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Well-to-Wheel Analysis of Natural Gas Fuel for Hybrid Truck Applications

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ABSTRACT: Following the tendency of sustainable development, compressed natural gas as an alternative fuel has been expanded applied in the transportation sector these years. Although several studies on the life cycle are quite comprehensive for passenger vehicles, it is problematic to apply these results to heavy-duty electric hybrid trucks. This study applies the Well-to-Wheel methodology on compressed natural gas fuel. The optimized hybrid electric truck model is built up to minimize the truck performance variation. The total CO₂ equivalent emissions and the methane leakage as indicators are compared among the three largest emitting countries. The results indicate that compressed natural gas-based hybrid trucks have 9.1%-18.7% less CO₂ equivalent emissions than diesel-based ones and the results are more obvious for heavy-duty trucks. Nevertheless, this advantage may be minimized by methane leakage, particularly in the recovery process, accounted for 7.3% Total CO₂ equivalent emissions increase in North America, 5.1% in Europe, 5.3% in China from well to wheel. Applying natural gas in hybrid electric trucks does have environmental benefits. Methane capturing and compression efficient improving can be the faster ways to help reach the emission reduction target

Keywords

Compressed natural gas, Well-to-Wheel analysis, Hybrid electric trucks, WtW CO₂ equivalent emissions, Methane leakage.

Highlights

- Compressed natural gas-based hybrid electric truck model is developed and optimized based on real cycles.
- Well-to-Wheel analysis is applied to figure out the methane leakage and carbon dioxide equivalent emissions of compressed natural gas lifetime.
- The same methodology is applied to North America, Europe and China to make a comparison.

ACRONYMS AND ABBREVIATION

AFR	Air to fuel ratio
AR5	Fifth Assessment Report of the Intergovernmental Panel on Climate Change
CN	China
CNG	Compressed natural gas
CNGV	Compressed natural gas vehicle
EIA	Energy information administration
EM	Electric machine
EPA	U.S. Environmental Protection Agency
EU	Europe
EV	Electric vehicle
FCV	Fuel cell vehicle
GCP	Global Carbon Project
GHG	Greenhouse gas
GREET	Greenhouse gases, regulated emissions, and energy use in transportation model, issued by Argonne
GWP	Global-warming potential
HDV	Heavy-duty vehicles
ICE	Internal combustion engine
IEA	International Energy Agency
LCA	Life cycle assessment
LDVs	Light Duty Vehicles
LNG	Liquefied natural gas
NA	North America
NG	Natural gas
NGV	Natural gas vehicles
PCA	Principal component analysis
PCs	Principal components
PC1	First Principal component
PC2	Second Principal component
PM	Particulate matter
SOC	State of charging
SUV	Sport Utility Vehicle
T&D	Transmission and distribution
TtW	Tank-to-Wheel
WtT	Well-to-Tank
WtW	Well-to-Wheel

1 INTRODUCTION

Under the energy shortage and pressing environmental concerns, the energy industry was looking for alternative solutions in the past years. The climate change is the consequence of

greenhouse gas (GHG) emissions, and CO₂, CH₄, N₂O from fuel utilization are the main players [1]. The global average volume of CO₂ reached the highest level at 407.4 parts per million in 2018 [2]. From the Global Carbon Project (GCP) statistics, China contributed 27% global CO₂ emission, following by North America 18% and Europe 17% [3].

Due to the global warming and environmental deterioration, more focus was being given to GHG emissions and strategic changes have been introduced, including new regulations on automotive GHG limits [4]. In 2017, GHG pollution from the road transport industry in Europe attained at 20.1%, 28.2% for U.S. in 2018 [5, 6]. Passenger vehicles constituted 41.0% of the main outlets, freight trucks represented for 23.2% and light-duty truck for 17.5% [7].

The air pollution caused by transportation was mainly from trucks, buses and other heavy-duty vehicles (HDV), the proportion of HDV increased by 36% between 1990 and 2010, and it is still growing [8]. About 30% of CO₂ emissions from HDV will continually increase to 40% by 2030 if no effective action implemented [9]. Nahlik et al. [10] reported that HD trucks accounted for 99% of California's emissions from intrastate goods. Based on these studies, alternative fuel development and technology innovations are important for the truck industry which could achieve a significant GHG reduction.

Different from traditional fuels, natural gas (NG) is usually considered as a low cost and less emissions alternative fuel [11]. With the lower carbon content in methane, it has a strong advantage in GHG emissions [12]. According to Energy Information Administration (EIA) 2019 statistics [13], NG emits about 53.1kg CO₂ per million British thermal units (Btu), which was only 51.18% of coal (anthracite) emissions. NG as a low-carbon dispatchable source has important strategic significance in the transformation of energy and transportation [14].

NG is used principally by vehicles in form of compressed natural gas (CNG) or liquefied natural gas (LNG) types. Generally, the CNG is used in passenger and light freight, road buses and public vehicles. The commercial use of LNG is limited by high production cost, most LNG is applied for line-cars, rail and water-borne transport, and agricultural machinery [15]. Over several years, natural gas vehicles (NGV) represented 1.32% of the global automotive market, the proportion of NGV usage came 66% from Asia, 8.6% from Europe and 1.4% from Africa and North America [16]. Although only 1% HDVs were natural gas based, this segment still has a lot of potential for natural gas demand [17]. The national petroleum council reported that CNG could become cost-competitive options for heavy-duty and medium-duty vehicles [18]. The expansion of heavy goods vehicles would bring the continued growth of LNG and CNG demand by EIA's 2018 Annual Energy Outlook prediction [19].

Based on the aforementioned review, a great opportunity exists in the transportation sector using CNG to reduce GHG emissions in heavy-duty trucks. Under the context of the transportation electrification, the transformation to electric vehicle (EV) would be an inevitable trend in the future. In the fuel life cycle, using EV could emit less GHG than internal combustion engine (ICE) vehicle in most fuel scenarios [20]. If all trucks were converted into electric ones by 2040, it would reduce 64% GHG emissions for road freight transportation [21]. In addition, the use of hybrid power chain is one of the faster means to achieve carbon emission reduction targets [22]. So far, using CNG for hybrid electric trucks may be a good combination. However, most of trucks have low combustion efficiency and higher levels of methane slip [23]. If the global methane emissions are also considered, the result may be differed.

One of the resources for this doubt is the methane emissions caused during the extraction and utilization. The GHG effect of methane is 28-36 times greater than that of CO₂ [24]. In Pennsylvania, methane emissions from abandoned oil and gas wells represented 5-8% of GHG emissions [25]. In 2012, about 155 million metric tons of CO₂ equivalent of methane were emitted from inadvertent leakage and routine venting [26]. From EPA's database [27], the CH₄ emissions from NG production were measured at 2300 Gg, about 0.42% of gross gas output. The environmental impact of this leakage would become more serious with the current boom in NG production and consumption.

The Well-to-Wheel (WtW) analysis is commonly used today to measure the effect of fuels for environmental assessment. The major influential works in this field are as follows: Khan et al. [28] integrated the WtW model into developing countries and concluded that the fuel

efficiency of NGVs' powertrain are 5–17% and 23–36% lower than that of gasoline and diesel ones. However, the details about upstream emissions and possible methane leakage did not mention too much. Bradbury et al. [26] drew the Sankey diagrams to explain the detailed emissions of NG stage by stage but provided an overview of the end-use combustion NG only from a national level. For European C-segment cars, CNG also shows a lower GHG emissions but a higher energy consumption than petrol or diesel vehicles in WtW process [16].

In addition to fuel research, the choice of vehicle power chain also has a great influence on the results of WtW. For hybrid electric vehicles, about 20–40% CO₂ emissions can be reduced by applying split hybrid configuration in transportation [29]. Similarly, hybrid buses also have potential to reduce emissions compared to diesel ones [30]. Hekkert et al. [12] believed that the innovation performance of hybrid vehicles may be better than NG based vehicles in the next years. Most of the current researchers use passenger cars as research models, due to their huge numbers and half of the total transport energy consumption [31]. Rousseau et al. [32] focused on the comparison of traditional SUV (Sport Utility Vehicle), hybrid and fuel cell SUV. They quantitatively discuss the performance of fuel economy, powertrain efficiency and greenhouse gas emissions. Curran et al. [33] made a comparison between the compressed natural gas vehicle (CNGV) and EVs and found that the efficient way of utilizing NG was due to the combustion efficiency. Although the power systems of these studies differ from each other, the data and results only suitable for the Light Duty Vehicles (LDVs).

Based on literature researches, the WtW studies mainly applied for passenger vehicles. Although this orientation has potential to emit less GHGs, the margin effect of this part is small. For hybrid electric trucks with high potential of reduction, the comprehensive WtW assessments are less numerous. Furthermore, the results obtained are based on their respective vehicle models for research, which are largely affected by road conditions, vehicle parameters, etc., and have great differences and uncertainties. It will be difficult to make a unified comparison and draw a relatively accurate conclusion. Although CNG-powered cars had emissions benefits by replacing petrol cars, there is still a high level of uncertainty in the amount of methane leakage occurring in the natural gas production process [34]. If the CH₄ leakage can be reduced by 45–70% than current estimates during WtW process, the climate benefits may be more significant [35]. But the specific leakage points were not introduced by these studies from well to wheel process. Meanwhile, the gas emissions from the upstream process are various from countries and regions because of technology development level and geological variation, but there is no unified discussion on these fields in current researches.

Based on the previous points, an independent emission assessment method is proposed in this study. More details about the upstream emissions of NG will be found in the following parts, and methane leakage as the main indicator can calibrate the final results. The use of a unified hybrid truck model greatly reduces the impact of vehicle parameters and performance on the CO₂ emissions. It evaluates the potential of GHGs emission reduction for CNG-based hybrid electric trucks which provide a precise guide for an updated policy formulation and transportation transformation. The results would be conducted in North America, Europe and China which contribute to the most CO₂ emissions in the world.

2 METHODOLOGY

Based on the resources of CO₂ emissions for the CNG life cycle, the estimated CO₂ emissions are divided into Well-to-Tank (emissions from the fuel production in upstream) and Tank-to-Wheel (emissions from fuel combustion in engine downstream) processes. The Well-to-Tank (WtT) process covers the steps of recovery, refining, compression, transmission and delivery pathways [36]. The Tank-to-Wheel (TtW) process considers only the CO₂ equivalent emissions of the fuel combustion. In this paper, the WtT results are combined with the TtW results to provide the comprehensive WtW analysis for CNG-based hybrid electric trucks. The total WtW CO₂ equivalent emissions calculated on the global-warming potential

(GWP) values are considered as the criterion, and the results from different countries will be compared.

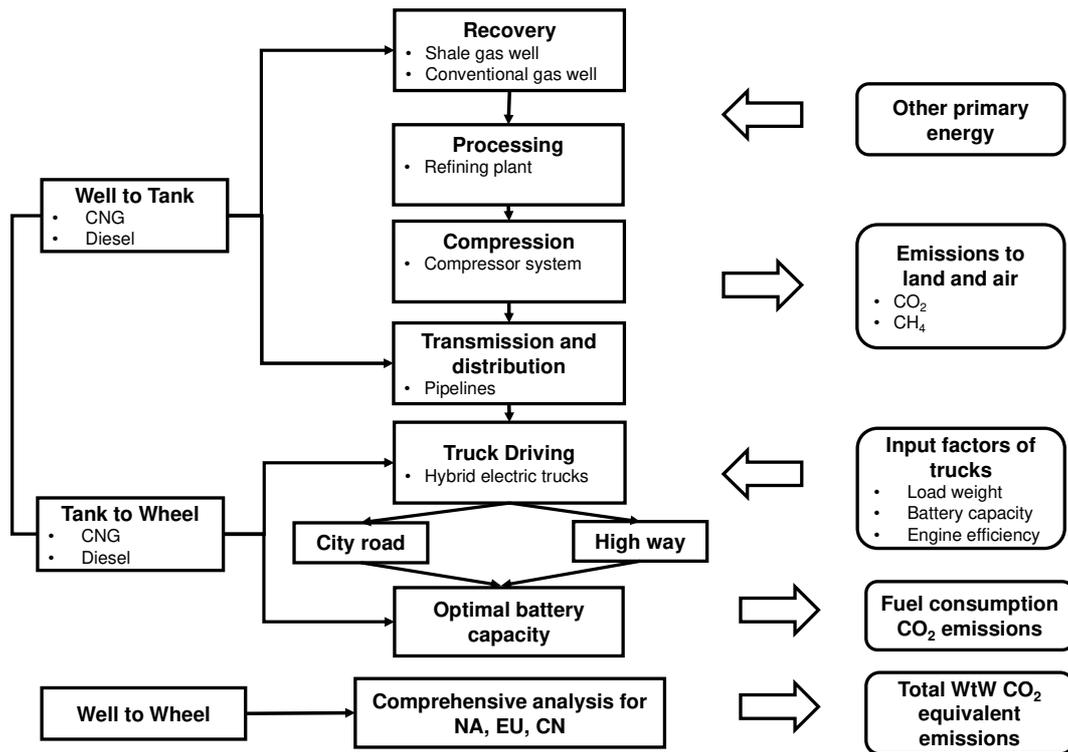


Figure 1. Methodology of Well-to-Wheel analysis.

The Well-to-Tank begins with natural gas recovery from an underground gas well. Both the shale gas and conventional gas are considered in this study. After the gas is recovered, it must be separated from liquid and impurities to ensure safe combustion. After processing, the natural gas is sent to the compressor station under low pressure pipelines. The compressor takes the NG from low pressure to high pressure for storage in tanks. The gas emitted at this whole stage is crucial for evaluation of the entire life cycle which are elaborated in the Section 3. Meanwhile, the gas emissions from a variety of supporting primary energy like diesel, gasoline, etc. used in the WtT process will also be considered.

In the Tank-to-Wheel process, different factors have various affection on the truck operation, including driving distance, facility, configuration and overall environmental characteristics. For the traveling parameters like operating modes or temperatures, speeds, accelerations and deceleration are difficult to control and test. In this paper, only the assembly units include engine, motor, gearbox, wheels, etc. are considered as influence factors of emissions.

The hybrid electric truck model is established to simulate the fuel consumption and gas emissions in real running urban road and highway. The architecture of drivetrain can be modeled by using the available component blocks like internal combustion engines (ICE), gearbox, electric machine, transmission elements, controls, shafts, wheels, brakes and others. The engine's performance, fuel consumption, emissions, etc. are all based on the states of that truck. Each component is described by numbers of parameters and can also be constituted into most of representative trucks. In order to give accurate and feasible guidance, the different input parameters of the truck are studied and optimized in this process. And the emissions from this part are presented in the Section 4.

The data involved in this study are mostly taken from IEA, EPA, EIA, GREET model and other works of literatures, and the other data are justifiable assumptions base on large research. The results of WtT and TtW will be integrated in the Section 5 to import a comprehensive evaluation for the whole process. The data of North America, Europe and China are used as

resources to study the up-to-date WtW GHG emissions and the results are compared to conventional diesel trucks since diesel is the primary fuel in HDVs. This WtW database has great meaning for supporting the transportation electrification, which would be necessary in many countries to meet the increasingly strict pollution standards.

3 WELL-TO-TANK PROCESS

The WtT process includes the emissions associated with gas production, processing, compression as well as transmissions and distribution. This cycle begins at the point of feedstock exploitation to where the fuel is transported to a truck for energy consumption. The general process flow is shown in Fig. 2.

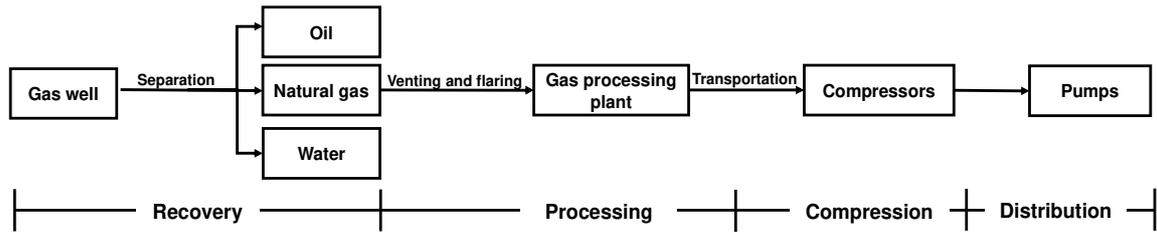


Figure 2. System boundary of Well-to-Tank analysis.

In order to be descriptive, the WtT process is broken into four distinct stages: recovery, processing, compression, transmission and distribution. Only the CO₂ equivalent emitted from the usage of primary energy, methane leakage, emissions from transportation, etc. are calculated in this part, and the methane emissions are in details. The initial needed energy for the well and infrastructure construction is out of this boundary and will be considered in the life cycle assessment (LCA). The key parameters of each stage in different countries are shown in Table 1. The main methodology presented in the following part is used commonly in each country, and the input parameters are reasonable assumed based on the literature study.

Table 1. Key parameters in each stage for different countries.

Parameters	Unit	Symbols	North America	Europe	China
Conventional NG	%	a	48	100	95
Shale gas	%	b	52	0	5
Recovery process					
Share of residual oil as feedstock input	%	α_{oilrec}	1	1.3	1
Share of diesel as feedstock input	%	α_{dierec}	11	0	12
Share of gasoline as feedstock input	%	$\alpha_{gasorec}$	1	0.7	1
Share of NG as feedstock input	%	α_{NGrec}	86	87	81
Share of electricity as feedstock input	%	α_{elerec}	1	1	5
Energy efficiency for conventional gas	%	$effi_{reccon}$	97.5	97.5	95.3
Energy efficiency for shale gas	%	$effi_{recsha}$	97.6	95.6	93.3
Share of combustion for diesel commercial boiler	%	β_{dieBoi_rec}	25	25	25
Share of combustion for diesel stationary engine	%	$\beta_{diestEng_r}$	50	50	50
Share of combustion for diesel turbine	%	β_{dieTub_rec}	25	25	25
Share of combustion for NG engine	%	β_{NGEng_rec}	50	50	50
Share of combustion for NG small industrial boiler	%	β_{NGsBoi_rec}	50	50	50
Processing Process					
Share of diesel as feedstock input	%	α_{diepro}	1	2	4
Share of NG as feedstock input	%	α_{NGpro}	96	95	93
Share of electricity as feedstock input	%	α_{elepro}	3	3	3

Energy efficiency	%	effi_{pro}	97.4	97.4	96.9
Loss factor	-	lf_{pro}	1	1	1
Share of combustion for diesel commercial boiler	%	$\beta_{\text{dieBoi_pro}}$	33	33	33
Share of combustion for diesel stationary engine	%	$\beta_{\text{diestEng_pro}}$	33	33	33
Share of combustion for diesel turbine	%	$\beta_{\text{dieTub_pro}}$	34	34	34
Share of combustion for NG large turbine	%	$\beta_{\text{NGTub_pro}}$	50	50	50
Share of combustion for NG industrial boiler	%	$\beta_{\text{NGinBoi_pro}}$	50	50	50
Compression process					
Share of electricity as feedstock input	%	α_{elecom}	100	100	100
Energy efficiency	%	effi_{com}	95	93	91
Share of combustion for diesel stationary engine	%	$\beta_{\text{diestEng_com}}$	50	50	50
Share of combustion for diesel turbine	%	$\beta_{\text{dieTub_com}}$	50	50	50
Share of combustion for NG engine	%	$\beta_{\text{NGEng_com}}$	100	100	100
Transmission and distribution					
Pipeline average distance from NG processing plants to refueling stations	km	d	1200	1250	1400
Loss factor	-	lf_{tra}	1.003	1.003	1.003

*The data contains in above table are from [37-48]

The emission factors for various types of equipment applied in the WtT process are shown in Table 2. as grams per kg fuel burned. These data are calculated based on the fuel stoichiometric components. As the difference exists between regions by geographical factors, not all the fuels are mined locally and these detailed data are not easy to obtain, so some emission factors use the average value to represent.

Table 2. Emission factors of fuel combustion for stationary applications (g/kg).

Symbols of emission factors	CH ₄ emissions value	CO ₂ emissions value	Explanations
$\text{EF}_{\text{die_inBoi}}$	0.154	4048.238	Residual oil in industrial boiler
$\text{EF}_{\text{die_coBoi}}$	0.036	3721.619	Diesel fuel in commercial boiler
$\text{EF}_{\text{pet_crude}}$	4.422	264.476	Crude as feedstocks used in refineries
$\text{EF}_{\text{die_stEng}}$	0.201	3673.762	Diesel fuel combustion at stationary reciprocating engine
$\text{EF}_{\text{dieTub}}$	0.144	3723.190	Diesel fuel combustion at turbine
$\text{EF}_{\text{pet_codie}}$	0.891	326.571	Conventional diesel as fuel
$\text{EF}_{\text{gaso_stEng}}$	0.143	3455.095	Gasoline combustion at stationary reciprocating engine
$\text{EF}_{\text{gaso_bst}}$	1.790	548.476	Gasoline blend stock as fuel
$\text{EF}_{\text{NG_sEng}}$	18.683	2705.190	NG combustion at stationary reciprocating engine
$\text{EF}_{\text{NG_Tub}}$	0.050	2826.810	NG combustion at large gas turbine
$\text{EF}_{\text{NG_inBoi}}$	0.050	2827.000	NG combustion at utility/ industrial boiler (>340 kw input)
$\text{EF}_{\text{NG_sBoi}}$	0.050	2826.810	NG combustion at small industrial boiler (34-340 kw input)
$\text{EF}_{\text{NG_fla}}$	2.333	2823.762	NG flaring in oil field
$\text{EF}_{\text{ele_fed}}$	12.463	143.952	Fuel-cycle emissions of electric generation from feedstock
$\text{EF}_{\text{ele_ful}}$	0.106	66.429	Fuel-cycle emissions of electric generation from fuel

3.1 Recovery

Natural gas is a gas mixture with a high methane component. Like oil, NG is formed from the bodies of animals and plants which are buried in the soil by the effects of the heat and pressure over thousands of years [49]. Many parts of raw NG are regularly used as fuel which will be vented, flared or unintentionally spilled into environment for conducting experiments, fixes or maintenance. About 2% of the estimated methane emissions from this flaring during oil and gas production [50]. Besides, the primary energy is needed to power this process, the incomplete

fuel combustion for conventional NG in recovery process is also one of the CH₄ emission sources. The total CH₄ emissions are carried out on these two parts which is expressed in Eq (1).

$$CH_{4rec} = ((CH_{4concom} + CH_{4conlek}) \times a + (CH_{4shacom} + CH_{4shalek}) \times b) \times lf_{pro} \quad (1)$$

where CH_{4rec} is the CH₄ emissions in recovery process (g/kg); $CH_{4concom}$ is the CH₄ emissions from feedstocks combustion for conventional NG in recovery process (g/kg); $CH_{4conlek}$ is the CH₄ leakage for conventional NG in recovery process (g/kg); $CH_{4shacom}$ is the CH₄ emissions from feedstocks combustion for shale gas in recovery process (g/kg); $CH_{4shalek}$ is the CH₄ leakage for shale gas in recovery process (g/kg); a is the conventional natural gas percentage (%); b is the shale gas percentage (%); lf_{pro} is the loss factor for processing process.

The CH₄ emissions from incomplete combustion part are mainly caused the usage of oil, diesel, gasoline, NG and electricity to provide energy in this process. For the conventional NG, these emissions can be calculated in Eq (2), and shale gas in Eq (3).

$$CH_{4concom} = CH_{4oil_rec} + CH_{4die_rec} + CH_{4gaso_rec} + CH_{4NG_rec} + CH_{4ele_rec} \quad (2)$$

where CH_{4oil_rec} is the CH₄ emissions from oil combustion as fuel in recovery process (g/kg); CH_{4die_rec} is the CH₄ emissions from diesel combustion as fuel in recovery process (g/kg); CH_{4gaso_rec} is the CH₄ emissions from gasoline combustion as fuel in recovery process (g/kg); CH_{4NG_rec} is the CH₄ emissions from NG combustion as fuel in recovery process (g/kg); CH_{4ele_rec} is the CH₄ emissions from electricity production in recovery process (g/kg).

$$CH_{4shacom} = CH_{4oil_sha} + CH_{4die_sha} + CH_{4gaso_sha} + CH_{4NG_sha} + CH_{4ele_sha} \quad (3)$$

where CH_{4oil_sha} is the CH₄ emissions from oil combustion as fuel for shale gas in recovery process (g/kg); CH_{4die_sha} is the CH₄ emissions from diesel combustion as fuel for shale gas in recovery process (g/kg); CH_{4gaso_sha} is the CH₄ emissions from gasoline combustion as fuel for shale gas in recovery process (g/kg); CH_{4NG_sha} is the CH₄ emissions from natural gas combustion as fuel for shale gas in recovery process (g/kg); CH_{4ele_sha} is the CH₄ emissions from electricity production for shale gas in recovery process (g/kg).

The CH₄ emissions from leakage part are mainly from venting and flaring. Flaring is the managed burning that may occur as a safety precaution in manufacturing and production activities. During the lifetime of conventional and shale gas, wells workovers and unloading also occur. In this research, the wells lifetime is estimated at 30 years, and the workovers per well lifetime assumed at 0.2 [51]. The leakage emissions in recovery process are carried out on Eq. (4) for conventional gas and Eq. (5) for shale gas.

$$CH_{4conlek} = CH_{4vencon_completion} + CH_{4vencon_workover} + CH_{4ven_unloading} + CH_{4lek_equipment} \quad (4)$$

where $CH_{4vencon_completion}$ is the CH₄ venting from conventional gas well completion (g/kg); $CH_{4vencon_workover}$ is the CH₄ venting from conventional gas well workover (g/kg); $CH_{4ven_unloading}$ is the CH₄ venting from liquid unloading (g/kg); $CH_{4lek_equipment}$ is the CH₄ venting and leakage from gas well equipment (g/kg).

$$CH_{4shalek} = CH_{4vensha_completion} + CH_{4vensha_workover} + CH_{4ven_unloading} + CH_{4lek_equipment} \quad (5)$$

where $CH_{4vensha_completion}$ is the CH₄ venting from shale gas well completion (g/kg); $CH_{4vensha_workover}$ is the CH₄ venting from shale gas well workover (g/kg).

The well equipment contributes the largest part of leakage, accounted for 91.8%-96.8% mainly from the pneumatic controller and other types of equipment. This part has great potential to be reduced with good control. Besides, liquid unloading is a major CH₄ leakage source for both conventional wells and unconventional wells.

3.2 Processing

After the production process, in order to separate water, oil, higher hydrocarbon, other impurities, and to rise the methane percentage, NG and shale gas must be refined before it used as a commercial fuel. The methane content rise from 78.3% to 92.8% after refining [26,52]. The total CH₄ emissions in this process will be calculated by the same way as recovery process, shown in Eq. (6) to Eq. (7).

$$CH_{4pro} = (CH_{4procom} + CH_{4prolek}) \times l_{fra} \quad (6)$$

where CH_{4pro} is the CH₄ emissions in processing process (g/kg); $CH_{4procom}$ is the CH₄ emissions from feedstocks combustion for conventional NG in processing process (g/kg); $CH_{4prolek}$ is the CH₄ leakage in processing process (g/kg); l_{fra} is the loss factor for the transmission and distribution process.

$$CH_{4procom} = CH_{4die_pro} + CH_{4gaso_pro} + CH_{4NG_pro} + CH_{4ele_pro} \quad (7)$$

where $CH_{4procom}$ is the CH₄ emissions from feedstocks combustion for conventional NG in processing process (g/kg); CH_{4die_pro} is the CH₄ emissions from diesel combustion as fuel in processing process (g/kg); CH_{4gaso_pro} is the CH₄ emissions from gasoline combustion as fuel in processing process (g/kg); CH_{4NG_pro} is the CH₄ emissions from NG combustion as fuel in processing process (g/kg); CH_{4ele_pro} is the CH₄ emissions from electricity production in processing process (g/kg).

3.3 Compression

After processing, the NG will be compressed to 276 bar to avoid the pressure drops during trucks refueling [53]. The compressor efficiency ranges from 91.7% to 98%, in this study it is maintained constantly at 95% in North America, 93% in Europe and 91% in China. After the compression process, the CNG is pumped and stored in the truck tank. The supported power during this process mainly come from the electricity produced by feedstock and fuel combustion.

$$CH_{4com} = (1 / effi_{com} - 1) \times \alpha_{elecom} \times (EF_{ele_fed} + EF_{ele_ful}) + CH_{4comlek} \quad (8)$$

where CH_{4com} is the CH₄ emissions in compression process (g/kg); $effi_{com}$ is the efficiency of compression process; α_{elecom} is the share of electricity as input in compression process (%); EF_{ele_fed} is the fuel-cycle emissions of electric generation from feedstock; EF_{ele_ful} is the fuel-cycle emissions of electric generation from fuel; $CH_{4comlek}$ is the CH₄ leakage in compression process (g/kg).

The emissions include two parts from electricity generation and methane leakage. For compressor systems, the efficiency determines how much energy is needed. The lower compressor efficiency in China results in a large amount of CO₂ emissions than Europe and North America. In addition, the causes of leakage are often the same. Most leakage points are connected valves, flanges, open-ended sides, pressure relievers. The main causes include compressor vents, leaky valves, exhaust engine reciprocating, and other equipment. The sum of these leaks is accounted for 22.6%-66.4% of CH₄ emissions in this stage. In consequence, it's essential to establish a regular monitor to find out the points and take effective measures.

3.4 Transmission and distribution

In North America, Europe and China, long-distance pipeline is a conventional way to distribute the processed NG. In this study, the lifetime of pipelines is assumed at 50 years. With the rising of gas field age, the pressure for feeding the NG into the pipeline will decline. So the

additional gas compressors are required in this stage which implies higher expended energy and GHG emissions.

Another source of CH₄ pollution is the methane leakage, which is estimated at 0.13% of gas-transported per 1000 km [16]. The safety valves, block valves, pipeline connectors and other measurement devices are the main leakage points [6]. The CH₄ emissions in transmission and distribution are various from each country due to the transportation distance. The proportion of methane emissions in each process from well to tank is summarized in Table 3.

$$CH_{4T\&D} = CH_{4tra_pip} + l_{tra_ven} * d + l_{dis_ven} \quad (9)$$

where $CH_{4T\&D}$ = CH₄ emissions in transmission and distribution process (g/kg); CH_{4tra_pip} = CH₄ emissions from electricity production for pipeline operation in transmission and distribution process (g/kg); l_{tra_ven} = CH₄ venting and leakage from NG processing plants to refueling stations per km (g/kg); d = the average pipeline distance from NG processing plants to refueling stations; l_{dis_ven} = CH₄ venting and leakage in distribution process (g/kg).

Table 3. CH₄ emissions proportion and main sources in WtT process.

WtT Stages	North America	Europe	China	Main sources of CH ₄ emissions
Recovery	0.702%	0.668%	0.788%	Venting and flaring, spilling, incomplete fuel combustion
Processing	0.054%	0.182%	0.195%	Leakage from connected valves and flanges, incomplete fuel combustion
Compressions	0.085%	0.081%	0.201%	Incomplete fuel combustion, leakage from connected valves, pressure relievers, compressor vents, leaky valves, exhaust engine reciprocating, and other equipment.
Transmission and distribution	0.427%	0.701%	0.812%	Leakage from safety valves, block valves, pipeline connectors and other measurement devices, incomplete fuel combustion
Total	1.267%	1.631%	1.995%	Leakage and incomplete fuel combustion

4 TANK-TO-WHEEL PROCESS

The used model is based on a virtual hybrid electric truck established by MATLAB, the results of different running scenes make a comprehensive comparison between diesel-based trucks and hybrid electrical ones. In order to be commercially understandable, the fuel consumption and CO₂ emissions are considered in units of kilograms per 100 kilometers. Basic truck characteristics considered in this study are given in Table 4. The key parameters are optimized to minimize the truck performance impact which will be explained in detail later, the other parameters are based on reasonable assumptions.

Table 4. Optimized parameters of hybrid electric truck.

Parameters	Unit	Value
Trailer load	kg	1000-25000
Truck weight	kg	12551
Accessories weight	kg	200
Battery weight	kg	2210
Battery capacity	kWh	160
Transmission efficiency	%	97
Generator power	kW	250
Max engine efficiency	%	45
Wheel radius	m	0.537

Truck front area	m ²	4.25
Air density	kg/m ³	1.293
Highway distance	km	300
City road distance	km	24

The downsized internal combustion engine (ICE) with light battery and small motor systems were selected to somewhat minimize the weight penalty. The gross weight of the model consists of mass weight, load weight, assembly units' weight (battery, essence, etc.). The variation of the load weight will be studied on highway driving cycle to research on the reduction effect of CNG-based trucks and diesel-based ones.

The connection of each unit inside the hybrid electric truck is presented in Fig. 3. The ICE is used to drive the electric machine (EM) to recharge the battery. The clutch will be activated during city driving, and the battery will provide required power to EM. During the highway driving, the ICE will provide the power. Consequently, this architecture can support a smaller power engine while maintaining a good performance during all driving conditions.

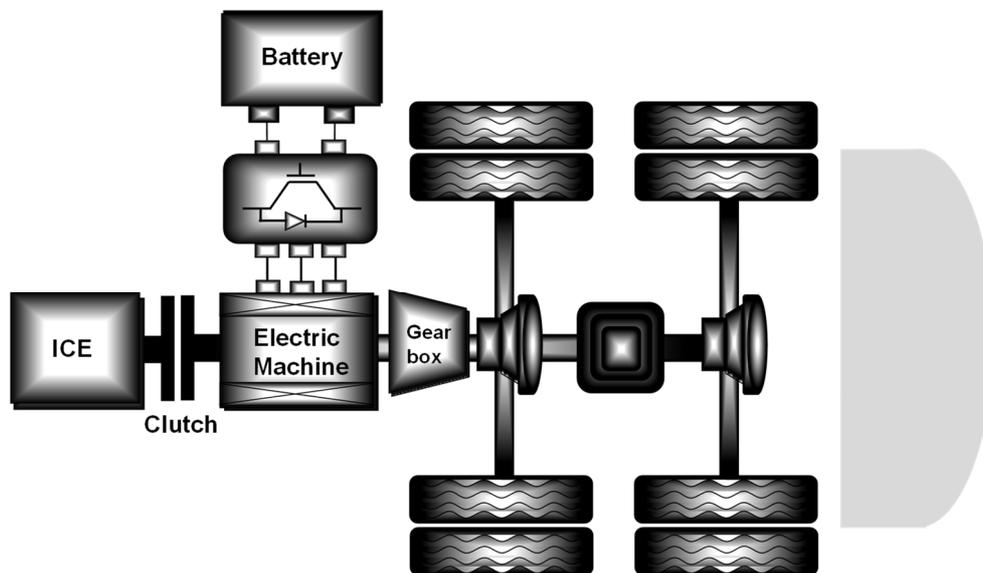


Figure 3. Configuration of hybrid drivetrain.

The model runs in two conditions. In the city, the truck runs only with battery to meet the restriction of city transportation for running 24 km. In the highway, the energy is completely supported by ICE, which can provide enough power for running 300 km. Fig. 4 to Fig. 5 show the speed of these two traveling scenes.

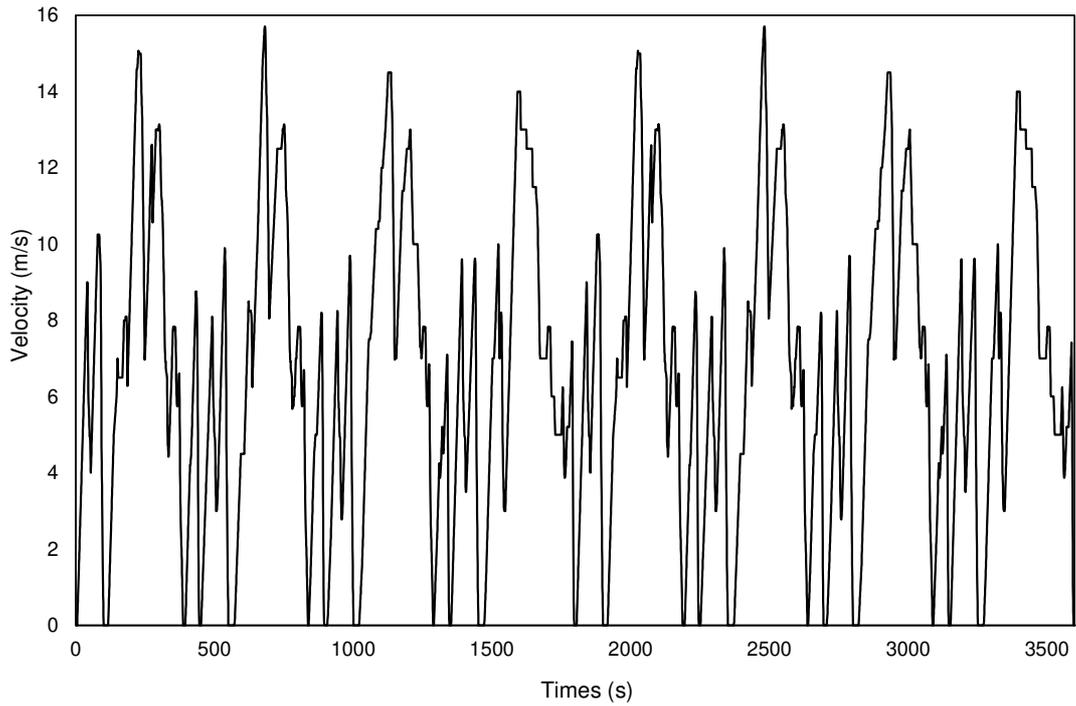


Figure 4. Real world city road driving cycle (24 km).

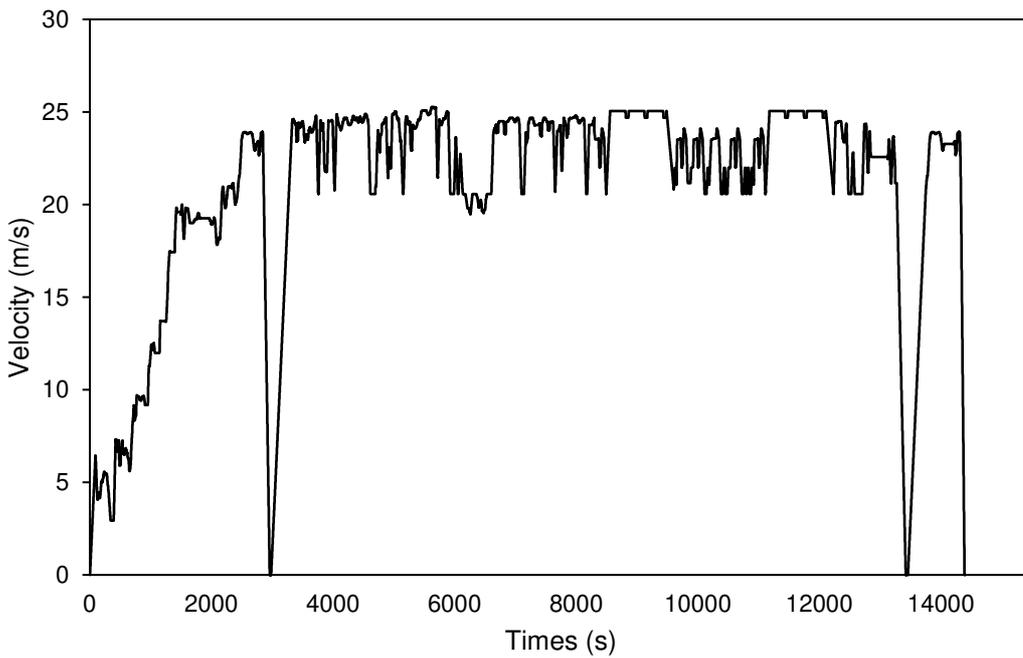


Figure 5. Real world highway driving cycle (300 km).

The thermal performance of the engine has a big effect on energy consumption in TtW process. The engine efficiency ranges from 29.2% to 53.5% [54-56]. The efficiency map is shown in Fig. 6, and the optimum engine efficiency as 45% is taken into account in this study. Besides, the stoichiometric air to fuel ratio (AFR) of NG is another contributing factor of energy loss. AFR of NG is 17, contrasted with diesel 14.6 [28]. If there is insufficient oxygen for transforming the CH_4 to CO_2 and H_2O , the incomplete combustion of fuel will generate CH_4 and other unburned hydrocarbons into atmosphere.

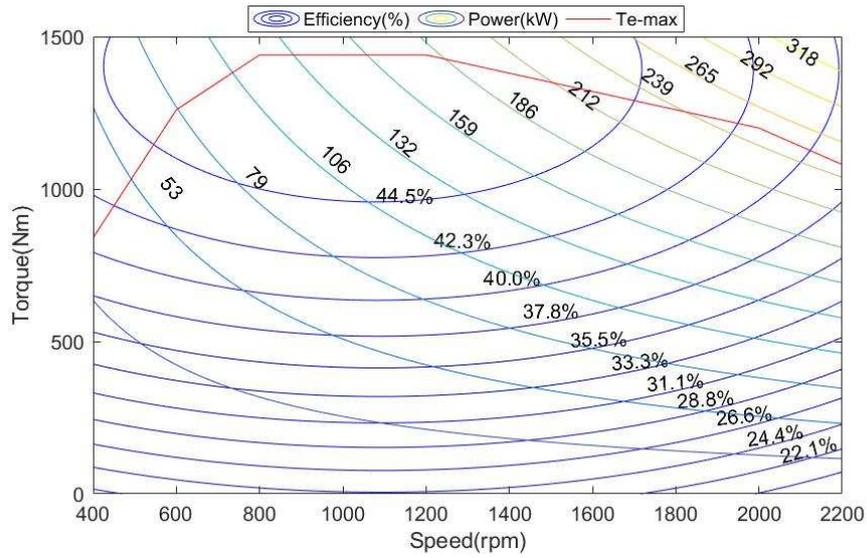


Figure 6. Efficiency map of hybrid electric truck engine

Considering cost saving and energy utilization efficiency, the optimal battery power is achieved by running in 5 different city cycles. The battery charge state is essential for the hybrid electric trucks, which can be illustrated by the State of Charging (SOC) [57]. It refers to the current power contained in the battery, 100% equal to full charge, otherwise, 0% means that the battery is fully discharged. In this study, the range of battery capacity starts at 80% and ends at 30%.

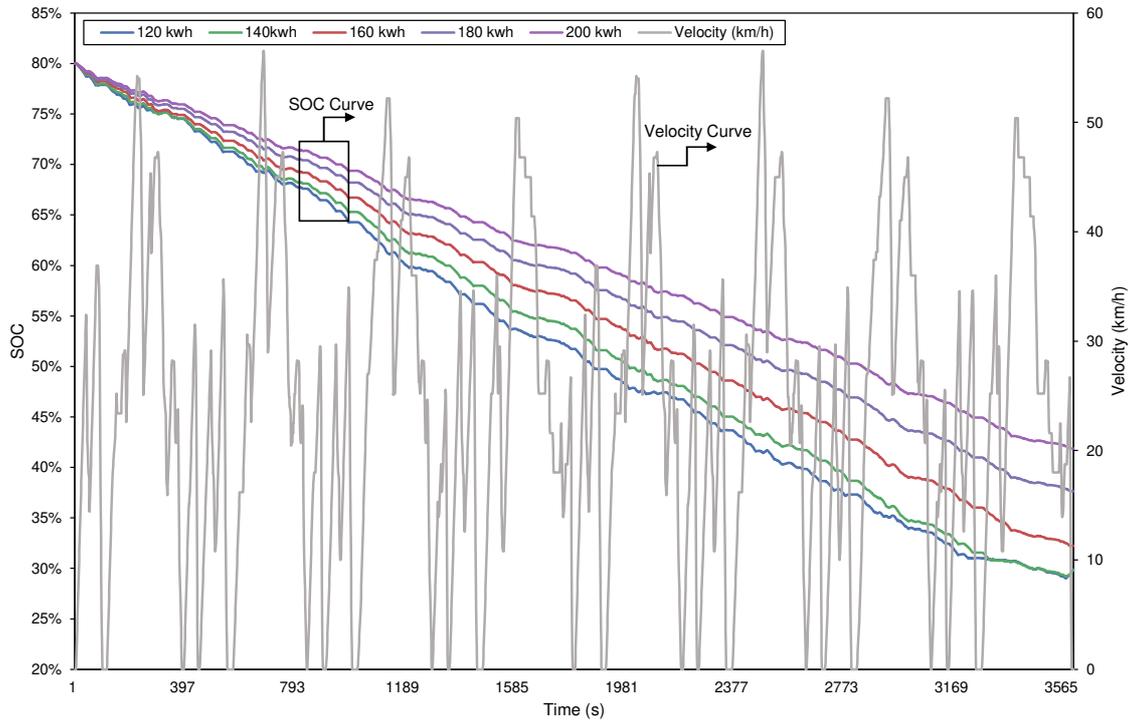


Figure 7. SOC vs. battery capacity variation when running in the city.

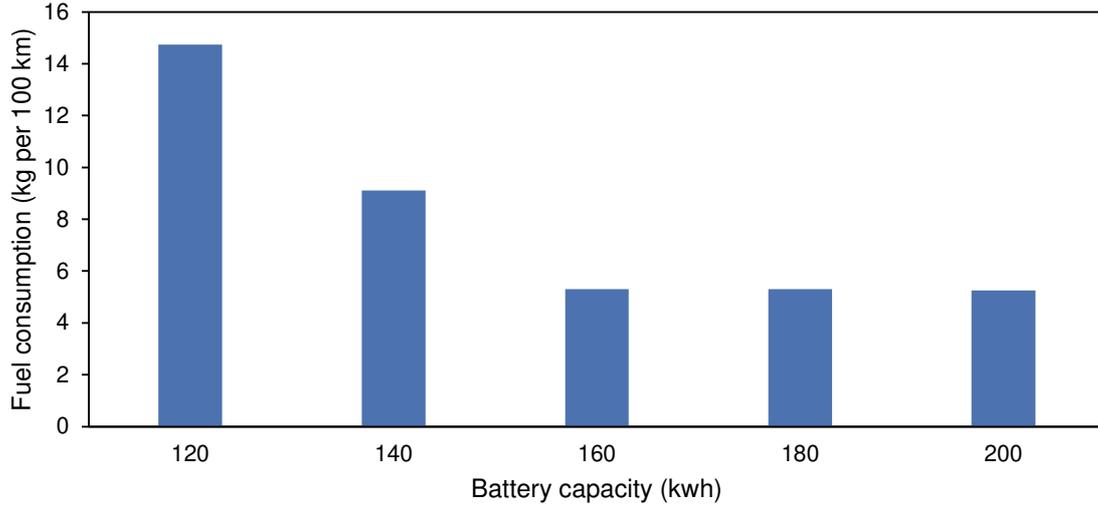


Figure 8. Fuel consumption with different battery capacity when running in the city.

In general, the battery capacity varies from 120 to 200 kWh. For 120 kWh battery, it is not enough to provide kinetic energy to complete 24 km full electric driving. For a 200 kWh battery, there is still 42% power remaining at the end. Considering the truck total weight, a 160 kWh battery is selected through simulation. For the battery weight, it is considered as the ratio of 13.8 kg/kWh [58].

5 RESULTS AND DISCUSSION

In order to further study on the sources of CO₂ emissions and compare results with different countries, CO₂ equivalent emission is introduced as a standard, which is calculated on the GWP values, based on Table 5. The CO₂ equivalent emissions from methane are equal to quantity (in kilograms) of methane emitted multiply by a methane GWP factor. On a 100-year basis, the GHG effect of methane is 30 times more potent than CO₂ [59].

Table 5. Global warming potentials of greenhouse gases: 100-year basis.

Type	AR5/GWP
CO ₂	1
CH ₄	30
N ₂ O	265

The critical parameters are defined as following to make an accurate explanation and comparison. If the methane effect converts into CO₂ equivalents, then the total WtW CO₂ equivalents produced in entire process can be obtained.

$$\text{Total WtW CO}_2 \text{ equivalent emissions} = \text{CO}_2 \text{ emitted during each process} + \text{CO}_2 \text{ equivalent emissions (due to CH}_4 \text{ emissions)}. \quad (10)$$

$$\text{Total TrW CO}_2 \text{ equivalent emissions} = \text{CO}_2 \text{ emitted from CNG combustion} + \text{CO}_2 \text{ equivalent emissions (due to CH}_4 \text{ emissions)}. \quad (11)$$

$$\text{Total WtW CO}_2 \text{ equivalent emissions} = \text{Total WtT CO}_2 \text{ equivalent emissions} + \text{Total TrW CO}_2 \text{ equivalent emissions}. \quad (12)$$

5.1 Uncertainty Analysis

Principal Component Analysis (PCA) is used in order to reduce the parameters of dataset by producing linear combinations of original parameters. PCA breaks down the matrix of initial data to express them as a least-square model [60].

$$X = A \times F + U \quad (13)$$

where, X is the original data matrix; A is the matrix of loadings of the original variables in the new reduced space; F is the matrix of scores of objects or samples; U is the matrix of residuals. PCA aims to reduce the dimensionality of datasets containing many interrelated variables, while retaining as much as possible of the systematic variation in the original data [61]. In the analysis, the large number of parameters are replaced by a few principal components (PCs) parameters.

The PCs are totally independent with each other and ordered so that the first PC (PC1) contains most of the original variation and the second PC (PC2) contains the second largest amounts, etc. PCA was carried out using XLSTAT 2014.5 software.

Due to the large number of parameters that affect the CO₂ and methane emissions, the uncertainties have calculated by selecting the key parameter of each stage of the WtT. Thus, the selection of the key parameters of each stage has found by using PCA. The contributions of the variables in each country are shown in Table 6, and the factor scores are shown in Table 7.

Table 6. The contributions of the variables in each country (%)

Countries	F1	F2	F3
North America	33.312	66.273	0.415
Europe	33.341	21.403	45.256
China	33.347	12.325	54.328

Table 7. The factor scores of key parameters

Parameters	F1	F2	F3	Parameters	F1	F2	F3
a	-0.045	-0.180	-0.020	α_{elepro}	-0.650	-0.016	0.016
b	-0.517	0.180	0.016	$effi_{pro}$	0.090	0.017	-0.022
α_{oilrec}	-0.665	-0.018	0.015	lf_{pro}	-0.666	-0.017	0.016
α_{dierec}	-0.614	0.009	0.050	β_{dieBoi_pro}	-0.415	-0.006	0.004
$\alpha_{gasorec}$	-0.667	-0.016	0.017	$\beta_{diestEng_pro}$	-0.415	-0.006	0.004
α_{NGrec}	-0.008	0.017	-0.034	β_{dieTub_pro}	-0.407	-0.006	0.004
α_{elerec}	-0.656	-0.023	0.029	β_{NGTub_pro}	-0.281	0.000	-0.002
$effi_{recon}$	0.087	0.019	-0.027	$\beta_{NGinBoi_pro}$	-0.281	0.000	-0.002
$effi_{recsha}$	0.077	0.027	-0.027	α_{elecom}	0.112	0.017	-0.021
β_{dieBoi_rec}	-0.477	-0.009	0.007	$effi_{com}$	0.057	0.025	-0.025
$\beta_{diestEng_r}$	-0.281	0.000	-0.002	$\beta_{diestEng_com}$	-0.281	0.000	-0.002
β_{dieTub_rec}	-0.477	-0.009	0.007	β_{dieTub_com}	-0.281	0.000	-0.002
β_{NGEng_rec}	-0.281	0.000	-0.002	β_{NGEng_com}	0.112	0.017	-0.021
β_{NGsBoi_rec}	-0.281	0.000	-0.002	d	9.362	-0.003	0.016
α_{diepro}	-0.656	-0.024	0.022	lf_{tra}	-0.666	-0.017	0.016
α_{NGpro}	0.070	0.022	-0.026				

The PCA results show clearly that the key parameter of three first stages i.e., recovery, processing, and compression is the energy efficiency “ $effi_{recon}$, $effi_{recsha}$, $effi_{pro}$, $effi_{com}$ ”. However, the key parameter of transmission and distribution is the distance “d”. Moreover, the PCA results show that the parameters “a” and “b” which are conventional NG and shale gas respectively, should be taken into consideration for North America.

Monte Carlo analysis as a common method is used to estimate the error model parameters [62]. According to the selected key parameters, a Monte Carlo runs 3000 times has performed in order to calculate the uncertainties of each stage of WtT as shown in Fig. 10 and Fig. 11.

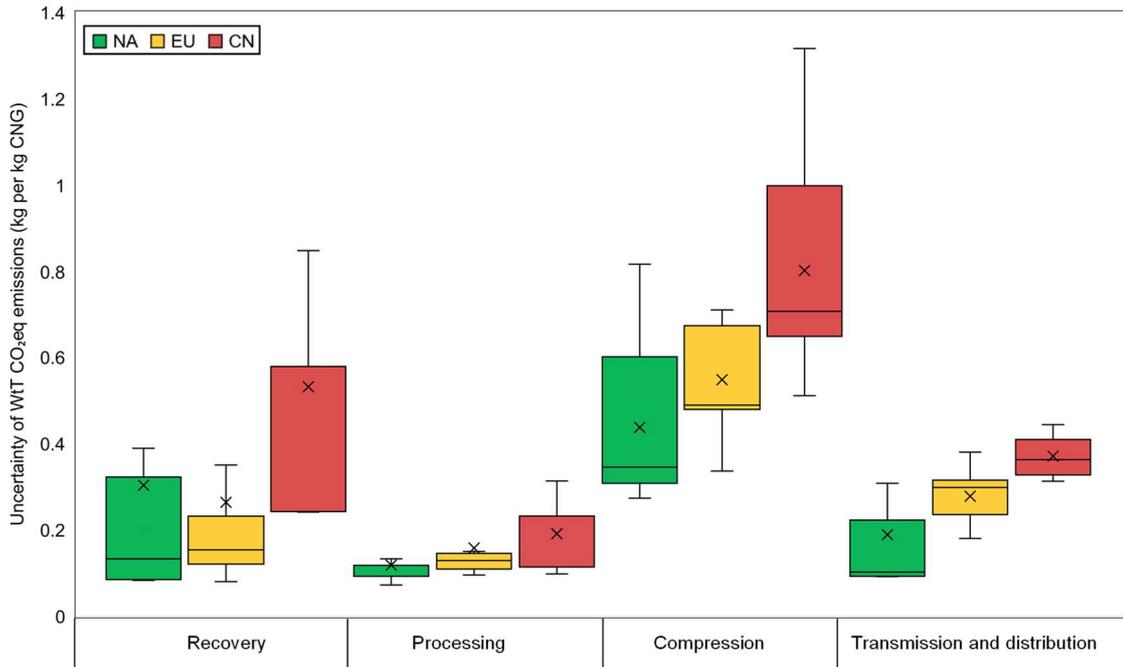


Figure 10. The ranges of WtT CO₂ equivalent emissions in each country

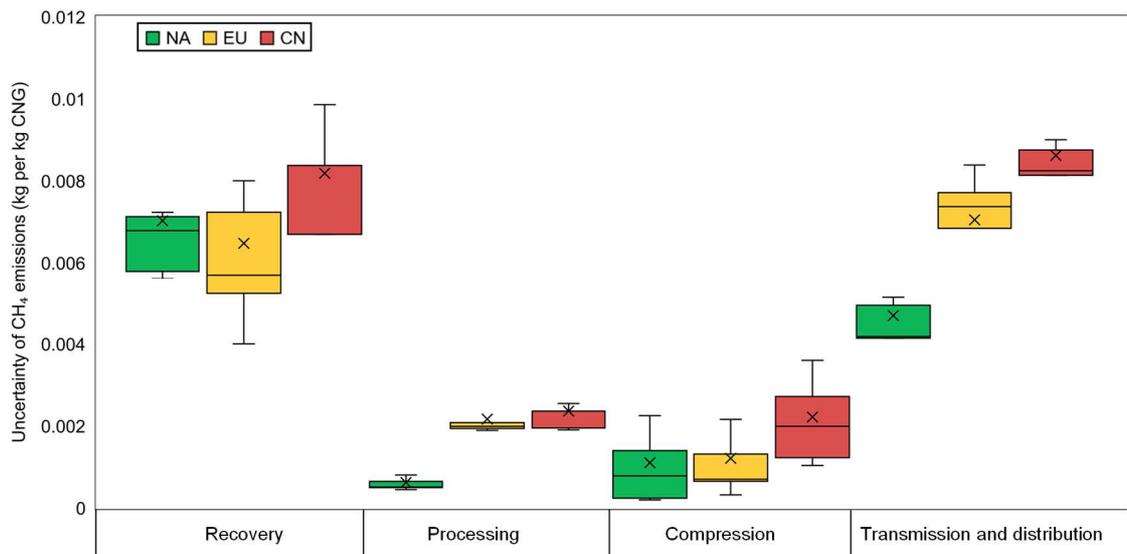


Figure 11. The ranges of WtT CH₄ emissions in each country

Due to the difference in technology between the countries, the variation of energy efficiency is the main source of the uncertainties of CO₂ and CH₄ emissions. In order to make a clear comparison, the mean values are considered as the possible standard for each country.

In terms of CO₂ emissions, the compression stage exhibited the largest interquartile. The values of the compressor efficiency range from 45% to 95%, which results in a huge difference in the final emissions. For the CH₄ emissions, the difference in the processing, compression, transmission and distribution is mostly caused by the proportion variation of process energy which provides power in the upstream stage. The uncertainty in the recovery stage is mostly caused by methane leakage caused by differences in mining methods and equipment.

5.2 Well-to-Tank analysis

Summary of the WtT process, CO₂ is the largest gas emission contributor, accounted for more than 96%, and about 2-3% of gas emissions come from methane emissions. The remaining gases such as N₂O, NO_x, SO_x, etc. are less than 1% which are not solely studied here. Although the CH₄ emissions proportion is not very high but it still has great importance for deep research due to its huge impact on GHGs emissions.

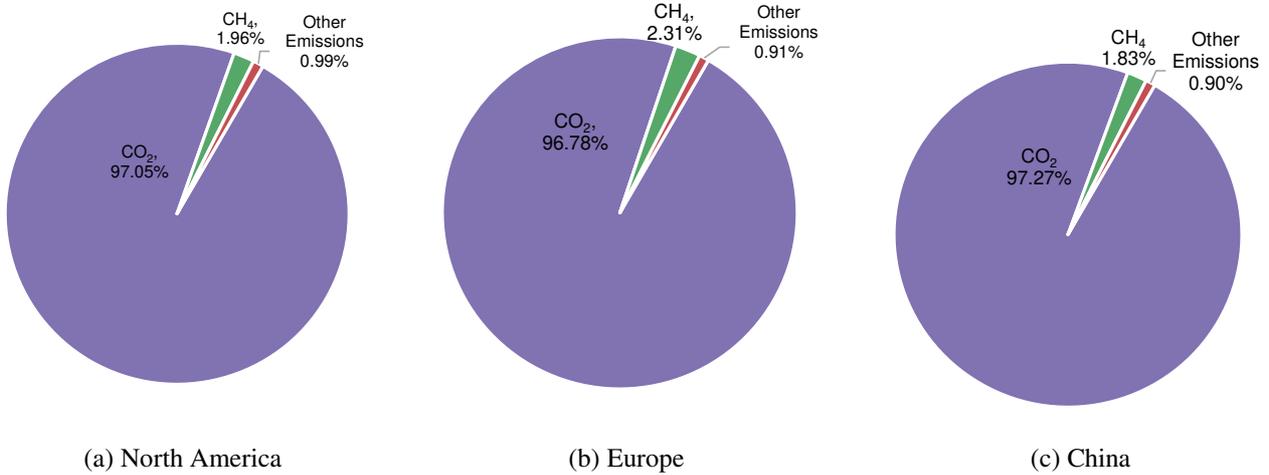


Figure 12. Well-to-Tank process gas emissions proportion.

According to the GWP factor, the CO₂ equivalent emissions of GHG in each stage are calculated. The emissions proportion of different countries are shown in Fig. 13. Among them, CO₂ is the CO₂ emissions produced by the direct use of process fuels, CO₂eq is calculated from other GHG emissions at this stage, since the CH₄ emissions accounted for a large part in WtT stage, it was highlighted in the Fig. 13.

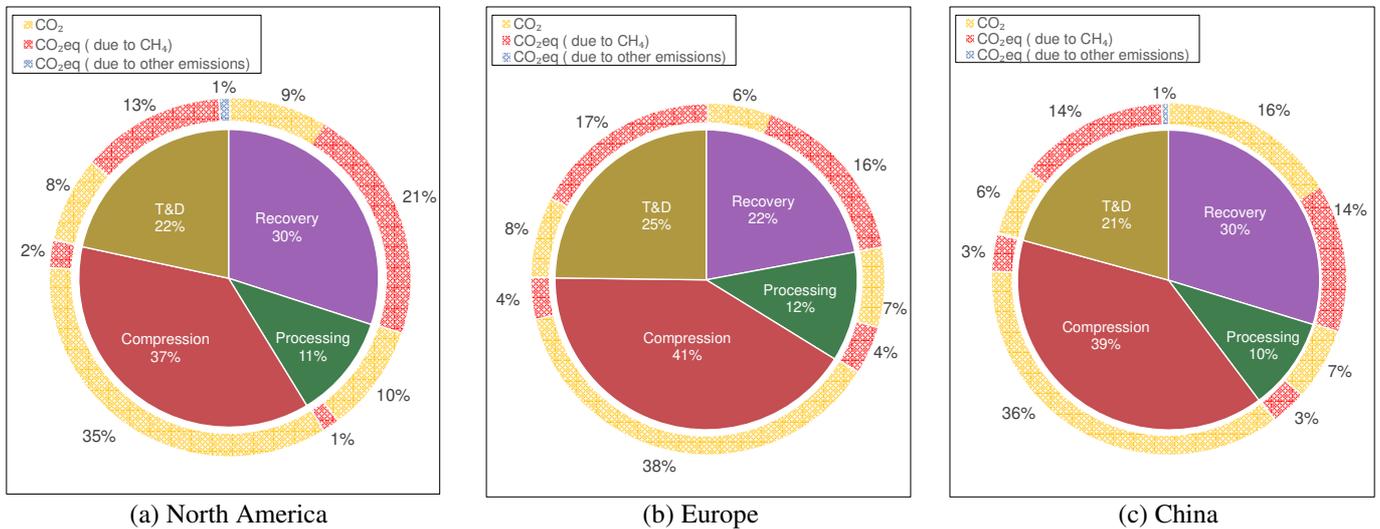


Figure 13. Gas emissions contribution in Well-to-Tank process (base on CO₂ equivalent emissions).

For North America, a large amount of emitted CO₂ come from the compression process, accounting for 37.4% of Total WtT CO₂ equivalent emissions. For Europe, a large amount of CO₂ is emitted into the atmosphere during compression accounted for 41.3% and distribution process, accounted for 24.8% of Total WtT CO₂ equivalent emissions. The biggest CO₂eq contributor of China is the compression and recovery stage, with 30.0% emissions from the recovery phase (16.3% emissions due to CH₄ emissions) and 39.6% from the compression stage. Obviously, the CO₂ equivalent emissions due to CH₄ emissions play an important role in WtT

process, it brought more than 35% increase of Total WtT CO₂ equivalent emissions. The detailed emissions for 1kg CNG production in each stage are shown in Fig. 14, where the CO₂eq caused by other gas emissions is too infinitesimal to discuss here.

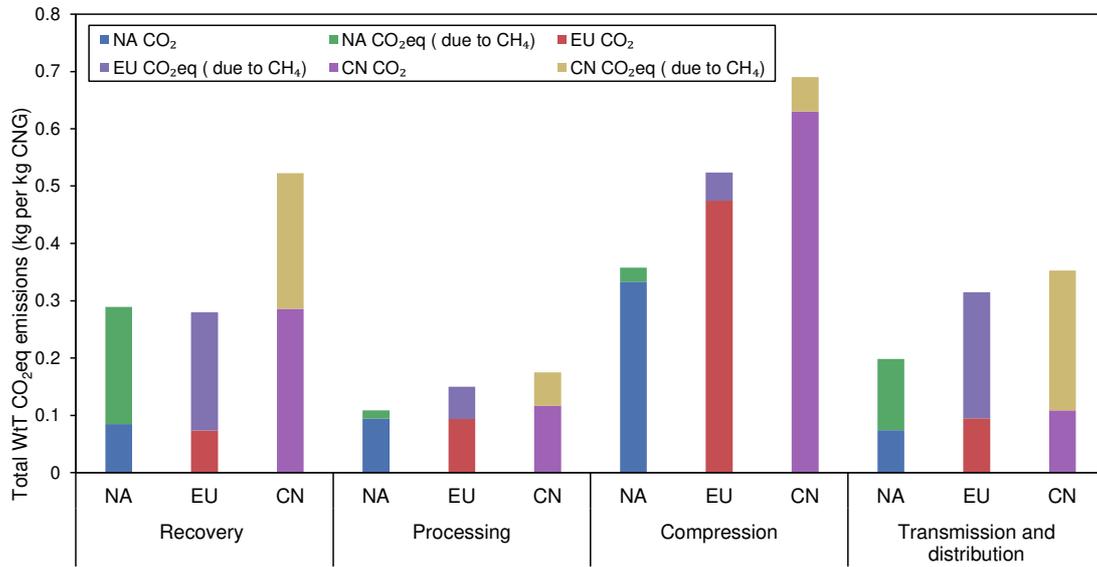


Figure 14. Total Well-to-Tank CO₂ equivalent emissions per kg NG production in each stage.

Obviously, if only considering the CO₂ emissions in each process, the compression process accounted for the most part, which is higher than that of the recovery process for all the countries (about 3-7 times). On the contrary, if the GHG effect factor is taken into consideration, the rise of methane emissions will bring a sharp increase in total WtT CO₂ equivalent emissions, especially in recovery and distribution process. The gap between the recovery and compression process is greatly reduced, which attracts more attention to the recovery process. Compared with each other, China's Total CO₂ equivalent emissions during WtT process are the most, 1.8 times higher than that of North America, the CO₂ equivalent emissions that occurred in the recovery process are obviously higher than other stages.

The variations of different factors like energy conversion efficiency, primary energy supply components, venting and flaring, geographical factors for each country etc. result in the difference of CO₂ equivalent emissions. China has a large number of natural gas resources especially shale gas which can be mass-developed. But the extraction technology still has huge potential to be improved. Improving energy efficiency in the recovery process as soon as possible is a crucial method to reduce CO₂ emissions for all the countries. In addition, effectively recover the flared gases can prevent them emits into atmosphere. Furthermore, the long average distance between the well and filling station also results in more energy consumption and emissions.

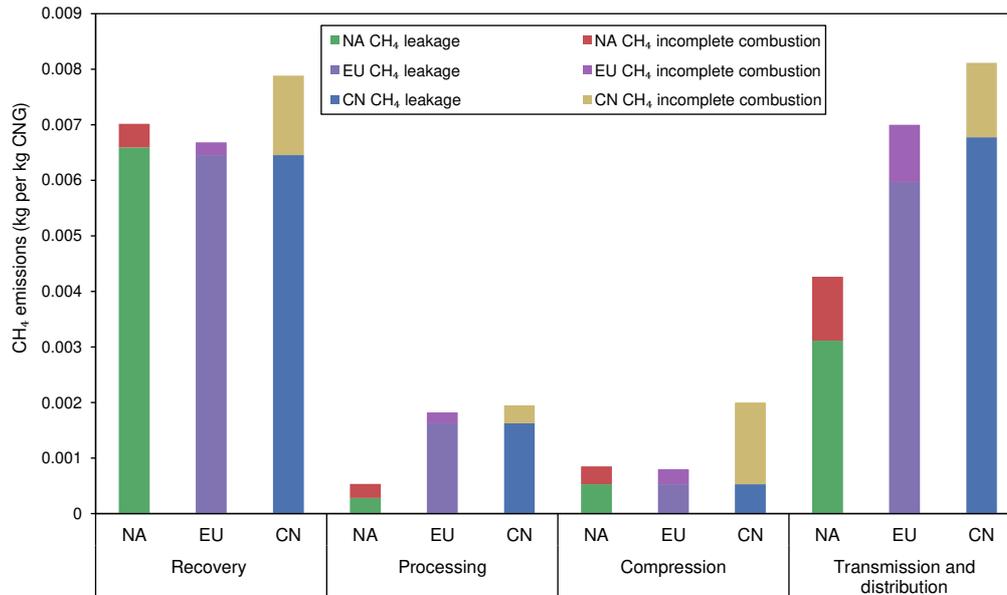


Figure 15. Well-to-Tank CH₄ emissions in each stage between North America, Europe and China.

Fig. 15 describes the number of methane emissions in different stages. As mentioned before, methane emissions consist of two parts, from incomplete fuel combustion and from leakage. The emissions from incomplete combustion are mostly caused by primary energy utilization, these emissions can be reduced by efficiency improving of combustion. The leakage emissions are caused by many reasons which are illustrated in Table 3. About 39.5%-55.3% methane emissions come from recovery process and most part of these emissions coming from the leakage (81.8%-96.5%). The venting and flaring are the main sources of this leakage. The second largest methane emission part is the transmission and distribution stage. And the greater possibility of leakage exits with the longer distribution distance.

5.3 Tank-to-Wheel analysis

The truck system transports high-pressure CNG to the combustion chamber for providing power when the truck running on the highway. After the NG was fully burned in the engine, the CO₂ is released directly into the atmosphere. For a CNG-based heavy hybrid electric truck carrying a 25 t load, 84.43 kg of CO₂ is emitted per 100 km, which accounted for 71.4% CO₂ equivalent emissions of the entire life cycle.

Methane slip or un-oxidized methane emissions usually occurs due to low temperatures of catalyst at lower loading and transient driving cycles. For CNG-based hybrid electric trucks, the methane emissions from TtW assumed to be 0.21%-0.60% [63,64], while for diesel-based trucks have about 0.013%-0.015% of methane emissions [65,66]. The methane emissions continue to increase with the amount of fuel consumed. Although the methane emissions from the CNG trucks is higher than diesel ones, CNG-based hybrid electric trucks still have good performance in fuel consumption and CO₂ emissions. For 25 t load weigh truck, it can save 15.84% energy, and this advantage will be more obvious for heavier trucks as shown in Fig. 16.

The crankcase and tailpipe emissions are the two largest sources in TtW process. If minimizing the engine-out emissions of unburned methane can be minimized, the advantages of CNG-based trucks in terms of emission reduction will become very absolute. The tailpipe methane emissions are various from engine type, truck age, catalyst age, and fuel injection, taking advanced technology may be a good method to solve methane emissions during the truck life cycle. Enforce closed crankcase technology and the methane oxidation activity of the exhaust catalyst improving can be proved to be an effective way to reduce emissions. In addition, dynamic vent capture solutions may be another choice [67].

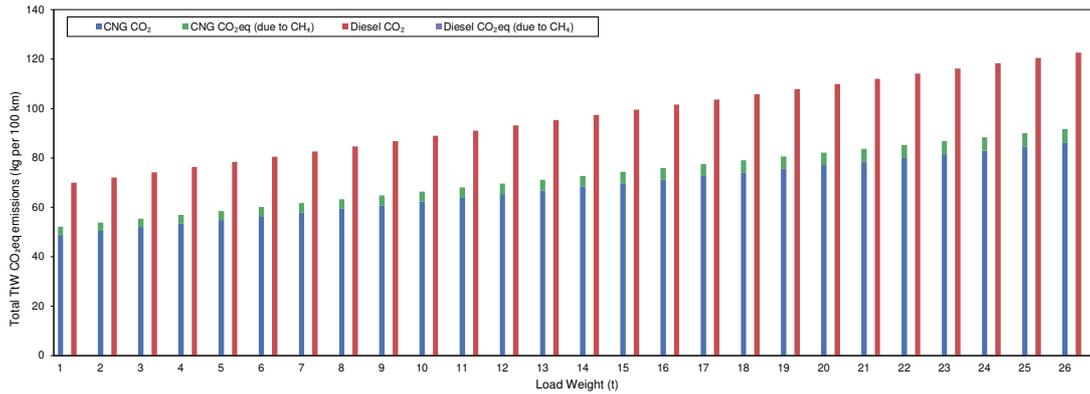


Figure 16. Total Tank-to-Wheel CO₂ equivalent emissions for CNG and diesel-based hybrid truck.

5.4 Well-to-Wheel analysis

Based on the analysis before, the benefits of using CNG as a fuel depend on minimizing CH₄ leakage (mainly in the recovery process) and slip during the entire fuel pathway. Combining the results of WtT and TtW, the obtained total WtW CO₂ equivalent emissions are shown in Fig. 17. Those emissions from WtW are 7.9% higher in Europe and 16.6% higher in China than North America. And about 13.3%-15.5% total WtW CO₂ equivalent emissions are caused by methane emissions due mainly to the methane leakage during the recovery process.

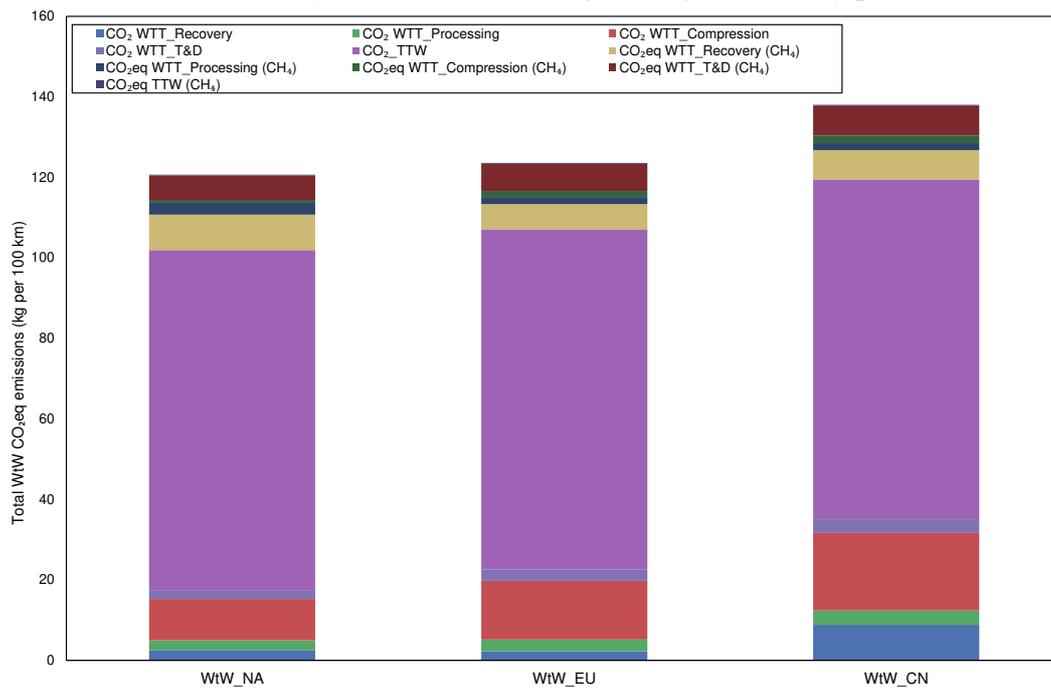


Figure 17. Total Well-to-Wheel CO₂ equivalent emissions in North America, Europe and China.

The CNG combustion during the driving cycle contributes the most total WtW CO₂ equivalent emissions, and the results are different from the load weight. Excluding the combustion part in TtW, a huge amount of CO₂ equivalent emissions come from the WtT stage, which is mainly caused by the methane emissions generated in the recovery process and the CO₂ emissions in the compression process. As shown in Fig. 18, the Total WtT CO₂ equivalent emissions contribute significantly to rise the Total WtW CO₂ equivalent emissions. For North America, the most Total WtT CO₂ equivalent emissions coming from the recovery process are due to high rate of methane emission. For Europe, the methane emissions from recovery process

are almost the same as North America, but the total WtT CO₂ equivalent emissions coming from compression process has a sharp growth. For China, the energy efficiency is lower than other countries which means a large amount of energy is needed to provide equal power with high pollution emissions.

The CNG-based trucks have lower CO₂ equivalent emissions during truck operation, about 9%-19% less than diesel ones. However, that difference is opposite in WtT process. Compared with diesel hybrid electric trucks, the total WtT CO₂ equivalent emissions of CNG-based ones is much higher, especially in China. For CNG-based hybrid trucks, about 25-36% WtW CO₂ equivalent emissions come from WtT process. If methane emissions from upstream can be reduced by 10%, it will bring about a 1.3%-1.5% reduction in CO₂ equivalent emissions in WTW stage. Although this ratio looks small, it will bring about 63-72 million tons of CO₂ equivalent emissions reduction for CNG-based hybrid trucks which are calculated on the number of heavy-duty hybrid vehicles sold now.

Considering the whole fuel value chain, the application of CNG in hybrid electric trucks is still more environmentally friendly than diesel, especially for the heavy-duty trucks. Applying CNG for hybrid electric trucks can reduce about 540-1080 million tons CO₂ equivalent emissions per year. Besides, the benefits of using CNG are different from each country due to complicated factors. If appropriate measures can be applied to reduce methane leakage and slips, the advantages for applying CNG in hybrid electric trucks will become more significant.

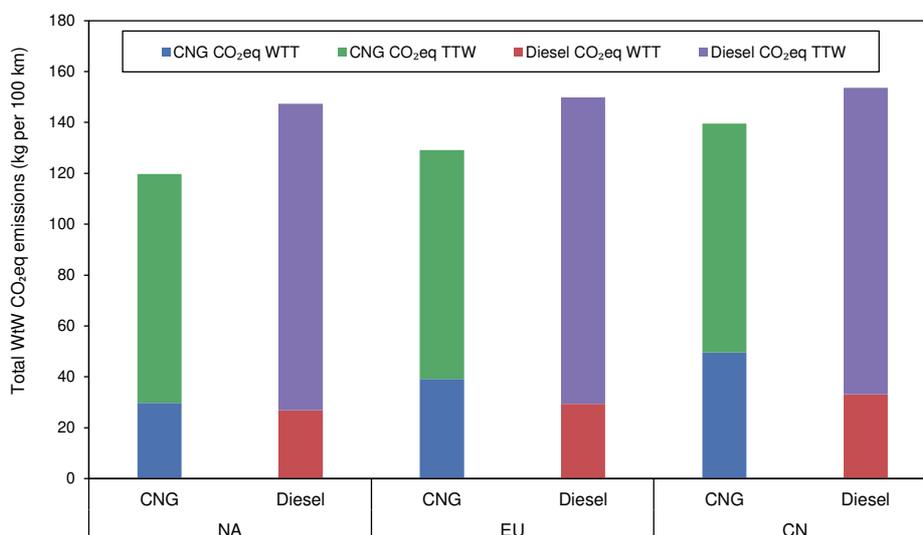


Figure 18. Well-to-Wheel CO₂ equivalent emissions comparison between CNG and diesel.

6 SUMMARY AND SUGGESTIONS

In this study, a detailed overview of the current transportation development and world carbon emissions situation were well introduced. Based on the current environmental pressure and the urgent need for energy conversion, the application of natural gas in heavy-duty hybrid trucks has discovered great potential to achieve carbon neutral targets. This study applying WtW methodology provides a detailed evaluation of CNG-based hybrid electric trucks. The results show the CNG-based hybrid electric trucks have a great opportunity to reduce the WtW CO₂ equivalent emissions, 9.1%-18.7% less than diesel-based trucks. Higher the load weigh appears, more the benefit seems significant. Nevertheless, methane emissions during fuel production and truck operation could reduce this advantage. The CO₂ equivalent emissions of CNG-based hybrid trucks are 10%-33% higher than that of diesel-based trucks in WtT process.

Reducing emissions upstream especially methane emissions will be a key to determine how much climate benefit for CNG-based hybrid electric trucks. The detailed methane leaks points

in different stage are pointed in the above analysis. Effective measures can be taken based on these research results respectively. The emissions of upstream are various form different countries which are different in geography, technology, policies, and other factors. Combing the research results and situation in North America, Europe and China, the following suggestion are recommended.

- Policy strategies.

Although alternative fuels have been used in transportation, the use of traditional energy sources in the fuel production stage is also an apparent source of emissions. Countries around the world should vigorously promote the application of alternative clean fuels, optimize the energy structure, and in particular reduce the proportion of primary energy in upstream of natural gas production. At the same time, applying the hybrid power and electric technology to realize the electrification of heavy-duty vehicles can help to accelerate the reduction of carbon emissions.

- Technology researches.

From energy utilization, improving energy efficiency and combustion efficiency is the key for all countries, especially for compression process. Using intelligent and automatic technology to improve the production efficiency of gas mining, compression efficiency may be a good way. In terms of transportation, the developing countries should speed up the phase-out and replacement of old vehicles, and adopt fuel-saving on-board equipment, such as carbon dioxide analyzers and fuel-saving speed controllers. In the combustion stage, the exhaust gas purification device, high-energy electronic ignition device, etc. are necessary to reduce the emissions.

Routinely venting and flaring emit a large amount of methane into atmosphere, capture technology is used to recover and utilize natural gas emitted during well completion and production, which in line with the economy and environmental protection optimal principles. Similarly, carbon capturing and carbon storage technologies are necessary. For China, it is better to strengthen its research and application in shale gas exploitation and give full play to its abundant shale gas resources.

- Fiscal subsidies.

The purchase of energy-efficient vehicles should be guided by reducing taxes. The countries should adopt price incentives to accelerate the transportation electrification and the fuel tax for urban transportation should be noticed.

- Laws and regulations.

Most of the carbon emissions and methane emissions from upstream are ignored. A greenhouse gas data management system should be established and monitoring targets for energy conservation and emission reduction should be improved. For compressed natural gas production, timely detection and repair of methane leaks in gas wells, processing plants, compression and large distribution facilities, which can help to alleviate the highest emissions situation. By formulating air quality management laws and regulations, the emission from production plants can be controlled.

Putting hybrid electric vehicles and new energy vehicles on the green list and restricting traditional fuel vehicles from driving on peak roads during peak hours are all effective measures to reduce greenhouse gas emissions.

This study identifies a great opportunity to reduce GHG emissions in the background of energy transmission. For different countries, specific analysis has been made based on their own development status. The results of this analysis provide another perspective for the decision makers while setting up transportation policies. Also, it points the direction of technology innovation with the tendency in transportation industry. This report focuses on gas pollution, and does not perform a thorough analysis of different hybrid electric truck powertrain. Optimizing the configuration and powertrain could be another interesting topic for deeper research. Other impacts such as economic benefits and the cost analysis are also beyond the reach of this work. Further studies based on these directions could bring lots of new ideas.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRedit authorship contribution statement

Fujing Zhang: Investigation, Methodology, Writing - original draft. Emil Obeid: Conceptualization, Supervision, Writing - review & editing. Wissam Bounader: Methodology, Supervision, Writing - review & editing. Assaad Zoughaib: Supervision, Writing - review & editing. Xiaobing Luo: Supervision, Writing - review & editing.

References

- [1] Demirbas A. Bioenergy, global warming, and environmental impacts. *Energy sources* 2004; 26:225-236.
- [2] Lindsey R. Climate news, stories, images, & video (ClimateWatch Magazine).
- [3] Ritchie H, Roser M. CO₂ and greenhouse gas emissions. *Our world in data* 2017.
- [4] Chambliss S, Miller J, Façanha C, et al. The impact of stringent fuel and vehicle standards on premature mortality and emissions. *The International Council on Clean Transportation* 2013.
- [5] EEA. Greenhouse gas emissions from transport in Europe. 2019.
- [6] EPA U. Fast facts on transportation greenhouse gas emissions, 2020.
- [7] Agency IE. CO₂ Emissions from Fuel Combustion 2018, 2018.
- [8] Todts W. Europe's lost decade of truck fuel economy, 2015.
- [9] Ambel CC. Too big to ignore – truck CO₂ emissions in 2030, 2015.
- [10] Nahlik MJ, Kaehr AT, Chester MV, et al. Goods movement life cycle assessment for greenhouse gas reduction goals. *Journal of Industrial Ecology* 2016; 20:317-328.
- [11] Commission E. Alternative Fuels Expert group report, 2017.
- [12] Hekkert MP, Hendriks FH, Faaij AP, et al. Natural gas as an alternative to crude oil in automotive fuel chains well-to-wheel analysis and transition strategy development. *Energy policy* 2005; 33:579-594.
- [13] Administration USEI. How much carbon dioxide is produced when different fuels are burned ? 2020.
- [14] García-Olivares A, Solé J, Osychenko O. Transportation in a 100% renewable energy system. *Energy Conversion and Management* 2018; 158:266-285.
- [15] Le Fevre C. A review of prospects for natural gas as a fuel in road transport. *Oxford Institute for Energy Studies: Oxford, UK* 2019.
- [16] Hagos DA, Ahlgren EO. Well-to-wheel assessment of natural gas vehicles and their fuel supply infrastructures—Perspectives on gas in transport in Denmark. *Transportation Research Part D: Transport and Environment* 2018; 65:14-35.
- [17] Sihvonen J. CNG and LNG for vehicles and ships - the facts 2018.
- [18] DOE U. An assessment of energy technologies and research opportunities. *Quadrennial Technology Review. United States Department of Energy* 2015.
- [19] Capuano L. International energy outlook 2018 (IEO2018). *US Energy Information Administration (EIA). Washington, DC, USA* 2018; 2018:21.
- [20] Yang Z, Wang B, Jiao K. Life cycle assessment of fuel cell, electric and internal combustion engine vehicles under different fuel scenarios and driving mileages in China. *Energy* 2020; 117365.
- [21] Talebian H, Herrera OE, Tran M, et al. Electrification of road freight transport: Policy implications in British Columbia. *Energy policy* 2018; 115:109-118.
- [22] García A, Monsalve-Serrano J, Martinez-Boggio S, et al. Dual fuel combustion and hybrid electric powertrains as potential solution to achieve 2025 emissions targets in medium duty trucks sector. *Energy Conversion and Management* 2020; 224:113320.
- [23] Grigoratos T, Fontaras G, Martini G, et al. A study of regulated and greenhouse gas emissions from a prototype heavy-duty compressed natural gas engine under transient and real life conditions. *Energy* 2016; 103:340-355.
- [24] Vallero DA: Air pollution calculations. Quantifying pollutant formation, transport, transformation, fate and risks, Elsevier, 2019.

- [25] Kang M, Christian S, Celia MA, et al. Identification and characterization of high methane-emitting abandoned oil and gas wells. *Proceedings of the National Academy of Sciences* 2016; 113:13636-13641.
- [26] Bradbury J, Clement Z, Down A. Greenhouse gas emissions and fuel use within the Natural gas supply chain—Sankey Diagram Methodology. Office of Energy Policy and Systems Analysis. United States Department of Energy, Washington, DC. July 2015.
- [27] Allen DT, Torres VM, Thomas J, et al. Measurements of methane emissions at natural gas production sites in the United States. *Proceedings of the National Academy of Sciences* 2013; 110:17768-17773.
- [28] Khan MI, Shahrestani M, Hayat T, et al. Life cycle (well-to-wheel) energy and environmental assessment of natural gas as transportation fuel in Pakistan. *Applied Energy* 2019; 242:1738-1752.
- [29] Gupta S, Patil V, Himabindu M, et al. Life-cycle analysis of energy and greenhouse gas emissions of automotive fuels in India: Part 1—Tank-to-Wheel analysis. *Energy* 2016; 96:684-698.
- [30] Lajunen A, Lipman T. Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses. *Energy* 2016; 106:329-342.
- [31] Fulton L, Lah O, Cuenot F. Transport pathways for light duty vehicles: towards a 2 scenario. *Sustainability* 2013; 5:1863-1874.
- [32] Rousseau A, Sharer P. Comparing apples to apples: well-to-wheel analysis of current ICE and fuel cell vehicle technologies. *SAE transactions* 2004; 610-619.
- [33] Curran SJ, Wagner RM, Graves RL, et al. Well-to-wheel analysis of direct and indirect use of natural gas in passenger vehicles. *Energy* 2014; 75:194-203.
- [34] Kollamthodi S, Norris J, Dun C, et al. The role of natural gas and biomethane in the transport sector. Final Report Report for Transport and Environment (T&E), Issue 2016.
- [35] Alvarez RA, Pacala SW, Winebrake JJ, et al. Greater focus needed on methane leakage from natural gas infrastructure. *Proceedings of the National Academy of Sciences* 2012; 109:6435-6440.
- [36] Commission CE. Full fuel cycle assessment well to tank energy inputs, emissions, and water impacts, Cupertino, 2007.
- [37] Ross JK. The economic benefits of HEPA-grade filtration for gas turbine operation in the power generation industry.
- [38] Gascoyne C, Aik A. Unconventional Gas and Implications for the LNG Market. Pacific Energy Summit, Jakarta, February 2011; 21-23.
- [39] Lixue J, Xunmin O, Linwei M, et al. Life-cycle GHG emission factors of final energy in China. *Energy Procedia* 2013; 37:2848-2855.
- [40] Shang C, Guo F. The state of the art of long-distance gas pipeline in China. *Gas Energy* 2018; 1:24-29.
- [41] Xunmin O. Life Cycle Analysis on Liquefied Natural Gas and Compressed Natural Gas in Heavy-duty Trucks with Methane Leakage Emphasized. *Energy Procedia* 2019; 158:3652-3657.
- [42] Moniz E J, Jacoby H D, Meggs A J M, et al. The future of natural gas[J]. Cambridge, MA: Massachusetts Institute of Technology, 2011.
- [43] Ran Q, Wang Y, Sun Y, et al. Volcanic gas reservoir characterization[M]. Elsevier, 2014.
- [44] Kurz R, Brun K. Upstream and Midstream Compression Applications: Part 1—Applications[C]. Turbo Expo: Power for Land, Sea, and Air. American Society of Mechanical Engineers, 2012, 44724: 11-21.
- [45] Moshfeghian M. How to Estimate Compressor Efficiency? *PetroSkills*. July 2015.
- [46] Bruschi R, Ercolani D, Donati E. Long distance transport of natural gas by high pressure pipelines[C]. 16th World Petroleum Congress. World Petroleum Congress, 2000.
- [47] Wei W, Peng X, Hou Y, et al. Gas in China[J]. The Impacts and Benefits of Structural Re-forms in the Transport, Energy and Telecommunications sectors. Adelaide: APEC Policy Support Unit, 2011: 370-384.
- [48] Bjørnmose J, Roca F, Turgot T, et al. An assessment of the gas and oil pipelines in Europe[J]. European Parliament, Brussels, 2009.

- [49] NEED. Intermediate Energy Infobook, 2019.
- [50] Exhibit O. Reducing Methane Emissions: Best Practice Guide. 2019.
- [51] Clark C, Han J, Burnham A, et al. Life-cycle analysis of shale gas and natural gas, Argonne National Lab.(ANL), Argonne, IL (United States), 2012.
- [52] Kraus RS. Petroleum refining process. Retrieved February 2011; 3:2013.
- [53] Elgin III RC,Hagen CL. Development and operation of a self-refueling compressed natural gas vehicle. *Applied Energy* 2015; 155:242-252.
- [54] Woodrooffe J. Reducing truck fuel use and emissions: Tires, aerodynamics, engine efficiency, and size and weight regulations[R]. University of Michigan, Ann Arbor, Transportation Research Institute, 2014.
- [55] Thiruvengadam A, Pradhan S, Thiruvengadam P, et al. Heavy-duty vehicle diesel engine efficiency evaluation and energy audit[J]. West Virginia University <http://www.theicct.org/heavy-duty-vehicle-diesel-engineefficiency-evaluation-and-energy-audit>, 2014.
- [56] Xin Q, Pinzon C F. Improving the environmental performance of heavy-duty vehicles and en-gines: key issues and system design approaches[J]. *Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance*, 2014: 225-278.
- [57] Feng Y,Dong Z. Optimal control of natural gas compression engine hybrid electric mining trucks for balanced fuel efficiency and overall emission improvement. *Energy* 2019; 189:116276.
- [58] Bou Nader WS, Mansour CJ, Nemer MG, et al. Exergo-technological explicit methodology for gas-turbine system optimization of series hybrid electric vehicles. *Proceedings of the institution of mechanical engineers, Part D: journal of automobile engineering* 2018; 232:1323-1338.
- [59] Ehhalt D, Prather M, Dentener F, et al. Atmospheric chemistry and greenhouse gases, Pacific Northwest National Lab.(PNNL), Richland, WA (United States), 2001.
- [60] Younes K, Grasset L. The application of DFRC method for the analysis of carbohydrates in a peat bog: Validation and comparison with conventional chemical and thermochemical degradation techniques[J]. *Chemical Geology*, 2020, 545: 119644.
- [61] Jolliffe I T, Morgan B J T. Principal component analysis and exploratory factor analysis[J]. *Statistical methods in medical research*, 1992, 1(1): 69-95.
- [62] Verbeeck H, Samson R, Verdonck F, et al. Parameter sensitivity and uncertainty of the forest carbon flux model FORUG: a Monte Carlo analysis[J]. *Tree physiology*, 2006, 26(6): 807-817.
- [63] Delgado A,Muncrief R. Assessment of heavy-duty natural gas vehicle emissions: Implications and policy recommendations 2015. International Council on Clean Transportation: Washington, USA 1-42.
- [64] Dunn M E, McTaggart-Cowan G P, Saunders J. High efficiency and low emission natural gas engines for heavy duty vehicles[M]//*Internal Combustion Engines: Performance, Fuel Economy and Emissions*. Woodhead Publishing, 2013: 123-136.
- [65] Thiruvengadam A, Besch M, Carder D, et al. Unregulated greenhouse gas and ammonia emissions from current technology heavy-duty vehicles. *Journal of the Air & Waste Management Association* 2016; 66:1045-1060.
- [66] Dunn M E, McTaggart-Cowan G P, Saunders J. High efficiency and low emission natural gas engines for heavy duty vehicles[M]//*Internal Combustion Engines: Performance, Fuel Economy and Emissions*. Woodhead Publishing, 2013: 123-136.
- [67] Oscar Delgado RM. Assessment of Heavy-Duty Natural Gas Vehicle Emissions: Implications and Policy Recommendations, The International Council on Clean Transportation, 2015.