trucks were calculated for this scenario using Eq. (3) and considering the fuel efficiency improvement tabulated in Table 3.

The historical data on truck utilization and GHG emissions in B.C. are based on the number of registered trucks in the province. Thus, the share of trucks entering from other provinces or from United States borders that are not registered in B.C. was not considered as the source of GHG emissions (the Weigh2GoBC program does not track vehicles entering the province unless they are registered in the program.) (Government of B.C, 2017a) To maintain the consistency of the data in the projection, we ignored the effect of incoming trucks on the vehicle-

Table 2
ICE truck characteristics (NRCan, 2016).

ICE Trucks	Average Fuel efficiency (lit/100 km)	Fuel type	Lifetime
LDT	11.7	Gasoline	300,000 km or 20 years
MDT	22,21.7	Gasoline, Diesel	450,000 km or 15 years
HDT	40	Diesel	900,000 km or 17 years

Table 3
Fuel efficiency improvement of freight trucks from deployment of federal regulations in the Current legislation fulfillment (CLF) Scenario.

	Phase 1		Phase 2	
	2014–2020	2021–2023	2024–2026	2027 onward
LDT	10%	20%	25%	30%
MDT	10%	15%	20%	25%
HDT	10%	20%	30%	35%

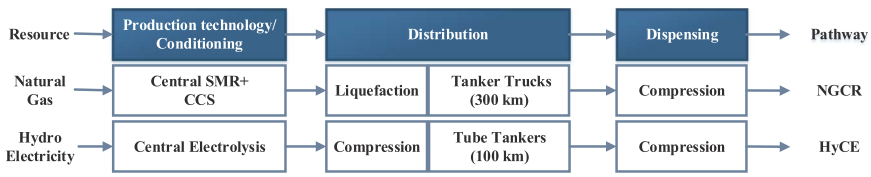

Fig. 2. Hydrogen production pathways.

Table 4
WTT energy requirement and GHG emissions for the selected hydrogen pathways (Argonne National Laboratory, 2016; BC Hydro, 2014; Cetinkaya et al., 2012; Damen et al., 2006; Edwards et al., 2014; Fridriksson et al., 2016; He et al., 2017; Levene et al., 2007; Melaina et al., 2013; NRCan, 2013; Ramachandran and Stimming, 2015; Ramsde et al., 2013; U.S. DRIVE Partnership, 2013).

	Feedstock Production, conditioning and transportation					
	Natural Gas			Hydro power		
GHG emissions	354 gCO_2eq/m^3			11 gCO_2eq/kWh		
	Feedstock transformation to hydrogen					
	Central Reforming + CCS			Central Electrolysis		
	NG	Electricity				
Energy Requirement	4.745 $m^3/kg\ H_2$	1.4 $kWh/kg\ H_2$		50.2 $kWh/kg\ H_2$		
GHG emissions	1768 gCO_2eq/kgH_2	11 gCO_2eq/kWh		11 gCO_2eq/kWh		
	Distribution and Dispensing					
	Gaseous delivery			Liquefied delivery		
	compression at dispenser to 875 bars	Delivery (tube trailer)	Compression to 250 bars	Liquid Hydrogen to gas compression to 875 bars	Delivery (tanker truck)	Liquefaction
Energy Requirement	2 $kWh/kg\ H_2$		1.5 $kWh/kg\ H_2$	0.6 $kWh/kg\ H_2$		9 $kWh/kg\ H_2$
GHG emissions	11 gCO_2eq/kWh	138 $gCO_2eq/$tonne.km	11 gCO_2eq/kWh	11 gCO_2eq/kWh	138 $gCO_2eq/$tonne.km	11 gCO_2eq/kWh

use intensity and GHG emissions of B.C.

2.3. GHG emissions projections from road freight transport in 2040: Electrification effect

As FC and BE trucks have zero tailpipe emissions, the WTW GHG emissions analysis is equivalent to the well-to-tank (WTT) evaluation. For fuel cell trucks, the WTT GHG emissions are involved in the production, transportation and distribution of hydrogen from the energy source to the on-board tank of vehicle. Fig. 2 shows the two selected hydrogen production pathways with WTT energy requirement and GHG emissions mentioned in Table 4. The pathway including central natural gas reforming (NGCR) was selected as it is the predominant industrial hydrogen production technology worldwide (Poudyal et al., 2015), and B.C. has large reserves of commercially available natural gas (NRCan, 2017). The HyCE is a renewable pathway for hydrogen production using central electrolysis which is feasible in B.C. due to the dominance of relatively cheap hydroelectric power. For the battery electric trucks, the WTT analysis accounts for the emissions associated with electricity generation. The electricity loss from transmission lines was estimated to be 10% (BC Hydro, 2017a).

The effect of electrification on the GHG emissions of road freight transport in 2040 was investigated by substituting the WTW GHG emissions of ICE trucks with the WTT GHG emissions of battery electric and fuel cell trucks in the BAU and CLF scenarios. For the BAU scenario, the fuel efficiency of all-electric trucks was estimated based on the energy efficiency of the powertrains provided by (Helmers and Marx, 2012), and the average fuel efficiency of ICE trucks in B.C. driven from Table 2. For battery electric trucks, the fuel efficiency was estimated at 2.5, 1.3 and 0.6 km/KWh for light-duty, medium-duty and heavy-duty trucks, respectively. The fuel efficiency of fuel cell trucks was estimated at 62, 35 and 16 km/kg H_2 for the aforementioned classes, correspondingly. For the CLF Scenario, some sections of the current legislation which were not dependent on the powertrain were applied to all-electric trucks, e.g., lower rolling resistance tires, aerodynamic drag improvements and speed limiters. These technologies are projected to increase the fuel efficiency by 15% for LDT, 10% for MDT and 20% for HDVs by 2027 (Canada Gazette Part II, 2017).

The following assumptions were considered in the WTW GHG emissions calculations of the all-electric freight trucks:

– This study considered the effects of uncertainties associated with the projection of new vehicles and the vehicle use-intensity on the stock of all-electric vehicles, energy requirements and the GHG emissions calculations. The uncertainties associated with vehicle average fuel efficiency, vehicle average lifetime and the technology efficiency for different components of fuel supply chain were not covered in this analysis.
– As the share of hydroelectricity is projected to stay above 86% of total electricity generation in B.C. (NEB, 2016), the GHG intensity of electricity generation was assumed to stay constant for the studied time-frame.
– The charging loss is included in the total fuel efficiency of the battery electric trucks (Thomas, 2009).
– The driving range of 120 km was assumed for all classes of battery electric trucks. Based on this assumption, the effect of battery weight on the fuel efficiency of battery electric trucks was not considered in this analysis (den Boer et al., 2013).
– The total electricity required in NGCR and HyCE pathways was assumed to be generated from hydropower.
– The ICE trucks were assumed to deliver hydrogen for both NGCR and HyCE pathways. In the BAU scenario the GHG emissions associated with hydrogen delivery was used from Table 4. In the CLF scenario, the fuel efficiency improvement of 35% was considered from fully deployment of federal regulations (Table 3).

3. Results and discussion

3.1. The projection of road freight transport characteristics in B.C

The historical data on the freight vehicle use-intensity in B.C. (Fig. 3(a)) show that the average annual distance driven per vehicle has decreased between 28% and 46% over 14 years. The regression analysis captured the historical trend and the minimum projected value was assumed to remain constant over the studied time frame. Due to uncertainties associated with the projections, the maximum positive and

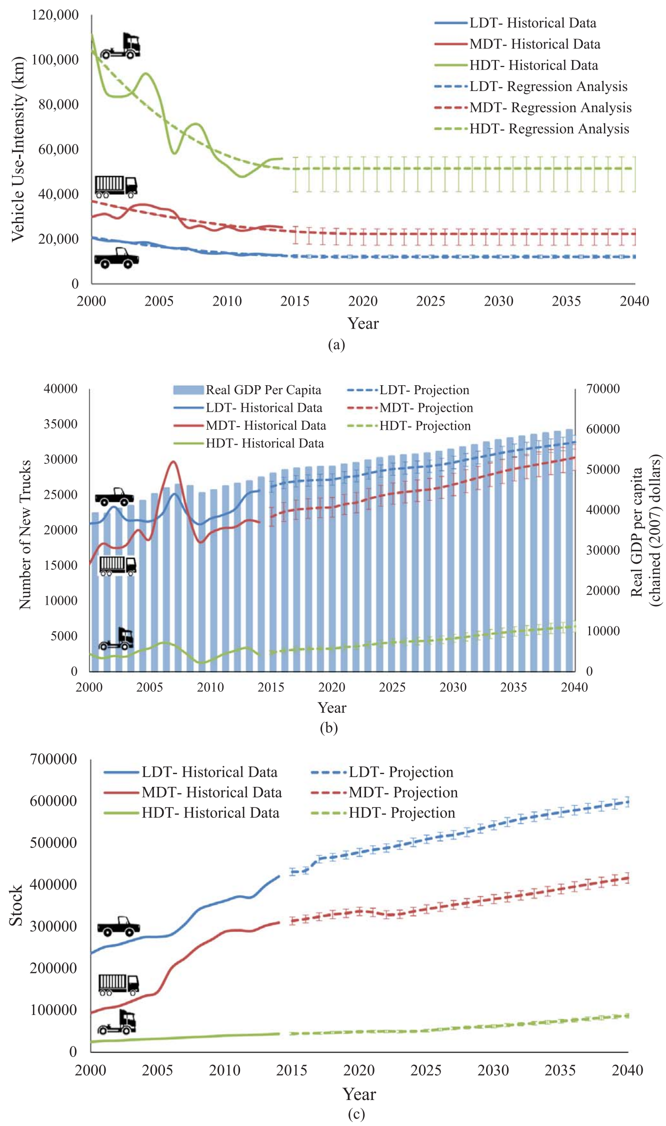

Fig. 3. Historical data and projections to 2040 for Light-duty trucks (LDT), Medium-duty trucks (MDT) and Heavy-duty trucks (HDT): (a) Freight vehicle use-intensity in B.C. - (b) Number of new freight vehicles in B.C. market – (c) Stock of freight vehicles in B.C.

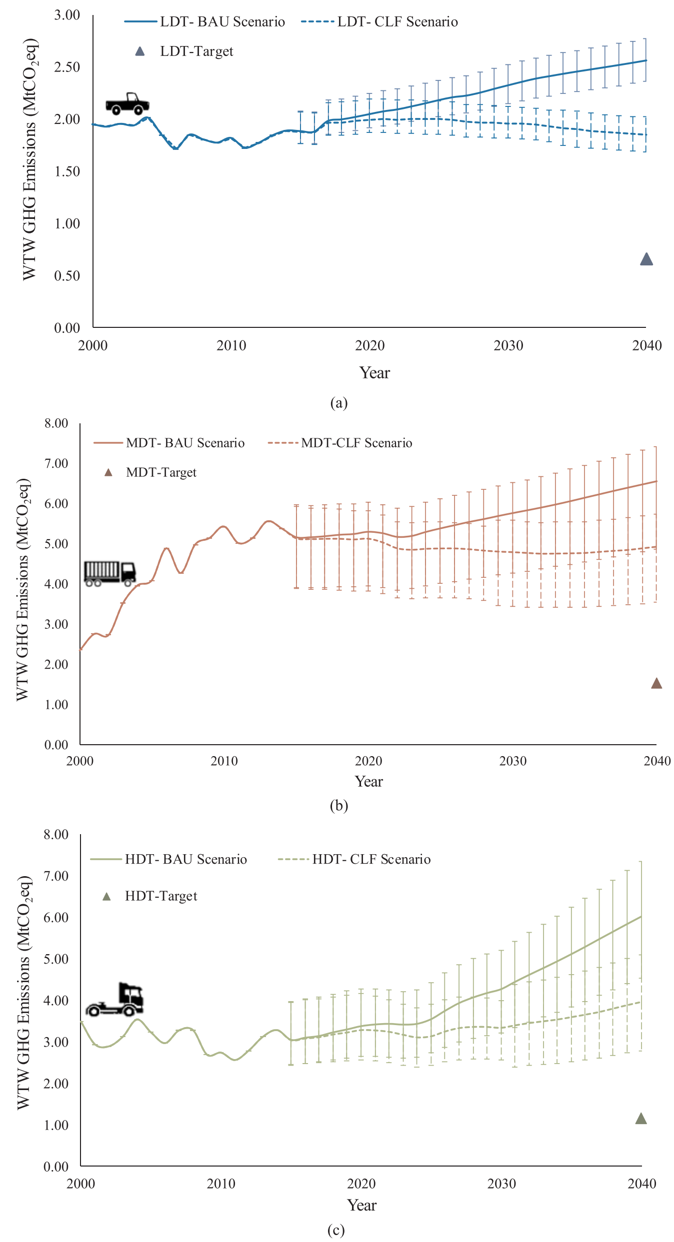

Fig. 4. WTW GHG emissions from road freight transportation in B.C. for business as usual (BAU) and current legislation fulfillment (CLF) scenarios - Historic data and projections to 2040 (a) Light-duty trucks (LDT) (b) Medium-duty trucks (MDT) (c) Heavy-duty trucks (HDT).

negative deviation from the polynomial fit was selected to account for the uncertainty region of the study domain. Fig. 3(b) shows that the number of new freight vehicles entering B.C.'s market will increase due to the projected increase in real GDP per capita in B.C. The model described in Sections 2–1 was calibrated to historical data and compared to the projected number of new vehicles, where the average difference was used as the range of uncertainty for the new vehicle projection. The stock of different truck classes was projected, using the projections on the number of new vehicles and the vehicle use intensity. Fig. 3(c) shows that the stock of heavy-duty truck (HDT) grows by 100% in 2040 compared with 2014, while the growth of medium-duty (MDT) and light-duty trucks (LDT) is 34% and 42%, respectively. It should be mentioned that the uncertainties associated with the vehicle use-intensity was not reflected in the stock projections, as the vehicle lifetime constraint measured in years was met prior to the lifetime constraint measured in total distance traveled for all vehicles classes (Eq. (2)).

3.2. The WTW GHG emissions projection from road freight transport in B.C.: BAU and CLF scenarios

Fig. 4 shows the results of the fuel-side WTW GHG emissions analysis for different freight truck classes in B.C. If the current ICE technology persists, the BAU scenario projects that the 2040 GHG emissions of LDTs, MDTs and HDTs will increase by 39%, 53% and 84%, respectively, from 2007 levels (regardless of associated uncertainties). With the fulfillment of the current legislation (CLF scenario), these emissions will increase by 11%, 28% and 50% from LDTs, MDTs and HDTs, respectively (regardless of associated uncertainties). For LDTs the GHG emissions stay unchanged for around 16 years and start to decrease afterwards. For MDTs, the GHG emissions will fall modestly or stay unchanged for around 19 years, then rise gradually afterwards. For HDTs, there are periods of 2–4 years with slight GHG emissions reductions, however, a net rising trend can be observed for studied time-frame. These results suggest that the current legislation, which focuses mainly on fuel efficiency improvement of ICE powertrains, will fail to meet GHG emissions reduction targets by 2040. Thus, switching to zero tailpipe emission powertrains are required as part of

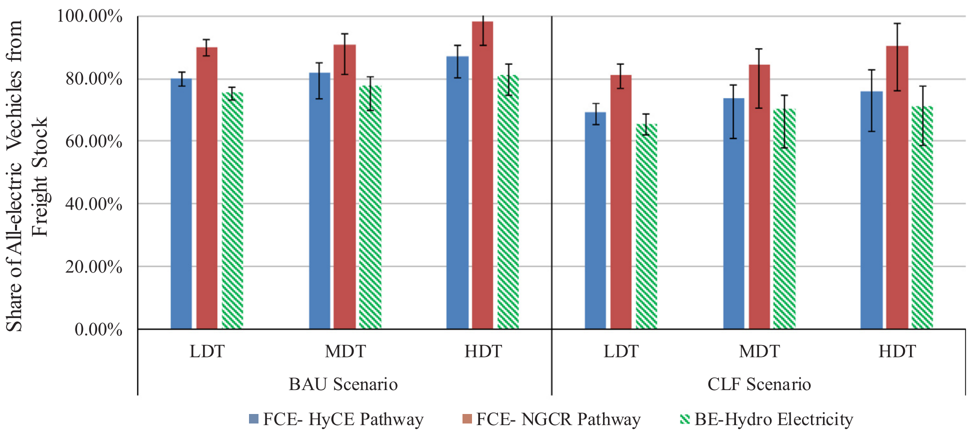

Fig. 5. Share of all-electric freight trucks (FCE: fuel cell electric, BE: battery electric) for 64% GHG emissions reduction from road freight transport in 2040 (from 2007 level): business as usual (BAU) and current legislation fulfillment (CLF) scenario.

the long-term solution.

3.3. The electrification effect on the 2040 GHG emissions of road freight transport in B.C

Fig. 5 shows the share of all-electric freight trucks required to reduce 64% GHG emissions from road freight transport in 2040 compared to those from 2007. The results suggest that the share of all-electric freight trucks (either battery electric or fuel cell) has to be more than 65% of the freight stock, regardless of the WTT pathway and the considered scenario. As the annual number of new trucks varies between 5% and 7% of the stock during the projection period (Section 3–1), the all-electric new trucks are required to reach 100% market share as early as 2025. Fig. 5 also indicates that less battery electric trucks are required to meet the target compared to fuel cell trucks. However, the market penetration of the battery technology is dependent on the duty cycle of the vehicle, especially, for long-haul HDTs, battery is a challenging technology to adopt. The same amount of GHG emissions could be reduced by 5–6% more heavy-duty fuel cell trucks, if hydrogen is produced via HyCE pathway. It is also observed that the full deployment of current legislation (CLF scenario) in ICE trucks has the same effect in terms of GHG emissions reduction as 7–10% penetration of all-electric freight trucks, in 2040.

3.4. B.C. resource assessment to support all-electric trucking

Fig. 6 compares the electricity requirement to support the 2040 all-electric trucking, described in Fig. 5, for BAU and CLF scenarios. The National energy Board projections (NEB, 2016) stated that the total electricity generation in B.C. will be around 81.1 TWh in 2040, of which 86% will be generated from large-scale hydroelectric dams. These projections also stated that the hydroelectricity production in B.C. will surpass the demand by 12% in 2040. Fig. 6 shows that the extra electricity generation in B.C. can support up to 33% of the fuel cell trucks (with HyCE pathway) and up to 72% of the battery electric trucks in BAU scenario, regardless of associated uncertainties. These percentages can increase up to 42% and 93%, respectively in CLF scenario. The NGCR pathway also requires electricity in different stages of hydrogen production, transportation and distribution. The total electricity requirement for meeting 2040 targets via this pathway is 69% and 55% of 2040 extra electricity generation in BAU and CLF scenarios, respectively. For illustrative purposes, the total electricity demand of all-electric trucks was compared to the projected capacity of Site C dam, which will be the 4th largest producer of hydroelectricity in B.C. The government of B.C. has announced plans to proceed with the Site C project despite opposition from indigenous communities and the mounting construction costs (Government of B.C, 2017b). As shown in Fig. 6, the required hydroelectric energy for FC HyCE pathway in BAU scenario is around 6.5 times the total electricity generation of Site C (BC Hydro, 2017b). Even supporting the battery electric trucks in the CLF scenario requires around 2.5 times the total electricity generation of Site C.

The total electricity generation (e.g., in TWh), may not give a comprehensive picture of the electricity availability to support the mass electrification in the road freight sector. In B.C., the installed generation capacity and the peak load of electricity is projected to be 21,000 MW and 16,900 MW in 2040, respectively (NEB, 2016). Assuming that sufficient battery electric trucks penetrate the market to meet the 2040 GHG emissions reduction target in the BAU scenario (Fig. 5). Even with the total extra generation capacity, up to 10% of all battery electric trucks could use DC fast chargers (50 kW), or up to 25% could use Level 2 AC chargers (19.2 kW) during peak hours. And if all battery electric trucks use off-peak hours for charging using Level 2 AC chargers (between 5 and 8 h), a 16,300 MW load will be added to the system. This

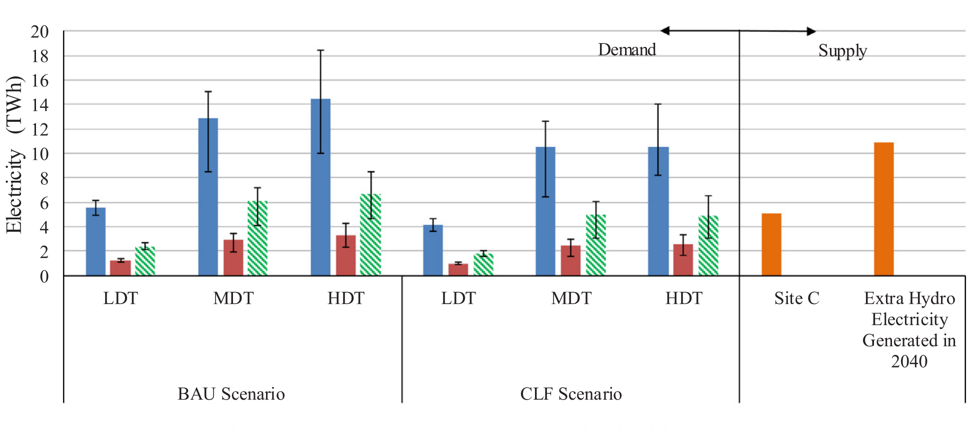

Fig. 6. Electricity requirement for 64% GHG emissions reduction from road freight transport in 2040 (from 2007 level) - FCE: fuel cell electric and BE: battery electric trucks- business as usual (BAU) and current legislation fulfillment (CLF) scenario.

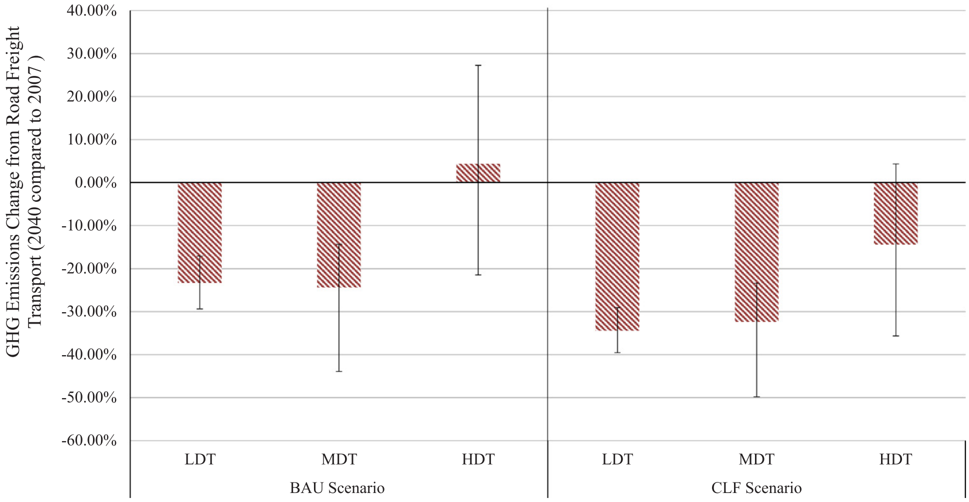

Fig. 7. GHG emissions change in 2040 road freight transport compared with 2007 – 100% of freight trucks running on hydrogen produced from central natural gas reforming (NGCR) pathway without carbon capture and sequestration (CCS)- business as usual (BAU) and current legislation fulfillment (CLF) scenario.

means peak hours may extend to midnight and early morning.

The projections on the total electricity generation show that the hydroelectric power can hardly satisfy the large electrification of road freight transport in B.C. Also, the projected installed electricity capacity is not ready to support the large percentage of battery electric trucks on the roads. It should also be noted that B.C. can no longer rely on any imported power to meet the forecast requirement. The BC Clean Energy Act called on BC Hydro to become self-sufficient in electricity production and a net exporter of clean electricity starting in 2016. Also, the Clean Energy Act banned the future development of large-scale hydroelectric storage dam projects on all rivers in B.C., except for site C. Thus, the diversification of the renewable supply mix seems to be inevitable to support large-scale electrification.

The latest BC hydro integrated resource plan (BC Hydro, 2013) assessed the long-term electricity generation potential of several renewable resources like wind, geothermal, biomass, solar, tidal and wave energy based on the technical and cost attributes. The results indicated that the wind, geothermal, and biomass resources have the least levelized[1] energy costs. The total technical onshore and offshore wind resource potential in B.C. was estimated at 102 TWh, of which 43% can be harvested for less than $200 per MWh. The geothermal resource potential in B.C. was estimated at around 12 TWh, of which 50% is below $200 per MWh. Only conventional hydrothermal resources using flash or binary technologies are considered within BC Hydro's resource assessment (BC Hydro, 2013). The wood-based biomass resources available for bioenergy production were estimated at 3.22 Million tonnes of dry wood for the 2026–2040 time-frame (Industrial Forestry Service, 2015). This translates to the technical electricity production potential of 4.5 TWh, generated mostly below $200 per MWh. From the National Energy Board projection database (NEB, 2016), 1.4% of B.C.'s wind resource potential and 40% of the combined biomass and geothermal potential will be used in electricity generation in 2040. These data illustrate the wind electricity potential in B.C. to support the electricity demand from the transportation sector. However, the intermittency associated with wind-generated electricity poses a challenge with regards to load leveling at large capacities (APS Physics, 2010).

The power-to-hydrogen pathway is a promising option to mitigate the intermittency of wind energy in a form of stored hydrogen. Hydrogen could be produced via electrolysis during off-peak demand hours at lower price and stored as an electricity back-up or directly used for transportation needs. In the short term, as the transportation is predominantly reliant on fossil fuels, the electrolytic hydrogen can be used in oil refineries to reduce the carbon intensity of the petroleum fuels (Al-Subaie et al., 2017). Also, electrolytic hydrogen can be injected to the natural gas system and used in hydrogen enriched natural gas (HCNG) engines (Mehra et al., 2017). Thus, the power-to-hydrogen is helpful to increase the flexibility of the power system and enables the high contribution of wind electricity in a short and long-term perspective (Maroufmashat and Fowler, 2017; Tractebel Engineering and Hinicio Consulting, 2017).

The NGCR pathway opens up the opportunity to partially unburden the renewable electricity generation to reduce GHG emissions from the road freight transport. The natural gas requirement for NGCR pathway is approximately 3×10^9 m^3 and 2.4×10^9 m^3 for BAU and CLF scenarios which is 3% of projected production for 2040 in B.C. (NEB, 2016). However, the GHG emissions reduction of the NGCR pathway is dependent on the deployment of large-scale carbon capture and sequestration (CCS) facilities, and CCS technology is yet to be widely deployed. The economic feasibility and potential environmental impacts of CCS may limit its application (Sawyer et al., 2008). The potential carbon storage reservoirs in B.C. are the sedimentary basins which are mostly located in the northeastern regions. These sites have been historically used for acid-gas injection (Bachu, 2004), however, their feasibility for CO2 storage needs further study. In this study, the CCS was considered with 85% efficiency (Damen et al., 2006). Fig. 7 shows that the NGCR pathway without CCS falls short of meeting the GHG emissions target in road freight transport, even with 100% of truck stock running on hydrogen.

3.5. *Comparative analysis of emission reductions and energy requirements across scenarios*

Converting more than 65% of all freight trucks to electric powertrain by 2040 may be challenging. Currently, there is uncertainty over the cost and lifetime of these vehicles. Also, the availability of charging stations and hydrogen refueling infrastructure in neighboring provinces and the United States can affect the all-electric long-haul transportation in B.C. Hence, we consider the penetration requirements for every 1% GHG emissions reduction from the trucking sector in 2040.

According to Fig. 8, 11,000 to 14,000 all-electric freight trucks are required for every 1% GHG reduction from B.C.'s road freight transport in 2040. As the contribution of HDTs to the GHG emissions is higher, a smaller number of all-electric HDTs is necessary to reduce the same amount of GHG emissions compared to the all-electric LDTs or MDTs. It is also observed that a larger number of all-electric trucks is required for every 1% GHG emissions reduction in CLF scenario than BAU scenario. Since the energy efficiency of ICE technology in CLF scenario is higher

[1] The levelized cost of a unit of energy ($/MWh) from a resource is the ratio of the present value of the total annual cost of an energy resource to the present value of its annual average energy benefit. The levelized cost is dependent on the accessibility of the generation sites to powerlines.

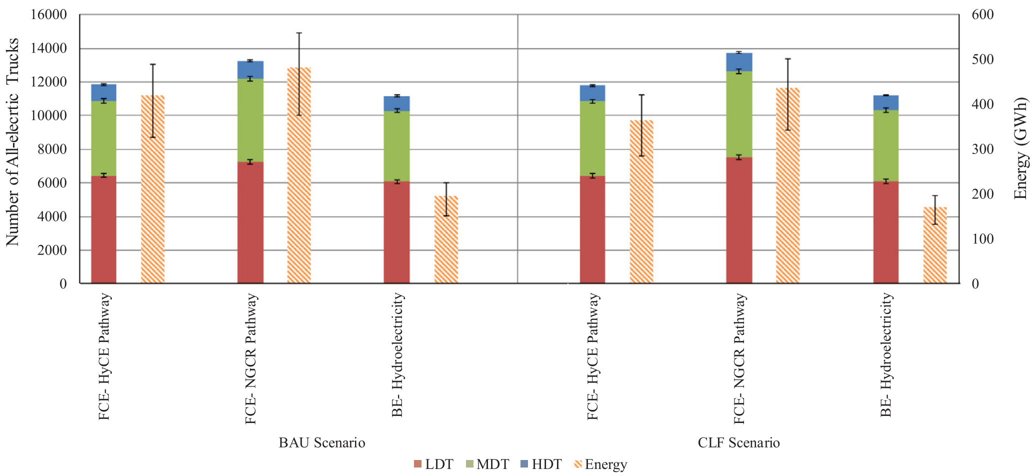

Fig. 8. 2040 projections on the number of all-electric trucks (FCE: fuel cell electric and BE: battery electric) and total energy required for 1% GHG emissions reduction from road freight transport in B.C.

than the BAU scenario, the CLF scenario is more resilient to emissions reduction. In other words, the ICE technology in CLF scenario is competing with all-electric powertrains in GHG emissions reduction.

In terms of well-to-wheels energy requirements (Table 4), the hydrogen dependent pathways require more than twice as much energy as the battery electric dependent pathway (i.e., 2.2 for the HyCE and 2.5 for the NGCR pathway). Amongst, the NGCR is the most energy intensive pathway for all-electric trucking. The hydroelectricity requirement for every 1% GHG emissions reduction from road freight transport is 1.5–1.8% of the B.C.'s 2040 total extra hydroelectricity generation for battery electric trucks and 3.3–3.8% for fuel cell trucks with HyCE pathway, depending on the scenario.

4. Conclusions and policy recommendations

In this study, the 2040 GHG emissions from road freight transport in B.C. was projected to investigate the effect of all-electric trucking on GHG emissions reduction. The analysis was built based on two scenarios named as the business as usual (BAU) with no technology improvement in ICE trucks and the current legislation fulfillment (CLF), which considered the full deployment of current legislation targeting freight transportation.

The analysis showed that the continuity of the current ICE technology (BAU scenario) by 2040 results in 39%, 53% and 84% GHG emissions increase from 2007 levels for LDTs, MDTs and HDTs, respectively. Also, the CLF scenario fail to set the GHG emissions on a downward trajectory. The projection results showed that all-electric trucking can help B.C. reduce 64% of the emissions from road freight transport by 2040. The WTW energy and GHG emissions analysis indicated that the share of all-electric freight trucks is required to be more than 65% of the stock, regardless of the WTT pathway and the considered scenario. Therefore, the government is required to enforce strict fleet emission regulations and allocate early-market subsidies for manufacturers, customers and the infrastructure developers to promote all-electric vehicles. Moreover, the partnerships between public authorities to mass-purchase electric vehicles for the public fleets, can provide reliable demand for vehicle manufacturers (Lambert, 2017c).

As the WTW energy efficiency of battery electric trucks is more than two times higher than fuel cell trucks, less battery electric trucks are required to meet the 2040 GHG emissions target. However, the adaptiveness of the battery technology is dependent on the duty cycle of the vehicle. Due to higher energy efficiency of battery electric trucks and the battery technology limitations, battery electric trucks are potentially fit to cover urban delivery with short and well-defined routes. This duty cycle is suited to light-duty and medium-duty classes. The heavy-duty class is suitable for long-haul application between the metropolitan areas which can be satisfied by fuel cell trucks. It is recommended that policy strategies support both fuel cell and battery electric powertrains, as they are complementary solutions to decarbonize road freight transport.

The analysis showed that every 1% GHG emissions reduction from road freight transport requires between 1.5% and 3.8% of 2040 extra hydroelectric generation in B.C. Thus, the B.C. hydroelectricity will fall short of generating sufficient energy to support all-electric trucking, required to fulfill the 2040 emissions reduction target. Therefore, B.C. has to undertake policies to incentivize electricity generation from diversified renewable energy resources. Wind energy provides reliability, wide scale resource availability and economic competitiveness with hydro power. The current B.C.'s policies such as 10-year exemption from participation rents for new wind projects lays the ground for wind energy development. However, more policies may be required to address the economic challenges of wind project developments in the private sector. Along with expanding energy resources, transmission capacity needs to be increased to meet the on-peak demand created by mass adoption of electric vehicles.

Natural gas may provide a pathway for low-carbon hydrogen production in B.C., but it would require CCS technology development and deployment. This pathway can help B.C. decrease the electricity requirements for all-electric trucking.

Acknowledgment

This work was funded by the Natural Sciences and Engineering Research Council of Canada through Vanier Canada Graduate Scholarship and the Pacific Institute for Climate Solutions.

References

Al-Subaie, A., Maroufmashat, A., Elkamel, A., Fowler, M., 2017. Presenting the Implementation of Power-to-Gas to an Oil Refinery as a Way to Reduce Carbon Intensity of Petroleum Fuels. Int. J. Hydrog. Energy 42, 19376–19388. http://dx.doi.org/10.1016/j.ijhydene.2017.06.067.
APS Physics, 2010. Integrating Renewable Electricity on the Grid.
ARB, 2015. Technology Assessment: Medium- and Heavy-duty Fuel Cell Electric Vehicles.
Argonne National Laboratory, 2016. GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model)- GREET_1_2016.
Bachu, S., 2004. Evaluation of CO2 Sequestration Capacity in Oil and Gas Reservoirs in the Western Canada Sedimentary Basin.
BC Hydro, 2011. Integrated Resource Plan Appendix 6B-1 Greenhouse Gas Reduction Scenarios for the Western Interconnection: (2010–2050).
BC Hydro, 2013. The Integrated Resource Plan (IRP) [WWW Document]. URL 〈https://www.bchydro.com/energy-in-bc/planning-for-our-future/irp/current-plan/document-centre/reports/november-2013-irp.html〉 (accessed 2 October 2017).
BC Hydro, 2014. BC Hydro's Greenhouse Gas Intensities 2004–2014 [WWW Document]. URL https://www.bchydro.com/content/dam/BCHydro/…/ghg-intensities-2004–2014.pdf%0A (accessed 19 January 2017).
BC Hydro, 2017a. BC Hydro's Service Plan 2017/18 – 2019/20.
BC Hydro, 2017b. Site C Clean Energy Project [WWW Document]. URL 〈https://www.sitecproject.com/〉 (accessed 7 May 2017).

den Boer, E., Pagenkopf, J., Aarnink, S., Kleiner, F., 2013. Zero Emissions Trucks An Overview of State-of-the-art Technologies and their Potential. 〈doi: http://dx.doi.org/13.4841.21〉.

CaFCP, 2016. Medium- & Heavy-duty Fuel Cell Electric Truck Action Plan for California.

CalSTA, 2014. California Freight Mobility Plan.

Canada Gazette Part II, 2010. Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations (SOR/2010-201) 144.

Canada Gazette Part II, 2013. Canadian Environmental Protection Act,1999: Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations 147.

Canada Gazette Part II, 2014. Regulations Amending the Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations SOR/2014-207 148.

Canada Gazette Part II, 2017. Regulations Amending the Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations and Other Regulations Made Under the Canadian Environmental Protection Act, 1999 151.

Cetinkaya, E., Dincer, I., Naterer, G.F., 2012. Life Cycle Assessment of Various Hydrogen Production Methods. Int. J. Hydrog. Energy 37, 2071–2080. http://dx.doi.org/10.1016/j.ijhydene.2011.10.064.

CHFCA, 2016. Canadian Hydrogen and Fuel Cell Sector Profile.

Damen, K., Troost, M., Van, Faaij, A., Turkenburg, W., 2006. A comparison of electricity and hydrogen production systems with CO 2 capture and storage. Part A: review and selection of promising conversion and capture technologies. Prog. Energy Combust. Sci. 32, 215–246. http://dx.doi.org/10.1016/j.pecs.2005.11.005.

Edwards, R., Larivé, J.-.F., Rickeard, D., Weindorf, W., 2014. Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context, Well-to-Tank (WTT) Report – Appendix 2, Version4a.

Eom, J., Schipper, L., Thompson, L., 2012. We Keep on truckin': trends in Freight Energy Use and Carbon Emissions in 11 IEA Countries. Energy Policy 45, 327–341. http://dx.doi.org/10.1016/j.enpol.2012.02.040.

Eudy, L., Post, M., Gikakis, C., 2015. Fuel Cell Buses in U.S. Transit Fleets: Current Status 2015.

Fridriksson, T., Mateos, A., Audinet, P., Orucu, Y., 2016. Green house Gases from Geothermal Power Production: Interim Technical Note.

Girvan, J. , & Hall, M., 2008. BC Fibre Model User Guide.

Government of B.C, 2008a. Greenhouse Gas Reduction (Renewable and Low Carbon Fuel Requirements) Act, Renewable and Low Carbon Fuel RequirementsRegulation, B.C. Reg. 394/2008 [WWW Document]. Gov. Br. Columbia. URL 〈http://www.bclaws.ca/EPLibraries/bclaws_new/document/ID/freeside/394_2008〉 (accessed 15 February 2017).

Government of B.C, 2008b. British Columbia's Revenue-Neutral Carbon Tax [WWW Document]. Gov. Br. Columbia. URL 〈http://www2.gov.bc.ca/gov/content/environment/climate-change/planning-and-action/carbon-tax〉 (accessed 20 December 2016).

Government of B.C, 2010. Clean Energy Act [WWW Document]. [SBC 2010] CHAPTER 22. URL 〈http://www.bclaws.ca/civix/document/id/consol24/consol24/00_10022_01〉 (accessed 15 March 2017).

Government of B.C, 2012. Clean Energy Act Greenhouse Gas Reduction (Clean energy) Regulation B.C. Reg. 102/2012 [WWW Document]. URL 〈http://www.bclaws.ca/civix/document/id/complete/statreg/102_2012〉.

Government of B.C, 2017a. Weigh2GoBC [WWW Document]. URL 〈https://www2.gov.bc.ca/gov/content/transportation/vehicle-safety-enforcement/services/weigh2gobc-join〉 (accessed 12 January 2017).

Government of B.C, 2017b. Site C Dam Information & Updates [WWW Document]. URL 〈https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/electricity/site-c〉 (accessed 15 December 2017).

Government of B.C, 2005. British Columbia Climate Action for the 21st Centry. Government of British Columbia.

Hao, H., Geng, Y., Li, W., Guo, B., 2015. Energy Consumption and GHG Emissions from China's Freight Transport Sector: scenarios through 2050. Energy Policy 85, 94–101. http://dx.doi.org/10.1016/j.enpol.2015.05.016.

He, C., Sun, H., Xu, Y., Lv, S., 2017. Hydrogen Refueling Station Siting of Expressway Based on the Optimization of Hydrogen Life Cycle Cost. Int. J. Hydrog. Energy 42, 16313–16324. http://dx.doi.org/10.1016/j.ijhydene.2017.05.073.

Helmers, E., Marx, P., 2012. Electric Cars: technical Characteristics and Environmental Impacts. Environ. Sci. Eur. 24, 1–15.

Hiscock, J., 2015. Smart Grid in Canada 2014. doi:015-018 RP-ANU 411-SGPLAN.

Howarth, R.W., 2014. A Bridge to Nowhere: methane Emissions and the Greenhouse Gas Footprint of Natural Gas. Energy Sci. Eng. 2, 47–60. http://dx.doi.org/10.1002/ese3.35.

HSU, T., 2017. Nikola Tweaks Hydrogen Truck Design, Raises Funding [WWW Document]. URL 〈https://www.trucks.com/2017/06/26/nikola-electric-truck-redesign/〉 (accessed 10 May 2017).

Hua, T., Ahluwalia, R., Eudy, L., Singer, G., Jermer, B., Asselin-Miller, N., Wessel, S., Patterson, T., Marcinkoski, J., 2014. Status of hydrogen fuel cell electric buses worldwide. J. Power Sources 269, 975–993. http://dx.doi.org/10.1016/j.jpowsour.2014.06.055.

Industrial Forestry Service, 2015. Wood Based Biomass in British Columbia and its Potential for New Electricity Generation.

Lambert, F., 2017a. BYD Announces New Electric Truck Assembly Factory in Canada [WWW Document]. URL 〈https://electrek.co/2017/11/15/byd-new-electric-truck-assembly-factory-canada/〉 (accessed 12 May 2017).

Lambert, F., 2017b. Tesla Semi [WWW Document]. URL 〈https://electrek.co/guides/tesla-semi/〉 (accessed 15 December 2017).

Lambert, F., 2017c. US Cities' Massive Electric Vehicles Order Increases to 114,000 Vehicles, 40 Companies Competing [WWW Document]. URL 〈https://electrek.co/2017/03/15/electric-vehicle-order-114000-vehicles-40-companies-competing/〉 (accessed 12 October 2017).

Levene, J.I., Mann, M.K., Margolis, R.M., Milbrandt, A., 2007. An analysis of hydrogen production from renewable electricity sources. Sol. Energy 81, 773–780. http://dx.doi.org/10.1016/j.solener.2006.10.005.

Limanond, T., Jomnonkwao, S., Srikaew, A., 2011. Projection of future transport energy demand of Thailand. Energy Policy 39, 2754–2763. http://dx.doi.org/10.1016/j.enpol.2011.02.045.

Maroufmashat, A., Fowler, M., 2017. Transition of Future Energy System Infrastructure; Through Power-to-Gas Pathways. Energies. http://dx.doi.org/10.3390/en10081089.

McJeon, H., Edmonds, J., Bauer, N., Clarke, L., Fisher, B., Flannery, B.P., Hilaire, J., Krey, V., Marangoni, G., Mi, R., Riahi, K., Rogner, H., Tavoni, M., 2014. Limited Impact on Decadal-scale Climate Change from Increased Use of Natural Gas. Nature 514, 482–485. http://dx.doi.org/10.1038/nature13837.

Mehra, R.K., Duan, H., Juknelevičius, R., Ma, F., Li, J., 2017. Progress in hydrogen enriched compressed natural gas (HCNG) internal combustion engines - a comprehensive review. Renew. Sustain. Energy Rev. http://dx.doi.org/10.1016/j.rser.2017.05.061.

Melaina, M., Penev, M., Heimiller, D., 2013. Resource Assessment for Hydrogen Production. Hydrogen Production Potential from Fossil and Renewable Energy Resources.

MNP, 2016. Clean Energy Vehicle Economic Opportunities Assessment.

Natural Gas Use in Transportation Roundtable, 2010. Natural Gas Use in the Canadian Transportation Sector: Deployment Roadmap.

NEB, 2016. Canada's Energy Future 2016: Energy Supply and Demand Projections to 2040.

NRCan, 2013. GHGenius Model 4.03.

NRCan, 2016. Road transportation secondary energy use and GHG emissions,British Columbia and territories [www document]. Nat. Resour. Can. 〈http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive/trends_tran_bct.cfm〉 (accessed 1 May 2017).

NRCan, 2017. British Columbia's Shale and tight resources [www document]. Nat. Resour. Can. 〈http://www.nrcan.gc.ca/energy/sources/shale-tight-resources/17692〉 (accessed 30 July 2017).

NREL, 2013. Clean Cities Guide to Alternative Fuel and Advanced Medium- and Heavy-Duty Vehicles. National Renewable Energy Laboratory (NREL), Golden, CO. http://dx.doi.org/10.2172/1092620.

O'Dell, J., 2017. Toyota's Heavy-Duty Fuel Cell Truck Finally Hits the Road [WWW Document]. URL 〈https://www.trucks.com/2017/10/12/toyota-hydrogen-fuel-cell-electric-truck-hits-road/〉 (accessed 11 May 2017).

OECD, 2011. Moving Freight with Better Trucks: Improving Safety, Productivity and Sustainability.

Poudyal, R.S., Tiwari, I., Koirala, A.R., Masukawa, H., Inoue, K., Tomo, T., Najafpour, M.M., Allakhverdiev, S.I., Veziroğlu, T.N., 2015. Compendium of hydrogen energy. Compend. Hydrog. Energy. http://dx.doi.org/10.1016/B978-1-78242-361-4.00010-8.

Ramachandran, S., Stimming, U., 2015. Well to wheel analysis of low carbon alternatives for road traffic. R. Soc. Chem. 8, 3313–3324. http://dx.doi.org/10.1039/c5ee01512j.

Ramsde, T., Ruth, M., Diakov, V., 2013. hydrogen pathways: updated Cost, well-to-wheels energy use, and emissions for the Current technology status of Ten hydrogen production. Deliv., Distrib. Scenar NREL/TP-6A10-60528.

Sawyer, D., Harding, R., Pozlott, C., Dickey, P., 2008. Carbon Capture and Storage — The Environmental and Economic Case and Challenges.

Thomas, C.E., 2009. Fuel cell and battery electric vehicles compared. Int. J. Hydrog. Energy 34, 6005–6020. http://dx.doi.org/10.1016/j.ijhydene.2009.06.003.

Tomes, D., Lakshmanan, P., Songstad, D. (Eds.), 2011. Biofuels. Springer-Verlag, New York.

Tractebel Engineering and Hinicio Consulting, 2017. Study on Early Business Cases for H2 in Energy Storage & More Broadly Power to H2 Applications.

U.S. Department of Energy, 2013. State of the States: Fuel cells in America 2013.

U.S. DRIVE Partnership, 2013. Hydrogen Delivery Technical Team Roadmap.

Venkatesh, A., Jaramillo, P., Griffin, W.M., Matthews, H.S., 2011. Uncertainty in life cycle greenhouse gas emissions from united states natural gas end-uses and its effects on policy. Environ. Sci. Technol. 45, 8182–8189. http://dx.doi.org/10.1021/es200930h.

Veziroğlu, T.N., Şahin, S., 2008. 21st century's energy: hydrogen energy system. Energy Convers. Manag 49, 1820–1831. http://dx.doi.org/10.1016/j.enconman.2007.08.015.

Wolinetz, J., Moorhouse, M., 2016. Biofuels in Canada: Tracking Progress in Tackling Greenhouse Gas Emissions from Transportation Fuels.