Comparative Life Cycle Analysis of Heavy-Duty Vehicles (Class 7/8) Fueled by Renewable Diesel, Electricity, and Hydrogen

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Executive Summary

Heavy-duty freight and equipment trucks account for approximately 35% of the greenhouse gas (GHG) emissions from the Canadian transportation sector. Despite Canada's targets of reducing its GHG emissions by 30% below 2005 levels by 2030 under the Paris Agreement and achieving net-zero emission status by 2050, emissions from the transportation sector, heavy-duty trucks, in particular, have grown steadily over the past two decades. Transformation of the existing fleet of heavy-duty diesel trucks to alternative fueled low emission vehicle technologies poses to have great potential to contain and reduce emissions from the global transportation industry. However, despite alternative fuels reducing/avoiding emissions at the vehicle tailpipe, significant emissions could occur during the fuel's production, distribution, storage, and refuelling phases. Hence a comprehensive cradle-to-grave life cycle assessment is required to assess the overall impacts of alternative fuels.

This study originated with the primary goal of assessing the greenhouse gas emissions of alternative fuels, namely, electricity, hydrogen, and renewable diesel, along with their vehicle technologies. Accordingly, 12 different fuel supply chain options (two electricity options, seven hydrogen options, and three renewable diesel options) are considered in this study, along with the relative vehicle technologies. Results show that electric trucks powered by British Columbia's grid electricity have the least GHG emissions, approximately 47 kgCO_2eq./100 km. The most eco-friendly fuel supply chain option for hydrogen fuel cell trucks is to generate hydrogen via electrolysis and to transport it via compressed gas trailers totalling 54 kgCO_2eq./100 km, whereas producing renewable diesel via soybeans has the least emissions of 63 kgCO_2eq./100 km out of the renewable diesel options considered in this study. Results show that using the aforementioned fuel supply chain options along with their vehicle technologies can reduce the GHG emissions generated from conventional diesel trucks, which is approximately 100 kgCO_2eq./100km. Nevertheless, electric trucks operated on electricity produced from high carbon-intensive energy sources, fuel cell trucks operated on hydrogen produced from coal gasification, and natural gas reforming could add an additional burden on the environment.

Despite the reduced GHG emission from these alternative fuels, the decision to transform heavy-duty trucks from fossil fuels to alternative fuels should be made by considering many other criteria along with the life cycle emissions of the fuel. These include economic aspects such as vehicle and fuel prices and infrastructure development costs, and other environmental parameters such as emissions during infrastructure development, maintenance and disposal. Additionally, social concerns such as user attitude towards alternative fuels and potential job

opportunities or losses should be weighed into the decision matrix. Moreover, technological constraints such as limited range of travel, prolonged refuelling periods of electric trucks, and inefficiencies of hydrogen production and fuel cell technologies, along with other macro-environmental parameters, should be considered when evaluating these alternative fuel options. Hence, the decision on the best alternative fuel option/options should be made by considering multiple decision criteria along with uncertainties related to them.

Introduction

Global greenhouse gas (GHG) emissions keep rising annually, significantly impacting the environment, economy, and society (Natural Resources Canada, 2007). The United States Environmental Protection Agency reports that approximately 14% of the global emissions arise from the transportation sector, mainly due to the use of fossil fuels for road, rail, air, and marine transportation (United States Environmental Protection Agency, 2022). Moreover, petroleum-based fuels such as gasoline and diesel cater to approximately 95% of the global transportation energy demand. The transport sector is Canada's second-largest source of GHG emissions, accounting for approximately 24% of the national GHG inventory, which is equivalent to 159 MT of CO_2 eq. (metric tons of carbon dioxide equivalent) emitted annually (Government of Canada, 2022c). Statistics show that the Canadian transport sector's GHG emissions have risen by 32% from 1990 to 2020. However, a drop of 14% in emissions was observed in 2020, mainly due to the impacts of COVID19 and mandated provincial lockdowns (Government of Canada, 2022b). Figure 1 shows the transportation sector's emissions variations (by vehicle type) from 1990 to 2020 (Government of Canada, 2022a).

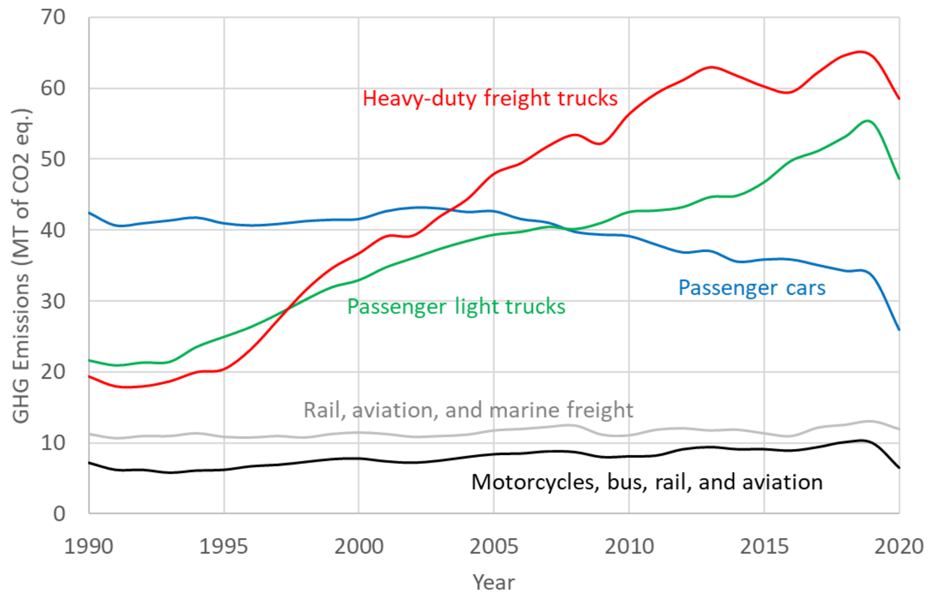


Figure 1: GHG emissions from the Canadian transport sector

The majority (approximately 35%) of the emissions from the Canadian transport sector are generated from heavy-duty freight trucks, equivalent to 64.5 MT of CO_2 eq. in 2019. This is approximately a three-fold increment compared to the emission levels in 1995. A steady increase in emissions has been observed from heavy-duty freight trucks over the years, mainly as a result of increased freight transportation demand with the expansion of the economy. Nevertheless, a steady decrease in emissions from passenger cars has been seen over the last two decades predominantly due to the improvements in vehicle technologies and efficiencies to reduce emissions and due to the adaptation of low-emission or zero-emission vehicles such as hybrid vehicles, plug-in hybrid electric vehicles (PHEVs), and electric vehicles (EVs).

Despite increasing emissions from the overall transport sector, Canada has pledged to reduce its GHG emissions by 30% below 2005 levels by 2030 under the Paris Agreement (Canadian Institute for Climate Choices, 2021). Moreover, the Government of Canada is committed to achieving net-zero emission status by 2050 (Government of Canada, 2022d). Along with national GHG reduction targets and plans, local governments and municipalities have started their programs to fight climate change. Accordingly, the City of Vancouver's Climate Emergency Action Plan targets on reducing carbon pollution by 50% by 2030 while being carbon neutral by 2050 (City of Vancouver, 2022). The use of gasoline and diesel in vehicles accounts for approximately 39% of the city's carbon emissions (City of Vancouver, 2020). Accordingly, the City of Vancouver is aiming to make sure that

- 90% of the people live within an easy walk for their daily needs
- 66% of the trips in Vancouver to be by active transportation and transit
- 50% of the km driven on Vancouver's roads to be zero emission vehicles by 2030.

Hence, it is critical that urgent measures are taken and implemented across multiple disciplines in order to achieve these long-term and short-term emission reduction goals.

As the vehicular segment with the most significant GHG emissions in the Canadian transport sector, it is critical that emissions from the heavy-duty trucks are assessed, controlled, and reduced to achieve local and Canadian emission reduction targets. The main reason for the vast GHG emissions from road freight transportation is that the current fleet of heavy-duty vehicles is highly dependent on fossil fuels, diesel in particular (Li et al., 2013). Nevertheless, using low-emission alternative fuels for road freight transportation has shown great potential as a viable solution to reduce emissions from heavy-duty freight vehicles. Accordingly, fuels such as hydrogen, electricity, and renewable diesel could be identified as alternative fuels to replace diesel derived from fossil fuels (Salvi et al., 2013). However, many other factors should be considered before deciding on the transformation of the conventional fleet of heavy-duty trucks into alternative fuels. For example, technology levels of zero-emission trucks, such as electric and fuel cell trucks, are still at their introductory level. Moreover, infrastructure for mass-scale hydrogen production, distribution, and storage are merely non-existent and hence would require vast investments in order to develop and maintain them. Hence the decision to switch to alternative fuels requires in-depth planning and analysis considering technological, economic, environmental, and social parameters.

Conventional diesel derived from crude oil emits approximately 0.44 kg of CO_2 per litre of diesel during its production, transportation, and storage processes, whereas diesel engines produce approximately 2.7kg of CO_2 per litre of diesel during their operation (Natural Resources Canada, 2014; Palou-Rivera & Wang, 2010). On the other hand, hydrogen fuel cell vehicles (HFCVs) and electric vehicles are categorized as zero-emission vehicles since they have zero GHG emissions at the tail pipe. Hence the transformation of the existing fleet of heavy-duty trucks to FCVs (fuel cell vehicles) or EVs could result in vast reductions in CO_2 emissions during the operational phase of the vehicle. Nevertheless, significant attention must be given to assessing GHG emissions during these fuels' production and distribution stages (hydrogen and electricity). Similarly, renewable diesel has the potential to reduce emissions at the fuel production stage, offsetting emissions expected during the operational stage of the vehicle. Hence the ultimate decision on the fuel option with the least emissions should be made considering the overall life cycle of the vehicle and the fuel supply chain rather than just the operational stage of the vehicle.

Accordingly, the main objective of this study is to conduct a comprehensive life cycle assessment to compare the environmental impacts of alternative fueled (renewable diesel, battery electric, hydrogen) heavy-duty freight and equipment vehicles. The final outcome of this report will support the City of Vancouver's Fleet Management team when replacing heavy duty vehicles in the Class 7 and 8 categories. The specific sub-objectives of this study are as follows.

1. To review published literature to identify the existing status of alternative fuel use for heavy-duty vehicles
2. To conduct a life cycle assessment to compare the emissions of the fuel supply chains of the aforementioned alternative fuel options
3. To assess and compare the environmental impacts of varying components in the drivetrains of renewable diesel, battery electric, hydrogen operated heavy-duty trucks
4. To assess and compare the overall emissions from each vehicle technology by combining fuel supply chain emissions and vehicle emissions and to provide recommendations

Figure 2 shows the integration of objectives of this study.

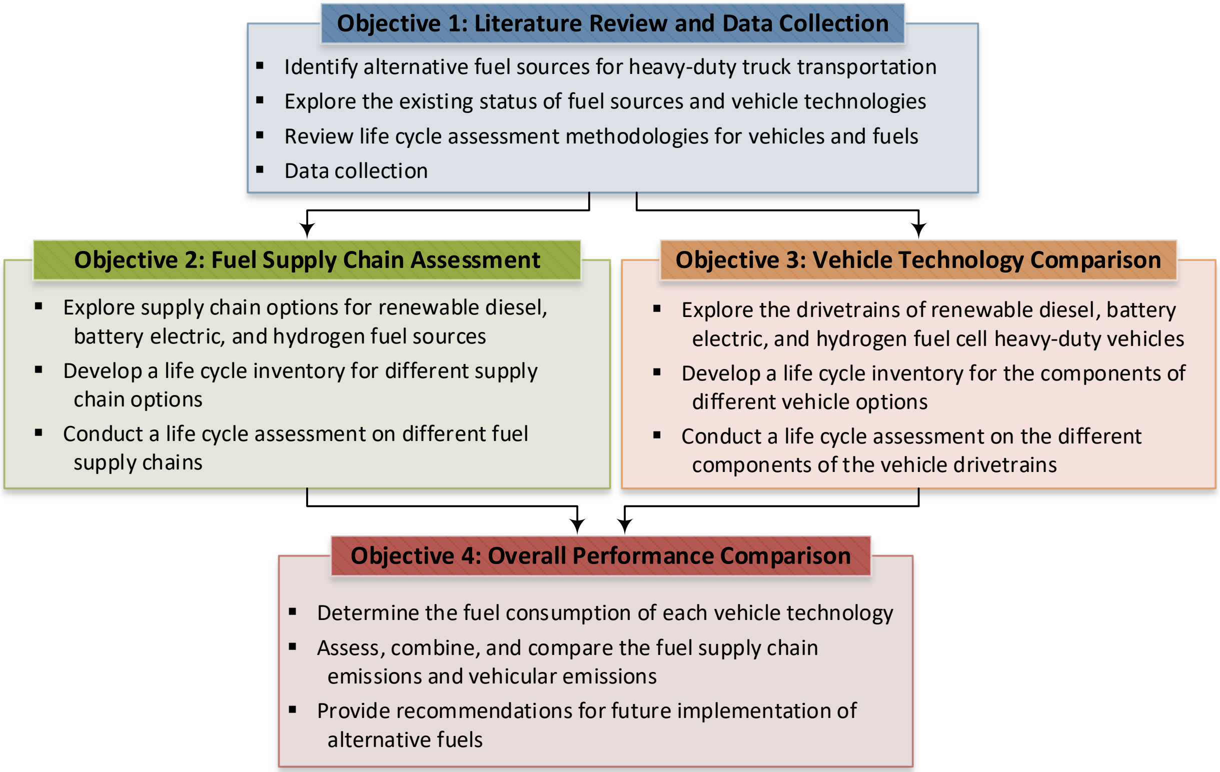


Figure 2: Integration of objectives

Literature Review

This section provides an overview of the current status of alternative transportation fuels. Moreover, the existing literature is reviewed to identify and compare different fuel (electricity, hydrogen, and renewable diesel) production methods and related vehicular technologies.

Alternative Fuels for Heavy-Duty Trucks

Approximately 5.7 Gt of CO_2 is generated annually from the global road transport sector, where heavy and medium duty trucks contribute by approximately 1.8 Gt of CO_2 (International Energy Agency, 2022a). Figure 3 shows the variation of the global CO_2 emissions from the tailpipe of heavy-duty and medium-duty vehicles over the years. Since 2020, an annual average tailpipe CO_2 emission increase of 2.2% has been recorded from heavy-duty trucks (International Energy Agency, 2022b). This is mainly due to the increased transportation needs and due to the existing fleet of vehicles predominantly depending on fuels such as gasoline and diesel derived from highly carbon-intensive fossil fuels.

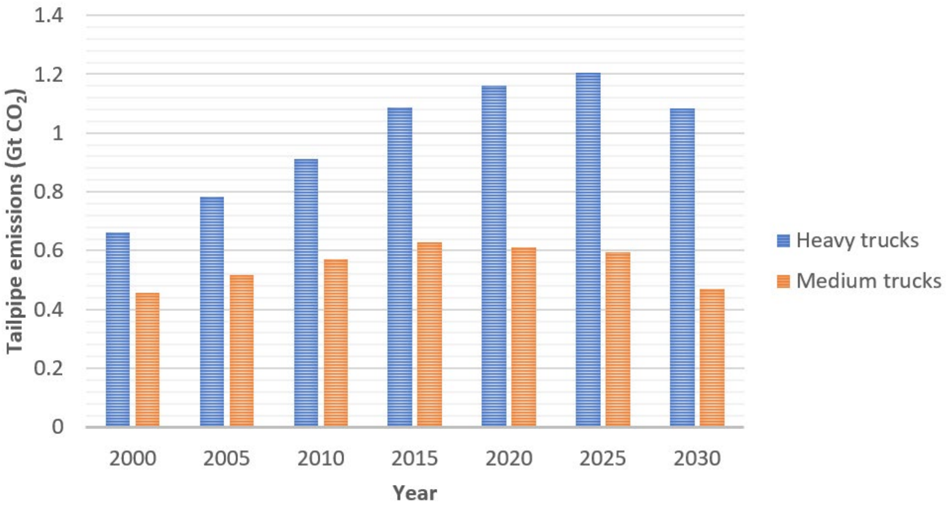
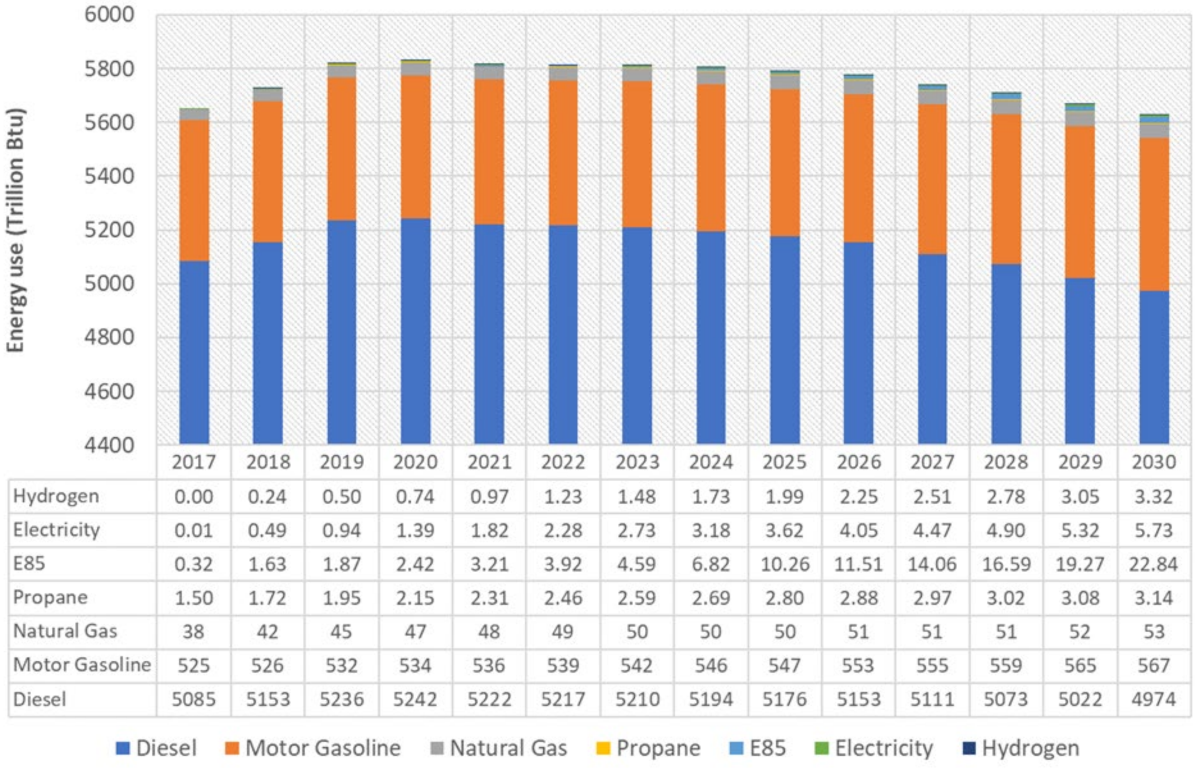


Figure 3: Global tailpipe emissions from heavy-duty and medium-duty trucks

However, the world, as well as individual nations, have pledged to reduce emissions from the transportation sector. A few viable strategies to reduce emissions from the heavy-duty transport sector would be to improve vehicle technologies in order to reduce fuel consumption and tailpipe emissions and to reduce the demand for heavy-duty transport by limiting transportation activities and planning and integrating infrastructure so that the transport demand is reduced. Another viable option is to low emission or renewable fuels such as electricity, hydrogen, renewable diesel, and natural gas. Figure 4 shows the energy demand for heavy-duty trucks in the United States (US) from 2017 to 2030 (U.S. Energy Information Administration, 2019). The figure presents actual energy use figures until 2019 and predictions for the future until 2030. As seen in the figure US expects that the energy use from heavy-duty truck transportation will peak around 2021/2022 and start reducing after that. Moreover, the use of diesel for heavy-duty truck transportation is expected to drop over these years, whereas the use of fuels such as electricity, hydrogen, and E85 are expected to grow with time. However, as of present, the use of these fuels for heavy-duty transportation is still in its preliminary stages.

One major challenge of adopting these alternative fuels for heavy-duty transportation is the lack of infrastructure. Especially, using a fuel like hydrogen would require huge investments to develop infrastructure to produce, distribute, store, and refuel hydrogen. Moreover, since fuel cell technology is still at its initial stages of implementation on the global stage, users could resist incorporating fuel cell trucks at once in larger quantities into their fleet of vehicles. Contrastingly, electric trucks have a greater potential of being used for heavy-duty transportation since developing infrastructure is not as challenging as infrastructure related to hydrogen fuel. However, technological constraints such as the limited range of electric trucks, the prolonged periods of recharging, and the potential requirement to replace batteries used to store energy are considered to be the most significant challenges to their implementation.

Nevertheless, electric and hydrogen fuel cell vehicles are categorized as zero-emission vehicles (ZEVs) and have a great potential to eradicate tailpipe emissions from heavy-duty trucks. On the other hand, renewable diesel could be used on the existing fleet of diesel trucks, and the current infrastructure could be used to distribute and refuel renewable diesel. However, this technology is not able to completely avoid GHG emissions during its operational phase (while being used in the vehicle). Hence, alternative fuels such as hydrogen, electricity, and renewable diesel has the potential to reduce emissions from the heavy-duty transport sector and to replace conventional diesel in the long run. However, many other technological, economic, social, and macro-environmental factors should be considered when selecting the best alternative fuel options.



	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Hydrogen	0.00	0.24	0.50	0.74	0.97	1.23	1.48	1.73	1.99	2.25	2.51	2.78	3.05	3.32
Electricity	0.01	0.49	0.94	1.39	1.82	2.28	2.73	3.18	3.62	4.05	4.47	4.90	5.32	5.73
E85	0.32	1.63	1.87	2.42	3.21	3.92	4.59	6.82	10.26	11.51	14.06	16.59	19.27	22.84
Propane	1.50	1.72	1.95	2.15	2.31	2.46	2.59	2.69	2.80	2.88	2.97	3.02	3.08	3.14
Natural Gas	38	42	45	47	48	49	50	50	50	51	51	51	52	53
Motor Gasoline	525	526	532	534	536	539	542	546	547	553	555	559	565	567
Diesel	5085	5153	5236	5242	5222	5217	5210	5194	5176	5153	5111	5073	5022	4974

Figure 4: US transportation energy use from freight trucks

Fuel Supply Chains and Vehicle Technologies

This section provides an overview of the vehicle technologies and fuel supply chains (production, distribution, storage) related to alternative fuel options considered in this study.

Electricity and Electric Vehicles

Electric vehicles have gained great popularity globally as well as in Canada over the past few years. Electric vehicles can be categorized into three types as follows.

1. *All-Electric Vehicles / Battery Electric Vehicles (BEVs) -* These vehicles have a battery that powers an electric motor to drive the vehicle. The battery can be charged by plugging charging equipment into the vehicle, and these vehicles typically have driving ranges of 150 – 400 miles (U.S. Department of Energy, 2022).
2. *Hybrid Electric Vehicles (HEVs) –* These vehicles are powered by an internal combustion engine (ICE) in combination with one or more electric motors. The ICE is powered by gasoline or diesel, whereas the electric motor uses the energy stored in a battery which is charged through regenerative braking (U.S. Department of Energy, 2022).
3. *Plug-In Hybrid Vehicles (PHEVs)* - Similar to hybrid vehicles, these vehicles are powered by an internal combustion engine and an electric motor. However, PHEVs have a larger battery capacity that allows them to operate in all-electric mode over a greater distance. The control unit decides the use of the engine or the motor (alone or combinedly) depending on the vehicle's driving conditions. The battery of PHEVs could be charged from regenerative braking or by connecting the vehicle to charging equipment. (U.S. Department of Energy, 2022)

Images of the drivetrains and the key components of these vehicles are provided in Appendix A of this report. Out of these vehicle types, BEVs completely eradicate direct tailpipe emissions and hence are categorized under zero-emission vehicles. Statistics show that 5.8% of all the new vehicles registered in Canada during the first quarter of 2022 were BEVs. Despite BEVs having zero tailpipe emissions there could be significant emissions and losses during producing and transmitting electricity. The emissions during producing electricity predominantly depend on the energy source used. Electricity generated from non-renewable carbon intensive sources such as natural gas and coal could have significantly high GHG emissions whereas electricity generated from nuclear energy, and renewable sources such as wind, hydropower, solar power, and geothermal would have low GHG emissions. Accordingly, GHG emissions related to electricity used to recharge the vehicle predominantly depends on the energy source or the electricity grid mix of that particular area. Table 1 shows different sources and quantities of electricity generated using those fuel sources in British Columbia, Alberta, and Canada as a whole.

Table 1: Electricity generation by source

Fuel Type	**British Columbia**		**Alberta**		**Canada**	
	GWh	*%*	*GWh*	*%*	*GWh*	*%*
Hydro / Wave / Tidal	56127	89.73	2043	2.53	392959	61.85
Wind	1694	2.71	4206	5.21	37206	5.86
Biomass / Geothermal	3310	5.29	1632	2.02	7918	1.25
Solar	20	0.03	319	0.40	2951	0.46
Uranium	0	0.00	0	0.00	78636	12.38
Coal & Coke	0	0.00	27817	34.46	35374	5.57
Natural Gas	1291	2.06	44597	55.24	76989	12.12
Oil	107	0.17	113	0.14	3359	0.53
Total	*62549*	*100.00*	*80728*	*100.00*	*635392*	*100.00*

As seen in the table, British Columbia highly depends on electricity generated from hydropower (approximately 90%) and has a grid emission factor as low as 9.7 tCO_2eq/GWh (tonnes of CO2-equivalent per Gigawatt-hour). Comparatively, Alberta's electricity grid which is highly dependent on carbon-intensive energy sources such as coal and natural gas (approximately 90% in total), has a grid emission factor of 590 tCO_2eq/GWh.

Hydrogen and Hydrogen Fuel Cell Vehicles

Hydrogen is a fuel with a higher energy density and emits zero-GHGs during combustion (Wanniarachchi et al., 2022). Therefore, hydrogen fuel is gaining popularity across the globe. Hydrogen fuel cell vehicles (HFCVs) / hydrogen fuel cell electric vehicles (HFCEVs) use a similar propulsion system to that of EVs. However, the energy is stored as hydrogen in hydrogen storage tanks and converted to electricity by a fuel cell. Similar to EVs, HFCVs are categorized as ZEVs since no harmful tailpipe emissions are generated.

The key global market segments for HFCVs are passenger and commercial vehicles, with passenger vehicles accommodating the highest market share of HFCVs (Next Move Strategy Consulting, 2022). Hydrogen fuel cell technology is gaining popularity across many countries, including the UK, France, Germany, U.S. and Canada (Next Move Strategy Consulting, 2022). As of August 2022, Canada possesses seven hydrogen refuelling stations (Glpautogas, 2022). The major reasons behind accelerated actions to propel the use of HFCVs are concerns revolving around climate change, environmental policies, and emission goals.

However, it is important to assess the overall environmental and economic performance of the hydrogen supply chain to determine its actual benefits. Moreover, a steady feedstock source is essential to ensure a reliable hydrogen supply. Different technologies for hydrogen production are available across its supply chain (Wanniarachchi et al., 2022). The technology choice depends on its economic, technological, and environmental performance. For example, water electrolysis is an established hydrogen production method, where electricity is required for production. When renewable electricity is used, it is considered one of the cleanest hydrogen production methods compared to well-known steam methane reforming (SMR) technology (Kakoulaki et al., 2021). Moreover, emissions from SMR methods can be reduced with the use of carbon capture and storage (CCS). However, this involves higher initial capital for CCS infrastructure (Wulf & Kaltschmitt, 2018). Therefore, the choice of technology may depend on various factors that define their costs and benefits. A summary of potential hydrogen production and transport methods is given in Table 2.

Table 2: Hydrogen production methods

Supply chain stage	Technology	Feedstock	Pros	Cons	Reference
Production	Steam Methane Reforming (SMR)	Natural gas, biogas	Commercially available, higher energy efficiency	Lower operational efficiency, highly energy-intensive	(Kim et al., 2014; Wanniarachchi et al., 2022)
	Gasification	Coal, biomass	Abundant feedstock, low cost	High reactor cost, lower system efficiencies	(Wanniarachchi et al., 2022)
	Water electrolysis – Proton exchange membrane (PEM)	Electricity (grid, solar, wind, other renewable), water	Higher efficiency, simple, compact, easy start-up, lower emissions during hydrogen production	Limited use due to prohibitive cost	(Wanniarachchi et al., 2022)
	Water electrolysis – Alkaline electrolyser	Electricity (grid, solar, wind, other renewable), water	Well-established, lower emissions during hydrogen production	Consumes more space	(Kim et al., 2014; Najdi et al., 2016)

Distribution	Pipelines	N/A	Least expensive mode	Higher investment costs, safety issues, environmental impacts	(International Energy Agency, 2012)
	High-pressure tube-trailers	N/A	Lower investment costs	Supply continuity and reliability may affect by uncertainties in road conditions, limited load capacity	(Cheng & Graham, 2009; Fonseca et al., 2008; Mintz et al., 2006)

Renewable Diesel and Diesel Vehicles

Renewable diesel is a cleaner fuel which can be directly used in an internal combustion engine without a modification since it is chemically identical to petroleum-derived fuels (Alternative Fuel Data Center, 2022; Bezergianni & Dimitriadis, 2013). Renewable diesel is a second-generation biofuel produced to overcome the limitations of first-generation fuels. Renewable diesel, also known as green fuel or drop-in biofuel, can be produced from various biomass sources via biological, thermal, or chemical processes.

Compared to bio-diesel, renewable diesel has a higher energy content, lower viscosity, zero sulphur, and involves flexible production processes, which produce fuels that meet fossil fuel specifications (Larnaudie et al., 2020; Ogunkoya et al., 2015). The major difference between biodiesel and renewable diesel is their production process, where biodiesel is produced from transesterification, and renewable diesel is often produced from catalytic hydro-processing of vegetable oils and fats (Bezergianni & Dimitriadis, 2013). In addition to hydro-processing, there are several other renewable diesel production methods (Alternative Fuel Data Center, 2022). Deoxygenation is another approach in which renewable diesel is produced by converting feedstock such as fatty acids into straight-chain n-alkanes through deoxygenation. Produced fuel is further upgraded to meet the ASTM D975 specifications for petroleum (Alternative Fuel Data Center, 2022; Larnaudie et al., 2020; Van Gerpen & He, 2014). Other methods are gasification, pyrolysis, and other thermo and biochemical processes (Alternative Fuel Data Center, 2022)(Chia et al., 2022). Table 3 provides a summary of renewable diesel production methods.

Table 3: Renewable diesel production methods

Production Method	*Description*	*Feedstock*	*Pros*	*Cons*	*Reference*
Catalytic hydro-treating	Reacting feedstock with hydrogen at high temperature and pressure with a catalyst	Vegetable oil, cashew nutshell	No-by products, low sulphur in fuel	May cause a shortage of edible oils, lack of sufficient feedstock when using edible oils	(Alternative Fuel Data Center, 2022; Larnaudie et al., 2020)
Pyrolysis (Slow/ fast/ flash)	Chemically decompose organic matter at high temperature in the absence of oxygen	Organic matter	Feedstock pre-treatment is not required	Energy-intensive	(Alternative Fuel Data Center, 2022; Chia et al., 2022; Larnaudie et al., 2020)
Gasification	Biomass is thermally converted syngas, which is catalytically converted to fuel	Biomass-derived syngas	Higher yield	Energy-intensive	(Alternative Fuel Data Center, 2022; Jones et al., 2009)
Biological sugar upgrading	Biochemical deconstruction, with adding organisms to convert sugars to hydrocarbons	N/A	The lignocellulosic feedstock does not compete with food production or animal feed, The lignocellulosic feedstock is abundantly available	Lower product yield	(Alternative Fuel Data Center, 2022; Larnaudie et al., 2020)

The table shows that the commercial method of renewable diesel production is hydro-treating/ processing (Alternative Fuel Data Center, 2022). However, hydro-treating is highly energy-intensive. According to a study by Xu et al. (2022), renewable diesel production with hydro-processing has been found to be more emission-intensive than biodiesel production with oil-seed pathways. However, biodiesel production with high free fatty acid feedstock such as tallow was found to be higher in GHG emissions than renewable diesel production due to energy intensiveness during pre-treatment (Xu et al., 2022). Moreover, methods that use edible oils, such as vegetable oil, face the constraint of lack of abundant feedstock (Alternative Fuel Data Center, 2022; Larnaudie et al., 2020). Moreover, certain methods such as pyrolysis and gasification are highly energy intensive. Therefore, depending on the energy source used, such methods could emit higher upstream GHG volumes.

As discussed above, there are multiple renewable diesel production methods, each with its advantages and disadvantages. Therefore, systematic and informed decisions need to be made with regard to investments in these novel bio-fuels. Decisions should be made considering the technical feasibility, economic viability, and environmental feasibility of the renewable diesel production routes. In addition, societal acceptance is also an important factor to be considered (Karunathilake et al., 2020). Several studies have conducted techno-economic and environmental performance assessments of renewable diesel. However, most studies are limited to assessing the triple bottom line (economic, environmental, and social) impacts during the operational stage. However, a product's or process's true costs and benefits can only be determined when the overall life cycle is considered (Di Lullo et al., 2021). There are few studies that have conducted life cycle assessments on different renewable diesel production pathways (Gong & You, 2017; Huo et al., 2011; Larnaudie et al., 2020; Xu et al., 2022). However, the literature lacks life cycle analysis-based real-world data on renewable diesel supply chain routes (Xu et al., 2022). Life cycle cost and life cycle assessment tools are commonly used triple bottom line performance evaluation tools (Kakodkar et al., 2022; Liang et al., 2019). Such comprehensive tools allow for holistic and informed decision-making to determine the true benefits and cost of an investment.

Renewable diesel is chemically identical to fossil-based diesel. Thus, it is compatible with the engine and existing infrastructure. Therefore, investments for modifications and additional infrastructure are avoided using renewable diesel (Alternative Fuel Data Center, 2022). Moreover, the renewable diesel production process is very flexible. Hence, it can be produced domestically with multiple feedstock types such as animal fats, inedible corn oil, cooking oil etc. (Diamond Green Diesel, 2020). This increases energy security (Alternative Fuel Data Center, 2022). Transport sector emissions are major contributors to atmospheric GHG emission levels. The lower emission intensity of renewable diesel will create a way forward for sustainable transportation (Singh et al., 2018).

As per the studies, the major challenge of using renewable diesel is its high cost. However, the economic performance can be improved by process yields. Yet it will not be sufficient to gain a competitive position in the fuel market. This can be achieved only via the reduction in capital costs through technological advances (Larnaudie et al., 2020). Moreover, in addition to cost improvements, policies, regulations, and government incentives are essential in promoting renewable diesel use. For example, the 19.3% GHG emission reduction mandate for diesel fuel promotes alternative low-carbon fuel use. Moreover, standards such as clean fuel standards, low-carbon fuel standards, carbon credits and pricing provide regulations to reduce carbon intensity (Diamond Green Diesel, 2020; Dyer et al., 2021; Government of Canada, 2016). As of August 2022, the City of Vancouver's current practice is utilizing renewable diesel for their heavy-duty equipment trucks.

A summary of different vehicle technologies (electric, fuel cell, and renewable diesel) is provided in Table 4.

Table 4: Vehicle technology comparison

	Hydrogen Fuel Cell Vehicle	Electric Vehicle	Renewable Diesel Vehicle
Fuel	Hydrogen	Electricity	Renewable diesel
Refuelling time	10-20 mins	1-8 hrs	10-20 mins
Range per refill	1200 km	200-800 km	1000-2000 km
Well-to-Tank efficiency	50%	90-95% (wind, solar) 30-40% (coal, crude oil)	-
Tank-to-Wheel efficiency	25-35%	50-80%	10-25%
Key components	Battery (auxiliary) Battery pack DC/DC converter Fuel filler Electric traction motor (FCEV) Power electronics controller (FCEV) Thermal system (cooling) (FCEV) Transmission (FCEV) Fuel cell stack Hydrogen fuel tank Exhaust system for water	Battery (all-electric auxiliary) Traction battery pack DC/DC converter Charge port Electric traction motor Power electronics controller Thermal system (cooling) Transmission (electric) Onboard charger	Battery Diesel exhaust filler Diesel exhaust fluid tank Fuel filler IC engine (compression-ignited) Electronic control module Fuel line Transmission Fuel pump Fuel tank Aftertreatment system
Advantages	Zero GHG emissions at tailpipe Short refuelling time	Zero GHG emissions at tailpipe	Short refuelling time Use of renewable resources for fuel production
Disadvantages	Limited infrastructure Novel technology	Shorter vehicle range Prolonged recharging time Replacement of battery pack	GHG emissions at tailpipe

Methodology

The objective of this study is to conduct a comprehensive life cycle assessment (LCA) to compare the environmental impacts of alternative fueled options for heavy-duty freight and equipment vehicles. Accordingly, the LCA for this study was carried out based on ISO 14040 (2006), environmental management- Life cycle assessment- Principles and framework. The analysis comprised four main steps, namely, goal and scope definition, inventory analysis, impact assessment, and interpretation of results (The International Standards Organisation, 2006). During the goal and scope definition stage, the product under consideration is defined and described while specifying the study's purpose and scope. Next, the inventory analysis identifies and quantifies the amounts of energy and material utilized and the environmental releases during each life cycle process. Finally, the impact assessment evaluates the potential human and ecological impacts, whereas the results generated will be assessed and discussed in the interpretation stage.

The LCA for this study is conducted under two phases considering the fuel supply chain emissions and vehicular emissions separately. Figure 5 different life cycle processes of a fuel and vehicle.

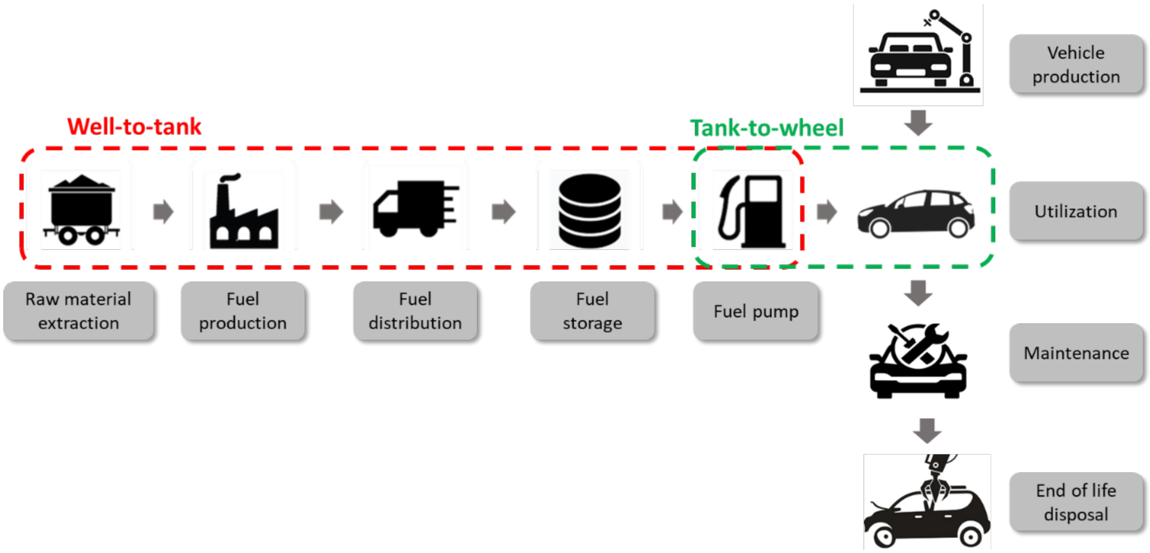


Figure 5: Fuel and vehicle life cycle processes

Phase 1: Fuel Supply Chain LCA

The fuel’s life cycle impacts are assessed in the first phase, whereas the vehicle’s life cycle impacts are assessed in the second phase. Different approaches could be used to conduct an LCA for a fuel supply chain as the following explains

- Well-to-tank approach: assesses the impacts of the fuel supply chain from raw material extraction to producing the fuel and delivering it to the refuelling station
- Tank-to-wheel approach: assesses the emissions from the fuel while being used in the vehicle
- Well-to-wheel approach: the combination of the above two processes

In this study, a well-to-wheel life cycle approach is used to assess the life cycle impacts of each fuel supply chain considering their feedstock extraction, fuel production, distribution, and emissions during the usage of fuel in the vehicle. Accordingly, LCAs are conducted on the three selected fuels: electricity, hydrogen, and renewable diesel.

Electricity LCA: British Columbia's electricity grid composition is used to assess the fuel supply chain impacts. Moreover, Alberta's electricity production and distribution impacts will be assessed and compared against that of BC's grid electricity. In this case, grid electricity mix of Alberta was selected as a different scenario to explore the impacts of a grid which is highly dependant on fossil fuels in contrast to BC's grid which is mainly dependant on hydro power.

Hydrogen LCA: Different pathways are used to produce and distribute hydrogen. Accordingly, different pathway scenarios are defined considering hydrogen production methods such as natural gas reforming (with and without carbon capturing), coal gasification (with and without carbon capturing), and water electrolysis (electricity from BC Grid, AB Grid, and solar power). Moreover, the emissions of delivering gaseous hydrogen from the production plant to the refuelling station are assessed and compared against delivering hydrogen in liquid state.

Renewable Diesel LCA: A hydrotreating and isomerization process along with a pyrolysis process is considered for producing renewable diesel along with its life cycle impacts. Different feedstocks such as forest residue, soybeans, and corn stover are considered for the analysis. Moreover, the impacts of delivering the fuel from the production plant to the refuelling station are considered.

Table 5 summarizes different fuel supply chain scenarios assessed and compared in this study.

Table 5: Fuel supply chain scenarios

Scenario	Code	Description
1	E_BC	British Columbia grid electricity production and transmission
2	E_AB	Alberta grid electricity production and transmission
3	H_E.bc	Hydrogen production from electrolysis (BC grid electricity)
4	H_E.ab	Hydrogen production from electrolysis (AB grid electricity)
5	H_E.se	Hydrogen production from electrolysis (solar-powered electricity)

6	H_G	Hydrogen production from gasification without carbon capturing
7	H_G.cc	Hydrogen production from gasification with carbon capturing
8	H_R	Hydrogen production from NG reforming with carbon capturing
9	H_R.cc	Hydrogen production from NG reforming without carbon capturing
10	RD_FR	Renewable diesel production from forest residue
11	RD_SB	Renewable diesel production from soybeans
12	RD_CS	Renewable diesel production from corn stover

Following assumptions about fuel and feedstock transportation were made during the fuel supply chain assessment.

- A 8% energy loss is expected during electricity transmission (The World Bank Data, 2022).
- Coal for hydrogen production via gasification is transported from Alberta over 1000 km via rail and 50 km via heavy-duty trucks.
- Natural gas for hydrogen production via steam reforming is transported from Alberta over 800 km via pipelines.
- Hydrogen refuelling station is located 50km from the hydrogen production plant (for all hydrogen production methods.
- Renewable diesel is produced in California and is transported via rail (1750km) and heavy-duty trucks (50km) to a bulk terminal and another 100km via heavy-duty trucks to the refuelling station.
- Only the operational impacts during the fuel production process are considered. The impacts of developing, maintaining, and disposing of infrastructure are not considered.

The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) Model (2021) by Argonne National Laboratory is used to conduct the life cycle assessment of the fuel supply chain. The detailed GREET pathways developed for this analysis is provided in Appendix B.

Phase 2: Vehicle LCA

Under the second phase of this study, an LCA is conducted on the components of each vehicle type, namely, heavy-duty electric truck, hydrogen fuel cell truck, and renewable diesel truck. Accordingly, for this study, the LCA of the vehicle is conducted for different components in the drivetrain of these vehicles. Hence, the LCA assessment is conducted by considering a Class 8 heavy-duty truck with a Gross Vehicle Weight Rating (GVWR) of over 33,000 pounds operated over 400,000 km during its service life with a payload of 17 tons. In addition, an inventory of components developed for heavy-duty vehicles: short-haul trucks on GREET Model 2021 was used for this analysis.

Since HFCVs and EVs are zero-emission vehicles, no tailpipe emissions were considered for these two vehicle technologies. Table 6 provides tailpipe emissions considered for the truck operated using renewable diesel.

Table 6: Tailpipe emissions from heavy-duty renewable diesel truck

Emission Type	Quantity
VOC	51.40 ug/m
CO	2.00 mg/m
NOx	1.30 mg/m
PM10	2.88 ug/m
PM2.5	2.65 ug/m
CH4	11.71 ug/m
N2O	1.79 ug/m
BC	0.32 ug/m
POC	0.56 ug/m

The following fuel consumption values were assumed for each of the vehicle types (Wang, 2001)

- Electric heavy-duty truck – 0.72 km/kWh (5.06 kJ/m)
- Fuel cell heavy-duty truck – 9.92 km/kg of H (12.10 kJ/m)
- Renewable diesel heavy-duty truck – 7 km/l of RD (19.06 kJ/m)

Findings

This section provides detailed information regarding the results obtained from the fuel LCA and the vehicle component LCA. Moreover, it presents an overall comparison of using electricity, hydrogen, and renewable diesel for a Class 8 heavy-duty truck.

Fuel Supply Chain Assessment

Electricity Supply Chain LCA Results

The grid GHG emissions of British Columbia and Alberta electric grids were assessed in this study. Figure 6 shows the GHG emission results obtained for the BC and AB grid electricity production and distribution (detailed results provided in Appendix C). The BC grid and AB grid emissions stood at 15.79 and 875.50 $gCO_2eq.$ per kWh of electricity. Comparatively, the AB grid emits 55 times the GHG emissions of the BC grid. This is mainly because BC produces its electricity from green and renewable sources such as hydropower, whereas AB is highly dependent on coal and natural gas for electricity production.

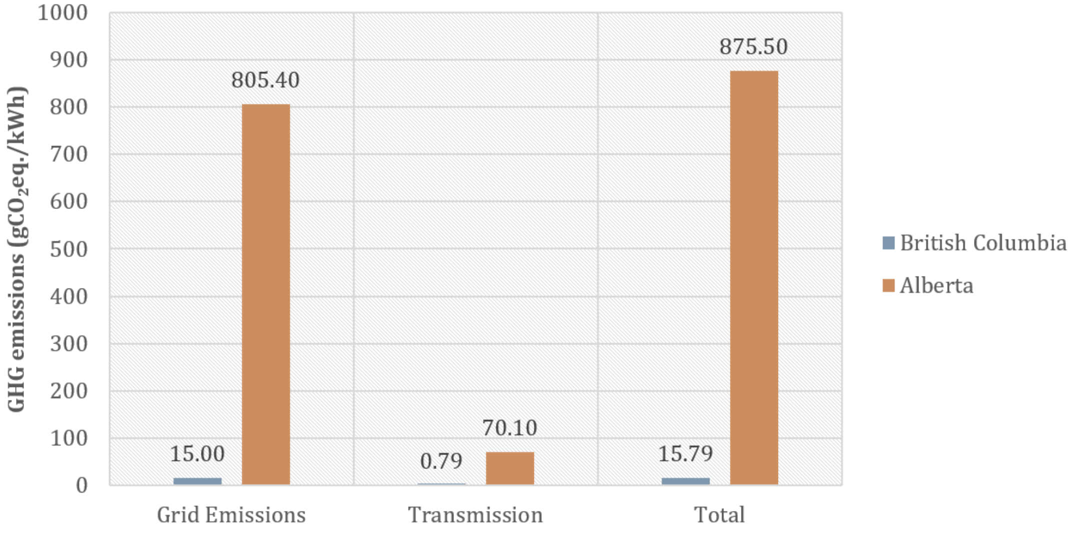


Figure 6: GHG emissions per kWh of electricity

Hydrogen Fuel LCA Results

The life cycle impacts during the hydrogen fuel production and distribution stages were evaluated separately in this study. Figure 7 shows the GHG emissions for different hydrogen production techniques and the total emissions of producing and distributing hydrogen in gaseous form. Appendix D provides the detailed results obtained from the GREET analysis.

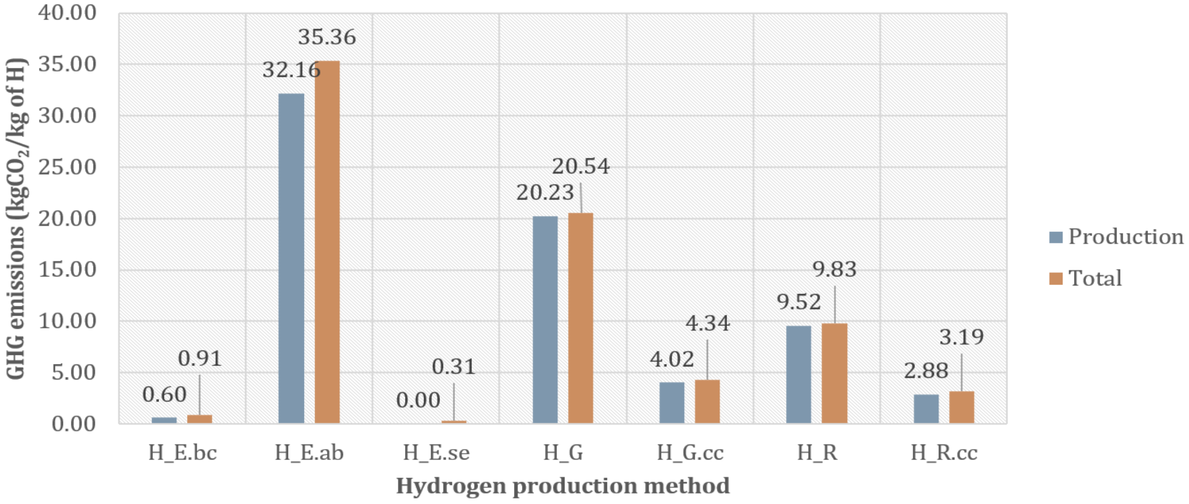


Figure 7: GHG emissions per kg of hydrogen

The lowest emissions were observed when hydrogen was produced from electrolysis from solar power, whereas the highest emissions were observed when hydrogen was produced from electrolysis from AB grid electricity. Since solar power is green and renewable, zero emissions are expected during electricity generation; hence, the production process emissions are negligible. On the other hand, hydrogen produced in AB from electrolysis has approximately 50 times the GHG emissions of hydrogen produced in BC from electrolysis, mainly as a result of the difference in energy sources used in each province to generate electricity. Moreover, when the transportation of the fuel is added to the production process, GHG emissions from BC and AB produced hydrogen (from electrolysis) total to 0.91 and 35.36 kgCO_2eq. per kg of hydrogen. This shows that the emissions of hydrogen production from electrolysis are highly dependent on the energy source for electricity production.

The second highest GHG emissions were recorded when hydrogen was produced via coal gasification. This was around 20.5 kgCO_2eq./kg of H. However, when the gasification plant was accompanied by a carbon capturing and storage system to capture the carbon while producing hydrogen, the emissions dropped by approximately 79%. Similarly, GHG emissions during hydrogen production via natural gas reforming without carbon capturing and with carbon capturing stood at 9.83 and 3.19 kgCO_2eq./kg of H, respectively. This is approximately a 68% drop in GHG emissions due to using carbon sequestration. Hence, significant GHG emission reductions could be attained by coupling hydrogen production via gasification and steam reforming along with carbon sequestration.

GHG emissions during compressing, transporting, and storing hydrogen amount to approximately 0.31 kgCO_2eq./kg of H. This is approximately 30% of emissions if hydrogen is produced via electrolysis. However, this is approximately 7% of emissions if hydrogen production via gasification with carbon capturing is considered. The GHG emissions during transportation of hydrogen in gaseous form are around 0.26 kgCO_2eq./kg of H compared to liquid form, which is around 0.027 kgCO_2eq./kg of H. The higher emissions during gaseous hydrogen transportation are a result of the low density of compressed hydrogen compared to liquid hydrogen. The greater density of liquid hydrogen allows a larger amount of hydrogen to be transported in the confined space, which is advantageous. However, a vast amount of energy is required to convert the produced hydrogen gas to liquid state. Hence, for practical application, gaseous hydrogen distribution is efficient for shorter transportation distances, whereas liquid hydrogen distribution is efficient when hydrogen needs to be distributed over greater distances. Accordingly, the best hydrogen distribution method should be decided based on the amount of hydrogen transported and the transportation distance.

Renewable Diesel LCA Results

Figure 8 provides the GHG emission per litre of renewable diesel results obtained for different feedstock types. Results for fuel production and total emissions (production and transportation) are shown separately. Appendix E provides the detailed results obtained from the GREET analysis.

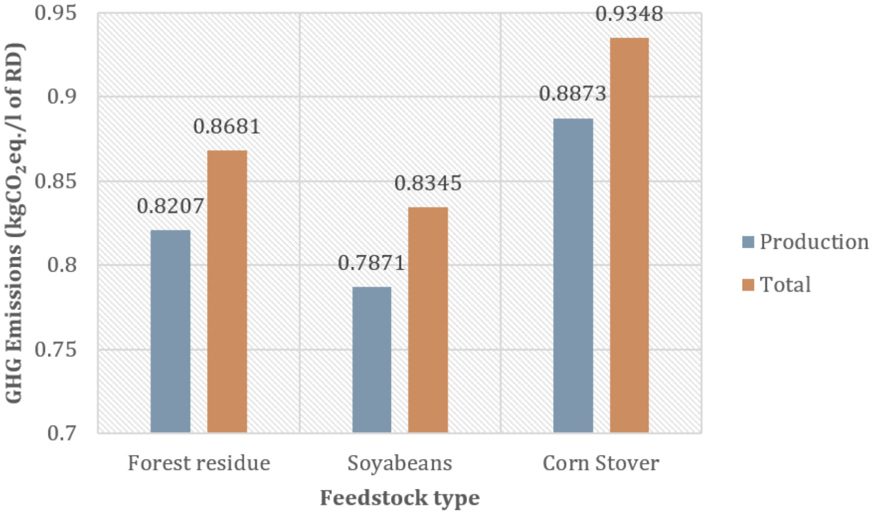
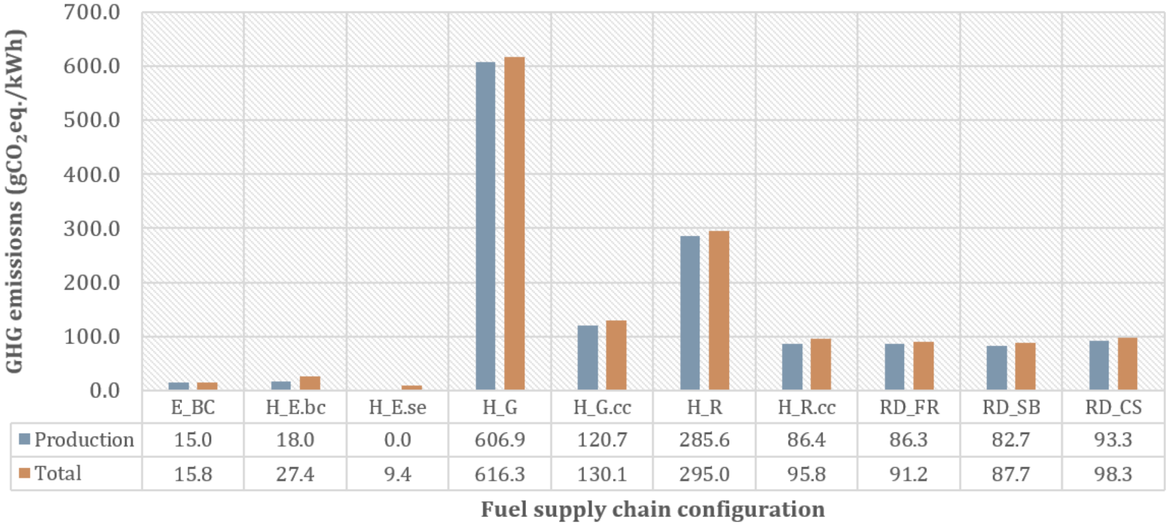


Figure 8: GHG emissions per l of renewable diesel

Comparatively, there is slight variation among the GHG emissions from the three different feedstock types. However, renewable diesel production from soybeans has the least GHG emissions of 0.83 kgCO$_2$eq./l of RD, and renewable diesel production from corn stover has the highest GHG emissions of 0.93 kgCO$_2$eq./l of RD. On average, approximately 6% of the production emissions are required to transport the produced renewable diesel from the production plant to the refuelling location.

Fuel Supply Chain LCA Summary

Figure 9 summarizes GHG emissions per kWh of all the fuel supply chain scenarios considered in this study. Only the fuel supply chains related to British Columbia are presented in the figure below.



	E_BC	H_E.bc	H_E.se	H_G	H_G.cc	H_R	H_R.cc	RD_FR	RD_SB	RD_CS
■ Production	15.0	18.0	0.0	606.9	120.7	285.6	86.4	86.3	82.7	93.3
■ Total	15.8	27.4	9.4	616.3	130.1	295.0	95.8	91.2	87.7	98.3

Figure 9: GHG emissions per kWh of fuel

Hydrogen production from coal gasification without carbon capturing and hydrogen production from natural gas reforming without carbon capturing are the fuel production methods with the highest GHG emissions. However, all other methods have an approximate average of 100 gCO2eq./kWh apart from BC grid electricity and electrolysis methods which have emissions lesser than 30 gCO2eq./kWh.

Vehicle Embodied Emissions

Figure 10, Figure 11, and Figure 12 show the GHG emissions and embodied energy of different components of an electric truck, hydrogen fuel cell truck, and diesel truck, respectively. The varying components of the vehicles are highlighted in Table 4. The detailed analysis results are provided under Appendix F. For the heavy-duty electric truck, the onboard lithium-ion battery accounts for approximately 80% of the GHG emissions from all the components. As a result, electric trucks have the highest embodied emissions which total up to 109 tCO_2eq. Comparatively, hydrogen fuel cell trucks have less embodied emissions (~40 $tCO_2eq.$). Conventional diesel trucks have the least embodied emissions of ~27 $tCO_2eq.$ out of the three vehicle types considered in this study. Despite, BC's electric supply chain showing the least emissions per kWh (as in Figure 9), significant embodied emissions are observed in the heavy-duty electric truck.

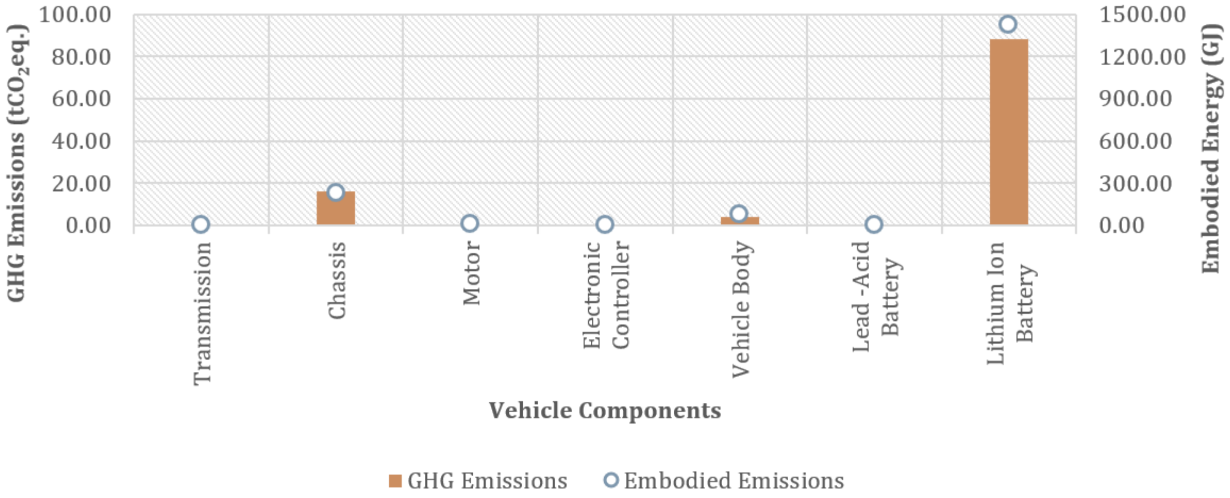


Figure 10: GHG emissions and embodied energy of components of an electric truck

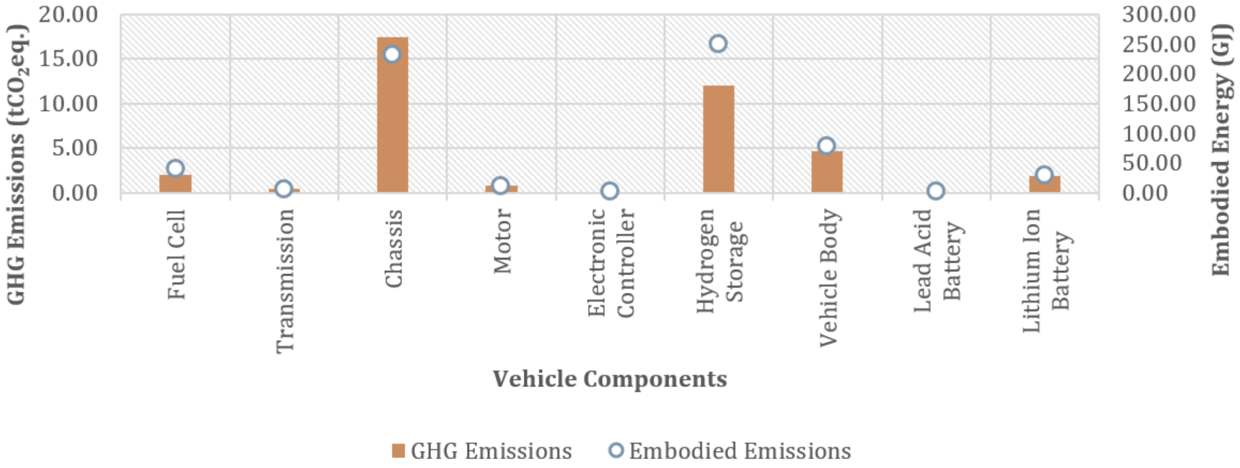


Figure 11: GHG emissions and embodied energy of components of a fuel cell truck

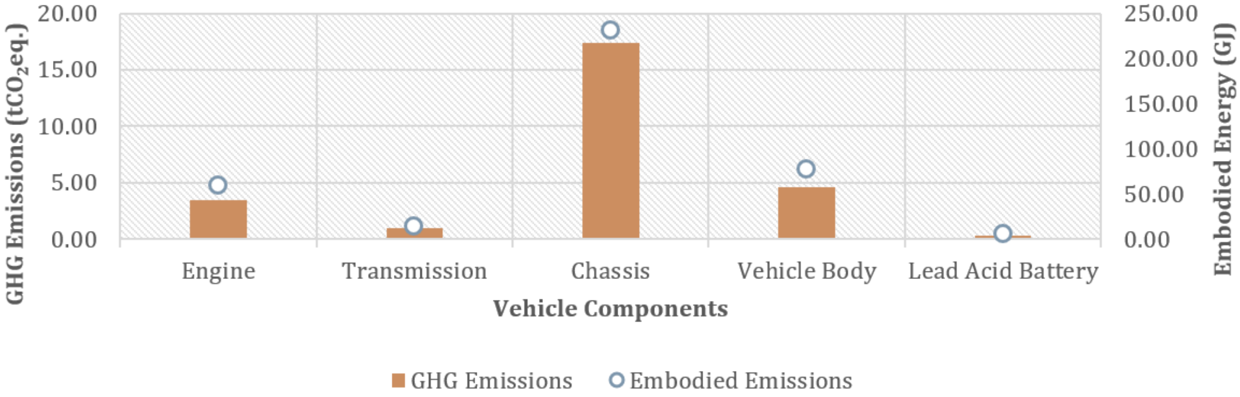


Figure 12: GHG emissions and embodied energy of components of a diesel vehicle

Overall Result Comparison

Figure 13 shows the well-to-wheel (WtW) emissions and the overall life cycle emissions (WtW + vehicle components) for different vehicle options under different fuel supply chains. Here, well-to-wheel emissions include the emissions during the fuel production and transportation/distribution stages, along with the emissions during operating the vehicle. The overall emissions include well-to-wheel emissions as well as vehicular component emissions. Accordingly, the emissions from the vehicle components were totalled and equally distributed over the distance travelled by the truck over its lifespan (400,000km) to determine the contribution from vehicle components.

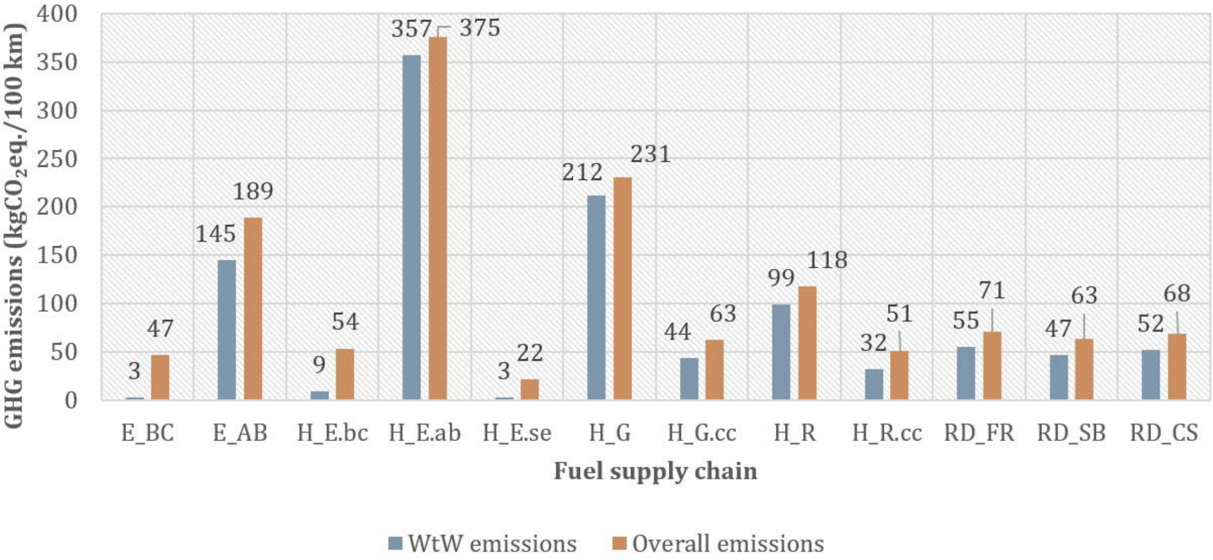


Figure 13: Overall GHG emissions for different vehicles for different fuel supply chains

As shown in the results, despite BC's grid electricity having the least well-to-wheel emissions (~3kgCO_2eq./100 km), when the vehicle embodied emissions are added to the fuel life cycle emissions, the overall emissions increase up to ~47kgCO_2eq./100km. Comparatively, the overall emissions of a hydrogen fuel cell heavy-duty truck (along with fuel emissions) is approximately ~54kgCO_2eq./100km. Moreover, the overall emissions of the renewable diesel options averages around ~68kgCO_2eq./100km.

Summary

The transformation from conventional diesel to alternative fuels such as electricity, hydrogen, and renewable diesel has a great potential to reduce GHG emissions from the heavy-duty freight and equipment transportation sector. Accordingly, this study was formulated with the primary goal of assessing the GHG emissions from different fuel supply chain options for these alternative fuels along with the emissions of these alternative fueled vehicles. Initially, existing literature was reviewed to explore the current status of using alternative fuels for heavy-duty trucks. However, despite all these fuels having great potential to reduce emissions from the heavy-duty transport sector, they are still at their initial stages of being implemented for heavy-duty trucks. Hence, significant technological, economic, and social challenges are expected during their practical implementation. Moreover, different fuel supply chain options were reviewed to identify different fuel production methods and feedstock types.

Based on the identified supply chain configurations, 12 different scenarios were defined for further analysis. This involved two electricity grid types, seven hydrogen scenarios, and three renewable diesel production scenarios. Compared to all fuel options, electricity from BC's grid has the least GHG emissions (15.8 gCO_2eq./kWh) per unit of fuel. Production of hydrogen from electrolysis from electricity from BC's grid seems to be the eco-friendliest method of hydrogen production which would release approximately 0.61 kgCO_2eq./kg H. Hydrogen production methods such as natural gas reforming and coal gasification have higher environmental burdens, approximately by 9.5 and 20 kgCO_2eq./kg H. However, these emissions could be reduced by approximately 70-80% by using carbon sequestration. Different methods used to produce renewable diesel have similar environmental emissions and average around 0.83 kgCO_2eq./l RD. Nevertheless, renewable diesel production from soybeans has the lowest emissions of 0.79 kgCO_2eq./l RD.

When analyzing the emissions of different components of the vehicles, approximately 80% of the emissions of the electric truck are as a result of the lithium-ion batteries used onboard of the vehicle. In total, the electric truck, the fuel cell truck, and the diesel truck had embodied emissions of 1750, 650, and 400 tCO_2eq. respectively. The electric and fuel cell trucks have higher embodied emissions than conventional diesel trucks due to having onboard lithium ion batteries and fuel cells. When fuel supply chain emissions are coupled with the vehicle operational emissions, yet again electric trucks have the least emissions. This is approximately 47 kgCO_2eq./100 km when electricity is supplied from the grid of BC. However, these values could be as high as 189 kgCO_2eq./100 km when the electricity sources are highly dependent on fossil

fuels. The well-to-wheel emissions of hydrogen trucks vary from 9-212 kgCO_2eq./100 km depending on the method of producing hydrogen. Least emissions are observed when hydrogen is produced via electrolysis, whereas the highest emissions are observed when hydrogen is produced via gasification. Nevertheless, lower well-to-wheel emissions (30-45 kgCO_2eq./100 km) are observed when hydrogen production via coal gasification or natural gas reforming with carbon capturing. In Alberta, the well-to-wheel emissions when hydrogen is produced via electrolysis is around 357 kgCO_2eq./100 km. Hence, for provinces like Alberta where fossil fuels are used to source electricity, the best option would be to go towards hydrogen production via natural gas steam reforming with carbon capturing and storage which will have well-to-wheel emissions of around 32 kgCO_2eq./100 km.

Moreover, the well-to-wheel emissions of both electric and hydrogen trucks predominantly depend on the well-to-tank emissions of the fuel (fuel production and distribution emissions) since no GHG emissions are expected during the operational phase of the vehicle. Contrastingly, renewable diesel trucks generate approximately 180 kgCO_2eq./100 km during operation of the vehicle. However, these emissions could be offset as biogenic CO_2 credits since renewable diesel is produced from plants and animal waste. Accordingly, the well-to-wheel emissions of a renewable diesel truck are approximately 50 kgCO_2eq./100 km. The embodied emission from the vehicle components could amount to 1-15% of the vehicle's well-to-wheel emissions for hydrogen and renewable diesel truck. However, this value is higher for electric trucks due to the higher embodied emissions of electric trucks and lower well-to-wheel emissions of electricity. Overall, most of these vehicles and fuels can reduce well-to-wheel emissions compared to conventional diesel trucks, which are around 100 kgCO_2eq./100 km. However, electric trucks that use electricity produced from fossil fuels and hydrogen trucks that use hydrogen produced from coal gasification and natural gas reforming (without carbon capturing) will have greater overall emissions compared to conventional diesel trucks. Based on the analysis conducted for this study, the least well-to-wheel emissions for each fuel supply chain (related to BC) are 3, 9, and 47 kgCO_2eq./100 km pertaining to electricity sourced from BC grid, hydrogen produced from electrolysis using BC grid electricity, and renewable diesel produced from soybeans respectively. Accordingly, the overall emissions (well-to-wheel emissions + vehicle embodied emissions) from the heavy-duty electric, fuel cell, and diesel trucks related to the aforementioned fuel supply chains are 47, 54, and 63 kgCO_2eq./100 km respectively.

Despite the great potential of reducing GHG emissions by transforming conventional diesel vehicles into alternative fuels many other aspects should be considered prior to mass-scale implementation of alternative fueled vehicles. This includes technical concerns such as the ability of electric trucks to generate enough power to operate the equipment in heavy-duty trucks. Moreover, despite electrolysis being the hydrogen production method with least emissions in BC, this method has a comparatively low energy conversion rate compared to hydrogen production via steam reforming. Furthermore, Canada's hydrogen refuelling infrastructure is still in its initial implementation stages, and would require vast investments in terms of infrastructure development for wide-scale implementation of heavy-duty fuel cell trucks. Finally, other concerns such as job creation/losses, availability of resources, reliability of the fuel supply chain, along with macro-environmental conditions such as government policies and rebates should be considered for the long-term, wide-scale implementation of alternative fueled heavy-duty vehicles.

Limitations of the Study

The following could be identified as limitations of the current study.

1. ***Results based on a particular case study:*** This study was conducted considering that the refuelling stations are located in Vancouver. Accordingly, the analyses were conducted predominantly assuming that the fuel is produced close to Vancouver or produced elsewhere and delivered to Vancouver. However, further analyses should be done to assess how the feedstock and fuel transportation/delivering impacts vary with different transportation distances.
2. ***Lack of life cycle data and uncertainty related to them:*** Results obtained from an LCA highly depend on the data used for the analysis. This study was conducted based on the life cycle data available in the GREET 2021 model. However, reasonable assumptions were made based on published literature in cases when relevant data was not available. Moreover, these data have a high degree of uncertainty. Hence, further studies should be conducted to assess how the ultimate results vary based on the uncertainty of life cycle data
3. ***Main focus on GHG emissions:*** This study predominantly focused on assessing the GHG emissions from the selected fuel supply chains and vehicles. However, to make more concise and informed decisions, many other aspects should be considered along with life cycle GHG emissions. These include economic aspects such as the cost of fuel and the cost of vehicles, other environmental attributes such as the impact on ecosystems and human health, and social aspects such as user perspectives on alternative fuels and vehicles.
4. ***Consideration of operational emissions:*** This study assessed the emissions during producing and delivering the fuel along with the emissions during the operation of the vehicle. Nevertheless, there could be substantial emissions during developing infrastructure to produce and deliver fuel which is not considered in this study.

Recommendations for Future Research

Based on the study conducted for this project, the following recommendations can be proposed for future research.

1. ***Develop of a framework to incorporate multiple decision criteria in best alternative fuel selection:*** The current study evaluates alternative fueled heavy-duty vehicles mainly on their life cycle GHG emissions. However, a framework should be developed to consider technical, economic, environmental, social, and macro-environmental aspects holistically when comparing these alternatives.
2. ***Incorporate variations and uncertainty into alternative evaluation process:*** Life cycle data and other parameters such as transportation distances and process efficiencies have a high degree of variations. Hence, further analysis should be conducted by incorporating these parameters in alternative evaluation.
3. ***Evaluate the impacts of supporting infrastructure:*** Despite the current study focusing on the operational phase emissions (emissions during production and distribution) of the fuel supply chain, significant emissions can be expected during developing underlying infrastructure which should be assessed in future studies.

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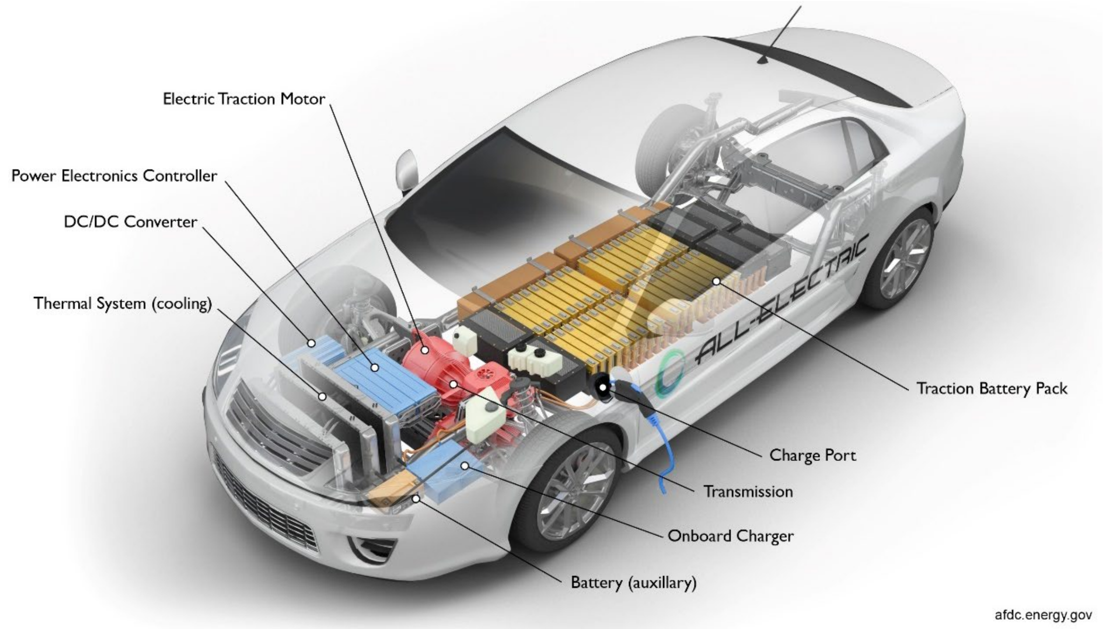
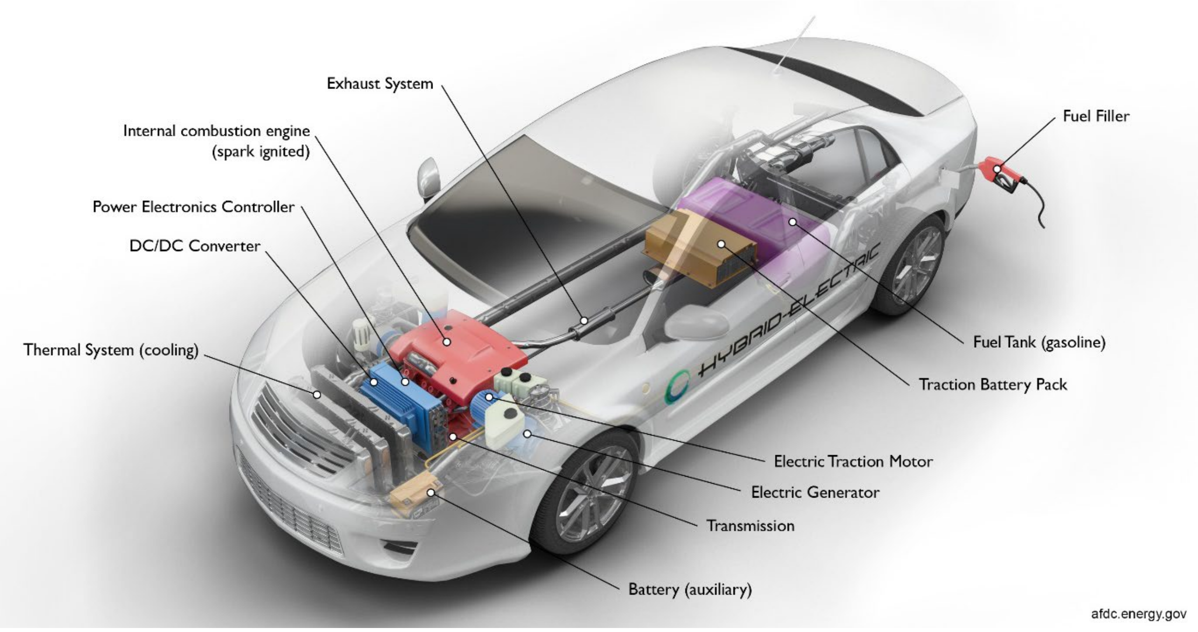
Appendices

Appendix A: Vehicle Technologies

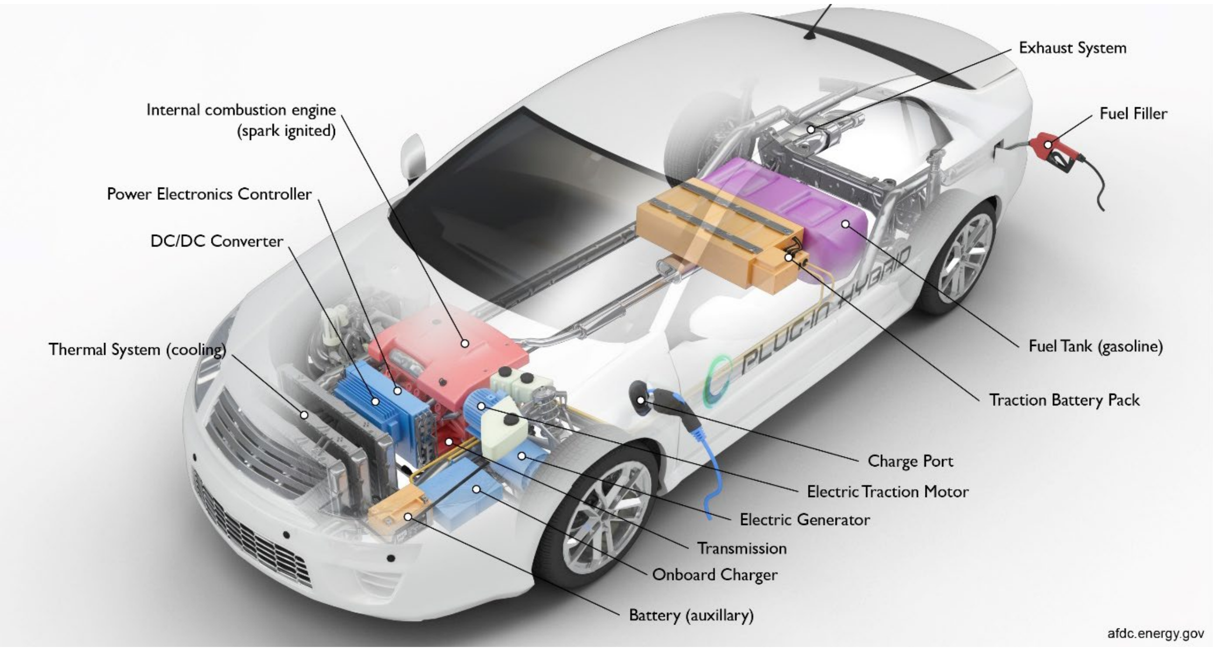
Battery Electric Vehicle *(image adopted from afdc.energy.gov)*



Hybrid Electric Vehicle *(image adopted from afdc.energy.gov)*



Plug-In Hybrid Vehicle *(image adopted from afdc.energy.gov)*



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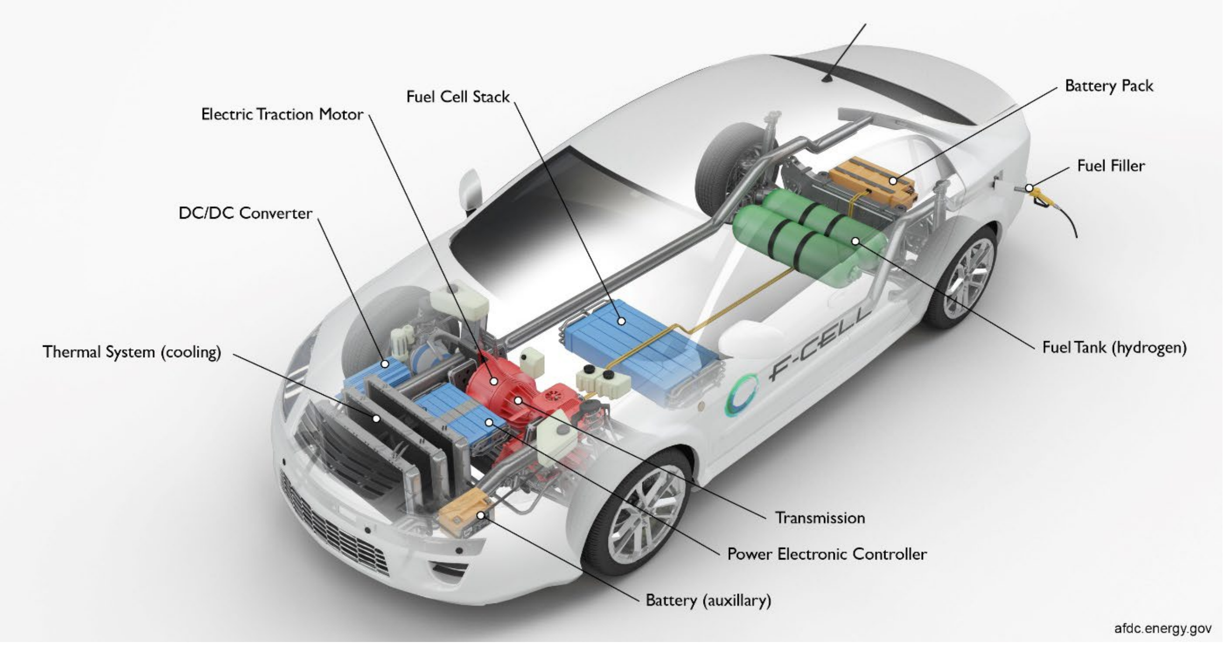
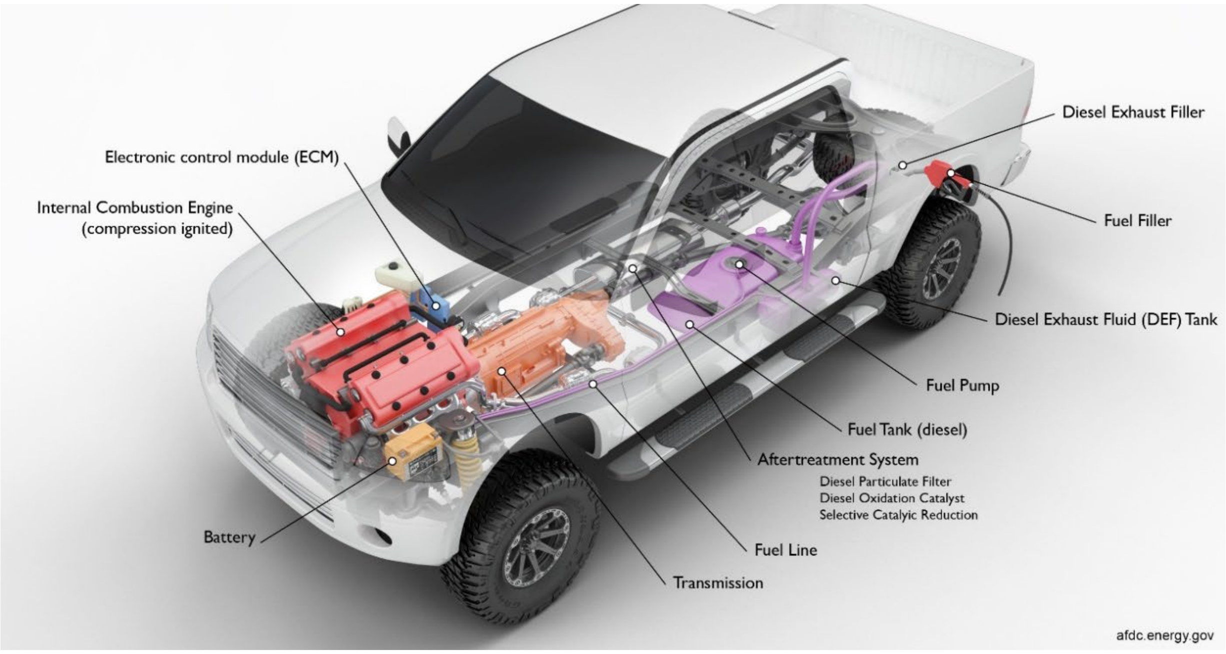
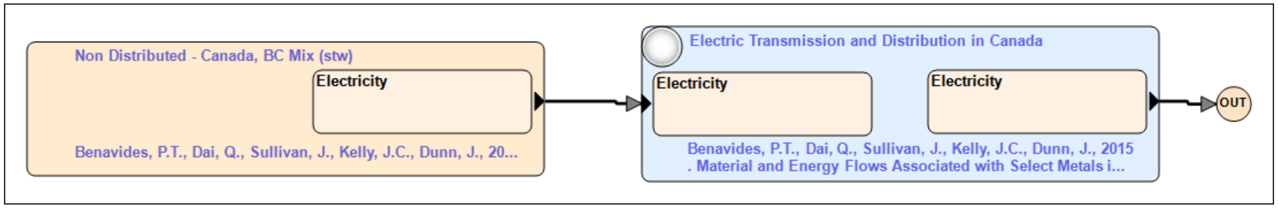


Diesel Vehicle *(image adopted from afdc.energy.gov)*

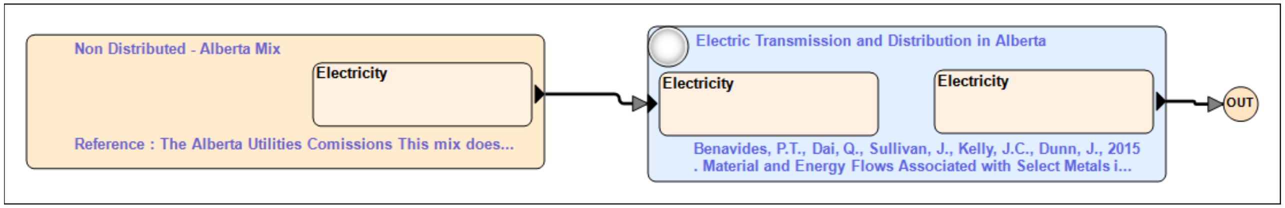


Appendix B: GREET Pathway Diagrams for Different Fuel Supply Chains

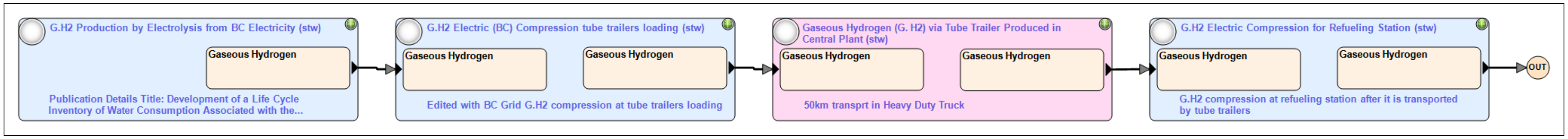
E_BC



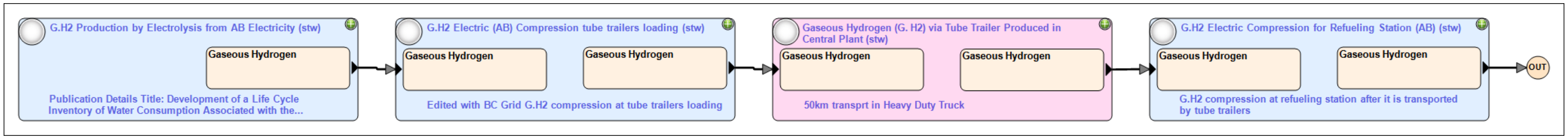
E_AB



H_E.bc



H_E.ab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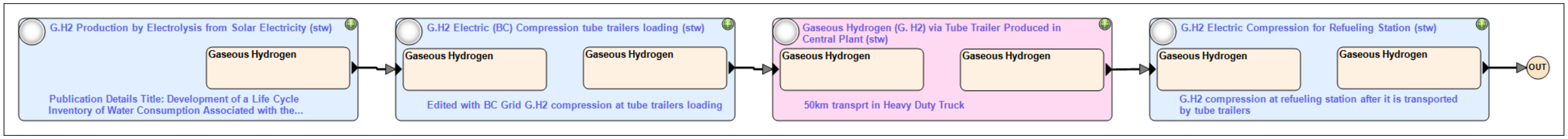
Gaseous Hydrogen
Publication Details Title: Development of a Life Cycle Inventory of Water Consumption Associated with the...
G.H2 Electric (AB) Compression tube trailers loading (stw)
Gaseous Hydrogen
Gaseous Hydrogen
Edited with BC Grid G.H2 compression at tube trailers loading
Gaseous Hydrogen (G. H2) via Tube Trailer Produced in Central Plant (stw)
Gaseous Hydrogen
Gaseous Hydrogen
50km transprt in Heavy Duty Truck
G.H2 Electric Compression for Refueling Station (AB) (stw)
Gaseous Hydrogen
Gaseous Hydrogen
G.H2 compression at refueling station after it is transported by tube trailers
OUT

H_E.se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Gaseous Hydrogen
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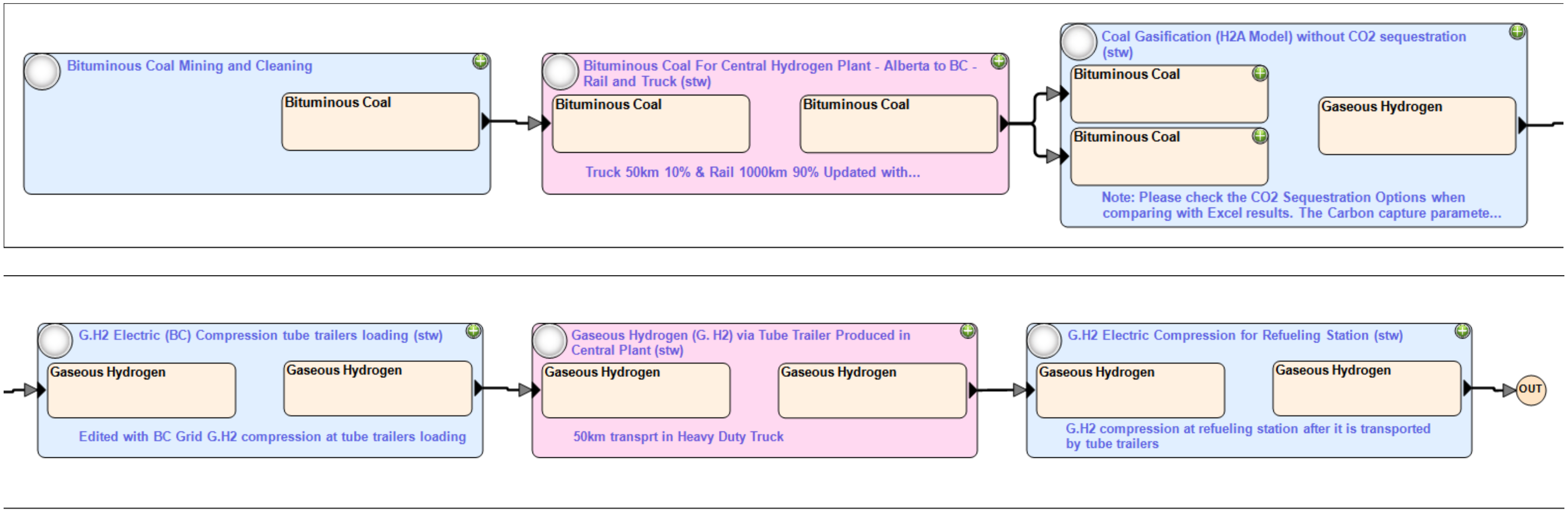
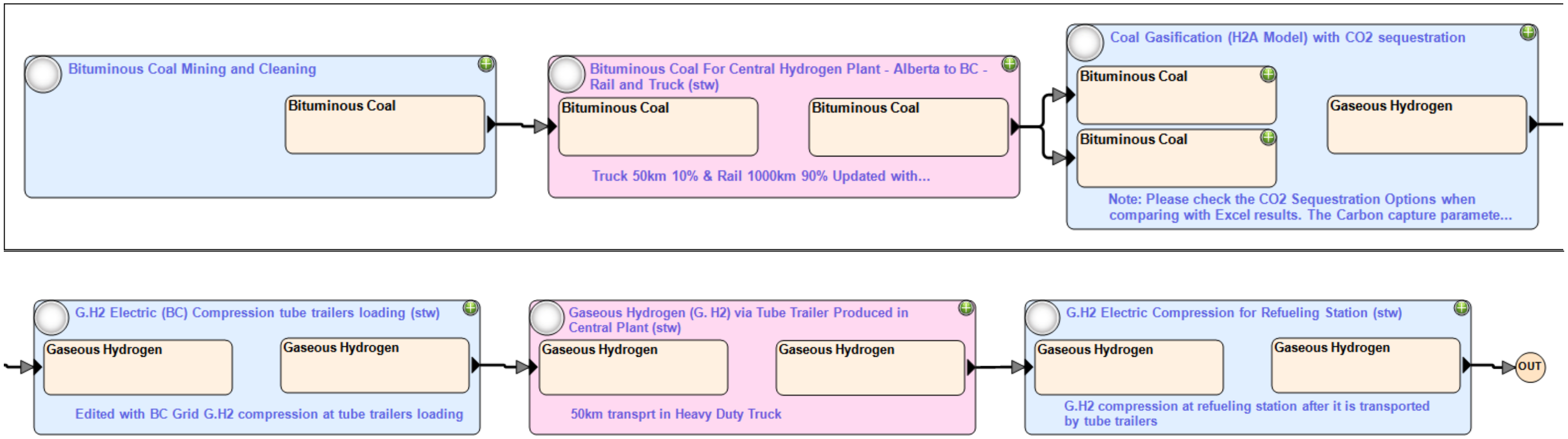
G.H2 Electric (BC) Compression tube trailers loading (stw)
Gaseous Hydrogen
Gaseous Hydrogen
Edited with BC Grid G.H2 compression at tube trailers loading
Gaseous Hydrogen (G. H2) via Tube Trailer Produced in Central Plant (stw)
Gaseous Hydrogen
Gaseous Hydrogen
50km transprt in Heavy Duty Truck
G.H2 Electric Compression for Refueling Station (stw)
Gaseous Hydrogen
Gaseous Hydrogen
G.H2 compression at refueling station after it is transported by tube trailers
OUT

H_G


Bituminous Coal Mining and Cleaning
Bituminous Coal
Bituminous Coal For Central Hydrogen Plant - Alberta to BC - Rail and Truck (stw)
Bituminous Coal
Bituminous Coal
Truck 50km 10% & Rail 1000km 90% Updated with...
Coal Gasification (H2A Model) without CO2 sequestration (stw)
Bituminous Coal
Bituminous Coal
Gaseous Hydrogen
Note: Please check the CO2 Sequestration Options when comparing with Excel results. The Carbon capture paramete...
G.H2 Electric (BC) Compression tube trailers loading (stw)
Gaseous Hydrogen
Gaseous Hydrogen
Edited with BC Grid G.H2 compression at tube trailers loading
Gaseous Hydrogen (G. H2) via Tube Trailer Produced in Central Plant (stw)
Gaseous Hydrogen
Gaseous Hydrogen
50km transprt in Heavy Duty Truck
G.H2 Electric Compression for Refueling Station (stw)
Gaseous Hydrogen
Gaseous Hydrogen
G.H2 compression at refueling station after it is transported by tube trailers
OUT

H_G.cc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Bituminous Coal For Central Hydrogen Plant - Alberta to BC - Rail and Truck (stw)
Bituminous Coal
Bituminous Coal
Truck 50km 10% & Rail 1000km 90% Updated with...
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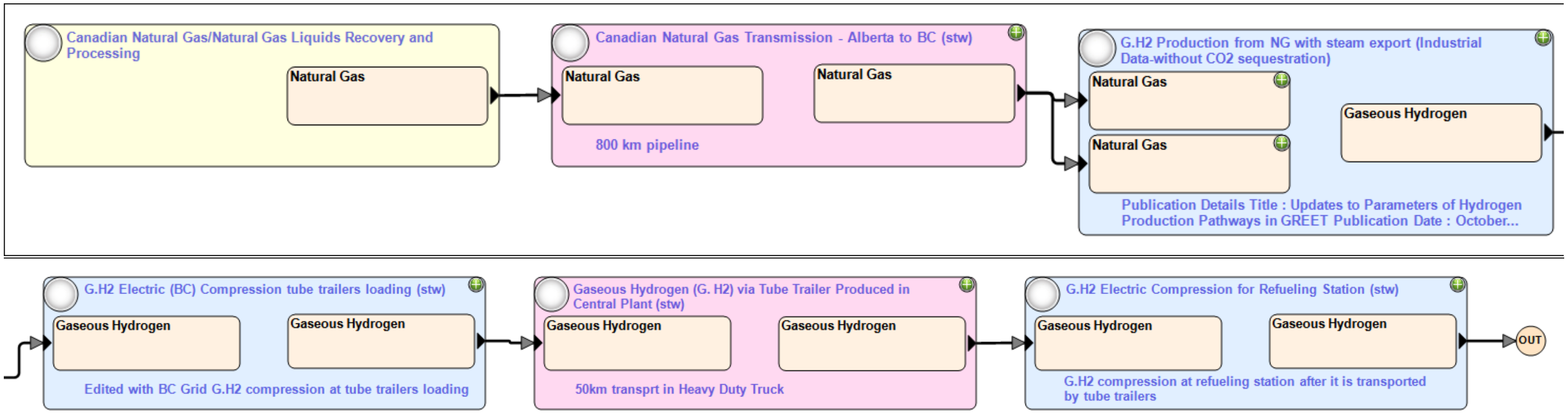
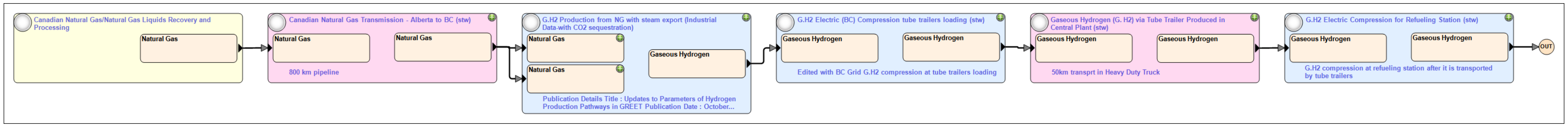
Bituminous Coal
Bituminous Coal
Gaseous Hydrogen
Note: Please check the CO2 Sequestration Options when comparing with Excel results. The Carbon capture paramete...
G.H2 Electric (BC) Compression tube trailers loading (stw)
Gaseous Hydrogen
Gaseous Hydrogen
Edited with BC Grid G.H2 compression at tube trailers loading
Gaseous Hydrogen (G. H2) via Tube Trailer Produced in Central Plant (stw)
Gaseous Hydrogen
Gaseous Hydrogen
50km transprt in Heavy Duty Truck
G.H2 Electric Compression for Refueling Station (stw)
Gaseous Hydrogen
Gaseous Hydrogen
G.H2 compression at refueling station after it is transported by tube trailers
OUT

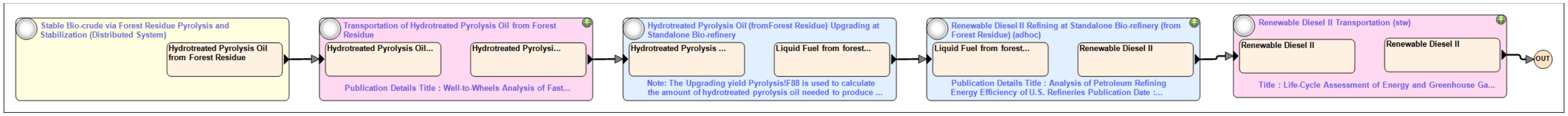
H_R


Canadian Natural Gas/Natural Gas Liquids Recovery and Processing
Natural Gas
Canadian Natural Gas Transmission - Alberta to BC (stw)
Natural Gas
Natural Gas
800 km pipeline
G.H2 Production from NG with steam export (Industrial Data-without CO2 sequestration)
Natural Gas
Natural Gas
Gaseous Hydrogen
Publication Details Title : Updates to Parameters of Hydrogen Production Pathways in GREET Publication Date : October...
G.H2 Electric (BC) Compression tube trailers loading (stw)
Gaseous Hydrogen
Gaseous Hydrogen
Edited with BC Grid G.H2 compression at tube trailers loading
Gaseous Hydrogen (G. H2) via Tube Trailer Produced in Central Plant (stw)
Gaseous Hydrogen
Gaseous Hydrogen
50km transprt in Heavy Duty Truck
G.H2 Electric Compression for Refueling Station (stw)
Gaseous Hydrogen
Gaseous Hydrogen
G.H2 compression at refueling station after it is transported by tube trailers
OUT

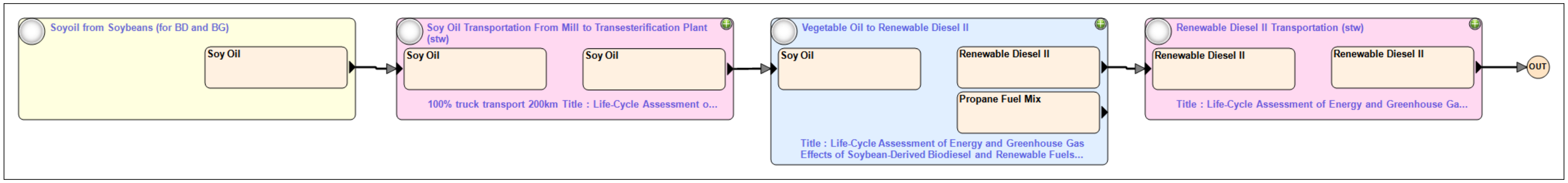
H_R.cc



RD_FR



RD_SB



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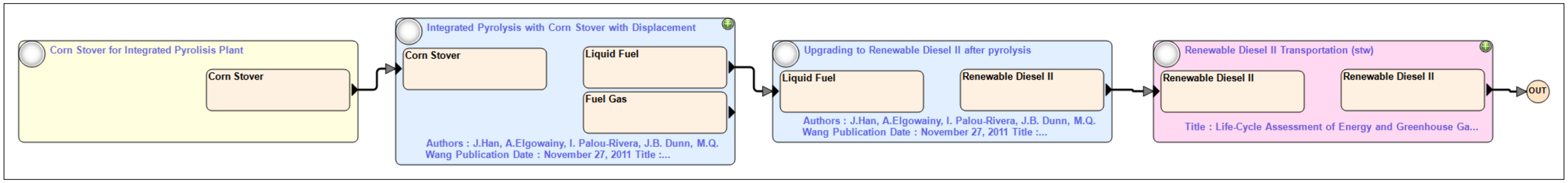

Appendix C: Electricity Grid Emissions

Emissions per kWh	BC Grid			AB Grid			Units
	Grid Mix	Transmission	Total	Grid Mix	Transmission	Total	
CO2 Total	12.86	0.68	13.53	764.00	66.40	830.40	g
CO2	93.57	4.92	98.49	764.00	66.50	830.50	g
CO2_Biogenic	-0.08	0.00	-0.09	0.00	0.00	0.00	kg
VOC	3.84	0.20	4.04	69.12	6.01	75.13	mg
CO	71.86	3.78	75.64	276.50	24.00	300.50	mg
NOx	53.12	2.80	55.91	593.60	51.60	645.20	mg
PM10	5.10	0.27	5.37	112.20	9.70	121.90	mg
PM2.5	4.73	0.25	4.98	52.23	4.54	56.77	mg
SOx	40.91	2.15	43.06	677.90	58.90	736.80	mg
CH4	37.41	1.97	39.38	1199.10	104.30	1303.40	mg
N2O	3.37	0.18	3.55	18.12	1.58	19.69	mg
BC	0.73	0.04	0.76	2.26	0.20	2.45	mg
POC	1.60	0.08	1.68	6.50	0.57	7.06	mg
GHG-100	15.00	0.79	15.79	805.40	70.10	875.50	g
GHG-20	17.05	0.90	17.95	871.40	75.70	947.10	g

Appendix D: Hydrogen Production and Distribution Emissions

Emissions per kg of H	Hydrogen Production Method							Units
	H_E.bc	H_E.ab	H_E.se	H_G	H_G.cc	H_R	H_R.cc	
CO2 Total	0.51	30.51	0.00	19.28	3.06	9.20	2.43	kg
CO2	3.74	30.51	0.00	19.34	3.06	9.20	2.43	kg
CO2_Biogenic	-3.22	0.00	0.00	-0.06	0.00	0.00	0.00	kg
VOC	0.15	2.76	0.00	1.85	1.88	0.93	1.17	g
CO	2.87	11.04	0.00	0.97	1.04	4.24	5.15	g
NOx	2.12	23.70	0.00	0.91	1.09	5.23	6.59	g
PM10	0.20	4.48	0.00	1.80	1.83	0.32	0.44	g
PM2.5	0.19	2.09	0.00	0.25	0.27	0.31	0.42	g
SOx	1.63	27.07	0.00	2.91	3.06	0.00	0.29	g
CH4	1.49	47.88	0.00	31.22	31.82	8.73	12.75	g
N2O	0.13	0.72	0.00	0.01	0.01	0.19	0.22	g
BC	29.00	90.10	0.00	7.62	8.11	35.34	50.48	mg
POC	63.70	259.40	0.00	14.03	17.91	91.61	131.80	mg
GHG-100	0.60	32.16	0.00	20.23	4.02	9.52	2.88	kg
GHG-20	0.68	34.79	0.00	21.95	5.77	10.00	3.58	kg

Emissions per kg of H	Gaseous Hydrogen Distribution				Liquified Hydrogen Distribution				Units
	1	2	3	Total	4	5	6	Total	
CO2 Total	0.0164	0.2499	0.0291	0.2954	0.1555	0.0262	0.0033	0.1850	kg
CO2	0.1196	0.2500	0.2115	0.5811	1.1323	0.0330	0.0238	1.1891	kg
CO2_Biogenic	-0.1031	0.0000	-0.1825	-0.2856	-0.9767	-0.0068	-0.0205	-1.0040	kg
VOC	0.0049	0.0381	0.0087	0.0517	0.0465	0.0041	0.0010	0.0516	g
CO	0.0918	0.5287	0.1625	0.7830	0.8696	0.0590	0.0185	0.9471	g
NOx	0.0678	0.3607	0.1201	0.5486	0.6428	0.0406	0.0136	0.6970	g
PM10	0.0066	0.0202	0.0116	0.0384	0.0618	0.0025	0.0013	0.0656	g
PM2.5	0.0061	0.0059	0.0107	0.0227	0.0573	0.0010	0.0012	0.0595	g
SOx	0.0523	0.0146	0.0925	0.1594	0.4951	0.0049	0.0104	0.5104	g
CH4	0.0478	0.3036	0.0846	0.4360	0.4528	0.0335	0.0097	0.4960	g
N2O	0.0043	0.0009	0.0076	0.0128	0.0408	0.0004	0.0008	0.0420	g
BC	0.9282	0.5660	1.6422	3.1364	8.7904	0.1180	0.1843	9.0927	mg
POC	2.0384	1.0051	3.6064	6.6499	19.3050	0.2354	0.4047	19.9451	mg
GHG-100	0.0191	0.2603	0.0339	0.3133	0.1815	0.0273	0.0039	0.2127	kg
GHG-20	0.0218	0.2770	0.0385	0.3373	0.2064	0.0291	0.0045	0.2400	kg

1 – Compression at tube trailer loading

2 – Gaseous hydrogen distribution via tube trailer

3 – Compression for refuelling station

4 – Liquefaction

5 – Liquified hydrogen transportation

4 – Storage at refuelling station

Appendix E: Renewable Diesel Production and Distribution Emissions

Emissions per l of RD	RD_FR	RD_SB	RD_CS	Distribution	Unit
CO2 Total	0.7527	0.5486	0.8862	0.0453	kg
CO2	0.7549	0.5507	0.8887	0.0452	kg
CO2_Biogenic	-0.0022	-0.0020	-0.0024	0.0000	kg
VOC	0.1338	0.6096	0.1986	0.0516	g
CO	0.5175	0.4681	0.4694	0.0403	g
NOx	0.6956	0.5825	0.5564	0.1932	g
PM10	50.5611	55.9250	86.7285	4.0056	mg
PM2.5	37.9785	44.0211	70.8790	3.4393	mg
SOx	0.1975	0.3330	0.3793	0.0026	g
CH4	2.0909	1.2677	2.0127	0.0575	g
N2O	15.1226	0.7463	-0.0002	0.0000	kg
BC	10.3028	11.2788	19.3707	0.3242	mg
POC	7.3168	10.5534	15.9954	2.6430	mg
GHG-100	0.8207	0.7871	0.8873	0.0475	kg
GHG-20	0.9357	0.8560	0.9982	0.0507	kg

Appendix F: Vehicle Life Cycle Emissions

Name	WTP	Operation	WTW	Powertrain	Transmission	Chassis	Motor	Electronic Controller	Hydrogen Storage	Vehicle Body	Lead-Acid Battery	Lithium-Ion Battery
Hydrogen Heavy-Duty Truck												
Total Energy (J/mi)	4.1E+07	7.8E+07	1.2E+08	1.6E+05	2.4E+04	9.2E+05	4.6E+04	6.2E+03	1.0E+06	3.1E+05	8.1E+03	1.1E+05
VOC (kg/mi)	8.7E-04	0.0E+00	8.7E-04	3.1E-06	1.9E-06	8.9E-05	1.4E-06	1.1E-07	1.7E-05	7.4E-06	2.1E-07	1.3E-06
CO (kg/mi)	1.6E-03	0.0E+00	1.6E-03	1.8E-05	1.2E-05	3.1E-04	9.3E-06	4.3E-07	3.9E-05	4.1E-05	3.9E-07	4.8E-06
NOx (kg/mi)	2.2E-03	0.0E+00	2.2E-03	7.6E-06	1.8E-06	7.6E-05	3.0E-06	3.3E-07	4.1E-05	1.9E-05	4.5E-07	8.5E-06
PM10 (kg/mi)	3.1E-04	0.0E+00	3.1E-04	4.1E-06	1.0E-06	3.0E-05	1.3E-06	1.3E-07	1.3E-05	1.1E-05	5.1E-07	3.4E-06
PM2.5 (kg/mi)	2.6E-04	0.0E+00	2.6E-04	2.0E-06	4.8E-07	1.5E-05	6.8E-07	6.1E-08	4.4E-06	4.2E-06	2.5E-07	1.5E-06
SOx (kg/mi)	1.6E-03	0.0E+00	1.6E-03	4.1E-05	7.1E-06	1.7E-04	5.2E-05	2.2E-06	3.2E-05	4.6E-05	4.9E-06	1.0E-04
CH4 (kg/mi)	1.6E-02	0.0E+00	1.6E-02	2.5E-05	3.7E-06	1.3E-04	6.0E-06	1.1E-06	1.3E-04	4.7E-05	1.8E-06	1.5E-05
CO2 (kg/mi)	6.7E+00	0.0E+00	6.7E+00	7.2E-03	1.6E-03	6.5E-02	3.0E-03	3.0E-04	4.4E-02	1.6E-02	3.4E-04	6.9E-03
N2O (kg/mi)	6.2E-05	0.0E+00	6.2E-05	2.1E-07	2.6E-08	1.1E-06	5.4E-08	1.2E-08	9.5E-07	4.5E-07	6.2E-09	1.5E-07
BC (kg/mi)	2.8E-05	0.0E+00	2.8E-05	4.5E-08	7.2E-09	4.2E-07	2.5E-08	2.5E-09	2.6E-07	1.1E-07	2.2E-09	6.4E-08
POC (kg/mi)	7.1E-05	0.0E+00	7.1E-05	1.2E-07	1.9E-08	8.9E-07	4.3E-08	5.0E-09	7.9E-07	2.5E-07	5.3E-09	1.4E-07
CO2_Biogenic (kg/mi)	-1.2E-02	0.0E+00	-1.2E-02	-4.6E-05	-4.8E-06	-1.4E-04	-3.5E-05	-1.5E-06	-3.3E-04	-4.7E-05	-1.4E-06	-5.7E-05
GHG-100 (kg/mi)	7.2E+00	0.0E+00	7.2E+00	8.0E-03	1.8E-03	7.0E-02	3.2E-03	3.4E-04	4.8E-02	1.8E-02	4.0E-04	7.2E-03
GHG-20 (kg/mi)	8.1E+00	0.0E+00	8.1E+00	9.6E-03	2.0E-03	7.7E-02	3.5E-03	4.0E-04	5.5E-02	2.1E-02	5.0E-04	7.9E-03
Electric Heavy-Duty Truck												
Total Energy (J/mi)	4.0E+07	3.8E+07	7.8E+07		2.3E+04	9.2E+05	4.5E+04	6.1E+03		3.1E+05	8.1E+03	7.3E+06
VOC (kg/mi)	5.1E-04	0.0E+00	5.1E-04		1.8E-06	8.9E-05	1.4E-06	1.1E-07		7.4E-06	2.1E-07	8.5E-05
CO (kg/mi)	1.8E-03	0.0E+00	1.8E-03		1.2E-05	3.1E-04	9.0E-06	4.2E-07		4.1E-05	3.9E-07	3.3E-04
NOx (kg/mi)	3.2E-03	0.0E+00	3.2E-03		1.8E-06	7.6E-05	2.9E-06	3.2E-07		1.9E-05	4.5E-07	6.2E-04

PM10 (kg/mi)	4.8E-04	0.0E+00	4.8E-04		1.0E-06	3.0E-05	1.3E-06	1.3E-07		1.1E-05	5.1E-07	2.5E-04
PM2.5 (kg/mi)	2.7E-04	0.0E+00	2.7E-04		4.7E-07	1.5E-05	6.7E-07	5.9E-08		4.2E-06	2.5E-07	1.0E-04
SOx (kg/mi)	2.8E-03	0.0E+00	2.8E-03		7.0E-06	1.7E-04	5.1E-05	2.2E-06		4.6E-05	4.9E-06	7.2E-03
CH4 (kg/mi)	9.6E-03	0.0E+00	9.6E-03		3.6E-06	1.3E-04	5.9E-06	1.0E-06		4.7E-05	1.8E-06	1.0E-03
CO2 (kg/mi)	4.4E+00	0.0E+00	4.4E+00		1.6E-03	6.5E-02	2.9E-03	2.9E-04		1.6E-02	3.4E-04	4.4E-01
N2O (kg/mi)	8.7E-05	0.0E+00	8.7E-05		2.5E-08	1.1E-06	5.2E-08	1.1E-08		4.5E-07	6.2E-09	9.9E-06
BC (kg/mi)	1.6E-05	0.0E+00	1.6E-05		7.0E-09	4.2E-07	2.5E-08	2.5E-09		1.1E-07	2.2E-09	4.5E-06
POC (kg/mi)	7.8E-05	0.0E+00	7.8E-05		1.9E-08	8.9E-07	4.2E-08	4.9E-09		2.5E-07	5.3E-09	9.7E-06
CO2_Biogenic	-5.5E-02	0.0E+00	-5.5E-02		-4.7E-06	-1.4E-04	-3.4E-05	-1.4E-06		-4.7E-05	-1.4E-06	-3.3E-03
GHG-100 (kg/mi)	4.7E+00	0.0E+00	4.7E+00		1.8E-03	7.0E-02	3.1E-03	3.3E-04		1.8E-02	4.0E-04	4.7E-01
GHG-20 (kg/mi)	5.2E+00	0.0E+00	5.2E+00		1.9E-03	7.7E-02	3.4E-03	3.9E-04		2.1E-02	5.0E-04	5.3E-01
Diesel Heavy-Duty Truck												
Total Energy (J/mi)	1.1E+08	1.2E+08	2.4E+08	2.4E+05	5.5E+04	9.2E+05				3.1E+05	2.4E+04	
VOC (kg/mi)	6.2E-04	3.3E-04	9.5E-04	1.1E-05	4.2E-06	8.9E-05				7.4E-06	6.4E-07	
CO (kg/mi)	1.9E-03	1.3E-02	1.5E-02	5.1E-05	2.9E-05	3.1E-04				4.1E-05	1.2E-06	
NOx (kg/mi)	2.6E-03	8.4E-03	1.1E-02	1.3E-05	4.2E-06	7.6E-05				1.9E-05	1.4E-06	
PM10 (kg/mi)	1.9E-04	1.9E-05	2.0E-04	8.2E-06	2.3E-06	3.0E-05				1.1E-05	1.5E-06	
PM2.5 (kg/mi)	1.4E-04	1.7E-05	1.6E-04	3.9E-06	1.1E-06	1.5E-05				4.2E-06	7.5E-07	
SOx (kg/mi)	7.1E-04	0.0E+00	7.1E-04	5.5E-05	1.6E-05	1.7E-04				4.6E-05	1.5E-05	
CH4 (kg/mi)	7.6E-03	7.5E-05	7.6E-03	3.2E-05	8.5E-06	1.3E-04				4.7E-05	5.4E-06	
CO2 (kg/mi)	2.7E+00	8.9E+00	1.2E+01	1.2E-02	3.8E-03	6.5E-02				1.6E-02	1.0E-03	
N2O (kg/mi)	5.5E-05	1.2E-05	6.6E-05	2.4E-07	5.9E-08	1.1E-06				4.5E-07	1.9E-08	
BC (kg/mi)	3.7E-05	2.1E-06	3.9E-05	6.8E-08	1.6E-08	4.2E-07				1.1E-07	6.5E-09	
POC (kg/mi)	2.8E-05	3.6E-06	3.2E-05	1.7E-07	4.4E-08	8.9E-07				2.5E-07	1.6E-08	
CO2_Biogenic (kg/mi)	-8.0E-03	-8.5E+00	-8.5E+00	-3.3E-05	-1.1E-05	-1.4E-04				-4.7E-05	-4.1E-06	
GHG-100 (kg/mi)	3.0E+00	4.2E-01	3.4E+00	1.4E-02	4.0E-03	7.0E-02				1.8E-02	1.2E-03	
GHG-20 (kg/mi)	3.4E+00	4.2E-01	3.8E+00	1.6E-02	4.4E-03	7.7E-02				2.1E-02	1.5E-03	