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Decarbonization of on-road freight transport and the role of LNG from a German perspective

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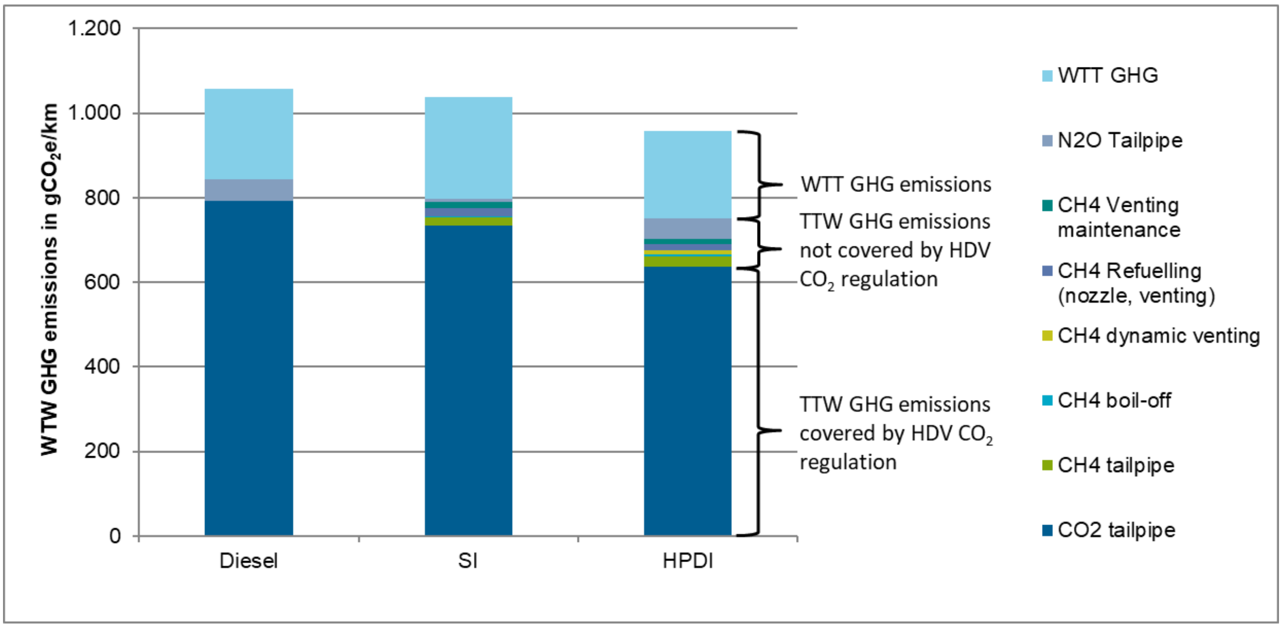
Summary

The use of trucks running on liquefied natural gas (LNG) instead of diesel is not a suitable measure for climate protection in road freight transport. Even in an optimistic scenario, greenhouse gas (GHG) emission reductions of less than 10 % are achieved when using LNG instead of diesel.

In theory, natural gas (methane) has several properties that make it an attractive fuel for combustion engines. Due to its molecular structure methane has a lower carbon content than diesel and produces around 25 % less CO_2 per unit of energy. However, natural gas must be compressed or liquefied to achieve the volumetric energy density required for its use as a transport fuel. While the volumetric energy density of LNG is still approximately 40 % lower than the volumetric energy density of diesel, it is significantly higher than that of compressed natural gas (CNG), making LNG a suitable fuel for long-haul transportation. The LNG is stored on in vacuum-insulated fuel tanks at temperatures of -125 °C to -160 °C.

Although LNG trucks have lower tailpipe CO_2 emissions due to the more favourable chemical composition of the fuel, they produce other GHGs elsewhere. In particular, the operation of the vehicles leads to considerable methane emissions. When released in to the atmosphere unburnt, methane is a very potent greenhouse gas. Further CO_2 and methane emissions take place during fuel extraction and supply (well-to-tank emissions, WTT).

Figure 1: WTW greenhouse gas emissions from diesel and LNG trucks for GWP 100y (high fuel quality)



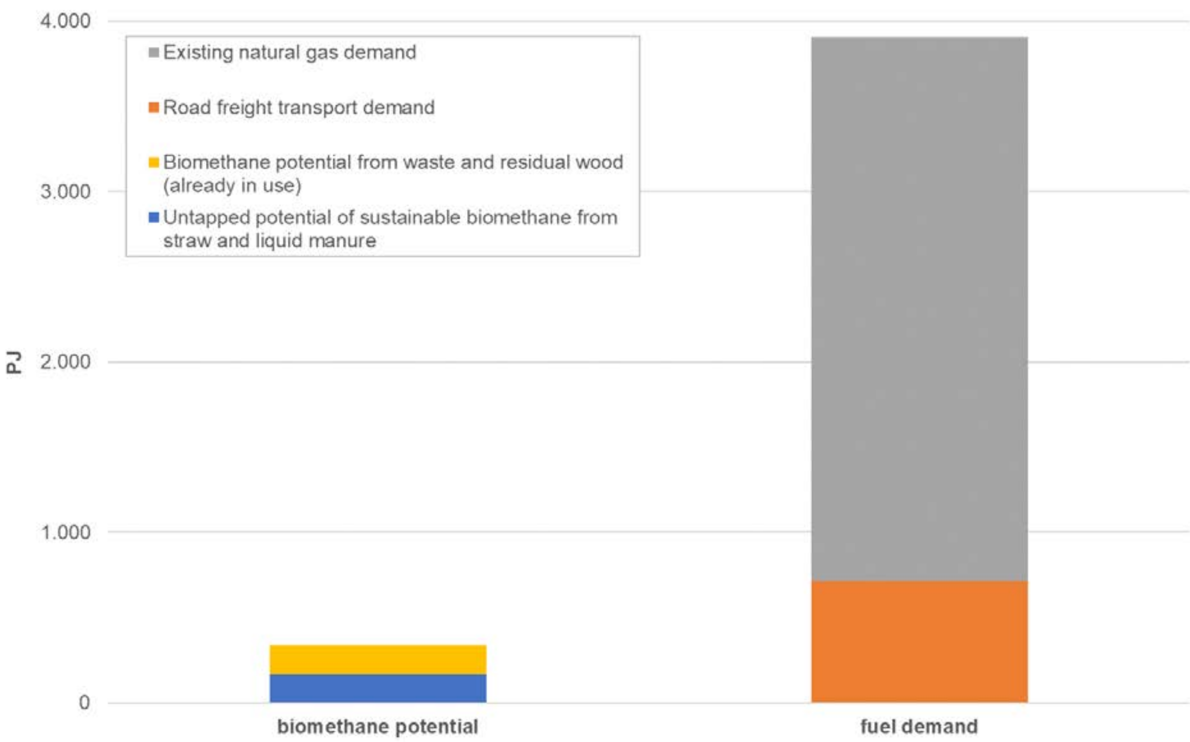
Source: Own calculations

In a direct comparison of total well-to-wheel (WTW) emissions, which includes both indirect WTT emissions and direct tank-to-wheel (TTW) emissions from the vehicle and refuelling, only vehicles with high- pressure direct injection natural gas (HPDI-NG) engines achieve slightly lower GHG emissions than comparable diesel vehicles (-7 % to -9 %). HPDI-NG engines are essentially diesel engines running on natural gas mixed with small amounts of diesel. However, the majority of LNG trucks are equipped with spark ignition-natural gas engines (SI-NG). SI-NG trucks have considerably lower upfront costs compared to HPDI-NG trucks, making them more popular with operators. Spark ignition engines are considerably less efficient than diesel engines, cancelling out most of the CO_2-benefits from using natural gas instead of diesel. When taking into account non-CO_2 GHG emissions, SI-NG trucks have approximately the same WTW GHG emissions as diesel trucks (-2 % to +1 %).

The determination of WTT emissions from LNG is associated with a high degree of uncertainty and may differ from those shown in the figure above. For example, the increasing share of natural gas from unconventional sources (fracking natural gas) in the EU invariably results in higher WTT emissions than those estimated by current WTT analyses for the EU. Moreover, the short-term (20 year) climate impacts from LNG trucks are particularly severe in comparison to diesel trucks.

Conversely, some actors argue that the overall GHG footprint of LNG trucks could be greatly reduced by using biomethane. However, our analysis shows that the currently untapped potential for sustainable biomethane production from straw and liquid manure in Germany is less than 25 % of the current road freight energy demand in Germany and is far outstripped by existing natural gas demand in other sectors, where rapid decarbonisation is equally required. Additional quantities of biomethane can be obtained if the production of synthetic biomethane from wood is available on an industrial scale and if the available wood is withdrawn from other uses. Making use of existing sustainable biomethane potentials through appropriate support policies can therefore at most make a small percentage contribution towards reducing overall GHG emissions from natural gas combustion. These GHG emission savings are unlikely to be entirely attributable to LNG trucks. In most climate protection scenarios, the available sustainable biomass is used in sectors other than transport due to its higher cost efficiency and limited potential for technological alternatives.

Figure 2: Domestic biomethane potential and today's fuel/natural gas demand of road freight transport and other sectors in Germany



Source: Own calculations based on primary energy potential from IFEU; IZES; ÖI (2019) and conversion efficiencies from http://webapp.dbfz.de/resources; fuel demand from DIW; DLR; KBA (2019) and AGEB (2020)

In the long term, synthetic methane from renewable electricity could become an option for powering LNG trucks with low climate impacts. This would require synthetic methane becoming available in sufficient quantities. However, powering an LNG truck would still require a few times more electricity compared to direct electrification of trucks through batteries or overhead catenary systems. Hydrogen fuels cells would also be a more energy efficient option compared to synthetic methane. It is therefore questionable whether synthetic methane can become a viable, cost-effective decarbonisation option for trucks, even in the long term. As a result, the switch to LNG could therefore lead to a lock-in into a cost-inefficient technology pathway or to a dead end of methane use in trucks and to stranded investments in infrastructures and drivetrain technology.

This leads us to the overall conclusion that LNG trucks should not be considered a suitable measure for climate protection in road freight transport.

We see two main policy implications arising from our analysis:

1. Take direct non-CO_2 GHG emissions into account in EU emission legislation. At present, the GHG emissions of LNG trucks are systematically underestimated in the EU HDV CO_2 emission standards as they do not take into account non-CO_2 GHG-emissions. Taking direct methane and nitrogen oxide emissions at vehicle level into account in the further development of the European certification methodology (i.e. Vehicle Energy Consumption Calculation Tool/VECTO) and corresponding standards could address this issue. Alternatively, stricter regulation of methane and nitrogen oxide emissions as part of air pollutant emission legislation (under post-EURO VI) and modifications to the EU Directive on Alternative Fuel Infrastructure (AFID), such as requirements for a GHG-minimising operation of LNG refueling infrastructure including reporting and monitoring, could also help minimize the non-CO_2 emissions.

2. Phase out subsidies for LNG trucks. Even though LNG trucks have no relevant climate benefits compared to diesel vehicles, they are heavily subsidised in Germany. This is currently done through three mechanisms:

    - exemption from the truck toll (cost savings of up to 20,000 € per year in 2020),
    - energy tax relief (cost savings of up to 42,000 € over 5 years) and
    - a purchase subsidy (12,000 €).

    We estimate that these subsidies lead to a very low cost-efficiency of GHG emission reduction (1,100 € with HPDI-NG trucks and 6,700 € with SI-NG trucks per tonne of CO_2-equivalent saved). By comparison, the penalties for failing to meet the targets of CO_2 emissions regulation for heavy duty vehicles from 2025 is equivalent to 260 €/t CO_2 (4,250 € per gCO_2/tkm deviation).[1] Other CO_2 abatement technologies in trucks that are available to meet the regulatory targets should therefore be significantly more cost-effective for real-world GHG abatement. Given the low subsidy efficiency and the risk of increasing, rather than decreasing, greenhouse gas emissions, an extension of the subsidies for LNG trucks seems unwarranted from a climate protection perspective.

[1] From the year 2030, possible penalties increase to around 420 €/t CO_2 (6,800 € per gCO_2/tkm deviation).

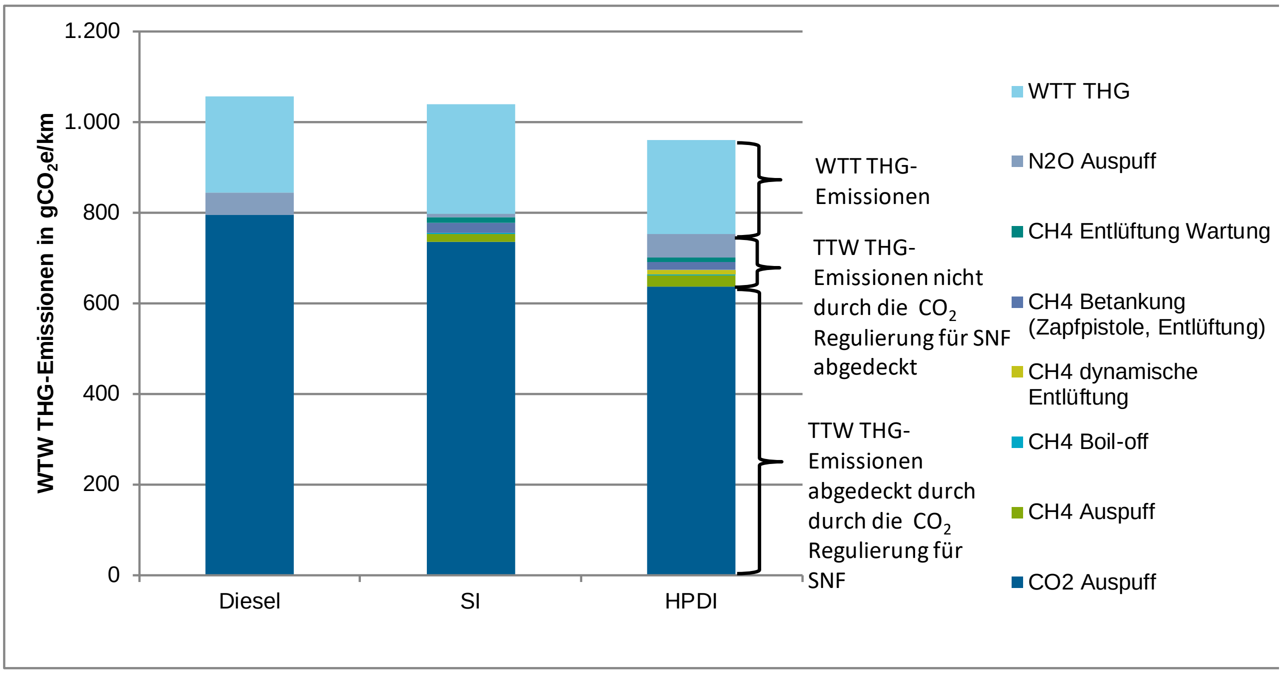
Zusammenfassung

Der Einsatz von Lkw, die mit verflüssigtem Erdgas (LNG) statt Diesel betrieben werden, ist keine geeignete Maßnahme für den Klimaschutz im Straßengüterverkehr. Selbst in einem optimistischen Szenario werden durch den Einsatz von LNG anstelle von Diesel weniger als 10 % Treibhausgas (THG)-Minderungen erreicht.

Theoretisch hat Erdgas mehrere Eigenschaften, die es zu einem geeigneten Kraftstoff für Verbrennungsmotoren machen. Erdgas hat einen geringeren Kohlenstoffgehalt als Diesel und erzeugt bei der Verbrennung etwa 25 % weniger CO_2 pro Energieeinheit. Das Erdgas muss jedoch verdichtet oder verflüssigt werden, um die für den Einsatz als Transportkraftstoff erforderliche Energiedichte zu erreichen. Die volumetrische Energiedichte von LNG ist zwar immer noch etwa 40 % niedriger als die von Diesel; sie ist jedoch deutlich höher als die von komprimiertem Erdgas (CNG). Dies macht LNG zu einem geeigneten Kraftstoff für den Langstreckentransport. Bei LNG-Lkw wird das verflüssigte Erdgas in vakuumisolierten Kraftstofftanks bei Temperaturen von -125 °C bis -160 °C gelagert.

LNG-Lkw verursachen zwar aufgrund der chemischen Zusammensetzung des Kraftstoffs geringere direkte CO_2-Emissionen, führt der Betrieb der Fahrzeuge zu erheblichen Methanemissionen. Wenn Methan unverbrannt in die Atmosphäre gelangt, ist es ein sehr starkes Treibhausgas. Weitere CO_2- und Methanemissionen entstehen bei der Kraftstoffgewinnung und -bereitstellung (sog. Well-to-Tank-Emissionen, WTT).

Abbildung 3: WTT-Treibhausgasemissionen von Diesel- und LNG-Lkw im Vergleich



Quelle: eigene Berechnungen

Im direkten Vergleich der gesamten Well-to-Wheel (WTW)-Emissionen, die sowohl die indirekten Vorkettenemissionen der Energiebereitstellung als auch die direkten Emissionen aus dem Fahrzeug und der Betankung umfassen, erreichen nur Fahrzeuge mit Erdgasmotoren mit Hochdruck-Direkteinspritzung (HPDI-NG) geringfügig niedrigere Treibhausgasemissionen als vergleichbare Dieselfahrzeuge (-7 % bis -9 %). HPDI-NG-Motoren sind im Wesentlichen Dieselmotoren, die mit einem

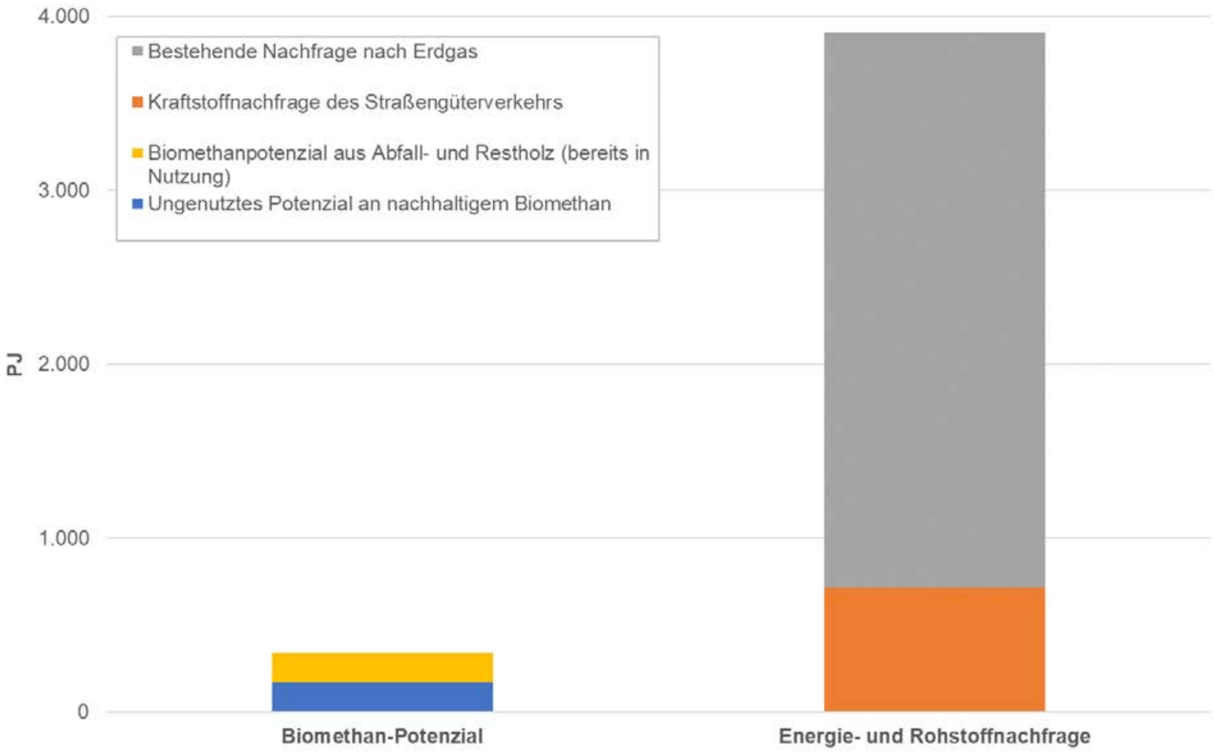
Gemisch aus Erdgas und kleineren Mengen Diesel betrieben werden. Rund drei Viertel der in Deutschland geförderten LNG-Lkw nutzen jedoch Erdgas-Ottomotoren. Lkw mit Erdgas-Ottomotoren haben im Vergleich zu HPDI-NG-Lkw niedrigere Anschaffungskosten, was sie bei den Betreibern beliebt macht. Ottomotoren sind jedoch erheblich weniger effizient als Dieselmotoren. Daher wird ein großer Teil des CO_2-Vorteils, der sich aus der Verwendung von Erdgas anstelle von Diesel ergibt, zunichte gemacht. Berücksichtigt man zudem die Methan-Emissionen, so haben LNG-Lkw mit Erdgas-Ottomotoren ungefähr die gleichen gesamten Treibhausgasemissionen wie Diesel-Lkw (-2 % bis +1 %).

Die Bestimmung der Well-to-Tank-Emissionen von LNG ist mit einem hohen Maß an Unsicherheit verbunden und kann somit von der obigen Darstellung abweichen. So führt beispielsweise der steigende Anteil von Erdgas aus unkonventionellen Quellen (Fracking-Erdgas) in der EU zu höheren Vorketten-Emissionen als in den aktuellen Analysen für die EU geschätzt. Darüber hinaus sind durch den Methanausstoß die kurzfristigen Klimawirkungen (über 20 Jahre) von LNG-Lkw besonders schwerwiegend im Vergleich zu Diesel-Lkw.

Umgekehrt argumentieren einige Akteure, dass der gesamte THG-Fußabdruck von LNG-Lkw durch die Verwendung von Biomethan stark reduziert werden könnte. Unsere Analyse zeigt jedoch, dass das derzeit ungenutzte Potenzial für eine nachhaltige Biomethanproduktion aus Stroh und Gülle in Deutschland weniger als 25 % des derzeitigen Energiebedarfs für den Straßengüterverkehr in Deutschland ausmacht und bei weitem von der bestehenden Erdgasnachfrage in anderen Sektoren übertroffen wird, in denen ebenfalls eine rasche Dekarbonisierung erforderlich ist. Zusätzliche Mengen an Biomethan können gewonnen werden, wenn die Herstellung von synthetischem Biomethan aus Holz im industriellen Maßstab verfügbar ist und falls das verfügbare Holz anderen Verwendungszwecken entzogen wird. Die Nutzung vorhandener nachhaltiger Biomethanpotenziale durch entsprechende Fördermaßnahmen kann daher allenfalls einen kleinen prozentualen Beitrag zur Reduzierung der Treibhausgasemissionen aus den Erdgas-verbrauchenden Sektoren leisten. Es wäre also sehr wahrscheinlich unangemessen, die begrenzten potentiellen THG-Emissionseinsparungen aus der Nutzung von Biomethan vorwiegend bei dem neu geschaffenen Erdgasbedarf durch LNG-Lkw zu erzielen. In den meisten Klimaschutzszenarien wird die verfügbare nachhaltige Biomasse aufgrund ihrer höheren Kosteneffizienz und des begrenzten Potenzials für technologische Alternativen in anderen Sektoren als dem Verkehrssektor eingesetzt.

Langfristig könnte synthetisches Methan aus erneuerbarem Strom eine treibhausgasarme Option für den Antrieb von LNG-Lkw werden. Voraussetzung dafür wäre, dass synthetisches Methan in ausreichender Menge für den Straßenverkehr zur Verfügung stünde. Allerdings würde der Antrieb eines Lkw mit synthetischem Methan im Vergleich zur direkten Elektrifizierung von Lkw über Batterien oder Oberleitungssysteme immer noch ein Mehrfaches an Strom benötigen. Wasserstoff-Brennstoffzellen wären auch eine energieeffizientere Option im Vergleich zu synthetischem Methan. Es ist daher fraglich, ob synthetisches Methan langfristig zu einer praktikablen, kostengünstigen Dekarbonisierungsoption für Lkw werden könnte. Vielmehr besteht die Gefahr, dass großangelegte Investitionen in LNG-Lkw und deren Infrastruktur auf dem Weg zu einer klimaneutralen Mobilität einen wenig kosteneffizienten Technologiepfad zementieren, bzw. keinen kontinuierlichen Rückgang der THG-Emissionen gewährleisten können und somit in eine Sackgasse führen.

Abbildung 4: Vergleich des einheimischen Biomethanpotenzials mit dem Energiebedarf des Straßengüterverkehrs und des gesamten Erdgas-Bedarfs in Deutschland



Quelle: Eigene Berechnung auf Basis der Primärenergiepotenziale aus IFEU; IZES; ÖI (2019) und der Konversionseffizienz von http://webapp.dbfz.de/resources; Energie- und Rohstoffnachfrage aus DIW; DLR; KBA (2019) und AGEB (2020)

Dies führt uns insgesamt zu der Einschätzung, dass LNG-Lkw keine geeignete Maßnahme für den Klimaschutz im Straßengüterverkehr darstellen.

Aus der vorliegenden Analyse lassen sich die folgenden politischen Schlussfolgerungen ziehen:

1. Berücksichtigung der direkten Nicht-CO_2-THG-Emissionen in der EU-Emissionsgesetzgebung. Gegenwärtig werden die THG-Emissionen von LNG-Lkw in den EU-Regulierungen der CO_2-Emissionen schwerer Nutzfahrzeuge systematisch unterschätzt, da sie Nicht-CO_2-THG-Emissionen nicht berücksichtigen. Die Berücksichtigung direkter Methan- und Stickoxidemissionen auf Fahrzeugebene bei der Weiterentwicklung der europäischen Zertifizierungsmethodik (d. h. Vehicle Energy Consumption Calculation Tool/VECTO) könnte dieses Problem beheben. Alternativ könnten auch eine strengere Regulierung der Methan- und Stickoxidemissionen im Rahmen der Luftschadstoffemissionsgesetzgebung (im Rahmen von Post-EURO VI) und Änderungen der EU-Richtlinie über die Infrastruktur für alternative Kraftstoffe (AFID), wie z. B. Anforderungen an einen THG-minimierenden Betrieb der LNG-Betankungsinfrastruktur einschließlich Berichterstattung und Überwachung, dazu beitragen, die Nicht-CO_2-Emissionen zu minimieren.

2. Auslaufen der Subventionen für LNG-Lkw. Auch wenn LNG-Lkw im Vergleich zu Dieselfahrzeugen keine relevanten Klimavorteile haben, werden sie in Deutschland stark subventioniert. Dies geschieht derzeit über drei Mechanismen:

- Befreiung von der Lkw-Maut (Kosteneinsparungen von bis zu 20.000 € pro Jahr im Jahr 2020),
- Energiesteuererleichterungen (Kosteneinsparungen von bis zu 42.000 € über 5 Jahre) und
- Kaufzuschuss (12.000 €).

Diese Subventionen weisen eine sehr niedrige Kosteneffizienz in Bezug auf Treibhausgasminderungen auf (1.100 € bei HPDI-NG-Lkw und 6.700 € bei Erdgas-Otto-Lkw pro eingesparter Tonne CO_2-Äquivalent). Im Vergleich dazu belaufen sich die Strafen für die Nichterfüllung der CO_2-Flottenzielwerte für schwere Nutzfahrzeuge ab 2025 auf 260 €/t CO_2 (4.250 € pro gCO_2/tkm Abweichung). Andere Technologien zur CO_2-Verringerung bei Lastkraftwagen, die verfügbar sind, um die Flottengrenzwerte zu erreichen, dürften daher für die reale THG-Verringerung wesentlich kosteneffizienter sein. Angesichts der geringen Fördermitteleffizienz und des Risikos, dass die Treibhausgasemissionen nicht verringert, sondern womöglich sogar erhöht werden, erscheint eine Verlängerung der Subventionen für LNG-Lkw aus Klimaschutzsicht nicht gerechtfertigt.

1. Motivation and background

In mid-2019, the EU finally adopted a CO_2 regulation for newly registered heavy-duty vehicles for the first time. Similar to the CO_2 emission standards for passenger cars and light commercial vehicles, the regulation requires vehicle manufacturers to reduce the CO_2 emissions of their new vehicle fleets over time. The regulation stipulates that the average CO_2 emissions of the new vehicle fleet must be reduced by 15 % by 2025 and by 30 % by 2030; the latter can be reviewed in 2022. Vehicle manufacturers must pay a financial penalty if they fail to achieve the required CO_2 reduction of the new vehicle fleet. The amount of the penalty payment is based on the size of the gap between the reduction target and the size of their new vehicle fleet. Other elements of the regulation include banking and borrowing for under- and overachieving the emission reduction, as well as special rules for crediting vehicles with zero and very low CO_2 emissions (see ICCT (2019) for more details on regulation).

The backbone of the CO_2 emission standards for heavy-duty vehicles is the VECTO[2] calculation tool, which is used to determine—as part of the vehicle registration process—the tailpipe CO_2 emissions (**T**ank-**t**o-**W**heel/TTW) released during typical use. In contrast to passenger cars and light commercial vehicles, TTW CO_2 emissions are therefore not determined on the chassis dynamometer, but by modeling the vehicle operation in a simulation environment (see ICCT (2018) for more details).

Vehicle manufacturers can use various strategies to achieve their targets:

- Improve the aerodynamic and rolling resistance of vehicles
- Improve the efficiency of the—currently predominant—diesel powertrain
- Develop and deploy alternative drive systems with potentially lower TTW CO_2 emissions (e.g. battery electric drivetrain, fuel cell electric drivetrain, natural gas drivetrain)

It is likely that a combination of different strategies to reduce TTW CO_2 emissions will be necessary to comply with the targets set by the CO_2 emission standards. It is also expected that different manufacturers will choose different strategies for compliance, depending on the individual need for emission reduction, the individual state of the art, individual target markets and their respective political framework conditions, as well as possible synergies with other internal developments and with external industrial partners.

The market development for liquefied natural gas (LNG) vehicles is a possible compliance strategy for vehicle manufacturers. The idea of this paper is therefore to closely examine the climate impacts of using LNG trucks as a compliance strategy. The VECTO certification approach, and thus the CO_2 emission standards, refer only to the tailpipe CO_2 emissions during use. For this reason, it is to be investigated whether this certification approach comprehensively captures all the climate impacts of LNG use in trucks. A decisive factor is that the GHG impact of methane emissions is much higher than that of CO_2. Therefore, methane emissions in the production, distribution and refuelling of LNG (Chapter 4) as well as possible methane release during vehicle operation (Chapter 3) have a significant impact on the climate impacts of LNG trucks.

Thus, the German Federal Environment Agency commissioned this study as part of project *Prüfung des Vorschlags der Europäischen Kommission für die post-2020- Gesetzgebung zur CO2-Minderung bei PKW und leichten Nutzfahrzeugen (FKZ: 3716 58 107 0)*.

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[2] **V**ehicle **E**nergy **C**onsumption calculation **TO**ol

2. Status quo of LNG truck market

The stock of heavy-duty trucks in Germany today consists almost exclusively of diesel-powered vehicles. At the beginning of 2019, natural gas trucks accounted for around 14,000 vehicles, or about 0.4 % of the total stock, but these were almost exclusively small trucks. In contrast, only about 0.1 % of the approximately 224,000 trucks with a payload of six tons or more were equipped with natural gas engines. Of the approximately 218,000 semitrailer tractors, 137 or 0.06 % had CNG drive at the beginning of 2019. LNG trucks are not listed separately in the official statistics but are included in the category "other", which, with 391 vehicles, accounted for 0.2 % of the total number of tractor units (KBA 2019).

However, this picture is likely to change for 2019 due to the current subsidy policy. As of the end of December 2019, the Federal Office for Goods Transport (Bundesamt für Güterverkehr - BAG) approved funding for the acquisition of a total of 184 CNG trucks and 656 LNG trucks.

In terms of sales figures for diesel tractor units, the German market is characterised by a small number of manufacturers. More than half of the newly registered tractor units are vehicles from the German manufacturers Daimler (28 %) and MAN (26 %). The third largest manufacturer is DAF Trucks (17 %), followed by Scania (14 %), Volvo (11 %) and Iveco (3 %).

A look at the vehicles currently available (Table 2-1) shows that it is mainly the manufacturers Iveco, Scania and Volvo that are pursuing CNG and LNG trucks. In addition to CNG trucks with a short range, all three manufacturers also offer LNG-powered models with a range of 1,000 km and more. Whereas Iveco and Scania's LNG trucks operate on the principle of spark injection (see 3.3.1.1) and run exclusively on natural gas, Volvo's trucks are equipped with HDPI (High Pressure Direct Injection) engines and also require small amounts of diesel fuel (see 3.3.1.2).

Of the LNG truck subsidy projects approved in Germany, 151 vehicles[3], or 23 %, are manufactured by Volvo, which offers efficient HPDI-NG trucks. More than three-quarters of the trucks come from Iveco and Scania and therefore have a less efficient SI-NG engine.

The vehicle manufacturers Daimler and MAN, which are important for the German truck market, have no natural gas trucks for long-distance haulage in their portfolio.

Table 2-1: Overview of currently available CNG and LNG trucks

Manufacturer	Model	Fuel	Power (kW)	Range (km)
IVECO	Stralis NP CNG	CNG	294	up to 1,000
IVECO	Stralis NP LNG	LNG	338	up to 1,500
IVECO	Stralis NP 400	CNG	294	up to 1,000
IVECO	Eurocargo Natural Power 12-16 ton	CNG	150	up to 400
Mercedes	Econic NGT	CNG	222	up to 400
RENAULT	Renault D Wide CNG	CNG	235	up to 400
SCANIA	P/G CNG Version 280	CNG	205	up to 425
SCANIA	P/G CNG Version 340	CNG	250	up to 425
SCANIA	P/G LNG Version 280	LNG	205	up to 1,100
SCANIA	P/G LNG Version 340	LNG	250	up to 1,100

3 Personal communication on 02.03.2020 by M. Löffler; Federal Office for Goods Transport

Manufacturer	Model	Fuel	Power (kW)	Range (km)
VOLVO	FE CNG	CNG	239	up to 400
VOLVO	FH LNG	LNG	340	up to 1,000
VOLVO	FM LNG	LNG	340	up to 1,000

Source: NGVA (2019)

3. Tank-to-Wheel emissions of LNG trucks

According to the European Commission's impact assessment accompanying the CO_2 standards proposal for heavy duty vehicles, LNG engines could have up to 20 % lower TTW CO_2 emissions than comparable diesel vehicles and the shift to LNG lorries would also have a positive impact on air pollutant emissions (European Commission 2018).

This section seeks to examine the validity of the European Commission's assumptions and presents the latest available evidence on how LNG trucks fare in comparison to diesel-powered vehicles with respect to GHG and pollutant emissions.

3.1. Fuel characteristics

In its pure form, methane has several properties that make it an attractive fuel for combustion engines. Due to its molecular structure methane has a lower carbon content than diesel and produces less CO_2 per unit of energy. Combusting enough diesel to produce 1 MJ of energy releases approximately 73 g of CO_2. Producing the same amount of energy through methane combustion releases around 25 % less CO_2 at 55 g/MJ.

Methane has the highest energy content per unit mass of all fossil fuels, at 50 MJ/kg. However, it is in the gas form at room temperature and pressure, and must be compressed or liquefied to achieve the volumetric energy density required for its use as a transport fuel. In its liquid form, 1 litre of methane contains 21 MJ (dena 2014). While this is still approximately 40 % lower than the volumetric energy density of diesel (~36 MJ/l), it is significantly higher than that of compressed methane, making it a suitable fuel for long-haul transportation.

While the main constituent of LNG is methane, it also contains smaller quantities of ethane and propane (DVGW 2016). The actual LNG composition depends on the traits of the reservoir, on the treatment of gas at the liquefaction facility, and on the handling of the LNG across the supply chain. The latter is responsible for the *weathering* or *ageing* of the LNG. During the journey of an LNG tanker, the liquified fuel evaporates and forms boil-off gas (BOG). The lower boiling point and faster evaporation rate of methane, compared to ethane and propane, means that BOG consists of mostly methane. Depending on the vessel and its propulsion technology, BOG can be utilized as fuel, re-liquefied or burned in a gasification unit. Therefore, the quality and properties of LNG steadily change during transport (Dobrota et al. 2013).

Table 3-1 shows the typical composition of LNG from 5 different sources (IGU 2012) and the impact of the composition on the energy density, carbon content, and anti-knock properties—quantified by the methane number (GIE 2012) —of the fuel. Compared to pure methane, heavy LNG mixtures, as those coming from Algeria, can have over 2 % lower energy density and over 3 % higher CO_2 emissions than pure methane. The methane number is also greatly affected by the LNG composition (Eilts and Klare 2018), directly impacting the thermal efficiency of spark-ignited stoichiometric LNG engines, as will be discussed in a later subsection.

Table 3-1: Typical molar composition of 5 different LNG mixtures with their respective energy density, carbon content, and methane number

	Methane	Ethane	Propane	Heavier HCs	Nitrogen	Energy content	Carbon content	Methane Number
	%	%	%	%	%	MJ/kg	gCO_2/MJ	-
Alaska	99.7	0.09	0.03	0.03	0.17	49.8	55.0	95
Algeria	88.0	9.0	2.5	0.5	0.6	48.9	56.7	76
Nigeria	92.1	5.3	2.1	0.5	0.1	49.4	56.2	79
Norway	91.8	5.7	1.3	0.4	0.8	48.9	56.1	81
Qatar	90.1	6.2	2.3	1	0.4	49.1	56.5	78

Source: IGU (2012). Methane numbers from GIE (2012).

3.2. Engine technology

Combustion engines are generally grouped as either positive ignition or compression ignition engines. In positive ignition engines, such as those used in gasoline passenger cars, the fuel and air are premixed ahead of combustion, and the fuel-air mixture is ignited by an external energy source, such as a spark plug. In compression ignition engines, typically using diesel fuel, the air and fuel are kept separate with combustion occurring as the fuel auto-ignites throughout its injection in the hot, compressed air, giving place to, what is called, a diffusion flame.

Heavy-duty NG engines exist as positive ignition engines, compression ignition engines, and a combination of both processes.

Positive ignition, also called spark ignition, NG engines are mono-fuel engines, in which NG-air mixtures with a stoichiometric composition (i.e., with just the right amount of air to combust all the fuel) or with a lean composition (i.e., with excess air) are premixed ahead of combustion and are ignited by a spark plug. The result is a propagating flame front that moves away from the ignition point outwards and pushes the piston downwards during the expansion stroke.

Compression ignition engines, which operate in the diesel cycle, rely on the direct injection of fuel into the hot air compressed contained in the combustion chamber. Due to the high auto-ignition temperature of methane, compression ignition NG engines do not exist as mono-fuel engines and require a combination of diesel and NG for their operation. Depending on the injection strategy—that is, on the timing of the NG and diesel injections and on their respective amounts—LNG compression ignition engines have received different names in the scientific literature (Florea et al. 2016). The most promising injection strategy for direct injected NG engines is dubbed High Pressure Direct Injection (HPDI).

Another type of NG engine combines the positive and compression ignition concepts. Such engines also require a combination of diesel and NG for their operation and are called dual fuel indirect ignition. In this technology, the NG and air are premixed at low pressure on the compression stroke as in a positive ignition engine. The premixed lean gas-air mixture is ignited by the compression ignition of a high-pressure diesel spray. Fumigated NG engines, as this concept is also called, present several challenges for the emissions control and result in low thermal efficiency (Kozarac et al. 2019).

Table 3-2 presents the assessments of Daimler and MAN on the aforementioned NG concepts, as presented in a Federal Ministry of Transport and Digital Infrastructure workshop (MAN 2015).

Table 3-2: OEM assessment of NG engine technology

	Dual-fuel, fumigated		Spark ignition, lean		Spark ignition, stoichiometric		HPDI	
	Daimler	MAN	Daimler	MAN	Daimler	MAN	Daimler	MAN
Thermal efficiency	-	-	-	--	-	--	o	o
CO_2 emissions	-	?	+	?	+	?	++	?
Pollutant emissions	--	--	o	-	o	++	o	-
Complexity	-	-	+	o	+	+	-	--
Power density	-	o	-	-	-	-	o	o

--/-/o/+/++ ranks the options from least to most favourable. "?" is used to indicate that an OEM assessment was not available.

Source: MAN (2015) and Röhl (2015)

Since only stoichiometric spark ignition (SI) and HPDI natural gas engines are seen by the industry as viable technology pathways, the remaining of the report will focus only on those two technologies.

3.3. GHG emissions

Natural gas engines have several sources of GHG emissions. The dominant source is the release of the carbon contained in the fuel during combustion. However, methane emissions from the combustion process and from leaks in the fuel system are also significant. Additionally, nitrogen oxide, a powerful GHG, can also be formed in the catalytic reactors of the emissions control system. This section discusses all GHG sources of SI and HPDI engines.

3.3.1. Tailpipe CO_2 emissions

3.3.1.1. Stoichiometric SI NG engines

Stoichiometric SI engines, which operate on what is known as the Otto cycle, have some intrinsic efficiency disadvantages compared to diesel engines. These are summarized below:

1. Knock: It is well known that the efficiency of combustion engines, regardless of the thermodynamic cycle, increases with higher compression ratios (Heywood 2018). To avoid engine damage by abnormal combustion, called knock, the compression ratio of SI engines must be limited and is significantly lower than that of diesel engines. The compression ratio of SI engines is selected to achieve the right balance between part- and full-load operation. To avoid knock at full-load operation, such as during acceleration or hill climbing, the combustion timing is delayed, reducing the thermal efficiency of the engine. This knock limitation is aggravated by the design approach followed by manufacturers developing heavy-duty SI-NG engines. NG engines are mostly derived from diesel engines and are more prone to knocking due to the geometry constrains placed by the legacy diesel architecture, and the resulting poor in-cylinder turbulence and slow flame propagation (Zhao et al. 2019).
2. Load control: The engine's torque output is inexorably linked to the amount of fuel injected. In stoichiometric engines, the amount of air used in combustion is directly dependent to the amount of fuel injected. At part load, the air flow into the engine must then be throttled to match the fuel rate, resulting in thermodynamic losses (Heywood 2018).
3. Air fuel mixture: The theoretical efficiency of an engine is dependent on a thermodynamic property of the air-fuel mixture called the *heat capacity ratio*. Lean mixtures, such as those used in

diesel engines, have higher heat capacity ratios and thus result in higher engine efficiencies, all other conditions being equal. As the fuel content of the air-fuel mixture increases, such as in stoichiometric engines, the heat capacity ratio is reduced (Heywood 2018).

4. Combustion efficiency: Combustion efficiency refers to the ability of engines to fully burn all the fuel injected. Engines with premixed combustion, such as SI NG engines, generally show high rates of unburned fuel. The premixed air-fuel mixture can access small crevices in the combustion chamber and escapes the main combustion event. NG engines derived from diesel engines tend to have larger crevices and thus exacerbate this phenomenon. This unburned fuel is either burned as the hot exhaust gases leave the cylinder, oxidized by the emissions control system, or emitted as unburned hydrocarbons into the atmosphere. In any case, since the fuel does not release its energy during the power stroke of the engine, it negatively affects the thermal efficiency of the engine (Cheng et al. 1993).

5. Sensitivity to fuel composition: NG engines are known to be sensitive to variations in fuel composition. LNG containing higher fractions of ethane and propane have worse anti-knock properties (see Methane Number in Table 3-1), and directly affect the thermal efficiency of the engine as discussed above (Chen et al. 2017).

The lower efficiency of stoichiometric SI engines, compared to diesel engines, has direct consequences on the CO_2 emissions performance: TTW CO_2 emissions are directly proportional to the fuel energy use per unit of work output and to the carbon content of the fuel (see Table 3-1). Table 3-3 presents a summary of the literature review of how stoichiometric SI-NG engines compare to diesel engines. The table presents the efficiency (i.e., energy consumption) and CO_2 emissions comparison separately, as reported in the different studies.

Table 3-3: Literature review of the relative change in energy consumption and CO_2 emissions of SI NG engines compared to diesel engines for heavy-duty applications

Energy consumption relative to diesel engines	CO_2 emissions relative to diesel engines	Source
21.5 %	N.A.	Langshaw et al. (2020)
19.0 %	-7.1 %	Cenex (2019)
24.1 %	N.A.	DLR; TUHH (2019)
N.A.	-10.1 %	TNO (2018)
N.A.	-8.9 %	TNO (2017)
16.8 %	-12.0 %	NGVA Europe (2017)
24.3 %	-3.2 %	LBST (2016)
11.1 %	N.A.	Burnham et al. (2016)
21.0 %	-0.5 %	IFEU (2015)
23.1 %	-7.4 %	IFEU (2015)
26.1 %	-3.6 %	dena (2014)
31.8 %	8.7 %	cenex (2012)

In average, SI NG engines consume 22 % more energy (i.e., are 18 % less efficient) than diesel HD engines. They also emit, in average, 4.9 % less CO_2 emissions than their diesel counterparts, thanks to the lower carbon content of the fuel.

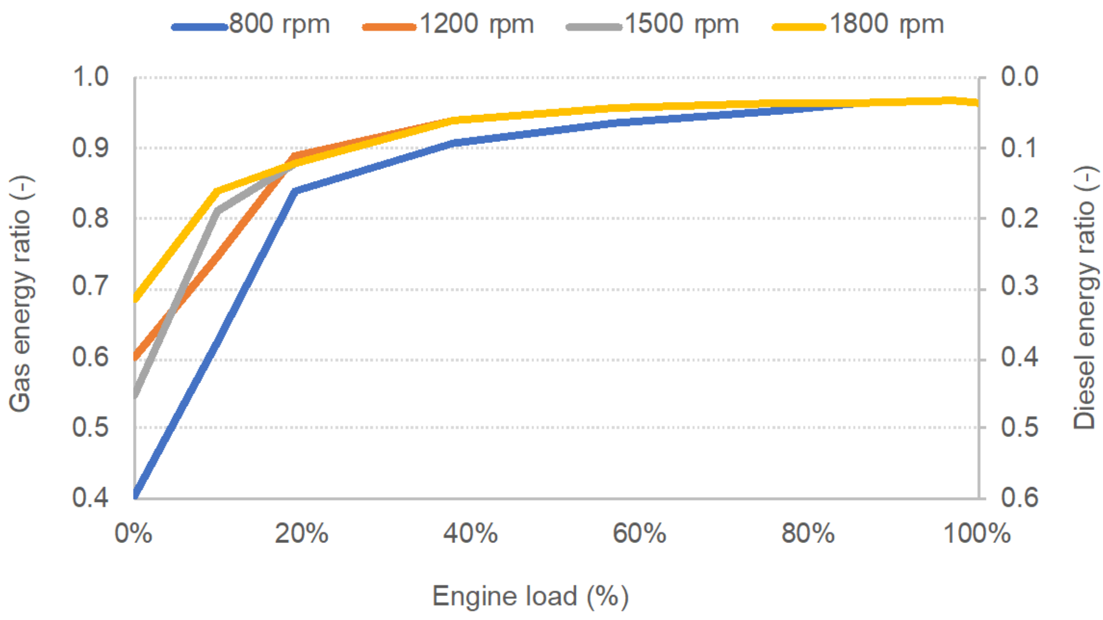
3.3.1.2. HPDI NG engines

As mentioned, HPDI engines retain the operating principles of the base diesel engine: direct injection near top-dead-centre, auto-ignition of the fuel sprays, diffusion flames, and the thermodynamic Diesel cycle. Consequently, the theoretical efficiency of HPDI engines is not impaired by the same disadvantages afflicting SI-NG engines. HPDI engines are not limited by knock and can operate at the same compression ratio of diesel engines, do not need to delay the combustion phasing at high load, and are less sensitive to variations in fuel composition. Furthermore, since HPDI engines operate on lean mixtures, the air flow is not throttled, and the mixture achieves a higher heat capacity ratio.

Still, HPDI engines present a number of challenges that can directly affect the thermal efficiency of this combustion concept. These are summarized below:

1. Need for pilot diesel injection: HPDI systems require the injection of diesel and NG, directly into the combustion chamber. Near the end of the compression stroke, a small amount of diesel is injected first, called pilot injection, and ignites spontaneously as it would do in a diesel engine. The NG injection occurs shortly thereafter and is ignited by the diffusion flame of the diesel pilot injection (McTaggart-Cowan et al. 2017). Since NG is not a fuel that auto-ignites easily, it is necessary to ensure a consistent performance of the pilot injection across all operating points. Accordingly, the amount of diesel fuel used in the pilot injection is similar across all operating points. As a consequence, the ratio of diesel to gas varies across the engine map. As shown in Figure 3-1, at high loads diesel represents approximately 4 % of the total fuel energy. At low loads it can account to up to 60 % (Ouelette; Goudie; McTaggart-Cowan 2016). As the diesel share of the total fuel injected increases, the CO_2 benefits of the HPDI concept are reduced.

Figure 3-1: HPDI engine gas energy ratio (energy in natural gas / total energy in fuel) as a function of torque for various speeds



Data source: Ouelette; Goudie; McTaggart-Cowan (2016)

2. Parasitic load of NG pump: Since LNG is stored at low pressure (< 10 bar), LNG fuel systems requires a pump to increase the pressure to approximately 300 bar for direct injection into the engine. However, pumping a cryogenic fluid, such as LNG, comes with its own set of challenges in sealing, insulation, thermal stress and material durability (Zhang 2010). As a consequence, HPDI engines have an efficiency disadvantage over diesel engines from the added parasitic load of the LNG pump. Over a typical road duty cycle, the parasitic load of the LNG pump accounts between 1 % and 3 % of the engine's fuel consumption (Ouelette; Goudie; McTaggart-Cowan 2016). Parasitic losses of LNG pumps of HPDI engines are expected to increase in the future, as LNG pumps move toward 500 bar of pressure. Current HPDI system with 300 bar will not be sufficient to deal with the higher peak cylinder pressures targeted by future engine designs, and can lead to a slower injection process, increased burn duration, and ultimately lower thermal efficiency (Arnberger; Golini; Mumford; Hasenbichler 2018).
3. Combustion efficiency: HPDI's late injection and non-premixed combustion gives it an advantage in terms of combustion efficiency compared to SI-NG engines; that is less fuel escapes the main combustion event. Still, HPDI engines have lower combustion efficiency than diesel engines. Nieman et al. (2019) estimates that approximately 2 % of the NG injected is not combusted during the power stroke of the engine. Florea et al. (2016) provides similar estimates.
4. Sensitivity to fuel composition: Compared to SI-NG engines, HPDI engines are less sensitive to the NG composition, as they are not limited by knock. Still, changes in the fuel composition do still impact the combustion behaviour. Higher concentrations of ethane or propane in the NG lead to higher fuel densities and hence greater fuel mass being injected for a given injection duration. This results in a longer combustion duration that can negatively affect the thermal efficiency of the engine (McTaggart-Cowan et al. 2017).

Table 3-4 presents a summary of the literature review of how HPDI engines compared to diesel engines. The table presents the efficiency (i.e., energy consumption) and CO_2 emissions comparison separately, as reported in the different studies.

Table 3-4: Literature review of the change in energy consumption and CO_2 emissions of HPDI-NG engines relative to diesel HD engines

Energy consumption relative to diesel engines	CO_2 emissions relative to diesel engines	Source
3.1 %	-19.4 %	Cenex (2019)
7.8 %	N.A.	DLR; TUHH (2019)
N.A.	-18.9 %	TNO (2019a)
3.5 %	-20.3 %	NGVA Europe (2017)
5.3 %	N.A.	Burnham et al. (2016)
0.2 %	-23.7 %	LBST (2016)

In average, HPDI engines consume 4 % more energy (i.e., are 3.8 % less efficient) than diesel HD engines. They also emit, in average, 20.5 % less CO_2 emissions than their diesel counterparts, thanks to the lower carbon content of the fuel.

3.3.2. Tailpipe methane emissions

Unburned methane emissions are a particular challenge for all natural-gas fuelled engines. As presented in section 3.3.1, NG engines suffer from combustion efficiency issues and not all of the NG is burned during combustion. While this has direct impacts on the thermal efficiency of the engine, it can also lead to high tailpipe emissions of methane. If the temperature in the cylinder is not high enough for post-oxidation, methane will leave the engine and would need to be handled by the aftertreatment system.

Methane is the least reactive hydrocarbon, and high energy is required to break the primary carbon-hydrogen bond. In practical terms, this means that higher temperatures are required for the after-treatment system to achieve high methane conversion rates, when compared with other longer-chained hydrocarbons (Raj 2016). Reliable catalytic methane oxidation requires exhaust gas temperatures above 500 °C. Below that temperature the conversion rate decreases rapidly (CIMAC 2014).

SI NG engines have higher tailpipe methane emissions since the premixed NG-air mixture goes into small crevices in compression stroke where the flame front cannot access, resulting in methane escaping the main combustion event. HDPI engines work with non-premixed (diffusion) combustion resulting in less methane going into the combustion chamber crevices. Even so, achieving the certification requirement of 0.5 g/kWh over the type-approval cycle is challenging for HPDI engines, as the use of exhaust gas recirculation (EGR) for NO_x control increases engine-out methane emissions (Ouelette; Goudie; McTaggart-Cowan 2016). Furthermore, HPDI engines have lower exhaust temperatures than SI-NG engines presenting a challenge for the oxidation catalysts.

Table 3-5 presents a summary of the literature review of the tailpipe methane emissions for stoichiometric SI and HPDI NG engines. The table presents the values as methane slip, that is, as a fraction of the LNG fuel consumed by the engine. HPDI engines have higher methane slip than SI engines in all literature sources consulted. In average, stoichiometric SI engines have 0.22 % of methane slip and HPDI engines 0.38 %. As a reference, the Euro VI methane limit of 0.5 g/kWh corresponds to a methane slip of approximately 0.25 %.

Table 3-5: Literature review of tailpipe methane emissions of HD-NG engines, presented as a fraction of LNG consumption (i.e. methane slip)

Stoichiometric SI engine	HPDI engine	Source
0.25 %	0.61 %	Imperial College London (2019)
0.04 %	0.18 %	TNO (2017)
0.40 %	0.81 %	Clark et al. (2017)
0.13 %	0.15 %	NGVA Europe (2017)
0.28 %	0.36 %	LBST (2016)
0.21 %	0.34 %	Burnham et al. (2016)
0.20 %	0.24 %	Kofod and Stephenson (2013)

In comparison to CO_2 emissions, methane emissions lead to a stronger greenhouse gas effect. The 5th assessment report of the IPCC lists GWP factors for methane and other greenhouse gases. With these factors the greenhouse effect of different GHG can be expressed as CO_2 equivalents and presented in a comparable way. The various greenhouse gases have different lifetimes in the atmosphere. For this reason, the greenhouse gas intensity must be related to a specific time period. It is common practice in life cycle assessment to relate the greenhouse gas effect to a period of 100 years and not to take into account so-called climate-carbon feedback.

The GWP factor of 30 is therefore used for fossil methane in the following. This means that the oxidation of methane to CO_2 is considered. The GWP factor of 265 is applied for all nitrogen oxide emissions (IPCC 2013)[4].

3.3.3. Non-tailpipe methane emissions

Although the design of LNG trucks strive to minimize the venting of methane, it is not possible to prevent small amounts of methane escaping to atmosphere (Kiwa 2013). Non-tailpipe emissions of methane can occur from boil-off venting of the LNG inside the truck's tank, crankcase emissions, dynamic venting of the fuel system, refuelling, or manual opening of venting valves. This section details each venting source.

3.3.3.1. Boil-off

LNG is stored on-board as a cryogenic fluid in cylindrical vessels made of two metallic layers separated by a vacuum insulation to minimize heat transfer from the environment into the tank (Zhang 2010). The inner cylinder is exposed to a cryogenic temperature between -125 °C and -160 °C (Nelles 2019). Despite the vacuum insulation layer, heat from the environment does transfer into the LNG tank of the vehicle, evaporating the cryogenic liquid and increasing the tank pressure; this is called boil-off. LNG tanks have a nominal operating pressure of around 10 bar. To avoid too high-pressure levels safety valves are required. When the tank's pressure reaches around 16 bar, LNG is vented into the environment (Nylund und Wenstedt 2019).

According to Regulation 110 of the United Nations Economic Commission for Europe (UNECE 2014), vehicle LNG tanks must have a design hold time of at least 5 days after being filled using the highest temperature and pressure allowed by the tank's design. However, there are instances over the lifetime of an LNG truck where the 5-day holding time limit may be exceeded. These include vehicle manufacturing, transport from the factory to the dealer, second-stage manufacturing (i.e., bodybuilders), maintenance, unexpected disruptions in logistic operations, and the vehicle's end of life.

In-use data for boil-off emissions from LNG tanks do not exist. The Dutch Organisation for Applied Scientific Research, TNO, carried out some measurements to estimate the emissions once boil-off venting takes place (TNO 2019b). In TNO's measurements, boil-off venting started after about two days of standstill, despite the LNG tank being certified under UNECE's R110. TNO speculated that this deviation from the LNG tank standards might be a result of refueling with warm LNG, instead of cold LNG as the vehicle's design required. Cold LNG—also called unsaturated LNG—is dispensed at around -150 °C and 3 bar. Warm LNG—also called saturated LNG—is dispensed at around -130°C and 8 bar. Typically, the hold time for a tank filled with cold LNG is about twice as long as for a tank filled with warm LNG (Mumford; Goudie; Saunders 2017). Warm LNG stations are the most common type in Europe (Kind und Schürstedt 2018).

[4] The 5th Assessment Report of the IPCC (2013) has been officially adopted. As there is no UNFCCC decision on this issue so far, it is common practice today to use the value from the 4th Assessment Report of the IPCC (2007) for the compilation of the GHG inventories. There the GWP (100 years) of methane is given as 25.

When boil-off venting does take place, Nylund und Wenstedt (2019) estimate that approximately 2 % to 4 % of the tank's fuel mass is released per day. Ursan (2011) estimates the daily boil-off venting emissions in 2.6 % of the initial amount of LNG in the tank. TNO (2017) provides estimates of the contribution of boil-off venting emissions relative to the vehicle's lifetime CO_2 tailpipe emissions. If 1 to 5 venting events occur per year, boil-off emissions would represent 0.4 % to 1.8 % of the lifetime tailpipe CO_2 emissions.

3.3.3.2. Crankcase emissions

Crankcase emissions, also known as "blow-by" emissions, occur mainly in premixed engines, such as SI-NG engines. As a small portion of the air-methane mixture in the cylinder slips through the piston rings, the unburned methane ends up in the engine's crankcase. In engines with open crankcase ventilation, these blow-by emissions are vented directly to the atmosphere. In the EU, crankcase emissions must be added to the tailpipe emissions towards compliance with the emissions standards (EC 2018a). Consequently, Euro VI SI-NG engines have closed crankcase ventilation systems which redirect the crankcase gases into the combustion chamber, and crankcase methane emissions are not of concern (Burnham et al. 2016). HPDI engines do not have significant crankcase methane emissions, due to their working principle and the late direct injection of NG in the compression stroke.

3.3.3.3. Dynamic venting

HPDI engines make use of a single unit to inject both NG and diesel into the combustion chamber. HPDI injectors are twin-fuel concentric needle injectors, with separate needles for controlling diesel and natural gas injection through different sets of holes. The working principle of this injector requires for the gas pressure to be carefully regulated relative to the diesel pressure. Thus, small amounts of NG may occasionally need to be vented during highly transient operation of the engine (e.g., sudden shifts in torque and speed) to regulate the gas pressure (McTaggart-Cowan et al. 2015). This is known as dynamic venting.

There is a lack of publicly available data on methane emissions by dynamic venting in HPDI engines. Clark et al. (2017) measured the dynamic venting emissions of an HPDI truck. The average emissions, relative to the total NG consumption of the HPDI engine, were 0.92 % with a maximum of 2.2 % occurring in urban operation. ICCT (2015) estimated the NG emissions through dynamic venting in 0.15 %.

According to Westport, the leading HPDI system manufacturer, newer HPDI generations have improved the dynamic venting performance to predict and avoid small fluctuations in diesel pressure which may cause venting (Mumford; Goudie; Saunders 2017). In addition, for EU applications, the vent gas is captured (EC 2018b) by returning it to the LNG tank space where it re-condenses (Ouelette; Goudie; McTaggart-Cowan 2016). There are no independent assessments available on the dynamic venting performance of newer HPDI systems. The value estimated by ICCT (2015) will be used in this analysis, since it is significantly lower than the measurements by Clark et al. (2017), thus capturing the latest improvements in dynamic venting.

3.3.3.4. Refuelling

Since the operating pressure of the on-board LNG tank is around 10 bar, the tank's boil-off gases need to be handled to reduce the tank pressure. Otherwise, there would not be enough pressure difference between the refuelling pump and the on-board LNG tank to drive the flow. Several options exist to do so: (1) Condensation of boil-off by the incoming LNG flow, if the pump's discharge pressure is high enough, (2) venting of boil-off into a receptable at the station prior to refuelling, (3) continuous boil-off capture during refuelling through a separate boil-off return line in the LNG refuelling nozzle, (4) manual venting of LNG to the environment. A study in the United States identified several instances of manual venting, and estimated that approximately 5 % of vehicles would be manually vented with methane emissions amounting to 4.2 % of the fuel delivered (Clark et al. 2017).

Table 3-6 summarizes the LNG refuelling emission factors available in the literature. All three sources present coherent refuelling emission estimates. The value estimated by Clark et al. (2017) will be used in this analysis, as it discriminates between nozzle leaks and manual venting, and is based on direct measurements.

Table 3-6: Refuelling methane emissions per unit of LNG mass delivered to vehicle

	Imperial College London (2019) *Middle scenario	**Clark et al. (2017)** *units converted to %	**ICCT (2015)**
Nozzle leaks	-	0.015 %	-
Manual venting of vehicle tanks	0.1 %	0.2 %	-
Total	**0.1 %**	**0.25 %**	**0.3 %**

3.3.3.5. Manual venting due to maintenance

TNO (2017) estimated the manual venting of the LNG tank due to maintenance of the fuel system in one full-tank worth of methane emissions over the lifetime of the vehicle. This represents approximately 0.17 % of the lifetime LNG fuel consumption.

3.3.4. N_2O emissions

Nitrogen oxide, N_2O, is formed inside emission control systems. During the catalytic reduction of NO_x to nitrogen, N_2O forms as an intermediate, unwanted product. Three-way catalysts—such as those used in stoichiometric SI NG engines—and selective catalytic reduction (SCR) systems—such as those used in HPDI NG engines—can produce non-negligible amounts of N_2O, depending on the catalyst formulation. In particular, ammonia slip catalysts used in SCR systems to comply with the 10-ppm ammonia emissions limit of Euro VI, can produce very high rates of N_2O (TNO 2017; Imperial College London 2019).

Table 3-7 presents a summary of the literature review of tailpipe N_2O emissions for stoichiometric SI and HPDI NG. The table presents the values as CO_2e (CO_2 equivalents) emissions relative to tailpipe CO_2 emissions using the 100-year global warming potential (GWP) of 265 (IPCC 2013). The four literature sources coincide in that stoichiometric SI engines have significantly lower N_2O emissions than HPDI and diesel engines.

In this analysis, HPDI and diesel engines are assumed to produce N_2O at the same rates, since the aftertreatment systems of both concepts are equivalent.

Table 3-7: Literature review of tailpipe N_2O emissions of HD-NG engines, presented as a fraction of tailpipe CO_2 emissions

Stoichiometric SI engine	HPDI engine	Source
0.1 %	12.1 %	Imperial College London (2019)
0.7 %	1.3 %	NGVA Europe (2017)
0.4 %	2 to 30 %	TNO (2017)
2.6 %	3.3 %	LBST (2016)

For this study, N_2O emissions were estimated from the available data in the literature in 0.95 % for stoichiometric SI engines and in 8 % for HPDI engines. Both values expressed as a fraction of CO_2 emissions using the 100-year global warming potential (GWP) of 265. Note that the N_2O emissions have little influence on the relative performance of HPDI LNG engines compared to diesel. In the following analysis, it is assumed that N_2O is produced at the same rate in the aftertreatment systems of HPDI LNG and diesel engines, given their common architecture.

3.3.5. Vehicle simulation

To assess the complete pump-to-wheel emissions of HD-NG vehicles over comparative drive cycles, all the elements presented in sections 3.3.1 through 3.3.4 are combined using vehicle simulation. The simulation tool used is VECTO; the European Commission's simulation tool for the CO_2 certification of HDVs (EC 2017). Since VECTO is not currently able to handle dual fuel vehicles, a methodology based on the simulation of VECTO's generic diesel tractor-trailer was pursued. The methodology is outlined below.

1. VECTO's generic diesel tractor-trailer is simulated over the Regional Delivery, and Long Haul cycles. Two payloads are used in the simulations, consistent with the CO_2 certification regulation for HDVs (EC 2017). A low payload of 2.6 tons is used for both the Regional Delivery and Long Haul cycles. In the high payload case, 12.9 tons are used for the Regional Delivery cycle and 19.3 tons for the Long Haul cycle.
2. LNG trucks have a weight penalty due to the weight of the cryogenic tanks and other elements of the fuel system. The VECTO simulations used for estimating the performance of LNG trucks are conducted increasing the mass in 522 kg (Robert 2011) with respect to the base diesel vehicle.
3. Using the time resolved simulation outputs and VECTO's default fuel characteristics for diesel, the fuel consumption in g/h is converted to energy consumption in MJ/s.
4. Using the averages of the literature review comparing NG and diesel engines (see columns *Energy consumption relative to diesel engines* in Table 3-3 and Table 3-4) the energy consumption values are adjusted to make them representative of stoichiometric SI and HPDI-NG engines.
5. For HPDI engines, the NG and diesel fractions used throughout the different duty cycles are estimated separately by using the gas energy ratios summarized in Figure 3-1.
6. Using the carbon contents for LNG from different origins (see Table 3-1) the energy consumption values are converted to LNG fuel consumption and CO_2 emissions for a best case (Alaska) and a worst case (Algeria) LNG fuel. For HPDI engines, the diesel energy fraction is converted

to diesel fuel consumption and CO_2 emissions using VECTO's default fuel characteristics for diesel.

7. Using the estimates for tailpipe methane emissions (see Table 3-5) and the LNG fuel consumption, the CO_2 equivalence of tailpipe methane emissions is estimated using 100-year GWP value of 30 (IPCC 2013).
8. Using the estimates for non-tailpipe methane emissions (see section 3.3.3) and the LNG fuel consumption, the CO_2 equivalence of non-tailpipe methane emissions is estimated using the 100-year GWP value of 30 respectively (IPCC 2013).
9. Using the estimates for N_2O emissions (see Table 3-7) and the tailpipe CO_2 emissions of the vehicle, the CO_2 equivalence of tailpipe N_2O emissions is estimated using 100-year GWP value of 265 (IPCC 2013). N_2O is assumed to be produced at the same rates in the aftertreatment systems of HPDI LNG and diesel engines.
10. All results are weight-averaged following the methodology in the heavy-duty CO_2 standards (Parliament and Council of the European Union 2019): The low and reference payload are weighted at 30 % and 70 %, respectively. The Regional Delivery and Long Haul cycles are weighted at 10 % and 90 %, respectively.

Table 3-8 presents the pump-to-wheel comparison of diesel, stoichiometric SI, and HPDI heavy-duty trucks, the best and worst LNG fuel (in terms of carbon content) using the 100-year GWPs for methane and nitrogen oxide. Detailed emissions over each cycle and payload can be found in the appendix.

Table 3-8: TTW GHG emissions (GWP 100y) of typical tractor-trailers powered by diesel and LNG engines

	Diesel	**Stoichiometric SI**		**HPDI**	
	-	**LNG from Algeria**	**LNG from Alaska**	**LNG from Algeria**	**LNG from Alaska**
Energy consumption LNG (MJ_{fuel}/km)	0.00	13.35	13.35	10.76	10.76
Energy consumption Diesel (MJ_{fuel}/km)	10.82	0.00	0.00	0.62	0.62
CO_2 (gCO_2/km)	793	757	735	655	637
Methane tailpipe (gCH_4/km)	0.00	0.61	0.59	0.85	0.82
Methane non-tailpipe (gCH_4/km)	0.00	1.29	1.24	1.38	1.33
Nitrogen oxide (g N_2O/km)	0.19	0.03	0.03	0.19	0.19
Total GHGs 100-year GWP (gCO_2e/km)	844	821	796	773	752
Change in CO_2 vs. diesel	**0.0 %**	**-4.5 %**	**-7.4 %**	**-17.4 %**	**-19.7 %**
Change in GHGs (GWP-100y) vs. diesel	**0.0 %**	**-2.6 %**	**-5.6 %**	**-8.4 %**	**-10.9 %**

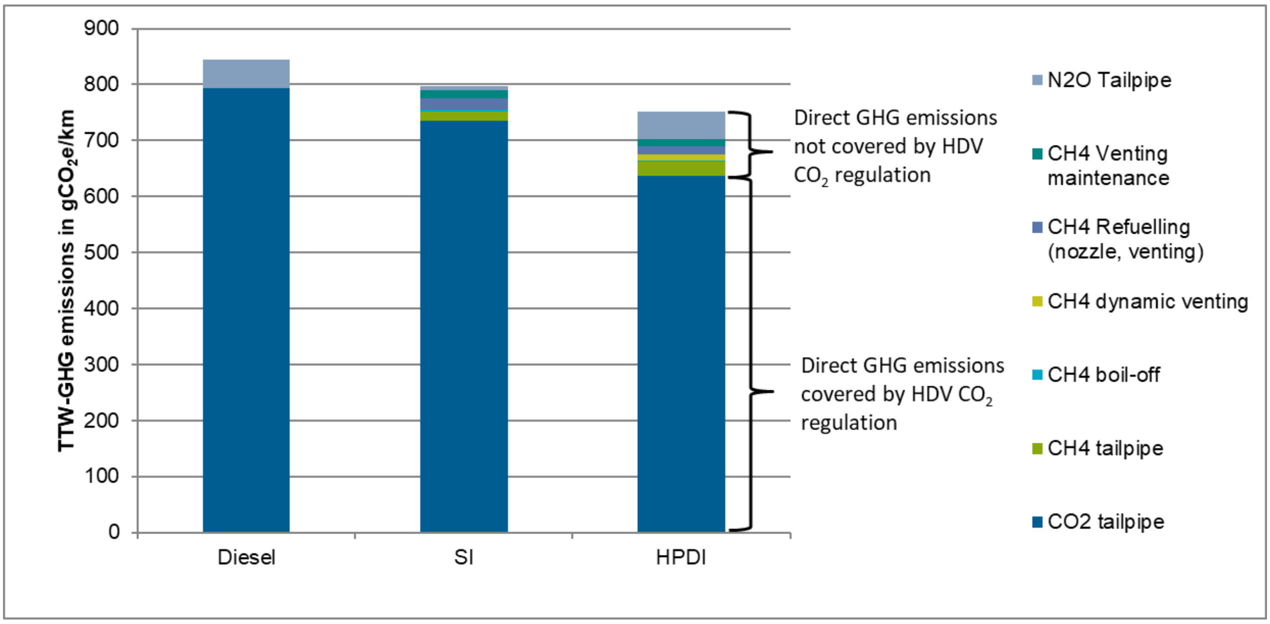
Source: Own VECTO simulations combined with literature review from multiple sources

3.3.6. Conclusions

LNG trucks have a CO_2 advantage over diesel trucks. Stoichiometric SI NG tractor-trailers emit 4.5 % to 7.4 % less CO_2 than when powered with a diesel engine, depending on the LNG quality. HPDI NG tractor-trailers emit 17.4 to 19.7 % less CO_2 than diesels. However, the climate benefits are significantly reduced when non-CO_2 GHGs are included in the TTW estimates.

Stoichiometric SI NG tractor-trailers have 2.6 % to 5.6 % lower TTW GHG emissions than diesel when using the 100-year GWP. HPDI-NG tractor-trailers have 8.4 % to 10.9 % lower TTW GHG emissions than diesel when using the 100-year GWP. The origin of the LNG not only has implications on the WTT emissions, but also has a significant impact on TTW emissions. Figure 3-2 shows the TTW GHG emissions from diesel and LNG trucks in detail using the example of high quality LNG from Alaska. It is obvious that the scope of the HDV CO_2 regulation, i.e. the tailpipe CO_2 emissions, underestimates total direct GHG emissions of LNG trucks in general, and those of HDPI-NG trucks in particular. Integrating the non-CO_2 emission GHG impact of LNG trucks into the CO_2 emission standards for heavy duty vehicles could be one option to improve the regulation.

Figure 3-2: TTW GHG emissions from diesel and LNG trucks by source (GWP 100y, high fuel quality)



Source: Own calculations

4. Well-to-Tank emissions of LNG supply

In addition to combustion-related tailpipe TTW emissions (see Section 3), the use of LNG causes greenhouse gas emissions due to upstream processes. These emissions are referred to here as well-to-tank-emissions (WTT).

4.1. Sources of GHG emission of LNG

The WTT emissions are primarily caused by energy consumption in the various process steps and by direct methane emissions. The processes include extraction and processing, liquefaction, transport by LNG carriers, distribution by truck within Europe and handling at the filling stations.

In the extraction and processing of natural gas, the associated methane emissions are particularly relevant. The climate impact of fossil methane emissions over a period of 100 years is 30 times greater than that of CO_2 emissions. (IPCC 2013)

According to the IEA (2019b), fugitive and vented methane emissions from natural gas production amount to 28.7 million tons in 2017. Fugitive methane emissions occur from unintended leakages, e.g. at faulty seals or leaking valves. Vented methane emissions on the other hand are the result of intentional releases e.g. for safety reasons or operational requirements (e.g. maintenance of pipelines). If one relates the methane emissions mentioned by the IEA to global natural gas production in 2017 (3,876 billion cubic meters, around 2.8 billion tons[5]), this results in losses of around 1 % of the methane in total for conventional und unconventional natural gas production.

Depending on the country of origin and production method, these emissions can vary significantly. A distinction can be made between the extraction from conventional fields in natural cavities in the earth and unconventional fields within certain geological rock formations. The latter includes, for example, shale gas from slate or tight gas from dense sand or limestone. In these unconventional fields, natural gas is produced using the fracking method. By pressing in a liquid mixture of water, sand and chemicals, the rock is broken up, one speaks of hydraulic fracturing. These fractures enable the natural gas to be mobilised and extracted. According to LBST (2016), most GHG emissions from the exploration, production and processing of shale gas are caused by the completion[6] of wells, combustion processes and diffuse methane emissions. Table 4-1 gives rates for methane leakage during shale gas production from different sources.

Table 4-1: Methane leakage in shale gas production

Methane emission rate [% of produced natural gas]	**Source**
0.4 %	Allen et al. (2013)
1.5 %	Brandt et al. (2014)
1.5 %	Brown et al. (2017)
2.1 % – 11.7 %	LBST (2016)
0.9 %	Cathles et al. (2012)
1.9 – 3.1 %	Environmental Protection Agency (2011)
3.6 – 7.9 %	Howarth (2009)
2 %	Jiang et al. (2011)

The literature values for methane leaks range between 0.4 % and almost 12 % of the natural gas produced. The wide range is, among other things, the result of different methodological approaches to the determination of leakages, e.g. mass balances through the analysis of the methane concentration at different heights or punctual measurements. Furthermore, leakages of different amounts can also occur depending on the extraction basin (LBST 2016). The Table illustrates that there are large differences in emissions or at least large uncertainties about the actual level of leakage. However, there are indications that shale gas production in North America leads to significant methane emissions (Howarth 2019).

Due to the uncertain data situation regarding methane emissions from the production of natural gas from unconventional sources, these should be treated with particular caution. Assuming a methane leakage range of 0.4 % to 11.7 % (Table 4-1), emissions during unconventional gas production alone could range from 2.4 gCO_2e/MJ_{LNG} to over 70 gCO_2e/MJ_{LNG}.

[5] Using a conversion factor of 0.735 kg/m³

[6] This process involves reinforcing the well with the casing, evaluating the pressure and temperature of the formation and installing the proper equipment to ensure an efficient flow of natural gas from the well.

Emissions from conventional natural gas production are significantly lower than from shale gas. JRC; CONCAWE; LBST (2014) assume a loss of 0.4 % in this step. Howarth (2009) assessed CH_4 emissions, as a percentage of CH_4 production over the life cycle of a well, at 1.7-6.0 % for conventional gas. Omara et al. (2016) measured the average CH_4 emission rates and found that emissions from conventional gas production sites were 23 times lower than from unconventional sites.

In addition to the production and processing of natural gas, the liquefaction of natural gas is associated with GHG emissions. The liquefaction usually takes place in a cryogenic plant near the gas fields. In particular, liquefaction leads to high electricity consumption, which is usually covered by electricity from gas-fired power plants (JRC; CONCAWE; LBST 2014). While JRC; CONCAWE; LBST (2014) assumed a power consumption of 0.036 MJ_{el}/MJ_{LNG}, Prussi et al. (2019) assumes a consumption of only 0.025 MJ_{el}/MJ_{LNG}.

Additionally, both studies assume methane emissions of 0.034 g/MJ_{LNG} in large-scale natural gas liquefaction plants. There are several possible sources of these methane emissions from liquefaction. These include fugitive and vented emissions. Methane can also escape into the environment due to incomplete combustion during flaring or in stationary combustion plants.

Further GHG emissions occur during the transport of LNG. The transport takes place in special ships, the LNG carriers. The boil off gases (BOG) that occur during the transport of LNG are usually used to operate the carriers in addition to conventional marine fuels. This can lead to fugitive methane emissions as well as emissions from venting and incomplete combustion. The amount of transport-related GHG emissions depends mainly on the duration and distance of transport and thus directly on the composition of LNG imports. While JRC; CONCAWE; LBST (2014) assumed an average transport distance of 5,500 nautical miles, the update by Prussi et al. (2019) assumes an average distance of 4,010 nautical miles. This is the weighted distance based on the largest exporters to the EU in 2015 (Qatar, Algeria, Nigeria and Norway).

The LNG is distributed to the filling stations by truck. The literature usually assumes a transport distance of 500 km. In addition to combustion-related CO_2 emissions from trucks, this can also lead to unwanted methane emissions. JRC; CONCAWE; LBST (2014), for example, assume losses of 0.1 gCH_4/MJ_{LNG}. According to JRC; CONCAWE; LBST (2014), the total GHG emissions from distribution will therefore amount to 3.7 gCO_2e/MJ_{LNG}. Methane emissions account for about two thirds and CO_2 emissions for one third. However, a GWP factor of 25 is used by JRC; CONCAWE; LBST (2014), which is taken from the 4th IPPC Assessment Report. Considering the more recent GWP factor of 30 for fossil methane, this step leads to 4.2 gCO_2e/MJ_{LNG}.

The operation of LNG filling stations only leads to low greenhouse gas emissions (LBST 2016). Direct methane emissions can occur during the supply of LNG and BOG to the filling stations. Imperial College London (2019) each indicate an average loss of 0.1 %, which can, however, also be up to 0.4 % during delivery and 2 % by BOG.

The storage tanks at refuelling stations also require active measures to prevent the venting of methane into the atmosphere due to boil-off. However, a review of existing LNG station designs found that the majority of refuelling stations available on the market had no boil-off management (Imperial College London 2019). On the other hand, according to information from DENA, BOG emissions are not permitted at mobile or stationary LNG filling stations. Usually the BOG is temporarily stored in CNG tanks and then used again.[7]

[7] Personal message from Valentin Zinnecker, German Energy Agency (dena)

Additional leakage can occur when refueling trucks at the fueling nozzle. However, these emissions and emissions on the vehicle side are already covered in section 3.3.3.4.

4.2. Overview of WTT factors

There are several publications listing WTT emission factors for diesel and LNG. However, these often refer to each other, in particular to the JEC WTT study from 2014 (JRC; CONCAWE; LBST 2014). It is currently being revised and the update is expected to be published in 2020. However, a presentation of interim results shows that there will be some changes compared to 2014. While the fuel-related emissions of LNG were about a quarter higher than those of diesel, in Prussi et al. (2019) emissions are listed to be about a fifth lower. The main reason for the lower LNG WTT CO_2e emissions in the update in Prussi et al. (2019) compared to JEC 2014 results from lower assumed transport distances and lower energy consumption in the liquefaction of natural gas. While JRC; CONCAWE; LBST (2014) assumed a mean transport distance of 5,500 nautical miles (nm), the revision assumes a distance of 4,010 nm. The revision uses the import mix from 2015 in the calculation of the values shown in Table 4-2. In addition to these aggregated values, country-specific values for EU member states will be published in the revision (Yugo 2019). However, these values could not be made available at the time of the preparation of this study.

Since 2015, however the share of LNG imports from Qatar decreased (see Section 4.3). The average transport distance might decrease due to this shift of importing countries, but this effect will probably be overcompensated by the increasing share of LNG from the USA. This LNG source is expected to lead to higher WTT emissions due to higher methane leakage during unconventional natural gas production. Of particular interest are the results of LBST (2016) which show that the proportion of US shale gas is crucial, as the WTT emissions in this case could be about twice as high as for LNG from other sources.

thinkstep AG (2017) shows generally lower WTT emissions than most other studies. However, GHG emissions of LNG from the USA are also in this study significantly higher than the ones from other sources (+58 % compared to LNG from Qatar).

The tables below give an overview of WTT emissions (Table 4-2). When comparing the values of the different literature sources, it should be noted that some sources like Prussi et al. (2019) and thinkstep AG (2017) used the GWP-100y factors from the 4th and others like LBST (2016) those from the 5th IPPC Assessment Report (IPCC 2013).

For the WTT emissions in Chapter 5, the values of Prussi et al. (2019) were used. The use of this source will ensure that new knowledge regarding WTT emissions from diesel fuel is taken into account. For example, emissions from crude oil production and transport will be more than twice as high in version 5 (10.4 gCO_2e/MJ) as in version 4 (4.7 g/CO_2e/MJ) (Prussi et al 2019).

Possible effects of higher LNG shares from unconventional sources are presented in a sensitivity analysis in Chapter 5. The values from Prussi et al. (2019) are converted to take into account the GWP factors from the 5th IPPC assessment report. The adjusted values are 20 gCO_2e/MJ for diesel and 18 gCO_2e/MJ for LNG.

Table 4-2: Overview of fuel-related WTT emissions from diesel and LNG from various literature sources (GWP 100y) in gCO_2e/MJ

	Prussi et al. (2019)[*,a]	Thinkstep (2017)[a]	LBST (2016)[b]	JRC; CONCAWE; LBST (2014)[*,a]	DLR; TUHH (2019)[*,b]
Diesel	20		16	15	19
LNG-Import	17			19	17
LNG (production on site)					20
LNG Qatar		15	22		
LNG Trinidad and Tobago			20		
LNG USA (Shale Gas)		24	41		

* These values may contain reading errors since they are directly read from graphs.
a: GHG emission calculation based on GWP values from 4th IPCC Assessment Report; b: GHG emission calculation based on GWP values from 5th IPCC Assessment Report

4.3. Origins of natural gas in Germany

According to IEA, global natural gas production in 2018 was 3.9 trillion cubic meters and world trade exceeded 1.2 trillion cubic meters (IEA 2019a) of which 0.8 trillion cubic meters were traded per pipeline according to BP (2019).

Today, the majority of natural gas consumption in Germany is covered by imports. In 2017, natural gas production in Germany only covered a share of around 7.1 percent of pure domestic consumption. Germany purchased its imported gas in 2017 exclusively via pipelines from various supplier countries. Of the 100.8 billion cubic meters of natural gas imported by Germany in 2018, around 55 % came from Russia, 25 % from Norway and 15 % from the Netherlands. The rest is sourced from other European countries (BP 2019). In the near future it is expected that LNG will be imported into the new LNG terminals in Brunsbüttel and Wilhelmshaven, which are currently being planned.

To diversify and saturate demand, however, LNG imports could become more important in the future. Europe currently purchases 14 % of its natural gas as LNG. In 2018 most of the LNG was imported from Qatar (33 %), Nigeria (17 %) and Algeria (13 %)[8].

According to a European-American declaration in July 2018, the purchase of LNG from the USA is to be expanded in the future[9]. Since the declaration, LNG imports from the USA have risen sharply. In 2018, 3.3 billion cubic meters of NG have already been imported as LNG from the USA. In 2019 the import increased to 13.6 billion cubic meters. This means that the share of LNG from the USA in total LNG imports rose from 5 % in 2018 to 14.3 % in 2019[10]. Before the agreement, the share was 2.3 %[11].

In the next few years, the current wave of global projects for LNG export terminals is predicted to increase export capacity by 140 billion cubic meters by 2023, representing an increase in global export capacity by 30 percent. Therefore, there will be a significant surplus of LNG by 2020. This is

8 https://ec.europa.eu/energy/en/topics/oil-gas-and-coal/liquefied-natural-gas-lng
9 https://europa.eu/rapid/press-release_STATEMENT-18-4687_de.htm
10 Data until 19 November 2019
11 https://ec.europa.eu/germany/news/20190502-fluessigerdgasimporte_de

mainly due to new LNG export terminals, especially in the USA and Australia, which are currently under construction and will be operational by 2020 (BMWi 2019).

Environmental impact of shale gas production (fracking)

The production of natural gas from non-conventional reservoirs is controversial not only from a climate protection perspective (see the discussion of WTT emissions on GHG emissions from production in Chapter 4). Local environmental impacts of the production method are discussed in some studies and led to the decision in 2017 not to allow unconventional production of natural gas for commercial purposes in Germany, unlike in the USA, for example. For further scientific testing and evaluation, several test wells have been approved, so that a decision can be taken at a later point in time, when the state of knowledge is better, on whether to permit the production of natural gas from non-conventional sites.

For the production of natural gas from unconventional sites, deep boreholes are initially drilled, from which horizontal wells are drilled into dense rock formations. To produce natural gas, so-called frack fluids (mixture of water, chemical additives and sand/ceramic particles) are pumped at high pressure from the horizontal wells into previously created cracks in the rock to stabilize the artificially created crevices. In this way, the natural gas escapes the dense rock formations and can be transported to the surface. The backflowing mixture of reservoir water and small portions of the frack fluids (flowback), which reaches the surface during the pre-treatment phase, but also during the production phase, must be safely disposed of because of the possible entry into near-surface water.

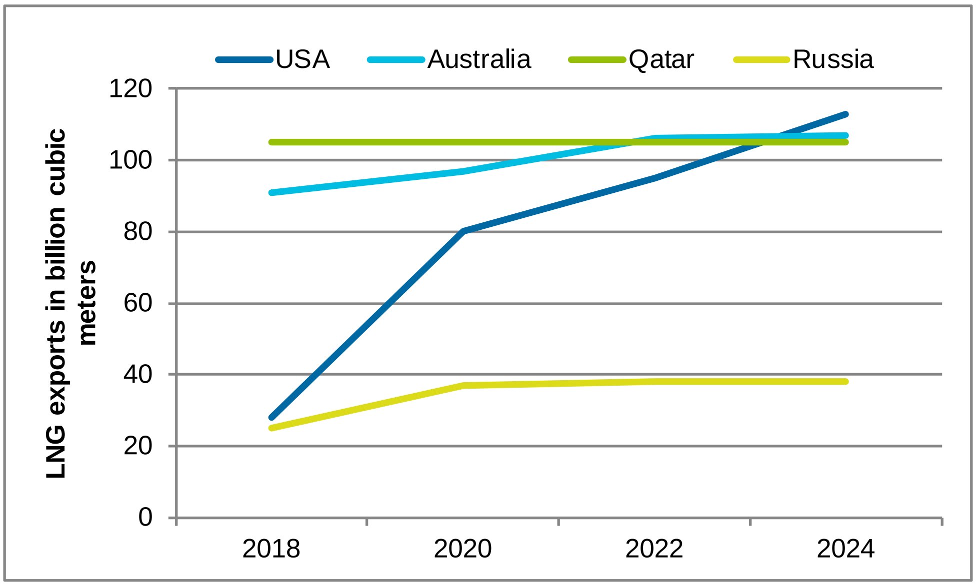
In the public debate, possible contamination of near-surface groundwater and drinking water is the subject of most debate. SRU (2013) and UBA (2014) also discuss the state of knowledge on underground pathways of water pollution, possible air pollution, soil and land use, biodiversity and effects on the seismicity of the area.

The composition of the frack fluid depends on the geological conditions and therefore varies from site to site. Which chemical additives are added to the frack fluid is often not known in detail. SRU (2013) summarises different studies and concludes that frequently used additives are classified as hazardous to health and the environment. Since no measurements of the concentration of chemical additives in the frack fluid and in the flowback are known in the literature, however, it is not possible to make any precise statement on the real exposure of people and the environment and on the exceeding of existing exposure thresholds. It is obvious, however, that insufficient sealing of the boreholes and possible leakages of the frack fluid and flowback can lead to contamination of the near-surface groundwater. SRU (2013) also points out that the artificial creation of cracks in the natural gas-bearing rock formations can also lead to the contamination of water sources used by humans (e.g. thermal and mineral water springs).

Volatile organic compounds (VOC) are components of the natural gas extracted and can therefore be released into the air. SRU (2013) refers to studies in the US, which, depending on the production site in question, make different statements regarding the pollution of the air with the carcinogenic VOC. The changes in the subsurface are irreversible and make other uses of the underground impossible. UBA (2014) estimates the land use to be higher than that of conventional deposits. SRU (2013) points out that the production rate decreases rapidly over time and therefore new vertical boreholes have to be created again and again. Both studies conclude that natural gas production from unconventional reservoirs represents a land use that can also lead, for example, to the reduction and fragmentation of habitats and the evasive behaviour of animals (SRU 2013). UBA (2014) considers the risk of man-made seismic activities from natural gas production from unconventional sources to be low.

In summary, SRU (2013) concludes that natural gas production from unconventional deposits should not be permitted commercially because of the insufficient state of knowledge, but that development via scientifically supported pilot projects is possible.

Figure 4-1: IEA forecast of LNG exports of selected exporters



Data source: IEA (2019)[12]

Today Qatar is the largest LNG exporter in the world. However, according to IEA forecasts, the US will multiply its current exports and become the world's largest exporter by 2024. Since 2005, the volume of shale gas produced has increased 14-fold, while the volume of conventionally produced natural gas has declined. In the long term, the share of unconventional gas like shale and tight gas is expected to rise to 90 % (EIA 2019). Other sources, such as LBST (2016), assume a significantly lower increase in natural gas production in the USA.

In addition to the expansion of the LNG infrastructure, the Northstream 2 project may also result in a significant change in the import structure. The pipeline from Russia, which has been under construction since 2018, is expected to transport up to 55 billion cubic meters of gas per year to Germany.

The change in the import structure of gaseous NG and LNG will have an impact on both TTW and WTT emissions from LNG trucks. At present, it is difficult to make a reliable prediction about the composition of the future LNG in Germany. However, this would be essential for a WTT emission assessment of LNG trucks.

4.4. Conclusions

The supply of LNG as fuel for trucks causes GHG emissions at various process steps such as natural gas production, liquefaction and LNG transport. Energy consumption and direct methane emissions play a major role here. These methane emissions are particularly high for LNG from unconventional natural gas production, although there are major uncertainties regarding the amount of leaked methane. Nevertheless, it appears that this LNG is associated with higher WTT emissions compared to LNG from conventional natural gas production.

In the medium term, this could have a negative impact on the WTT emissions of LNG used in Europe and Germany, as rising shares of LNG from the USA and rising shares of natural gas from unconventional sources in natural gas production in the USA are currently being observed. On the other

12 https://www.iea.org/gas2019/

hand, the share of natural gas from Russia could increase due to the additional capacities through the Northstream 2 pipeline.

However, it is currently unclear how the natural gas market and the LNG mix in Germany and the EU will develop in the coming years. There is therefore great uncertainty about future WTT emissions from LNG.

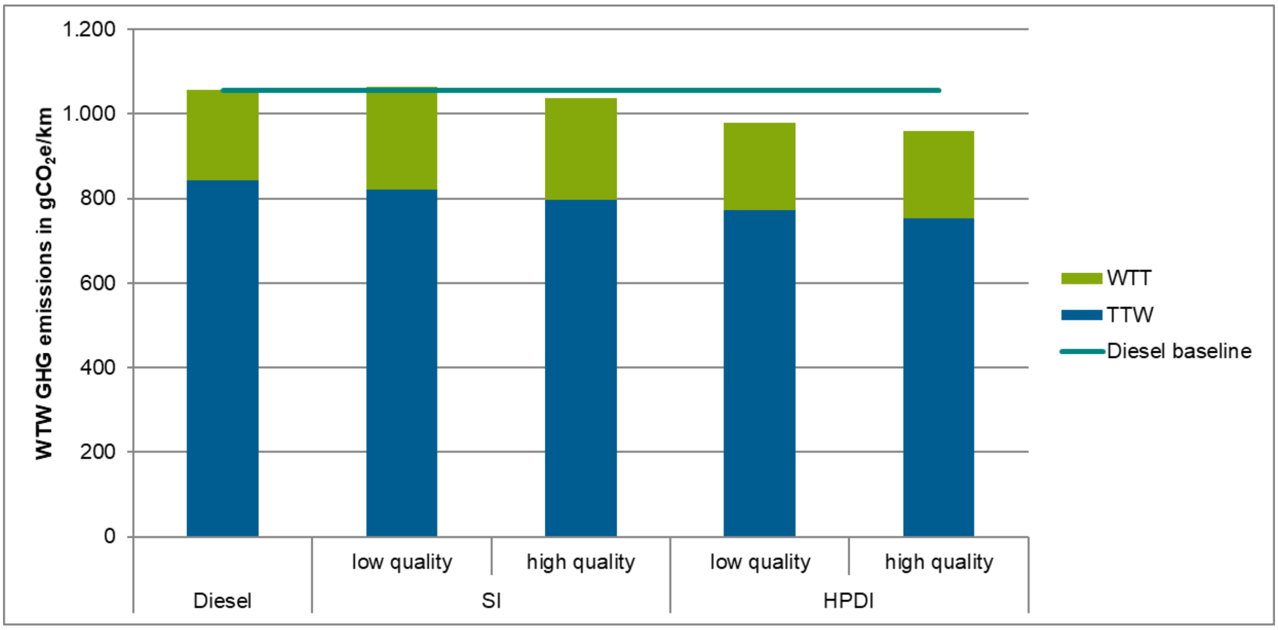
5. Well-to-Wheel GHG Emissions

This section combines WTT emissions (Section 4) and TTW emissions (section 3). It is necessary to distinguish between different vehicle efficiencies for SI and HDPI engines and fuel quality, because TTW emissions differ due to the different composition of LNG. Within the calculation of the TTW emissions in Figure 5-1 LNG from Algeria is used as LNG with low quality and from Alaska as LNG with high quality.

The values from Prussi et al. (2019) are used to calculate the WTT emissions. However, they are adjusted to consider the current GWP factors from the 5th Assessment Report of the IPCC (IPCC 2013). Due to the adjustment, the factors are 18 gCO_2e/MJ for LNG and 20 gCO_2e/MJ for diesel.

The WTT emissions include the upstream process steps up to and including delivery to the filling station. Methane emissions generated during the refuelling process and on the side of the vehicle are included in the TTW emissions at this point.

Figure 5-1: WTW greenhouse gas emissions from diesel and LNG trucks for different fuel qualities and engine types (GWP 100y)



Source: Own calculations

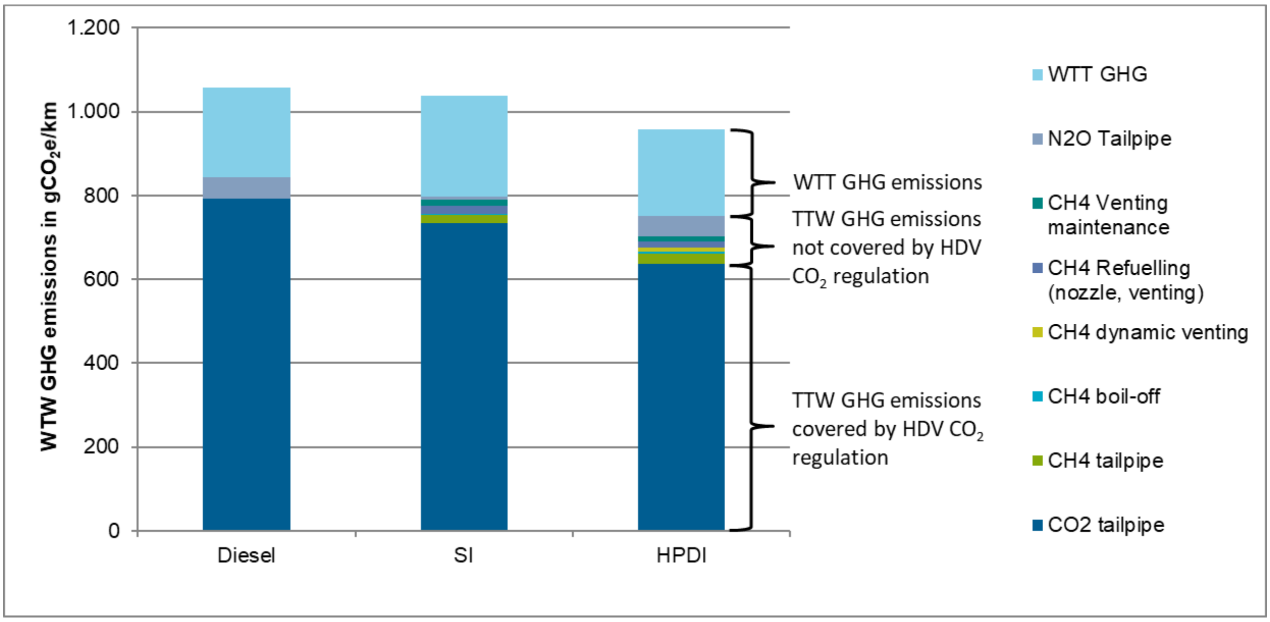
Figure 5-1 clearly shows that the use of LNG vehicles with SI engines does not lead to any relevant reduction in greenhouse gas emissions or that, depending on fuel quality, additional emissions may even occur (+1 % to -2 % WTW emissions). With an average fuel quality[13], they cause 1.051

[13] Average of low and high fuel quality.

gCO_2e/km. HPDI-NG trucks cause lower WTW GHG emissions than diesel trucks (-7 % to -9 %), the average emissions of 969 gCO_2e/km are about 8 % below those of a diesel truck.

It is important to note that this reduction is much smaller than the reduction of direct CO_2 emissions (-17 % to -20 %) that are calculated in VECTO. If only tailpipe CO_2 emissions are considered, the climate benefit of LNG trucks is clearly overestimated (Figure 5-2).

Figure 5-2: Greenhouse gas emissions from diesel and LNG trucks by source for GWP 100y (high fuel quality)



Source: Own calculations

Table 5-1: Comparison of CO_2 and WTW greenhouse gas emissions from diesel and LNG trucks for different fuel qualities and engine types

	Diesel	Stoichiometric SI		HPDI	
	-	low quality	high quality	low quality	high quality
TTW CO_2 (gCO_2/km)	793	757	735	655	637
WTW GHG 100-year GWP (gCO_2e/km)	1,056	1,063	1,038	979	959
Change in TTW CO_2 vs. diesel	**0.0 %**	**-4.5 %**	**-7.4 %**	**-17.4 %**	**-19.7 %**
Change in WTW GHG (GWP-100y) vs. diesel	**0.0 %**	**0.6 %**	**-1.7 %**	**-7.3 %**	**-9.2 %**

Source: Own calculations

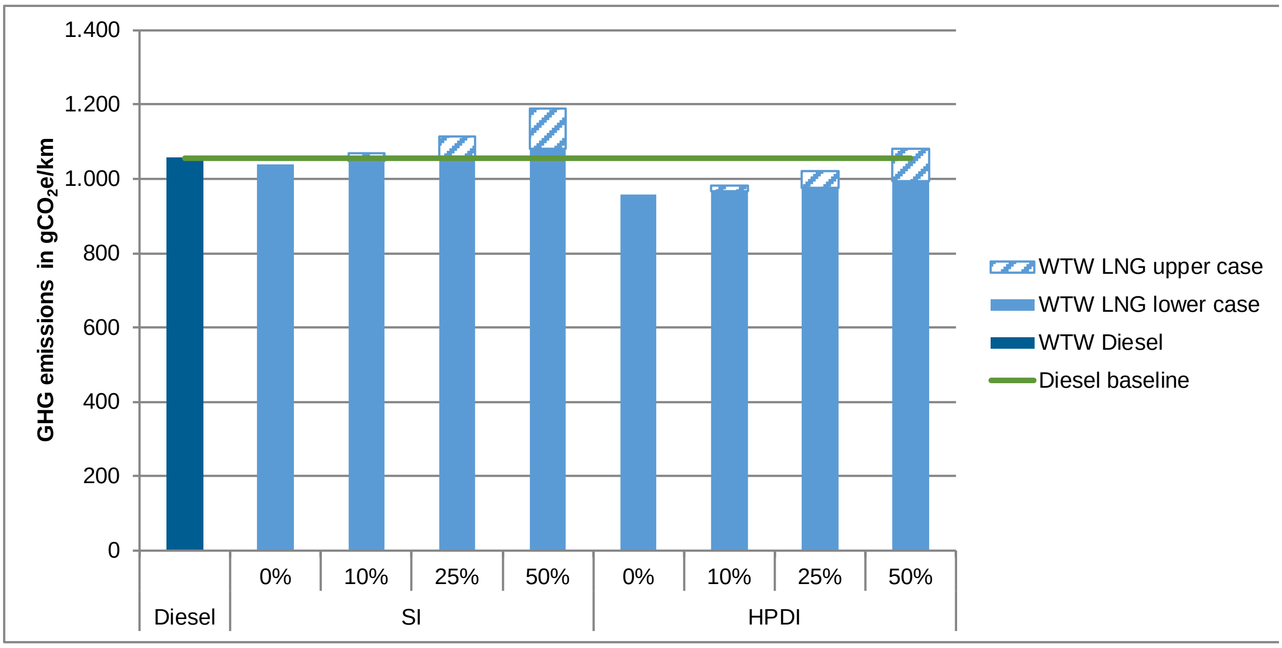
It is important to highlight that these results are likely to underestimate the WTW GHG emissions of LNG trucks. This is because Prussi et al. (2019) do not take into account that already more than 14 % of LNG imports in Europe is from the USA, where fracking natural gas from unconventional production plays a major role.

Due to the uncertainty, especially in regarding methane emissions of unconventional natural gas production and the future composition of LNG imports in Germany, the standard approach is supplemented by two sensitivities with literature values on fracking LNG WTT factors: 24 gCO_2e/MJ (thinkstep AG 2017) as lower case and 41 gCO_2e/MJ (LBST 2016)[14] as an upper case example. Table 4-1 even shows methane leakage of up to 11.7 % (equals ~70 gCO2e/MJ of the methane obtained by fracking). The selected upper limit for the climate impact due to fracking is therefore rather conservative and may well be higher.

Figure 5-3 shows the WTW GHG emissions for different proportions of LNG from unconventional production in the LNG mix. A high fuel quality was chosen for the example. The sensitivities show the risk that the increasing share of LNG from fracking could lead to higher emissions for an LNG truck compared to a diesel truck.

From a share of 21 % (lower case) or 6 % (upper case) fracking LNG in the fuel, LNG trucks with an SI engine would cause higher WTW GHG emissions than diesel trucks. In HPDI trucks, this is only the case with much larger amounts of fracking LNG, and only in the upper-case scenario. From a share of 40 % fracking LNG, the emissions would be higher than those of a diesel truck. In the lower-case scenario, the WTW emissions of HPDI trucks would be about 3 % lower than those of a diesel truck even if only fracking LNG were used.

Figure 5-3: WTW greenhouse gas emissions from diesel and LNG trucks for different engine types and for different proportions (0 %, 10 %, 25 %, 50 %) of LNG from unconventional production in fuel (GWP 100y, high fuel quality)



Source: Own calculations

Short-term climate impact of additional methane emissions (GWP 20y)

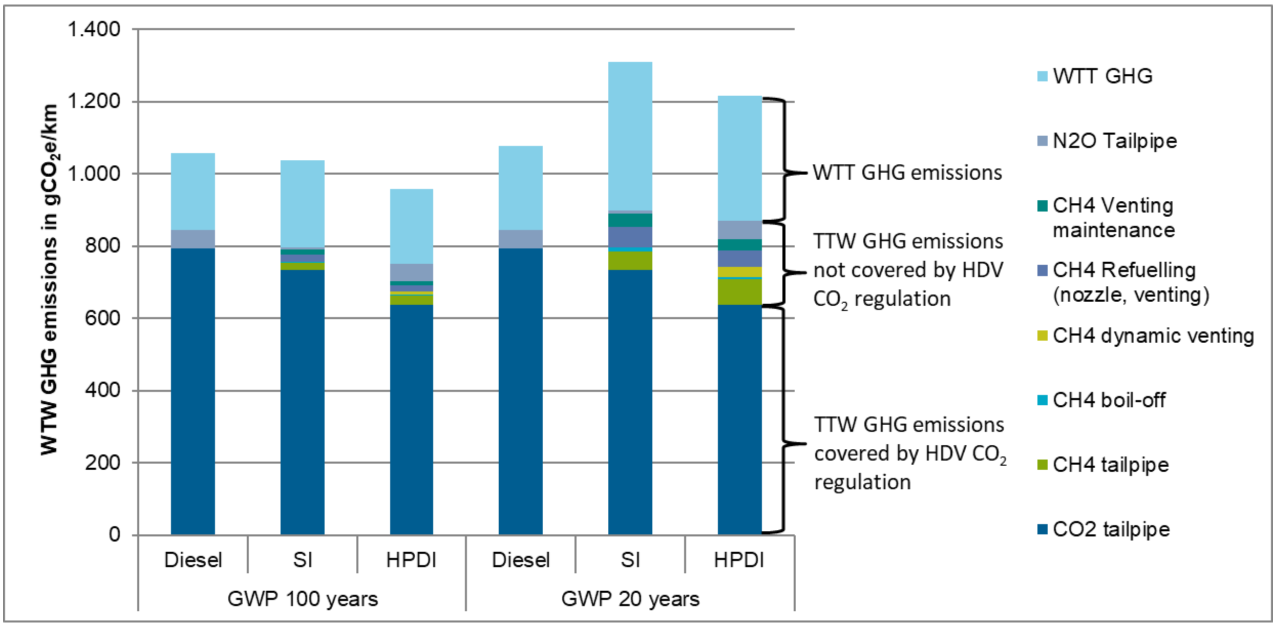
Methane is a short-live climate pollutant which has a lifetime of 12 years in the atmosphere (EIB 2016). For this reason, methane, in contrast to carbon dioxide, has a very strong short-term climate impact. A short-term perspective on climate impact can be important if triggering possible tipping points for the climate (e.g. melting of the ice shield on Greenland, release of methane hydrates and

[14] Average value of the given estimation in this literature source.

methane from permafrost soils) with their non-linear and irreversible dynamics on the global climate becomes more probable. It can therefore make sense to take a look at the effect in relation to a shorter period than the usual 100 years. A typical short-term perspective is the time period of 20 years, if short-term effects are of interest. The GWP of methane jumps to 85 in this short-term perspective (IPCC 2013), the GWP 20y values of carbon dioxide and nitrogen oxide remain the same or very similar to the 100 year period (1 and 264). Potential indirect effects on possible tipping points are not included in these values. As a result, the additional methane emissions become more relevant for the WTW GHG emission balance, if the short-term perspective is applied.

Stoichiometric SI NG tractor-trailers have 21.5 % to 24.2 % higher WTW GHG emissions than diesel vehicles when using the 20-year GWP. HPDI-NG tractor-trailers have 12.8 % to 15.1 % higher TTW GHG emissions than diesel in this case.

Figure 5-4: Greenhouse gas emissions from diesel and LNG trucks by source for GWP 100y and GWP 20y (high fuel quality)



Source: Own calculations

6. Biomethane and synthetic methane as renewable fuel options

The technical optimisation of LNG trucks and the development of the necessary infrastructure and value chains only make sense with a long-term climate protection perspective. The available GHG emission budgets resulting from the objectives of the Paris Agreement set the target of zero emissions for road transport in 2050. Alternative fuel options for road transport must therefore have the potential to be emission-free to meet this perspective.

6.1. Biomethane

Biomethane[15] can be produced from various biogenic sources. IFEU; IZES; ÖI (2019) estimates the total annual energetically available, sustainable biomass potential in Germany at around 920 - 950

[15] Biomethane is upgraded biogas from which the non-energetically usable fraction of the biogas (mainly carbon dioxide) is removed.

PJ (primary energy). DBFZ; UFZ (2019) indicates the primary energy potential for technically usable biomass with around 1,030 PJ in a similar order of magnitude. However, most of this potential is already being used for energy and materials in various applications.

Typical sustainable feedstocks[16] for biomethane production that have not yet been used almost completely in other applications are straw and liquid manure. IFEU; IZES; ÖI (2019) states that the usable primary energy potential for straw is around 180 PJ and for liquid manure around 100 PJ, with a share of liquid manure already being used for other energy purposes and thus not available for truck transport. Together, this results in an available maximum domestic biomethane potential from untapped straw and liquid manure for truck use of around 170 PJ[17]. DBFZ; UFZ (2019) assume in their models slightly lower exploitable technical primary energy potentials with 140 PJ of straw and 90 PJ of liquid manure and show for these two feedstocks a slightly lower potential for biomethane production.

From a technical point of view, the biomethane potential from liquid manure is easier to exploit, since biogas production with subsequent processing into biomethane is an established technology in small plants. Plants that produce biogas purely on the basis of straw are rather rare so far. The extent to which the existing biomethane potential can be harnessed therefore depends, among other things, on the possible increase of biogas production capacities. A complete tapping of the existing potentials in the near future seems unrealistic. According to BLE (2019), about 1.4 PJ of biomethane are currently used in road transport.

In the medium term, biomethane can also be produced from wood in synthesis plants if necessary. However, these plants are not yet available on the market and are not yet ready for biomethane production (IFEU; IZES; ÖI 2019). The sustainable biomethane potential can thus increase in the medium term, whereby the use of waste and residual wood for biomethane production is in strong competition with other exploitation options (e.g. heat and power generation), where the wood potential is already being used today. The use of wood as biomethane feedstock would therefore be linked to the fact that other climate-friendly energy sources would have to be used in applications that currently rely on wood as feedstock. IFEU; IZES; ÖI (2019) assumes a primary energy source potential of around 250 PJ as the potential for synthetic biomethane from wood (forest and industrial waste wood). Due to other sustainability restrictions for the use of wood, the primary energy potential in DBFZ 2019 is higher at around 630 PJ. These primary energy potentials result in a range of biomethane potential from wood from 170 PJ to 420 PJ[18].

The GHG balances of biomethane production from straw and from manure are different. Emissions can occur during biomethane production in open fermentation residue stores, as diffuse methane emissions in the entire production plant and as methane slip during biomethane processing. IFEU (2016) states GHG emissions of 24 gCO_2e/MJ for biomethane from liquid manure. GHG emissions are lower with 10 gCO_2e/MJ when produced from straw. In the sense of a consequential LCA, a GHG avoidance bonus can also be credited for biomethane from liquid manure. If the storage of unfermented liquid manure is included in the balance, biomethane from liquid manure has negative GHG emissions. The biomethane used in the transport sector in Germany currently has average GHG emissions of 9 gCO_2e/MJ (BLE 2019).

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16 Sustainable feedstocks for advanced biofuels are listed in RED II (EU/2018/2001) in Annex IX, Part A.

17 The resource database of the DBFZ (http://webapp.dbfz.de/resources) and the values assumed there were used for the conversion from primary energy potential to available energy as biomethane. The calculation is based on the total primary energy potential of liquid manure.

18 The calculations for the conversion from primary energy to biomethane potential are again based on the resource database of the DBFZ.

6.2. Synthetic methane from renewable electricity

Synthetic methane can be produced via the Sabatier process which uses hydrogen and carbon dioxide as feedstocks for methane production. Although first small production plants of synthetic methane exist, the technology is still on the verge of industrialisation. Especially, carbon dioxide capturing from air is in the early demonstration phase and requires technology development for large-scale implementation. In contrast to biogenic energy sources, there are no detailed studies on production potentials that take sustainability criteria and other potential barriers for market development into account sufficiently. First rough estimates for synthetic liquid fuels assume that at least 10 years will be needed to set up production plants on an industrial scale (Timmerberg und Kaltschmitt 2019; DECHEMA 2019). For methane, a slightly faster upscaling can be assumed, but sound estimations of available quantities of synthetic methane in the next 10 years are not existing today. In the long-term perspective, the potential of synthetic methane is expected to be higher than the one of biomethane.

Furthermore, sustainability criteria which ensure that methane is produced on the basis of green and climate-friendly hydrogen have not yet been laid down. The European Commission is expected to make first specifications in this regard in a delegated act within the framework of RED II by the end of 2021.

Synthetic methane has the potential to be produced with very low GHG emission impact. However, the prerequisites for this are a precisely defined electricity supply and the use of climate-friendly carbon dioxide sources. In electricity systems with a share of fossil power generation, if sustainability requirements are not taken into account, higher GHG emissions can be expected from synthetic methane production than from the use of fossil LNG. ÖI (2019a) specifies which criteria should be applied for the production of synthetic methane:

- Electricity used for the production of synthetic methane can only be assessed as renewable electricity if it comes from additional renewable plants that would not have been built without methane production.
- The plants for methane production should be operated in such a way that they are grid-compatible and should not exacerbate existing and potential grid bottlenecks in the electricity system.
- The carbon dioxide for methane production may only come from sources that allow a carbon dioxide cycle with the air (e.g. carbon dioxide from the air and from biogenic industrial processes). If carbon dioxide from fossil industrial processes is to be used, the transformation of these processes towards climate-friendly and long-term zero-emission processes must not be slowed down.

An estimate of whether, how much and at what cost liquid methane will be available for truck transport at what time is, from today's point of view, associated with high uncertainties (see also next chapter).

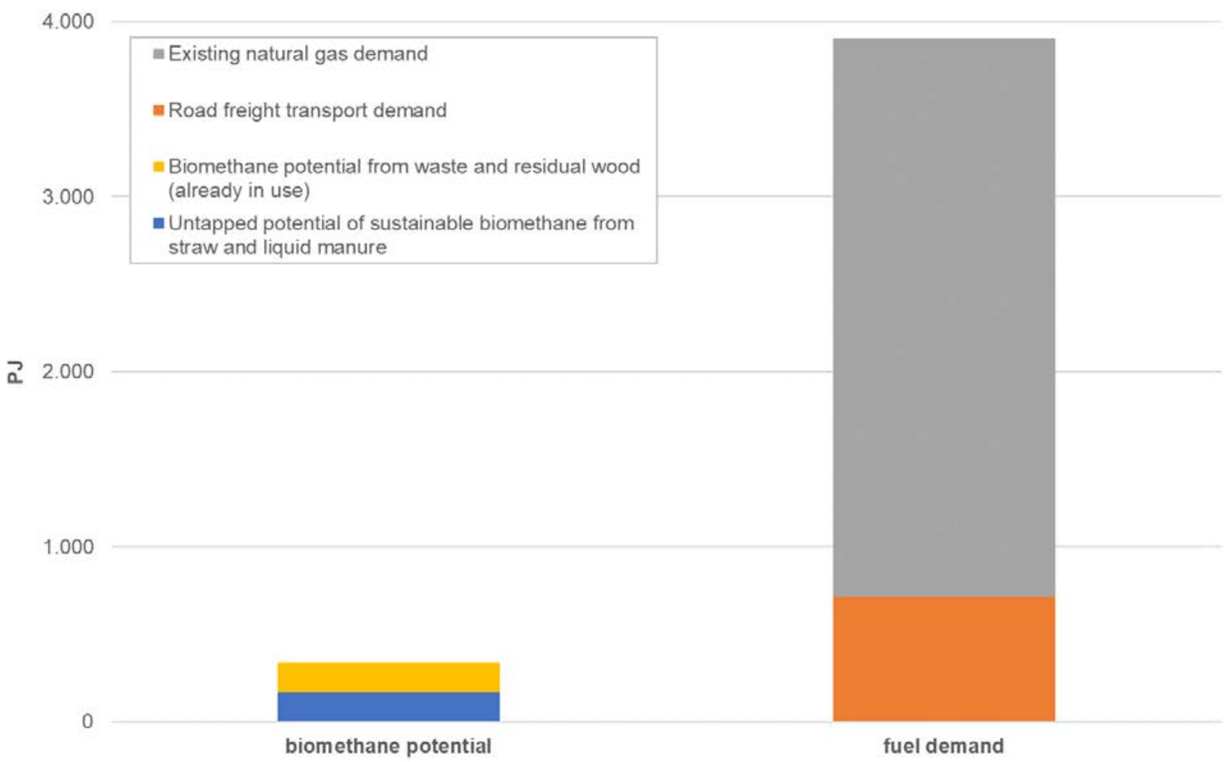
6.3. Competition for low GHG emitting methane

Today's energy demand in road freight transport is above 700 PJ per year (DIW; DLR; KBA 2019)[19]. Obviously, the short- and mid-term potential of producing and making low GHG emitting methane available for truck transport is much smaller and could cover only a small share of total fuel demand in freight transport. The domestic available potential of sustainable biomethane from straw and liquid manure (roughly 170 PJ), for example, if fully mobilised for biomethane production and fully allocated

[19] The total fuel demand of road freight transport in Germany was 16.586 t in 2018. By assuming 100 % diesel share in road freight transported, this translates into an energy demand in road freight transport of 713 PJ per year.

to truck transport[20], is limited to less than 25% of the current energy demand for truck transport (Figure 6-1). If the use of wood for the production of synthetic biomethane becomes available on an industrial scale and the available sustainable quantities of wood are withdrawn from other uses, further biogas potential can be tapped. However, today there is a large demand for low-emitting alternatives for the use of natural gas in other sectors that currently have a demand of more than 3,000 PJ of natural gas (AGEB 2020).

Figure 6-1: Domestic biomethane potential and today's fuel/natural gas demand of road freight transport and other sectors in Germany



Source. Own calculations based on primary energy potential from IFEU; IZES; ÖI (2019) and conversion efficiencies from http://webapp.dbfz.de/resources; fuel demand from DIW; DLR; KBA (2019) and AGEB (2020).

In the long-term perspective the availability of low emitting synthetic methane could increase. However, most climate protection scenarios allocate the sustainable biomass (including its converted end products such as biogas) and the available quantities of synthetic methane in other sectors such as the industry sector and high temperature heat production (BCG; Prognos 2018; Oeko-Institut; Fraunhofer ISI 2015) due to cost advantages, existing infrastructure and missing alternatives for climate protection. Imports of large quantities of biomethane are also not associated with advantages for climate protection, since potential exporting countries need biomethane for their climate protection ambitions and thus in most cases no additional climate protection effect would be associated with imports.

As a result, the share of low GHG emitting methane in transport is rather small in most climate protection scenarios since other technical climate protection options for the transport sector have smaller costs than using renewable methane. In road freight transport, battery electric trucks and

20 Both the mobilisation of biomass resources that have not yet been tapped and their use in truck transport would not be feasible immediately. It would take several years to set up the infrastructure and production facilities.

grid-integrated transport options are more cost-efficient than the widespread use of renewable liquid or gaseous fuels. However, for non-electrified shares of long-haul truck services several technical options such as climate-friendly diesel fuels, hydrogen or methane are possible alternatives. Among these options, however, hydrogen use in fuel cell trucks is more efficient than the use of synthetic diesel and methane in trucks (ÖI; HHN; IAO; Intraplan 2020).

6.4. Conclusions

Biomethane and synthetic methane can both be fuels with low GHG emissions. However, the risk of additional GHG emissions from methane slip and nitrogen oxide is the same as with fossil LNG and would worsen the GHG balance of these fuels. In the long term, these issues could rule out the use of renewable methane in trucks since it does not comply with the required emission level under the Paris Agreement. A very substantial reduction of these unwanted additional GHG emission is therefore the prerequisite for any use of methane in trucks as a climate protection option.

However, the medium-term production potential of biomethane and synthetic methane is limited and also in the long-term perspective there is a strong competition with other applications and sectors if larger quantities are available. Most studies allocate the available biomass and synthetic methane in other sectors since there exist more cost-efficient climate protection options for truck transport. The switch to LNG might therefore lead to a lock-in into a cost-inefficient technology pathway or to a dead end of methane use in trucks and to stranded investments in infrastructures and drivetrain technology.

7. Pollutant emissions of LNG trucks

Methane, the main constituent of natural gas, is the simplest of all hydrocarbons. This molecular simplicity and its related physical and chemical properties have implications on the combustion behaviour of natural gas. Compared to diesel, natural gas has the reputation of being a clean-burning fuel, particularly for trucks and buses. Recent technology developments in diesel and natural gas HD engines warrant a revaluation of this notion and of its application to public policy.

The conventional wisdom that natural gas engines are cleaner than diesel is rooted on the fact that diesel combustion produces significant amounts of soot and nitrogen oxides (NO_x) that need to be cleaned up with complex aftertreatment systems. The stoichiometric combustion of natural gas, on the other hand, produces no visible soot emissions and require simpler aftertreatment systems to deal with NO_x emissions. The two sections below evaluate the latest available evidence to assess whether this conventional wisdom also holds for trucks equipped with the latest engine and aftertreatment technologies.

7.1. Nitrogen oxides (NO_x)

NO_x is produced in the high temperature conditions that occur during the combustion process of any fuel. Depending on the air-fuel ratio used by the engine, two different aftertreatment systems exist to control tailpipe NO_x emissions.

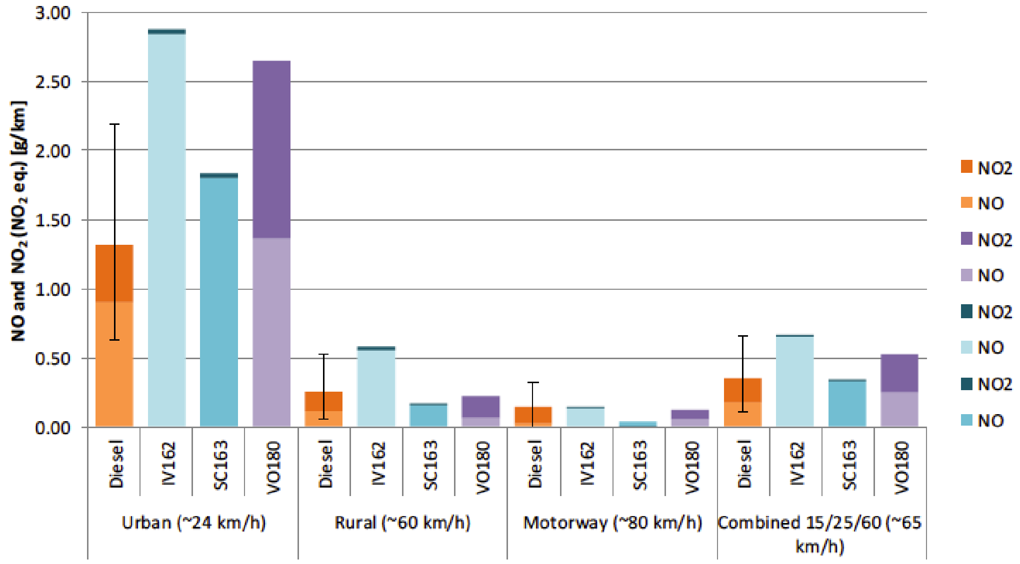
For lean combustion, such as HPDI-LNG and diesel engines, NO_x control relies on selective catalytic reduction (SCR) systems, which can achieve NO_x conversion rates above 99 % when properly designed and calibrated (Neely et al. 2019).

Stoichiometric combustion, such as SI-NG engines, use a three-way catalyst (TWC) that simultaneously reduces the emissions of CO, unburned hydrocarbons, and NO_x. TWCs can be very effective at reducing NO_x emissions when the engine is operated within a narrow band of air-fuel ratios near the stoichiometric point (College of Engineering -Center for Environmental Research and Technology - University of California 2018). A simple calibration strategy to achieve low NO_x emissions is to operate the engine slightly rich. However, such a strategy results in high ammonia[21] (NH_3) emission (Smith et al. 2017). Since Euro VI standards set a 10-ppm limit for NH_3, manufacturers need to carefully calibrate the SI-NG engines to simultaneously attain low NO_x and NH_3 emissions.

As a conclusion, the NO_x performance of diesel and LNG engines is highly dependent on the emissions control design and the system calibration. There is no intrinsic technology limitation to effectively reduce NO_x emissions on either type of engines. This conclusion is reinforced by the findings of two recent reports on the real-world emissions of NG and diesel HD engines, summarized below.

The Dutch Organisation for Applied Scientific Research, TNO, tested three LNG vehicles on the road and compared the NO_x emissions to its database of on-road diesel emissions (TNO 2019b). The test campaign included one HPDI-LNG truck (equipped with an SCR emissions control system) and two SI-LNG trucks (equipped with TWC emission control system). The results (figure below) show that rural, motorway, and combined NO_x emissions of LNG trucks are within the spread of the diesel vehicles, while the urban emissions of some LNG trucks are slightly higher than the highest emitting diesel in TNO's database.

Figure 7-1: NO_x emissions of three LNG trucks compared to the results for 6 Euro VI diesel vehicles over the same test conditions. Error bars represent the minimum and maximum values in the database for the diesel vehicles.



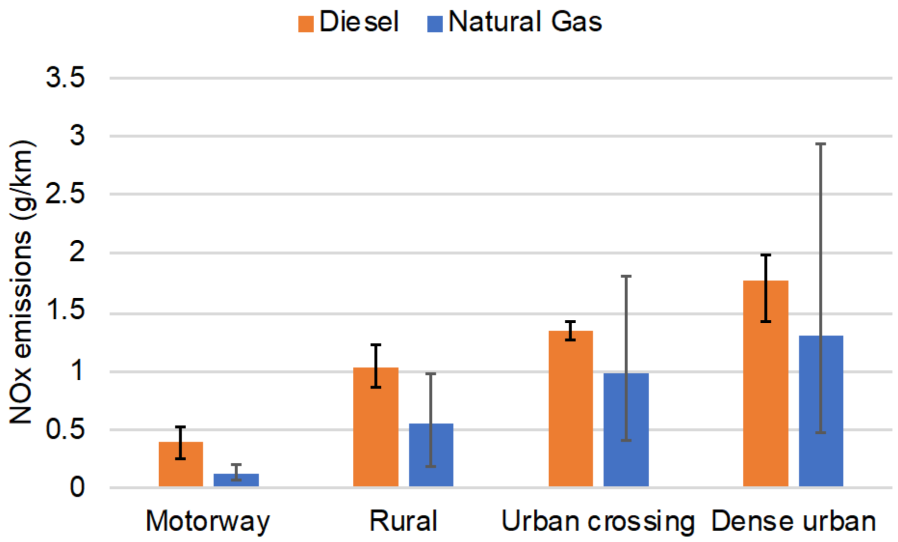
Source. TNO (2019b).

The Equilibré project aimed to compare the economic and environmental performances of diesel and natural gas trucks (EQUILIBRE; IFSTTAR 2018). The project assessed the NO_x performance of five NG tractor-trailers (including three SI LNG trucks) and four diesel tractor-trailers over several thousand kilometres. The results of the testing show that the spread (see max/min bars in figure

21 NH_3 emissions represent a serious threat to urban air quality, given ammonia's significant role in the formation of secondary particles, and can negate or offset the air quality and health benefits of lower NO_x emissions.

below) of the NO_x emissions of diesel and NG trucks overlap and that NG trucks can have significantly lower or significantly higher emissions than diesel trucks, particularly on urban operation.

Figure 7-2: NO_x emissions of 5 SI-NG trucks and 4 diesel trucks. Error bars represent the minimum and maximum values. Data from the Equilibré Project.



Data source: EQUILIBRE; IFSTTAR (2018).

7.2. Particulate emissions

Particulates are formed during combustion through several complex mechanisms. In lean combustion with diffusion flames, such as diesel and HPDI-LNG engines, soot particles form in fuel rich pockets with high enough temperatures to decompose the fuel into elementary carbon particles (Heywood 2018). In stoichiometric SI-NG engines, particle formation is dominated by the unwanted combustion of lubricant oil, which leaks into the combustion chamber through the piston rings (Guido et al. 2019).

While NG engines produce significantly less engine-out particle mass (PM) emissions than diesel engines, the fact that diesel engines are equipped with particulate filters (DPF), make the PM emissions of NG and diesel engines comparable. Emission testing done in the United States showed that stoichiometric SI-NG engines had PM emissions ranging from 60 % lower to 40 % higher than diesels equipped with DPFs, depending on the duty cycle (Burnham et al. 2016).

Regarding the number of particulates emitted, several studies indicate that SI-NG engines have significantly higher PN emissions than diesel-fuelled vehicles certified to the same emission standards (Giechaskiel 2018; Khalek et al. 2018; Wang et al. 2017). These results are attributable to the current lack of exhaust filters for SI-NG engines, which are able to meet the PN and PM emissions standards without them. The future adoption and introduction of Step E of the Euro VI regulation (European Commission 2019) however, is expected to drive particulate filters for SI-NG engines as well, closing the PN gap between SI-NG and diesel engines. HPDI-LNG engines already equip particulate filters to control particle emissions.

7.3. Conclusions

Advances in emission control systems for diesel engines driven by the latest emission standards, new combustion concepts for natural gas engines—such as HPDI-LNG engines—and a more robust understanding of ultrafine particulate emissions of unfiltered SI-NG engines challenge the well-established narrative that natural gas engines produce less pollutant emissions than the diesel counterparts.

The available results show that the NO_x emissions range of NG and diesel engines overlap, that NG powertrains have similar PM emissions as diesel engines with DPF, and that unfiltered NG exhaust contains more particles (i.e., higher PN emissions) than the DPF-filtered exhaust from diesel engines.

Technology interventions such as improvements in the aftertreatment architecture, better calibration of engines and emission control systems, and addition of particle filters to SI-NG engines have the potential of further reducing the pollutant emissions of diesel and NG engines.

The simplified conventional wisdom that natural gas engines are cleaner than diesel is no longer valid in the current HDV technology landscape.

8. Cost comparison of LNG and diesel trucks

The following sections show the user costs of LNG trucks compared to diesel trucks in Germany (section 8.1). Furthermore, the costs of LNG infrastructure are presented (Section 8.2).

8.1. TCO perspective

Essential for the demand for LNG trucks are the vehicle availability of the manufacturers, an available filling station network and in particular the possibility of an economic operation of the vehicles, i.e. the total costs in comparison to the diesel drive. These costs are also referred to as total costs of ownership (TCO). At around 50 %, personnel costs dominate the TCO of a diesel truck from the point of view of a truck operator (ÖI 2018). While LNG trucks incur higher acquisition costs and higher costs for the maintenance of the vehicles, vehicle operation results in lower costs for fuels and truck toll.

The TCO for diesel and LNG trucks will therefore be estimated and compared below. The analysis is supplemented by a cost estimate without financial support for LNG trucks. The TCO calculation is based on ÖI (2018), but has been adjusted in some aspects. The following important assumptions are made in the calculation:

- Inflation rate from 2019: 1.6 % per year.
- Vehicle purchase: January 2020.
- Holding period: 5 years.
- Annual mileage: 120,000 km/a.

Costs that are completely independent of the drive technology, such as driver costs, insurance, parking or vehicle cleaning, are not taken into account.

8.1.1. Vehicle acquisition/financing

The acquisition of LNG trucks today leads to high additional costs compared to diesel trucks. Various sources estimate the additional costs at 35,000 € (LIQVIS 2019), 40,000 € (IFEU 2015) and 45,000 € (Kern 2018). The additional costs also depend on the engine technology. Shell (2019), for example, estimate today’s additional costs for SI-LNG trucks and HPDI-LNG trucks at 40,000 €. According to

Kern (2018), the costs for the Volvo FH 460 LNG, which has an HPDI engine, at 135,000 € are 45,000 € higher than the costs of the comparable diesel truck (90,000 €). These additional costs are used in the figure below. For vehicles with an SI engine, however, additional costs of 35,000 € are assumed in Figure 8-1. In Figure 8-1, a residual value of 25 % of the purchase price is included for both diesel and LNG trucks in accordance with ÖI (2018). An interest rate of 2 % is applied to the financing.

In Germany, however, the acquisition of LNG trucks is currently subsidised with 12,000 € and CNG trucks with 8,000 €. A total of 994 LNG and 339 CNG trucks were approved within one year (VerkehrsRundschau 2019).

8.1.2. Energy costs

The TCO (excluding personnel costs) of trucks is dominated by energy costs due to the high mileage per vehicle. In terms of energy costs, LNG trucks are significantly lower than diesel vehicles. This is due to lower prices for LNG and the current regulation on energy taxes. According to ÖI (2018), the price for LNG (excluding taxes) is 0.037 $€_{2015}$/kWh. Of this amount, € 0.02 $€_{2015}$/kWh is due to procurement and € 0.017 $€_{2015}$/kWh to distribution and sales. This means that the price of LNG without taxes is around 30 % lower than that of diesel (0.052 $€_{2015}$/kWh). The final price of LNG per kWh, including the energy tax, with 0.05 $€_{2015}$/kWh is almost half that of the price of diesel fuel (0.1 $€_{2015}$/kWh).

The taxation of fuels is regulated in the German Energy Tax Act (Energiesteuergesetz). Since 2003, the energy tax on diesel has been 47.04 ct/l. The taxation of natural gas for motor vehicles is currently reduced from 31.80 €/MWh to 13.90 €/MWh. However, the energy tax rate will be successively increased until 2026.

Energy costs are determined not only by the energy price but also by the efficiency of drive technology. SI-NG vehicles have significantly higher energy consumption than diesel vehicles (+22 %) (section 3.3.1.1). In contrast, the energy consumption[22] of HPDI-NG vehicles is only about 4 % higher than that of a diesel vehicle. However, HDPI-NG vehicles require a certain amount of diesel (section 3.3.1.2). The energy costs in Figure 8-1 correspond to around 198,000 € (diesel), 136,000 € (SI NG) and 121,000 € (HDPI NG) for an annual mileage of 120,000 km and a 5-year service period. Due to the current tax relief, the subsidy currently amounts to around 34,000 € for an HPDI-NG truck and 42,000 € for an SI NG truck over this 5-year period.

In addition, it is planned in Germany to introduce a CO_2 price on fuels. This price is planned to amount to 25 €/tCO_2 in 2021 and to increase annually (2022: 30 €/tCO_2; 2023: 35 €/tCO_2; 2024: 45 €/tCO_2). This surcharge will increase the fuel costs of diesel vehicles more than those of LNG trucks due to the higher direct CO_2 emissions. Figure 8-1 below already takes this component into account.

8.1.3. Other operational costs

Driver costs account for the largest share of operational costs. However, these costs are not included in Figure 8-1 because it is assumed that they do not differ between drive technologies. In addition, the truck toll and the costs for maintenance, repair and care play a major role.

[22]Energy consumption including small quantities of diesel fuel.

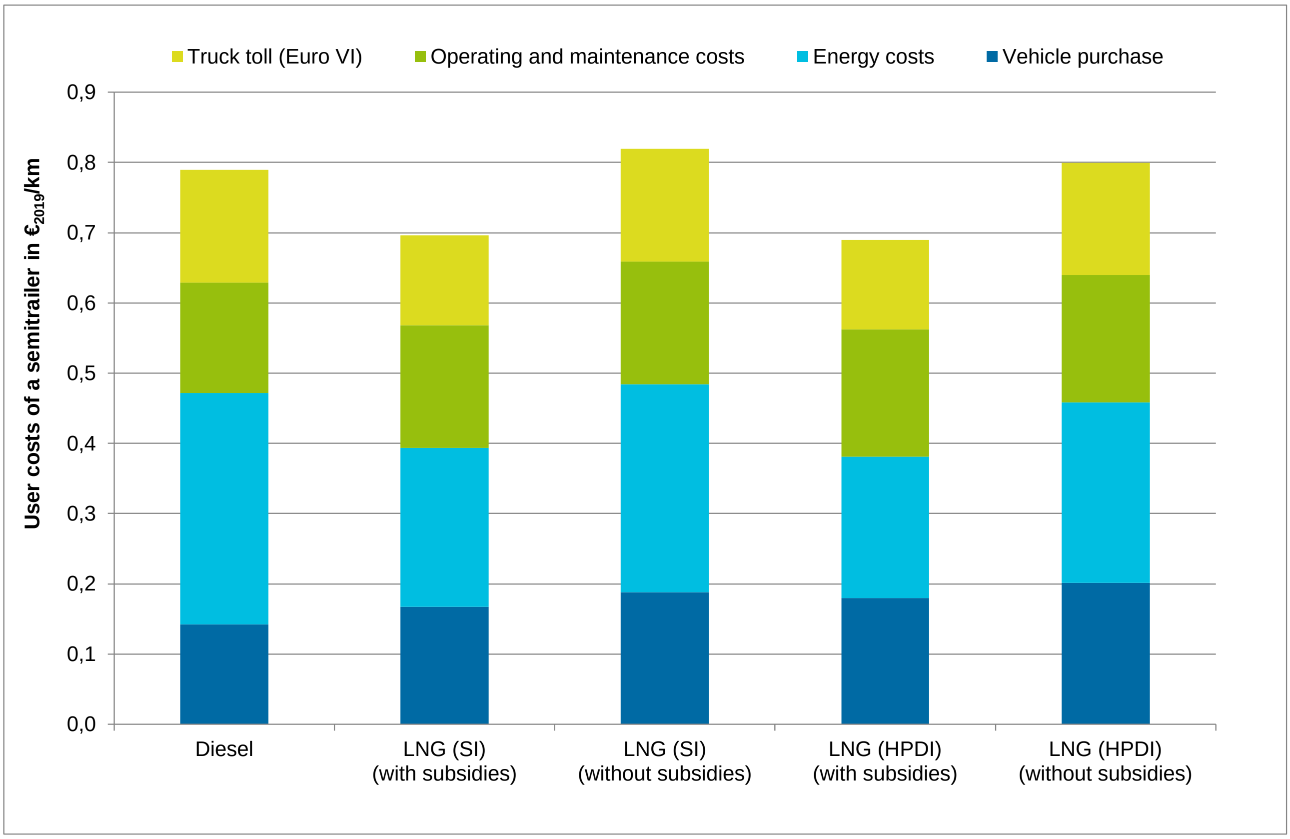
Toll costs are a decisive cost parameter for the TCO. Natural gas trucks are exempt from tolls up to and including 2020. Assuming that 90 % of the mileage is on toll roads, a diesel truck newly registered at the beginning of 2020 with an annual mileage of 120,000 km will cause costs of around 96,000 $€_{2019}$ within five years. In the same period, natural gas vehicles currently incur toll costs of around 76,000 €, as they are exempt from tolls in 2020. The exemption of the toll rate for EURO VI trucks of 0.187 €/km corresponds to a subsidy of NG trucks of around 20,000 €.

According to ÖI (2018) the costs for the maintenance, care and repair of LNG trucks are slightly higher than those of diesel trucks (0.16 €/km for an LNG truck compared to 0.14 €/km for a diesel truck). For diesel vehicles and HPDI-NG trucks, additional costs are incurred due to the consumption of AdBlue. However, with 0.006 €/km these costs are relatively low.

8.1.4. Results of TCO comparison

The following Figure 8-1 shows the TCO related to the mileage in $€_{2019}$/km. Under current conditions, an LNG truck has a significant cost advantage over a diesel truck. The km costs of an LNG truck are about 0.7 €/km, 12 % lower than those of a diesel truck, which costs about 0.8 €/km. The figure shows, however, that the TCO of LNG trucks would still be slightly higher than that of comparable diesel vehicles without the subsidy for purchase, the energy tax exemption and the toll exemption.

Figure 8-1: User costs of a semitrailer (5 years lifetime)



Source: Own calculations

The German government plans to introduce a CO_2 surcharge on the truck toll from 2023 onwards, making use of the legal options provided by the ongoing amendment to the Eurovignette Directive

(Klimakabinett 2019). This could shift the TCO comparison in favor of LNG trucks with lower direct CO_2 emissions compared to Diesel trucks. Figure 8-1 does not include such a CO_2 surcharge on tolls, as the design is still open.

8.2. Cost of LNG infrastructure

In addition to lower user costs, the establishment of a filling station network is crucial for greater use of LNG trucks. In the framework of the implementation of the AFI Directive, the Federal Government has developed the National Strategic Framework for the Development of Infrastructure for Alternative Fuels.

For the LNG supply of heavy commercial vehicles, a filling station backbone network along the Trans-European Transport Core Network (TEN-T) is to be initiated by 2025 in order to facilitate the pan-European traffic of LNG trucks. According to the National Strategy Framework, an appropriate basic network is already in place with a few (<10) locations along the TEN-T core network (BMVI 2016). Currently, seven publicly accessible LNG filling stations are in operation; the Federal Government assumes that a network of 20 filling stations will be available in the coming years (Deutscher Bundestag 2019). In contrast, the LNG Task Force, an association of DENA, the mineral oil industry, vehicle manufacturers and other associations, has much more ambitious goals: 40 filling stations by the end of 2020 and 200 by 2025[23].

LBST (2016) give detailed breakdown of costs for LNG filling stations. They put the investment costs at approximately 1 million €, the running costs at around € 27,000 per year. Technische Universität Kaiserslautern (2018) mention investment costs of 1.5 million € per filling station. Based on a network of 200 filling stations, the investment costs amount to around 200 to 300 million €. To achieve a comparable level at service stations as for diesel, further service stations would nevertheless have to be equipped with LNG for refuelling. This also includes filling stations at private depots.

There is currently no LNG terminal in Germany, but three possible locations Brunsbüttel, Stade (near Hamburg) and Wilhelmshaven are being discussed. The investment costs for the Brunsbüttel site are estimated at 500 million euros[24]. It is to be implemented as a Floating Storage and Regasification Unit (FSRU), resulting in significantly lower costs compared to a new construction of a fixed terminal on land (800 million to 1 billion €).

8.3. Conclusion

Today, LNG trucks in Germany show clear TCO cost advantages over diesel-powered vehicles from the user's point of view. The main reason for this is the promotion through investment subsidies, toll exemption and energy tax relief. However, subsidies through the toll exemption currently only apply until 2020 inclusive; those through a tax reduction will be reduced until 2026. However, the appropriateness of these subsidies for LNG trucks is at least disputable in view of the GHG balance of LNG trucks shown in Section 5.

Without additional subsidies, LNG trucks have slightly higher user costs than comparable diesel trucks. Depending on the political framework (e.g. a CO_2 component in the truck toll), LNG trucks can still have cost advantages for users even without state subsidies for purchase or the energy tax.

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23 https://www.dena.de/newsroom/meldungen/2019/lng-tankstellen-neue-karte-zeigt-standorte/

24 https://www.ndr.de/nachrichten/schleswig-holstein/Bundesrat-erleichtert-Investitionen-fuer-LNG-Terminals,lng166.html

The investment requirement for the construction of an energy supply infrastructure necessary for long-distance road haulage seems manageable.

9. Take-aways and implications for policymaking

The aim of this report was to examine the climate protection impact of the use of LNG trucks compared to diesel trucks more closely. In addition to the direct CO_2 emissions during the use of trucks, which are used as the basis for the European CO_2 emission standards, it is important to include other direct greenhouse gas emissions, especially methane. In addition, upstream GHG emissions from fuel supply must also be considered for a meaningful assessment.

From the results of the emissions comparison (Chapter 3 to 5), taking into account the analyses regarding the user costs of HGVs and the current framework conditions regarding the promotion of LNG vehicles (Chapter 6), some conclusions can be drawn which should be taken into account when discussing future policy measures regarding LNG HGVs.

Greenhouse gas emissions

The analyses show that the use of trucks using fossil LNG leads to only minor reductions in GHG emissions compared to diesel trucks and may even lead to additional GHG emissions.

When using LNG from conventional production, the new technology of HPDI-NG trucks lead to lower WTW GHG emissions (-7 % to -9 %) in direct comparison to diesel vehicles. The standard SI-NG trucks, which account for over 75 % of the LNG trucks funded in Germany, have approximately the same WTW emissions as diesel trucks (-1.7 % to +0.6 %). However, this depends strongly on the origin and quality of the LNG. The analysis also highlights that there are still very large uncertainties with regard to WTT GHG emissions from LNG, especially if fracking LNG is used. As the share of US LNG in the EU is steadily increasing, the use of fracking LNG with higher WTT emissions becomes more likely. This would result in higher WTW GHG emissions for LNG trucks.

From 6 % to 21 % of fracking LNG in fuel, LNG trucks with an SI engine would cause higher WTW GHG emissions than diesel trucks, even if they use LNG with a high methane content (high quality). In the case of HPDI trucks, this is only the case for much larger quantities of fracking LNG. Above 40 % fracking LNG, HDPI-NG trucks could also cause higher emissions than a diesel truck.

It is clear from the analyses that only the comparison of greenhouse gas emissions as CO_2-equivalents (CO_2e) makes sense in this emissions comparison, since methane emissions have a very high climate impact. If the focus is placed on the short-term effects and the climate impact of the emissions is related to a period of 20 years, the use of LNG trucks leads to significant increases in emissions compared to diesel trucks.

CO_2 emission standards

Taking direct methane and nitrogen oxide emissions at vehicle level into account in the further development of the European certification methodology (i.e., VECTO) and the respective standards could help to minimise climate-damaging incentive structures. The alternative could be the implementation of strict methane and nitrogen oxide limits as part of the Euro pollutant emission standards.

Currently, the European regulation for CO_2 standards for heavy-duty vehicles is based on direct CO_2 emissions (TTW CO_2), which are calculated with the VECTO simulation tool. Other direct greenhouse gas emissions from trucks are not taken into account. As the analyses show, LNG trucks perform significantly better in terms of direct CO_2 emissions than comparable diesel vehicles (HPDI up to -20 %; SI up to -7 %). However, the limitation to CO_2 emissions implies a GHG reduction potential for LNG trucks compared to diesel vehicles, which does not exist in practice. If the TTW CO_2e emissions are considered, the reduction in emissions from LNG trucks is only about half as great (SI up to -6 %; HPDI up to -11 %).

When comparing the various technology options, it becomes clear that the sole focus on CO_2 at vehicle level (TTW) is not suitable. If tailpipe and non-tailpipe methane emissions as well as nitrogen oxide emissions are included in the consideration, clear differences between the various drive technologies become apparent. With the limitation to CO_2, GHG emissions are systematically underestimated for LNG trucks and especially for trucks with HPDI engines.

This overestimation of the climate benefit of LNG trucks can have adverse effects through several mechanisms. For example, investments in LNG trucks compete with investments in efficiency measures, where a reduction in CO_2 emissions generally corresponds to a reduction in CO_2e.

In order to treat the different drive types fairly, both with regard to CO_2 regulation and incentive systems, it would therefore be desirable if, in addition to CO_2, the emission of other greenhouse gases at the vehicle level were also taken into account in the further development of the European certification methodology (i.e. Vehicle Energy Consumption Calculation Tool/VECTO) and corresponding standards. In the case that an integration into the simulation tool VECTO does not succeed or does not seem feasible due to missing accuracy, a stricter regulation of methane and nitrogen oxide emissions as part of air pollutant emission legislation (under post-EURO VI) and modifications to the EU Directive on Alternative Fuel Infrastructure (AFID), such as requirements for a GHG-minimising operation of LNG refueling infrastructure including reporting and monitoring. This could also help reduce the non-CO_2 emissions, and indirectly, a limitation of the climate impact of methane and nitrogen oxide emissions could thus be achieved.

Truck toll

A truck toll that takes into account the GHG emissions of the vehicles provides incentives for efficient diesel and efficient LNG trucks. To avoid false incentives, TTW GHG emissions should be used as a basis for toll pricing instead of TTW CO_2 emissions.

LNG trucks are currently being exempted from the toll. This corresponds to a subsidy of approximately 20,000 €, although the vehicles only have a small to zero climate benefit. However, this subsidy will expire after 2020. The German government plans to introduce a CO_2 surcharge on the truck toll from 2023 onwards, making use of the legal options provided by the ongoing amendment to the Eurovignette Directive (Klimakabinett 2019).

This is also demanded by Working Group 5 of the National Platform Future of Mobility in a current report (Nationale Plattform Zukunft der Mobilität, Arbeitsgruppe 5 2019). Until this date, however, an extension of the current toll exemption is being called for in order to reduce the existing cost disadvantages of LNG trucks compared to diesel trucks and to ensure planning security for the forwarders already today. Such an extension of the toll exemption cannot be justified, at least from the point of view of climate protection, in view of the above results.

Differentiation of the toll on the basis of CO_2 emissions, which is what the German government is aiming for, would favour particularly efficient trucks, regardless of the drive type. For a fair comparison between the drive systems, however, it would also be important here to use not only direct CO_2 emissions but all direct GHG emissions of the vehicles as a basis for assessment. If the direct CO_2 emissions were used, LNG trucks would be privileged over diesel trucks.

Additional national incentive measures

From the perspective of GHG emission reduction and low subsidy efficiency, it is difficult to justify an extension of the measure to promote LNG trucks.

Today, LNG trucks in Germany are promoted through various instruments. In addition to the toll exemption listed above, one of these is the Directive on the promotion of energy-efficient and/or low-CO_2 heavy goods vehicles in road haulage companies, which is in force until end of 2020 and supports the purchase of LNG trucks with 12,000 €. Secondly, there is the energy tax relief for natural gas as fuel in motor vehicles, which is valid until 2026. The energy tax rate, however, will be successively increased until 2026. Nevertheless, due to the current tax relief, the subsidy currently amounts to around 34,000 € for an HPDI-NG truck and 42,000 € for an SI-NG truck over a 5-year period.

The TCO analysis has shown that LNG trucks today cause significantly lower total costs for users. However, this is exclusively due to the existing funding instruments. Without these instruments, LNG trucks have slightly higher user costs compared to diesel vehicles.

The TCO calculation (Figure 8-1) includes government subsidies of about 74,000 € for SI-NG trucks and 65,000 € for HPDI-NG trucks. If the subsidy amount is related to the GHG savings (see section 5), the subsidy efficiency can be calculated. It indicates the amount of subsidies required in order to reduce one ton of CO_2e. In the case of SI-NG trucks with high fuel quality, the subsidy efficiency is around 6,700 €/tCO_2e. With low fuel quality, additional emissions occur despite subsidies. HPDI-NG trucks have a subsidy efficiency of between 1,100 and 1,400 €/tCO_2e. In addition, there is a risk that, despite high subsidies, there will be no reduction or even an increase in WTW GHG emissions.

Due to the poor subsidy efficiency and the risk of increasing GHG emissions, it seems questionable for both the subsidy for acquisition costs and the energy tax reduction to be extended. Furthermore, with the European CO_2 emission standards for HDVs and the CO_2 surcharge on fuels, instruments have already been implemented that promote the deployment and the use of LNG trucks.

Long-term GHG mitigation potential of renewable methane in trucks

The potential for climate-friendly liquified methane (biogas, synthetic e-methane) is limited and there is strong competition from other applications and sectors.

Investments in new engine concepts and new distribution and refueling infrastructures for LNG trucks only make sense as part of a long-term climate protection strategy that complies with the Paris Agreement if renewable and climate-friendly methane will be available in relevant quantities for truck transport. From today's perspective, it is not clear which energy sources and drive concepts will become established as a climate protection option in truck transport for long-haul services in the medium to long term. In local and regional delivery services, battery electric drives in trucks have great advantages and are a very promising drive technology option for climate protection. Several studies show that the direct use of electricity via grid-connected or perhaps even battery electric trucks is the most cost-efficient climate protection option for a relevant proportion of long-haul services in heavy duty road transport (BCG; Prognos 2018; ÖI 2019b). Other energy supply options for the non-electrified parts of truck transport are climate-friendly diesel fuels, methane or hydrogen. Among these options, however, hydrogen use in fuel cell trucks is more efficient than the use of synthetic diesel and methane in trucks.

Climate-friendly biomethane is very limited in terms of quantity. IFEU (2019) states a national sustainable primary energy potential for biomethane production which would translate in biomethane of about 130 PJ. This compares to today's fuel demand in road freight transport of more than 700 PJ and existing natural gas demand of more than 3,000 PJ. Synthetic e-methane probably has a larger volume potential, but has not yet been produced industrially today. If synthetic e-methane is to contribute to climate protection, a considerable increase in renewable power generation capacities and the industrialization of CO_2 capture from air as a key technology is necessary. It is therefore unclear when and in which quantities climate-friendly methane will be available.

The risk of additional GHG emissions from methane slip and nitrogen oxide is the same as with fossil LNG and would worsen the GHG balance of these fuels. A very substantial reduction of these unwanted additional GHG emission is therefore the prerequisite for any use of methane in trucks as a climate protection option. However, the production potential of biomethane and synthetic methane is limited and there is a strong competition with other applications and sectors if larger quantities are available. Most studies allocate the available biomass and synthetic methane in other sectors since there exist more cost-efficient climate protection options for truck transport. The switch to LNG might therefore lead to a lock-in into a cost-inefficient technology pathway or to a dead end of methane use in trucks and to stranded investments in infrastructures and drivetrain technology.

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Appendix

Urban Delivery, 2.6 tonne payload	Diesel	SI		HPDI	
		Low quality	High quality	Low quality	High quality
Energy consumption LNG (MJ of fuel/km)	0.00	19.37	19.37	13.98	13.98
Energy consumption Diesel (MJ of fuel/km)	15.57	0.00	0.00	2.52	2.52
CO2 (g CO2/km)	1141.41	1098.16	1065.23	977.51	953.74
CH4 tailpipe (g CH4/km)	0.00	0.89	0.86	1.11	1.07
CH4 non-tailpipe (g CH4/km)	0.00	1.87	1.80	1.79	1.72
N2O (g N2O/km)	0.28	0.04	0.04	0.28	0.28
Total 20-year GWP (gCO2-eq/km)	1216.57	1343.03	1301.32	1298.73	1266.07
Change relative to diesel	0%	10%	7%	7%	4%
Total 100-year GWP (gCO2-eq/km)	1216.85	1191.27	1155.04	1139.80	1112.89
Change relative to diesel	0.0%	-2.1%	-5.1%	-6.3%	-8.5%

Regional Delivery, 2.6 tonne payload	Diesel	SI		HPDI	
		Low quality	High quality	Low quality	High quality
Energy consumption LNG (MJ of fuel/km)	0.00	11.56	11.56	9.06	9.06
Energy consumption Diesel (MJ of fuel/km)	9.33	0.00	0.00	0.79	0.79
CO2 (g CO2/km)	683.71	655.21	635.57	571.28	555.88
CH4 tailpipe (g CH4/km)	0.00	0.53	0.51	0.72	0.69
CH4 non-tailpipe (g CH4/km)	0.00	1.12	1.08	1.16	1.12
N2O (g N2O/km)	0.17	0.02	0.02	0.17	0.17
Total 20-year GWP (gCO2-eq/km)	727.52	801.31	776.43	774.57	753.40
Change relative to diesel	0%	10%	7%	6%	4%
Total 100-year GWP (gCO2-eq/km)	727.69	710.77	689.15	671.54	654.10
Change relative to diesel	0.0%	-2.3%	-5.3%	-7.7%	-10.1%

Long Haul, 2.6 tonne payload	Diesel	SI		HPDI	
		Low quality	High quality	Low quality	High quality
Energy consumption LNG (MJ of fuel/km)	0.00	10.71	10.71	8.59	8.59
Energy consumption Diesel (MJ of fuel/km)	8.67	0.00	0.00	0.53	0.53
CO2 (g CO2/km)	635.23	607.37	589.16	526.35	511.74
CH4 tailpipe (g CH4/km)	0.00	0.49	0.47	0.68	0.66
CH4 non-tailpipe (g CH4/km)	0.00	1.04	1.00	1.10	1.06
N2O (g N2O/km)	0.15	0.02	0.02	0.15	0.15
Total 20-year GWP (gCO2-eq/km)	675.56	742.81	719.74	717.93	697.85
Change relative to diesel	0%	10%	7%	6%	3%
Total 100-year GWP (gCO2-eq/km)	675.71	658.87	638.84	620.21	603.67
Change relative to diesel	0.0%	-2.5%	-5.5%	-8.2%	-10.7%

Urban Delivery, 12.9 tonne payload	Diesel	SI		HPDI	
		Low quality	High quality	Low quality	High quality
Energy consumption LNG (MJ of fuel/km)	0.00	26.11	26.11	19.59	19.59
Energy consumption Diesel (MJ of fuel/km)	21.05	0.00	0.00	2.65	2.65
CO2 (g CO2/km)	1542.76	1480.39	1436.01	1305.32	1272.01
CH4 tailpipe (g CH4/km)	0.00	1.20	1.15	1.55	1.50
CH4 non-tailpipe (g CH4/km)	0.00	2.52	2.43	2.51	2.42
N2O (g N2O/km)	0.38	0.05	0.05	0.38	0.38
Total 20-year GWP (gCO2-eq/km)	1643.00	1810.49	1754.26	1750.45	1704.67
Change relative to diesel	0%	10%	7%	7%	4%
Total 100-year GWP (gCO2-eq/km)	1643.38	1605.91	1557.08	1527.66	1489.95
Change relative to diesel	0.0%	-2.3%	-5.3%	-7.0%	-9.3%

Regional Delivery, 12.9 tonne payload	Diesel	SI		HPDI	
		Low quality	High quality	Low quality	High quality
Energy consumption LNG (MJ of fuel/km)	0.00	14.65	14.65	11.63	11.63
Energy consumption Diesel (MJ of fuel/km)	11.85	0.00	0.00	0.86	0.86
CO2 (g CO2/km)	868.41	830.75	805.84	722.00	702.23
CH4 tailpipe (g CH4/km)	0.00	0.67	0.65	0.92	0.89
CH4 non-tailpipe (g CH4/km)	0.00	1.42	1.37	1.49	1.43
N2O (g N2O/km)	0.21	0.03	0.03	0.21	0.21
Total 20-year GWP (gCO2-eq/km)	923.75	1016.00	984.44	982.02	954.86
Change relative to diesel	0%	10%	7%	6%	3%
Total 100-year GWP (gCO2-eq/km)	923.96	901.19	873.79	849.79	827.41
Change relative to diesel	0.0%	-2.5%	-5.4%	-8.0%	-10.4%

Long Haul, 19.3 tonne payload	Diesel	SI		HPDI	
		Low quality	High quality	Low quality	High quality
Energy consumption LNG (MJ of fuel/km)	0.00	14.43	14.43	11.68	11.68
Energy consumption Diesel (MJ of fuel/km)	11.70	0.00	0.00	0.62	0.62
CO2 (g CO2/km)	857.83	818.11	793.58	707.27	687.41
CH4 tailpipe (g CH4/km)	0.00	0.66	0.64	0.92	0.89
CH4 non-tailpipe (g CH4/km)	0.00	1.39	1.34	1.49	1.44
N2O (g N2O/km)	0.21	0.03	0.03	0.21	0.21
Total 20-year GWP (gCO2-eq/km)	912.00	1000.54	969.46	966.98	939.70
Change relative to diesel	0%	10%	6%	6%	3%
Total 100-year GWP (gCO2-eq/km)	912.21	887.48	860.49	834.19	811.71
Change relative to diesel	0.0%	-2.7%	-5.7%	-8.6%	-11.0%