Natural Gas as a Fuel for Heavy Goods Vehicles

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1 Introduction

1.1 Context

The transport sector plays a vital role in economic activity and mobility across the globe, supporting national and international movement and trade. Between 2000-2015, the energy consumed by the road freight sector grew by 50% (23 EJ to 36 EJ) and in 2017, 32% of transport-related energy demand was due to road freight [1]. By 2030, the World Bank predicts that global freight volumes could grow by 70%, which is greater than the forecasted 50% growth in passenger traffic [2]. In OECD countries, transport is the sector that is most dependent on oil as its primary energy source, illustrated in Figure 1 [3]. The primary energy source for road freight are petroleum-derived fuels, accounting for more than 97% of the final sectoral energy [3]. The importance of oil as a fuel source for the transport sector is evident; however, there are considerable downsides to oil dependence.

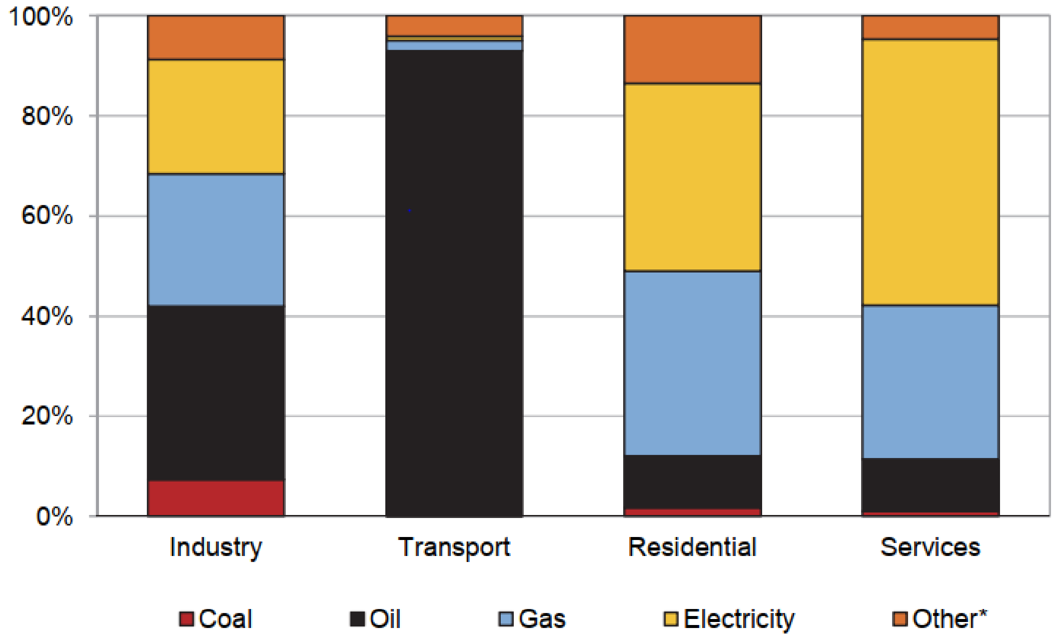

Figure 1: Sources and proportion of energy used by sector across OECD countries in 2016, from [3].

Greenhouse gas (GHG) emissions from the transport sector have increased at a faster rate than any other energy-consuming sector [4]. In 2010, the combined transport sector (including road, rail, aviation, etc.) was responsible for 14% of the total global carbon dioxide (CO_2) emissions [4]. In the UK, despite progress in reducing GHG emissions produced by the transportation sector, GHG emissions from heavy goods vehicles (HGVs) during the period 2003-2015 saw a reduction of only 2.7%, significantly less than the reductions for light vans (20.7%), buses and coaches (24.2%), and cars and taxis (10.2%) [5]. Furthermore, approximately 70% of the CO_2 produced by HGVs in the UK are emitted during long haul and regional duty cycles. Therefore, there is a need decarbonise HGVs for the transport sector to meet climate change targets.

The emissions produced by HGVs are also relevant in the context of urban transport, where noxious emissions can have detrimental impacts on public health. Approximately 54% of the world's population lived in an urban area in 2014, and this figure is expected to rise to 66% by 2050 (or 60% by 2030) [6]. In London, the total mortality burden due to poor air quality is equivalent to approximately 9,400 deaths annually, with the economic costs of these health impacts estimated to be up to £3.7 bn [7]. HGVs contribute to reduced air quality due to the emission of a range of air pollutants, including nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO) and unburned hydrocarbons. For example, in London in 2010, HGVs were found to be responsible for 7.6% of NOx, and 3.1% of PM10 emissions [8].

Alternative fuel sources offer the potential to decarbonise and reduce the oil dependency of the road freight sector, however, they currently account for only 3.4% of final energy in road freight transport (2.2% biofuels and 1.2% natural gas) [1]. Natural gas has been considered as an alternative to diesel for HGVs for a variety of reasons. The main drivers for natural gas in HGVs include energy security, economics, operating noise reduction, and the potential to reduce emissions (of GHGs and air pollutants) and noise. Natural gas has a lower CO2 intensity compared to diesel [9]; the principal component of natural gas, methane (CH4), has a higher ratio of hydrogen to carbon atoms (4:1) than the average for diesel (~2:1), and therefore less CO2 is emitted per unit of chemical energy released by combustion [10].

The lower carbon content of natural gas compared to diesel does not necessarily result in reduced GHG emissions across the well-to-wheel (WTW) lifecycle once methane leakages are taken into account [1]. Methane has a global warming effect that is 28-34 times higher than CO2 over a 100 year time horizon [11]. Therefore, any methane leakage can offset the lower carbon intensity of natural gas. The global warming potential (GWP) of methane for 20- and 100-year time horizons is presented in Table 1. Methane leakages can occur throughout the fuel supply chain and operation of the vehicle. As such, it is important to consider GHG emissions across the entire well-to-wheel lifecycle [1].

Table 1: Global Warming Potential CO2-equivalent for methane (the lower and upper bounds are without and with climate-carbon feedbacks[1], respectively) [11].

Global Warming Potential	Methane (CH4)
20-year time horizon	84-86
100-year time horizon	28-34

1.2 Types of Road Freight Vehicles

There is a notable variation in the types of vehicles used for road freight, with different vehicles used for specific applications across a wide range of weight categories. There are also differences in the categorisation of vehicle types across the world, as demonstrated in Table 2 which shows the different vehicle weight categories across various major markets. HGVs are typically defined as commercial vehicles with a gross vehicle weight greater than 15 tonnes, serving long-haul routes, have two to four (or more) axles, and a power rating between 200-600 kW. The International Energy Agency estimates that HGVs account for approximately 70% of freight activity and about 50% of truck energy use [1]. Figure 2 illustrates the dependence of HGVs for freight transport in the European Union (EU), where more than 90% of freight tonne-kilometres are completed on vehicles with a maximum gross vehicle weight exceeding 20 t [12]. While electrification is gaining traction for passenger and light-duty vehicles, HGVs (and long-distance freight transport) remain dependent on oil as a fuel source.

[1] The Intergovernmental Panel on Climate Change states that despite the significant uncertainties in the carbon cycle, including climate-carbon feedback for non-CO2 gases (as well as CO2) provides a better estimate of the global warming potential [11].

Table 2: Heavy vehicle classification schemes in the United States, European Union, China, and Japan [1].

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<tr><th colspan="2">United States</th><th colspan="4">European Union</th><th colspan="4">China</th><th colspan="4">Japan</th></tr>
<tr><th>Vehicle Category</th><th>Weight [t]</th><th>Vehicle Category</th><th>Weight [t]</th><th>Trailers & Semitrailers Category</th><th>Weight [t]</th><th>Trucks Category</th><th>Weight [t]</th><th>Tractors Category</th><th>Weight [t]</th><th>Trucks Category</th><th>Weight [t]</th><th>Tractors Category</th><th>Weight [t]</th></tr>
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<tr><td>4</td><td>6.35-7.26</td><td rowspan="3">O2</td><td rowspan="3">0.75-3.5</td><td colspan="2">5.5-7</td></tr>
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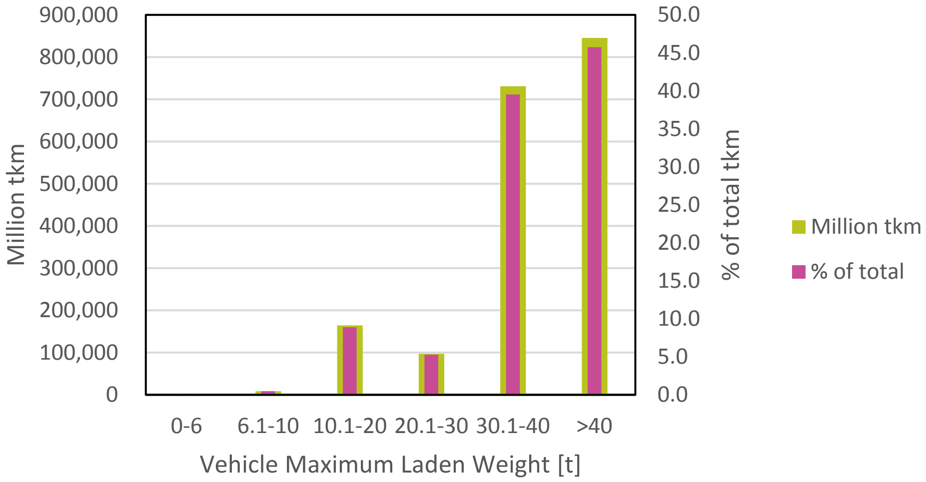

Figure 2: Million tonne-kilometres (tkm) by vehicle maximum laden weight in the EU-28 [12].

1.3 Natural Gas Heavy Goods Vehicles

There are currently over 26 million natural gas vehicles and over 31,000 refuelling stations across the world, with over 50% of these vehicles in China, Iran, and India [13]. Despite the rapid uptake of natural gas vehicles in developing countries, the Intergovernmental Panel on Climate Change (IPCC) predicts that by 2050, the biggest transport energy consumers will continue to be North America (by a significant margin), followed by Europe and China [11]. However, the majority of these vehicles are not freight vehicles, with natural gas HGVs accounting for about 1% of total stock in 2015 [1]. These heavy-duty vehicles have been used for various applications including refuse collection, buses, and freight delivery.

In the United States, the use of natural gas trucks became more attractive with the expansion of domestic shale and tight gas production, leading to a dramatic drop in wellhead natural gas prices from 2009. The Fixing America's Surface Transportation Act, which requires that the United States Department of Transportation sets aspirational targets for the deployment of infrastructure for alternative fuels along key corridors, has promoted the development of natural gas stations since 2015 [1] such that there are now 1,680 compressed natural gas (CNG) stations and 144 liquified natural gas (LNG) stations [14]. In the North American market, several natural gas HGV models are offered from different original equipment manufacturers.

The market growth for natural gas trucks in China has been driven by several factors including the favourable price differential to diesel, the low costs of retrofitting existing vehicles to run on CNG, and government policies aimed at improving air quality. The use of natural gas in transport has increased by an annual growth rate of approximately 11% between 2010 and 2016, of which a significant share is attributed to natural gas trucks [1]. The number of stations supplying natural gas in China has grown from around 1,000 in 2008 to 7,950 in 2016, and the number of LNG heavy-duty vehicles grew from 7,000 in 2010 to 132,000 in 2015 [1].

In the EU, there are approximately 9,350 medium- and heavy-duty natural gas trucks, with over 80% of these trucks operating in Italy, Sweden, Spain, and France [15]. Compared to China and the United States, there is less of a cost advantage of natural gas in Europe and fewer government incentives have been offered. However, the Alternative Fuels Infrastructure Directive requires EU member states to develop national policy frameworks to promote and develop the relevant infrastructure for alternative fuels including CNG and LNG. The directive suggests that the average distance between refuelling stations should be 150 km and 400 km for CNG and LNG, respectively [16].

1.4 Compressed Natural Gas Versus Liquefied Natural Gas

Natural gas is a mixture of paraffinic hydrocarbons such as methane, ethane, propane, and butane. Small amounts of higher hydrocarbons, such as ethylene, may be present and trace amounts of hydrogen sulphide and nitrogen may also be present. The energy density (per unit weight and volume) for several transportation fuels, including LNG and CNG, are shown in Figure 4. The energy content of natural gas (CNG or LNG) per unit weight is approximately 15% higher than diesel fuel (using typical net calorific values of 50 MJ/kg and 43 MJ/kg for natural gas and diesel, respectively) [17], indicating that natural gas can offer the same amount of energy for less weight.

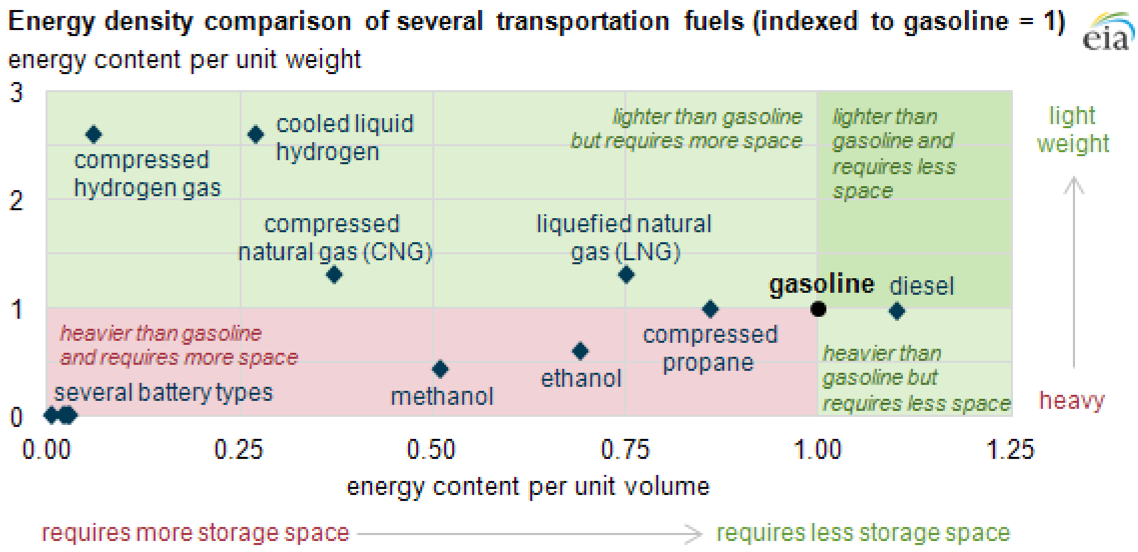

Figure 3: Comparison of the energy density of various transport fuels, from [18].

However, natural gas has a significantly lower density than diesel; at atmospheric temperature and pressure the density of natural gas is approximately 1,000 times lower than diesel. Natural gas must be either compressed to a pressure of 200-300 bar (CNG) or liquefied by cooling it to -162°C (LNG) to increase the volumetric energy density so that it can be stored on the vehicle in on-board cylinders [19]. LNG is approximately 600 times denser than natural gas at atmospheric temperature and pressure (CNG is only 200-300 times denser). This means that LNG can offer 2-3 times the energy for the same capacity fuel tank, directly translating to 2-3 times greater vehicle range. However, the energy content of LNG per unit volume is still below diesel (Figure 4), meaning that LNG storage tanks would take up more space on the vehicle.

1.5 Scope and Objectives

The objective of this report is to evaluate the literature to ascertain the potential for natural gas to reduce lifecycle greenhouse gas emissions produced by road freight. As discussed, HGVs operating on long-distance routes are responsible for the majority of freight activity. For such applications, LNG offers a greater range advantage compared to CNG. Therefore, this review is focused on HGVs (with a gross vehicle weight greater than 15 tonnes) and LNG powertrains. Where we use evidence from other types of vehicles, this will be highlighted explicitly. For perspective, we refer back to diesel HGVs, currently the dominant fuel.

We review published literature on existing and future natural gas HGVs across the fuel supply chain (well-to-pump, WTP), refuelling (pump-to-tank, PTT), and vehicle operation (tank-to-wheel, TTW). These three phases are combined to become a well-to-wheel (WTW) analysis. LNG and CNG pathways are different in the WTP and PTT aspects, however, natural gas engine technologies can operate with either CNG or LNG. Therefore, we include data on CNG heavy vehicles in the TTW phase, but the focus of the other sections is on LNG. A secondary objective is to evaluate whether natural gas offers additional benefits in terms of tailpipe emissions of air pollutants.

The types of emissions investigated in this report across the WTW lifecycle are outlined in Table 3.

Table 3: The types of emissions investigated in each phase of the well-to-wheel analysis in this report.

	Emission Type						
	CO2	**CH4**	**N2O**	**NMHC**	**NOx**	**CO**	**PM**
Well-to-pump	√	√					
Pump-to-tank		√					
Tank-to-wheel	√	√	√	√	√	√	√

1.6 Report Structure

The report is structured as follows:

- Section 2 provides an overall WTW systems analysis to identify the factors that influence the ability of LNG to be an environmentally viable alternative fuel for HGVs.
- Section 3 examines the WTP phase of the LNG supply chain and the range of methane emissions produced during this stage.
- Section 4 investigates the mechanisms and ranges of methane leakage during the storage and refuelling phases (PTT stage).
- Section 5 focuses on the TTW, which assesses the literature on the various natural gas engine technologies, GHG emissions produced (CO2 and CH4), and the air pollutants that affect air quality. An evaluation of the literature surrounding current and predicted future fuel efficiency of natural gas HGVs is also presented.
- Section 6 presents a synthesis of the literature review and identifies where current and future natural gas engines need to be in terms of fuel efficiency and emissions compared to diesel engines.

2 Well-to-Wheel Systems Analysis

The entire WTW lifecycle of LNG as a vehicle fuel is outlined in Figure 4, beginning with the production, transmission, and storage of the natural gas, further processing and transport to refuelling stations, operations at fuelling stations, and ending with the vehicle operation [20]. The methane leakage rate across the WTW lifecycle is the principal factor for evaluating any potential environmental benefits to using natural gas as an alternative fuel source for HGVs. It should be noted that embedded/embodied emissions are considered out of the scope as for high-mileage HGVs operational emissions are likely to dominate.

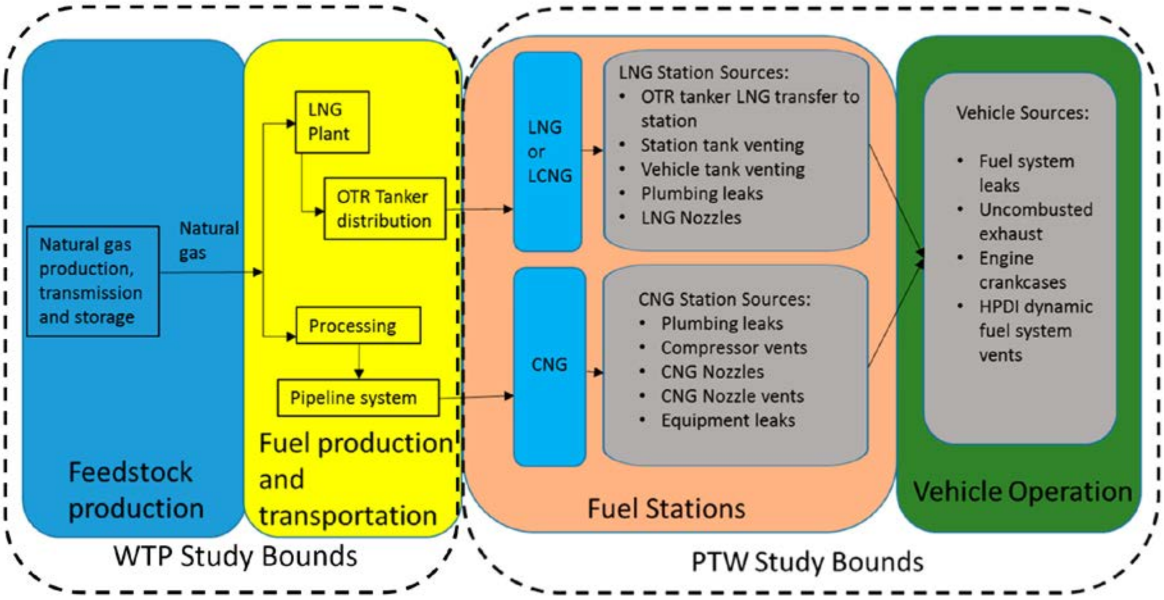

Figure 4: The well-to-wheel lifecycle of LNG as a transport fuel with the well-to-pump and pump-to-wheel system boundaries, from [20]. Note: embedded/embodied emissions are out of scope.

In a recent whole-lifecycle evaluation of natural gas vehicles, Cai et al. [21] presented a comparison of the WTW CO2e emissions for LNG and CNG HGVs. A summary of the results for an LNG short-haul freight truck, a CNG refuse truck, and a CNG transit bus are presented in Table 4. The study found that the WTW GHG emissions of the three natural gas vehicles were 1%, 6%, and 8% higher than an equivalent diesel vehicle, respectively. The WTW GHG emissions of all three vehicles were strongly dependent on the vehicle fuel economy, and the results reflect that natural gas engines are not currently as fuel efficient as diesel engines. Table 4 shows that 76-77% of the WTW GHG emissions arose from CO2 tailpipe combustion emissions for the natural gas vehicles.

The same study found that the supply chain contributed 19% of the WTW GHG emissions for the LNG short-haul truck and approximately 20% for the CNG vehicles. The difference between the LNG and CNG pathways was attributed to higher rates of methane leakage from long-distance and local transmission of natural gas in the CNG pathway, whereas LNG is typically transported with lower rates of methane leakage. For the LNG pathway, the liquefaction process and methane leakages due to LNG boil-off were identified as the main contributors to GHG emissions in the supply chain stage.

Table 4: Well-to-wheel CO2-equivalent emissions for three different heavy goods vehicle types using compressed and liquefied natural gas compared to an equivalent diesel vehicle. Percentages indicate the proportion of emissions across the well-to-wheel lifecycle, from [21].

WTW Stage	LNG Short Haul Freight		CNG Refuse Truck		CNG Transit Bus	
	[gCO2e/tonne-km]	[%]	[gCO2e/tonne-km]	[%]	[gCO2e/tonne-km]	[%]
Supply Chain	8	13%	35	19%	40	19%
Fuel Production	7	11%	7	4%	7	4%
Vehicle Operation	48	76%	138	77%	160	77%
Total	63	100%	180	100%	208	100%
Diesel-Equiv. Vehicle	63		169		193	
Natural Gas/Diesel Ratio	1.00		1.07		1.08	

This is also in line with two studies focused on the UK and Swedish markets that found that, while the vehicle operation has a significant impact on any potential emissions reductions, the WTT stages can also provide a substantial contribution if there are methane leakages throughout the supply chain [22, 23]. From these studies examining the WTW lifecycle, it is clear that there are two principal factors that influence the ability of natural gas vehicles to reduce GHG emissions [1, 21]:

1. The vehicle's fuel efficiency relative to equivalent diesel vehicles.
2. The methane leakage rate including:
    a. across the supply chain (WTP);
    b. at storage at refuelling stations and during refuelling (PTT); and
    c. during the operation of the vehicle (TTW).

Cai et al. [21] presented a sensitivity analysis examining various fuel economies and well-to-wheel methane leakage rates. The analysis shows that the methane leakage rate across the entire WTW lifecycle must be less than 2.8% (relative to throughput) for LNG vehicles to provide GHG emissions reductions [21]. For the North American supply chain, Cai et al. [21] stated it is possible if improvements are made to vehicle technologies and methane leakage is reduced throughout the supply chain. However, if methane leakages across the supply chain are larger than current estimates suggest, then the fuel economy for natural gas vehicles would need to significantly improve to be 'on par' with diesel [21].

The following sections of this report will discuss each aspect of the well-to-wheel emissions of LNG as a fuel for HGVs in detail.

3 Well-to-Pump

The first stage of the LNG lifecycle examined is the well-to-pump phase, which covers the extraction of the natural gas to its distribution to refuelling stations. This section is focused on a literature review to establish general supply chain emissions from natural gas, and an in-depth examination of the supply chain emissions for LNG as a transport fuel.

3.1 General Supply Chain Emissions from Natural Gas

The survey of WTP natural gas emissions presented herein builds upon the 2015 review undertaken by Balcombe et al. [24]. Several notable updates since the 2015 study include two studies by Balcombe et al. [25, 26] and incorporate new data in 2016 and 2017, respectively. One issue with the literature examining emissions across the WTP supply chain is the lack of standard reporting units and variation in estimation methods used. There are also differences in the supply chain depending on the region (e.g. the UK supply chain is different from the North American supply chain). Figure 5 provides an example of a typical natural gas supply chain and outlines the various stages and sources of emissions.

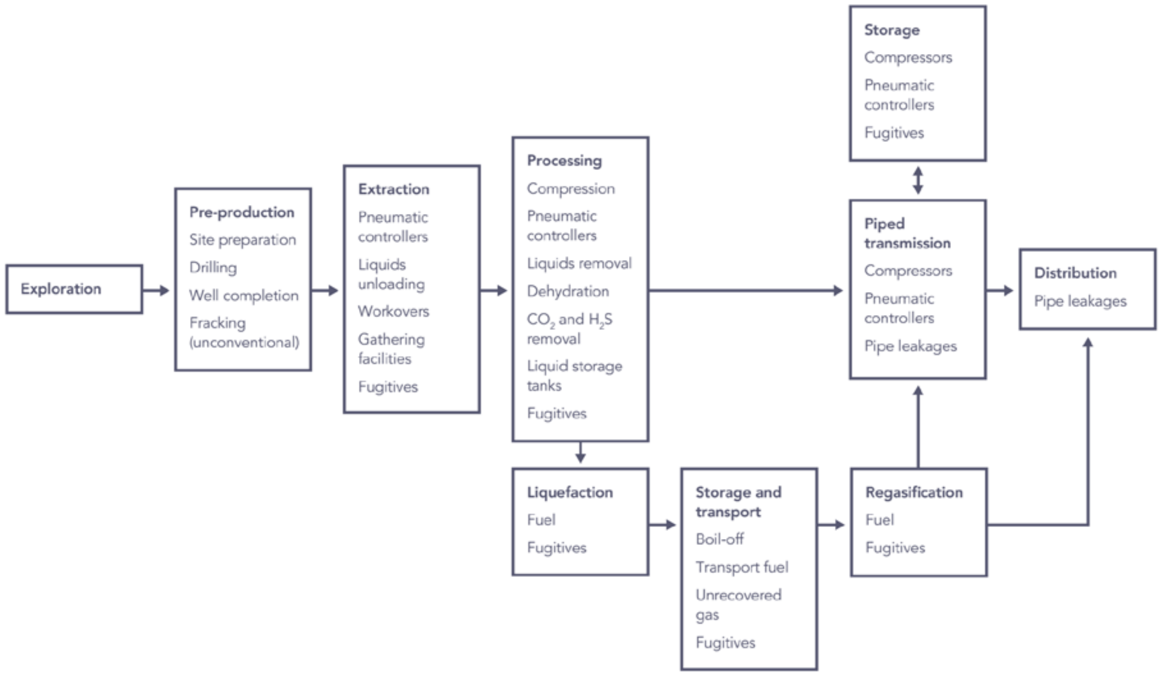

Figure 5: Typical example of the natural gas supply chain, from [24].

The most comprehensive report of the literature examined is presented by Balcombe et al. [26], which gives a summary of the mean values and estimated distributions at each stage in the natural gas supply chain from over 450 studies surveyed up to 2017. Other relevant recent studies include the work presented by Cai et al. [21], Burnham [27], Alvarez et al. [28], and Littlefield et al. [29]. The ranges of methane emissions presented in these studies vary significantly and the majority are focused on the supply chains associated with North American natural gas. The literature suggests that methane emissions (as a percentage of total volumetric throughout) are within the range of 0.2-10%. The high variation is primarily due to the different methodologies, observational data, and the whether the estimates were made using a bottom-up (i.e. observation of methane leakages along each stage of the supply chain) or top-down approach (i.e. observations of aggregate natural gas supply and demand). Furthermore, the ranges are sensitive to the inclusion of super-emitters, which can be described as a small number of sites (e.g. extraction or procession plants) that produce extremely high methane emissions [21, 28]. The aggregated methane emissions for a typical natural gas supply chain (WTP) from the literature are given in Table 5.

Table 5: Aggregated ranges of methane emissions in the natural gas supply chain.

Year	Region	Methane Emissions Range (Percentage of Throughput from Extraction to Distribution [%])		Uncertainty Range	Methodology	Source
		Lower Nominal	Upper Nominal			
2018	North America	2.30%		95% confidence interval	Facility-scale bottom-up validated with top-down studies	[28]
		2.00%	2.70%			
2017	North America	0.99%		Not reported	Literature survey and LCA GREET model using EPA 2016 GHGI	[21]
		1.32% (conventional gas supply)	1.34% (shale gas supply)			
2017	North America	1.70%		95% confidence interval	Bottom-up and Monte-Carlo LCA	[29]
		1.30%	2.20%			
2015	Global	2.20%		Mean across estimates	Literature survey	[24]
		1.60%		Median across estimates		
		0.20%	10.00%	Range across estimates		
2017	Global	0.20%	10.00%	Range across estimates	Literature survey	[25]
2018	Global	0.80%	2.20%	Median estimate across 160 scenarios	Literature survey and Monte-Carlo simulation	[26]

The overall methane leakage can be further separated into each stage of the supply chain. Cai et al. [21] presented a breakdown of the methane emissions across the North American natural gas supply chain from various sources and compared their estimates to earlier studies, shown in Table 6. It is evident from the table that the processing is the least significant stage in terms of methane leakage, while the leakage during gas field production (25-57%), transmission and storage (19-32%) and distribution (10-32%) can all produce significant methane emissions. The WTP values presented in Cai et al. [21] rely on the assumptions used in GREET for natural gas North American pathways and are presented in Appendix A of this report. More recent studies (since 2016) have higher estimates of the contribution from the transmission and storage stage relative to the distribution stage.

Table 6: Natural gas supply chain emissions per stage across the well-to-pump phase, from [21].

Stage	Methane Emissions (Percentage of Volumetric Natural Gas Stage Throughput [%])							Range Contribution to Total	
	EPA GHGI 5 yr Avg.	EPA GHGI 2011 Data	EPA GHGI 2012 Data	EPA GHGI 2013 Data	EPA GHGI 2014 Data	Cai et al. Conv. Gas (2016)	Cai et al. Shale Gas (2016)	Low	High
Gas Field	1.32	0.45	0.34	0.34	0.71	0.7	0.77	25%	57%
Processing	0.17	0.12	0.13	0.16	0.13	0.13	0.13	7%	12%
Transmission and Storage	0.49	0.44	0.39	0.44	0.36	0.36	0.36	19%	32%
Distribution	0.57	0.36	0.4	0.43	0.14	0.14	0.14	10%	32%
Total	2.53	1.36	1.25	1.36	1.33	1.32	1.34		

3.2 Liquefied Natural Gas Supply Chain Emissions

The LNG supply chain will vary depending on the region, for instance, some regions have greater international transportation differences (e.g. from North or West Africa to Asia), as well as different levels of leakage in high-pressure pipelines for national distribution. Arteconi et al. [30] presented a case study comparing the lifecycle GHG emissions for diesel and LNG HGVs in Italy. Two alternative LNG pathways were investigated: 1) LNG is imported into Europe via LNG methane carriers to regasification terminals (LNG-TER), and 2) LNG is produced locally in small-scale liquefaction plants at service stations (LNG-SSL). Their results are summarised in Table 7 and show that importing LNG and using regasification terminal (LNG-TER) resulted in a 10% reduction in total WTW GHG emissions compared to an equivalent diesel vehicle. However, using small-scale regasification plants (LNG-SSL) was only found to provide a 3% reduction in GHG emissions compared to diesel. The lower tailpipe emissions were offset by greater GHG emissions in the supply chain as a result of inefficient small-scale liquefaction systems. This does indicate that the total emissions of the LNG-SSL pathway would decrease linearly with an increase in the efficiency of liquefaction such that if the efficiency of small-scale plants were to reach 90%, the WTW emissions of this route would be 9% lower than diesel [30].

Table 7: Well-to-wheel heavy goods vehicle greenhouse gas emissions for two liquefied natural gas pathways (LNG-TER: regasification terminal, LNG-SSL: locally produced small-scale liquefaction at refuelling station) and a diesel baseline for comparison, from [30].

Pathway	Production [kg CO2e/km]	Distribution [kg CO2e/km]	Combustion [kg CO2e/km]	Diesel pilot [kg CO2e/km]	Total [kg CO2e/km]
Diesel	0.200	0.021	1.635	–	1.856
LNG-TER	0.160	0.088	1.401	0.015	1.664
LNG-SSL	0.389	0.001	1.401	0.015	1.806

For North American natural gas supply chains, Cai et al. [21] found that, in terms of natural gas transmission, the CNG supply chain generally produces greater GHG emissions compared to LNG due to leakages along the long-distance pipelines used to deliver CNG to refuelling stations. Since LNG liquefaction plants are often located close to natural gas sources, transmission occurs through shorter high-pressure pipelines and can result in less methane leakage.

4 Pump-to-Tank

The PTT phase comprises the storage of LNG at the refuelling station to its delivery into the vehicle's tank. There is limited published literature on evidence of methane emissions during the PTT phase, however, methane leakages can occur through several mechanisms at refuelling stations and may constitute up to 21% of the total PTW emissions [20]. There are several mechanisms by which methane emissions can occur at refuelling stations, and there are some differences between the operating mechanisms at LNG and CNG stations. Common to both LNG and CNG stations are continuous unintentional leaks from fuel nozzles (and other fuel delivery system components) due to imperfect seals that allow pressurised natural gas to escape into the atmosphere. Furthermore, methane emissions can occur during the hose-vehicle coupling at the start and end of each refilling event [20].

4.1 Liquefied Natural Gas Refuelling Stations and Process

As LNG is a cryogenic liquid that is stored at temperatures as low as −162 °C, heat transfer from the environment to the stored LNG causes evaporation and the generation of boil-off gas (BOG). This causes a build-up of pressure within the storage vessels. To ensure that pressures remain within safe limits and the LNG pressure and temperatures are maintained within a suitable range for delivery to vehicles, the BOG must be vented, and in some station designs, the BOG is vented directly to the atmosphere [31]. This section examines the various designs for LNG refuelling station designs, along with the mechanisms and magnitudes of the methane emissions produced.

LNG can be delivered to vehicles at a refuelling station in two forms: unsaturated LNG (dispensed at less than −143 °C and 0.34 MPa), or saturated LNG (dispensed at −125 to −131 °C and 0.69 to 0.93 MPa). Unsaturated LNG has a lower temperature, higher density, and can be stored on vehicles longer than saturated LNG. However, the lower pressure of the unsaturated LNG means that auxiliary equipment in the vehicle fuel supply system is required to increase the fuel pressure delivered to the engine [31]. There is a lack of evidence regarding fuel station emissions using these different forms of LNG.

For LNG refuelling in general, the BOG generated in the vehicle's storage tanks must be dealt prior to refuelling, as otherwise there is not enough of a pressure difference between the pump system and the on-board storage tank. The operating sequence of refilling a vehicle LNG tank at a refuelling station must manage the high-pressure BOG in the on-board LNG tanks. Several options for the refuelling operating sequence [31]:

1. *No vapour back to the station*

   Use the station pressure to overcome the tank pressure and condense the BOG (only possible if the on-board tank pressure has sufficient margin below the relief valve pressure and the station pump has sufficient discharge pressure available).

2. *Vapour back to the station*

   Use a vapour return line routed through the fill receptacle or a separate vapour return line to reduce the tank pressure prior to filling.

3. *Vapour back to the station and continue to vapour back during fill operation*

   Transfer the LNG from the refuelling station to an on-board LNG tank while the BOG in the tank is returned to the station by the vapour return line. In this method, the LNG pressure at the station does not need to be too high; however, it is only possible with a separate vent return line.

4. *Manual vent of BOG*

Vent the BOG to the atmosphere to reduce the on-board tank pressure before proceeding with the process described in option (1).

The storage tanks at refuelling stations also require careful management to prevent the venting of methane into the atmosphere due to BOG generated as a result of heat transfer into the tanks. While it is possible to re-condense the BOG using an on-site liquefier or directing the BOG into the low-pressure natural gas grid [31], these components significantly increase the cost of refuelling stations. A review of existing LNG station designs found that the majority of refuelling stations available on the market had no BOG management. Of patented LNG refuelling station designs, 44% were found to have no BOG management [31].

4.2 Evidence for Methane Emissions at Refuelling Stations

The latest measurements of methane emissions at refuelling stations are presented by Clark et al. [20], and these data have been incorporated into the latest evaluation of WTW emissions by Cai et al. [21]. The study by Clark et al. [20] followed a bottom-up measurement methodology that measured methane emissions from different components of the refuelling station system. Sources of methane emissions included leaks from mechanical fittings at stations and on vehicles, vents from storage tanks, compressors and fuelling systems, and releases during fuelling hose disconnects, as well as vehicle tailpipe and crankcase vent emissions (covered in Section 5). Hand-held methane detectors were used to locate leaks from stations and on-board fuel storage and transfer systems. Methane emissions from refuelling stations were gathered from six LNG stations, all fed by cryogenic tanker truck deliveries. Methane emissions were also characterised from eight CNG stations, seven of which were fed directly from pipelines, and one fed from an LNG station.

The LNG stations visited were all commissioned after 2011. LNG storage tank boil-off, pressure relief valve venting and manual venting of on-board LNG vehicle tanks by drivers prior to refuelling were also observed during the study. The summarised ranges of methane emissions for the various mechanisms at LNG and CNG refuelling stations are given in Table 8. Regarding venting from the vehicle fuel tank, UNECE Regulation 110 [32] requires that, after a full-fill, the minimum holding time without venting of LNG in vehicle fuel tanks be 5 days (Annex 3B, paragraph 2.7) [32]. For intensively-used vehicles, it is unlikely that LNG will be vented from the fuel tank. However, in the event that an LNG tank remains full after 5 days, 2-4% of LNG may boil off and be vented for every following day (Gunnarson et al. [33], Ursan et al. [34]). Therefore, we have estimated the upper bound of vehicle fuel tank venting as 3% of throughput.

In summary, the main source of methane emissions during the PTT phase is the venting of methane to the atmosphere due to BOG pressure build-up in the station and on-board storage tanks. The management of BOG from on-board LNG tanks, the flexibility of stations to refuel vehicles with different fuel supply systems, and the minimisation of BOG generation in the station storage tanks are critical to reducing fugitive methane emissions.

Table 8: Summary of the range of methane leakage (as a percentage of throughput) during all stages of the pump-to-tank stage.

Source	Methane leakage Percentage of Throughput [%]			Note
	Low	Middle	High	
Delivery	0.1	0.1	0.4	
Station tank BOG	0.0	0.1	2.0	
Continuous leaks at stations	-	-	-	Negligible
Fuelling nozzle	-	-	-	Negligible
Vehicle fuel tank	0.0	0.1	3.0	
Vehicle manual vent	0.0	0.1	4.2	
Total	0.1	0.4	9.3	

5 Tank-to-Wheel

The TTW phase is focused on the emissions produced by the vehicle during operation. This section of the report presents a description of the various natural gas engine technologies, including their fuel efficiency relative to diesel engines, GHG and air pollutant emissions. The engine technologies are identical for CNG and LNG, and so results from both fuels are included and not distinguished. In addition to the CO2 emissions produced by the vehicles, preventing methane emissions is vital for a competitive natural gas HGV. The various mechanisms through which methane can be emitted during the TTW phase are also described in this section.

5.1 Natural Gas Engine Technologies

The use of natural gas, gasoline, and diesel for transportation require an internal combustion engine to convert the fuel's energy into vehicle motion. Many of the technologies used in natural gas engines are similar to conventional diesel/gasoline engines. Internal combustion engines can be broadly classified into two categories; spark-ignition (SI), and compression ignition (CI), and correspond to gasoline and diesel engines, respectively. SI engines use a spark plug to ignite the air/fuel mixture within the cylinder, while the ignition in CI engines occurs solely due to the compression of the fuel. SI engines typically require near-stoichiometric[2] fuel and air mixtures, however, CI engines are able to operate in lean conditions, where there is more air than is required by the combustion process. The advantage of being able to run lean is that the intake air flow rate does not need to be throttled, as in an SI engine, and this provides a significant benefit in terms of energy efficiency [35-37].

Natural gas engines are either: 1) dedicated (mono-fuel) Otto-cycle engines 2) or diesel-cycle (dual fuel) engines. The dedicated Otto-cycle engines utilise 100% natural gas and SI technology. For SI engines, the fuel octane rating is an important parameter to quantify the ability of the fuel to resist pre-ignition during compression (commonly known as knock). Natural gas has an octane rating of 120-130, which is higher than typical gasoline at 90-98, therefore natural gas SI engines are able to operate with higher compression ratios and potentially be more energy efficient than gasoline SI engines.

The diesel-cycle engines (CI) operate with natural gas-diesel mixtures. Due to the high octane rating of natural gas and low cetane number (a measure of the fuel's combustion speed) relative to diesel, it is not suitable for use in CI engines. Therefore, to utilise natural gas in CI engines, diesel is also injected

[2] A stoichiometric mixture is the ideal air/fuel mixture that enables combustion to completely burn all fuel present in the cylinder.

into the cylinder to provide the ignition on compression. These CI engines are therefore called dual-fuel engines (distinct from bi-fuel engines which may be SI engines that operate on gasoline or natural gas independently). Depending on the engine configuration, between 50-95% of the fuel energy supplied to a dual-fuel engine may be in the form of natural gas, which is also referred to as the diesel substitution ratio. The average values observed for the substitution of diesel by natural gas over micro-trips ranged from 4-34% on an energy basis [20].

Four different engine technologies are available for natural gas vehicles:

1) Spark-Ignition Stoichiometric (SIS)

A SIS engine uses an exact air to fuel ratio required to combust all fuel molecules within the chamber. For natural gas, methane and air are completely converted to their products of reaction during combustion; H2O, CO2, and N2. While these engines provide a cleaner combustion process and therefore cleaner exhaust gases compared to conventional engines, the fuel consumption is higher and power output lower relative to diesel engines [21].

2) Spark-Ignition Lean Burn (SILB)

Lean burn engines are designed to allow for greater quantities of air to enter the combustion cylinder than is required for combustion (i.e. greater than in a stoichiometric engine). The lean air/fuel mixture decreases the temperature of combustion and results in lower NOx emissions [38]. Lean burn engines have poor transient response and performance but may be complemented with advanced fuel control and closed loop technologies that can monitor combustion and provide adjustments if necessary [39]. In many cases, the reduced performance is compensated by the addition of a turbocharger.

3) Dual Fuel (DF)

Dual fuel engines utilise two types of fuel to produce combustion as opposed to a single fuel source. Generally, diesel is the primary fuel and natural gas is added to the incoming air in the intake manifold and it is common for diesel engines to be retrofitted [10, 40]. This air/natural gas mixture is ignited by an injection of diesel at the end of the compression stroke. Dual fuel engines can offer advantages over other natural gas engine technologies, including higher thermal efficiency (relative to SI engines), flexible fuel capabilities (dual fuel engines can also run on only diesel), reduced fuel costs, along with the potential to reduce some air pollutant emissions [10, 41, 42].

4) High-Pressure Direct Injection (HPDI)

High-pressure direction injection (HPDI) engines are a type of a dual fuel engine that use diesel as a pilot ignition source and injects the gas at high-pressure (e.g. >300 bar) into the combustion chamber at the end of the compression stroke. In HPDI engines, the diesel injection accounts for approximately 5% of the fuel energy, with the balance provided by natural gas [43]. Some studies have recently claimed that newer generation HPDI engines are able to offer similar levels of performance and drivability to diesel [29, 44].

An overview of the various engine technologies, after-treatment, and natural gas fuel composition are presented in Table 9. The following sections are focused on the literature examining GHG and air pollutant emissions produced by various natural gas HGVs and other heavy-duty vehicles.

Table 9: Natural gas engine technologies, after-treatment, and percentage of natural gas used, from [44, 45].

Engine Type	After-Treatment	Natural Gas Proportion Used [%]	Original Equipment Manufacturer
Spark-Ignition Stoichiometric	3-way catalyst	100%	Cummins, Scania, Waukesha, IVECO
Spark-Ignition Lean Burn	Oxy-catalyst	100%	Cummins, MAN, Doosan, GE
High-Pressure Direct Injection	Catalyzed DPF, Urea SCR	95-98%	Westport, Volvo
Dual fuel	Oxy-catalyst	0-95%	Volvo (retrofit)

The following terms are used to denote the following different engine types and fuels in the tables presented in the following sections:

- SILB – Spark-ignition lean burn.
- SIS – Spark-ignition stoichiometric.
- CI – Compression-ignition.
- HPDI – High-pressure direct injection.
- DF – Dual fuel.
- NG – Natural gas.
- D – Diesel.

5.2 Tailpipe CO2 Emissions

This section examines tailpipe CO2 emissions from natural gas HGVs. The emissions presented in this section are solely focused on CO2 and do not include contributions from methane unless stated otherwise. Several studies have investigated the TTW GHG emissions produced by SI Stoichiometric natural gas HGVs [20, 22, 46-48]. Clark et al. [20] investigated the emissions produced by various SI stoichiometric natural gas heavy vehicles over various drive cycles using a chassis dynamometer. The most recent on-road study was undertaken by Vermuelen et al. [47], who conducted a series of real-world emissions measurements from two Euro VI LNG HGVs (Scania G340 with an automatic gearbox, Iveco Stralis Hi Road with a manual gearbox) across urban, rural, and motorway drive cycles. The results were compared against an average of six baseline Euro VI diesel HGVs from previous tests. The summary of the CO2 emissions produced by the various diesel and natural gas vehicles from the literature are presented in Table 10.

Table 10: Summary of tailpipe CO2 emissions from various diesel and natural gas engines.

Vehicle Type	Fuel	Engine Type	CO2 Emissions [g/km]				Source
			Avg.	Std	Min	Max	
Freight Truck	Diesel	CI	1,139	351	654	1,768	[10, 48-50]
	NG	SIS	1,142	434	540	2,376	[47-51]
	NG	HPDI	1,286	235	906	1,624	[50]
	NG	DF	926	321	649	1,678	[10, 48]
Refuse Truck	Diesel	CI	2,278	651	1,802	3,020	[50]
	NG	SIS	1,898	752	1,068	3,323	[50, 52]
Transit Bus	Diesel	CI	2,210	1,059	1,170	5,440	[53]
	NG	SILB	1,048	452	470	2,344	[53-55]
	NG	SIS	1,110	406	334	1,677	[50, 54-57]

The average tailpipe CO_2 emissions produced by the two LNG HGVs across all routes were generally 5-10% lower than the diesel HGVs. The two LNG HGVs emitted less CO_2 than the diesel across the majority of test cases. However, one of the tests with the Scania G340 at a low load condition (10% payload) in urban driving showed higher CO_2 emissions than comparable diesel vehicles. While the sample size of this study is limited to two LNG vehicles, the results indicate that TTW CO_2 emissions may are 5-10% lower than diesel.

The results from Vermuelen et al. [47] are broadly in line with a CO_2 emissions study undertaken by Cryogas (LNG supplier in Poland) using an IVECO LNG HGV, where it was reported that CO_2 emissions from an LNG vehicle (0.65 kg/km) were 11% lower than for a comparable diesel vehicle (0.73 kg/km) [58]. While there remains variation in the data, the results indicate that natural gas can provide a reduction in tailpipe CO_2 emissions compared to conventional diesel vehicles.

5.3 Methane Emissions

Methane slip occurs due to natural gas leakages throughout the vehicle system, of which there are three potential mechanisms. The first is the potential for unburned methane to be emitted via the tailpipe due to incomplete combustion. Generally, catalysts are used to control the tailpipe methane emissions. A three-way catalyst is paired with SI Stoichiometric engines, and an oxidation catalyst is used to control the emissions from lean burn SI and CI engines [38, 45]. The second mechanism of methane leakage is through the engine crankcase. Methane can escape from the combustion chamber into the engine crankcase. If the engine crankcase is vented to the atmosphere, any methane present will also be vented. Crankcase ventilation systems and improved oxidation catalysts are currently available to minimise or eliminate crankcase methane emissions, however, the International Council on Clean Transportation (ICCT) stated that up to 2015 at least, there has been little incentive for manufacturers to implement these technologies [59]. The final mechanism, limited to HPDI engines, is dynamic venting that occurs due to the behaviour (transient operation) of the fuel rail pressure control system and can emit small amounts of gas to the atmosphere via a pipe [59]. This section will present the findings of various studies investigating the methane emissions each of the three potential mechanisms; via the tailpipe, crankcase, and dynamic venting.

5.3.1 Tailpipe Methane Emissions

The range of tailpipe methane emissions produced by various natural gas vehicles (and one diesel for comparison) are given in Table 11. For all the various natural gas engine technologies, it is clear that the lowest fuel-specific methane emissions are produced by SI stoichiometric engines. The SI lean burn engine produces significantly greater methane emissions, agreeing with the findings presented by Yoon et al. [54]. The methane emissions due to stoichiometric combustion with a three-way catalyst are substantially lower due to the high exhaust temperature, while the lower temperatures produced by lean burn combustion do not enable the oxidation catalyst to remove similar levels of methane [38]. There are numerous factors which can explain the variation in methane emissions produced, from differences in vehicle age, catalyst temperature, engine speed, vehicle load, transient behaviour, and emissions diffusion between neighbouring micro-trips [60]. However, these results suggest that a stoichiometric engine with a three-way catalyst can provide an effective method for reducing methane emissions. Furthermore, a lean burn engine with an oxidation catalyst will not be able to meet Euro VI emissions standards without appropriate thermal management of the gases entering the catalyst.

Table 11: Tailpipe methane emissions quantified as methane slip for various vehicle and engine types.

Vehicle Type	Fuel	Engine Type	Methane Emissions [%]				Source
			Avg.	Std	Min	Max	
Freight Truck	NG	SIS	0.253	0.294	0.002	1.335	[20, 22, 47, 48, 51]
	NG	HPDI	0.612	0.166	0.353	0.871	[20]
	NG	DF	11.769	6.333	0.292	29.157	[10, 22, 48]
Refuse Truck	NG	SIS	0.353	0.260	0.108	0.979	[20]
Transit Bus	NG	SIS	0.783	0.283	0.096	1.048	[20, 54, 55]
	NG	SILB	4.146	1.775	0.723	9.440	[53-55, 61]
	Diesel	CI	0.011	0.009	0.000	0.038	[53, 61]

5.3.2 Crankcase Methane Emissions

Clark et al. [20] summarised all published findings on crankcase emissions for various SI stoichiometric natural gas engines. The summary presented by Clark et al. of the crankcase methane emissions defined as methane slip is presented in Table 12. During one measurement, the crankcase methane emissions were not characterised separately from the tailpipe emissions during on-road testing; the vehicle was operated over the same route twice and routed the crankcase vent emissions through the tailpipe sampling system once to provide an estimate of the emissions produced. Delgado and Muncrief [59] also suggested that if the exhaust gas recirculation for a SIS natural gas engine is on average 20%, then the methane crankcase emissions would be within 0.4-0.8%, which is within the range given for HGVs in Table 12.

It should be noted that since HPDI engines introduce fuel just prior to ignition the natural gas is unable to penetrate the crevices between the piston and cylinder and crankcase methane leakages are thought to be negligible [59].

Table 12: Summary of the crankcase methane emissions quantified as methane slip for different natural gas vehicles [20].

Vehicle Type	Engine Type	Crankcase Methane Emissions [%]			
		Avg.	Std	Min	Max
Freight truck	SIS	0.673	0.205	0.361	1.124
Refuse truck	SIS	0.734	0.157	0.537	1.054
Transit bus	SIS	0.832	0.177	0.638	1.172

5.3.3 Dynamic Venting (High-Pressure Direct Injection Engines)

HPDI engines do not produce significant, if any, methane emissions through the crankcase. However, these engines do have a dynamic venting system that is used during transient engine behaviour (sudden starting and stopping), directly venting methane into the atmosphere. The only significant study on dynamic venting of methane in HPDI engines was undertaken by Clark et al. [20]. The estimated methane emissions due to dynamic venting by four HPDI tractors are shown in Table 13. From the table, it is seen that while it is possible for no dynamic venting to occur, the methane emissions can be greater than 2% of the fuel used. Other studies have also suggested that the methane emissions produced by dynamic venting could be within a similar range to crankcase methane leakage [59]. However, there is a lack of publicly available data on methane emissions by dynamic venting in HPDI engines.

Table 13: The fuel-specific methane emissions produced by dynamic venting in high pressure direct injection natural gas vehicles [20].

Vehicle Type	Engine Type	Samples	Methane Emissions [%]		
			Avg.	Min	Max
Freight Truck	HDPI	4	0.927	0.000	2.210

5.4 N2O Emissions

N2O is a potent GHG with a GWP of 298 over a 100-year time-horizon [62] and is produced by complex reactions occurring in combustion and emissions control catalysts. N2O emissions are dependent on the fuel, combustion and emissions control systems, and the combustion and catalyst temperatures and so no simple relationship for N2O emissions can be derived from the fuel, air, and nitrogen compositions. Table 14 summarises the N2O estimated averages and standard deviations produced by various diesel and natural gas HGVs and refuse trucks with different engine types. While the natural gas stoichiometric vehicles were found to have lower N2O emissions, the natural gas HPDI vehicle was found to emit considerably greater levels of N2O, relative to diesel. While there is a sparse amount of data on N2O emissions for natural gas vehicles, the data indicates that diesel HGVs may be able to produce lower N2O emissions. In 2002, Lipman et al. [63] reported that diesel and natural gas vehicles appear to emit the same order of magnitude of N2O. However, this may no longer be the case now that modern heavy-duty diesel engines meeting the latest NOx emissions standards are equipped with selective catalytic reduction, which can lead to significantly higher N2O emissions than natural gas engines depending on the driving cycle and loading conditions [47]. Based on the present literature, it is difficult to make a definitive statement that natural gas HGVs emit more or less N2O than diesel HGVs and this is a future research need.

Table 14: Summary of the N2O emissions produced by various diesel and natural gas engines.

Vehicle Type	Fuel	Engine Type	N2O Emissions [g/km]				Source
			Avg.	Std	Min	Max	
Freight Truck	Diesel	CI	0.028	0.008	0.019	0.037	[50]
	NG	SIS	0.004	0.005	0.000	0.012	[50, 64]
	NG	HPDI	0.587	0.971	0.052	3.517	[50, 64]
Refuse Truck	Diesel	CI	0.000	0.000	0.000	0.000	[50]
	NG	SIS	0.071	0.084	0.006	0.255	[50, 52, 64]
Transit Bus	NG	SIS	0.021	0.013	0.006	0.047	[50, 56, 64]

5.5 Air Pollutant Emissions

The air pollutant emissions of both natural gas and diesel HGVs and the data presented herein were collected from several studies. Cai et al. [21] summarised the non-GHG emissions produced by a variety of lean burn diesel and stoichiometric CNG and LNG HGVs across a variety of in-service and chassis dynamometer drive cycles. Vermuelen et al. [47] investigated the on-road air pollutant emissions produced by two LNG HGVs. Wayne et al. [53] presented emissions data from natural gas and diesel/hybrid-electric diesel buses. Stettler et al. [10] investigated the emissions from dual fuel freight trucks through chassis dynamometer measurements. Thiruvengadam et al. [65] summarised on-road emissions from natural gas and diesel heavy-duty vehicles. Table 15 shows a summary of air pollutant emissions from natural gas vehicles with different engine technologies and compares those with the emissions from diesel vehicles.

Table 15: Summary of other air pollutant emissions produced by different types of diesel and natural gas heavy goods vehicles.

Vehicle Type	Fuel	Engine Type	NMHC [g/km]		NOx [g/km]		CO [g/km]		PM [mg/km]		Source
			Avg.	Std	Avg.	std	Avg.	Std	Avg.	Std	
Freight Truck	D	CI	0.003	0.004	2.244	4.480	1.353	1.957	4.492	1.920	[48-50]
	NG	SIS	0.031	0.031	0.294	0.508	3.727	2.255	3.665	2.523	[47-51]
	NG	DF	-	-	4.889	4.932	7.730	8.048	31.204	23.843	[48, 49]
	NG	HPDI	0.034	0.023	0.425	0.106	0.040	0.017	2.748	1.056	[65]
Refuse Truck	D	CI	0.017	0.004	0.630	0.172	0.050	0.006	4.801	1.225	[50]
	NG	SIS	0.328	0.519	0.145	0.194	11.085	6.451	3.237	1.834	[50, 52]
Transit Bus	D	CI	-	-	13.591	9.204	0.189	0.284	13.642	11.689	[53]
	NG	SILB	1.124	0.125	13.958	9.125	0.387	0.492	15.100	15.258	[53, 55]
	NG	SIS	0.094	0.056	0.716	0.636	13.074	12.675	2.106	2.647	[50, 54-57]

The synthesised test results indicate that dual fuel HGVs can have the highest NOx and PM emissions, while the SI stoichiometric and HPDI engines show similar levels of emissions that are less than the diesel engines. Despite the reductions in CO, NOx, and PM, the SI stoichiometric engine produced higher non-methane hydrocarbons (NMHC) emissions compared to diesel. Across the emissions produced by HGVs, the HPDI engine produced the lowest emissions of all air pollutants examined. The natural gas refuse truck, while producing higher CO and NMHC, emitted lower levels of NOx and PM compared to the diesel equivalent. The emissions produced by the diesel and natural gas (SI lean burn) transit buses are similar. However, the natural gas SI stoichiometric transit buses produce lower emissions for all air pollutants except CO by a substantial amount at 13 g/km on average compared to 0.2-0.4 for the diesel and SI lean burn).

In a comparison of the NO and NO2 produced per kilometre across a variety of drive cycles and test conditions, both diesel and natural gas HGVs were found to emit substantially more NOx in urban driving compared to rural and motorway trips. There is a notable difference in the NOx emissions produced by the two LNG HGVs, with one LNG HGV (Iveco) producing more NOx emissions than the diesel vehicles. Combining the results for urban/rural/highway driving (15%/25%/60%) to represent an average vehicle performance, one of the LNG vehicles is found to have average emissions similar to the average of the 6 tested diesel, while the other LNG vehicle has NOx emissions that equal those of the highest emitting vehicle in the sample of diesel trucks. For the tested LNG vehicles, a detailed analysis of the NOx emissions revealed that the effect of cold starts are not as significant as for diesel vehicles [47]. While NOx emissions are higher during a cold start, the three-way catalyst heats up rapidly, leading to a smaller contribution from the cold start itself. For both LNG trucks higher NOx emissions have also been observed in urban trips during accelerations when the engine and three-way catalyst are warm. For both LNG vehicles this leads to average NOx emissions during urban driving conditions (with a warm engine and catalyst) that are higher than the average for comparable diesel vehicles. Thus, the high emissions produced in urban driving by the diesel vehicles are primarily due to the cold engine start; the NOx emissions reduction system (selective catalytic reduction, SCR) requires time to warm up to reach its ideal operating temperature. The NOx emissions produced by a warm engine will be, on average, around 0.5-1.0 g/km. Cai et al. [21] also noted that diesel vehicles can produce significantly greater tailpipe emissions compared to natural gas vehicles, when SCR performs poorly.

In a study of on-road heavy-duty vehicles, the particle mass emissions from the natural gas HGVs varied significantly across the different drive cycles; from 80% lower up to 40% greater than diesel equipped with Diesel Particulate Filters (DPFs), depending on the duty-cycle [49, 50]. Cai et al. [21] also noted that in absolute terms, both the natural gas HGVs and diesel HGVs with DPFs produced very low PM emissions (0.62-6.21 mg/km).

Vermuelen et al. [47]compared particle number (PN) emissions for two LNG HGVs and the average of diesel HGVs. The particle number emissions were found to be low for all their test vehicles; the PN level is on average 6.0×10^{11} particles/km for motorway driving. For other diesel vehicles, the levels for non-DPF Euro III HDV and Euro V HD vehicle with a DPF are 6×10^{13} and 2×10^{11} particles/km, respectively [66, 67]. However, on average the LNG HGVs emitted more particles than their diesel counterparts (all fitted with diesel particulate filters). Further caution in the interpretation of the results is necessary as the diesel vehicles were tested in the lab while for the LNG trucks particle numbers were measured on the road.

The two LNG vehicles also had higher total hydrocarbon emissions than their diesel counterparts under urban driving conditions and over 85% of these hydrocarbons are methane. As the tested LNG vehicles were relatively new and therefore relatively little ageing of the three-way catalysts, these results may not be valid for older vehicles. Diesel catalysts also face similar issues with deterioration over time. Most LNG and diesel emissions results are for new vehicles and there is a lack of evidence on the effectiveness of ageing emissions control systems.

The latest studies indicate that natural gas HGVs produce low levels of air pollutants, but the advantage over diesel has diminished due to the introduction of the European Euro VI emissions standards and equivalent standards in the rest of the world, which have and will continue to advance emissions control technologies such as selective catalytic reduction and diesel particulate filters to control NOx and PM emissions from diesel vehicles, respectively. We note that there is a lack of data on the deterioration of emissions control systems for both diesel and natural gas vehicles.

5.6 Current and Future Fuel Efficiency of Natural Gas Vehicles

The fuel efficiency of LNG compared to diesel is an important factor that influences the ability of LNG to become an environmentally viable alternative fuel source for HGVs. The fuel consumption of a vehicle is dependent on not only the engine technology but also other aspects such as the powertrain efficiency, aerodynamic drag, load conditions, rolling resistance, amongst others. Furthermore, the drive cycle also has a significant influence on the fuel consumption, with urban cycles far more intensive than long-haul cycles. A summary of the fuel efficiency ranges of various natural gas heavy vehicles relative to their diesel counterparts is presented in Table 16. From the table, it is evident that there is a significant variation in the fuel efficiency of natural gas heavy vehicles. The evidence suggests that there is a significant fuel efficiency penalty for natural gas engines. For SIS, HPDI and dual fuel engines, there is a 22% (7% to 44%), 17% (4% to 44%), and 14% (-2% to 40%) fuel consumption penalty compared to similar diesel engines.

Table 16: Ranges of the fuel efficiency of various natural gas heavy vehicles relative to diesel.

Vehicle Type	Fuel	Engine Type	Fuel Consumption Relative to Diesel Counterpart [%]				Source
			Avg.	Std	Min	Max	
Freight Truck	NG	SIS	124	9	107	146	[47, 48, 50]
	NG	HPDI	117	12	104	144	[50]
	NG	DF	111	11	94	140	[10, 48]

The ICCT stated that numerous cost-effective technologies are presently available that can deliver fuel consumption reductions in diesel vehicles of up 30-40% [59]. Improved engine technology is one avenue that can 'contribute a significant share of the expected reductions' [59]. Various studies have provided differing estimates of the potential improvements in fuel efficiency that can be achieved through developing advanced engine technologies, and Delgado and Muncrief [59] predicted that diesel engines will improve by around 3.5% from 2018-2025 and they assumed that natural gas engines will follow the same rate of improvement in fuel efficiency as diesel engines such that the efficiency penalty remains stable at 10% and 15% for CI and SI engines, respectively [59]. However, the same authors acknowledged that potential efficiency improvements and uncertainties suggest that the likely range of the efficiency penalty relative to diesel is from 0 to 15%. It should be noted that in their modelling up to 2040 an efficiency penalty of 10% was used as they assumed the efficiency gap to diesel will remain during this time horizon [59]. This is in line with the EPA's [68] statement that natural gas vehicles operate with a 5-15% fuel efficiency penalty relative to diesel (considered across 2017-2025). These estimates are in line with the data for today's technology and it is likely that the fuel efficiency of natural gas freight vehicles relative to diesel will be in the range of a 0-15% for the foreseeable future.

6 Summary and Conclusions

The main conclusions of this review of evidence on the use of natural gas for HGVs are that:

- The two main parameters affecting the overall WTW GHG emission of natural gas HGVs compared to diesel are the fuel consumption relative to diesel and methane leakages across the supply chain.
- For WTP methane emissions, the significant variation in the data makes it difficult to generalise across different supply chains and geographic regions. Methane leakage rates are estimated to be 1.6% nominally, with a range of 0.2% to 10%.
- These WTP emissions are dominated by methane leakage during gas field production (25-57%), transmission and storage (19-32%), and distribution (10-32%).
- For PTT, the main source of methane emissions is the venting of methane to the atmosphere due to BOG pressure build-up in the station and on-board storage tanks. The management of BOG from on-board LNG tanks, the flexibility of stations to refuel vehicles with different fuel supply systems, and the minimisation of BOG generation in the station storage tanks are critical to reducing fugitive methane emissions. Methane leakage rates are estimated to be 1.6% nominally, with a range of 0.1% to 9.3%.
- There is substantial variation in available data in the literature on TTW methane emissions. Several factors can explain this variation, including differences in vehicle age, catalyst temperature, engine speed, vehicle load, and duty/drive cycle. Furthermore, few measurements exist to quantify non-tailpipe TTW emissions including crankcase emissions and dynamic venting.

- While natural gas HGVs do emit less CO2 than comparable diesel engines, the potential CO2 benefit of natural gas is not fully exploited due to lower energy efficiencies of natural gas engines. Furthermore, methane emissions contribute significantly to total GHG emissions.
- There are four primary natural gas engine types used for heavy-duty vehicles; stoichiometric spark-ignited engines (SIS), dual fuel engines (DF), spark-ignited lean burn (SILB) and high-pressure direct injection (HPDI). There is a lack of evidence for the widespread use of SILB engines for road freight vehicles.
- In general terms, SIS engines suffer from greater efficiency losses relative to diesel, however, tailpipe methane emissions are effectively controlled by three-way catalysts. In comparison, DF and HPDI engines have higher TTW methane emission but benefit from higher efficiencies due to compression ignition.
- Non-tailpipe methane emissions occur via the crankcase for SIS and DF engines, and through dynamic venting in the case of HPDI engines.
- The evidence regarding N2O emissions for the different natural gas engines relative to diesel is inconclusive and requires further research.
- While there is evidence that air pollutant emissions from natural gas engines (particularly SIS) are lower than from diesel engines, the advancements in diesel emissions control required by more stringent emissions regulations (e.g. Euro VI in Europe) means that the air pollutant benefits of natural gas engines that did exist have been diminished.
- The long-term view of the efficiency of natural gas engines relative to diesel suggests that the energy efficiency penalty will remain in the range of 0-15%, with a likely value of 10% up to 2040 without the intervention of regulatory change.

To synthesise this information, we have distilled our review into the potential ranges of WTW methane emissions and the engine efficiency relative to diesel for SIS, DF and HPDI engines in Table 17 and Table 18. These values are used in Figure 6 to demonstrate the central estimate and expected range of WTW GHG emissions of natural gas freight vehicles relative to diesel vehicles.

Table 17: Well-to-wheel methane emissions as a percentage of throughput for three different engine technologies; central, low, and high estimates.

Engine Technology		Methane Emissions [%]			
		WTP	PTT	TTW	Total WTW
SIS	Central	1.6	0.4	0.8	2.7
	Low	0.2	0.1	0.0	0.3
	High	10.0	9.3	2.4	20.3
DF	Central	1.6	0.4	11.8	13.5
	Low	0.2	0.1	0.3	0.6
	High	10.0	9.3	29.2	42.2
HPDI	Central	1.6	0.4	1.7	3.7
	Low	0.2	0.1	0.9	1.2
	High	10.0	9.3	2.9	20.7

Table 18: The energy efficiency of the different natural gas engine technologies relative to diesel.

Engine Technology		Energy Efficiency Relative to Diesel
SIS	Central	0.81
	Low	0.68
	High	0.94
DF	Central	0.90
	Low	0.72
	High	1.06
HPDI	Central	0.85
	Low	0.70
	High	0.96

Figure 6 demonstrates that natural gas HGVs are likely to have higher WTW GHG emissions compared to diesel. SIS vehicles are closer to achieving the parity compared to diesel given lower TTW methane emissions, despite lower efficiency compared to DF and HPDI engines. For HPDI and DF engines to provide lower WTW GHG emissions relative to diesel, reducing WTW methane emissions and improving efficiencies relative to diesel are a priority. However, given the stable efficiency penalty relative to diesel, the WTW GHG savings are likely to be in the order of 5-10% even if WTW methane emissions are reduced to zero. If the efficiency penalty can be eliminated, a WTW methane leakage rate of above ~2.2% would negate the benefits of natural gas vehicles and lead to higher overall GHG emissions, highlighting the need to rigorously control methane emissions across the supply chain. In the best-case scenario, if the efficiency penalty is reduced to zero and methane emissions are eliminated, the full potential of the lower carbon intensity of methane would be exploited and a WTW GHG emissions reduction of ~16% could be achieved.

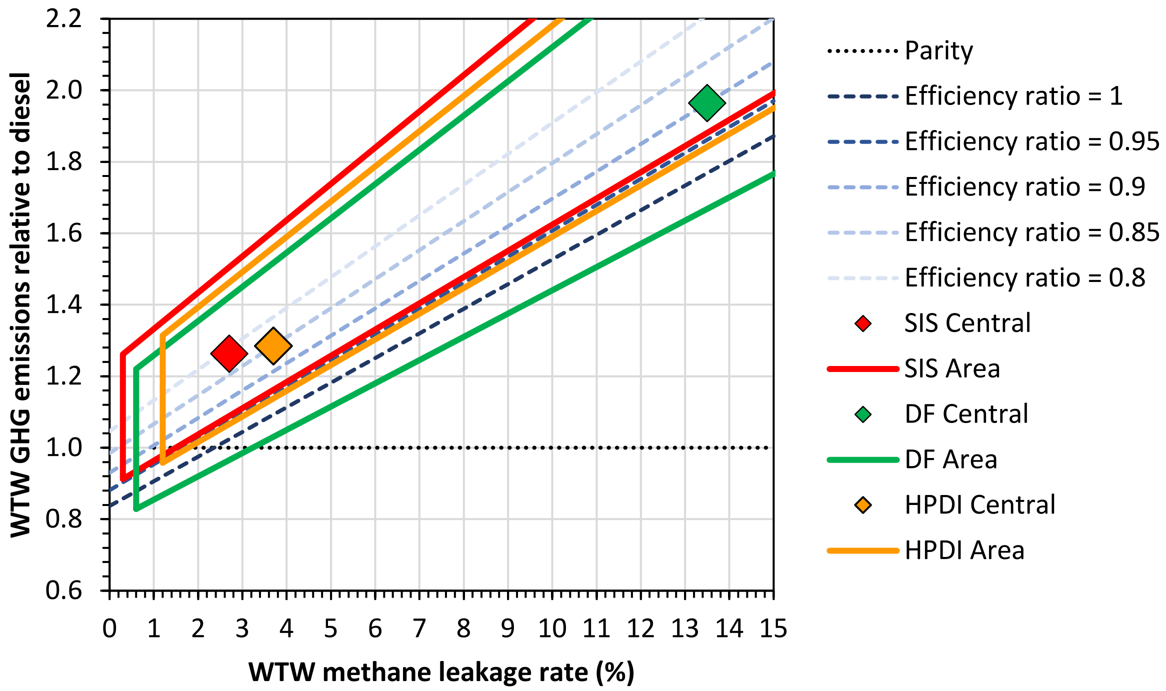

Figure 6: Total well-to-wheel greenhouse gas emissions of spark-ignited (SI), dual-fuel (DF), and high pressure direct injection (HPDI) natural gas heavy goods vehicle engine technologies relative to diesel and as a function of WTW methane leakage rates. The dashed lines indicate different natural gas to diesel engine efficiency ratios.

The outlook for the future is that electrification is likely to lead to greater WTW GHG emissions reductions in the 2030 timeframe than are possible with natural gas HGVs [69]. Figure 7 shows that emissions savings of up to 60% relative to today's diesel vehicles could be enabled by hydrogen fuel cell, electric overhead catenary charging, and electric induction charging based vehicles in China, Europe and the US in 2030.

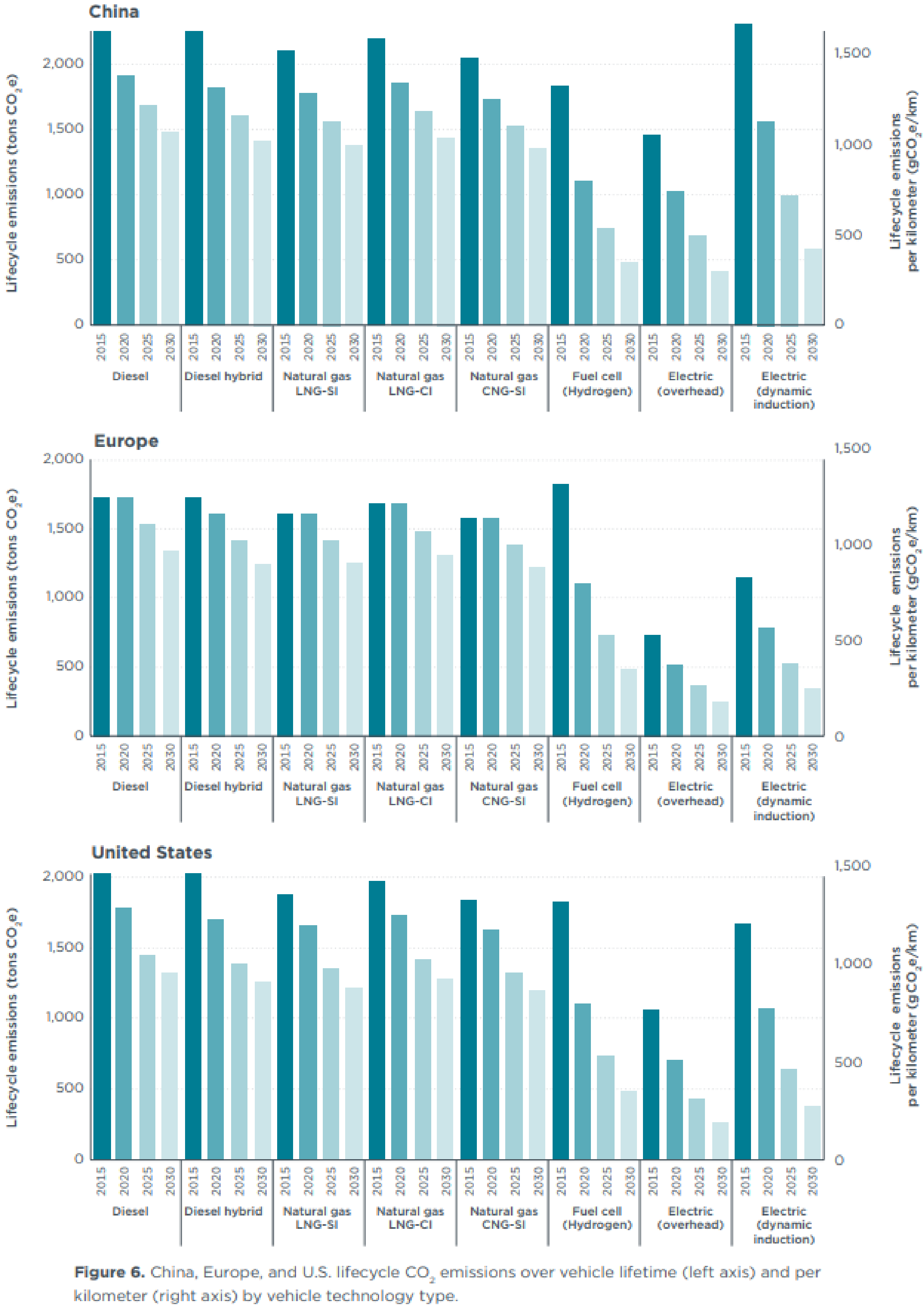

Figure 7: WTW GHG emissions for different HGV vehicle technologies up to 2030 in China, Europe and the US, from [69].

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Appendix A: Assumptions for Well-to-Pump Methane Emissions

The main assumptions used by Cai et al. [21] in GREET to estimate the well-to-pump methane emissions are presented in Table 19 and Table 20.

Table 19: Main parameters for methane leakage estimation, fugitive CO2 emissions, and flaring greenhouse gas emissions in the natural gas industry, from [21].

	Units	Conventional	Shale	Source/Notes
Well Lifetime	Years	30	30	Argonne assumption
Well Methane Content	mass %	76	83	EPA 2016
NG Production over Well Lifetime	NG billion cubic feet	N/A*	1.6	This study
NG Production over Well Lifetime	NG million Btu	N/A*	1,600,000	INTEK 2011 and Argonne assumption of NG LHV
NGL Production over Well Lifetime	NGL million Btu	N/A*	242,000	EPA 2016 and EIA 2015
Well Completion and Workovers (Venting)	metric ton NG per completion or workover	0.71	37	Conv: EPA 2010 and Shale: EPA 2016
Well Completion and Workovers (w/ REC)	metric ton NG per completion or workover	N/A*	3	EPA 2016
Well Completions/ Workovers that Vent	%	N/A*	63	EPA 2016
Controlled CH_4 Reductions for Completion/Workovers	%	0	0	EPA 2016
Average Number of Workovers per Well Lifetime	Workovers occurrences per lifetime	0.2	0.2	EPA 2012
Liquid Unloading (Venting)	g CH_4 per million Btu NG	9	9	EPA 2016
Controlled CH_4 Reductions for Liquid Unloading	%	0	0	EPA 2016

Potential Well Equipment (Leakage and Venting)	g CH_4 per million Btu NG	150	150	EPA 2016
Controlled CH_4 Reductions for Well Equipment	%	10	10	EPA 2016
Well Equipment Flaring	Btu NG per million Btu NG	10,486	10,327	EPA 2016
Well Equipment (CO_2 from Venting)	g CO_2 per million Btu NG	17	17	EPA 2016
Processing (Leakage and Venting)	g CH_4 per million Btu NG	26	26	EPA 2016
Processing (CO_2 from Venting)	g CO_2 per million Btu NG	819	819	EPA 2016
Transmission and Storage (Leakage and Venting)	g CH_4 per million Btu NG	75	75	EPA 2016
Distribution (Leakage and Venting)	g CH_4 per million Btu NG	28	28	EPA 2016
Distribution - Station (Leakage and Venting)	g CH_4 per million Btu NG	18	18	EPA 2016 and EIA 2013

**Emission sources not included for conventional NG, only for shale gas.*

Table 20: Values of natural gas throughput by stage, from [21].

	Units	Values	Sources
Dry NG Production	Quadrillion Btu	25.3	EIA 2016
NGL Production	Quadrillion Btu	3.7	EIA 2015
NG Production Stage (Dry NG and NGL)	Quadrillion Btu	29.0	EIA 2016 and EIA 2015
NG Processing Stage (Dry NG and NGL)	Quadrillion Btu	29.0	EIA 2016 and EIA 2015
NG Transmission Stage	Quadrillion Btu	25.3	EIA 2016
Percent of Local Distribution NG Deliveries	%	63.0	EIA 2013
NG Distribution Stage	Quadrillion Btu	15.8	EIA 2016 and EIA 2013