Natural gas in transport

An assessment of different routes

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Author(s):
TNO: Ruud Verbeek
Norbert Ligterink
Jan Meulenbrugge
Gertjan Koornneef
ECN: Pieter Kroon
Hein de Wilde
CE Delft: Bettina Kampman
Harry Croezen
Sanne Aarnink

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Further information on this study can be obtained from the contact person, Bettina Kampman.

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Preface

The Ministry of Infrastructure and Environment commissioned this assessment of different routes of natural gas last year as part of her work package aimed at making transport more sustainable. Faced with a changing energy supply in the coming years, in which natural gas will play an important role, it was necessary to assess what the different routes of natural gas to transport are. Determine what conditions both environmental and safety, would have to be addressed in order to allow for natural gas to be used in the transport sector as an intermediate fuel on a road towards more sustainable alternatives. The study was overseen by a supervisory interdepartmental group which consisted of representatives from the Ministries of Finance and Economic Affairs. From within the Ministry of Infrastructure & Environment, representatives of all different transport modes , environment and external safety and risk management took part of the supervisory group.

Furthermore the study made use of valuable input that was gathered from stakeholders and industries in the field of natural gas. For this purpose a number of stakeholder consultations were organised in 2012 and 2013. This sharing of information was greatly appreciated by the Ministry and used for this report.

The following assessment is a first guidance document on how natural gas can best be used in transport and what issues need to be addressed. As natural gas will play an important role in the energy mix in Holland, Europe and the world the coming years, we are confident that more information on the application of natural gas in transport will become more readily available and provide us with better data. Thereby allowing to make more accurate assessments in the field of environmental performance and safety standards.

The Dutch Ministry of Infrastructure and Environment

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Samenvatting

Achtergrond en doel van de studie

Zorgen over klimaatverandering en over de leveringszekerheid van fossiele brandstoffen gaan in de komende tientallen jaren waarschijnlijk voor grote veranderingen zorgen in het gebruik van energie door de transportsector. Transport is verantwoordelijk voor een kwart van de broeikasgasemissies in de EU. In 2050 zal de transport sector de CO_2-emissies moeten hebben verlaagd tot een fractie van de huidige waarden en zal daarbovenop grotendeels onafhankelijk van olie moeten zijn.

Een toename van het gebruik van aardgas in de transportsector kan substantieel bijdragen aan een betere leveringszekerheid van energie. Daarnaast kunnen aardgas en uit aardgas gemaakte brandstoffen of energiedragers (zoals GTL, DME, waterstof en elektriciteit) een bijdrage leveren aan een betere luchtkwaliteit en een reductie van uitstoot van broeikasgassen. Voor een aantal transporttoepassingen is er een levensvatbare business case voor het gebruik van aardgas of uit aardgas gemaakte brandstoffen. Dientengevolge neemt de interesse vanuit de industrie en de gebruikte aardgasvolumes toe.

In 2012 is er een Green Deal afgesloten en ondersteund door de nieuwe regering, met als doel om gebruik van aardgas in de transportsector te bevorderen (*Green Deal 'LNG: Rijn en Wadden'*). De ministeries van Economische Zaken en Infrastructuur en Milieu werken samen met industriepartners om de ambitieuze doelen te realiseren.

Doelstelling

Het belangrijkste doel van deze studie, uitgevoerd in opdracht van het ministerie van Infrastructuur en Milieu, is om verschillende brandstofroutes voor gebruik van aardgas als primaire energiebron in de transportsector met elkaar te vergelijken, m.b.t. broeikasgasemissies, energierendement, vervuilende emissies (in Nederland) en kosten vanuit het perspectief van de eindgebruiker. Deze vergelijking behelst de gehele *Well-To-Wheel* (WTW) keten van de verschillende brandstoffen, van de winning van gas tot het gebruik in verschillende transporttoepassingen[1]. Specifiek voor LNG (vloeibaar gemaakt aardgas) is de impact van een grootschalige introductie als transport voor zwaar transport over water en weg onderzocht, gebaseerd op de ambities van de Green Deal. Dit betreft zowel het emissie reductie potentieel als de kosten en externe veiligheid van de LNG-distributie. De tijdshorizon van de studie is 2025.

Naast deze studie naar de impact op milieu en veiligheid, heeft het ministerie van Economische Zaken opdracht gegeven aan consultant PWC om de economische impact van een introductie van aardgas als transportbrandstof te onderzoeken.

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[1] Alle transportmodaliteiten zijn in deze studie meegenomen, met uitzondering van spoorvervoer.

Keuze van energiedragers en transportsegmenten

De matrix van combinaties van energiedragers en transportsegmenten die in deze studie zijn bestudeerd wordt getoond in Tabel 1. De selectiecriteria zijn primair gebaseerd op de vereiste actieradius en secundair op de brandstofkwaliteit en beschikbaarheid van technologie. De opslagcapaciteit voor elektriciteit en waterstof is bijvoorbeeld niet voldoende voor de meeste schepen en zware vrachtwagens. Voor alle transportsegmenten is er een referentietechnologie en -brandstof vastgelegd. Voor de waterstof- en elektriciteitsroute zijn scenario's met en zonder CO_2-opslag (CCS) onderzocht.

Tabel 1 Geselecteerde combinaties van energiedragers en transportsegmenten

Energiedrager Transportsegment	LNG	CNG	GTL	DME	H_2 Met en zonder CO_2-opslag	Elektriciteit met en zonder CO_2-opslag	Referentie brandstof
Light-duty: personenauto en bestelauto	-	X	X	-	X	X	Benzine, diesel
Distributietruck en stadsbus	X	X	X	-	X	X	Diesel
Trekker-oplegger	X	-	X	X	X	-	Diesel
Binnenvaartschip	X	-	X	-	-	-	Diesel
Zeeschip (emission control area)	X	-	-	-	-	-	MGO
Zeeschip (diepzee)	X	-	-	-	-	-	HFO/MDO
Vliegtuig	X	-	X	-	-	-	Kerosine

Belangrijkste aannames

Voor deze studie met tijdshorizon 2025 zijn een aanzienlijk aantal aannames benodigd. De voor de scope en uitkomst belangrijkste aannames zijn:

- Het uitgangspunt voor het volume voor de toepassing van LNG in Nederland komt voort uit de ambitie in de Green Deal 'LNG: Rijn en Wadden', zijnde 2,5 miljoen ton LNG in 2025. Dit zou 10 tot 15% van het dieselgebruik in de transportsector vervangen. Meerdere bronnen geven aan dat het genoemde LNG-volume alleen realistisch is voor 2030 of daarna. Desalniettemin is 2,5 miljoen ton in 2025 aangehouden als basis voor de veiligheidsanalyse alsmede voor de milieutechnische en kosten analyse naar de inzet van LNG.
- Voor de Well-To-Tank (WTT) analyse van GTL en LNG is de afstand van Qatar tot Rotterdam als basis genomen voor de schatting van de bijdrage van het vervoer van de brandstoffen. Voor gas dat via pijpleidingen wordt geïmporteerd wordt een gelijkwaardige opsplitsing tussen gas uit Noorwegen en uit Rusland aangenomen.
- De meeste data voor de WTT emissies en energiegebruik zijn ontleend aan de JRC-studie uit 2011 (Edwards et al., 2011a). Hoewel representatieve gemiddelde waardes zijn gekozen voor deze studie, is er vrijwel altijd sprake van onzekerheid. Belangrijke punten zijn methaanemissies tijdens conversie en distributie van (vloeibaar of gasvormig) gas. Ook het energiegebruik tijdens de productie van GTL is onzeker gezien het momenteel beperkte aantal GTL-fabrieken.
- De prijzen van alle energiedragers zijn geschat voor de situatie in 2025. De aardgasprijs is onzeker en beïnvloedt de resultaten van deze studie sterk. Daarom is er een hoge en lage aardgasprijs aangenomen, in lijn met de aannames van PWC m.b.t. de economische impact van aardgas.
- De belangrijkste aannames voor emissies en kosten van de voertuigen zijn gebaseerd op voertuigtechnologie van 2020.

- De belastingen op energiedragers en op de vervoersmodaliteiten (zoals auto's) hebben een grote invloed op de kostenanalyse. In deze studie is er daarom gewerkt met een kostenanalyse met en zonder belastingen. Er is gebruik gemaakt van de belastingniveaus die in 2015 geldig zullen zijn.

De studie heeft geleid tot de onderstaande conclusies.

Belangrijkste conclusies uit de kostenanalyse

De resultaten leiden tot de volgende generieke conclusies voor wat betreft kosten vanuit het perspectief van de eindgebruiker:

- Behalve voor de GTL-route, zijn alle voertuigen en schepen voor aardgas of van aardgas afgeleide energiedragers duurder dan de referentie voertuigen en schepen.
- Deze additionele investeringskosten worden in sommige, maar niet alle gevallen, gecompenseerd door lagere brandstofkosten.
- Voor wegtransport vertoont de belastingheffing op verschillende brandstoffen en energiedragers significante verschillen. CNG, LNG, waterstof en elektriciteit profiteren van een lager belastingniveau per eenheid energie in vergelijking met diesel en benzine, wat bijdraagt aan de compensatie van de hogere voertuigkosten. Een vergelijking van de kosten inclusief belasting toont aan dat in sommige gevallen de kilometerkosten van aardgas alternatieven lager zijn dan de referentie, ondanks het feit dat de totale kosten zonder belastingen hoger zijn.
  Bij scheepvaart en luchtvaart worden brandstoffen niet belast.

Belangrijkste conclusies per transportsegment

In Tabel 2wordt een overzicht gegeven van de Well-To-Wheel broeikasgas-emissies, energierendementen en vervuilende emissies van op aardgas gebaseerde brandstoffen en energiedragers voor het jaar 2025. Dit is vergeleken met de voer-, vaar- of vliegtuigen met de referentiebrandstof.

Personenauto's en lichte bestelwagens (referentie diesel of benzine)

- De toepassing van CNG leidt tot een 10-15% lagere emissie van broeikasgassen (WTW) in vergelijking met diesel en 15-20% reductie in vergelijking met benzine. De NO_x-uitstoot is ca. 50% in vergelijking met diesel, maar er is geen significante reductie van deeltjes emissie.
- De toepassing van GTL resulteert in vergelijkbare broeikasgas-, NO_x- en deeltjes emissies.
- Batterij-elektrische voertuigen (voorzien van elektriciteit uit gascentrales) hebben een naar verwachting 50% lagere emissie van broeikasgassen.
- Waterstof-elektrische voertuigen met brandstofcel (voorzien van waterstof uit aardgas) hebben een naar verwachting 33% lagere emissie van broeikasgassen.
- Zowel batterij- als waterstof-elektrische voertuigen reduceren de WTW NO_x en deeltjes emissies met 90%. De broeikasgasemissies kunnen verder worden gereduceerd als afvang en opslag van CO_2 wordt toegepast, al zorgt dat wel voor een verhoging van het WTW energieverbruik met 10%.

Tabel 2 **WTW broeikasgasemissies, energieverbruik en vervuilende emissies van brandstoffen/ energiedragers geproduceerd uit aardgas voor 2025. Referentie is diesel, tenzij anders vermeld. Een '+' voor vervuilende emissies betekent een reductie**

Transport Segment	Broeikas gasemissies	Energie verbruik	Vervuilende emissies	Opmerkingen
CNG in personenauto's	-17%	3%	o+	Referentie is benzine
CNG in lichte bestelauto's	−12%	11%		Referentie is diesel
Batterij elektrische auto's	≈ -55%	≈ -45%	++	Referentie is benzine; rijpheid en rendement nog aan te tonen
Waterstof elektrische auto's	≈ -33%	≈ -12%	++	Indicatief, rijpheid en rendement nog aan te tonen
GTL in trucks, auto's, DME in trucks	0 tot -5%	30 - 35%	o	In pure of gemende vorm
Batterij elektrische trucks en bussen	≈ -15% tot -25%	≈ -5% tot 5%	++	Rijpheid en rendement nog aan te tonen
Waterstof in trucks en bussen	≈ -8%	≈ 20%	++	Indicatief, rijpheid en rendement nog aan te tonen
Aardgas in trucks en bussen	0 tot -19%	0 tot 14%	o	Dual-fuel of pilot motoren mogelijk onvoldoende beschikbaar
GTL in binnenvaartschepen	0	35%	+	
LNG in binnenvaartschepen	≈ 0	4%	+	Potentieel broeikasgas -20% bij lage methaanemissie
LNG in zeeschepen	≈ 0 to -20%	≈ 5%	++	Potentieel broeikasgas -20% bij lage methaanemissie
LNG in vliegtuigen	≈ -13%	11%	o	Referentie is kerosine. Indicatief, geen toepassing verwacht in 2025
GTL in vliegtuigen	≈ 4%	≈ 35%	o	Referentie is kerosine. Synthetise kerosine 100% compatibel met kerosine

Trucks en bussen (referentie diesel)

- Broeikasgasemissies van voertuigen op aardgas (CNG of LNG) zijn 0 tot 20% lager, afhankelijk van type motor en toepassing. Dual-fuel of pilot-diesel motoren kunnen de hogere besparingen realiseren (met enige onzekerheid over de beschikbaarheid van motoren gezien de strenge methaan emissie eisen).
- GTL leidt tot vergelijkbare broeikasgasemissies in pure of gemengde toepassing, ca. 5% reductie van broeikasgasemissies mogelijk in ongemengde toepassing in een op GTL geoptimaliseerde motor. De WTW energieconsumptie stijgt met 30-35%.
- Broeikasgasemissies van batterij-elektrische trucks en bussen zijn ca. 20% lager, 60% als CO_2-opslag wordt toegepast.
- Broeikasgasemissies van waterstof-elektrische trucks en bussen zijn ca. 10% lager en 70% als CO_2-opslag wordt toegepast.
- Vervuilende NO_x- en deeltjes emissies zijn vergelijkbaar voor alle trucks en bussen met verbrandingsmotor ten gevolge van de strenge emissie-eisen en geavanceerde motortechnologie. Elektrische en waterstof trucks en bussen hebben geen emissie uit de uitlaat.

Binnenvaartschepen (referentie diesel)

- Bij toepassing van LNG zijn de broeikasgasemissies ongeveer gelijk aan diesel ten gevolge van de relatief hoge methaanemissies. Als deze methaanemissies middels wetgeving en technologieontwikkeling worden gereduceerd, dan zijn besparingen tot 20% mogelijk.
- NO_x en SO_x (uitlaat) emissiereductie bij de toepassing van aardgas is beperkt gezien de verwachte strenge emissie-eisen vanaf 2016 en de verplichte toepassing van ultra laagzwavelige diesel. Bij vervanging van oudere motoren is er uiteraard een grotere reductie. NO_x- en deeltjes emissiereductie is dan ca. 70%.
- GTL in binnenvaartschepen verhoogt het WTW energieverbruik met ca. 35%, de broeikasgassen blijven gelijk. NO_x en deeltjes emissies worden met ca. 10% gereduceerd.

Zeeschepen (referentie afhankelijk van scheepstype)

- Toepassing van LNG veroorzaakt een broeikasgasreductie van 0 tot 20%. De hoogste reductie wordt bereikt bij zeer grote scheepsmotoren. Als de methaanemissies middels wetgeving en technologieontwikkeling worden gereduceerd, dan zijn besparingen tot 20% mogelijk voor alle motortypes.
- Schepen binnen de Emission Control Area's (ECA): grote reducties van SO_x- en deeltjes emissies bij toepassing van LNG. NO_x-emissiereductie is mogelijk als toekomstige NO_x-emissies bij dieselmotoren niet verder worden teruggebracht (als Tier III NO_x niet wordt geeffectueerd).
- Schepen buiten de ECA's: grote reducties van SO_x- en deeltjes emissies bij toepassing van LNG. Grote reductie van NO_x-emissies, afhankelijk van motortype en regelstrategie.

Luchtvaart (referentie kerosine)

- Broeikasgasemissies nemen enigszins toe bij toepassing van GTL, terwijl de toepassing van LNG resulteert in een reductie van 10-15%. De invloed op NO_x- en deeltjes emissies wordt als verwaarloosbaar beschouwd.
  Bij toepassing van GTL wordt het WTW-energieverbruik met 35% verhoogd.
- De toepassing van LNG in 2020/2025 is niet erg realistisch gezien de grote uitdagingen met LNG-opslag aan boord van het vliegtuig en de veiligheidsrichtlijnen. De toepassing van GTL is realistisch, aangezien de eigenschappen vergelijkbaar zijn met kerosine.

Impact van het 2,5 miljoen ton LNG-scenario

De belangrijkste milieu-impact bij het gebruik van 2,5 miljoen ton LNG per jaar in de Nederlandse transportsector:

- De shift naar LNG zou jaarlijks ongeveer 650 kton broeikasgasemissies (WTW) besparen, terwijl NO_x- en PM_{10}-deeltjes emissies in Nederland met 26 resp. 1,3 kton dalen. SO_x-emissies zouden met bijna 7,7 kton per jaar worden gereduceerd.
- Het WTW energieverbruik zou stijgen met ongeveer 7 miljoen GJ, vergelijkbaar met 6% van de energie-inhoud van het totale volume LNG.
- De meeste broeikasgasreductie worden bereikt met het gebruik van LNG in wegtransport.
- NO_{x-}, PM_{10-} en SO_x-emissiereducties wordt met name bereikt door LNG-toepassing in scheepvaart (kustvaart en diepzee).

De procentuele effecten per transportsegment voor het 2,5 miljoen ton LNG-scenario zijn samengevat in Tabel 3. De toepassing van LNG in zeeschepen leidt tot grote SO_x-reducties, hoewel deze voornamelijk buiten het Nederlandse zeegebied gerealiseerd worden.

Tabel 3 **Scenario resultaten: procentuele effecten van de toepassing van LNG in 2025 per segment**

	WTW energie-verbruik	WTW broeikas-gasemissies	NO_x-emissies	PM_{10}-emissies	SO_x-emissies
Distributietruck	1%	-19%	-2%	-8%	
Trekker-oplegger	5%	-13%	-3%	-14%	
Binnenvaartschip	4%	-1%	-1%	-52%	-87%
Kustvaartschip	7%	0%	1%	-37%	-93%
Diepzeeschip 5.500 TEU	9%	-4%	-77%	-57%	-100%
Diepzeeschip 15.000 TEU	6%	-12%	-46%	-55%	-95%

Het 2,5 miljoen ton scenario beïnvloedt waarschijnlijk ook de kosten:

- De totale kosten voor voertuig- en scheepseigenaren dalen in vergelijking met de referentiebrandstoffen, maar een groot deel van deze besparingen hebben te maken met de lagere belasting op LNG (uitgaande van 2015-niveau). Zonder belastingen stijgen de kosten voor wegtransport bij zowel het hoge als lage aardgasprijsscenario, maar uiteraard in verschillende mate. Voor maritiem transport wordt verwacht dat de kosten stijgen, hier wordt geen belasting op brandstoffen geheven.
- Aannemende dat de belastingniveaus op 2015-niveau blijven, dalen de belastinginkomsten van de overheid ten gevolge van de shift naar LNG met ca. € 170 miljoen in 2025.

Verduurzamingspotentieel

Er zijn verschillende opties om de verschillende aardgasroutes in de toekomst te verduurzamen. CNG en LNG kunnen bijvoorbeeld worden vervangen door biomethaan uit biomassa, elektriciteit kan door verschillende duurzame productiemethodes worden geproduceerd.

De toepassing van biobrandstoffen is een belangrijke optie is voor het minder koolstof intensief maken van de transportsector. Echter, de totale hoeveelheid biomassa is beperkt, zodat slechts een deel van het totale brandstofverbruik kan worden verduurzaamd via deze route (zeker gezien de competitie tussen sectoren en toepassingen om deze schaarse grondstof). Daarbovenop is er een discussie gaande over ‘voedsel versus brandstof’, *indirect land use change* effecten en andere duurzaamheidsaspecten. Zowel gasvormige als vloeibare biobrandstoffen zullen duurder zijn dan fossiele brandstoffen. Aannemende dat het totale gebruik van aardgas in de transportsector ca. 10% zal zijn in 2025, dan zal biogas als middel om de brandstofroutes minder koolstof intensief te maken nog geen dominante rol spelen in 2025.

Het gebruik van elektriciteit opgewekt uit wind en zon als energiebron voor transport kent minder beperkingen in vergelijking tot biomassa. Echter, deze energiebronnen kennen een sterk wisselend karakter, aangezien ze afhankelijk zijn van de wind- en zonnekracht. Verder zijn de routes om elektriciteit en waterstof te produceren uit zon en wind aanzienlijk duurder dan de productieroutes op basis van aardgas.

Externe veiligheid als belangrijke randvoorwaarde

Onderdeel van deze studie is een onderzoek naar de externe veiligheidsrisico's van de denkbeeldige LNG-distributieketen en infrastructuur voor weg- en watertransport, alsmede een identificatie van mogelijke veiligheidsproblemen. Vanuit het veiligheidsonderzoek kan worden geconcludeerd dat LNG-bunkerstations en transport over het water geen problemen lijken te veroorzaken m.b.t. externe veiligheid, hoewel er aandacht moet worden besteed aan het groepsrisico rondom bunkerstations.
LNG-tankstations hebben betrekkelijk grote risicocontouren, maar er zijn meerdere opties beschikbaar om de risico's te beperken, waardoor er waarschijnlijk voldoende veilige locaties zijn voor deze tankstations.
Het transport van LNG over de weg vereist specifieke aandacht. Aangezien LNG diesel zal vervangen en niet LPG, komt het LNG-transport over de weg ('basisnet weg') bovenop dat van LPG, waardoor het risiconiveau van een groot deel van de wegsegmenten overschreden kan worden. Zonder verdere acties kan het verwachte LNG-volume niet geabsorbeerd worden door het 'basisnet weg'. Dit vereist verder onderzoek.
Aanbevolen wordt om het risicoberekeningsmodel voor wegtransport (RBM II) adequaat aan te passen op toepassing van LNG (in deze studie is een benadering van de LNG-risicoberekeningen gebruikt). De identificatie van specifieke LNG ongeval- en effectscenario's, het onderzoeken van specifieke faalfrequenties voor kritische LNG-installatie onderdelen en het verbeteren van het huidige effectmodel, zal allemaal leiden tot meer realistische risico niveaus van LNG en zouden nader onderzocht moeten worden.

Aanbevelingen

Monitor rendementen en emissies van nieuwe aandrijftechnologieën

In veel gevallen zijn voorspellingen gedaan van (2020) aandrijflijnrendementen en –emissies met beperkte (real-world) informatie, resulterend in onzekerheden. Daarom wordt aanbevolen om in de toekomst de volgende parameters te onderzoeken en monitoren:

- rendementen van waterstof- en batterij-elektrische voertuigen;
- energierendementen en methaanemissies van aardgasmotoren voor het zware wegverkeer;
- methaanemissies van scheepsmotoren.

Monitor de toegestane variatie in de LNG-specificaties voor verschillende transportsegmenten

Dit kan worden gedaan door deelname aan het CEN-standaardisatieproces en door deelname aan motortest en –ontwikkelingsprogramma's. Een lage LNG-kwaliteit (methaangetal) kan de ontwikkeling van motoren met hoge rendementen vertragen en kan leiden tot additionele emissie van broeikasgassen.

Stimuleer LNG-distributie via waterwegen

Vanwege potentiele veiligheidsrisico's wordt aanbevolen om het LNG-transport zo veel mogelijk via waterwegen te laten plaatsvinden. Daarnaast wordt aanbevolen om een specifieke LNG-stofcategorie op te nemen in RBM II en om effectmodellen voor LNG zoals verdamping en dispersie te valideren en om state-of-art technologie en veiligheidsmaatregelen toe te passen bij alle LNG-materiaal en -installaties.

Ontwikkeling van bio-CNG en LNG en onderzoek naar andere biobrandstof opties

In het kader van de verduurzaming van de brandstofroutes wordt aanbevolen om bio-CNG en bio-LNG te ontwikkelen als hernieuwbare alternatieven. Hierbij dient rekening gehouden te worden met de beperkte beschikbaarheid van biomassa en duurzaamheidsaspecten. Daarnaast wordt aanbevolen om de WTW broeikasgasemissies en ketenefficiëntie van bio-CNG en bio-LNG ook te vergelijken met het alternatief van inzet van vloeibare biobrandstoffen, zoals biodiesel, HVO en BTL.

Summary

Background and aim of this study

Concerns on climate change and on security of supply of fossil fuels are likely to induce major changes in energy use of the transport sector over the next decades. Transport is responsible for a quarter of the EU's greenhouse gas emissions. Around 2050 the transport sector needs to have reduced its CO_2 emission to a fraction of the current values and in addition needs to be largely independent of oil.

Increased application of natural gas in the transport sector could substantially contribute to improved security of supply. In addition natural gas and fuels or energy carriers derived from natural gas, such as GTL, DME (dimethyl-ether), H_2 and electricity, may be beneficial for air quality and GHG emissions. For a number of transport applications, there is a viable business case to use (fuels derived from) natural gas. Consequently, the interest of industry is growing and gas volumes are increasing.

In 2012 a Green Deal was supported by the new government that aims at wider application of natural gas in the transport sector (*Green Deal 'LNG: Rijn en Wadden'*). The Ministries of Economic Affairs and Infrastructure & Environment work together with industry partners in achieving these ambitious targets.

Objective

The key objective of this study, commissioned by the Dutch Ministry of Infrastructure and Environment, is to compare the various fuel pathways for use of natural gas as a primary energy source in the transport sector, in terms of greenhouse gas emissions, energy efficiency, pollutant emissions (in the Netherlands) and costs from the user perspective. The comparison covers the entire Well-To-Wheel (WTW) energy chain, ranging from gas production to the propulsion of the various modes of transport[2]. Specifically for LNG, the impact of a large scale introduction of LNG used as a fuel in heavy-duty transport has been assessed, based on the Green Deal 'LNG: Rijn en Wadden' ambition. This covers both emission reduction potential, costs and the external safety of the LNG distribution. The time horizon of the study is 2025.

In addition to this study into the environmental and safety conditions, the Ministry of Economic Affairs has commissioned a study by the consultancy company PWC, on the economic impact of the introduction of natural gas.

Choice of energy carriers and transport segments

Table 1 shows the matrix of the combinations of energy carriers and transport segments that were selected for this analysis. The selection criteria are primarily based on the required autonomy (range) and secondly on fuel quality and availability of technology. As an example, the storage capacity of electricity and hydrogen is not sufficient for all (mainstream) shipping segments and heavy trucks. For all transport segments, a reference technology and fuel were defined.

For the hydrogen and electricity routes, scenarios with and without carbon capture and storage (CCS) are assessed.

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[2] All transport modes, with the exception of railway transport, are included.

Table 1 Selected combinations of energy carrier and transport segment

Energy carrier Transport segment	LNG	CNG	GTL	DME	H_2 With and without CO_2 storage	Electricity with and without CO_2 storage	Reference fuel
LD: Passenger car and van	-	X	X	-	X	X	Petrol, diesel
Rigid truck and city bus	X	X	X	-	X	X	Diesel
Tractor-semi-trailer	X	-	X	X	X	-	Diesel
Inland ships	X	-	X	-	-	-	Diesel
Sea ships Emission Control Area	X	-	-	-	-	-	MGO
Sea ships Deep sea	X	-	-	-	-	-	HFO/MDO
Air plane	X	-	X	-	-	-	Kerosene

Key assumptions

For this study with the time horizon of 2025, a significant number of assumptions need to be defined. Key assumptions, either defining the scope of the study or significantly influencing the results are:

- The assumed volume of LNG used for transport in the Netherlands follows the ambition in the Green Deal 'LNG: Rijn en Wadden', being 2.5 million tons of LNG in 2025. This would substitute 10-15% of the diesel use in the transport sector. Several sources indicate that this kind of LNG volume is only realistic for 2030 or later. Nevertheless, 2.5 million tons of LNG in 2025 is used as the basis for the safety analysis and projection of the overall environmental and financial effects of LNG.
- For the well to tank (WTT) calculations of LNG and GTL the distance from Qatar to Rotterdam is taken as a mean reference for estimating the contribution of transport of the fuel. For pipeline gas an equal split between gas from Norway and Russia is assumed.
- Most data on WTT emissions and energy use are taken from the 2011 JRC study (Edwards et al., 2011a). Although representative mean values are chosen for this study, most data have uncertainty ranges. Important issues are methane emissions during conversion and distribution of gas (liquid or gaseous). Also the energy use in GTL production is uncertain due to the currently limited number of GTL plants.
- 2025 prices for all energy carriers are assumed. The natural gas price shows high uncertainty and influences the conclusions of this study. Therefore a high and low NG price is used in the analysis and conclusions. These high and low NG price assumptions are in line with the study of PWC on the economic impact of natural gas.
- Assumptions for vehicle emissions and cost are based on vehicle technology in 2020.
- Taxes on energy carriers and on the vehicles, ships and airplanes have a large impact on the cost analysis. In this study, the cost analysis is done with and without taxes. Current forecasts for 2015 tax levels are used.

The study led to the following main conclusions.

Main conclusions on costs

The following general conclusions can be drawn from the cost analysis from end user perspective:

- Except for the GTL route, all natural gas options require vehicles and ships that are more expensive than the reference.

- These additional investment costs are in some cases, but not all, compensated by lower fuel cost.
- In road transport, tax levels on the various fuels and energy carriers vary significantly. CNG, LNG, hydrogen and electricity benefit from a lower tax per unit energy content compared to diesel and petrol, which also contributes to compensate for additional vehicle costs. Cost comparisons including taxes therefore show that in some cases, overall cost per kilometer of the NG alternatives are lower than the references, even though overall costs excluding taxes are higher. In shipping and aviation, fuels are not taxed.

Main conclusions per transport segment

An overview of the Well-To-Wheel GHG emissions, energy consumption and pollutant emissions with alternative fuels in 2025 is presented in Table 2. The reference is the vehicle, ship or airplane with the 2020 reference powertrain to which all other fuels produced from natural gas are compared.

Passenger cars and vans (gas derived fuels vs. reference diesel)

- Application of CNG leads to about 10-15% lower WTW GHG emissions. $NO_x \approx 50\%$ lower than diesel, but no difference in particulate emissions.
- GTL results in the same GHG emissions and the same levels of NO_x and particulates emissions.
- Battery electric vehicles (charged with electricity from gas fired power stations) are expected to have around 50% lower GHG emissions.
- H_2 fuel cell vehicles are expected to have about 33% lower WTW GHG emissions (assuming the hydrogen is produced from natural gas).
- Both battery electric and H_2 fuel cell vehicles show 90% lower WTW NO_x and particulate emissions. GHG emissions can be further reduced by CO_2 capture and storage, but this will increase WTW energy consumption by about 10%.

Table 2 WTW GHG emission, energy consumption and pollutant emissions of alternative fuels produced from natural gas for the year 2025. Reference is the diesel powertrain (in hybrid configuration for bus and rigid truck), unless otherwise noted. For pollutant emissions: '+' means reduction

Transport segment	GHG emission	Energy consumption	Pollutant emissions	Remarks/Issues
CNG in passenger cars	-17%	3%	o +	Reference is petrol
CNG in vans	–12%	11%		Reference is diesel
Electric passenger cars	≈ -45%	≈ -35%	++	Reference is petrol Maturity & efficiency to be demonstrated
H_2 fuel cell passenger cars	≈ -30%	≈ -10%	++	Indicative, maturity & efficiency to be demonstrated
GTL in trucks, cars, DME in trucks	0 to -5%	30%	o	As pure fuel or blend
Electric trucks and buses	≈ -15% to -25%	≈ -5% to 5%	++	Maturity & efficiency to be demonstrated
H_2 fuel cell trucks and buses	≈ -8%	≈ 20%	++	Indicative, maturity & efficiency to be demonstrated
Natural gas in trucks and buses	0 to -19%	0 to 14%	o	Dual-fuel or pilot engines may not be sufficiently available
GTL inland ships	0	30%	+	
LNG inland ships	≈ 0	4%	+	Potentially GHG ≈ -20% with low methane emission

Transport segment	GHG emission	Energy consumption	Pollutant emissions	Remarks/Issues
LNG in sea ships	≈ 0 to -20%	≈ 5%	++	GHG -20% for ships with low methane emission
LNG in airplanes	≈ -13%	11%	o	Reference is kerosene. Indicative/no commercial application by 2025
GTL in airplanes	≈ 4%	≈ 35%	o	Reference is kerosene Synthetic kerosene 100% compatible with kerosene

Trucks and buses (reference diesel)

- GHG emissions of natural gas vehicles (CNG or LNG) are 0 to 20% lower depending on engine type and application. High savings can be achieved with dual-fuel or pilot diesel engines (with some uncertainty regarding availability due to stringent CH_4 emission requirements)
- GTL results in the same GHG emission, both as pure fuel or blend with diesel. About 5% GHG emission savings could be achieved if it is used as a pure fuel in an engine optimised for GTL. With GTL energy consumption increases with 30-35%.
- GHG emissions of battery electric vehicles are about 20% lower, and 60% lower if CCS is applied.
- GHG emissions of hydrogen fuel cell vehicles are about 10% lower, and 70% if CCS is applied.
- Pollutant emissions of NO_x and particulates will be very similar for all vehicles with combustion engines, due to the stringent and comprehensive emissions standards and the advanced emission control systems for the diesel vehicles. Electric and hydrogen vehicles will have zero (tailpipe) emissions.

Inland Ships (reference diesel)

- With LNG, GHG emissions will be about equal to diesel due to relatively high methane emissions with natural gas. If the recommended gradual reduction of engine methane emissions, via emission regulations and technology development, would be achieved, then GHG savings of up to 20% would be possible.
- NO_x and local SOx emission reductions are expected to be small due to the expected stringent emissions requirements from 2016 onwards and the mandatory application of ultra-low sulphur diesel. In case of replacement of older diesel engines, there obviously will be large reductions. NO_x and PM reduction is then about 70%.
- GTL in inland ships increases WTW energy use by about 35% and has a neutral effect on GHG emissions. It reduces NO_x and particulate emissions by about 10%.

Sea Ships (reference depending on ship type)

- With LNG: 0–20% GHG emission reduction. The higher reductions are currently only achieved with very large ship engines. If the recommended gradual reduction of engine methane emissions, via emission regulations, would be achieved, GHG savings up to 20% are possible for all engine types.
- Within Emission Control Areas (ECAs): large reductions of SO_x and PM emissions with LNG. NO_x reduction is possible if future NO_x emissions are not further limited for diesel engines (i.e. if Tier III NO_x is not imposed).

- Outside ECAs: large reduction of SO_x and PM with LNG. Large NO_x emission reduction with LNG, depending on engine type and engine management strategy.

Aviation (reference kerosene)

- GHG emissions increase slightly with GTL, whereas LNG results in about 10% to 15% GHG emission reduction. Impact on NO_x and PM_{10} emissions are expected to be negligible. With GTL energy consumption increases with 35%.
- Application of LNG by 2020/2025 is not very realistic given the challenges with LNG storage on board of a plane and safety regulations. Application of GTL is realistic, since this will be developed as drop in fuel (compatible with Kerosene).

Main impacts of the 2.5 million ton LNG scenario

The main environmental impacts for use of 2.5 million ton LNG per annum in the Dutch transport sector, based on 2020 vehicle and ship technologies, are:

- This shift to LNG would reduce annual WTW GHG emission by about 650 kton CO_2, NO_x and PM_{10} emissions in the Netherlands would be reduced by about 26 and 1.3 kton respectively. SO_x emissions would be reduced by almost 7.7 kton per year.
- Overall WTW energy use would increase, by about 7 million GJ, equalling 6% of the energy content of the total amount of LNG used.
- The main GHG reduction benefits are achieved with LNG use in road transport.
- NO_x, PM_{10} and SO_x emission reductions mainly result from LNG use in maritime transport (short sea and deep sea).

The relative effects per transport segment for the 2.5 million ton LNG scenario are shown in Table 3. The use of LNG in sea ships leads to substantial SO_x emission reductions, although those reductions occur mostly outside Dutch territory.

Table 3 Scenario results: Relative environmental effects for LNG in 2025 per transport segment

	Relative change in WTW energy use	Relative change in WTW GHG	Relative change in NO_x	Relative change in PM	Relative change in SO_x
Rigid truck	1%	-19%	-2%	-8%	
Tractor-trailer	5%	-13%	-3%	-14%	
Inland ship	4%	-1%	-1%	-52%	-87%*
Short sea ship	7%	0%	1%	-37%	-93%
Deep sea ship 5,500 TEU	9%	-4%	-77%	-57%	-100%
Deep sea ship 15,000 TEU	6%	-12%	-46%	-55%	-95%

*Absolute numbers are small, though, also in the reference fuel case.

The scenario is expected to impact costs as well:

- The overall cost to vehicle and ship owners was found to decrease compared to the reference fuels, but a large part of these savings are related to lower fuel taxes in road transport (assuming 2015 tax levels). Road transport cost without taxes were found to increase in both NG price scenarios, albeit to a different extent. Cost of sea shipping is expected to increase (as no taxes are applied there).
- Assuming taxes are kept at 2015 levels, the shift to LNG will reduce government tax revenues by about € 170 million, in 2025.

Potential for decarbonisation

A range of options exist to decarbonize the various natural gas routes in the future. For example, CNG and LNG could be replaced by biomethane from biomass. The natural gas-based electricity production could be replaced by a range of renewable electricity options.

It can be concluded that biofuel application is one of the key options for decarbonisation of the transport sector. Nevertheless the overall amount of bio feedstock is limited, implying that only a part of the total fuel use can be decarbonized by this route, especially since other sectors and applications compete for the same feedstock. In addition, a discussion about food versus fuel, indirect land use changes, and other sustainability issues is ongoing. The biofuels, both liquid and gaseous, will have additional cost compared to fossil fuels. Assuming that the total use of natural gas in the transport sector will be in the order of max. 10% in 2025, decarbonisation by substitution with biogas will not yet play a dominant role by 2025.

The use of electricity from wind and sun as an energy source for transport has less limitations compared to biomass, but they are sources with intermittent supply, as they depend on the fluctuating intensity of wind and solar radiation. Furthermore, the routes to produce hydrogen and electricity from sun and wind energy are more expensive than the conventional production routes based on natural gas.

External safety as key boundary condition

Part of this study was an assessment of the external safety impacts of the projected LNG distribution chain and infrastructure for road and sea transport as well as the identification of possible safety issues. From the safety assessment it can be concluded that LNG bunkering stations and transport over water seem to pose no problem with respect to external safety although attention needs to paid to the societal risk around the bunkering stations. However, LNG filling stations have fairly large risk contours, but different options are available to reduce the risks, creating probably sufficient possibilities for safe locations for these filling stations. The transport of LNG over the road needs detailed attention. Since LNG will replace diesel and not LPG as a transport fuel, the projected LNG transport volume over the road (‘basisnet weg’) will be additional to LPG and will pose a problem due to exceeding the risk level for a large number of the road segments. Without any actions, the expected volume of LNG cannot be absorbed by the ‘basisnet weg’. This requires further investigation.
Adjusting the risk calculation model for road transport (RBM II) to accommodate LNG properly is proposed (a rough approximation for the LNG risk calculations was used in the underlying study). Identification of specific LNG incident and effect scenario’s, assessing specific failure frequencies for critical LNG installation parts and improving current effect models will all lead to more realistic risk levels of LNG and should also be subject to further study.

Recommendations

Monitor efficiency and emissions of new technologies

In many cases, projections of (2020) driveline efficiencies and emissions had to be made with very little (real-world) information, resulting in substantial uncertainties. It is therefore recommended to investigate and monitor the following parameters in the near future:

- efficiencies of fuel cell and battery electric vehicles;
- energy efficiencies and methane emissions of HD natural gas engines;
- methane emissions of ship engines.

Closely monitor allowable ranges in LNG specifications for different transport applications

This can be done by participation in the CEN standardisation process and by participation in engine test and development programs. Lower LNG quality (methane number) may delay the development of higher efficiency engines and lead to additional GHG emission.

Stimulate LNG distribution via water ways

To address the potential safety issues it is recommended to ensure LNG transport will take place as much via water transport; to create a LNG specific substance category in RBM II; to validate effect models for LNG phenomena like evaporation and dispersion and to apply state of the art technology and safety measures for all LNG equipment and installations.

Develop bio-CNG and LNG, and investigate other biofuel options

It is recommended to develop bio-CNG and bio-LNG, as renewable low-carbon alternatives for the natural gas options, thereby considering limitations in biomass feedstock availability and sustainability issues. In addition it is recommended to compare bio-CNG and bio LNG in terms of (WTW) GHG emissions and energy efficiency, relative to the performance of the alternative of using liquid biofuels such as biodiesel, HVO and BTL.

1 Introduction

1.1 Background

Climate change and concerns on security of supply of fossil fuels are likely to induce major changes in energy use of the transport sector over the next decades. Transport is responsible for a quarter of EU greenhouse gas emissions. Around 2050 the transport sector needs to have reduced its CO_2 emission to a fraction of the current values and in addition needs to be largely independent of oil. Market penetration of natural gas in the transport sector could substantially contribute to improved security of supply.
In addition natural gas will be beneficial for air quality and related health issues and contribute in some subsectors to intermediate climate change targets.

Natural gas offers the perspective of a major and relatively clean energy source for the transport sector. Moreover, application of natural gas will improve the security of supply as it will lower the dependency on oil. Natural gas as a primary source of energy for the transport sector can be used in different forms. The most obvious applications are in the form of compressed natural gas (CNG) and liquefied natural gas (LNG). However, by conversion of natural gas into Gas to Liquids (GTL) gas can be applied more easily, because in this case it can directly substitute diesel. For the future, also other routes are conceivable, such as conversion into dimethyl ether (DME) and hydrogen. Moreover, electricity that powers the currently increasing fleet of electric vehicles is generated for an important part from natural gas. For a number of transport applications, there is a viable business case to use (fuels derived from) natural gas and volumes are increasing.

Last year a Green Deal was supported by the new Cabinet that aims at wider application of natural gas in the transport sector (‘*Green Deal LNG Rijn Wadden’)*. The Ministries of Economic Affairs and Infrastructure and Environment work together with industry partners in this Green deal.

In addition to this study into the environmental and safety conditions, the Ministry of Economic Affairs has commissioned a study that is currently undertaken by PWC on the economic impact of the business for the introduction of natural gas.

1.2 Objective

Against this background the key objective of our study is to compare the various fuel pathways for use of natural gas as a primary energy source in the transport sector in terms of: energy efficiency, CO_2 emissions, polluting emissions and costs. The comparison covers the entire Well-To-Wheel energy chain, ranging from gas production to powering of the vehicle. For all routes, the potential for decarbonisation needs to be assessed. Specifically for LNG, the impact of the fuel distribution on external safety needs to be assessed. The time horizon of the study is 2025.

Specific research questions include:

- Comparing different routes to use natural gas as primary energy source in the transport sector, regarding environmental impact and cost. The focus

is on the LNG and GTL route for application in trucks, inland and seagoing vessels.
- Identification and evaluation of (future) options to decarbonize the different gas chains.
- Safety assessment of the future LNG distribution chain and infrastructure.

1.3 Starting point

The starting point of the current study was given by the Dutch Ministry of Infrastructure and Environment to be **2.5 mln ton LNG in 2025 applied in the transport sector** in the Netherlands.
The underlying considerations for this rather ambitious starting point are:

- the ‘Green deal Rijn en Wadden’: 2 to 3 million tonnes of LNG as transport fuel in 2030;
- the scenario of the LNG platform of 50 inland vessels, 50 ocean-going vessels and 500 trucks running on LNG by 2015.

1.4 Commissioning company and consortium

This report has been commissioned by the Netherlands Ministry of Infrastructure and Environment. The study was carried out jointly by the consortium TNO, CE Delft and ECN. The combined knowledge and experience of the consortium covers all issues of the study.

1.5 Policy support

The Department of Vehicle Emissions and Fuels (V&B) of the directorate Climate, Air and Noise (KLG) of Ministry of Infrastructure and Environment currently develops a department-wide strategy on vehicle emissions and fuel. The study presented in the current reports aims to support the strategy on vehicle emissions and fuel of the Ministry, especially regarding policies to guide the introduction of LNG and GTL as transport fuels.

1.6 Additional considerations

- As of January 2015 stricter limits will be in force for the Sulphur Emissions Control Area. LNG is one of the solutions to meet the stricter limits.
- The Netherlands have a relatively strong position in the European gas market, that will be extended by the large scale roll-out of LNG as a transport fuel.
- Current transport emissions and resulting air pollution exceeds in some locations air quality regulations, thereby blocking further economic developments. On of the solutions to solve this issue is application of LNG in transport along with the associated low emissions of SO_x, NO_x and particulates.

1.7 Links with other studies and stakeholders

The study was carried out in consultation with the following institutions, thereby contributing to a broadly supported and well balanced study:

- PricewaterhouseCoopers that currently carries out a study on the economic impact of using LNG in the transport sector. Focusing on the business case

of using LNG as a transport fuel for the different parts of the transport chain.
- Nationaal LNG Platform (www.nationaallngplatform.nl).
- A sounding board group of multiple stakeholders, including commercial parties.
- A guiding Committee, with members from various departments of the Ministry of Infrastructure and Environment and of the Ministries of Finance and Economic Affairs.

1.8 Structure of the report

Chapter 2 describes the s*election of the most relevant routes in 2020-2030,* and subsequent reviews these options to define the fuel chains and the reference vehicles, ships and planes.
Chapter 3 provides an analysis of the e*nvironmental impacts and cost of (gas powered) vehicles and ships*. In this chapter the *tank-to wheel* energy consumption, GHG emissions and pollutant emissions of the vehicles, ships and planes are derived and summarized.
Chapter 4 presents the *environmental impacts and cost of the Well-To-Tank part of the gas routes* regarding: energy use, CO_2 emissions as well as costs. In addition the emissions of air polluting compounds relevant for the Netherlands are estimated.
Chapter 5 describes the *potential for decarbonisation of the routes selected*, by a qualitative assessment including maturity of the technology, sustainability issues and costs.
Chapter 6 describes an *assessment of safety issues*, focusing on the external safety of the intended LNG distribution chain and infrastructure for road and sea transport and the identification of possible safety issues.
Chapter 7 provides an *overall assessment* by combining the Well-To-Tank results and the Tank-To-Wheel results to derive at the full Well-To-Wheel (i.e. life cycle) emissions, energy use and cost. In addition the findings on future decarbonisation potential and safety issues are included to provide an overall, comprehensive picture of the various natural gas applications.
Chapter 8 gives the c*onclusions and recommendations*.

2 Selection of the most relevant routes in 2020-2030

2.1 Introduction

The objective of Chapter 2 is to define the fuel transport segment combinations and to define the fuel chains and the reference vehicles, ships and planes.

From a societal point of view, the following selection criteria can be used:
- safety of production, distribution and usage of the fuel;
- Well-To-Wheel/propellor energy efficiency and GHG emissions of fossil and renewable fuel chains;
- energy security: availability of fuels or feed stock from different location across the world;
- low pollutant emissions or even zero emissions for example for urban application;
- costs for realization of refueling infrastructure.

The energy efficiency of a driveline is one of the most important parameter which determines fuel costs and GHG emissions. The GHG emission is furthermore determined by the carbon content of the fuel and by the possible methane emissions.

Pollutant emissions can be minimised for all fuels, just by adding emission control systems. For combustion engines, this is determined by the pollutant emissions legislation. Zero (Tank-To-Wheel) pollutant emissions of the vehicles/ships/planes are only possible with fully electric or hydrogen fuel cell drivelines.

2.2 Selection of fuel and transport mode options

The analysis in Section 2.3 has resulted in a proposal for fuel and transport combinations which will be the bases for further ‘chain’ analysis. These are the Well To Wheel analysis on energy consumption, CO_2 emissions, pollutant emissions and costs. The ‘matrix’ for fuel and transport combination was initially provided by the Ministry of Infrastructure and Environment (I&M), to be evaluated in the project. This led to a proposal for selected options for the steering group meeting and the stakeholders meeting in October 2012. Consequently a final matrix for fuel and transport combinations was established. This is presented in Table 4.
LNG and GTL are realistic options for (non-electric) railway transport, but this is not included in this study because of the relatively low potential in the Netherlands.

Table 4 Selected options for further analysis (Chapter 3) for the application of different fuels

Route Modality	LNG	CNG	GTL	DME	H_2 with and without CO_2 storage	Electricity With and without CO_2 storage	Reference fuel
LD: Passenger car and van	-	X	X	-	X	X	B, D
Rigid truck and city bus	X	X	X	-	X	X	D
Tractor-semi-trailer	X	-	X	X	X	-	D
Inland ships	X	-	X	-	-	-	D
Sea ship Emission Control Area	X	-	-	-	-	-	MGO
Sea ships Deep sea	X	-	-	-	-	-	HFO/MDO
Air plane	X	-	X	-	-	-	Kerosene

2.3 Evaluation of fuel options for the various transport modes

For the owner of the vehicle, ship or plane the main selection criteria for fuel and driveline technology are:

- costs: sum of investment, maintenance and fuel costs including possible subsidies;
- availability in the desired specification or model;
- possibilities to use the vehicle, ship or plane for the meant purpose:
  - fulfil the autonomy or range requirements;
  - vicinity of fuel stations;
  - constrains of authorities or clients for environmental reasons.

The energy density per unit of volume and per unit of mass is important to determine the autonomy of the vehicle, ship or plane. Refer to Figure 1.
It can be seen that conventional liquid fuels and GTL have the highest energy density. The energy densities are also the basis of Figure 2, where for a number of applications the fuel options are given.

Figure 1 Energy density of fuels: volumetric (MJ/dm^3) and mass based (MJ/kg). The latter includes the tank weight

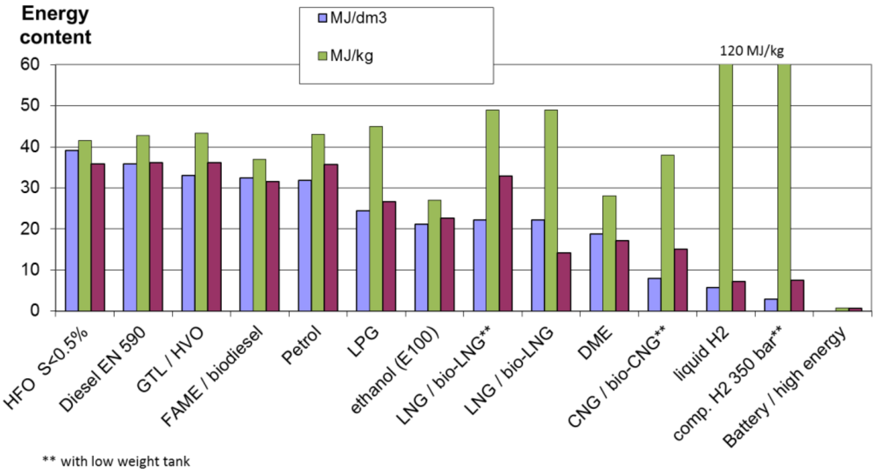
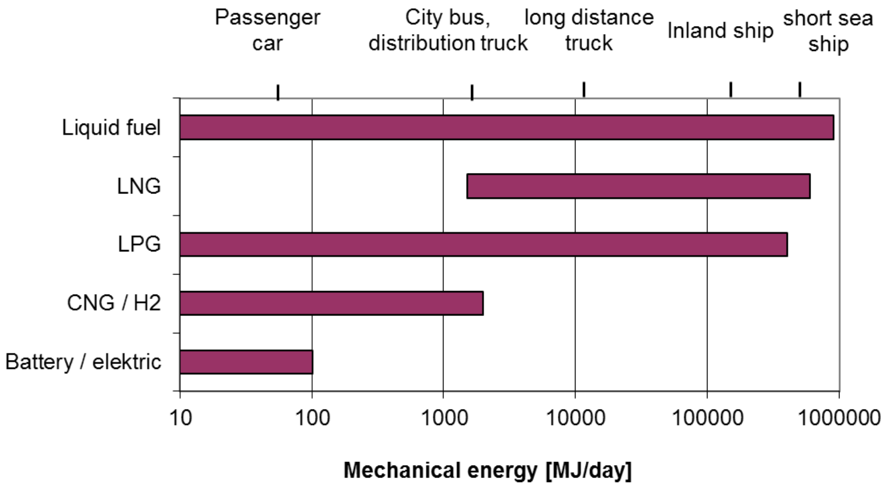


Figure 2 Fuel options for a number of transport applications, based on autonomy requirements and space available for fuel storage



Source: Verbeek, 2010.

Below follows per transport mode a description of fuel options.

2.3.1 Passenger cars and light duty vehicles

In the selection of fuels, the low autonomy vehicles are grouped together, and the long-haul truck remains as the single high-autonomy vehicle. For the latter only liquid fuels are considered, while the low-autonomy vehicles have a wide range of possible energy carriers: diesel, petrol, GTL, CNG, electricity, and hydrogen. This selection is applied in most of the low autonomy vehicles: passenger cars, vans, buses and rigid trucks.

The usage of passenger cars determine the balance between the fixed costs and the cost per kilometre. There is a main distinction in Dutch passenger cars: business use, typically diesel-fuelled, and family or private use. This distinction appears in the annual mileage, total mileage, and the fraction of the total distance on the motorway. The latter affect the fuel consumption, as urban driving is associated with more dynamics and higher fuel consumption for a conventional combustion engine. The annual mileage and total mileage used here are based on the average diesel and petrol vehicle, which are the typical choice for business and family use, respectively. The business use is 30,000 km annual mileage with 400,000 km total mileage. The family use corresponds to 15,000 and 200,000 km.

Light commercial vehicles, or vans, come in three weight classes for emission legislation. The heaviest class: 1,750-3,500 kg is the most common, in particular for use by small companies and utility companies. The fuel consumption depends very much on the use: heavy payload or equipment will increase the urban fuel consumption, and on the motorway the large frontal area may lead to diesel fuel consumptions above 10 litre per 100 km. For the reference vehicle is considered a less extreme fuel consumption, partly by its use and partly by the CO_2 regulations for vans taking effect.

Most of the alternative drivelines and fuels are viable for passenger cars and vans. The notable exception is LNG fuel. Both the small tank size and relief evaporation risks makes LNG less viable for small vehicles with limited daily mileage.

Table 5 Overview suitability of fuels for cars and vans

Fuel	Possible applications	Preferred applications
Diesel	All cars + vans, reference fuel	**All cars + vans**
Petrol	All cars + vans, reference fuel	**All cars**
GTL	All cars + vans, captive fleets may be necessary for refuelling	**Captive fleets**
CNG	All applications with driving range < 300 km/day	**Vans, taxi**$^{1)}$
LNG	No options due to too small LNG tank size and possible tank evaporation losses	-
Electricity	All applications with driving range < 125 km/day	**Vans, taxi**$^{1)}$
Hydrogen	All applications with driving range < 300 km/day	**Vans, taxi**$^{1)}$
DME	Probably no development and production of cars. Also not recommended to limit the number of fuel options per vehicle category	-

1) Increased benefit of low emissions and improved pay back of investment with vehicles with a high distance driven per day in urban areas.

2.3.2 Heavy duty vehicles

Heavy duty vehicles are all vehicles over 3.5 ton gross vehicle weight. Two of the three selected reference vehicles are low autonomy vehicles: the bus which drives mainly urban and rural, and the rigid truck for distribution. The tractor-trailer combination is the long-haulage truck with a high autonomy.

The standard bus is 12 meters long and weighs, including passengers, about 14.5 ton, given an average passenger occupancy. A rigid truck is in the same range, however, the engine is typically more powerful (designed for the 19-20 ton gross vehicle weight, and motorway usage), and the usage is different as well. The amount of motorway driving for trucks is higher than of any other vehicle: distribution trucks have 15% urban driving, long-haul trucks 5%.
Long-haul truck may carry 40–50 ton. In practice the average, except for international transport and transport of building materials is around 30.5 ton. The rated engine power is about 300 kW. The tractor-trailer combination is the most common heavy-goods vehicle in the Netherlands. The tractor-trailer combination has become more common in recent years, but their prevalence is still much below the tractor-trailer combination.

An overview of the fuel options and applications for trucks and buses is presented in Table 6. The main options for 2020-2030 are in bold.
Hydrogen fuel cell and DME drivelines are expected to play at best a modest role in the 2020-2030 timeframe, since only a few (DME only one) OEMs are currently working on it (on a project basis).

GTL has been a drop-in fuel, replacing diesel. With the introduction of Euro VI this is no longer possible. The vehicle has to be tested for GTL fuel separately. Very likely the fuel also has to be tuned for the use of GTL. However, unlike LNG the vehicle technology can be identical to that of the diesel variant.

Alternative drivelines, such as hybridisation, electric, and hydrogen fuel cell technology are expected only in the case of a limited autonomy and engine power. Typically urban usage will yield more gains for such technology. In a sense the long-haul truck is the only vehicle were, due to the power demand and autonomy, deviations from the traditional driveline is not expected.
For heavy transport LNG is the only viable alternative to diesel and GTL.

Table 6 **Overview suitability of fuels for trucks and buses**

Fuel	Possible applications	Preferred applications
Diesel	Reference fuel	**All trucks and buses**
GTL	All trucks and buses (Extension of type approval probably necessary)	**Buses, municipal vehicles and others**1)
CNG	Applications with driving range < 250 km/day	**City buses, city and regional distribution**1) 2)
LNG	Applications with driving range < 500 km/day	**City, regional and national distribution**1) 2)
Electricity	Applications with driving range < 125 km/day This may gradually increase to 250 km/day in 2025	**Light (city) trucks, municipal vehicles, city buses**1) 2)
Hydrogen	Applications driving range < 300 km/day (Timely) development and production of trucks very uncertain. Also not recommended to limit the number of fuel options per vehicle category	City buses and city and regional distribution1) 2)
DME	Possibly no series production of trucks. Reason to pursue is mainly WTW efficiency and costs with sustainable DME production	Trucks/national distribution1)

1) Captive fleets as long as no fully developed infrastructure for refuelling.

2) During transition period) improved pay back of investment with a high distance driven per day.

2.3.3 Inland ships

An overview of the fuel options and possible applications is presented in Table 7.

Table 7 **Overview suitability of fuels for inland ships (recommended fuel options in bold)**

Fuel	Possible applications	Preferred applications
Diesel	Reference fuel	**All ships**
GTL	All inland ships	**All ships**
CNG	Applications with quite low autonomy requirements	Canal cruise, light ferries
LNG	All ships with good packaging options of LNG tanks	**Many (standard) ships (including ferries)**
Electricity	Applications with low autonomy requirements	Canal cruise, light ferries, applications with high power ratio
Hydrogen	Applications with quite low autonomy requirements and high power ratio	Canal cruise, light ferries, port ships, applications with high power ratio
DME	Probably no engines available. Also not recommended to limit the number of fuel options per transport category. Safety issue with (heavy) liquid gas	-

In order to focus product development and production costs of driveline and of infrastructure it is recommended to limit the number of fuel options as much as possible. Therefore the following fuel options are recommended:

- Diesel, GTL and LNG: Applications which require high autonomy. Generally larger ships on high average power.
- CNG for lower autonomy and max power requirements.
- Electric or hydrogen (with fuel cells): quite small ships with high power ratio and/or dynamic operation (< 75 kW max).

For the more detailed Well-To-Wheel analysis for this study, only LNG and GTL will be included. The reference fuel is diesel EN 590 with 10 ppm S.

2.3.4 Sea ships

An overview of the fuel options and possible applications is presented in Table 8.

Table 8 Overview suitability of fuels for sea ships (recommended fuel options in bold)

Fuel	Possible applications	Preferred applications
HFO S < 0.5%	Reference fuel world wide. S < 0.5% for 2020 and later	**All ships/high autonomy**
HFO S < 3.5%	In combination with SO_x scrubber such that equivalent SO_x emissions is achieved as with 0.5% S fuel	All ships/high autonomy
MDO S < 0.5%		All ships/high autonomy
MGO	Reference fuel for Emission Control Area's (0.1% S)	All ships/high autonomy
Diesel EN 590	All ships but not recommended, because value of EN 590 is higher in other applications	-
GTL	All ships but not recommended, because value is higher in other applications	-
CNG	autonomy too low	-
LNG	All ships with good packaging options for LNG tanks	**Most (standard) ships (including ferries)**
Electricity	Autonomy too low	-
Hydrogen	Autonomy too low	-
DME	Not recommended in order to limit the number of fuel options	-

The following options are recommended for further analysis.
Fuels for Emission Control Area's:
- MGO: Marine Gas Oil, the reference fuel;
- LNG: Liquefied Natural Gas;
- GTL.

Instead of MGO also HFO in combination with a SO_x scrubber can be used.
Fuels for deep sea application:
- HFO or MDO with max 0.5% sulphur (required for 2020 and later);
- LNG.

2.3.5 Air planes

An overview of the fuel options and possible applications is presented in Table 9. The use of LNG for air planes is still at the stage of desktop studies. LNG tanks are expected to be placed in the cargo space, to allow for a small surface area and spherical shapes, for pressure containment and limited heat exchange. Similar as for ships, some cargo space must be sacrificed for LNG tanks. This will adversely affect the fuel consumption per ton cargo.

Table 9 Overview suitability of fuels for air planes (recommended fuel options in bold)

Fuel	Possible applications	Preferred applications
Kerosene	All applications	**All applications**
GTL - kerosene	All applications	**All applications**
CNG	Autonomy too small, impossible packaging	-
LNG	A conventional tank within the cargo space might be possible for continental transport Intercontinental transport requires the development and certification of light weight cryogenic fuel tanks which fit within the wings. This will likely not be in time for the 2020-2030 period	-
Petrol	For very small planes with piston engines	Small planes
Diesel	For very small planes with piston engines	Small planes
Electricity	Autonomy too small	-
Hydrogen	Autonomy too small	-
DME	Autonomy too small	-

LNG and GTL or 'synthetic kerosene' will be included in the matrix for the fuel transport mode options.

2.4 Reference vehicles and ships for the various transport modes

2.4.1 Reference light duty vehicles

Three reference vehicles are defined: two passenger cars and one van type. Refer to Table 10. The reference engine types are included in Table 11.

Table 10 Reference light duty vehicle

Type	Application	Reference weight	Reference max. power	Reference usage
Passenger car, business driver	Daily commuting, 30,000 km/y	1,350 kg	80 kW	50% motorway 30% rural 20% urban
Passenger car	Daily commuting, 15,000 km/y	1,350 kg	80 kW	40% motorway 30% rural 30% urban
Light Commercial Vehicle, 3.5 ton	Small business, 40,000 km/y	2.2 ton	120 kW	50% motorway 30% rural 20% urban

Table 11 Reference (2020 technology, Euro VI)

Fuel	Engine technology	Application
Petrol	Spark ignition, lambda = 1, 3-way catalyst	Daily commuting
Diesel, GTL	Compression ignition, EGR, DPF, SCR	Daily commuting + business
CNG	Spark ignition, lambda = 1, 3-way catalyst	Daily commuting + business

2.4.2 Reference heavy duty vehicles

Three reference HD vehicles are defined: two trucks and one city bus. Refer to Table 12. The reference engine types are included in Table 13.

For the rigid truck and the bus, a diesel parallel hybrid driveline is chosen as the reference. Also for CNG and LNG this driveline is chosen. The hybrid driveline for these vehicles is seen as a logical step forward, also towards a fully electric or H_2 fuel cell driveline. The comparison is judged to be more valuable if state of the drivelines are compared for all fuels. The tractor-trailer has a conventional drivetrain, because in a long haulage application, a hybrid electric driveline would not contribute to better fuel efficiency.

Table 12 **Reference trucks and buses**

Type	Application	Reference weight	Reference Power	Reference usage
Rigid truck, box type, 18 ton, 2 axles	Regional distribution 60,000 km/y	15 ton	220 kW	Motorway + 15% urban
Tractor - trailer, box type, 5 axles, 50 ton	Long haul 120,000 km/y	30.5 ton	330 kW	Motorway + 5% urban
City bus, 18 ton, 12 m	Urban line, 60,000 km/y	15 ton	200 kW	Urban bus cycle

Table 13 **Reference engine technology (2020 or Euro VI)**

Fuel	Engine technology	Application
Diesel, GTL	CI, conventional combustion, EGR, DPF, SCR	All
CNG	Lambda = 1, 3-way catalyst	Regional distribution + bus
LNG	Lambda = 1, 3-way catalyst	National distribution, long haulage
LNG dual fuel	20% Diesel plus 80% NG (energy content)	National distribution, long haulage
LNG diesel pilot	<5% Diesel plus >95% NG (energy content)	National distribution, long haulage

2.4.3 Reference inland ship

In Verbeek (2011) a reference inland ship was defined together with the industry. This ship with a width of 11.45 m can sail to for example Ludwigshafen or Basel. Some more characteristics are given in Table 14. The details on engine power and energy consumption are included in Section 2.4.5. The following gas engine options are compared to the standard diesel operation (also refer to Table 15):

- dual fuel with 80% gas, 20% EN 590 low sulphur fuel;
- diesel pilot with 98% gas and 2% diesel (pilot) injection;
- spark ignition 100% gas engines in diesel-electric configuration.

Table 14 **Reference inland ship**

Type	Application	Water displacement	Reference max. power	Reference fuel
110 m x 11.45 m CCR4	Rotterdam-Ludwigshafen (bunkering in R'dam)	2,865 ton	1,125 kW 1,300 rpm	Diesel EN 590 S < 10 ppm

Table 15 Reference inland ship technology, CCR4

Fuel	Engine/driveline technology
Diesel, GTL	CI, conventional combustion, SCR
LNG dual fuel	80% gas injection or mixing with inlet air plus 20% diesel injection for ignition of the gas
LNG diesel pilot	98% gas injection or mixing and 2% diesel injection for ignition
LNG, 100% gas	Spark Ignition engines in diesel-electric configuration. Relatively small gas engines are generator sets. Number of engines in operation is dependent on required propulsion power

2.4.4 Reference sea ships

Three reference sea ships are defined. They are all container ships. One is for short sea application and two for deep sea, inter-continental transport. Refer to Table 16.

Table 16 Reference sea ship

Type	Application	Water displacement	Reference max. power	Reference fuel
Container feeder 800 TEU Tier III, short sea/North sea ship	Several places - 20 days autonomy required (50% of autonomy with diesel)	14,560 ton	8,400 kW 500 rpm	> 2015: MGO S < 0.10%
Container feeder 5,500 TEU Tier II, world-wide operation	60 days autonomy	85,624 ton	30 MW	> 2020: HFO or MDO S < 0.50%
Container feeder 15,000 TEU Tier II, world-wide operation	60 days autonomy	237,770 ton	65 MW	> 2020: HFO or MDO S < 0.50%

The following gas engine options are compared to the standard diesel operation (also refer to Table 15):

Short sea ship (800 TEU)

- MGO with max 0.1% sulphur (reference);
- Dual fuel with 90% gas, 10% MGO;
- Diesel pilot with 98% gas and 2% MGO.

An alternative for MGO would be the use of HFO (or MDO) in combination with a SO_x scrubber. The number of SO_x srubbers currently fitted is very low, even though in ECA's low SO_x would be required starting in 2015. The number of installations could accelerate (till 2015), but this is uncertain.

Deep sea ship (5,500 TEU):

- HFO with max 0.5% sulphur (reference);
- Diesel pilot with 99% gas and 1% MGO.

Deep sea ship (15,000 TEU):
- HFO with max 0.5% sulphur (reference);
- Diesel pilot with 98% gas and 2% MGO;
- Dual fuel with 90% gas, 10% HFO (< 0.5% S).

2.4.5 Power and operational characteristics of ships

An overview of the design and operation assumptions for the propulsion power are included in Table 17. The specifications for the inland ship and the short sea ship are based on Verbeek (2011). For the 5,500 and 18,000 TEU ships, ships from Maersk are taken as an example.

Table 17 **Power and operational characteristics of reference ships**

	Max speed (at 80% MCR)	Cruise speed	Max. power	(Average) propulsion power
	Knots	Knots	MW	MW
Inland ship	7 (upstream)	7	1.1	0.9
Short sea ship	20	17	8.4	4
Deep sea 5,500 TEU	20	20	30	24
Deep sea 18,000 TEU	23	19	65	29

LNG tank size

The required LNG tank size is dependent on required autonomy of the ship, but it is also dependent on the fuel usage strategy of the ship owner.
For example for deep sea ships it can be decided for economic reasons to sail on HFO outside the Emission Control Area and to sail on LNG inside the Emission Control Area. In that case, it can be decided to only install LNG tank capacity for the ECA parts of the trip. The installed dual-fuel or pilot diesel engines have the flexibility to either run on (mainly) LNG or HFO. For this projection, the LNG tank size is suitable for the entire trip autonomy. Taking into account the world-wide 0.5% sulphur limit, it seems logical to be prepared to carry enough LNG for the entire trip.

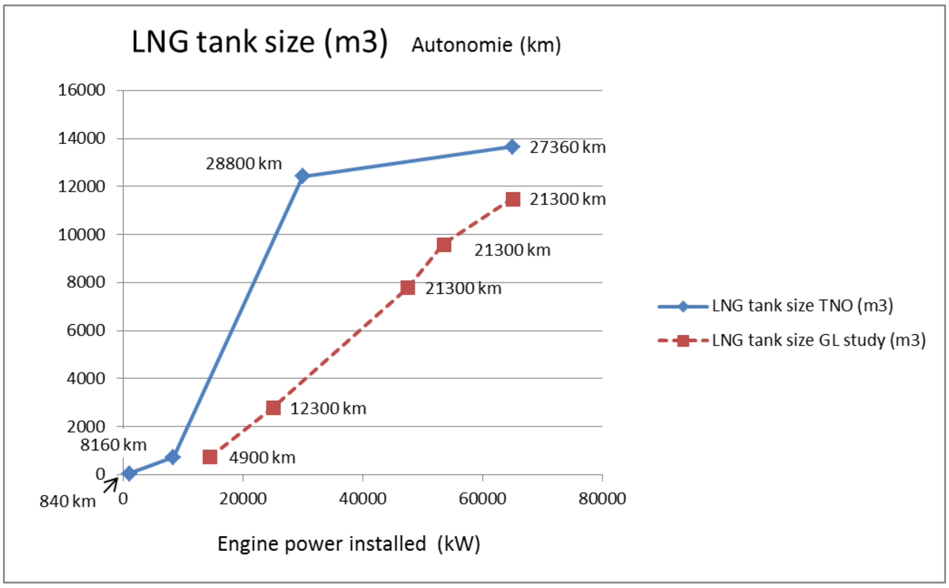
The required tank size is calculated based on the assumed autonomy in days, the average propulsion power (24 hours per day) and the engine efficiency. This led to the tank sizes as presented in the Table 18.

Table 18 **LNG tank size and autonomy of reference ships**

	Inland ship 208	Short sea ship 800 TEU	Sea ship 5,500 TEU	Sea ship 18,000 TEU
Power installed (kW)	1,125	8,400	30,000	65,000
Mechanical energy (kWh/km)	69	131	648	833
LNG tank size TNO (m^3)	42	729	12,428	13,662
Autonomie (km)	840	8,160	28,800	27,360

The results of the projected autonomy are compared to those of a Germanischer Loydd-MAN study (GL-MAN 2012). The results are presented in Figure 3 below. This shows that the autonomies in kilometer of the current study are somewhat larger than those of the GL-MAN study. The tank size to meet the autonomy requirements is quite dependent on the sailing speed.

Figure 3 **Comparison of LNG tanks size from this study (blue) and from GL-MAN (2012)**



It is assumed that the LNG tanks are actually taking up space in for example the middle section of the ship, where normally containers can be placed. The LNG thus lead to reduced cargo space. Per ship, the number of containers is calculated that cannot be stored anymore due to the space of the LNG tanks. It is hereby assumed that 75% of the space is effectively used to store liquid natural gas. This calculation leads to a cargo space loss of about 1% for the inland ship and 3 to 8% for the sea ships. The much more favourable number for the inland ship is related to the much shorter autonomy (5 days rather than 20-60 days) and the low velocity leading to a relatively low energy consumption.

The actual cargo loss factor and related fuel efficiency penalty are dependent on many factors, such as:

- The type of ship: container or bulk.
- Whether the cargo is limited by space or by weight.
- Whether the ship is generally fully loaded or only partially loaded.
- The type of LNG tank which is used. (Light weight) atmospheric membrane tanks take up less space and can be packaged more favourably.
- The already mentioned fuel usage strategy: it can be decided to use HFO (or MDO) outside ECA's.
- Ship design: for a new ship it can be decided to increase the size slightly and maintain the full cargo capacity. A lower fuel penalty may then be possible.

Also for diesel ships there are space requirements, especially if some fuel flexibility needs to be maintained. This is space required for a SO_x scrubber and a (larger) SCR $deNO_x$ catalyst.
A full study regarding the effect of space requirements depending on ship type, is outside the scope of this study. Taking into account all uncertainties,

for the energy efficiency calculation the following cargo loss factors are assumed for LNG:
- inland ship: 1%;
- sea ships: 2%.

2.5 Upstream: from production to the user

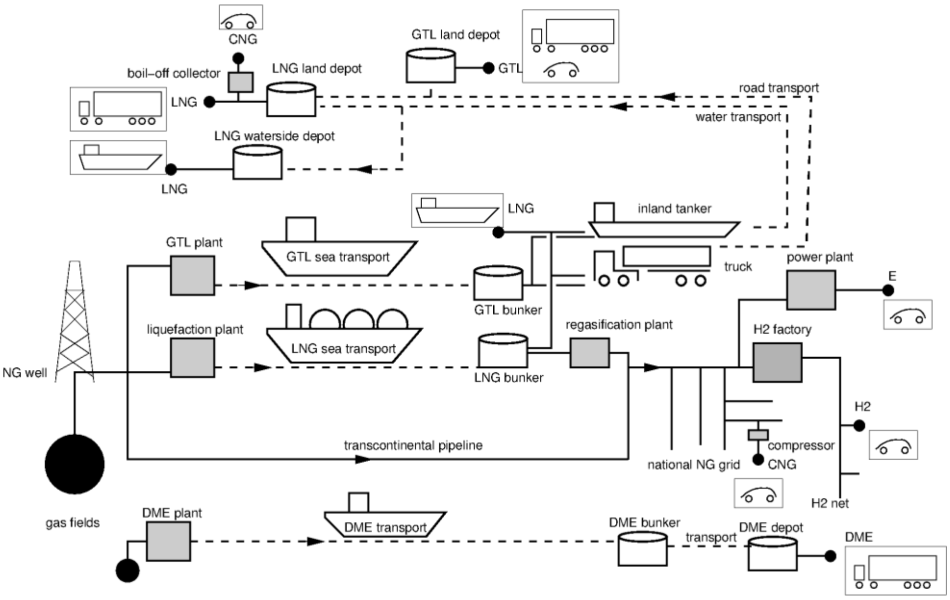
2.5.1 Different fossil routes

This paragraph focuses on the different fossil routes to make transport fuels, see Table 19 and Figure 4. Diesel, marine gasoil (MGO), heavy fuel oil (HFO) and kerosene are the reference fuels; all made from crude oil. Liquefied natural gas (LNG) and gas to liquid fuels (GTL) are both made from natural gas and exported to the Netherlands. Natural gas, imported by pipeline from Norway or the Russian Federation are key sources for compressed natural gas (CNG). CNG is compressed at the gas stations. It is also possible to use the imported gas for the production of hydrogen (H_2) and electricity. LNG is an additional source for the production of CNG, H_2 and electricity. Finally natural gas can be used to produce dimethyl ether (DME), an LPG like fuel. This latter route is possibly attractive to convert natural gas from remote gas fields prior to transport in liquid form to the Netherlands.

Table 19 Transport fuels and source

Transport fuels	Source
Diesel, MGO, HFO, Kerosene	Oil route (using standard JRC data)
LNG, GTL	Qatar (12% of the proven reserves of natural gas and largest LNG and GTL exporter in the world)
CNG, H_2, Electricity	Natural gas originating from: – Norway and the Russian Federation 50%/50% – LNG GATE terminal in Rotterdam and Dutch gas pipeline distribution network
DME	South America (small remote gas fields)

Figure 4 Schematic overview of natural gas based fuel routes



2.5.2 Steps in oil route

The reference fuels in this report are all made from (fossil) crude oil. The first step in the route from well to wheel is oil exploration. On land or at sea the oil is pumped out of the oil field, cleaned and transported, mostly by pipeline, to a local storage. The energy needed for the oil exploration is often locally produced because of the remote location of most oil fields.
There are different types of crude oil, classified from heavy to light, and with different sulfur contents ranging from low to high. On many locations not only the oil is pumped up, but also associated natural gas and water. This associated gas can be flared or vented, both causing additional CO_2 eq. emissions. Alternatively the associated gas can be transported and marketed or applied for local electricity production. Furthermore the natural gas can be pumped back into the oil field to maintain the pressure in the oil field.
At some of the sites where natural gas is explored, some crude oil is produced in the form of so called gas condensate. This condensate is easier to transport than gas and is used as a feedstock in refineries or chemical plants.
However, gas condensate is excluded from the reference fuel route because crude oil is by far the main feedstock for the production of transportation fuels.

From the local storage the crude oil must be transported to a refinery.
The dominant way of transport is by pipeline to a harbor with oil storage facilities, where part of the oil may be used by local refineries. From the harbor the oil is exported with large oil tankers to European harbors with oil storage tanks and local refineries (for instance in Rotterdam). If the oil is refined in a (local) refinery, for instance the Middle East, oil products for the European market have to be transported to Europe by oil tankers. Currently, most oil products used on the European market are (still) produced from crude oil in European refineries. There is, however, a growing unbalance between the refinery output mix (i.e. the spectrum of different fuel types produced) and the demand mix for oil products, for the European market. This unbalance between refinery output mix and demand mix results in Europe increasingly importing diesel and exporting gasoline.

The different reference fuels, distinguished in the current study, are all produced in a refineries:

- petrol;
- kerosene;
- road diesel;
- inland ships diesel;
- marine gasoil (MGO)[3] (0.1% S[4]);
- marine diesel oil (MDO) (< 0.5% S per 1-1-2020);
- marine heavy fuel oil (HFO of MFO) (< 0.5% S per 1-1-2020);
- marine heavy fuel oil (max. 3.5% S, used with onboard desulphurization).

The final distribution to the trucks and cars takes mostly place at a public gas station. Some of the large transport companies and bus companies have their own on site fuelling stations. The distribution of oil products to fuelling stations for the road transport sector takes place with tank trucks that are loaded at regional oil distribution stations. The regional distribution stations

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[3] MGO and MDO are not always separated in statistics and called gasoil or diesel oil. MGO looks like road diesel and is used in diesel engines with high rotation (above 1,000 RPM). MDO can contain a certain percentage of residual oils and is used in diesel engines with al medium or low rotations (300-1,000 RPM).

[4] Used in sulfur controlled areas (SECA) like the North Sea per 1-1-2015 and in harbors.

are supplied by (inland) ships. In addition, some distribution stations are located near refineries and are supplied by pipelines.

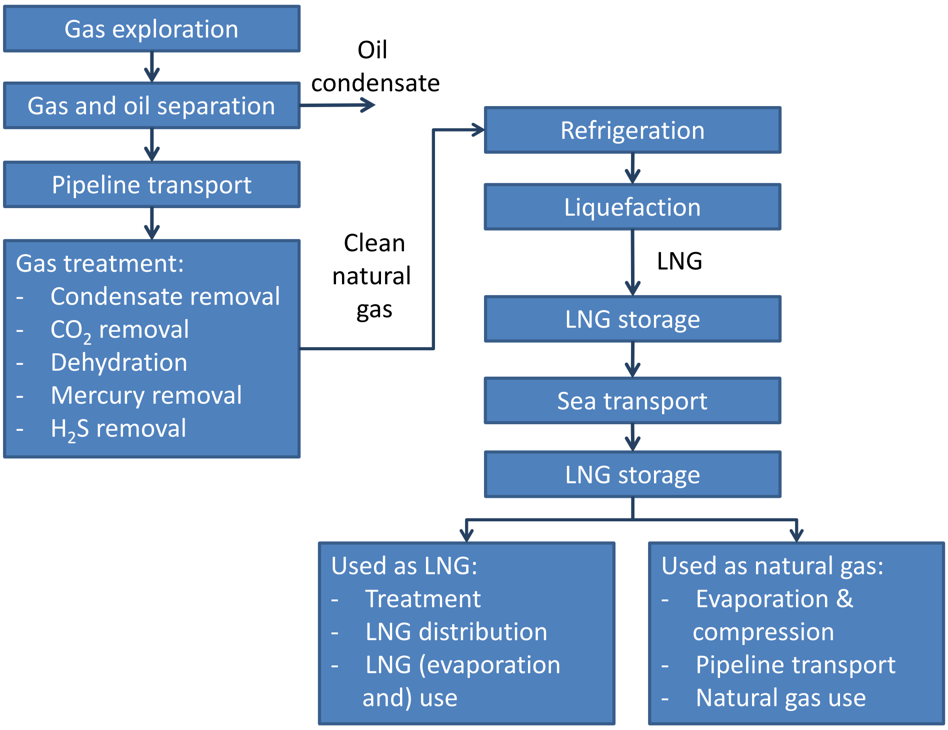
Transport of kerosene to Schiphol takes place by underground pipelines from Rotterdam and Amsterdam. About 75% of the planes is fuelled by the underground pipeline system, while the remaining 25% of the planes is fuelled via tank trucks. Before 1999 the kerosene was transported to Schiphol with 15 inland ships each day.
Supply of MGO, MDO, and HFO to ships is mainly carried out by bunker ships that are loaded from storage tanks. A lot of small companies are involved in the bunkering of ships.

2.5.3 Steps in the gas route (LNG)

In 2011, 30.5% of the global export of natural gas was in the form of LNG and the remainder was exported by pipeline. The main LNG exporting countries, covering some 81% of the global export in 2011, include: Russian Federation (5%), Trinidad and Tobago (7%), Algeria (6%), Nigeria (8%), Qatar (25%), Australia (9%), Indonesia (11%), and Malaysia (10%). Norway, the only Western European LNG producer, had a market share of 2%.

After the exploration, cleaning, and transport by pipeline, the gas is cooled in stages until it is liquefied, see Figure 5. The final temperature is below -162°C. At this temperature methane, the main component of natural gas, condensates from gas into liquid. LNG may also contain nitrogen, ethane, propane and other hydrocarbons. The liquefying of natural gas consumes much energy.

Figure 5 **A typical LNG route**



The LNG is mostly stored at a harbor location and subsequently transported by a LNG carrier to the importing country. During the sea transport the LNG is kept at its low temperature by the evaporation (boil-off) of gas above the storage tanks. The evaporation process consumes energy and thereby cools the tanks. The boil-off gas is used for the propulsion of the LNG carrier.

At the importing country the LNG is pumped from the ship into on land storage tanks. If the LNG is used for the local natural gas network is has to be evaporated (by adding heat) and subsequently compressed to the regulated transport pressure. It is important that the LNG gas properties meet the quality ranges of the gas transport net.
The LNG can also be used (in an engine) in its liquid form. The LNG has to meet the quality specifications (just like for the natural gas in its gaseous form in the pipeline network). If this is not the case a treatment step has to be applied (HIT, 2011). Next, the LNG can be transported by short sea tanker vessels or inland tanker vessels to LNG distribution stations. Subsequently, the LNG can be further distributed with tank trucks to gas stations or companies with a large LNG fleet. Trucks, busses, and cars can tank LNG at the gas station. The distribution of LNG to LNG fuelled ships takes mainly place with LNG bunker tankers. If necessary it is possible to fill an LNG fuelled ship with a tank truck. If the number of LNG fuelled inland ships per day is limited, it is possible that the vessels dock at the quay and directly tank from the local on shore LNG storage facility.

An important issue is the leakage of LNG from the storage tanks, which occurs if no LNG is used and temperature rises over time. Storage tanks in vehicles are designed for a certain pressure raise. But if no LNG is used it is possible that after about 10 days a truck has to vent natural gas directly in the atmosphere (Rolande, 2012; Westport, 2013). But also lower ‘hold times’ are reported, for instance a week in a Tiax study (2012). The evaporation of the LNG in the tank costs energy and lowers the tank temperature. So only a small part of the LNG is directly emitted to the atmosphere, with methane as a major greenhouse gas. It is also possible to use a flare when the pressure becomes too high and venting of gas is required (the burning of methane to CO_2 lowers the CO_2 eq. of the emission). For trucks this is at this moment not the main option. It should be mentioned that also damage of the LNG tank insulation or repair and maintenance activities can cause unforeseen additional methane emissions.

2.5.4 Steps in the gas to liquid route (GTL)

If natural gas is produced and there is no local market for the gas, there are three main options available. The first is to export it by pipeline, the second is to export it in the form of LNG and the third option is to convert it in a large chemical plant into a liquid fuel or chemical feedstock. This last option is called gas to liquid (GTL). The largest GTL plant, producing about 6-7 mln ton of liquid product per year, has been built by Shell in Qatar (investment costs 18–19 bln $) and started its first production in 2011.

The first part of the GTL route is similar to the LNG route described above, but the liquefaction plant is replaced by a GTL plant. The liquid product, that does not need to be cooled, is exported with oil tankers. The GTL fuels can be directly distributed as a final product (diesel, kerosene or lubrication oil) to the end users. Alternatively it is possible to blend the GTL fuels with fossil oil products to improve the quality.

2.5.5 Steps in the gas to Dimethyl Ether route (DME)

It is also possible to use natural gas to make DME (CH_3-O-CH_3), an LPG like fuel. DME might be an interesting alternative to the increasing use of natural gas as a source of transport fuels. DME received a lot of attention in the '90s, because it is a fuel with low polluting emission levels in cars and trucks. However, the relative air quality advantage gradually decreased with the development of cleaner engines and after treatment technologies, also allowing to apply conventional fuels in a cleaner way. In the development of biofuels, DME is one of the many routes.

In the synthesis of DME from natural gas, the intermediates in the production route are synthesis gas (mixture of H_2 and CO) and methanol. In 2009 a 80,000 ton DME promotion plant with methanol as feedstock started production in Japan (Itochu, 2009). The DME of this demonstration plant can be used in boilers, furnaces, power plants (including fuel cells), automobiles (as diesel substitute) as well as chemical feedstock. The most common use of DME is as an aerosol propellant (in spray cans).

The route of DME production is almost the same as for GTL. Instead of the GTL production plant there is a DME plant. The production of DME (CH_3-O-CH_3) is expected to be attractive at a relatively small scale. Therefore in this project the DME plants are assumed to be located at small remote gas fields in Southern America. Because DME is a gas, DME-liquid has to be transported and distributed under pressure. DME can be used directly in vehicles, but can also be mixed with LPG. In this report only the option of DME as a new fuel for tractor-semi-trailer is investigated. Those vehicles are currently running on diesel and not on LPG. So, to implement this in practice a dedicated DME heavy engines has to be developed and produced. Also a distribution structure at gas stations for DME has to be set up. A third factor might be the safety of the DME distribution with tank trucks and at gas stations. This is not part of this project but, based on its properties, the same kind of problems with DME can be expected as with LNG (VROM, 2005).

In Sweden a first pilot BioDME plant was inaugurated on Sept 9, 2010, in Piteå. Based on gasification of black liquor residue from the pulp and paper industry about 4 ton of Bio-DME is produced per day. The DME is delivered to 4 gas station and 10 Volvo trucks are running on this fuel[5].

2.5.6 Steps in the gas route (CNG)

The extraction of gas normally requires only a small amount of energy because the underground gas is already under pressure. After separation of the liquid components in the gas, drying, and cleaning, the gas is transported by a pipeline. Depending on the gas pressure in the reservoir compressors for gas transport may be needed at the extraction location. In addition, during the transport by pipeline every 100 to 150 km a compressor station is required (Marcogaz, 2012).

According to BP (BP, 2012)[6] 1% of the proved reserve of natural gas is located in Norway (enough for 20.4 years at the 2011 rate of production) and 21.4% is located in the Russian Federation (enough for 73.5 years at the current production level). Also Turkmenistan has a large amount of the proven reserves:11.7%. The biggest reserves in the middle east are located in Iran (15.9%) and Qatar (12.0%). As the reference pipeline gas route for the

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[5] http://www.chemrec.se/.

[6] The annual BP publication is mainly based on convention natural gas reserves.

calculations in the current study we assume a 50% sourcing of gas from Norway and a 50% sourcing of gas from the Russian Federation.

A lot of natural gas is stored in underground gas storages or in the form of LNG to cope with seasonal fluctuations, for example related to fluctuations in heating demand. In contrast, the demand of the transport sector does not fluctuate that much, making storage a less important step in the gas route.

The largest Dutch gas field in Slochteren has a relative low combustion value. Therefore the largest distribution network in the Netherlands to consumers, buildings and industry, uses this G-gas. Often foreign gas imported in the Netherlands has a higher combustion value than G-gas. Therefore, when the imported gas arrives in the Netherlands, it might be necessary to mix it with some nitrogen to lower the combustion value to the value of Groningen gas (G-gas). For large industrial consumers and power plants there is a separate H-gas network in the Netherlands for gas with a higher combustion value. Offshore gas fields in the Netherlands deliver gas for the H-gas network.

Because most gas stations are near the G-gas network, G-gas will most likely be the main source for CNG (compressed natural gas) in the Netherlands.
The G-gas is compressed with electric compressors to 200 bar at the gas station and subsequently stored locally. When a truck or car arrives to fuel, the CNG tank of the vehicle is filled with stored gas and gas compressed during the time the vehicle stays at the station (fast filling).
If the vehicle to be fuelled stays at a secured location, then alternatively it is possible to fill the tanks during the night. This is called slow filling and not assumed in the CNG baseline. The compression of the gas is an important energy consuming post in the CNG route. Also the leakage of methane is an issue here.

2.6 Scenario for the safety assessment

To make a safety assessment of the use of LNG as a transport fuel (see Chapter 6) a picture for a fully rolled out LNG infrastructure is needed. In this paragraph such a picture, based on a high penetration scenario in trucks and ships, is drawn and transport volumes and distances are calculated.

2.6.1 High penetration scenario for 2025

A specific large scale distribution plan for LNG in the Netherlands was not yet available at the start of the study. In parallel, the Dutch LNG platform (www.nationaallngplatform.nl) is working on a plan for the LNG infrastructure, but their first draft was not in time to include in the calculations for the current study. Therefore an independent LNG infrastructure development scenario is developed in this study with the aim of providing a reasonable data input for the safety analyses. In order to derive a clear picture of the potential safety risks involved a high LNG penetration scenario, which could be realized in 2025 (or later), is assumed in this study. Assumptions regarding this scenario are documented below. Please note that the scenario is not based on any concept or information of the national or local government, apart from the starting point of the gas volume to be distributed.

2.6.2 Total use of LNG in transport 2.5 mln ton

By mid-2012 there were two different targets discussed for the expected future volume of LNG to be distributed in the Netherlands:

1. The '50-50-500' target in 2015 of the LNG platform. This target is based on a market penetration in 2015 of at least 50 inland vessels, 50 sea vessels and 500 trucks all fuelling LNG. For example, the companies Gasunie and Vopak are planning a small LNG station for LNG transshipments to tank lorries near the big LNG Gate terminal in Rotterdam. Also a quay is planned for LNG distribution with inland ships.
2. The second LNG target is based on the estimated potential for LNG on the Dutch market of 2 to 3 mln ton in 2030, in connection to in the 'Green Deal Rijn en Wadden'. According to the Green Deal information the environmental benefits of this scenario include an annual CO_2 reduction of 1 mln ton, as well as a reduction in particulate matter emissions of 400-600 ton. Recently the LNG platform announced that they envisioned a less ambitious scenario for the LNG rollout to be more realistic, at least for 2025. To this end a preliminary potential of LNG for the transport sector was projected at about 1 to 1.25 mln ton in 2025. The LNG platform explained that, in addition to the LNG use for transport in the Netherlands, LNG landed at the GATE terminal could be further transported to the Nordic countries.

As basis for the safety analysis, described elsewhere in the current report we focus on **2.5 mln ton LNG in 2025**. Like the LNG platform we don't expect that this kind of volume will be reached in 2025. However, this scenario is more representative for a fully rolled out LNG distribution structure and therefore better indicates the safety issues, related to large scale LNG use in transport. If the volume is lower also the number of inland intermediate LNG storage points for distribution to inland ships and fuels stations is probably lower, whereas the distribution distances per kg LNG are larger. So a lower volume does not lead to a proportional effect on safety.

As the properties of LNG depend on its composition two main figures for the calculations had to be assumed: a density of 0.45 ton/m^3 (range 0.43-0.47) and a lower combustion value of 46 GJ/ton. Based on these starting points the 2.5 mln ton equals 5.55 mln m^3 LNG/year and 115 mln GJ/year (= 115 PJ/year).

2.6.3 The 2.5 mln ton scenario per type of vehicle

The 2.5 mln ton needs to be divided over three transport modes: inland navigation, road transport (assumed is truck transport), and sea shipping. The distribution scenario resulting is shown in Table 20.

Inland shipping (0.55 mln ton LNG)

In 2010 about 40 PJ fuel was used by inland shipping. Transport within the Netherlands consumes about 6.6 PJ while the rest is used as 'bunker fuel' for international transport with inland ships. Of this bunker fuel about 7.5 PJ is also consumed on Dutch waterways. It is important to take into account that the volume of Inland shipping is growing (Verdonk, 2012). Fuel consumption will reach about 50 PJ in 2025. This consumption can be broken down in 17.5 PJ consumed on Dutch waterways and 32.5 PJ used on foreign waterways.

The consumption of foreign ships is not exactly known, but estimated in the current study at 30%. In the LNG scenario it is estimated that about 50%[7] of inland navigation by Dutch and foreign vessels uses LNG as fuel. To reach this target, not only the largest vessels, but also smaller ships will have to be converted to LNG.

Trucks (1.0 mln ton LNG)

The fuel consumption on Dutch roads by trucks and tractor-trailers in 2010 is estimated at about 97 PJ. The main part of this fuel is consumed by the 145,000 Dutch trucks and tractor-trailers. But in addition foreign trucks tank in the Netherlands and, not included, Dutch trucks also drive in foreign countries. The overall fuel consumption is expected to grow in the reference scenario to about 113 PJ in 2025 (Verdonk, 2012). In the LNG scenario it is expected that LNG is preferentially used in large trucks and tractors with a high annual mileage (90,000 km/y). A 40% market penetration of LNG fuelling trucks can be reached[8] based on a number of 40,000 high mileage trucks and tractors.

Sea ships (0.95 mln ton LNG)

A substantial percentage of the global demand for heavy bunker fuel (HFO) of sea ships is supplied in the Netherlands (mainly Rotterdam). The strong position of Rotterdam as a favorable port for ships to bunker results from the large size of the harbor but also from the presence of refineries and oil storage capacity. These conditions results in a good market to buy bunker oil.
Bunker fuels sold in Rotterdam are not only produced by the local refineries, but also imported from other countries. Although the strong market position in bunker fuels of Rotterdam does not automatically imply a similar position in the LNG bunker market for sea ships it could be an indication that the potential LNG market is much bigger than 2.5 mln ton, as taken as the overall 2025 starting point for LNG distribution in the Netherlands in the current study.

In our scenario for 2.5 mln ton LNG in 2025 we focus on MGO/MDO to be substituted by LNG. MGO is mostly used by short sea ships. Because these vessels sail a lot in SECA areas, they are an interesting market for LNG.
Our LNG scenario assumes 250 vessels bunkering LNG by 2025, resulting in a substitution of 29% of the MGO by LNG. In this scenario it is assumed that the ships bunker only 33% of their fuel in the Netherlands. The LNG tank capacity is a critical factor. In the limited examples of LNG powered vessels available so far bunkering intervals amount between one and two weeks. So an inland vessel might return to the Netherlands in this timeframe, whereas a sea going vessel usually will not return in this timeframe.
As a final step in our LNG scenario, the LNG amount remaining is assumed to be used by deep sea ships. These ships are much larger than short sea ships. For example 110 deep sea ships, assumed to bunker one out of the three times in the Netherlands, already result in an LNG demand of 0,64 mln ton. However, as already mentioned above, the potential LNG market can be much larger.

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[7] This figure is based on the starting point of 3,400 Dutch inland vessels in 2025. About 27% have been built after 2015 (assuming 85% LNG fuelled) while 31% is renovated (assuming renovation of existing ships every 20 years and 80% of the vessels to be LNG fuelled after renovation). This results in 50% of the Dutch vessels to be LNG fuelled in 2025; foreign ships are assumed to reach also 50% LNG fuelling.

[8] For pragmatic reasons, it is assumed in the calculation that the amount of LNG tanked by Dutch trucks in foreign countries is the same as the amount of LNG tanked by foreign truck in the Netherlands.

Resulting demand

The resulting demand is depicted in Table 20. The first columns show some key characteristics of the different vehicles. The fourth column gives the number of vehicles. In the next columns, the LNG penetration is shown relative to the total fuel consumption in 2025 of the vehicle category used in reference scenario. Based on the demand scenario, summarized in Table 20 an infrastructure and distribution structure scenario is developed for the different modes of transportation.

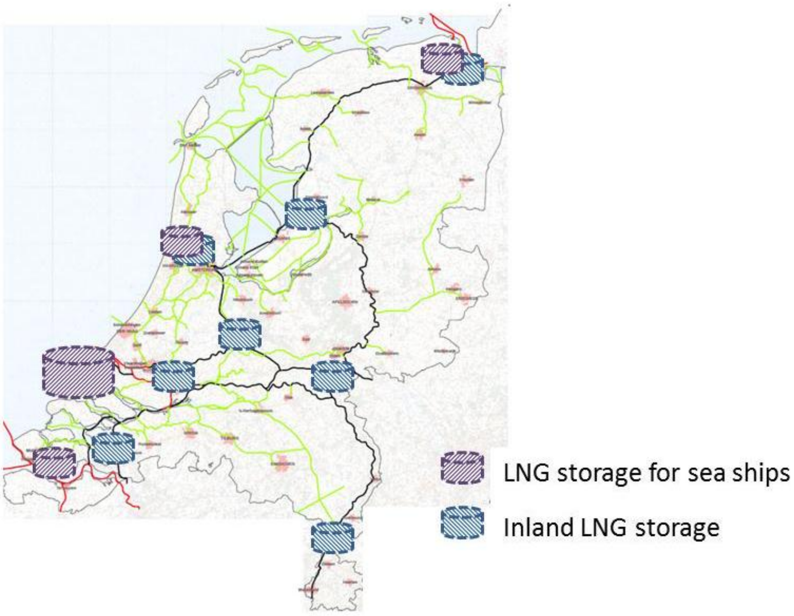
Table 20 Possible scenario for 2.5 mln ton of LNG in transport in the Netherlands

Vehicle	kW per vehicle or ship	Ton LNG/y per vehicle or ship	GJ/y per vehicle or ship	Number of vehicles or ships	Penetration in fuel sold	Mln ton LNG/y in NL
Inland ship large	1,125	400	18	800	50%	0.32
Inland ship small	500	110	5	800	50%	0.09
Foreign inland ship						0.15
Subtotal inland ships						0.55
Short sea ships	8,400	3,750	173	250	29%	0.31
Deep sea ships	22,000	17,391	800,000	110	4%	0.64
Truck/trailer	220-330	25	1147	40,000	40%	1.00
Total						2.50

2.6.4 Distribution structure

After shipping with LNG carriers to the Netherlands and landing at the Maasvlakte, the LNG can be further distributed to other sea harbors like for instance Amsterdam, Vlissingen, Moerdijk/Dordrecht and the Eemshaven.
In the various harbors LNG can be further distributed from local storage facilities with tanker ships to the different LNG fueled sea ships. With inland tanker ships it can also be distributed to inland LNG storage locations. It is assumed that all inland shipping for LNG distribution takes place on the main shipping routes, that are also used for distributing other liquid fuels (Werkgroep Basisnet water, 2008). Inland ships fueled by LNG can be tanked with inland tanker ships or alternatively at a quay near the inland storage facilities. From the different storage facilities, that are all situated along waterways, the LNG can be further distributed with tanker trucks to gas stations for road transport. If necessary, a tanker truck can also be used to fill an inland ship fueled by LNG.

Figure 6 Possible scenario for a distribution structure used for calculation purposes



To make a calculation of distribution distances and LNG volumes to be transported a geographical distribution structure is needed. The structure shown in Figure 6 is used in the current study. This figure of the waterways was taken from another publication (Werkgroep Basisnet water, 2008). The locations chosen are not based on any investment plan, and only applied for volume calculation purposes.

In January 2013 the EU published a directive proposal on the deployment of alternative fuels infrastructure (EC, 2013). This proposal includes the obligation to ensure that there are publicly accessible LNG refueling point in all maritime ports of Trans-European Transport (TEN-T) Core by 2020 (Rotterdam, Amsterdam, Vlissingen, Terneuzen) and in all inland ports of TEN-T in 2025 (Utrecht, Arnhem, Enschede) (European Commission, 2011). Information about this directive came in after the calculations for the distribution structure were made. There are two main differences with the possible scenario. We did not put in Enschede because it is a less important waterway and there is no safety area check around the canals to Enschede (Werkgroep Basisnet water, 2008). Secondly, although the Eemshaven is not mentioned in TEN-T, we put it in because it is a sea harbor and two core inland waterway start in the Eems Dollard area.

2.6.5 Distribution vehicles

LNG transport and distribution can take place by: sea ships (LNG carriers), inland vessels or trucks.

LNG carriers

Up to September 2012, approximately 358 LNG carriers have been build and 76 are ordered. The mean storage capacity of an LNG Carrier is 150,000 m^3. The current capacity range varies from 70,000 to 270,000 m^3 (www.shipbuildinghistory.com, 2012). The LNG carriers are used to transport LNG from LNG exporting countries to LNG importing countries. For an additional use of the 2.5 mln ton of LNG, the starting point of the current study, per year about 37 extra LNG carriers have to deliver to the Netherlands.

LNG distribution tankers

There is less information available on LNG distribution tankers, to further distribute the imported LNG. VEKA is developing tankers for LNG distribution. They sail for 25% on the boil off of the LNG and can also use their own LNG. In addition they can sail on diesel (VEKA, 2012). LNG distribution vessels developed by VEKA include:

- short sea LNG tankers with two tanks and a capacity of 2 * 2,000 m^3 (= 1,800 ton LNG/tanker);
- inland navigation tanker with 4 tanks and a capacity of 4 * 200 m^3 (= 360 ton LNG/tanker).

For the distribution of large quantities of LNG, related to the 2.5 mln ton, the short sea LNG tanker described above is not efficient, due to its limited capacity. Therefore in this picture for the current study a tanker with a capacity of 7,200 ton is assumed (4 * 4,000 m^3 will be used).

Tank trucks

The LNG for the transport sector is transported in the Netherlands by inland vessels or by tank trucks. A tank truck contains 40 m^3 of LNG (18 ton) and can drive 100,000 km/year (range 60,000-120,000 km/year). If we estimate the mean distribution distance for an LNG truck at 70 km, it follows that one truck can distribute about 13,000 ton/year (GIIGNL, 2009).

2.6.6 Distribution volumes

Based on the sample of the distribution structure and the volume distribution of the LNG scenario as a next step we can calculate the amount of distribution movements and kilometers to be spanned. Every distribution movement also requires time for loading and unloading of the vehicle. In the calculations it is assumed that all LNG distribution starts at the LNG storage at the Maasvlakte. It is also possible that other countries deliver LNG to the Netherlands with short sea ships or inland ships. However, this alternative will likely have a minor impact on the safety calculations. In addition our scenario does not take into account the distribution of LNG for transport purposes from Rotterdam to Belgium and Germany.

Table 21 Possible scenario for the distribution of 2.5 mln ton of LNG in transport in 2025

	Storage stations	Size vehicle m^3 LNG	Number of movements/y	LNG (mln ton/y)	Loaded (km/y)	Loaded (km/day)
Delivery with a LNG carrier	1	150,000	37	2.50		
Distribution with sea ships	4	16,000	229	1.65	24,285	67
Distribution with inland ships	8	800	2,071	0.75	234,010	641
Distribution with tank trucks	100-200	40	55,429	1.00	3,880,055	10,630

Based on the above data, as well as additional assumptions, an estimation can be made of the number of distribution vehicles: 2 short sea ships, 20-30 inland ships and 80-120 tank trucks. In addition 15 to 20 tank ships are needed to deliver in sea harbors LNG fuel to 10 sea ships and 130 inland ships per day. About 30 ships can fuel themselves near inland storage stations. It is possible that at on these locations also tanker ships are available, because it usually complicated to dock a ship at the quay when it's not sailing in the direction where the fuelling facilities are on the starboard (right) side.

If the number of times for refueling is set on 30 for ships and 140 for trucks and trailers the amount of fuel for each refueling can be calculated, see Table 22. The table also gives a range, depending on the power range of the different vehicles. Table 22 shows that the amount of LNG for refueling of a deep sea ship can be substantial higher than the mean value. The range indicated for trucks is not based on refueling every two days, but based on extended tanks allowing fuelling only once a week.

Table 22 **Amount of fuel per refueling**

Vehicle	LNG (mean) (ton)	LNG (mean) (m^3)	Range (m^3)
Inland ship large	13	30	20-50
Inland ship small	2	8	6-20
Short sea ships	125	278	150-600
Deep sea ships	580	1,288	600-4,500
Truck/trailer	0.18	0.40	0.4-1.2

In the field of Trucks, for example, Volvo is developing a truck driving on 25% diesel and 75% LNG with a range of 500 to 1,000 km, depending on the circumstances. If a truck is driving 100,000 km per year. This truck needs to frequent the LNG station about 133 times a year (or once every 2 to 3 days). Each time it will tank about 200 kg LNG. Other truck producers like Mercedes, Iveco and Scania, which develop 100% LNG trucks might have different tank volumes, but this example is taken for the calculation.

2.6.7 Detailed figures

In Table 23 and Table 24 some detailed results are given. Also, to make it possible to do the safety calculations in more detail, the assumed locations are given. The locations are only chosen for the purpose of the safety calculations.

Table 23 **Details of assumed delivery structure: delivery (mln ton/y)**

Assumed location	Inland shipping	For road transport	Sea ships	Total	
Eemshaven	0.02	0.08	0.01	0.11	4%
Zwolle	0.02	0.15		0.16	6%
Nijmegen	0.02	0.15		0.17	7%
Utrecht	0.02	0.14		0.16	6%
Amsterdam	0.09	0.10	0.15	0.35	14%
Maasvlakte	0.13		0.72	0.85	34%
Moerdijk	0.20	0.19	0.02	0.41	16%
Bergen op Zoom	0.04	0.08		0.12	5%
Vlissingen			0.05	0.05	2%
Maasbracht	0.02	0.11		0.13	5%
Total	0.55	1.00	0.95	2.50	

Table 24 **Details of assumed delivery structure: amount of vehicles per year**

Assumed location	LNG delivery sea ship	LNG delivery inland ship	Refueling of sea ships	Refueling of inland ships	Tank trucks
Eemshaven	15		36	2,088	1,963
Zwolle		452	0	1,691	1,589
Nijmegen		468	0	1,943	1,827
Utrecht		447	0	1,713	1,610
Amsterdam	71		576	9,628	9,049
Maasvlakte	-229		2,736	13,898	13,062
Moerdijk	120	-1,730	72	21,154	19,882
Bergen op Zoom		341	0	4,746	4,461
Vlissingen	24	-341	180	0	0
Maasbracht		363	0	2,114	1,987
Totaal	0	0	3,600	58,976	55,429

After landing at the Maasvlakte it is assumed that LNG is delivered to other harbors by short sea shipping tankers. With those tankers also fuel is distributed to an inland location around Moerdijk/Dordrecht, where most of the inland ships can be refueled. Delivery in sea harbors (including Moerdijk) takes place by ships. Delivery to inland ships in other harbors could possibly take place at the quay.

Tank trucks deliver LNG to public gas stations or LNG stations at locations of transport companies (industrial areas). According to the Netherlands Petroleum Industry Association VNPI about 45% of the diesel sold in the Netherlands is directly delivered to the own storage of transport companies or is sold via special gas stations for trucks. This amount of diesel is also used for transport in foreign countries.
The number of (public and private) gas stations needed for 40,000 trucks is estimated to be between 100 and 200. This may be compared to the existing situation in which about 2,000 of the 4,200 current public gas stations, also have a deliver place for at least two diesel trucks at the same time (Bovag, 2009).

Whith each truck refueling every 2 to 3 days and 40,000 trucks, this involves about 15,000 station visits a day. If a stations delivers to 100 trucks a day about 150 LNG stations are needed. Every station sells about 15 ton LNG/day and every 1½ day a LNG delivery tank truck has to visit the station. In the Netherlands, there are special roads with safety zones and roads for liquid fuels with a 30 m Pool fire Attention Area (in Dutch ‘plasaandachtsgebied’; PAG). Given the number of LNG gas stations, it is not possible to deliver all LNG fuel to the gas stations by roads with safety zones or by roads with a Pool fire Attention Area (Basisnet Werkgroep weg, 2009). This is also the case for fuels like petrol and LPG.

2.7 Cost calculation methodology

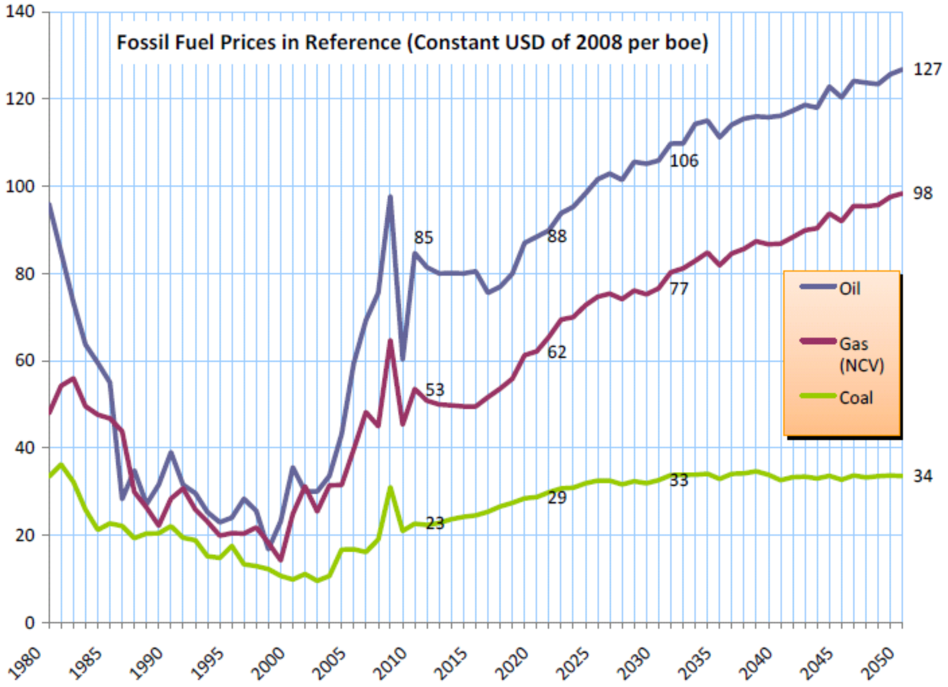
We propose to consider both actual supply costs and market prices for the considered transportation fuels. In this way insight can be given in aspects such as added value per chain link, requirements for subsidies for stimulating alternative, natural gas based transportation fuels and the leeway policy has in e.g. developing taxation regimes.

Commodity market prices

For commodity market prices we propose to start from the values considered in the EU Roadmap 2050 and the EU White Paper for transportation[9]. These studies are the basis for the EU policy for the coming years and can be considered as generally accepted and authoritative within the European policy field. Commodity prices considered in both studies are summarized in Figure 7.

The Reference scenario assumes a relatively high oil price environment compared with previous projections, and similar to projections from the International Energy Agency (IEA), with oil prices of 59 $/barrel in 2005 rising to 106 $/barrel in 2030 and 127 $/barrel in 2050 (in year 2008-dollars).

Figure 7 **Anticipated development of commodity prices in time**



For economic calculations we propose utilizing a linear approach to the illustrated price evolutions.

Commodity price of gas is assumed to remain linked to the crude oil price (see Figure 8). Uncertainty in prices is given as ranging from +30% to -45% for oil and gas.

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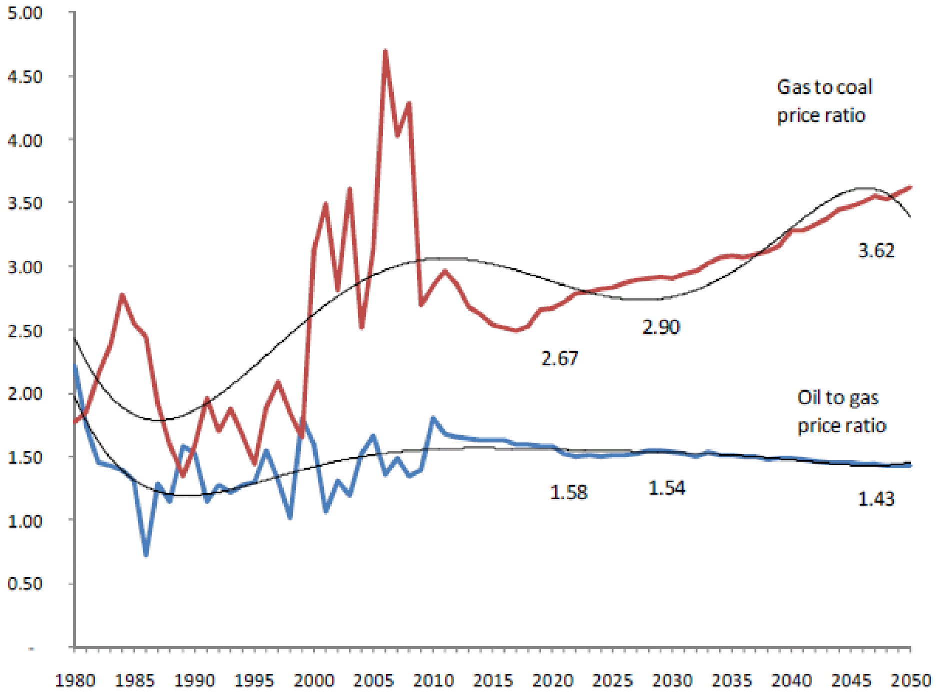
[9] See: www.roadmap2050.eu; http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=SEC:2011:0358:FIN:EN:PDF.

Figure 8 Development in fuel prices, relative to each other



In the Roadmap CO_2 prices are assumed to amount to $ 43 per metric ton in 2015 and to $ 54 in 2030.

Calculating actual specific supply costs

In view of the anticipated developments of commodity prices in time we propose estimating net discounted costs per chain link.

Generic basic assumptions proposed for these calculations are:

- an interest rate of 5% (see IEA levelised costs methodology);
- inflation rate of 2% (see SDE methodology);
- corporation tax rate of 25% (see EU roadmap, SDE methodology);
- exchange rate EUR/USD = 1.3 (see EU roadmap).

Assumptions specific for each chain link concern:

- term for loan;
- depreciation period;
- required return on investment;
- equity share.

Costs for fixed and variable operational costs will also be estimated per chain link. Some first indications of the economic calculation parameters and aspects such as typical scale are given in the following subparagraphs.

2.8 Basic assumptions for production plants

Characteristics

Characterisation of the different upstream production plants has been based on:

- data for existing plants concerning CAPEX, efficiency, scale, location;
- market studies and design studies for supply chains of gas based transportation fuels;
- authoritative desk top studies, e.g. JEC (2007).

Table 25 Primary basic assumptions for considered production plants

	LNG	CNG	GTL	DME	H_2		Power
					No CO_2 seq.	With CO_2 seq.	
Remote gas or pipeline gas	Remote	Remote	Remote	Remote	Pipeline	Pipeline	Pipeline
Typical scale (Mt/a production capacity)	4 (3-8)	2.5 (0.1-2.5)	6 (1-6)	0.6	0.05	0.05	0.3 (gas use)
CAPEX (M€)							
a Gas based plant	900	480	19,000	180	60		
b Shuttle tankers	360	800					
c Receiving station	320						
d No. of tankers	2	5					
e Cargo per tanker (metric ton)							
OPEX							
a Fixed (M€/a)				15	3		
b Feedstock efficiency	93%	94%	70%	70%	75%	70%	
c Transportation distance (km) to NL	6,000-2,0000	1,000-2,000	6,000-20,000	6,000-20,000			

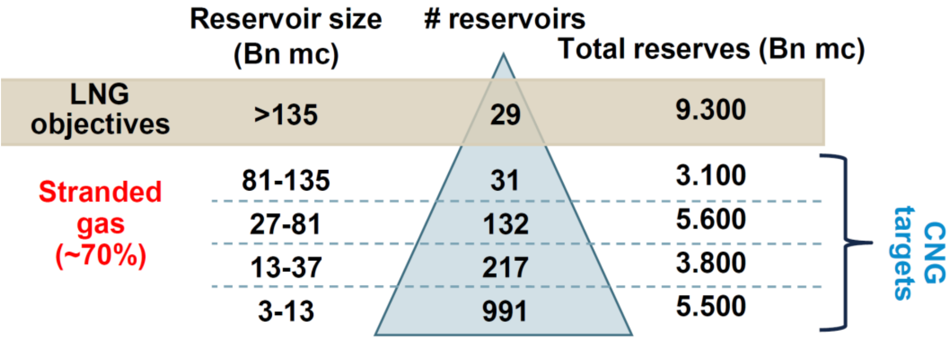
As indicated by Figure 9 and Table 25 typical production capacity of the different considered production processes differ significantly as a function of technology, distance to market and gas reservoir size.

LNG is primarily an option for large reservoirs at long distances from markets. Current LNG initiatives primarily concern world scale ‘trains’ ranging in size from 3 megatons/a to 5 megatons/a of LNG, with exceptionally large trains reaching a production capacity of 8 megatons/a.

GtL was generally seen as an option for smaller reservoirs, but with the recently realized Shell Pearl plant in Qatar (6 megatons of GtL per year), the technology has been significantly scaled up.

CNG is generally considered an option viable for small to medium scale reservoirs at a maximum distance of 1,000–2,000 kilometres from markets. Transports of stranded gas is however still very much a theoretical possibility as so far there no CNG project is operational and no CNG tankers have been build yet.
Methanol and associated DME production is also more suitable for reservoirs of ‘limited’ capacity as world scale methanol plants have a typical size of 1 megaton MeOH/year. However, in view of the higher energy density, transportation distances can be larger compared with CNG.

Figure 9 Indicative illustration of stranded gas reserves per category of reservoir size and most viable monetization option



	Reservoir size (Bn mc)	# reservoirs	Total reserves (Bn mc)	
LNG objectives	>135	29	9.300	
Stranded gas (~70%)	81-135	31	3.100	CNG targets
	27-81	132	5.600	
	13-37	217	3.800	
	3-13	991	5.500	

Regions with relevant stranded gas reserves are shown in Figure 10.

This study focuses on current industrial practice, however a note concerning a new development that may change the structure of supply in the future. Though large scale production facilities are currently the industrial standard, there is also a trend in miniaturization of LNG, methanol and GtL in order to cut flaring emissions of associated gas and monetize associated gas or small scale stranded gas reservoirs. Examples are:

- mini LNG plants in Norway, aimed at supplying LNG for near shore shipping;
- Petrobras mini GtL aimed at cutting flaring of associated gas.

Figure 10 Regions with relevant stranded gas or remote reserves

Economic parameters

For calculating production costs and costs for transportation by shuttle tankers we utilize the following basic assumptions[10]:

- term for loan 20 years;
- depreciation period 20 years;
- required return on investment 10%;
- equity share 25%.

All parameters have been based (or will be based) on publicly available information on real world projects and on information provided orally by experts in the field. Terms for loan and depreciation of loans have a significant length in view of the size of the investments.

2.9 Potential to decarbonize the various routes

Based on publicly available information following possible routes have been identified for decarbonising the considered transportation fuels. Some routes are already mature whilst other are still early in the R&D phase, as indicated by the colouring:

- existing commercial production routes;
- demonstrated production routes;
- desk top.

Table 26 **Renewable alternative processes (decreasing technical probability and/or economic viability from top down)**

LNG	CNG	GTL	DME	H_2	Power
Biomass anaerobic digestion + mini LNG	Anaeribic digestion + compression	HVO from biomass	Biomass gasification + MeOH/DME	Wind and solar power (surplus) + H_2O electrolysis	Wind and solar power
Biomass gasification + mini LNG	Biomass gasification + compression	BTL: biomass gasification + Fischer Tropsch processing		Biomass gasification + H_2 production	Biomass boiler or co-combustion

Biomass digestion and conversion of biogas to CNG is common practice in countries like Sweden and Switzerland. Conversion of biogas into LNG is applied commercially in the USA (and UK?), based on landfill gas.

Hydropower utilization for H_2 production has been in use as a production route for NH_3 since the 1910s. Recently wind power for H_2 production has been introduced on a Norwegian island for providing back up for periods with limited wind.

Production of methanol from CO_2 from geological reservoirs is produced or will be produced in very short term in Iceland near the geothermal power station on Reykjanes peninsula.

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[10] See e.g. http://www.lngworldnews.com/klaipedos-nafta-signs-deal-on-lng-investments-lithuania/; http://www.kbr.com/Newsroom/Publications/technical-papers/LNG-Liquefaction-Not-All-Plants-Are-Created-Equal.pdf.

Production of H_2 and methanol from biomass and waste was demonstrated in the 1980's in Finland and Germany (Berrenrath), utilizing Hoch Temperatur Winkler gasification process. A wood to methanol plant based on this technology is planned to be realized in Sweden.

There are several BTL projects in preparation. A 100,000 ton diesel fuel plant of UPM BioVerno in being built in Lappeenranta (Finland). The production should start in 2014. Secondly a 130,000 tons of biodiesel and naphtha plan of Forest BTL in Kemi (Northern Finland) is expected to start production at the end of 2016.

2.10 Security of supply – general analysis

Security of supply

Factors that enhance the security of supply of natural gas compared to oil include:

- Natural gas imported by the LNG-route comes in addition to the gas imported by pipeline from Russia, thereby lowering the price of piped gas.
- Natural gas/LNG import requires much higher investments compared to oil. For this reason, mostly long term contracts are being made (order of 20 years).

Factors that reduce the security of supply include:

- Gas is supplied to some extent by the same key countries that supply oil. Nevertheless, substitution of oil by gas involves a shift from OPEC to especially Russia.
- More complicated to maintain a strategic stock for gas, compared to oil.
- LNG with a low content of higher hydrocarbons is preferred (as this facilitates a wider application without complicated conditioning steps). For this reason a single or just a few selected suppliers are preferred over a wider portfolio over supplying countries/companies.
- Note the recent booming developments in shale gas production worldwide. Especially the rapidly increasing shale gas production in the USA may become a 'game changer' in the gas world.

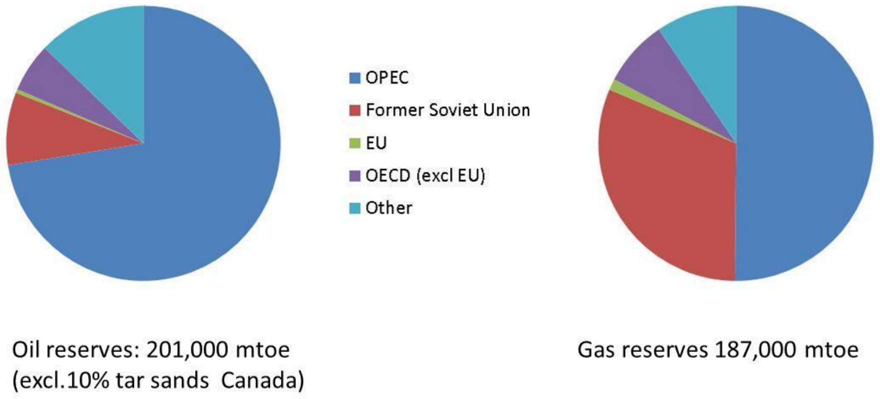
Natural gas only contributes moderately to the overall energy supply:

- A market penetration in the transport sector of 2.5 mln ton LNG, would equal a substitution of about 12.5% of the oil use in the transport sector. The projection of the LNG platform - of about 1 to 1.25 mln ton LNG in 2025 - would only involve a substitution of about 6% of the of the oil use in the transport sector in the Netherlands.

Proven reserves

At the current (2010) rates of production, BP (2011) projects global oil supplies for oil to last for 46 years, compared to 59 years for natural gas. So gas will last longer, compared to oil. The distribution of the *proven* reserves is indicated in Figure 11, clearly showing the key role of the former Soviet Union. Looking at the OECD reserves compared to current consumption are 13.5 year for oil and 14.7 year for gas.
So both for gas and oil the OECD member will be depend on non OECD reserves for their future consumption. It should be stated that BP only gives proven reserves with certain economic restriction related to current production costs and prices.

Figure 11 Comparison of global reserves for oil and gas



Oil reserves: 201,000 mtoe
(excl.10% tar sands Canada)

Gas reserves 187,000 mtoe

Source: BP, 2011.

Unconventional oil and gas

In addition to ‘conventional’ gas and oil, also ‘unconventional’ gas and oil supplies have been estimated. The ‘World Energy Outlook’ by OECD/IEA 2012 presents the overview given here in Table 27. Unconventional oil and gas are more difficult to produce. But the energy use for the production of unconventional gas is lower than for unconventional oil. Moreover, the uncertainties are large, especially regarding the countries with the largest supplies of unconventional reserves.

Table 27 Potential recoverable volumes

1,000 mtoe	Gas conventional	Gas unconventional	Oil conventional	Oil unconventional
E. Europe/Eurasia	130	40	61	82
Middle East	113	11	157	7
Asia Pacific	39	85	19	11
OECD Americas	42	60	43	263
Africa	44	36	43	5
Latin America	29	43	39	75
OECD Europe	22	20	13	4
Total	416	295	375	447

Note: World demand in 2011: 4.5 mtoe oil and 3.1 mtoe gas.
Source: OECD/IEA, 2012.

Potentially recoverable volumes

Finally ‘Potentially recoverable’ oil and gas can be distinguished (Table 28). ‘Potentially recoverable’ implies that the oil and gas supplies are present, but in a location, concentration, and/or configuration that complicates recovery at current state of technology and costs. For example gas hydrates that can be found on the seafloor, and in ocean and deep lake sediments. Although (very) complicated to win at present, on the long term these supplies could be important because of the very large volumes involved. However, the complete use of these supplies, and the resulting CO_2 emissions, would have extreme implications on global warming!

Table 28 **Potentially recoverable oil and gas**

Energy source	Current (1,000 Mtoe)	Recoverable (1,000 Mtoe)	Current demand	Years current	Years recoverable
Oil	231	822	4.5	52	184
Gas	187	822	3.1	61	269
Gas incl. 50% hydrates	187	3,041	3.1	61	'994'
Total oil and gas	419	1,644	7.5	56	218
Total oil and gas incl. 50% hydrates	419	3,863	7.5	56	'513'

The supplies of potentially recoverable oil and gas as listed in Table 28, would meet the current demand for about 200 years. However, uncertainties on availability and recoverability are very large.

2.11 Conclusions

The analysis of Chapter 2 consists of the following parts:
- the establishment of the matrix of transport segment and fuel options;
- the definition of reference vehicles, ships and plane (Tank-To-Wheel);
- the definition of the fuel production and transport routes with in particular also the LNG distribution infrastructure in the Netherlands (Well-To-Tank).

Regarding the transport segments and fuels matrix, the following is concluded:
- The choice of fuel options per transport segment is primarily based on the required autonomy (storage capacity) and secondary on fuel quality and availability of technology.
- The energy storage capacity of battery-electric and hydrogen is not sufficient for all (main stream) shipping segments. Battery-electric is also not suitable for larger trucks.
- GTL is not used for sea shipping, because the premium quality is not relevant in that segment.
- DME is only used for long-distance trucks, because product development is currently only pursued for that category.
- LNG for planes is pursued as an option, although the availability (and certification) of technology by 2025 is highly unlikely.

With respect to the reference vehicles, ships and plane, the following is concluded:
- The reference vehicles, ships and plane are based on technology sold in 2020.
- A large number of reference vehicles and ships and drive lines for alternative fuels are defined. Refer to Table 29.
- For passenger cars and vans, the energy consumption of drivelines with combustion engine is based on the CO_2 legislation including correction for real-world driving.
- For the rigid truck and city bus, the improvement in efficiency is based on planned introduction of EU CO_2 monitoring and certification. The hybrid-electric driveline is chosen as reference for diesel, natural gas and GTL fuel.

Table 29 Overview total number of driveline configuration for reference vehicles, ships and plane

	Diesel + petrol (kerosene)	Natural gas	GTL	Hydrogen + electricity
Passenger car and van	5	3	3	5
HD vehicles	5	8	3	5
Inland ship	1	3	1	0
Sea ships	3	5	0	0
Air plane	1	1	1	0

Fuel production and transport (Well-To-Tank):

- Natural gas can be supplied to the Netherlands by different supply and conversion routes:
  - in gaseous form, by pipeline (Russia, Norway);
  - in the form of LNG, transported by ship;
  - converted to GTL, transported by ship;
  - in the form of DME, transported by ship.
- Substitution of diesel (or petrol) by natural gas can be achieved by the following key fuel options:
  - compressed natural gas (CNG);
  - liquefied natural gas (LNG);
  - hydrogen;
  - electricity.
- Before rolling-out one of the fuel options to a larger scale, it is important to evaluate the rather different implications for each option in terms of: CO_2 reduction, costs, decarbonisation potential, and safety.
- A fully rolled-out LNG infrastructure in the Netherlands would involve a LNG volume in the order of 2.5 mln ton LNG. It is unlikely that this volume will be reached by 2025 already. Nevertheless it is important to base the safety assessment on a full scale situation, rather than on an introductory phase with lower volumes, as in this latter case the frequencies of LNG distribution movements and volumes are not representative for the full scale situation.
- A high penetration scenario with a volume of 2.5 mln ton LNG, would involve a substitution in the order of 10-15% of the conventional diesel fuel in the transport sector. Therefore the impact on security of supply is modest. Nevertheless a wider spread of suppliers improves security of supply, especially because the gas reserves are expected to be somewhat larger than for oil.
- The LNG platform expects a use of LNG for the transport sector of 1 to 1.25 mln ton in 2025. The LNG platform explained that, in addition to the LNG use for transport in the Netherlands, LNG landed at the GATE terminal could be further transported to the Nordic countries.

3 Environmental impacts and cost of vehicles and ships

3.1 Introduction

In this chapter the energy consumption, GHG emissions and pollutant emissions of the vehicles, ships and planes are derived and summarized. It is focussed on the application of a fuel for each transport mode. It deals only with the Tank-To-Wheel (TTW) or tank-to-propeller emissions and energy consumption. The TTW greenhouse gas (GHG) emissions are generally calculated from the fuel energy consumption and the possible methane (CH_4) emissions of the typical engines per transport segment. The CO_2 emissions of the combustion of the fuels is primarily dependent on the hydrogen to carbon ration of the fuel. The higher the H_2 content, the lower the specific CO_2 emissions. The following specific TTW CO_2 emissions are used for the different fuels:

- Electric: 0 CO_2 g/MJ
- H_2: 0 g/MJ
- Natural gas CNG/LNG: 56.1 g/MJ
- Petrol: 72 g/MJ
- GTL: 71.3 g/MJ
- Diesel EN 590: 74.1 g/MJ
- MGO/MDO: 74 g/MJ
- HFO: 77 g/MJ

For the different transport modes, the following is described in this chapter:
A description of and tables with the emission factors for pollutant emissions, GHG emissions and energy consumption. For all road transport this is described in Section 3.2 to 3.4. Ships are included in Section 3.5 (back ground) and Section 3.6 (emission factors), while air planes are covered in Section 3.7.
A description of the additional driveline costs compared to the reference fuel.

3.2 Vehicle emission regulations and targets

The current development of light-duty vehicle is very much driven by CO_2 targets. In the heavy duty vehicles, the Euro VI legislation of pollutant emissions will be a major transition. In 2020 the reference vehicles will likely be in the final phases of Euro VI legislation. In theory, it is meant to yield ‘equal emissions’ for all fuels and technologies. For real world emissions there will be some differences, already in the legislation but also because some technology, such as the three-way catalyst and the diesel particulates filter, is efficient and robust, while other technology requires specialized control and maintenance which can lead to higher ‘real-world’ emissions.

The real-world emission factors are based on the emission model Versit+, underlying the Dutch national emission factors. The emission factors are annually published by the Ministry of Infrastructure and the Environment. Detailed emission factors are regularly updated by CBS (national bureau of statistics). Euro VI emission factors are not the result of emission tests, as yet, but based on the scaling of emission factors of measured vehicles in earlier Euro-classes, e.g. Euro V, taking into account the quality of the legislation and test procedures.

Table 30 **Implementation dates of emission legislation**

Legislation	New models	All sales
Passenger cars 6-I	1 Sep 2014	1 Sept 2015
Vans Euro 6-I	1 Sep 2015	1 Sep 2016
Heavy-Duty Euro VI	31 Dec 2012	31 Dec 2013
Passenger cars 6-II	1 Sept 2017	1 Sept 2018
Vans Euro 6-II	1 Sept 2018	1 Sept 2019

CO_2 emissions of passengers cars is decreasing. In 2015 an average type-approval value of 120 g/km must be met for the new sales. In the Netherlands this value is already reached in 2012. In 2025 the average type approval is 95 g/km. The corresponding real-world emissions are substantially higher: 120 g/km corresponds to 155–160 g/km in real world, 95 g/km to 135–140 g/km. These values are for 30,000 km/year use, with limited urban mileage. For higher urban mileage the real-world values are higher.

Methane slip, the emission of unburned methane from the engine, contributes significantly to the CO_2 equivalent GHG emissions of current dual-fuel and lean burn engines. A few grams of methane per kWh adds 10-15% to the GHG emissions. For three-way catalyst stoichiometric engines the levels of methane slip are typically a factor ten lower. With Euro VI legislation on gas powered vehicles, and ECE legislation on dual fuel, the GHG contributions of methane slip are expected to be small compared with the CO_2 emission. See Table 31.

Table 31 **Methane slip contribution to GHG emissions**

Engine technology Euro-VI or ECE dual fuel regulation (R49)	Methane fraction in CO_2 equivalent GHG emissions
Stoichiometric three-way catalyst	< 0.5%
Pilot injection	1%
Dual fuel 40%	0.5%
Dual fuel 70%	1%

The urban driving is low engine load with high dynamics. Hence technological improvements, such as hybridisation, and drive lines with a more constant efficiency such as electric drive lines and fuel cells, mainly yield the improvements on the urban part of driving. The higher weight, due to batteries, with net increase assumed around 200 kg, will require additional propulsion energy, mainly in urban driving as both the acceleration and braking and the rolling resistance are affected by the weight increase.

Historically the CO_2 emission of heavy-duty engines decreases about 1% a year. This is the value on the ETC test cycle. However, this decrease is not fully realized on the road, due to the increase in engine power, with the same tonnage and usage. The higher engine power leads to a lower engine load and engine efficiency. The engine power of distribution trucks are typically higher than needed, as distribution trucks, unlike long-haul tractor trailers, will seldom reaches the allowed gross vehicle weight.

The weighing over road types of the total usage of all the vehicles depends very much on the usage. These are derived from the numbers of CBS.
The majority of buses are line service operated, urban and regional services.

Table 32 Usage mix on different roads to determine aggregate emission factors

Usage mix	Urban	Rural	Mway
Business car, vans	20%	30%	50%
Family car	30%	30%	40%
Bus	50%	50%	0%
Distribution truck	15%	30%	55%
Long-haul truck	5%	30%	65%

3.3 Emission factors passenger cars and light duty vehicles

All diesel fuelled vehicles are expected to have a diesel particulate filter (DPF) in 2020. The PM emissions, from the exhaust, are expected to be small. The values are typically in the range of a few grams per MJ.

3.3.1 Passenger cars

The energy usage and pollutant emissions of passenger cars are based on the respective values for urban, rural and motorway driving. The main difference between car 1 and 2 (Table 34) is the amount of urban driving in relation to motorway driving. For urban driving, the fuel consumption is determined by the low load drive train efficiency.
All cars are expected to have some form of hybridisation, to achieve a CO_2 emission of about 100 g/km on the test. The reference vehicles are not the compact cars, but the slightly larger and heavier business and family car models, of about 1,350 kg.

The electric driveline, either through the use of batteries, or the use of fuel cell technology, require less energy at the tank level, due to the high driveline efficiency of transforming the stored energy into mechanical power.
Currently a drawback is, that substantial energy is needed for climate control, especially for heating. For cars with combustion engines 'waste heat' for heating is more or less available for free.
For battery electric vehicles, at the moment the first production vehicles are evaluated on the road in several test programs.
Eventually, a 80% efficiency is to be expected for electric vehicles (Carroll et al, 2012). In a field test in the Netherlands with 12 Nissan Leaves over 70,000 km an average energy consumption of 235 Wh/km is reported (Kievit, 2012). This converts to 0.85 MJ/km. For 2020 technology, some improvements in energy efficiency are expected, which leads to: 0.7 to 0.8 MJ/km (Table 34).

Laboratory values of conversion efficiencies for fuel cells can be high. Mansouri and Clay (2012) reports an expectation of fuel cell efficiency of 70%, but this is yet to be demonstrated. For H_2 fuel cell vehicles, data from modeling and also some field test data are available (refer to table below). The data shows a wide range in efficiencies. For 2020, an energy consumption of 1.1 to 1.2 MJ/km is projected. The uncertainty is relatively high.

Table 33 Energy consumption values for H2 passenger cars, data from various reports

Fuel energy consumption		Data type	Reference
kg/100 km	MJ/km		
0.7	0.84	Modelled	JRC, 2008
0.6	0.72	2035 projection	MIT, 2008
1.4	1.68	Test vehicles	NREL, 2012
0.9	1.08	2nd generation vehicles	NREL, 2012

The energy consumption and emission factors for the Well-To-Wheel analysis are presented in Table 34.

Table 34 Emission factors of passenger cars for two different usage profiles

Passenger car 1: diesel, 30,000 km/yr	Unit	Diesel	Petrol	CNG	GTL	H_2	Electricity
Energy efficiency	MJ/km	1.9	2.09	2.09	1.9	1.2	0.8
GHG emissions	CO_2 eq./km	139	150	117	134	0	0
NO_x emissions	g/km	0.12	0.03	0.06	0.12	0	0
PM_{10} emissions	g/km	0.005	0.005	0.005	0.005	0	0

Passenger car 2: petrol, 15,000 km/yr	Unit	Diesel	Petrol	CNG	GTL	H_2	Electricity
Energy efficiency	MJ/km	2	2.2	2.2	2	1.1	0.7
GHG emissions	CO_2 eq./km	146	158	123	141	0	0
NO_x emissions	g/km	0.12	0.04	0.07	0.12	0	0
PM_{10} emissions	g/km	0.005	0.005	0.005	0.005	0	0

3.3.2 Vans

Currently most vans sold are larger vehicles, which are class III: above 1,750 kg. Most of these vehicle are fuelled with diesel. The typical distance a day is limited, and the vehicles are used in a ‘back-to-base’ usage. Hence there are few limitations to use other, low density fuels for such vehicles. The full range of fuels are included in the reference van, except for electric vehicle, as the amount energy and the distance poses some restrictions on the autonomy.
Also in the business cases petrol has been dropped as a viable alternative for commercial use. The emission limits for vans are less strict than for passengers cars, reflected in the higher emissions. The CO_2 legislation is at its earliest stages. The testing procedure is not yet tuned to the usage of light commercial vehicles, such that the gap between type-approval value and real-world CO_2 emission is expected to be large but unknown. Current values reflect a positive effect of upcoming legislation.

Table 35 Emission factors of vans

Van	Unit	Diesel	CNG SI	GTL	H_2
Energy efficiency	MJ/km	2.1	2.31	2.1	1.4
GHG emissions	CO_2 eq./km	154	130	148	0
NO_x emissions	g/km	0.2	0.08	0.2	0
PM_{10} emissions	g/km	0.007	0.007	0.007	0

3.4 Heavy duty vehicles

Heavy duty vehicles are tested as engine. The same engine is used in different applications. The typical range of rated power is from 100 kW to 400 kW. The emission are closely related to the usage and power. An appropriate engine size for the application will prevent circumstances of limited functioning of the emission control. It is expected the Euro VI legislation will cover all possible applications of the engines in transport, from urban buses to long-haulage tractor trailer combinations.

Unlike the passenger cars, hybridisation in heavy duty vehicles will not necessarily bring great benefits. For international transport, it is not expected at all. For buses and distribution trucks hybridisation may be viable. It is considered to be especially attractive for spark ignition engines, because of its larger effect on driveline efficiency with these engine types. In order to maintain a fuels comparison, the diesel hybrid is chosen as the reference for the rigid truck and the city bus. Hybridisation for buses, has been considered a natural choice for years. However, the successful implementations of hybrid technology for trucks and buses, still has to be proven in the market. For this study, it is assumed that the reduction in energy consumption of a hybrid drive train, results in a proportional reduction in the pollutant emissions. This is to be expected since the emissions are regulated on an energy output (g/kWh) basis.

For this study, the reference technology is Euro VI. It is assumed, that the pollutant emission levels of diesel, gas (CNG and LNG) and GTL are the same. Up to Euro V, natural gas and GTL generally have significant lower emissions. For Euro VI however, in addition to the very stringent levels also the test procedure has greatly improved. This most probably secures low real-world emission levels for regular diesel fuel. Also for natural gas and GTL no data is available to demonstrate possible lower real-world emissions than regular diesel fuel.

With Euro VI, the difference between regular diesel fuel and GTL is considered to be small or negligible, due to the advanced, closed loop, emission control systems. The particulates level is extremely low due to the wall-flow particulates filter which will be mounted. Up to Euro V (also for passenger cars up to Euro 5), the NO_x and PM emissions are 10 to 20% lower. Refer to the factsheets report, TNO/CE Delft (2012).
Formally GTL cannot be used as a drop in fuel for Euro VI. This is because of the stringent legislation which includes more extensive on-board diagnosis. These systems may not work properly with GTL. The formal correct application of GTL with Euro VI, is that the engine/truck OEM implements a special calibration for GTL and performs a separate type approval. This may lead to either a lower energy consumption, lower AdBlue consumption or to possibly lower pollutant emissions. Optisation to the lower energy consumption while meeting the Euro VI level is considered the most logical choice, since this will provide the best value to the owner of the vehicle. With Euro V engines, it was demonstrated that a simple recalibration, the energy consumption would be reduced by 4% with pure HVO which has very similar properties as GTL (Nylund, 2011). It is assumed, that with Euro VI an efficiency advantage of 4% can be achieved with GTL.

3.4.1 Rigid, distribution trucks

Two-axle, rigid trucks are commonly used in distribution. The payload of 10 ton is seldom needed in urban and regional distribution. The urban mileage is 15%. The total weight used is 15 ton, of the 20 ton maximal gross vehicle weight. The engines of such vehicles are such that a 25 kW/ton specific power is not uncommon. Therefore, the fuel consumption is higher than for long-haul tractor trailers, where the specific power can be as low as 8 kW/ton.

The reduction of fuel consumption by hybridisation is expected to yield similar reductions in pollutant emissions. The problems with failing after treatment with Euro V technology are not expected for Euro VI technology as the in-service conformity part of Euro VI legislation is expected to cover the different engine loads for hybrid applications.

The spark ignition (SI) engine with three way catalyst is nowadays the vehicle with the lowest pollutant emissions. However, with the introduction of Euro VI, closed-loop SCR and DPF are both expected to be fitted on diesel vehicles, making the emissions a par with current SI engine vehicles.

Electric drive-trains are viable for urban usage. An engine efficiency of below 30% is expected for heavy-duty vehicles in urban usage, while 40% is possible on the motorway. Also hybridisation will achieve part of this gain.
The pollutant emissions are expected to scale with the energy consumption of the combustion engines. Therefore, a lower pollutant emission of hybrid vehicles is expected. This assumption is only valid for Euro VI technology.
For Euro V technology the hybridisation may adversely affect the pollutant emission, in particular the NO_x emissions.

Table 36 Emission factors of rigid truck

Rigid truck	Unit	Diesel, standard	Diesel, hybrid	CNG, SI hybrid	LNG 99%, pilot hybrid	LNG 40%, dual fuel, hybrid	GTL, hybrid	H_2, fuel cell	Electric
Energy efficiency	MJ (primary)/ km	9.4	8.46	9.4	8.46	8.46	8.2	6.8	5.22
GHG emissions	CO_2 (eq.)/ km	688	619	527	476	561	572	0	0
NO_x emissions	g/km	1.1	0.99	0.99	0.99	0.99	0.99	0	0
PM_{10} emissions	g/km	0.012	0.011	0.011	0.011	0.011	0.011	0	0

3.4.2 City bus

City buses are with 14.5 ton total weight quite similar to rigid trucks. However, both the engine size and the usage is very different. Buses make many stops, have a lower rated engine power, and a lower average velocity. The fuel consumption is higher, in case of a 50/50% mix of urban and rural use. The engine loads are typically also higher, effecting a higher particulate matter emission.

Table 37 **Emission factors of city bus**

City bus	Unit	Diesel, standard	Diesel, hybrid	CNG, SI hybrid	LNG, SI hybrid	GTL, hybrid	H_2	Electric
Energy efficiency	MJ (primary)/km	11.4	9.12	10.26	10.26	8.7	7.5	5
GHG emissions	CO_2 (eq.)/km	834	668	576	576	555	0	0
NO_x emissions	g/km	1.1	0.88	0.88	0.88	0.88	0	
PM_{10} emissions	g/km	0.03	0.024	0.024	0.024	0.024	0	0

Very recently The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) issued the final report concerning a range of urban-bus driveline technologies (McKinsey, 2012). This work was initiated by the European Community and some 40 companies and government agencies participated. Their results showed the following numbers for energy consumption for 2020:

Diesel standard	10.9 MJ/km
Diesel (serial) hybrid:	8.8 MJ/km
CNG (non-hybrid)	14.0 MJ/km
H_2 fuel cell:	7.9 MJ/km
Battery electric:	4.7 MJ/km

These values compare well with the values in Table 37. Only the energy consumption of the CNG driveline is considerably higher even after subtracting the benefit of the hybrid driveline of some 25%. The McKinsey study more reflects the current difference between HD diesel and Otto (gas) engines.
In this study, it is assumed that gas engine efficiencies go up substantially and come more in line with the ratios between diesel and Otto efficiencies which is currently seen with ship engines and some passenger car engines.

3.4.3 Tractor-trailer

Tractor-trailers are used for heavier transport over larger distances. A typical tractor-trailer combination weighs 30.5 tons, which is not a full load.
The maximal gross vehicle weight is 40-50 tons. The specific power, i.e., rated power per total weight is more favourable than for distribution trucks. Therefore the engine load on the motorway is 20-40%, which makes efficient use of the available engine power. Hence, despite the double total weight, compared to distribution trucks the fuel consumption is only fractionally higher. This is also due to the limited urban mileage of 5% of the total distance.

Table 38 **Emission factors of tractor-trailer**

Tractor-trailer	Unit	Diesel	LNG, SI	LNG 99%, pilot	LNG 70%, dual fuel	GTL	DME	H_2
Energy efficiency	MJ (fuel)/ km	12.4	13.64	12.4	12.4	11.9	12.5	10
GHG emissions	CO_2 (eq.)/ km	908	765	698	759	838	827	0
NO_x emissions	g/km	1.1	1.1	1.1	1.1	1.1	1.1	0
PM_{10} emissions	g/km	0.013	0.012	0.012	0.012	0.012	0.012	0

3.5 Background energy consumption and emission levels for ships

3.5.1 Energy consumption

The fuel energy consumption is based on the engine efficiency and the propulsion power. For the ships using LNG also a correction factor is applied for the cargo loss due to the size and the less favourable packaging of the LNG tanks.

The engine efficiency is based on Verbeek (2011) and also on some new literature.

Table 39 **Engine efficiencies for different ship types for diesel and natural gas engine**

	Engine efficiency		Source
	Diesel engine	Natural gas engine (diesel pilot, dual fuel, spark ignition)	
Inland ship	43%	42%	Verbeek, 2011
Short sea ship	46%	44%	Verbeek, 2011
Deep sea 5,500 TEU, 30 MW	47%	45%	Internet
Deep sea 18,000 TEU, 65 MW	50%	48% Tier III 50% Tier II	Internet Lauer, 2010

An overview of the design and operation assumptions for the propulsion power are included in Table 18 in Section 2.4.6.

Correction factor for efficiency for loss of cargo space due to LNG tank size

Refer to Section 2.4.5. For the energy efficiency calculation the following average cargo loss factors are assumed:
- inland ship: 1%;
- sea ships: 2%.

For the energy consumption and GHG emission calculations these percentages are added to the nominal energy consumption. So not a penalty on the number of containers but a penalty on the energy consumption.

3.5.2 Emissions

There are no formal emission factors for ship engines. Moreover, the fuel sulphur levels of HFO and MDO will be reduced in the coming decade, because of IMO legislation. This will lead to a strong reduction in emission levels, especially for SO_x and particulates. The emissions legislation, which are non-road Stage IIIB (earlier CCR4) for inland ships and Tier II and Tier III for sea ships, will also be used as a guideline for the pollutant emissions.
The combustion optimisation is generally such that NO_x and particulate emissions are just below the limit values, because that generally leads to the lowest fuel consumption. The method that will be used is the same as used in ship chain analysis report (Verbeek, 2011). Numbers will be updated with newer legislation such as the lower fuel sulphur level for 2020 and later and also numbers for new engine types will be estimated or calculated. In Table 40 an overview is given of the specific method per emission component.

Table 40 Method for determination of emission levels

	Diesel engine	Natural gas engine (diesel pilot, dual fuel, spark ignition)
NO_x	Based on non road (CCR/Stage) and IMO emission legislation and formal statements of compliance of OEMs with specific limits	
Particulates (PM)	Based on CCR/Stage legislation (inland shipping) and literature Sea ships: PM calculation based on empirical formula and fuel sulphur content	
SO_x	Based on calculation with fuel sulphur content	
CH_4	Negligible	Based on literature stationary gas engines

3.5.3 Emissions Inland ship

Diesel engine

For the diesel engines, it is to be expected that the NO_x and particulates emissions are just below the emission limits of the applicable legislation.
For engines installed in 2020, this will likely be non-road Stage IIIB, which comes instead of the earlier planned CCR4 legislation. This is expected to enter into force in 2016/2017.
The precise Stage IIIB emissions legislation is not yet finalized. Numbers that have been proposed are about 1.8 to 2.0 g/kWh for NO_x and 0.025 g/kWh for particulates. These values are close to those of Euro V for trucks. It is generally expected that the NO_x level will be achieved with selective catalytic reduction of NO_x, just like what is generally done for trucks. With this catalytic reduction an aqueous urea solution (also called AdBlue) is injected upstream of the catalyst. The particulate level is expected to be met by combustion optimization.

The expected Stage IIIB limit values and the emission factors for diesel engines are presented in Table 41. SO_2 is not included in this table because since 1 January 2011 it is almost sulfur free with a limit of 10 ppm or 0.001% (fuel quality norm EN 590).

Diesel engine using GTL

GTL stands for Gas To Liquid and is generally used for synthetic diesel fuel produced from natural gas. Sometimes it is also identified by FT or Fischer Tropsch diesel. GTL falls under the Technical Specification TS 15940 (2012) for paraffinic diesel fuels. This specification also applies to HVO (Hydrotreated Vegetable Oil) and BTL (Biomass To Liquid) and CTL (Coal to Liquid).
The paraffinic diesel fuels are known to have excellent properties. The cetane number, which is a measure of the quality of the auto-ignition, is substantially higher than from conventional diesel fuel. GTL has a cetane number of about 75, while conventional diesel fuel has a cetane number around 50. HVO can even have cetane numbers well above 80. High cetane numbers are known to have a positive effect on NO_x and particulate emissions. The higher cetane number leads to a shorter ignition delay after the fuel is injected. This leads to a more gradual combustion with lower NO_x and particulates emissions. In TNO/CE Delft (2008) the results for GTL were compared for a large number of tests which were published. For HD engines the NO_x reduction was in a band width of up to about 20% reduction, with an average of about 10% reduction. The particulate emission reduction was even slightly better with an average of about 15% reduction. Also passenger car diesel engines showed similar reduction percentages with GTL. No specific data was available for inland ship engines, but it is generally expected that also for those engines, the higher cetane number has a similar effect. For both NO_x and particulates emission a 10% lower emission is taken than for regular diesel EN 590 for the inland ship engine. Refer to Table 41.

Table 41 **Emission limit values and emission factors for diesel engines for inland shipping, reference year 2020**

		NO_x	PM
Limit value (CCR 4)	g/kWh	1.8	0.025
Emission factor with EN 590 diesel	g/kWh	1.6	0.025
Emission factor with GTL	g/kWh	1.46	0.022
Emission control technology		SCR deNO_x catalyst	Combustion optimisation

Natural gas engines

Three types of natural gas engines are proposed for inland shipping:
1. Dual-fuel gas engine with about 20% diesel fuel.
2. Pilot injection gas engine without 1-2% diesel fuel.
3. Spark-ignition lean-burn gas engine.

For the first two, diesel fuel is used to initiate the combustion of the gas. The emission factors of the dual-fuel and pilot-injection diesel engines are presented in Table 42.

Table 42 **Emission factors for pilot injection and dual-fuel gas engines for inland shipping, technology year 2020**

		NO_x	PM
Limit value (CCR 4)	g/kWh	1.8	0.025
Emission factor	g/kWh	1.6	0.020
Emission control technology		Combustion optimisation Optional: SCR deNO_x catalyst and/or oxidation catalyst	Combustion optimisation

The precise PM level is quite uncertain. There can be some difference between the pilot injection and dual fuel engines, but lack of experimental data prevents differentiation between the two technologies. Based on experience with dual fuel truck engines, the PM level could be quite close to the CCR4 diesel engine.

The PM level of the pilot injection gas engine could be somewhat lower since the combustion may more resemble those of a lean-burn spark ignition engine.

The required NO_x level is not easily met with combustion optimization. Especially for dual-fuel technology an SCR deNO_x catalyst may be necessary to achieve the required NO_x level. An oxidation catalyst instead of or in addition to the SCR catalyst may be necessary to limit methane emission.

The required NO_x level for spark-ignition lean burn gas engines can reasonably be met without NO_x after treatment. Variation in natural gas quality will make this more difficult though. Also to limit the methane emission, an oxidation catalyst may be necessary. The PM emission factor is based on data provided by the spark ignition engine manufacturers for Verbeek (2011).

This corresponds quite well with published data of bus engines, where PM levels are in the range of 0.01 to 0.02 g/kWh.

Table 43 **Emission control spark-ignition lean burn gas engines for inland shipping reference year 2020**

		NO_x	PM
Limit value (CCR 4)	g/kWh	1.8	0.025
Emission factor	g/kWh	1.6	0.020
Emission control technology		Combustion optimisation Optional: oxidation catalyst	-

In 2016 much more stringent emission requirements will be introduced for inland shipping. This must lead to a fourfold reduction of both NO_x and particules emission. Engine will likely be equipped with SCR deNO_x catalysts. Due to this, it is expected that new ships or new installations of diesel or LNG engines will have very similar NO_x and PM emissions for 2016 and later.

3.5.4 Emissions sea ships

Emissions legislation

The IMO emissions legislation for sea shipping is focussed on reduction of sulphur oxide (SO_x) and nitrogen oxide (NO_x). The coordination is with the International Maritime Organisation (IMO) and the treaty is called MARPOL (Marine Pollution). The legislation is in principle world-wide. More stringent emission limits are issued for 'Emission Control Areas' (ECA's). This can be for SO_x (SECA) and/or NO_x (NECA). Examples are the Baltic Sea, North Sea and the US East and West coasts.

The SO_x control is implemented via limits of the fuel sulphur content.

In Table 44 the limits are shown for both the SECA and world-wide.

The SO_x limits can alternatively be met by using a SO_x scrubber instead of using low sulphur fuel.

Table 44 **IMO fuel quality requirements in order to limit SO_x emissions**

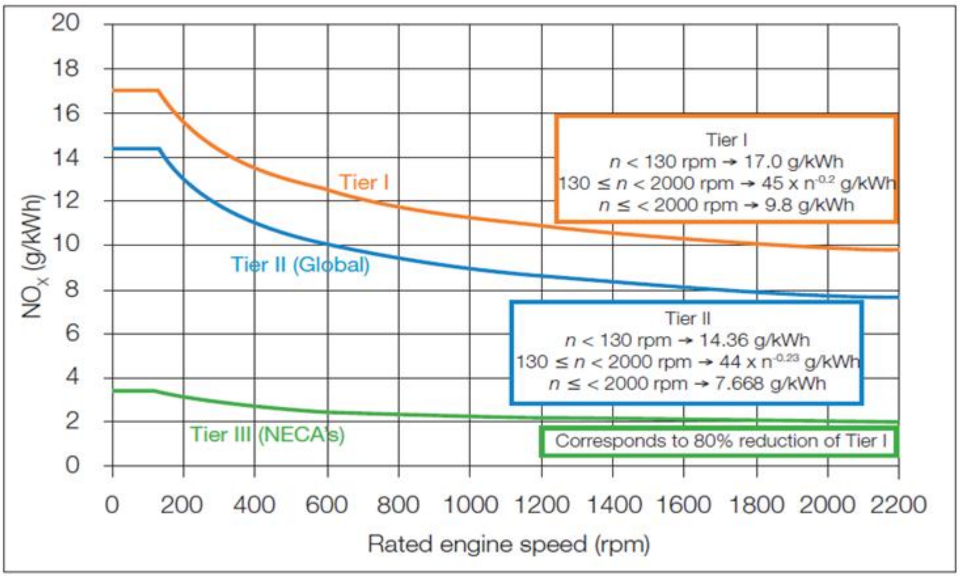
Fuel S content	2008	2010	2012	2015	2020
SO_x Emission Control Area (SECA)	1.50%	1%		0.10%	
World-wide	4.50%		3.50%		0.50%

The NO_x limits for different Tier classes are presented in Figure 12. The dates for entry into force are included in Table 45. In 2011 Tier II entered into force. The NO_x limits are 15 to 25% lower than Tier I, which entered into force in 2005. The NO_x limits for Tier III are 80% lower than for Tier I. Tier III is planned for NECA's for 2016. A NECA is currently planned for the Baltic Sea. This still needs to be decided for the North Sea.

Table 45 **Introduction dates and NO_x emission limit ranges for Tier I, II and III (see also Figure 12)**

NO_x (g/kWh)	Tier I	Tier II	Tier III
Year	2005	2011	2016
NO_x Emission Control Area (NECA)			2-3.4
World-wide	9.8-17	7.7-14.4	

Figure 12 **IMO MARPOL NO_x limits**



Short sea ship

Diesel engine

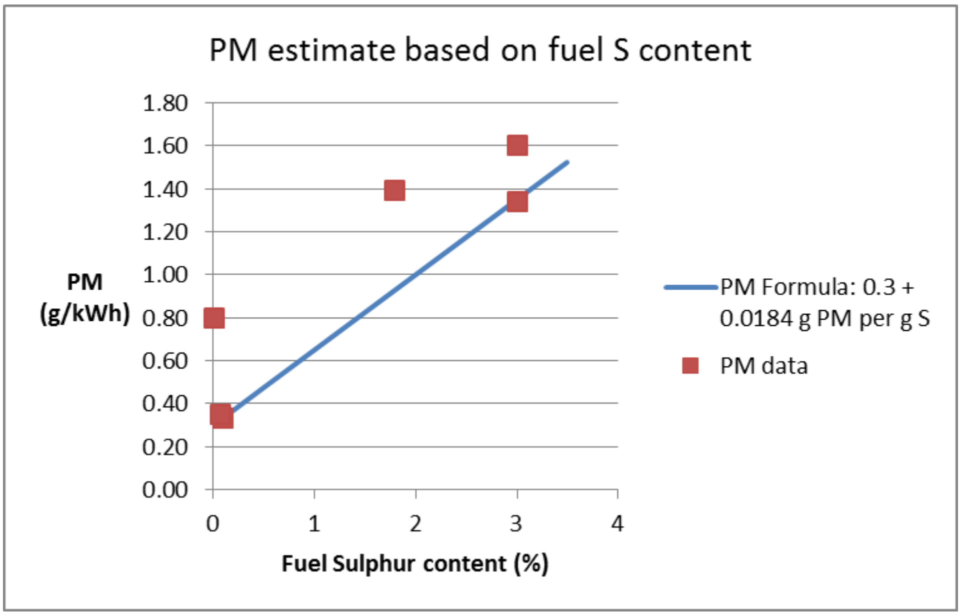
For this study, it is assumed that the Tier III level applies in the Emission Control Areas where the short sea ships are generally sailing. For the North and Baltic Seas, it is still uncertain whether Tier III will be enforced for 2016 or later.
The application of an SCR $deNO_x$ catalyst seems is the most logical emission control technology to meet the required NO_x level. Exhaust gas recirculation (EGR), may be an alternative since relatively high quality fuel is used (MGO).

There is no limit value for particulates emission (PM), although PM is limited via the fuel sulphur content. The fuel S content has a strong linear effect on the PM emission. The following equation is used:
PM (g/kWh) = PM_{0-S} + constant x BSFC x ppmS x 10^min9
PM_{0-S} is the PM level with sulphur free fuel.

The constant of the slope represents the share of sulphur in the fuel, which ends up as sulphate (SO_4, H_2SO_4) in the particulate mass, plus the adsorbed water (because of the hygroscopic properties of sulphate). Several values for the slope were published in the past. Such as the number of 157 mg PM per g Sulphur by EPA and 184 mg PM per g S by CONCAWE. TNO used in the past a somewhat lower number of 136 mg PM per g S for truck engines.

In Figure 13 below the slope of CONCAWE is plotted in actual PM data of ships found in the literature (Lauer, 2010; Winnes, 2010; Bandemehr, 2011). This steepest slope gives the best fit. The initial PM value is set to 0.3 g/kWh. This is the PM emission which would be there without sulphur in the fuel. For this study, the 0.3 g/kWh plus the CONCAWE slope is used.

Figure 13 **Particulate emission of ship diesel engines as a function of the fuel sulphur content**



In Table 46 the PM emission is calculated based on this formula for the applicable sulphur levels. For short sea, where MGO is used, the PM level is 0.33 g/kWh.

Table 46 **PM level diesel engines estimated as a function of the fuel sulphur content**

	S content m/m		PM total
	%	ppm	g/kWh
MGO	0.1	1,000	0.33
HFO/MDO	0.5	5,000	0.47

In Table 47 the NO_x and PM levels according to Tier III are given together with the emission factors for short sea (Emission Control Area).

Table 47 **Emission factors for diesel engines Tier III for short sea shipping, technology year 2020**

		NO_x	PM
Legislation/ Limit value Tier III (engine speed is 500 rpm)	g/kWh	2.6	Limited via S limit in fuel: S < 0.1%
Emission factor short sea ECA	g/kWh	2.3	0.33
Emission control technology		SCR deNO_x catalyst	-

Natural gas engines

Two types of gas engines are offered for the short sea segment:

1. Pilot injection gas engine without 1-2% diesel fuel (also called dual fuel in practice).
2. Dual-fuel gas engine with about 5-10% diesel fuel.

One of the main suppliers of the pilot injection gas engines states that these engines are Tier III compliant without SCR after treatment. The scarcely available data of the dual-fuel engines shows higher NO_x levels, namely around 8-10 g/kWh. It is very well possible that with further combustion optimisations much lower NO_x value can be achieved. At this point, it is not unlikely though that for some engines types, an SCR catalyst will need to be installed in order to meet the required Tier III NO_x level.

For PM emission practically no data is available, except for general statements as '50% reduction compared to MDO diesel'. The level for MDO is about 0.42 g/kWh (0,8% sulphur). Based on this a level of 0.2 g/kWh is chosen. This is basically 33% below the lowest level for similar diesel engines (with sulphur free fuel). It is not unlikely that some engines have significantly lower PM levels, but due to a lack of data the 0.2 g/kWh level is used. Refer to Table 48.

Table 48 Emission factors for pilot injection and dual-fuel gas engines for short sea shipping, technology year 2020

		NO_x	PM
Limit value Tier III	g/kWh	2.6	-
Emission factor	g/kWh	2.3	0.2
Emission control technology		Combustion optimisation Optional: SCR deNO$_x$ catalyst	Combustion optimisation

Deep sea ship

The Tier II level is from 2011 applicable for new ships or new engines.
This is also assumed to be the applicable level for 2020–2025 for world-wide application. It should be noted that if deep sea ships sail in NECA's (NO_x Emission Control Area's, also the NO_x level should be controlled to Tier III level. For ship diesel engines and natural gas which cannot meet the Tier III level with combustion optimisation, this would mean that NO_x emission control would need to be installed.

Diesel engine

The NO_x limit is engine speed dependent, reason why different NO_x limits and emissions factors are given for medium speed and slow speed engines.
The required NO_x levels can be met by the current diesel engines provided diesel fuel with a reasonable quality is used. The NO_x value of 10 g/kWh for the medium speed engine is based on Verbeek (2011). For the slow speed engine, a value is derived from Laursen (2012).
The PM value is calculated with the equation presented above (refer to blue line in Figure 13.

Table 49 **Emission factors for Tier II diesel engines for sea ships, technology year 2020**

		NO_x	NO_x	PM
		Medium speed	**Slow speed**	
Legislation/ Limit value Tier II	g/kWh	10.5	14.4	Limited via S limit in fuel: S < 0.5%
Emission factor	g/kWh	10	11	0.34
Emission control technology		Optional: SCR deNO$_x$ catalyst for NECA	-	-

Natural gas engines

The two types of gas engines offered for this segment are basically the same as for the short sea segment. Pilot and dual fuel engines are both available for the medium speed and slow speed classes:

1. Pilot injection gas engine with 1-2% diesel fuel (also called dual fuel in practice).
2. Dual-fuel gas engine with about 5-10% diesel fuel.

One of the main engine suppliers has announced that also slow speed gas engines with diesel pilot injection will meet the Tier III level. This means for this engine size NO_x is lower than 3.6 g/kWh. On the other hand for the slow speed dual fuel, values were presented around 8-11 g/kWh (Laursen, 2012). This publication also shows a NO_x-fuel consumption trade-off for dual fuel engines. The engine would show an about 25% lower NO_x than the diesel engine, but if the engine would be tuned to the original (diesel) NO_x level, the fuel consumption would be 1-3% lower. This may open the possibility to a location dependent NO_x emission (provided the switch can be made with the engine control): namely low NO_x tuning in NECA's and low fuel consumption tuning outside NECA's. It is also possible that the for NECA required Tier III level cannot be achieved and special NO_x emission control is necessary (such as SCR or EGR). For the slow speed diesel engine two NO_x emission factors are given (low and high) to show the possible range in emissions performance. This can either be the difference between two engine types, or a difference in calibration within the same engine. For PM emission, the same level is used for medium speed and slow speed (same as for short sea).

Table 50 **Emission factors for pilot diesel/dual fuel gas engines Tier II for deep sea ships, technology year 2020**

		NO_x	NO_x	PM
		Medium speed	**Slow speed**	
Limit value Tier II	g/kWh	10.5	14.4	-
Limit value Tier III		2.6	3.7	-
Emission factor	g/kWh	2.3	a) 3.5 * b) 8	0.2
Emission control technology		Combustion optimization		-

*) Different NO_x levels are possible depending on engine optimization.

SO_x emissions for ships

The SO_x emissions are proportional to the fuel sulphur content and the quantity of fuel combusted. The latter is calculated from the engine efficiency and the propulsion power needed. 90-95% of the fuel sulphur ends up as the gaseous SO_2. A small proportion, 5-10% ends up as particulate matter (SO_4, H_2SO_4). Refer to Duyzer (2007).

An overview of the specific SO_2 emissions for different fuel types is presented in Table 51 below. Refer also to Verbeek (2011). For this calculation, it is assumed that 100% of the fuel sulphur is converted to SO_2.

Table 51 Specific SO_2 emissions for different diesel fuels and LNG

Fuel	Average S content (m/m)			SO_2 emission	
				Per kg fuel	Per MJ fuel energy
	%	ppm	g/kg	g/kg	g/MJ
HFO	2.7	27,000	27	54	1.265
HFO/MDO s < 0.5%	0.5	5,000	5	10	0.234
MGO	0.08	800	0.8	1.6	0.0375
EN 590	0.0008	8	0.008	0.016	0.000375
LNG	0.0005	3.5	0.0035	0.007	0.000143
GTL	0.0004	4	0.004	0.008	0.000187

For the calculation of the SO_2 emission per MJ fuel energy, the following heating values are used:

- HFO, MDO, MGO, EN 590: 42.7 MJ/kg.
- LNG: 49 MJ/kg.

For dual fuel and pilot diesel gas engines, the SO_2 emission is calculated by adding up the SO_2 emissions of the diesel share and the LNG share on an energy contribution basis.

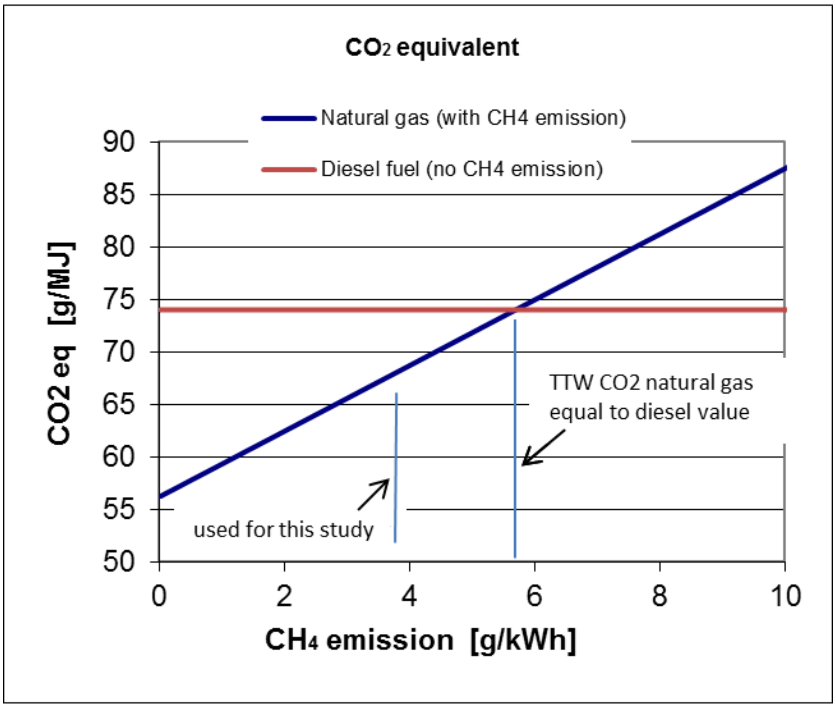
Methane emissions for ships

Methane emissions are not regularly made available by the engine OEMs. The methane emission is multiplied by 25 in order to obtain the CO_2 equivalent for the contribution to the GHG emissions. In the figure below the GHG emission of natural gas engines is plotted as a function of the methane emission. It can be seen that with approximately at 6 g/kWh methane emission, the GHG emission is equal to that of a diesel engine (with the same efficiency). Some years ago in Norway, the maximum methane emission level for ship engines was set to this 6 g/kWh in order to receive tax credits for CO_2 emissions for gas engines. According to direct feedback from Dutch representatives of engine manufacturers (Wärtsilä, MAN and Caterpillar), dual-fuel and pilot diesel engines can comply with this. Also very large engines allegedly have much lower methane emissions. In Kryger et al. (2011), a methane emission of 0.2 g/kWh is reported for a large 2-stroke dual fuel engine. This source also mentions 4-8 g/kWh for other dual or mono fuel engines.

It is also emphasized that lowering methane emissions is an important development item for the coming decade. From governmental point of view, it is recommended to further follow this development and consider implementation of requirements in either an efficiency/CO_2 design index or in pollutant emissions legislation.

For this study a value from the literature is used. This is based on the average methane emission of a large number of stationary gas engines (Engelen, 2009 and Olthuis and Engelen, 2007). In Verbeek (2011) these numbers are transferred to a g/MJ fuel energy value. This number is 0.53 g methane per MJ fuel energy, which converts to around 4 g methane emission per kWh mechanical energy and about 13 g CO_2 equivalent per MJ fuel energy.

Figure 14 **Comparison of GHG (CO_2 equivalent) emissions between diesel and natural gas engine as a function of methane emissions of the gas engine**



3.6 Emission factors for ships

The emission factors for ships are based on the calculation based on the specific emission derived in Section 3.2 in combination with the mechanical energy or the fuel energy per kilometre. This is dependent on the components:

- NO_x, PM: is based on specific emission times mechanical energy per km;
- GHG, SO_x, CH_4: is based on specific emission times fuel energy per km.

Inland ships

The Tank-To-Wheel (TTW) emission factors for inland ships are presented in Table 52.

Table 52 **Emissions factors for inland ship**

		Diesel EN 590	LNG pilot 2% diesel	LNG dual fuel 20% diesel	LNG lean-burn SI	GTL
Fuel energy use	MJ/km	581	601	601	601	581
GHG emission	**kg/km**	43	42	44	42	41
NO_x	g/km	111	112	112	112	100
PM_{10}	g/km	2.0	1.0	1.0	1.0	1.8
SO_x	g/km	0.22	0.09	0.11	0.09	0.11
CH_4	g/km	0	319	319	319	0

Sea ships

The Tank-To-Wheel (TTW) emission factors for the 800 TEU short sea ship are presented in Table 53.

Table 53 **Emissions factors for short sea ship**

		Diesel MGO	LNG dual fuel 10% MGO	LNG diesel pilot 2% MGO
Fuel energy use	MJ/km	1,026	1,094	1,094
GHG emission	**kg/km**	76	78	76
NO_x	g/km	301	308	308
PM_{10}	g/km	43	27	27
SO_x	g/km	38	4	1
CH_4	g/km	0	597	597

The Tank-To-Wheel (TTW) emission factors for the 5,500 TEU sea ship are presented in Table 54.

Table 54 **Emissions factors for the 5,500 TEU sea ship**

		HFO 0.5% S	LNG diesel pilot 1% MGO
Fuel energy use	MJ/km	4,963	5,287
GHG emission	**kg/km**	384	368
NO_x	g/km	6,479	1,520
PM_{10}	g/km	305	132
SO_x	g/km	1,161	3
CH_4	g/km	0	2,885

The Tank-To-Wheel (TTW) emission factors for the 18,000 TEU sea ship are presented Table 55.

Table 55 Emissions factors for the 18,000 TEU sea ship

		HFO 0.5% S	LNG diesel pilot 2% MGO	LNG dual fuel 10% HFO
Fuel energy use	MJ/km	5,998	6,373	6,118
GHG emission	**kg/km**	464	444	369
NO_x	g/km	9,164	2,974	6,798
PM_{10}	g/km	393	170	184
SO_x	g/km	1,404	6	143
CH_4	g/km	0	3,477	3,338

3.7 Emission factors for air planes

The energy efficiency and emissions as a result of using LNG are only briefly analysed. It is estimated that the take-off weight of the plane would increase by 5-10% due to the weight of the LNG tanks (twice the size of diesel tanks due to the lower energy per litre). The LNG tanks would probably not or only partially fit in the wings which would also result in a loss in cargo space and/or number of passengers. As a result of the increased weight and loss of space with LNG an energy efficiency reduction of 10% is assumed. It is furthermore assumed that the gas turbine efficiency and specific emissions are the same for all three fuels: LNG, GTL and Jet fuel.

It should be noted that it is not considered realistic, that there would be a fleet of planes on LNG by 2025. It would take much more time to developed gas turbines and LNG tank systems for planes and to formally release these parts by manufacturers and certify them by aviation authorities.

The Tank-To-Wheel (TTW) emission factors for the an middle class air plane (e.g. 150 passengers, B737) are presented in Table 56. The emissions of current planes are available from the CBS. It is unclear what would the technology of a gas jet turbine engine. The typical use of a middle class plane in Europe is a continental flight of 1,000 km. The take-off emission are included in this.
The GHG emission for LNG does not include, the adverse effects of the strong increase in water vapour emission with LNG. This would almost certainly lead to wider contrails, which would consequently lead to higher ambient temperatures.

Table 56 Emissions factors for a middle class air plane

		Kerosine	GTL	LNG
Fuel energy use	MJ/km	117	117	129
GHG emission	**kg/km**	8,560	8,560	7,240
NO_x	g/km	22	22	22
PM_{10}	g/km	0.4	0.4	0.4

3.8 Natural gas fuel quality

Several properties of natural gas as a fuel for combustion engines for vehicles and ships are important:

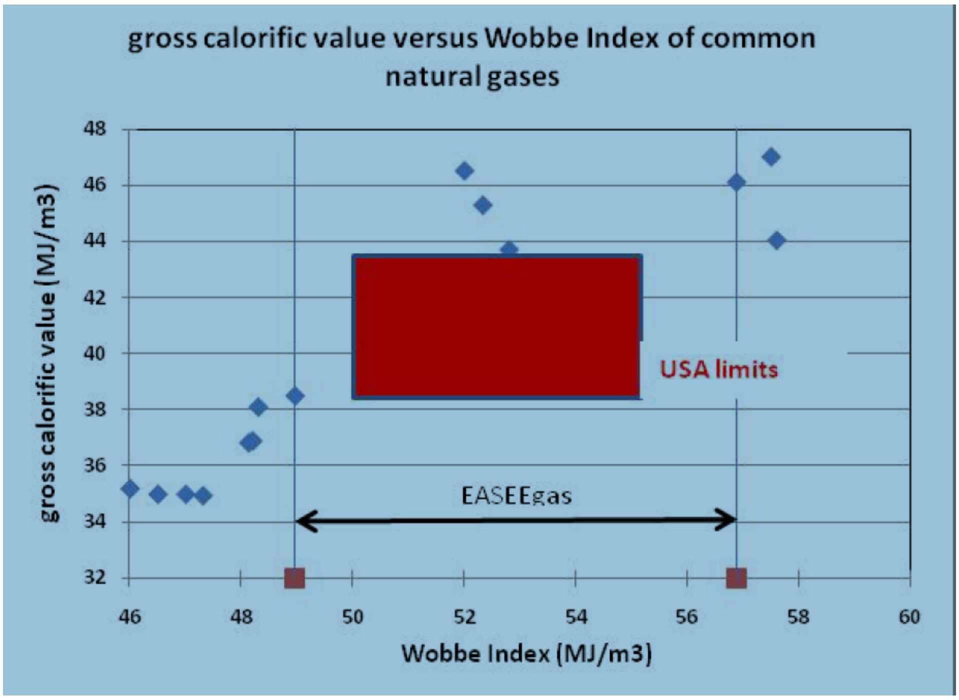
- Methane number:
  Measure for resistance to auto-ignition (resistance to knock of the engine), comparable to octane number of petrol.
- Heating or calorific value:
  The heat of combustion per kg.
- Wobbe index:
  Heating value divided by the square root of the density, important for air-fuel ratio.
- Sensitivity to weathering (only for LNG):
  Weathering is the accumulations of higher hydrocarbons within LNG, which leads to a lower methane number.

These properties are determined by the composition of natural gas. For both pipeline gas as well as LNG, the composition can vary substantially. Apart from methane, natural gas contains higher hydrocarbons (ethane, propane and butane) and also some inert components (such as N_2 and CO_2). The non-methane components typically add up to some 2 to 10% (by volume) and in a few cases up to 20% for both pipeline gas as well as LNG. Especially the methane number and the sensitivity to weathering (only applicable to LNG) deteriorate when the quantity of higher hydrocarbons increases. Weathering can happen when a vehicle or a ship is not used sufficiently. When a large proportion of the gas is withdrawn from the gas phase from the LNG tank, either via the engine or via blow-off, the higher hydrocarbons will accumulate. Eventually this can lead to a quality which cannot be used by the engine and needs to be removed. The relatively small tanks of trucks are more sensitive to weathering, than LNG tanks of ships. This is because of the higher relative heat inflow in relation to the volume of the tank.

Variations in the properties can have impact on fuel consumption, pollutant emissions (especially NO_x), power output and possibilities to optimise an engine on a certain fuel. The response on these parameters is quite dependent on the engine type and fuel supply system. Stoichiometric running (mono-fuel) gas engine such as used for passenger cars and some trucks, can generally accommodate variations easier with small effects on NO_x and specific power output. When a relative high methane number can be guaranteed, the engine can be designed for a higher efficiency. This is because there is more scope to optimise parameters such as compression ratio, ignition timing, turbo charging and specific power output. In (CEN N.106 2012) an example is show where an engine optimised for a methane number of 80 has a 2.6% higher efficiency than an engine optimised for a methane number of 70 (fuel consumption difference is then about 6%). Similar positive effects are for example seen when petrol engines are re-calibrated for use with ethanol blends (which also increases knock resistance). Fuel consumption can go down by 10-15% with a further optimised engine design.

In Europe the gas suppliers are organised with the EASEE. They propose a wider range gas quality, then for example is applicable for USA. This is shown in the figure below. Because of this wide range for Europe, it is recommended to closely monitor engine performance and possible weathering issues in the future. The latter especially for LNG tanks of HD vehicles.

Figure 15 Comparison of gas quality range for Europe (EASEE) and for USA



Source: EUROMOT, 2011b.

In Europe natural gas quality is addressed within the CEN Technical Committee TC 408: Project Committee – Natural gas and biomethane for use in transport and injection in the natural gas grid. This Committee consists of representatives of road vehicle manufacturers and gas suppliers and addresses both pipeline gas as well as LNG. The current plans foresee in delivery of natural gas for transportation in the same (rather wide) quality range as in the European grids (and LNG supplies), but optionally also in a higher quality for transportation. That this is realistic is demonstrated with an LNG production site in Norway, where heavier hydrocarbons are stripped from the LNG to make such a higher quality for transportation available[11].

There are several relevant publications regarding natural gas quality:
- document numbers 106 and 103 from CEN/TC408;
- position papers from EUROMOT: EUROMOT, 2011a and EUROMOT, 2011b.

3.9 Noise emission of vehicles with different fuels

The noise emission of the combustion engine is a substantial part of the noise emission of a vehicle. So replacement of a diesel engine by a more quite gas engine or electric motor leads to a substantial noise reduction of the vehicle.

Passenger cars
In the figure below, shows the noise reduction of an electric and a hybrid electric vehicle compared to a conventional car (Verheijen, 2009). It can be seen that the advantage is mostly there, up to 10 dB(A) at low speed.
At higher speeds, other noise sources such as tire and wind noise are more dominant, and the reduction is less.

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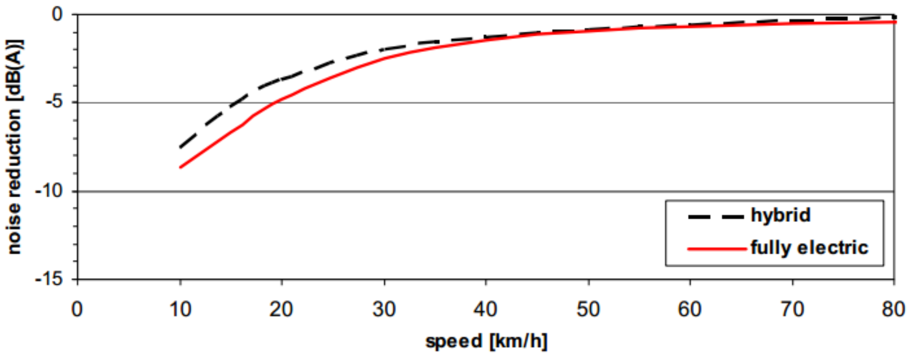
[11] Weblog: http://www.bio-lng.info/blog/?p=415. Production site of Gasnor/Shell.

Figure 16 Noise reduction of an electric and a hybrid electric vehicle as a function of vehicle speed



Source: Verheijen, 2009.

Trucks

In the Netherlands a noise certification standard for delivery trucks and fork lifts was launched in 1998. This standard, which is called the 'Piek'[12], is focused on the loading and unloading of trucks in cities. The PIEK-standard has been adopted in several countries like the UK, France, Germany and Belgium.

The measurement procedure is described in Dittrich et al. (2010). It is focused on constant speed, acceleration and braking at low speed and all handling related to loading and unloading of trucks. Several noise levels were defined within the standard:
60 dB(A): 'PIEK' level at façade for night delivery 23.00–07.00 hrs;
65 dB(A): 'PIEK' level at façade for evening delivery 19.00-23.00 hrs;
72 dB(A): 'PIEK-light' level for trucks.

In the Netherlands about six truck types are available with the PIEK-light certificate (< 72 DB(A)). These are five natural gas (CNG or LNG) trucks and one hybrid-diesel truck.

3.10 Cost and taxes of vehicles and ships

The cost analysis in this report is carried out from the perspective of the users (i.e. vehicle owners), who will take total cost of ownership (TCO) into account when deciding between different fuel options.

When analysing the financial implications of the various natural gas options of owners, two main cost elements need to be taken into account:
- vehicle cost (purchase cost and operational cost);
- fuel/energy carrier cost.

For most of the NG options, new infrastructure needs to be developed to distribute the gas, hydrogen or electricity to the filling stations and then to the vehicles and ships. In our analysis, this cost of the fuelling infrastructure is assumed to be included in the fuel/energy carrier cost.

Taxes are included as the cost assessment, and costs will be calculated both with and without taxes. Taxes may change over time, of course, but as future developments are quite impossible to predict, the current taxation system and levels are taken for all vehicles and fuels.

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[12] http://www.piek-international.com/english/.

For all the vehicle and ship types assessed in this report, costs were estimated, and additional cost of the natural gas options were derived. The cost estimates are aimed at the year 2025, and assume a large scale roll-out of the natural gas routes. It therefore seems reasonable to assume that cost of the NG vehicles are lower than today: the cost of a new technology is typically high at first but tends to decrease once production volumes increase. How much lower, though, is difficult to determine without a detailed assessment of the technology and of the potential global growth of the production volumes, both outside the scope of this project.

Converting the purchase cost to a cost per kilometre (the main unit with which we will compare the various routes in Chapter 7) requires also data on vehicle lifetime (or residual value after a certain period of time), in years or rather in total kilometres over the vehicle's lifetime.

Other cost items such as maintenance and insurance cost were not included in the calculations, but they can differ between the various technologies. For example, in the current situation, CNG and LNG vehicles and ships are found to have somewhat higher maintenance cost than the reference technology. However, the differences are likely to reduce over time as the new technology develops.

The cost estimates used in this study were based on a study of relevant literature and a consultation of stakeholders (via the LNG Platform and communications with vehicle and ship manufacturers). It is important to realise, though, that the uncertainty of these estimates is relatively high. For the LNG option in aviation, it was decided that the cost data were too limited and uncertain to include in the report. Note that the fuel and energy carrier cost will be derived in the next chapter, the overall cost results can be found in Chapter 7.

3.10.1 Light duty vehicles: passenger cars and vans

Taxes included here are purchase tax (BPM) and annual registration tax (MRB). A VAT level of 21% (2013 level) is included for the two passenger cars, assuming private ownership. Vans (and heavy duty vehicles) are assumed to be bought by companies who can reclaim the VAT.

BPM and MRB levels for 2015 were assumed to apply. The BPM tariff is differentiated by fuel and CO_2 emissions of the vehicle (as measured at type approval), MRB is differentiated by fuel, vehicle weight and CO_2 emissions, and differs between provinces. In all cases, passenger cars were assumed to emit 95 gr CO_2/km, in line with the 2020 target of the European CO_2 regulation, vehicle weight was assumed to be 1,200 kg. MRB levels of Zuid-Holland were used.

The resulting assumptions for passenger car 1 and 2 are shown in Table 57. As can be seen, CNG vehicles are expected to remain somewhat more expensive than diesel cars (CE Delft, 2010; AEA, 2009; ECN, 2008), and diesel cars are slightly more costly than petrol cars. GTL can be used in standard diesel vehicles. Purchase and registration taxes for hydrogen and battery electric vehicles are zero until (and including) 2015. It may well be that this tax exemption is reduced after 2015 (the impact of this incentive on government revenues will increase when the market share of these vehicles increases in the future), but as tax levels for 2015 are used throughout this report, BPM and MRB taxes are assumed to be zero for these vehicles.

The vehicle cost of the alternative fuel vehicles (H_2, electricity) are based on McKinsey, 2010; ECN, 2010; EC, 2011; ECN, 2008 and assume a large-scale roll-out of these vehicle technologies by 2025. Therefore, significant cost reductions are assumed, compared to the current situation: on the one hand, significant increases of production levels typically leads to significant cost reductions, on the other hand, these technologies are likely to become attractive to consumers only if cost are significantly reduced.

Table 57 **Purchase cost of passenger car 1 (€): reference vehicle is a diesel car, 30,000 km/yr**

	Diesel	CNG	GTL	H_2	Electricity
Purchase cost excl. taxes	17,600	18,300	17,600	26,600	23,600
Purchase tax (BPM)	3,090	1,056	3,090	0	0
Annual registration tax (MRB)	1,200	832	1,200	0	0

Table 58 **Purchase cost of passenger car 2 (€): reference vehicle is a petrol car, 15,000 km/yr**

	Petrol	CNG	GTL	H_2	Electricity
Purchase cost excl. taxes	16,800	18,300	17,600	26,600	23,600
Purchase tax (BPM)	1,056	1,056	3,090	0	0
Annual registration tax (MRB)	608	832	1,200	0	0

Purchasing cost of the vans assessed in this report are given in Table 59. BPM and VAT are taken to be zero, the MRB tariff is independent of fuel/energy carriers.

Table 59 **Purchase cost of vans (€)**

	Diesel	CNG	GTL	H_2
Purchase cost excl. taxes	19,800	21,500	19,800	29,500
Purchase tax (BPM)	-	-	-	-
Annual registration tax (MRB)	508	508	508	0

3.10.2 Heavy duty vehicles: trucks and busses

The cost of the heavy duty vehicles were mostly derived from Cenex, 2008; DAF, 2011; Courage, 2009; CE Delft, 2011; ECN, 2008 and stakeholder input, and given in Table 60, Table 61 and Table 62. Purchase tax is zero and it is assumed that VAT does not have to be paid. However, owners have to pay annual registration taxes and an Eurovignet is also assumed. The taxes are all independent of fuel/energy carriers, though.

Table 60 Purchase cost of rigid trucks (€)

	Diesel	Diesel, hybrid	CNG, SI hybrid	LNG, pilot hybrid	LNG, dual fuel hybrid	GTL, hybrid	H_2	Electricity
Purchase cost, both excl. and incl. taxes	98,300	108,000	128,000	128,000	128,000	108,000	248,000	168,000
Annual registration tax (MRB)	288	288	288	288	288	288	0	0
Eurovignet (annual)	750	750	750	750	750	750	750	750

Table 61 Purchase cost of bus (€)

	Diesel	Diesel, hybrid	CNG, SI hybrid	LNG, SI hybrid	GTL, hybrid	H_2	Electricity
Purchase cost, both excl. and incl. taxes	270,000	290,000	310,000	315,000	290,000	420,000	470,000
Annual registration tax (MRB)	708	708	0	0	708	0	0

Table 62 Purchase cost of tractor-trailer (€)

	Diesel	LNG, SI	LNG, pilot	LNG, dual fuel	GTL	DME	H_2
Purchase cost, both excl. and incl. taxes	145,000	165,000	165,000	165,000	145,000	160,000	345,000
Annual registration tax (MRB)	456	456	456	456	456	456	0
Eurovignet (annual)	1,250	1,250	1,250	1,250	1,250	1,250	1,250

3.10.3 Ships

There are only few ships that run on LNG at the moment, making it difficult to estimate additional cost for LNG in 2025 accurately. The estimates given in the following Table 63 till Table 66, based on Germanischer Lloyd; Marintek, 2008; American clean skies foundation; DNV, 2011; DNV, 2012 and stakeholder estimates, are thus relatively uncertain. No purchase nor registration taxes have to be paid for ships.

Table 63 Purchase cost of inland ships (€)

	Diesel	LNG, pilot	LNG, dual fuel	LNG, lean burn SI
Purchase cost	-	600,000	600,000	600,000

Table 64 Purchase cost of short sea ships (€)

	MGO	LNG, pilot	LNG, dual fuel
Purchase cost	-	3,000,000	3,000,000

Table 65 Purchase cost of deep sea ships 5,500 TEU (€)

	HFO	LNG, dual fuel
Purchase cost	-	15,000,000

Table 66 Purchase cost of deep sea ships 15,000 TEU (€)

	HFO	LNG, pilot	LNG, dual fuel
Purchase cost	250,000,000	272,000,000	272,000,000

3.10.4 Aviation

Reliable cost estimates for LNG airplanes are not yet available, it was thus decided not to carry out cost calculations for aviation in this report.

3.10.5 Vehicle lifetime and annual kilometres

In the cost analysis, vehicle lifetime and annual kilometres are also important parameters, as:

- the purchase cost and vehicle taxes will be depreciated over the vehicle’s lifetime;
- the total fuel cost per kilometre of the various alternatives (determined in the next chapter) will depend on fuel use and cost, but also on total kilometres.

To this end, the following assumptions were made, based on literature and stakeholder input. Different lifetimes and annual kilometres were assumed for the various vehicle and ship types, but they were assumed to be independent of the fuel/energy carrier.

It is important to note that the cost analysis depends quite strongly on these values. Shorter lifetimes increase the vehicle cost per kilometre, and reduce the fuel cost over the lifetime. As will be seen in the results (Chapter 7), some of the natural gas routes have higher vehicle purchase cost but lower fuel cost over the lifetime of the vehicles. If their lifetime would be lower than that of the reference vehicles, fuel savings will reduce and additional vehicle cost per kilometre will increase. Both effects have a negative impact on the overall cost assessment of this route, and on how the NG route compares to the reference fuel and other natural gas alternatives.

Table 67 Average lifetime and annual mileage of the various vehicles and ships

	Lifetime (years)	Annual kilometres (km)
Passenger car no. 1	13	30,000
Passenger car no. 1	13	15,000
Van	12	18,500
Truck	12	60,000
Bus	14	50,000
Tractor-semitrailer	8	120,000
Inland ship	25	120,000
Short sea ship	25	283,500
Deep sea ship 5,500 TEU	25	382,500
Deep sea ship 15,000 TEU	25	382,500

3.11 Conclusions

The conclusion with respect to Tank-To-Wheel (TTW) pollutant and GHG emissions are summarised below.

Passenger cars and vans

- Application of natural gas has clear advantages in the fields of NO_x and GHG emissions compared to diesel, petrol and GTL. No significant difference in particulate emissions is expected due to the tight legislation which implies the application of particulate filters on all diesel vehicles.
- For GTL the same emission factors are used as for diesel. There may be small advantages on pollutant emissions and engine efficiency but no data is available to support this quantitatively for these engines with advanced emission control systems.
- Battery electric and H_2 fuel cell vehicles have no direct pollutant emissions and a higher TTW energy efficiency.

Trucks and buses

- Application of natural gas leads to a substantial advantage in GHG emission, but not in pollutant emissions NO_x and Particulates. This is due to the thorough Euro VI test procedures which also lead to very low emissions with diesel.
- For GTL and DME, the same emission factors are used as for diesel. There may be small advantages on pollutant emissions and engine efficiency but no data is available to support this quantitatively for these engines with advanced emission control systems.
- Battery electric and H_2 fuel cell vehicles have no direct pollutant emissions.

Inland ships

- Application of natural gas leads to lower particulates and SO_x emission. No significant difference is expected for NO_x, since CCR4 legislation leads to the application of SCR deNO_x catalysts on diesel engines. GHG emission is not expected to benefit from natural gas due to the relatively high methane emission (no legislation on this point) and some loss in engine efficiency.
- GTL is expected to lead to about 10% lower NO_x and Particulates levels, and no change in GHG emissions.

Short sea ships in Emission Control Areas (for NO_x and SO_x)

- Application of natural gas leads to lower particulates and SO_x emission. No significant difference is expected for NO_x, since the Tier legislation leads to the application of SCR deNO_x catalysts on diesel engines.
- GHG emission is not expected to benefit from natural gas due to the relatively high methane emission (no legislation on this point) and loss in engine efficiency and cargo space due to the size of the LNG fuel storage.

Deep sea ships

- Application of natural gas leads to much lower particulates and SO_x emissions. There may be large advantages in NO_x emission, but this is also strongly dependent on engine calibration and design strategy.
- GHG emission is not expected to benefit from natural gas due to the relatively high methane emission (no legislation on this point) and loss in engine efficiency and cargo space due to the size of the LNG fuel storage.

4 Environmental impacts and cost of the upstream part of the routes

4.1 Introduction

This chapter evaluates the upstream part of the various fuels chains, i.e. the Well-To-Wheel trajectory, regarding: energy use, CO_2 emissions as well as costs. In addition the emissions of air polluting compounds are estimated, where relevant for the air quality in the Netherlands.

4.2 Well-To-Tank emissions (WTT) and efficiency

Methodology and key data sources

Most of the data for this project are directly taken from the JRC/EUCAR/CONCAWE study on well to wheel efficiencies (Edwards et al., 2011a, 2011b; 2011c). The explanation of data directly taken from this source is not repeated in this report. This data can be found in the internet site of the JRC (http://iet.jrc.ec.europa.eu/about-jec/). This chapter only provides additional information on the main points of discussion and on routes which are not in the JRC study. In the next sections, first the main differences and updates in the last JRC study are discussed and a comparison is made with data in the GREET model (ANL, 2012). Subsequently the electricity chain is illustrated. Finally this chapter discusses the use of compressed hydrogen and the uncertainty of Gas to Liquid (GTL) versus Liquefied Natural Gas (LNG).

The first step in the JEC analysis is to identify the energy use and CO_2 emissions of all separate steps in the well to tank route. If electricity or liquid fossil fuel is involved, directly the total chain emissions are added.
Then starting from the last distribution step, a backwards calculation is made and every step is multiplied with a factor related to the losses of the main energy carrier before it is in the fuel tank. If for instance 20% of the natural gas is used before it is in the car tank, the emissions of gas exploration per MJ explored gas are multiplied with a factor 1.2. So the energy use of a process step like LNG production in the tables is influenced by the amount of LNG used or lost before it is in the fuel tank.

Changes in de latest JRC study

The latest (third) version of the JRC study is of 2011. This study includes some new routes but also presents more recent data. The main differences compared to the 2007 data include:

- The energy use of crude oil extraction increased from 3 to 6% in the fossil fuel chains. Also the CO_2 emission increased. The Greet model is still based on the lower value.
- The energy use of the GTL production has decreased from 0.59 MJ/MJ fuel to 0.54 MJ/MJ fuel (65% efficiency). In addition the methane emission in the process has been removed. The Greet model is based on a value of about 0.64 MJ/MJ fuel.
- The efficiency of DME production has not changed and is still taken as 0.41 MJ/MJ fuel. The Greet model uses about 0.47 MJ/MJ fuel.

Methane leakage and global warming potential

Another issue in the JRC study is the Global Warming Potential (GWP). In the fourth assessment report the Intergovernmental Panel on Climate Change (IPCC) published new values, see Table 68 (IPCC, 2007). These values are used to convert the effect of other greenhouse gasses into so called CO_2 equivalents (CO_2 eq.) over a time horizon of 100 years. The latest figures show an increase of the greenhouse impact of methane compared to carbon dioxide. So even if the emission factors of methane and nitrous oxide (another important greenhouse gas) would not have changed between 2007 and 2011, the amount of CO_2 eq. might be higher. Finally the short term effects are also different. In the last column also the factors for a 20 year time horizon are given. So if we look at the warming effect within two decades, especially methane has a substantial higher GWP. This implies that leakage or otherwise escaping methane resulting from the use of natural gas or LNG, might have a substantial larger effect on climate change in the next decades than calculated now in the current study, where we use the 100 years GWP of the 2007 IPCC report are used (IPCC, 2007).

Table 68 IPCC factors

Gas	1996 IPPC GWPs (100 years)	2001 IPCC GWPs (100 years)	2007 IPPC GWPs (100 years)	2007 IPPC GWPs (20 years)
Carbon dioxide (CO_2)	1	1	1	1
Methane (CH_4)	21	23	25	72
Nitrous Oxide (N_2O)	310	296	298	289

Source: IPCC, 2007.

Note: Other Greenhouse gasses are not emitted in significant quantities in any of the processes considered in this study.

Supply and production chain of electricity

Because the JRC study does not contain an electric car route based on natural gas (only), this route was constructed for this project. The exploration and transport of natural gas was taken from the JRC study. The mean efficiency of gas power plants in 2025 is estimated at 56%. For new power plants the efficiency lies between 56 and 59% (Seebregts, 2009). Because a growth in electric demand by transport will be related to new gas power stations, in this study 58% is used. The transport and distribution losses of electricity are estimated at 3.5 % for the build environment (large offices) by ECN.
For private houses, it is estimated to be 5.5%. For the current study 5% transport and distribution losses is used for electric cars.

The last step in the electric Well-To-Tank (WTT) route is the charger, used to change the electricity from alternating to direct current (AC/DC conversion). Tesla Motors, a manufacturer of electric vehicles, mentions in 2006 a charger efficiency of 93% (Eberhard, 2006). In 2010 Bakker mentions a charger efficiency of 90% (Bakker, 2010) and in 2009 JRC mentions 87% (Nemry et al., 2009). Other studies mention charging efficiencies which are even lower, but these also include the losses in the battery. For only the chargers an efficiency of 93% could be used. For normal charging the charger is available (built in) in the electric car. Consequently, in the latter case the charger is not a part of the WTT chain but rather of the TTW chain. For fast charging the (much larger) charger is located outside the car, although one automobile producer puts it also in the car (Masson, 2012). This makes the calculations more complex because additional assumptions have to be made for the percentage of electricity from a fast charger outside the car and this has to be corrected in the TTW energy use. For this reason, it was decided to attribute the total electricity use of the charger to the TTW route.

Liquid versus compressed hydrogen

Liquefaction of hydrogen (H_2) costs much more energy compared to natural gas. According to the JRC study is the energy use for the liquefaction of hydrogen 0.54 MJ/MJ_{H2} and for liquefaction of natural gas 0.07 MJ/MJ_{LNG} (Edwards et al., 2011b). This large difference is mainly caused by the much lower temperature needed to liquefy hydrogen (-253°C or 20 K) compared to -162°C or 111 K for LNG. Secondly, also the compression of the hydrogen cost more energy: 0.22 MJ/MJ_{H2} for hydrogen compression compared to 0.06 MJ/MJ_{CNG} for natural gas. This difference is caused by the lower combustion value of gaseous hydrogen (10,8 $MJ/m^3{}_{H2}$) compared to natural gas (36-40 MJ/m^3). Because of the lower heat of combustion per m^3, also the transport and distribution of hydrogen will cost more energy than for natural gas and will require pipelines with a larger diameter. The difference in properties makes it clear that the option of to use of LNG compared to CNG is not comparable to the case for liquid versus compressed hydrogen. Liquefaction of hydrogen costs substantial additional energy, compared to natural gas liquefaction. For this reason, the use of liquid hydrogen is not further analyzed as an important chain in this study.

Transport of LNG

For the transport of LNG JEC mentions an energy use of 0.09 MJ/MJ.
The direct use is 0.0674 MJ/MJ LNG transported. The difference is caused by rounding of the 0.09 figure and by the LNG consumption in the following steps (see methodology). An important issue is that before 2007 all LNG carriers used steam turbines. The reason for the use of steam technology is that in the steam boiler both gas, from the boil off, and liquid fuel can be used.
After 2007, and including orders, only 30% of the new LNG carriers use (more efficient) steam turbines and 70% use engines (which are even more energy efficient). They started with diesel engines (and on board liquefaction of the LNG boil off) but the newest carriers use dual fuel LNG/diesel engines to make electricity, and electricity is used for the propulsion of the ship. There are several reasons why electricity and multiple gas engines has an advantage. Multiple engines make maintenance of gas engines at sea possible and guarantees always power in harbors. At the end of 2012 the penetration of engines was about 18%, but this will increase over time. Thus, for the 2025 case the use of engines is a better reference than the use of steam turbines. The fuel efficiency from fuel to propeller shaft will increase with more than 40% the next decade from a steam turbine with 30% efficiency to a gas engine (via electricity) with 43%. Instead of the 0.09 MJ/MJ from JEC we will use 0.07 MJ/MJ.
The corresponding CO_2 eq. emission factor is 3.4 gCO_2 eq./MJ (based on 2.9 g CO_2/MJ and 0,022 g CH_4/MJ instead of the JEC figure of 5.5 gCO_2 eq./MJ. The figures includes the waiting time in the harbors and for the Suez canal and the energy use and boil off (from the small amount of LNG taken back to keep the storage tanks on the low temperature) during the back trip.

Gas to Liquid (GTL) versus Liquefied Natural Gas (LNG)

LNG

For large gas fields at remote locations there are two main options: liquefaction into LNG or conversion into GTL. Currently there are already more than 30 LNG liquefaction plants in the world. The energy use for liquefaction differs per installation (ranging from 0.07 to 0.013 MJ/MJ_{LNG}).

Next to the JRC and GREET data, much additional information is available, for instance Yost, 2003; Durr, 2005; Thomas, 2009; Australia Pacific LNG, 2010. We use 0.08 MJ/MJ_{LNG} in the calculations. Key factors controlling the energy use are: (1) the efficiency of the gas turbines used, which drive the compressors and (2) whether the flue gas of those gas turbines is used to produce steam (combined heat and power) (Durr, 2005). In case of the CO_2 eq. emission the range in energy use results in a range for the CO_2 emission. Furthermore, the CO_2 content of the gas can influence the emissions (Yost, 2003) and the emission of methane is important (Australia Pacific LNG, 2010).

GTL

Evaluating GTL efficiency is challenging as only a few plants have been built up till now - by Petro SA, Sasol and Shell - and information is limited. For the GTL production, the plant of Shell in Qatar attracts most attention, given its large size (Shell, 2012). It can be calculated that the theoretical energy losses are at least 23%, based on the composition of gas from Qatar, taken from (Shah, 2008). Main reason is that methane contains 4 hydrogen atoms per carbon atom, whereas in diesel this is only around 2.2. So if all carbon atoms are converted into diesel a lot of hydrogen, and hydrogen combustion energy, is lost. Next to the chemical ‘loss’, there is also energy (electricity) needed for the process. The FT-process of Shell makes first long-chained waxy hydrocarbon molecules which are later cracked into the desired products. For this cracking step additional hydrogen is needed. In the current study we use the figure of 0.49 MJ/MJ GTL, which is the lower end of the range in the JRC study. A calculation based on rough data from a Shell publication results in 0.46 MJ/MJ GTL (Brown, 2009). A study of students of 2007 mentions an efficiency of 62% (0,61 MJ/MJ GTL) which could be improved to about 66,5% (0,50 MJ/MJ) (MDP, 2007). Another Shell publication shows in a picture CO_2 eq. emissions, of GTL and what potentially could be reached with increased process efficiency. The data we use for the CO_2 emissions is in line with increased process efficiency (Mansar, 2007). If Shell takes into account CH_4 emissions (which are not mentioned in the JRC study), the potential efficiency might be better. It can be concluded that the picture for GTL has a bigger uncertainty than for LNG. Therefore it is possible that the energy use might be 0.03 to 0.05 MJ/MJ fuel better than the 0.49 MJ/MJ we use. However, it also could be worse by the same value. The CO_2 eq. emissions are probably on the lower end of the available information and can be higher if the natural gas contains much CO_2 or if there are more than negligible methane emissions.

Results

With the data sources explained in the above sections, a set of different chains was calculated. Like in the JRC report, in most chains the total emissions from electricity use are directly included in the conversion and distribution step. This implies that the exploration and transport of fuels for electricity production are not included in the exploration and transport step. For the WTT calculation of electricity (from gas) this is not the case. For this reason the exploration and transport consumption in those routes are higher. For CO_2 capture and storage (CCS) also the additional energy use in exploration and transport is added. Conversion includes liquefaction, GTL and DME production in foreign countries, followed by transport to the Netherlands. Distribution includes compression at the fuel station. In addition the following assumptions were made. For piped natural gas a 50:50 mix of gas from Norway (1,000 km) and from Russia (7,000 km) is used.

For LNG and GTL it is assumed that the mean transport distance equals the distance to Qatar, although LNG is also available with a shorter transport distances (Norway, Algeria). DME is assumed to originate from small gas fields in South America and therefore involves the largest transport distance. Finally CO_2 capture and storage (CCS) costs less energy for hydrogen production compared to electricity production, because the hydrogen production process has a concentrated CO_2 stream as by product. In this study we only look at CCS for electricity and hydrogen production. In refineries CCS might be used on the concentrated CO_2 stream of the hydrogen production, reducing the CO_2 emission of the conversion step with 7 to 13% (depending on the actual situation). CCS is also possible in the GTL route. According to JEC a substantial part of the CO_2 emitted by the GTL plant is scrubbed out of the syngas before the FT synthesis and is available in virtually pure form. Also CO_2 is available from the hydrogen production. If CCS applied CO_2 emission of the conversion step might be reduced with 50-70%. According to JEC 70% reduction by CCS increases the energy use of the conversion step with 24%.

WTT Energy use

Table 69 shows that the WTT energy use of diesel and petrol are the lowest, followed by compressed natural gas (CNG) from piped natural gas. LNG costs more energy than piped natural gas. The direct use of LNG is ‘better’ than CNG and making CNG from LNG at the fuel station is ‘better’ than evaporation, pipeline transport and compression at the fuel station. The WTT energy consumption is substantially higher than what was presented in Verbeek (2011): The latter listed 0.16 MJ/MJ, versus 0.24 MJ/MJ now. This is especially due to a higher energy consumption during sea transport and distribution listed in recent publications.

Looking at DME and GTL, the WTT energy use of DME is lower. However, this balance is influenced by the uncertainties. The TTW emissions of both hydrogen and electricity are substantial higher, but this is compensated by the better tank to wheel (TTW) emissions of those energy carriers. Liquification of hydrogen costs a substantial amount of energy. Finally CO_2 capture and storage costs less energy for hydrogen production compared to electricity production, because the hydrogen production process has a concentrated CO_2 stream as by product.

Table 69 WTT energy use of different chains for road transport

	Exploration MJ/MJ fuel	Transport MJ/MJ fuel	Conversion MJ/MJ fuel	Distribution MJ/MJ fuel	Total MJ/MJ fuel
Diesel	0.06	0.01	0.10	0.02	0.19
Petrol	0.06	0.01	0.08	0.02	0.17
LNG	0.03	0.05	0.09	0.03	0.20
CNG from LNG at the station	0.03	0.05	0.09	0.06	0.23
CNG from LNG	0.03	0.05	0.09	0.10	0.27
CNG from NG	0.03	0.11	0.00	0.07	0.20
GTL	0.04	0.04	0.49	0.02	0.59
DME	0.03	0.06	0.39	0.03	0.51
H_2-L	0.04	0.16	0.94	0.03	1.17
H_2-G	0.04	0.16	0.32	0.23	0.75
H_2-L + CO_2 storage	0.04	0.17	1.02	0.03	1.26
H_2-G + CO_2 storage	0.04	0.17	0.40	0.23	0.84
H_2-L from LNG	0.04	0.07	1.12	0.03	1.26
H_2-G from LNG	0.04	0.07	0.50	0.22	0.83
H_2-L from LNG + CO_2 storage	0.04	0.07	1.20	0.03	1.34
H_2-G from LNG+ CO_2 storage	0.04	0.07	0.58	0.22	0.91
Electricity from NG	0.04	0.19	0.76	0.05	1.04

	Exploration MJ/MJ fuel	Transport MJ/MJ fuel	Conversion MJ/MJ fuel	Distribution MJ/MJ fuel	Total MJ/MJ fuel
Electricity from LNG	0.06	0.10	0.90	0.05	1.11
Electricity from NG with CCS	0.05	0.21	0.96	0.05	1.27
Electricity from LNG with CCS	0.06	0.11	1.10	0.05	1.32

Note: NG is piped natural gas; CCS is carbon capture and storage.

WTT GHG emissions

Table 70 shows the different CO_2 eq. emissions in the TTW chain. The picture is generally comparable to the energy use, but the emissions of methane, and the associated CO_2 eq. impact, results in differences. The last column shows the contribution of CO_2 eq. resulting from methane emissions, relative the overall CO_2 eq. emission. In case of hydrogen and electricity the CO_2 eq. emissions are higher, because all emissions are in the WTT chain. Finally the chains with CO_2 storage have substantial lower emissions. Because CO_2 is substantially lower with CO_2 storage the percentage of CH_4 is higher.

Table 70 WTT CO_2 eq. emissions of different chains for road transport

	Exploration CO_2 eq./MJ	Transport CO_2 eq./MJ	Conversion CO_2 eq./MJ	Distribution CO_2 eq./MJ	Total CO_2 eq./MJ	% CH_4 in CO_2 eq.
Diesel	5.3	0.9	8.6	1.9	16.7	0%
Petrol	5.2	0.9	7.0	1.0	14.1	0%
LNG	3.5	3.4	5.7	4.4	17.0	37%
CNG from LNG at the station	3.5	3.4	5.7	5.9	18.5	34%
CNG from LNG	3.5	3.5	5.7	5.3	17.9	23%
CNG from NG	3.6	8.4	0.0	3.5	15.5	35%
GTL	5.0	2.7	10.2	1.0	18.8	17%
DME	4.6	4.3	9.1	1.6	19.6	16%
H_2-L	5.0	12.4	109.7	1.7	128.8	8%
H_2-G	5.0	12.4	74.2	9.7	101.3	8%
H_2-L + CO_2 storage	5.2	13.0	44.6	1.7	64.6	16%
H_2-G + CO_2 storage	5.2	13.0	8.0	9.7	36.0	22%
H_2-L from LNG	4.6	4.5	121.8	1.7	132.6	6%
H_2-G from LNG	4.6	4.5	85.2	9.0	103.3	6%
H_2-L from LNG + CO_2 storage	4.8	4.7	55.7	1.7	67.0	12%
H_2-G from LNG+ CO_2 storage	4.8	4.7	19.2	9.0	37.7	16%
Electricity from NG	6.4	14.8	103.1	0.0	124.3	7%
Electricity from LNG	6.6	6.5	111.5	0.0	124.6	5%
Electricity from NG with CCS	7.1	16.5	11.5	0.0	35.1	29%
Electricity from LNG with CCS	7.2	7.2	19.9	0.0	34.3	20%

Note: NG is piped natural gas; CCS is carbon capture and storage.

Other fossil fuels

Table 71 shows the WTT figures for the other fossil fuels used in this study. Conversion figures are partly based on calculations with the SERUM refinery model of ECN and include the low sulfur IMO demands (0.1% for MDO and 0.5% for HFO). Because distribution takes place by ship or pipeline the distribution emissions are lower than for rood transport.

Table 71 **WTW energy use and GHG emissions of other fossil fuels**

Fossil fuel routes	MDO	HFO	Kerosene
MJ/MJ Exploration (MJ/MJ fuel)	0.06	0.06	0.06
MJ?MJ Transport (MJ/MJ fuel)	0.01	0.01	0.01
MJ Conversion (MJ/MJ fuel)	0.09	0.08	0.09
MJ Distribution (MJ/MJ fuel)	0.00	0.00	0.00
Total (MJ/MJ fuel)	0.17	0.15	0.17
CO_2 Exploration (g CO_2/MJ fuel)	5.3	5.3	5.2
CO_2 Transport (g CO_2/MJ fuel)	0.9	0.9	0.9
CO_2 Conversion (g CO_2/MJ fuel)	8.1	7.9	8.1
CO_2 Distribution (g CO_2/MJ fuel)	0.1	0.1	0.2
Total (g CO_2/MJ fuel)	14.4	14.3	14.4

Impacts on air quality in the Netherlands

For the air polluting emissions in the Netherlands, not the whole TTW route is important. The key emission sources to be considered are the conversion in refineries, the electricity production, the production of hydrogen and the transport of the fuel to the tank station. The emission factors used are related to the fuel consumption in the conversion or transportation step of the TTW route. The emission factors used can be found in Table 72. It should be mentioned that the emissions in the WTT chain are released at different and often less harmful locations, compared to the TTW emissions.

Table 72 **Emission factors in g/GJ fuel used in conversion or distribution step**

	NO_x	PM_{10}	SO_2
Gas power station (electricity)	17		
Hydrogen production	17		
Oil refinery	34	2	69
Road distribution	88.7	8.1	0.5
Inland water distribution	191.0	3.4	0.4
Short sea distribution	293	29	37

4.3 Cost of the energy carriers

Commodity cost of natural gas and related transportation fuels considered in this study have been assumed to be primarily based on crude oil price.
The only exception concerns a scenario in which the natural gas price is assumed to be linked to the coal price.

4.3.1 Fossil fuel reference commodity prices

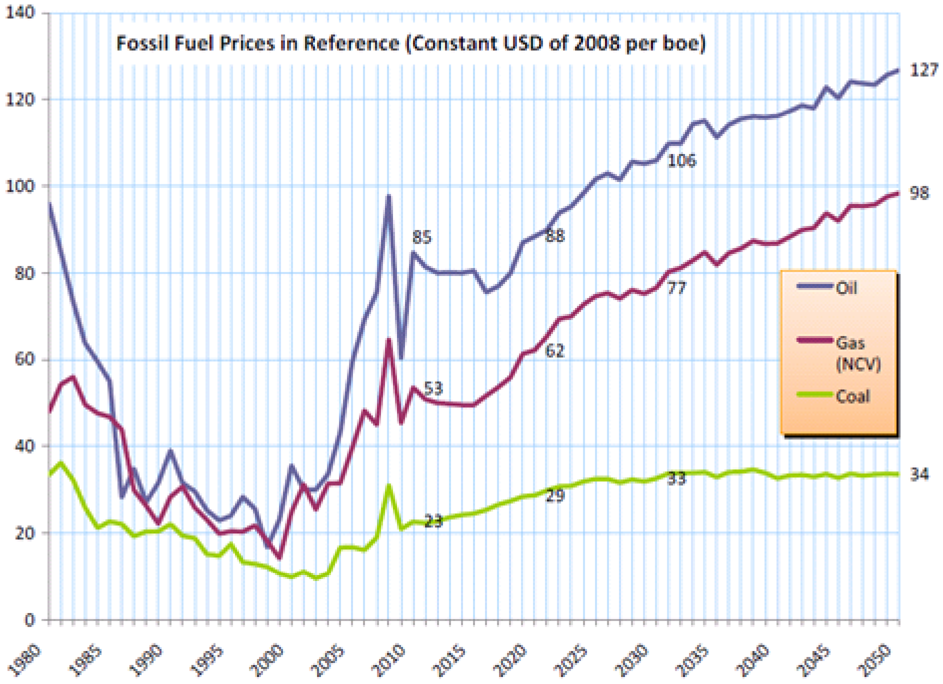
Oil price and coal price forecasts and assumed links between these and commodity prices for natural gas based transportation fuels are discussed below.
Future oil and steam coal prices were adopted from the EU roadmap 2050. This source was chosen as it is the basis of current long term EU energy policy. Prices of gasoline and other reference fossil fuels are assumed to be linked to the crude price via a simple €/GJ$_{commodity}$ ÷ €/GJ$_{crude}$ ratio, the assumed ratios as in Table 73. This approach is adopted from the authoritative JEC (2007) study.

Table 73 Assumed commodity to crude ratio's (€/$GJ_{commodity}$ ÷ €/GJ_{crude})

	Gasoline	Diesel	MGO	HFO	Kerosine
Crude to commodity ratio	1.4	1.3	1.2	0.7	1.2

The ratios have been based on actual market price overviews[13].

Figure 17 Crude oil, natural gas and steam coal price forecasts



Source: EU, 2011.

4.3.2 Natural gas prices

For the pipeline natural gas commodity price two approaches are applied:

- commodity price being linked with crude oil price;
- commodity price being linked to steam coal price.

In the first approach the market dynamics remain as they currently are and the gas price thus remains connected with the market price for crude oil. Based on the EU roadmap report (see EU, 2010) and assuming a $ to € ratio of 1.25 ÷ 1 the associated pipeline gas commodity price would amount to € 9.3/GJ.

In the second approach the connection with the crude oil price is abandoned and instead the natural gas commodity price is linked to the price of steam coal.
The assumption behind this approach is that the oil price remains high and that as a result there is an increased trade of natural gas at the spot market. This trend next forces the abandoning of the crude oil tot natural gas relation. We assume that the natural gas commodity price will next find a new

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[13] See http://www-static.shell.com/static/nld/imgs/736_wide/benz-crude-platts-advpr-2009-2010.jpg; http://www.brandstofprijzen.info/brandstof-zonder-belasting.php; http://www.bovagrai.info/auto/2011/7.5.html; http://www.iata.org/whatwedo/economics/fuel_monitor/pages/price_development.aspx, EIM, 2011 and JEC, 2007.

equilibrium based on the production costs for steam coal. The reasoning behind this assumption is that natural gas is primarily applied in heat production and power generation and that steam coal is the main fossil competitor of natural gas in power generation. We assume the natural gas price will reach a value at which power generation costs for natural gas based base load power generation are at the same level as steam coal based base load generation costs.

That there can be a competition between natural gas and coal in the power sector, even for base load generation is illustrated by the investment decision for Electrabel's Eemscentrale which was realized in the 1970s (a period with cheap natural gas) and by current developments in the US power sector where cheap shale gas is replacing steam coal in power generation[14].
The natural gas price required for generation costs that are on par with generation costs for coal based generation have been derived on the basis of the basic assumptions given in Table 74.

Table 74 Basic assumptions for calculating power generation costs

	Coal	n.g.
Capacity, MWe	1,000	1,000
Efficiency	47%	59%
Annual full load time equivalent (hours)	6,000	6,000
Investment (€/kW$_e$)	1,400	700
Annual costs, ex fuel		
a) CAPEX M€/year, at 12% annual capital charge	168	84
b) OPEX M€/year		
– per cent of investment	4%	2%
– M€/year	56	14
c) Coal tax M€/year	15	
– for LHV GJ/metric ton	25	
– and tax, €/metric ton	14	
d) CO_2 levy M€/jaar	8	4
– for levy €/ton CO_2	1.9	1.9

4.3.3 Natural gas related transportation fuels

For estimating the commodity prices of natural gas based transportation fuels different approaches per fuel are applied.

CNG price

The CNG commodity price is assumed to be equal to pipeline natural gas commodity price.
This approach implicitly assumes that CNG is supplied via large filling stations, which can be characterized as a bulk consumer. If a filling station extracts less than 10 million m^3 of natural gas annually, the commodity price will be raised with a surcharge.

LNG price

The price of LNG is assumed to be either linked to the natural gas price or to the HFO price.

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[14] See e.g.: http://www.forbes.com/sites/energysource/2012/05/30/shale-gas-takes-on-coal-to-power-americas-electrical-plants/, http://www.pacificenergydevelopment.com/1/post/2012/11/shale-gas-challenges-coals-strengths.html.

The first approach refers to a situation in which LNG can be readily regasified and supplied to conventional natural gas producers in industry and built environment and in which it competes with pipeline gas. As the costs for regasification (see e.g. ECN, 2006) are small, the market price for LNG will be comparable with that of pipeline gas.
In the second approach LNG competes with HFO and its price is related to that of its competitor. Based on DMA's extensive study (DMA, 2011), a ratio of 0.7 €/GJ_{LNG} ÷ 1 €/GJ_{HFO} is assumed.

Hydrogen

Hydrogen commodity prices are estimated based on pipeline gas commodity prices. The hydrogen price is calculated based on the assumptions in Table 75. Investment costs and plant size are based on the two new production plants in the Botlek area.

Table 75 Basic assumptions for hydrogen commodity cost calculation

	Basic assumptions		
Energy efficiency (see JEC, 2007)	76%		
M€ investment[15]	180		
Production volume[16]			
– kton/year	103		
– GJ/year	12,375,983		
Annual costs ex fuel (based on JEC, 2007), M€			
– CAPEX	22	12%	Annual capital charge
– OPEX	8	4.50%	% of investment
	30		

DME

The commodity price for DME has been estimated based on the approach in JEC (2007), assuming fixed operational costs and capital expenditure of € 3.3/GJ and a net energy efficiency for production of 70%.

GtL

Commodity costs for GtL are assumed to be comparable to that of diesel as it concerns more or less the same fuel. GtL perhaps has a lower content of aromatics and produces less particle matter during combustion but without isomerisation cloud point of GtL is higher, making it less suitable as a winter diesel.

4.3.4 Distribution costs

For distribution costs estimates following sources or approaches are applied:

- Distribution costs for gasoline and diesel are based on the same sources as utilized for estimating gasoline and diesel commodity costs (JEC, 2007).
- Distribution costs for GtL are assumed to be comparable to distribution costs for diesel.
- Distribution costs for MGO, HFO and kerosene are estimated assuming a specific cost of € 0.1/liter. Specific distribution costs are assumed to be somewhat lower than costs for distributing diesel of gasoline as MGO, HFO

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[15] Investment costs refer to the new Air Liquide and Air Products plants in the Botlek area, see e.g.: www.nieuwsbladtransport.nl/Nieuws/Article/tabid/85/ArticleID/23599/ArticleName/AirProductsopentnieuwegrotewaterstoffabriekinBotlek/Default.aspx.

[16] Production volume refers to the new Air Liquide and Air Products plants in the Botlek area, see e.g. RCI, 2011.

and kero are supplied to bulk consumers and bulk filling facilities, while gasoline and diesel are also distributed to small filling stations in the country.

- Distribution costs for H_2 and DME have been adopted from JEC (2007).
- For LNG distribution specific costs per liter are assumed to be comparable with those of diesel.
- Power distribution costs have been based on grid connection costs, assuming utilization of a 55 kW fast-fill facility with a capacity utilization rate of 30%.
- For CNG, distribution costs are based on HEI (2009). These estimates refer to a filling station with a delivery capacity of 150 m^3/hour and capacity utilization rate of 15-45% at approximately 1 kilometer of the natural gas distribution network.

4.3.5 Overview of 2025 costs levels

The resulting commodity prices and distribution costs are summarized in Table 76.

Table 76 Overview of estimated commodity costs and distribution costs

	Gasoline	Diesel	MGO	HFO	Kero	LNG		CNG	
€/GJ						High NG Price	Low NG price	High NG price	High NG price
Commodity price (f.o.b.)	18.0	15.4	15.4	9.0	15.4	9.3	8.2	9.3	9.3
Distrbution, processing, etc.	4.6	3.3	2.8	2.5	2.9	6.0	6.0	10.8	10.8
Total (price at the filling station), excl. taxes	22.6	18.7	18.2	11.5	18.3	15.3	14.2	20.1	20.1

	Power without CCS		H_2 without CCS		DME	GTL	H_2 with CCS		Power with CCS	
€/GJ	High NG price	Low NG price	High NG price	Low NG price			High NG price	Low NG price	High NG price	Low NG price
Commodity price (f.o.b.)	20.6	19.8	14.6	14.1	16.6	*15.4*	19.41	18.8	26.2	25.3
Distribution, processing, etc.	0.5	0.5	3.0	3.0	6.0	*3.3*	3.0	3.0	0.5	0.5
Total (price at the filling station), excl. taxes	21.1	20.3	17.6	17.1	22.6	*20.6*	22.41	21.8	26.8	25.9

Market prices for LNG calculated in this study are similar to the numbers in the ‘current policies scenario’ considered in PWC’s 2013 study on LNG in maritime transport. PWC, however assumes a bandwidth by way of considering different scenarios, while in this study one point is considered. Both studies also apply a similar approach by linking the LNG price to the HVO price. An overview of the key cost data and ratios is shown in Table 77.

Table 77 Comparison of fuel cost used in this study with the cost assumed in (PWC, 2013)

This study	Low NG price (€/GJ)	High NG price (€/GJ)
Diesel	18.7	

MGO	18.2	
HFO	11.5	
LNG	14.2	15.3
LNG/diesel	*0.76*	*0.82*
LNG/MGO	*0.78*	*0.84*
LNG/MGO	*1.2*	*1.3*
PWC:	Low	High
LNG/diesel	*0.6*	*0.8*
LNG/MGO	*0.7*	*0.9*
LNG/MGO	*1.1*	*1.3*

4.4 Taxation of the energy carriers

To derive the cost per kilometre for the various fuel/vehicle combinations from the consumer perspective, the different types of taxes on the fuels and energy carriers will need to be taken into account. In the current situation, these are the following:

- excise duty and other taxes (e.g. voorraadheffing) on diesel, petrol, LNG and GTL for road transport;
- energy tax (Regulerende Energiebelasting) on CNG and electricity, for all transport modes;
- VAT on all fuels and energy carriers for private (i.e. non-company) owners of vehicles.

Fuels used for shipping and aviation are currently not taxed (CNG and electricity are not used to propel these modes).

History has shown that these taxes are quite dynamic, and the level of these taxes is likely to be quite different in 2025 than in the current situation. However, because of the uncertainty of future developments, the expected 2015 tax levels are used in this report. Recent government decisions on increases of CNG and LNG tax levels between 2013 and 2015 are therefore included, as well as estimates for the annual indexation of excised duties between 2013 and 2015.

In the Netherlands, energy tax (REB) on electricity is differentiated strongly between small-scale consumers and large-scale consumers. The first, with an annual electricity demand between 0 and 10,000 kWh pay 0.117 €/kWh whereas the large scale consumers (> 10 mln kWh/yr) are charged only 0.0005 €/kWh (in 2013). Therefore, when charging an electric vehicle, the actual cost of the electricity will depend strongly on whether this is done at home (i.e. at a small-scale consumer) or at a larger scale consumer (e.g. at a company site during work hours, or a public fast charging station that has a high throughput). In this study, the current tax level of consumers between 50,001 and 10 mln kWh/yr was chosen as an estimate for the average tax to be paid for electric vehicle owners in 2025: 0.0113 €/kWh. It has to be realised, though, that some electric vehicle owners will have to pay more, and others less.

The CNG energy tax level is also strongly differentiated, with a high tariff for small-scale users and a low one for large-scale user. A separate tariff is defined for CNG used for road transport: 0.16 €/Nm^3 in 2015. However, CNG suppliers that are also large-scale consumers of natural gas may choose to rather pay the much lower tax level of that category. As it is currently not clear to what extent CNG suppliers can and will use this opportunity for lower taxes, this is not taken into account in the calculations in this report.

LNG is currently taxed as LPG, and GTL as diesel[17]. There is currently no excise duty or energy tax defined for hydrogen.

Table 78 Fuel and energy carrier taxes on road transport fuels used in this report (excise duty and other taxes, energy taxes), excl. VAT

	Diesel	Petrol	CNG	LNG	GTL	H_2	Electricity
Tax per standard unit	0.489 €/l	0.780 €/l	0.16 €/Nm^3	0.325 €/kg	0.489 €/l	0	0.0118 €/kWh
Tax in €/GJ	13.64	24.24	4.26	6.63	14.25	0	3.14

In line with the vehicle taxation assumed in this report (Section 3.8), the current 21% VAT was added to all fuels (incl. excise duties) for the two passenger cars, but not for the other vehicle categories.

To illustrate these data, an overview of the road transport fuel and energy carrier tax levels used in this report are also shown in Figure 18. Clearly, there is a large range of taxes in place, with relatively high taxes on petrol, and much lower levels on many of the natural gas routes. Note that these data translate to quite different taxes per kilometre, as the energy efficiency of the various drive trains differ (i.e. the GJ/km). This is especially true for electricity (and hydrogen): the energy efficiency of electric vehicles is typically about 2.5 times of that of vehicles with a combustion engine, resulting in much less GJ electricity per kilometre. As explained above, fuels for shipping and aviation are not taxed at all.

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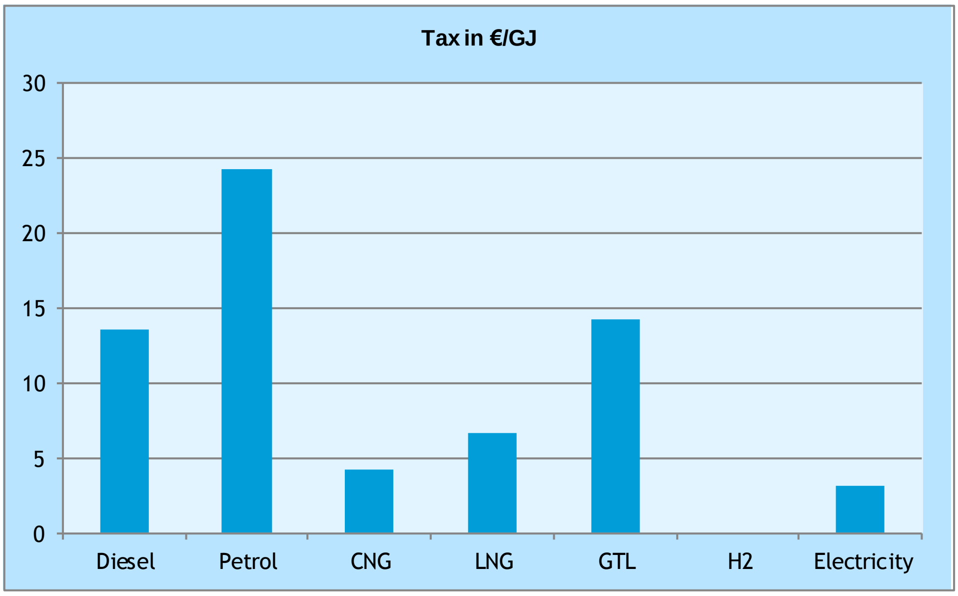
[17] Excise duty levels are defined in €/litre, but as GTL has somewhat lower energy content as diesel, the tariff per GJ is somewhat higher for GTL than for diesel.

Figure 18 Taxes on fuels and energy carriers for road transport as used in this report, incl. excise duty and energy tax, excl. VAT



4.5 Conclusions

In the Well-To-Tank part the main greenhouse gas emissions are CO_2 and methane (CH_4). The Global Warming Potential (GWP 100 years) of methane has increased over time in the IPPC publications from 21 in 1996 to 25 in 2007. This means that one kg of methane has over a 100 year period the same effect as 25 kg CO_2. So the routes are substantial sensitive to the amount of methane emissions. But this is not the whole story. The GWP of methane for 20 years is 72. So the short term effects of methane are substantial higher than the number of CO_2 eq. indicates.

The route of liquid hydrogen compered to gaseous hydrogen costs substantial more energy than LNG compared to CNG.

Due to the limited number of Gas to Liquid (GTL) projects the public knowhow of the energy use of making GTL is also limited.

The WTT CO_2 eq. emissions of electricity and hydrogen without Carbon capture and storage (CCS) are substantial higher than the other routes. Also the energy use is higher. But this is compensated by the absence of CO_2 emission in the TTW route and by the better efficiency of the vehicles on electricity or hydrogen.

Two estimates will be used for the natural gas price: a high NG price, linked to the oil price, and a low NG price, in line with low estimates used in recent literature. Based on these commodity prices, estimates could be derived regarding the cost for consumers of the various NG-based fuels and energy carriers. These were found to vary widely, and range from 14.2 €/GJ for LNG to 29.5 €/GJ for electricity (all excluding taxes).

The tax levels for the road transport fuel and energy carriers range widely:

- taxes for petrol are the highest (24 €/GJ), while diesel and GTL are taxed around 13.5-14.5 €/GJ;
- in contrast, taxes for CNG, LNG are much lower (about 4 €/GJ), thereby close to electricity with a slightly lower tax value of about 3 €/GJ;
- fuels for shipping and aviation and hydrogen are not taxed.

5 Potential for decarbonisation

5.1 Introduction

In this chapter, the various routes will be assessed within the context of the future decarbonisation of the transport sector. The EU has set itself and its Member States ambitious GHG emission goals for the future - 80% overall GHG reduction in 2050, with a subtarget of 60% reduction in the transport sector - and has implemented various policies in the transport sector that are aimed at reducing GHG emissions and to gradually shift from fossil fuels towards renewable energy.

Some of the natural gas chains investigated in this report have lower greenhouse gas emissions (WTW) than the reference fuels and could therefore contribute to these goals, but except for the hydrogen and electricity routes with CCS, these benefits are relatively limited. Meeting the CO_2 emission goals of 2020 and beyond clearly require a shift to renewable energy or other CO_2 mitigation options such as CCS.

The previous chapters looked at the potential effects of the various natural gas routes on the life cycle GHG emissions of transport. This chapter will now focus on the shift to renewable energy, and on the question whether the natural gas routes can all shift to renewable energy sources to similar extends. Issues that will be addressed here are

- CO_2 emissions and energy efficiency of potential renewable energy options cost;
- future potential to convert the route to renewable energy;
- potential timing of this shift to renewable energy sources, potential in 2025;
- potential lock-in effects: could investments in the routes form a barrier to future decarbonisation and deployment of renewable energy options in the transport sector;
- does the current policy framework promote a shift to renewable energy?

5.2 Most promising renewable energy options

Different renewable options exist for the various natural gas routes analysed in this report. The renewable alternatives considered in this study were selected on the basis of four criteria: the low carbon alternative technology

- should produce a transport fuel with the same specifications as the fossil reference it should substitute;
- should already be commercially available or should become commercially available before 2020;
- should be employable in the Netherlands;
- should allow production of decarbonized or low carbon alternatives at price levels that are not prohibitive.

Without the first precondition a shift from natural gas based transportation fuel to a renewable alternative cannot be made readily, but will require additional investments for e.g. adjusting of vehicles.

The second criterion is related to the time window considered in this study, the period between 2020–2030.
The low carbon alternative should allow for the replacement of a significant proportion of the natural gas based transport fuel after 2030. Given the 'normal' speed with which new technologies are introduced in the industry the technology should already be commercially available or should become so within a few years.

The third criterion is aimed at excluding low carbon production chains which require renewable energy sources not available in and not importable into the Netherlands. Hydrogen production based on large scale hydropower for example is not really an option for this country.

The criterion related to price levels per unit of renewable transport fuel is aimed at excluding renewable alternatives which will require prohibitive subsidies when implemented on a large scale.
A level of prohibitive subsidies of costs is defined here as requiring more than the total current SDE budget of € 3 billion.

The renewable alternatives selected and excluded on the basis of these criteria are mentioned in Table 79.

Table 79 Renewable alternative processes (decreasing technical probability and/or economic viability from top down)

LNG	CNG	GTL	DME	H_2	Power
Biomass anaerobic digestion + mini LNG	Anaeribic digestion + compression	HVO from biomass	Biomass gasification + MeOH/DME	Wind and solar power (surplus) + H_2O electrolysis	Wind and solar power
Biomass gasification + mini LNG	Biomass gasification + compression	BTL: biomass gasification + Fischer Tropsch processing		Biomass gasification + H_2 production	Biomass boiler or co-combustion

BTL: Biomass gasification + Fischer Tropsch processing.

Specifications of the different excluded and selected technologies in relation to the criteria 2 and 4 are given in Table 80. All technologies measure up to the first and third precondition.

Table 80 SNG = Synthetic Natural Gas

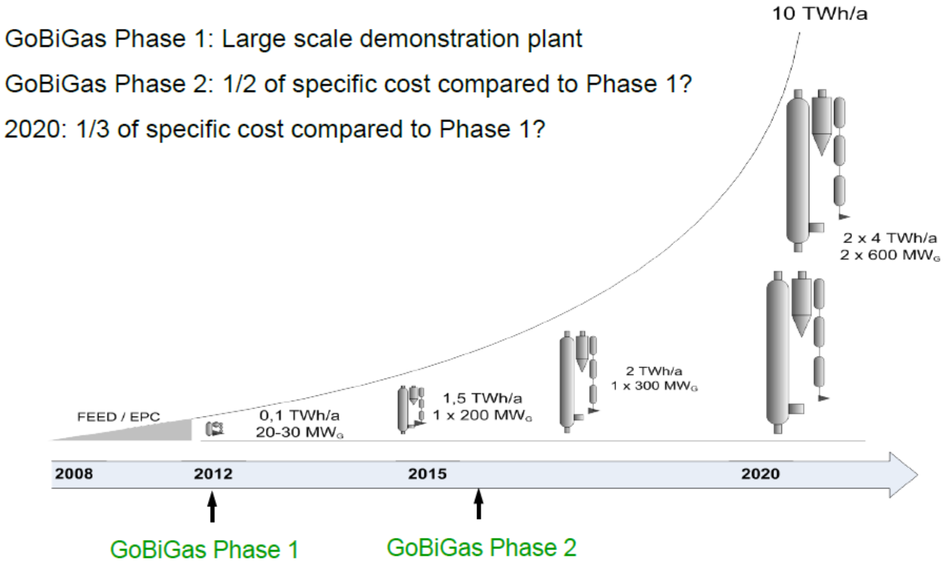
	Development status	Based on	Price level	Potential
LNG alternatives				
A.d. and mini LNG	Commercial	Residual biomass, Energy crops		
Biomass gasification + SNG production	Pilot, 1st commercial demo planned for 2016?			
CNG alternatives				
A.D. and compression	Commercial	Residual biomass, Energy crops		
Biomass gasification + SNG production	Pilot			
GtL alternatives				
HVO production	Commercial (Neste)	Dutch or imported vegetable oil	€ 25/GJ - € 35/GJ	Large
BtL	Demonstrated (Choren β)/ commercial plants being built in Finland	Imported wood		Large
DME alternative				
Biomass gasification + methanol production	Commercial	Imported wood		Large
H_2-alternatives				
Wind power + water electrolysis	Commercial	Dutch wind		
Biomass gasification	Commercial	Imported wood		Large
Renewable power				
Wind power	Commercial	Dutch wind		100 GWhe
Co-combustion	Commercial	Imported wood		Large

LNG and SNG production

Anaerobic digestion of non woody biomass with subsequent gas treatment (CO_2 removal) and liquefaction or compression of biomethane was considered the most viable option. This route seems to be commercially viable even without subsidies when based on central digestion of the dry fraction of surplus manure (see ZLTO, 2011).

SNG production was evaluated as probably being in a too early stage of development as a first semi commercial is still being constructed and should become operational in 2013. It will next be the basis of a 10 year research program. Though a second installation at commercial scale has been planned to become operational in 2016 this is still uncertain as long as there is no practical experience with the demo-scale installation.

Figure 19 **Plans for the development of gasification in Sweden: the GoBiGas project**



Source, see www.egatec2011.dk/presentations/thursday12/PS2Ea_Gunnarsson_egatec2011.pdf

GtL, DME and H_2

As an alternative for GtL only HVO production as applied at Neste in Rotterdam was selected.

Biomass gasification and subsequent conversion of syngas into hydrogen or ethanol on the other hand were evaluated as being commercially proven, in view of the commercial installations in Berrenrath (methanol) and Oulu (ammonia), that were operated in the nineteen eighties.

5.3 Assessment of the various routes

These renewable energy have now been assessed qualitatively against the following criteria:
- maturity of the technology;
- energy efficiency (Well-To-Wheel);
- CO_2 emissions (Well-To-Wheel);
- sustainability potential;
- costs;
- other pros and cons, including feedstock availability.

The amount of waste as feedstock is, compared to the total energy demand of the transport sector, very limited. If a feedstock is needed grown on farmland, there is a direct food versus fuel discussion. Non-food (lignocellulosic) biomass is one of the key options to contribute to decarbonization of the transport sector, although overall bio feedstock availability is limited (ECN, 2011). Although the food versus fuel discussion might be less there are still other sustainability issues

An overview of the scores is shown in Table 81.

Table 81 Scores of different routes for decarbonisation of transport fuels

	LNG	CNG	GTL	DME	H_2	H_2	H_2	Electricity	Electricity	Electricity
Evaluation Criteria	**Anaerobic digestion + mini-LNG**	**Anaerobic digestion + compression**	**HVO production**	**Biomass gasification + methanol prod.**	**Wind power + electrolysis**	**Solar power + electrolysis**	**Biomass gasification + H_2 prod.**	**Wind power**	**Solar power**	**Biomass (direct) co-firing**
Maturity	o	+ +	+ +	o	+	+	o	+ + +	+ +	+ + +
E-efficiency	+[1]	o	+ +	+	o	o	+	+ + +	+ +	+ + +
CO_2 emission	+ +	+ +	+	+ +	+ + +	+ + +	+ +	+ + +	+ + +	+ +
Sustainability potential	+	+	-	+	+ +[3]	+ +[3]	+	+ +[3]	+ +[3]	+
Costs	- -	- -	-	- -[2]	- -	- - -	- -[2]	-/o[4]	- -[5]	-/o[4]
Pros, cons, feedstock availability	Small scale, waste also used elsewhere, food vs. fuel	Small scale, waste also used elsewhere, food vs. fuel	Food vs. fuel	Lingo cellulosic biomass (2nd gen.)	Windy location required, limited commercial electrolysis know how, intermittency	Limited commercial electrolysis know how, intermittency	Ligno-cellulosic biomass (2nd gen.)	Windy location required, inter-mittency issue	Inter-mittency issue	Ligno-cellulosic biomass (2nd gen.)

	best			*average*			*worst*
Ranking scale	+ + +	+ +	+	o	-	- -	- - -

Footnotes/remarks

1) Liquefaction combined with cryogenic gas cleaning (CO_2 removal) results in relatively better efficiency
2) Expensive production plant
3) Relatively small surface area required, compared to biomass
4) Cheapest sustainable option in large quantities
5) Future cost reduction expected

The main issues related to the various types of renewable energy are the following.

Biomass based routes

The overall amount of biomass is limited and the transport sector is not the only sector interested. In the Netherlands there is a growing use of waste streams for energy purposes. It is possible to grow additional biomass, but a discussion about food versus fuel and other sustainability issues is ongoing, also taking into account the growing claims on global land for other purposes.

The route of small scale digestion is relatively costly and is not very energy efficient.

Non-food (lignocellulosic) biomass used for gasification has a greater potential. However lignocellulosic biomass is also used outside the transport. Within the transport sector, there are competing routes for this source, especially production of bioethanol and BTL.

Wind and sun

The use of electricity from renewable sources (wind, sun) as a source for transport fuels has less limitations compared to biomass, especially because these options require less surface area. Sun and wind are sources with intermittency, as they depend on the fluctuating intensity of wind and solar radiation. Here biomass could play a balancing role. In addition smart charging of electric vehicles can balance intermittencies and similarly hydrogen production (and storage).

5.4 Policies to decarbonise the various energy routes

5.4.1 Introduction

All of the routes investigated here have renewable energy options as an alternative, whose share could gradually increase over time without having to modify fuelling (or charging) infrastructure or the vehicle and engine technology. If the renewable energy is cheaper than the natural gas, the market will do this without government intervention, but if it is not, as in the current situation, policy measures and incentives are needed to achieve this transition.

There are a number of policies in place, both in the Netherlands and on EU level, to promote the use of renewable energy in transport that also apply to natural gas used in transport. However, these policies differ between the transport modes and the various natural gas routes. For example, some of the gas routes (GTL in road transport) fall under the biofuels obligation, where others (e.g. the CNG or LNG routes) can apply for SDE+ subsidy.

In the following, we provide an overview of the current situation regarding the relevant policy measures in the Netherlands. Note that this overview focusses on the policies that promote the decarbonisation of the various routes, and does not look at policies that promote the natural gas routes itself.

5.4.2 Biofuels obligation

The Dutch biofuels obligation applies to fuel suppliers that sell diesel and/or petrol to road transport. These have to ensure that a minimum share of the transport fuels they sell is renewable. This share increases over time, was 4.5% in 2012 and is 5% in 2013. In addition, a minimum share of 3.5% needs to be met for diesel and petrol, how fuel suppliers meet the rest of the obligation is up to them.

The biofuels obligation is the Netherland's transposition of the transport part of the Renewable Energy Directive, RED (EC, 2009a), which sets a target of 10% renewable energy in transport for 2020, for all Member States. Most of this target is expected to be met by biofuels, which have to meet the sustainability criteria defined in the RED to count towards the target.

Other renewable energy options that may count towards the target are renewable electricity, biokerosine and biomethane. The latter can be either used directly in transport, as bio-CNG or bio-LNG, or administratively, via injection into the natural gas grid (the so-called 'groen gas' or 'green gas' route). This 'green gas' route is currently the preferred option for many biomethane suppliers. The renewable electricity contribution is determined by multiplying the amount of electricity used in transport by the share of renewable electricity, either in the Netherlands or in the EU. If the renewable electricity is used in road transport, it can also be multiplied by 2.5 to compensate for the higher energy efficiency of electric vehicles.

However, the biofuels obligation only applies to suppliers of diesel and petrol for road transport and does not apply to electricity, kerosene or natural gas suppliers. Suppliers of these fuels/energy carriers may 'opt-in' the biofuels obligation, voluntary submitting them to this obligation. This means that they have to meet the target mentioned above (5% in 2013), but any excess renewable energy may be sold to other fuel suppliers via 'biotickets'. This is therefore an interesting option for suppliers that offer any of these three types of energy carriers to Dutch transport, and intent to have higher shares of renewable energy in their fuel than the minimum target. This option to 'opt-in' has not (yet) been put in place for hydrogen suppliers.

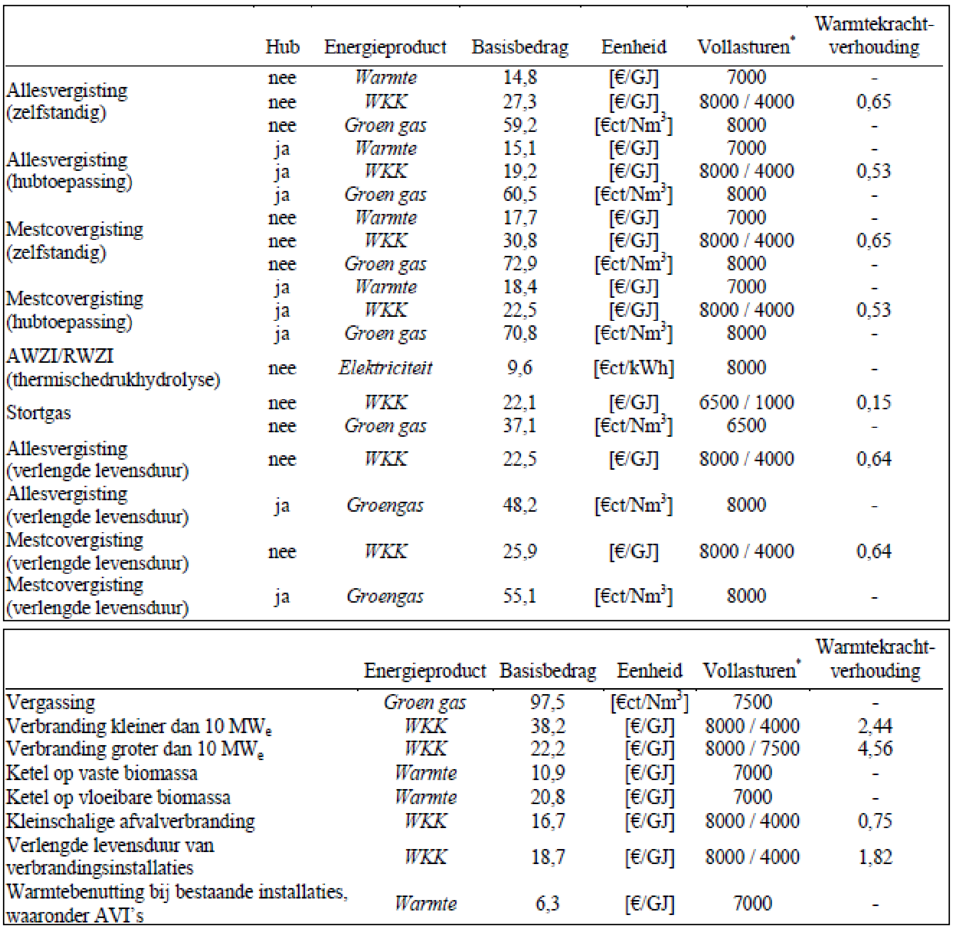
This biofuels obligation is therefore an effective policy to ensure an increase of renewable energy in the reference fuels of road transport, and in GTL, which counts as diesel in the obligation. It can provide support to increase renewable energy in CNG, LNG and electricity in road transport, but as it is only voluntary for suppliers of these fuels, it does not ensure this transition. The obligation does not impact suppliers of hydrogen or DME, as it is not (yet) included in opt-in option, and it does not extend to the shipping sector. Renewable hydrogen, DME and all forms of renewable energy in inland shipping are, however, included in the Renewable Energy Directive, i.e. these count towards the 10% target for 2020. It is therefore likely that these routes will also be included in the Dutch legislation in the future, once they become relevant.

5.4.3 SDE+

The SDE+ subsidy scheme provides financial incentives to producers of renewable electricity, heat and biogas, and can also be used in case this renewable energy is then used in the transport sector. Producers have to choose, however, whether they want to use the SDE+ or the opt-in option of the biofuels obligation, they can not apply to both.

The SDE+ compensates for the excess costs for production of power, heat or green gas compared with the fossil fuel based commodity price.
The production costs – the so-called basic rate or 'Basis Bedrag' - are estimated per production technology by a group of experts and on the basis of information from initiators and projects in the field. The basic rates currently considered are given in Table 82.

Table 82 Overview of the basic rates that apply to the various forms of biogas in the SDE+



	Hub	Energieproduct	Basisbedrag	Eenheid	Vollasturen*	Warmtekracht-verhouding
Allesvergisting (zelfstandig)	nee	*Warmte*	14,8	[€/GJ]	7000	-
	nee	*WKK*	27,3	[€/GJ]	8000 / 4000	0,65
	nee	*Groen gas*	59,2	[€ct/Nm^3]	8000	-
Allesvergisting (hubtoepassing)	ja	*Warmte*	15,1	[€/GJ]	7000	-
	ja	*WKK*	19,2	[€/GJ]	8000 / 4000	0,53
	ja	*Groen gas*	60,5	[€ct/Nm^3]	8000	-
Mestcovergisting (zelfstandig)	nee	*Warmte*	17,7	[€/GJ]	7000	-
	nee	*WKK*	30,8	[€/GJ]	8000 / 4000	0,65
	nee	*Groen gas*	72,9	[€ct/Nm^3]	8000	-
Mestcovergisting (hubtoepassing)	ja	*Warmte*	18,4	[€/GJ]	7000	-
	ja	*WKK*	22,5	[€/GJ]	8000 / 4000	0,53
	ja	*Groen gas*	70,8	[€ct/Nm^3]	8000	-
AWZI/RWZI (thermischedrukhydrolyse)	nee	*Elektriciteit*	9,6	[€ct/kWh]	8000	-
Stortgas	nee	*WKK*	22,1	[€/GJ]	6500 / 1000	0,15
	nee	*Groen gas*	37,1	[€ct/Nm^3]	6500	-
Allesvergisting (verlengde levensduur)	nee	*WKK*	22,5	[€/GJ]	8000 / 4000	0,64
Allesvergisting (verlengde levensduur)	ja	*Groengas*	48,2	[€ct/Nm^3]	8000	-
Mestcovergisting (verlengde levensduur)	nee	*WKK*	25,9	[€/GJ]	8000 / 4000	0,64
Mestcovergisting (verlengde levensduur)	ja	*Groengas*	55,1	[€ct/Nm^3]	8000	-

	Energieproduct	Basisbedrag	Eenheid	Vollasturen*	Warmtekracht-verhouding
Vergassing	*Groen gas*	97,5	[€ct/Nm^3]	7500	-
Verbranding kleiner dan 10 MW$_e$	*WKK*	38,2	[€/GJ]	8000 / 4000	2,44
Verbranding groter dan 10 MW$_e$	*WKK*	22,2	[€/GJ]	8000 / 7500	4,56
Ketel op vaste biomassa	*Warmte*	10,9	[€/GJ]	7000	-
Ketel op vloeibare biomassa	*Warmte*	20,8	[€/GJ]	7000	-
Kleinschalige afvalverbranding	*WKK*	16,7	[€/GJ]	8000 / 4000	0,75
Verlengde levensduur van verbrandingsinstallaties	*WKK*	18,7	[€/GJ]	8000 / 4000	1,82
Warmtebenutting bij bestaande installaties, waaronder AVI's	*Warmte*	6,3	[€/GJ]	7000	-

Source: www.ecn.nl/docs/library/report/2011/e11054.pdf.

5.4.4 EU ETS

Electricity production is included in the EU Emission Trading System (EU ETS). Electricity producers therefore have to submit CO_2 emission allowances for every ton of CO_2 they emit. These allowances have a market value, as they can be bought and sold, and traded between participants of the system.

The CO_2 emissions of renewable energy are counted as zero in this system, which provides a financial incentive to increase the share of renewable energy production – provided that the price of emission allowances is high enough to compensate the higher cost of the RE. In the current situation, the price of the allowances is, however, much too low to contribute to this shift. The SDE+ scheme provides much more significant compensation.

Aviation was also planned to be included in the ETS, but this decision has been delayed recently[18]. If this will indeed be the case in the future, shifting to biofuel will reduce the amount of emission allowances that the aviation operators need to submit, as biofuels would count as zero CO_2 emissions in the system. However, the incentive would be very limited as long as the price of the allowance is low, additional cost of biokerosine and bio-LNG cost are currently much higher than the allowance price.

Note that hydrogen production plants (as well as oil refineries) in the EU are also included in the EU ETS. However, they do not have to submit allowances for the fuels they produce, only for the direct emissions of the plants. Shifting to renewable hydrogen may reduce these direct emissions to some extend, but the resulting incentive is expected to be very limited.

5.4.5 Fuel Quality Directive

This EU directive (EC, 2009b) has set a GHG reduction target for the average Well-To-Wheel GHG emissions of transport fuels, in 2020: fuel suppliers have to ensure that these emissions reduce by 6%, between 2010 and 2020.

The national implementation of the FQD requires fuel suppliers to reduce the GHG emissions of their fuels as follows[19]:
- 2% in 2014;
- 4% in 2017; and
- 6% in 2020.

It is expected that the renewable transport fuels and energy that is used to comply with the biofuels obligation will significantly contribute to these targets as well.

Note that the FQD target only applies to fuels used in road transport, non-road mobile machinery (including inland shipping), agricultural and forestry tractors and recreational craft while not at sea. It does not, therefore, incentivise renewable energy options in sea shipping and aviation.

5.4.6 The overall renewable energy target

The EU Renewable Energy Directive sets mandatory renewable energy targets for all Member States for 2020, the target for the Netherlands is 14%. In 2012, the Dutch government decided to aim for a more ambitious target, 16% renewable energy in 2020[20]. A range of renewable energy sources are expected to be used to meet this target, and various policies are implemented to increase the share of renewable energy in the various sectors and thus meet this target – including the policy measures such as the biofuels obligation and SDE+ listed above.

Transport energy, excluding bunker fuels and kerosene (for international, non-EU use), are also included in the overall renewable energy target. The renewable energy in this sector counts towards the transport target mentioned above as well as towards this overall target of 16%. It should be noted that the national and EU targets itself, however, will not provide a direct incentive to fuel suppliers or users to increase the share of renewable

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[18] http://ec.europa.eu/clima/policies/transport/aviation/index_en.htm.

[19] http://www.agentschapnl.nl/programmas-regelingen/nederlands-beleid-biobrandstoffen #verplichting.

[20] See http://www.government.nl/issues/energy/sustainable-energy.

energy, only specific policy measures (obligations, financial incentive, etc.) will be effective in that respect.

5.5 Conclusions

A range of options exist to decarbonise the various natural gas routes in the future. For example, CNG and LNG can be gradually replaced by biomethane (produced by anaerobic digestion and perhaps, in the future, gasification of biomass), GTL can be replaced by biodiesels such as HVO and BTL and various renewable electricity options exist that can replace the natural gas-based electricity production.

When comparing these options, the main issue is that the biomass based routes are faced with a limited overall amount of biomass. Furthermore, the transport sector is not the only sector interested in these feedstocks.
Coal power plants can use it as fuel, the chemical industry as a feedstock and the build environment as source of green gas.

The use of waste is a preferred and highly sustainable option, but the resource of it is rather small. It is possible to grow additional biomass on farmland, but a discussion about food versus fuel and other sustainability issues is ongoing. For the first generation of biofuels the amount of fuel produced per ha of farmland and the CO_2 eq. reduction is not always high. For instance the route of small scale digestion is relatively costly and is not very energy efficient. Also fresh bio feedstock from farmland is expensive. Non-food (lignocellulosic) biomass used for gasification of chemical/biological conversion has a greater potential and causes less discussion about food versus fuel. More waste is available, but it has to be collected (for instance forest residues).
For additional biomass also land area is needed causing sustainability issues, but the CO_2 eq. reduction might be better. In general lignocellulosic feedstock costs are lower but the conversion processes are more expensive, and not as far developed as first generation processes.

It can be concluded that biofuels are one of the key options to contribute to decarbonization of the transport sector, although overall bio feedstock availability is limited (ECN, 2011). Those Biofuels will have additional cost compared to fossil fuels. Decarbonisation can take place in both liquid and gaseous routes, due to the limited penetration there is no prove for a lock in effect in the next decade.
The use of electricity from wind, sun as a source for transport fuels has less limitations compared to biomass, especially because these options require less surface area. Sun and wind are, however, sources with intermittency, as they depend on the fluctuating intensity of wind and solar radiation. With growing penetration of sustainable electricity, additional storage/consumption options are needed. Car batteries or hydrogen are such an option. Direct use of electricity is more efficient than making first hydrogen from it[21].

Some of these renewable options are already being promoted by existing policies, namely the biofuels obligation, the FQD and the SDE+ subsidies. However, the incentives differ strongly between the various routes, and a number of routes, namely all shipping options as well as the use of H_2 and DME in transport are not yet explicitly included in the Dutch renewable energy policy.

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[21] It is even technical possible to take a next step and combine hydrogen with CO_2 to make gaseous or liquid fuels. If this is still a decarbonisation route, depends on the CO_2 source.

With the exception of sea shipping, however, these routes are included in the RED and the FQD, and are likely to be included in the Dutch biofuels obligation in the future.

An overview of the current policy incentives is shown in Table 83.

Table 83 Overview of current policy incentives for renewable energy in the Netherlands (status January 2013)

Transport mode	Reference fuel	LNG	CNG	GTL	DME	H_2	Electricity
Road transport: passenger cars, truck, bus, trailer-truck	Biofuel obligation FQD	SDE+ Voluntary opt-in in biofuels obligation FQD	SDE+ Voluntary opt-in in biofuels obligation FQD	Biofuel obligation FQD	FQD	FQD	SDE+ Voluntary opt-in in biofuels obligation ETS FQD
Shipping: inland, short sea and deep sea	No incentive	No incentive	-	No incentive	-	-	-
Aviation	Voluntary opt-in in biofuels obligation ETS	Voluntary opt-in in biofuels obligation ETS	-	Voluntary opt-in in biofuels obligation ETS	-	-	-

NB. The options indicated by '-' are not considered in this report.

6 Assessment of safety issues

6.1 Introduction

The safety part of this assessment aims at the analysis of the external safety of the intended LNG distribution chain and infrastructure for road and sea transport and the identification of possible safety issues. Furthermore, missing knowledge for a final determination of the safety risks will be identified.

The safety assessment is reported separately in detail in Dutch (TNO report 2013 'Veiligheid van aardgastransportroutes', J.J. Meulenbrugge, I.M.E. Raben and H.G. Bos). Below the results of the safety assessment, an important boundary condition for the introduction of LNG as transport fuel, are summarized.

It is important to note that the risk calculations have been performed using the currently available risk tools like SafetiNL, the draft PGS 33 document for the description of the installations and the draft guideline for risk calculation for LNG filling and bunkering stations. These are all draft documents and contain assumptions for the design and dimensions of the installations, the modeling (and physical behavior) of LNG and the failure frequencies. Also the projected total transport volume of LNG in 2025 is based on 'the Green Deal Rijn en Wadden' (agreement between ministries of Economic Affairs and Environment and private LNG-companies of 2012) and is an estimate for the real transport volume in 2025.
For transport risks, currently no LNG specific (draft) tools or documents exist; a qualitative indication is given based on existing tools for transport of other hazardous materials.
It is believed that these assumptions are on the conservative side, meaning that when more definitive and improved figures and information become available, the calculated risks may well be smaller than the risks calculated in this study.

6.2 Risks of LNG filling and bunkering stations (fixed installations)

The risk of the LNG installations are calculated using the standard risk tools in the Netherlands: SafetiNL and PGS- design criteria (e.g. double wall tanks). The basis for the calculations is a total LNG usage of 2.5 Mton in 2025 of which 1,0 Mton will be used for transport fuels for trucks and the remaining volume as transport fuel for inland and short-sea ships. The calculated distances depicting the 10^{-6} risk contour of various LNG stations are presented in Table 84.

Table 84 **Distances till the individual risk contours (in meters) for different LNG installations**

IR contour	LNG Bunkering station (m)	LNG Filling station (m)
10^{-5}	60	5
10^{-6}	125	90
10^{-7}	580	170
10^{-8}	760	230

LNG bunkering station

The calculated 10^{-6} risk contour for bunkering stations is 125 m. This is a considerable distance but given the industrial locations where these bunkering stations will be located (and therefore the absence of vulnerable objects), locations suitable for establishing these stations will be available.
Attention should be paid to the Societal Risk. Due to the large 10^{-7} and 10^{-8} contours and the related large effect areas, occupation over a large area should be taken into account. With locations carefully chosen, it is expected that problems with external safety can be avoided.

LNG filling station

The 10^{-6} risk contour for a LNG filling station is 90 m. This is roughly the same as for a standard LPG filling station with a throughput > 1,000 m^3/year.
The LNG filling station is calculated with a typical throughput of 5,000 m^3 per year.
For this study LNG filling stations are calculated with an aboveground LNG storage tank (with associated higher vulnerability than an underground storage tank).
A risk contour of 90 m for a LNG filling station may cause problems with the external safety for many of the existing fuel stations. There is, however, a number of actions that can be taken to reduce the calculated risks:

- Optimization of the design of the LNG installations: e.g. underground/protected storage tanks will lead to lower risks.
- Improved impact modeling: specific and validated effect models for LNG will lead to more realistic calculations. Especially the model for pool spreading and evaporation on water and the dispersion model for LNG need further validation.
  Besides the instantaneous release of large amounts of LNG and the subsequent effects needs further investigation.
- Drafting of LNG specific failure frequencies: LNG installations have proven elsewhere to be safe but specific data are lacking, especially for small scale distribution. Therefore generic failure frequencies of tanks and hoses have been used.

These options seem to give room for LNG filling stations to be introduced in several places, especially those outside urban areas.

6.3 Risk of LNG transport routes

LNG transport the basic transportation road network (‘basisnet weg’)

The transport calculations are performed using the software package RBM II and the scenario’s and failure frequencies as described in HART (Handleiding Risicoberekeningen Transport), according to the official procedure to calculate transport risks of hazardous materials in the Netherlands.
The road transport volume of LNG is estimated to be 1 Mton per year in 2025, based on the assumptions used in the ‘Green Deal Rijn en Wadden’.
In this study it is assumed that the numbers of LNG trucks transports and the distribution over the roads will be similar to the diesel transports. The number of diesel tucks is corrected for the lower total volume of LNG and for the smaller content of a LNG tank truck compared to a diesel truck.
In this way, for the distribution of LNG by tanker trucks it is foreseen that a majority of the road sections of the ‘basisnet weg’ in the Netherlands will be used for LNG transport. *For most of these road segments, LNG transport will lead to exceedance of the accepted risk level for these segments.*

This high degree of exceedance can be illustrated by the fact that the LNG transport will be additional to the LPG transport. The latter is the risk determining factor on the roads and consumes most of the accepted risk level. The projected LNG volume is more than double the current LPG volume for LPG filling stations. So, the (currently already limited) free risk space left on the 'basisnet weg' is insufficient to accommodate this relatively large LNG transport volume on the road.

The following picture (Figure 20) shows the most critical road segments where a new 10^{-6} risk contour is expected These critical road segments are primarily located around Rotterdam (A15, A16, A20) and possibly around Eindhoven and Venlo. Especially at these road segments and locations problems with external safety might be expected, and hence need further investigation.

It is important to note that the level of magnitude of the risks calculated for the road transport might be rather conservative due to:
- LNG is calculated in RBM II with the example substance propane (GF3) because RBM II cannot specifically calculate with LNG. This gives an overestimation of the risks.
- The current models are not validated for LNG phenomena (e.g. evaporation, dispersion) and might therefore also be conservative.
- Calculations are performed with a transport volume of 1 Mton per year, this is probably an overestimate for the reference year 2025.

These points, once solved, might lead to better and more realistic calculations of the risks of LNG.

However even if lower volumes and more realistic risk calculations are applied, the introduction of LNG road transport will still lead to exceedance of the risk levels for the 'basisnet weg' at many road segments and locations.

To proceed with the introduction of LNG as a transport fuel, the following actions are recommended:
- introduce a LNG specific substance class in RBM II to allow for specific LNG risk calculations with effect models validated for LNG phenomena;
- reduce the road transport volumes as much as possible by a modal shift to water transport.

Additionally the starting points and boundary conditions of the 'basisnet weg' could be reconsidered to allow more transport and related higher risk levels.

Figure 20 **Most critical road segments**

LNG transport the basic network Water ('basisnet water')

For transport over the 'basisnet water', no problems are expected. It is therefore unlikely that inland transport of LNG at any location will pose a problem with the 10^{-6} risk contour.

LNG transport by rail

Rail transport was not anticipated in this safety study for the following reasons:

- many railways cross city centers and additional risks of LNG transport in these areas is not preferred;
- there is always the possibility of venting of the tankers due to boil off during long journeys and/or parking , which will not be easily accepted;
- the LNG depots and filling stations are often not located near railways, leading to additional handling and transport which makes transport by rail inefficient.

For cross-border transport to the Ruhr region the 'Betuwe route' railway might be an option. When relevant a Betuwe route LNG safety study will need to be performed separately.

6.4 Conclusions

The entire safety study is based on reasonable assumptions for the transport volume, the modality, the transport routes, the design and dimensions of the installations, etc.

Several of these assumptions may give rise to discussion, however the final conclusion seems robust and relatively independent of the underlying assumptions:

- LNG bunkering stations seem to pose no problem with the external safety although attention is required for the societal risk.
- LNG filling stations have fairly large risk contours but some options are available to reduce the risk, creating probably sufficient possibilities for safe locations for these filling stations.
- The transport of LNG over water seems to be possible without any problems related to external safety.
- The transport of LNG over the road ('basisnet weg') in a significant volume will pose a significant problem due to exceed the risk level for a large number of road segments. Without any additional actions the expected volume of LNG cannot be absorbed by the 'basisnet weg'.

7 Overall assessment

7.1 Introduction

In this chapter, the results of the previous chapters are combined to provide an overall assessment of the various routes. Well-To-Tank and Tank-To-Wheel results are combined to determine Well-To-Wheel (i.e. life cycle) emissions, energy use and costs. The findings regarding future decarbonisation potential are included to provide an overall, comprehensive picture of the various natural gas applications in transport. Note that the safety assessment is not included here as only LNG safety has been assessed, and the findings do not lead to a strong preference for specific applications.

The Well-To-Wheel results are first given for the individual transport modes and vehicle categories. Based on these results, a specific scenario is developed to estimate the total impacts of a given volume of LNG in 2025: 2.5 mln ton. This scenario is in line with the one used for the safety assessment described in the previous chapter.

7.2 Natural gas in Light Duty Vehicles

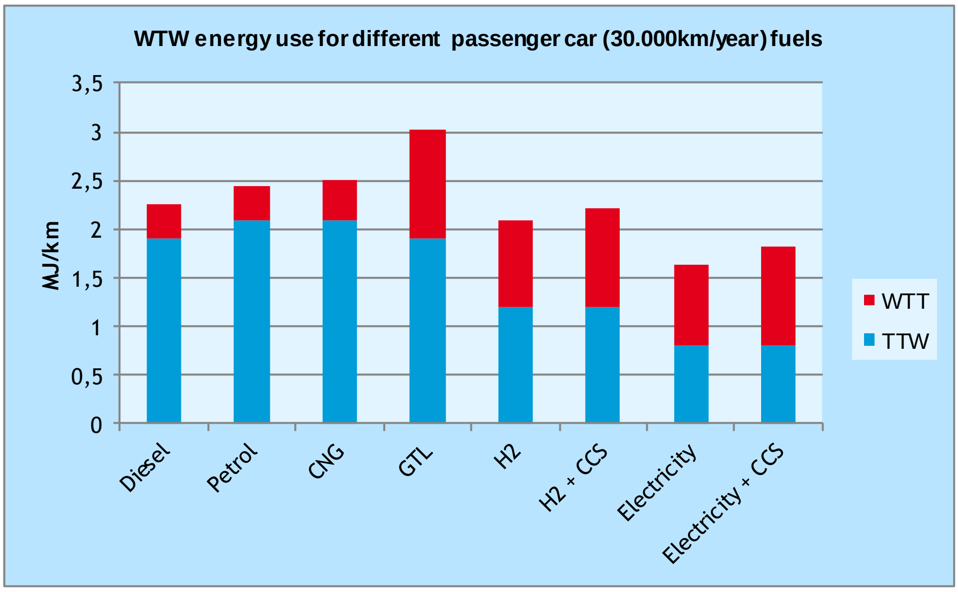
Combining the WTT and TTW results presented earlier, the WTW emissions and energy use of the various fuels/energy carriers can be calculated. In the following, these results are presented for the various light duty vehicles assessed in this report: the two passenger car applications and vans. All results are shown as specific values per kilometre, to allow a fair comparison of the various alternatives.

7.2.1 Passenger cars

The WTW emissions and energy use of the two passenger car applications are very similar, so only the results for passenger car no. 1 (30,000 km/yr, diesel as reference fuel) are shown here for all fuels and energy carriers.

When comparing the Well-To-Wheel energy use results, Figure 21, it can be concluded that the CNG and GTL routes are less energy efficient than the reference fuel diesel, where the performance of CNG is comparable to that of petrol. The production of GTL is relatively energy intensive, compared to diesel, petrol and CNG, resulting in significantly higher WTW energy use per kilometre. The NG-to-hydrogen and electricity routes, however, are expected to improve overall energy efficiency, especially due to the relatively high efficiency of these drive trains compared to the internal combustion engine used in the other options. As CCS requires energy input, energy use of these routes is somewhat higher than that of H_2 and electricity without CCS.

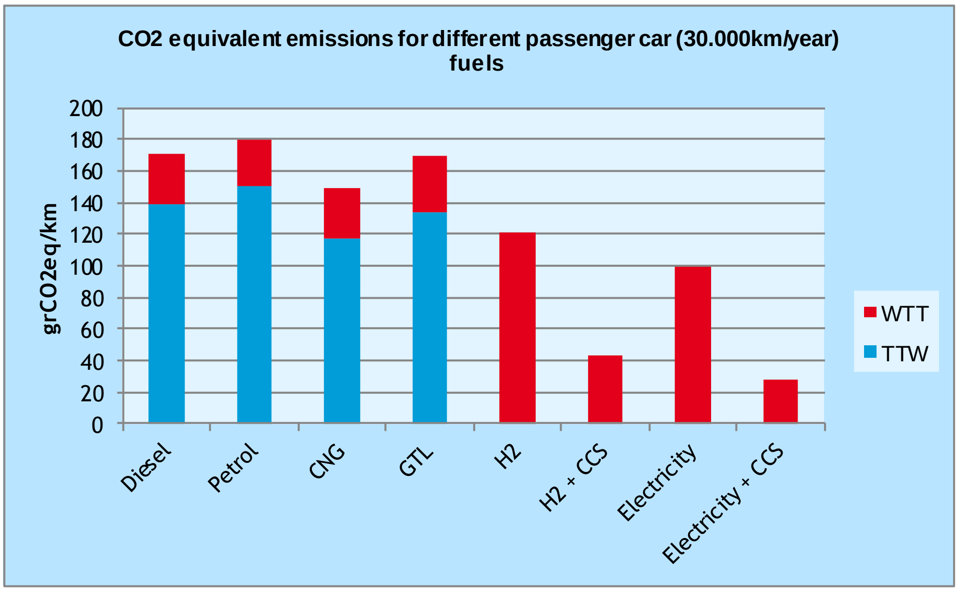
Figure 21 WTW energy use for different NG-based energy carriers - passenger cars, 30,000 km/yr



The graph of Well-To-Wheel CO_2 emissions is shown below. It is somewhat different than that of the energy use due to the lower carbon content of the natural gas compared to diesel and petrol. CNG therefore scores relatively well in the Tank-To-Wheel part of the emissions. Furthermore, the CCS routes score significantly better than the other routes, as a significant part of the carbon content of the consumed natural gas is then sequestered.

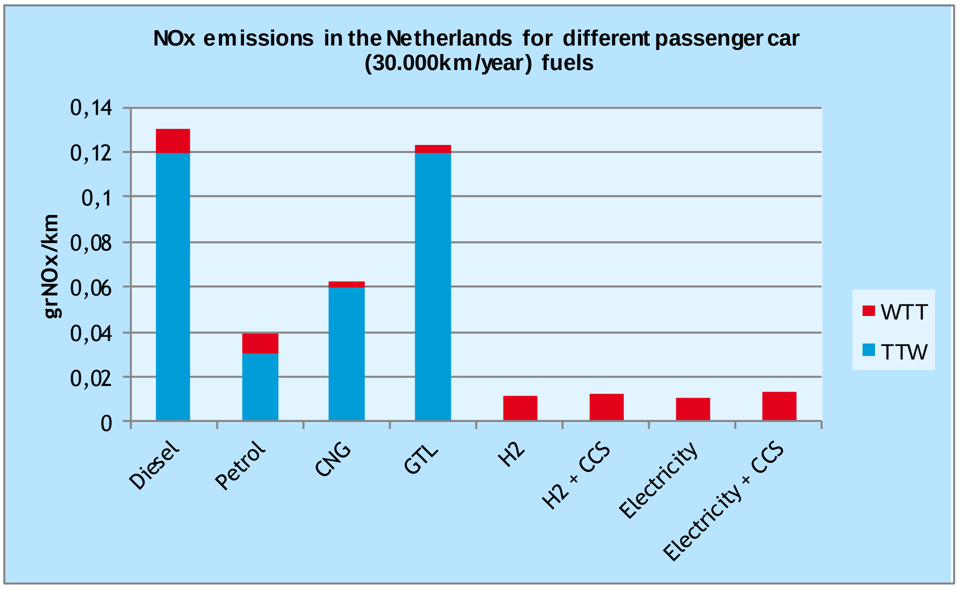
When comparing different natural gas routes on WTW energy use and WTW CO_2 eq. emissions, there can be a big difference between the WTT and TTW distribution. This is caused by the difference in where the CO_2 is released in the route. If we compare the differences in total column length of CNG, GTL, H_2 and electricity in Figure 21 and Figure 22 they are almost the same.
As expected there is almost a direct relation between total energy use and total CO_2 eq. emission. Difference are related to methane emissions and the some differences fuels used in the WTT part. In case of GTL, much hydrogen is used in the GTL production, increasing the carbon content of the fuel in the TTW part. In case of electricity and hydrogen all CO_2 eq. emissions take place in the WTT part.

Figure 22 **WTW GHG emissions for different NG-based energy carriers - passenger cars, 30,000 km/y**



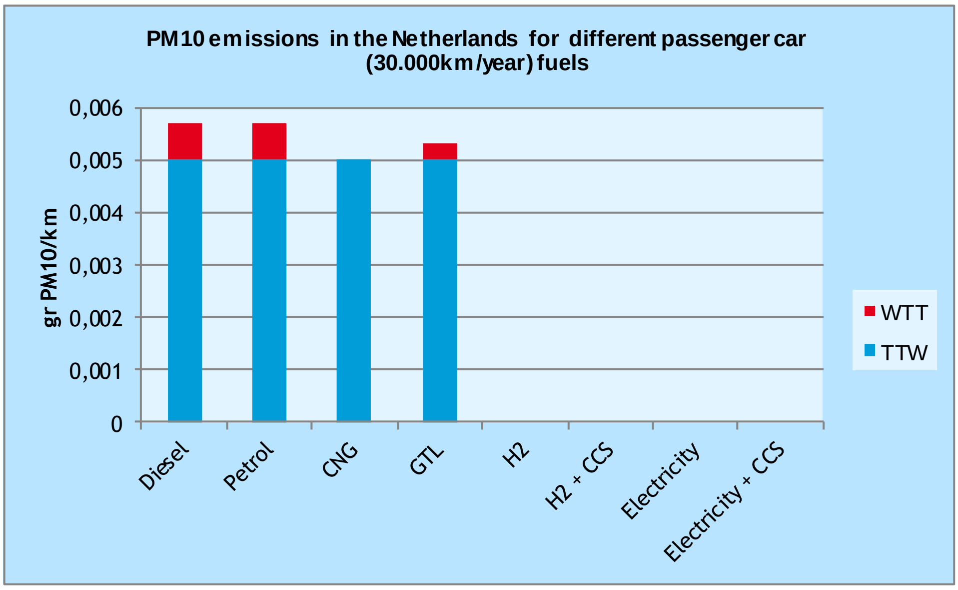
NO$_x$ emissions of diesel cars are expected to be significantly higher than those of petrol cars, even in 2025 – albeit the levels will be much lower than in the current situation. As GTL is used in standard Euro 6 diesel vehicles, their TTW emissions are more or less the same. WTT NO$_x$ emissions of GTL are expected to be somewhat lower than that of diesel. The petrol and CNG vehicles have much lower NO$_x$ emissions than diesel and GTL. NO$_x$ emissions of the H$_2$ and electricity routes are even lower. In these cases, the vehicle emissions (TTW) are zero, but some NO$_x$ emissions occur at the hydrogen conversion or power plant.

Figure 23 **NO$_x$ emissions for different NG-based energy carriers - passenger cars, 30,000 km/y**



PM$_{10}$ emissions are quite comparable for the routes that use internal combustion engines as the emissions standards are converging. PM$_{10}$ emissions are expected to be zero for the hydrogen and electricity routes.

Figure 24 PM$_{10}$ emissions for different NG-based energy carriers - passenger cars 30,000 km/y



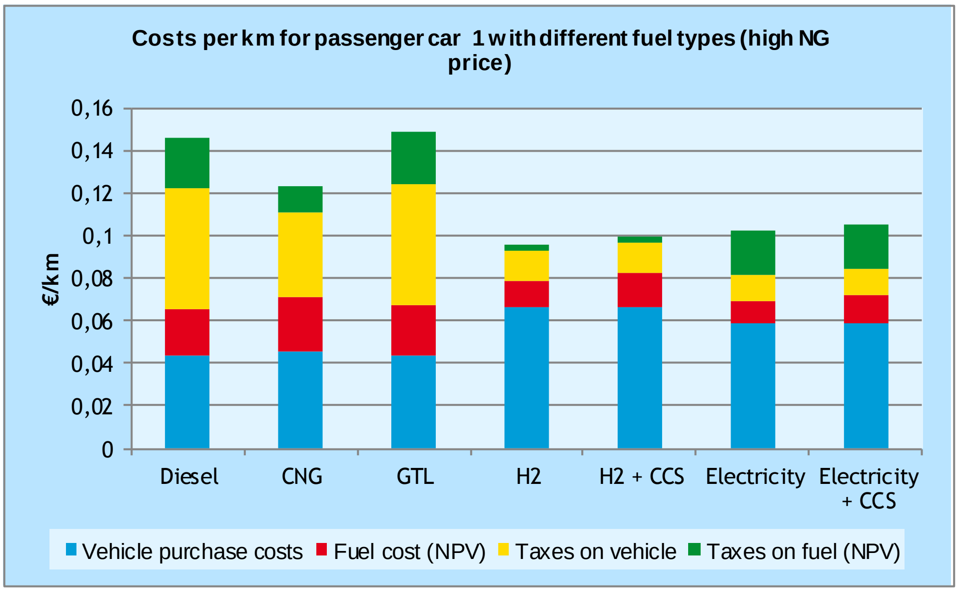
Cost per kilometre are shown in Figure 25 below, for passenger car (30,000 km/year) and the high natural gas price scenario. Total cost are composed of

- vehicle purchase cost;
- fuel cost (net present value, NPV, see Chapter 3 and 4);
- taxes on the vehicle;
- taxes on the fuel and energy carriers (NPV).

The lower two (blue and red) columns represent the cost per kilometre without taxes, the upper two (yellow and green) are vehicle and fuel taxes, at current tax levels (as explained in Section 3.10).

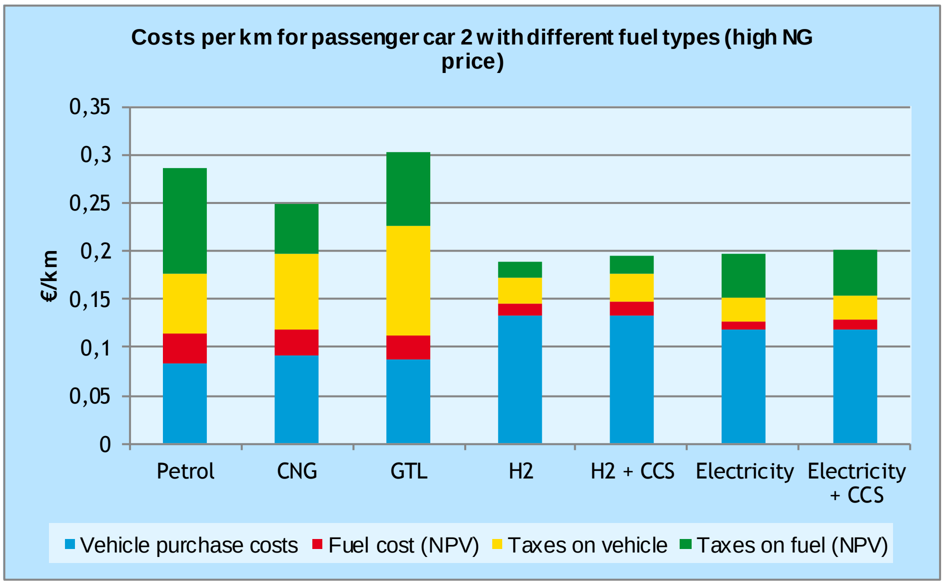
The figure clearly shows the significant impact of taxation on the total cost of the various fuels: without taxes the cost of diesel, CNG and GTL are quite comparable, with diesel being the cheapest. Driving on hydrogen or electricity produced from natural gas leads to higher cost – mainly due to the higher purchase cost of the vehicles, which are only partly compensated by lower energy cost. With taxes on vehicle and fuels, however, the hydrogen and electricity routes are the most attractive to car owners, with the assumptions regarding vehicle and energy cost used in this report (see Chapters 3 and 4). This is mainly due to the exemption from all vehicle taxes except VAT: MRB and BPM are currently zero for these zero-emission cars. The relatively low tax on CNG (4.3 €/GJ versus 12 €/GJ for diesel and 25.3 €/GJ for petrol) results in an overall cost advantage of about 0.02 € /km for CNG cars, compared to diesel or petrol.

Figure 25 Cost per km for different NG-based energy carriers - passenger cars 30,000 km/y, high NG price



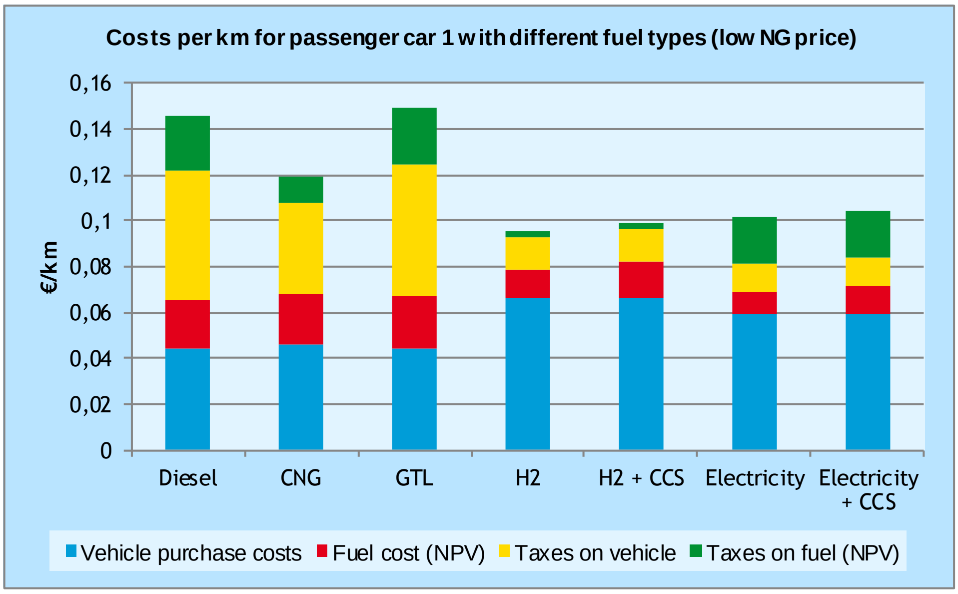
As these cost depend quite strongly on the annually driven kilometres and lifetime of the vehicles, cost results for passenger car 2 are somewhat different, and shown in Figure 26. However, even though the cost levels are higher, the overall conclusions are the same.

Figure 26 Cost per km for different NG-based energy carriers - passenger cars 15,000 km/y, high NG price



If the low natural gas cost is assumed, the costs of the various NG routes are reduced somewhat, but overall findings are not affected. Figure 27 shows the result for passenger car 1, at low NG price.

Figure 27 Cost per km for different NG-based energy carriers - passenger cars 30,000 km/y, low NG price



With these results, it can be concluded that for passenger cars, the routes where natural gas is converted to hydrogen or electricity score best from an environmental point of view. They achieve the highest WTW energy efficiency, reduce CO_2 emissions (especially if CCS is applied as well), have very low NO_x emissions (at power plant, vehicle emissions are zero) and negligible PM_{10} emissions. The cost of these routes are, however, higher than the reference and the other NG routes (CNG and GTL) if taxes are excluded. If the current taxation scheme would still apply in 2025, cost including taxes would be favourable for electricity and hydrogen produced from NG.
When comparing the natural gas options that use conventional (ICE) drive trains, we can conclude that CNG has some benefits regarding cost including taxes, GHG and pollutant emissions. WTW energy use per kilometre is somewhat higher than that of the reference fuels, and cost excluding taxes as well. GTL has no benefits compared to the rest of the fuels.

7.2.2 Vans

The same calculations were done for vans, the results of which are shown next.

When comparing the various energy options, the overall trends and conclusions are very similar to those of passenger cars:

- the hydrogen and electricity routes score well on both energy efficiency and (all) emissions;
- compared to diesel, CNG has (some) benefits regarding CO_2 and pollutant emissions, but Well-To-Wheel energy use is somewhat higher;
- GTL has no significant benefits regarding these criteria.

Figure 28 WTW energy use for different NG-based energy carriers - vans

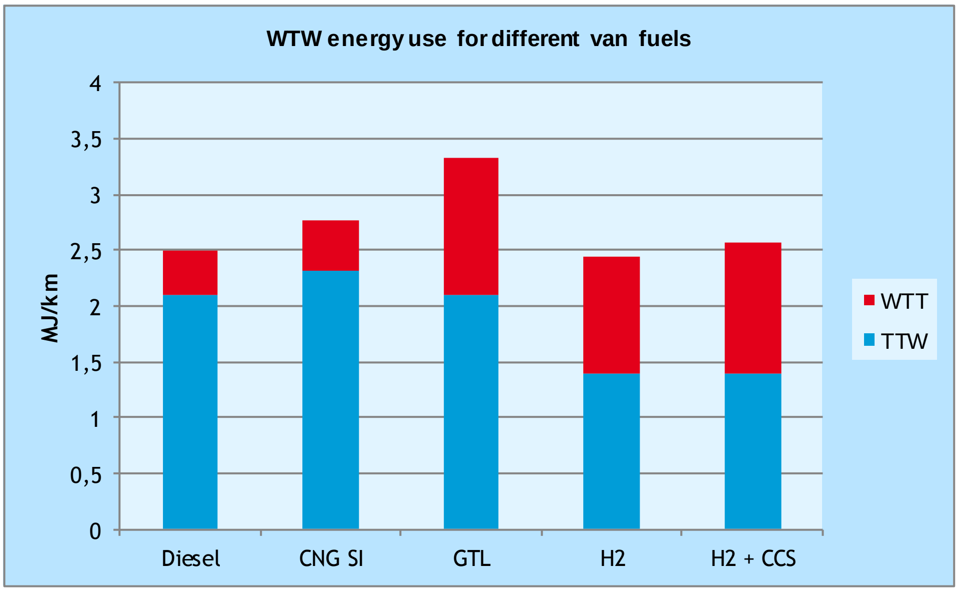


Figure 29 WTW GHG emissions for different NG-based energy carriers - vans

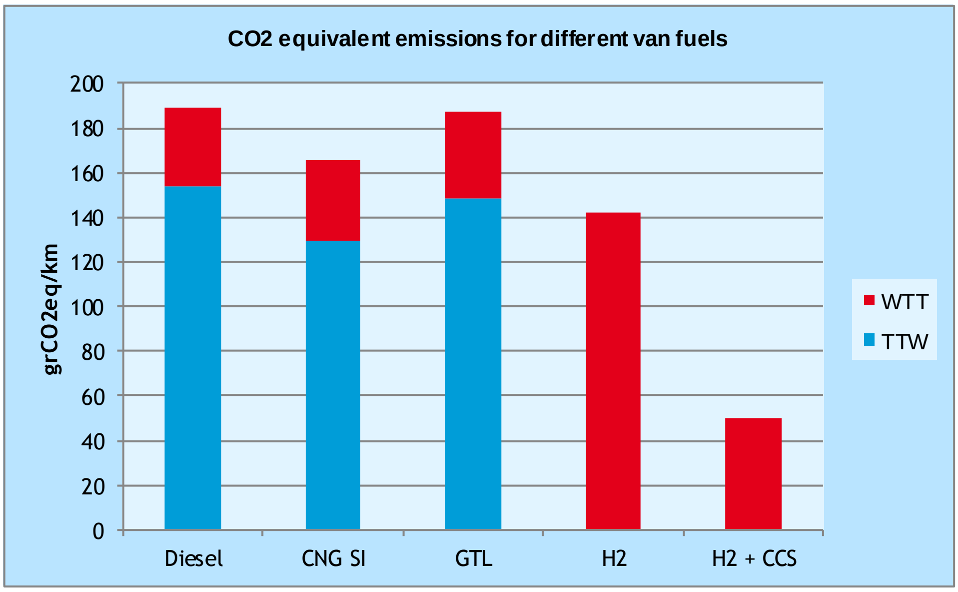


Figure 30 NO_x emissions for different NG-based energy carriers - vans

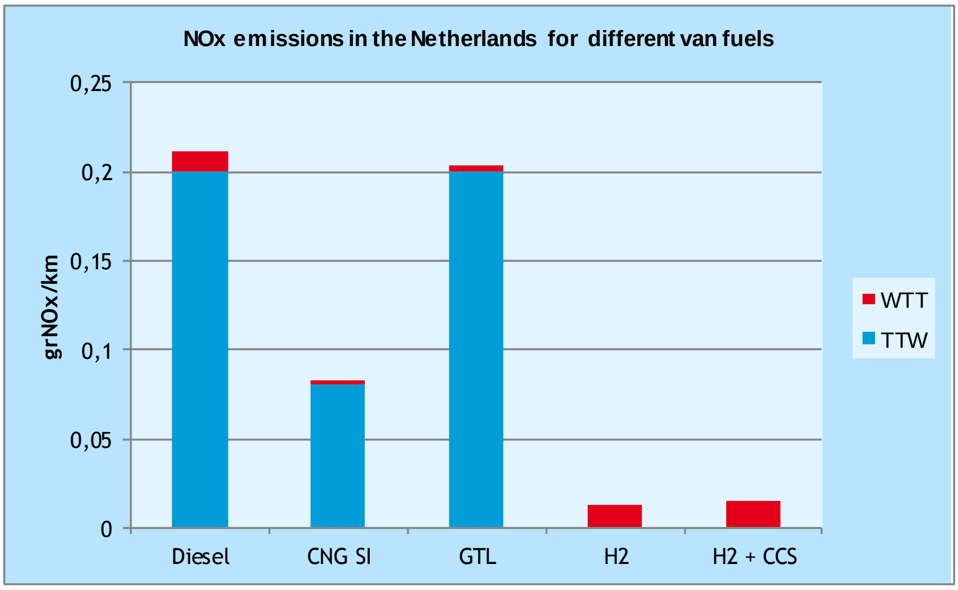
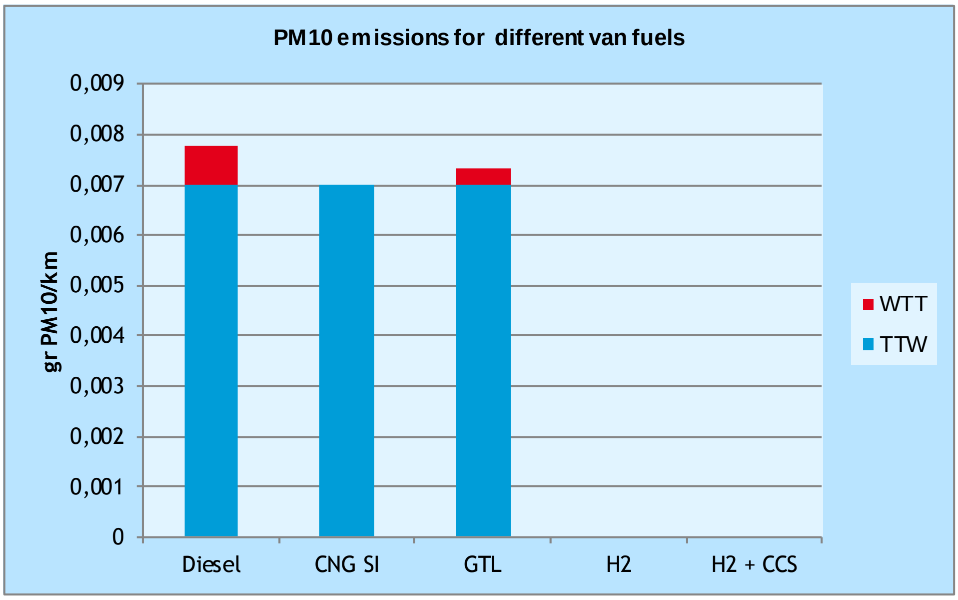


Figure 31 PM_{10} emissions for different NG-based energy carriers - vans



The only differences are related to the cost:

- With the high NG price assumption, the cost of CNG use in vans is higher than that of the reference fuels also with taxes included, mainly because of the relative high purchase cost of CNG vans. In the low LNG price assumption, CNG results in about the same cost per kilometre.
- Cost of hydrogen in vans is also higher than that of the reference fuel and the alternatives, also with taxes included. This is mainly due to the relatively costly vehicles, which cannot be compensated by the lower fuel cost.

Figure 32 Cost for different NG-based energy carriers - vans, high NG price

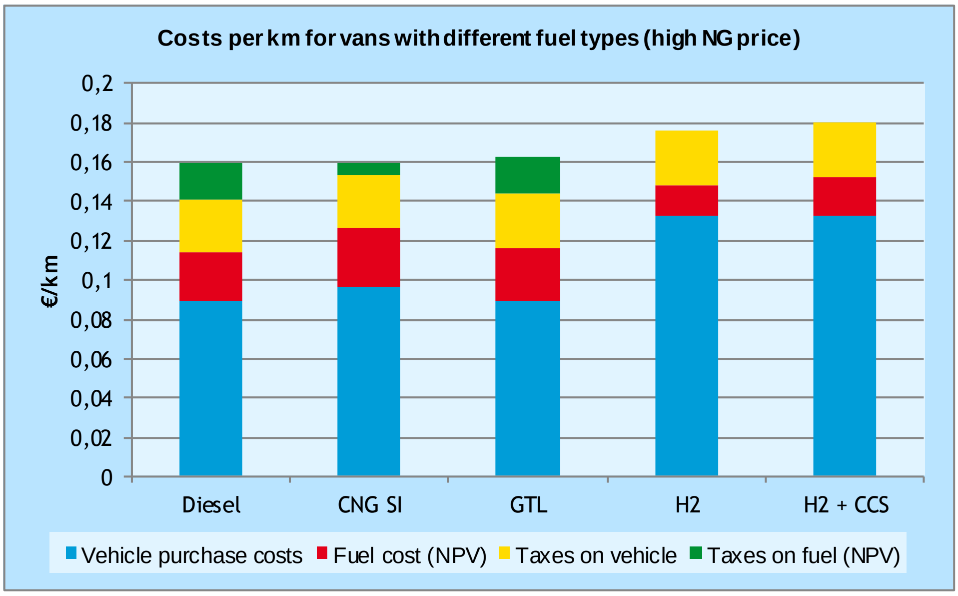
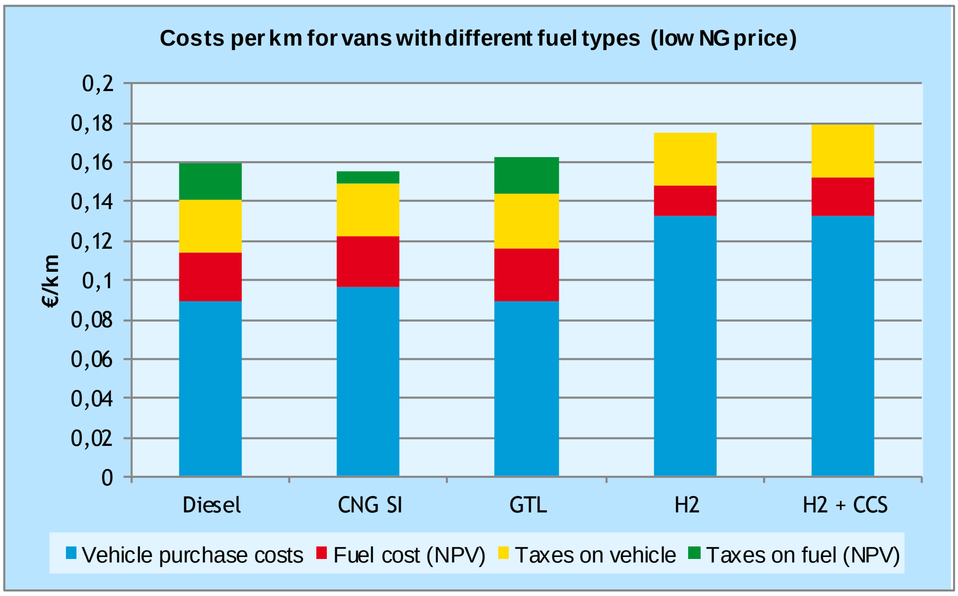


Figure 33 Cost for different NG-based energy carriers - vans, low NG price



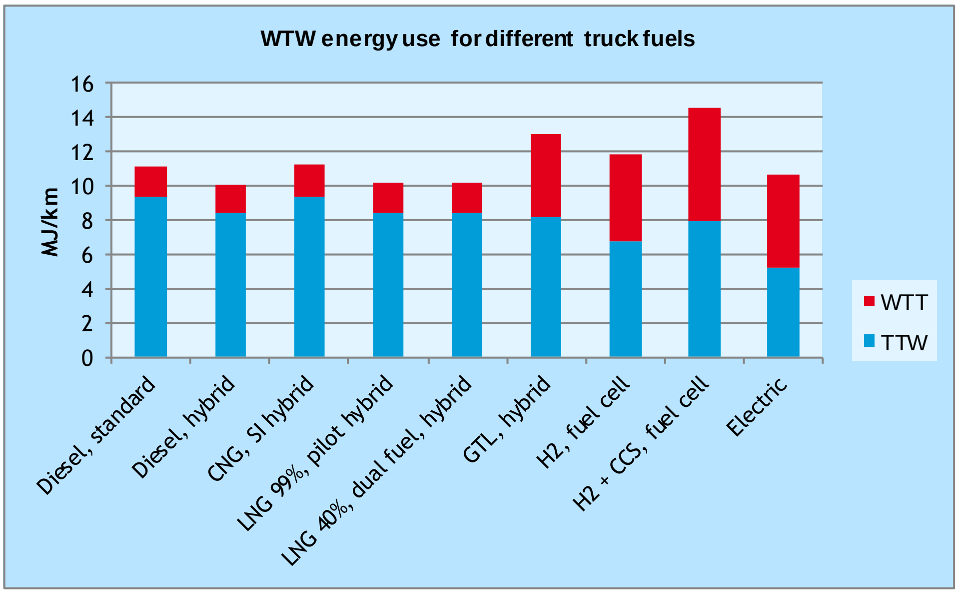
7.3 Natural gas in Heavy Duty Vehicles

7.3.1 Rigid trucks

The Well-To-Wheel results for the rigid truck are shown in the following figures.

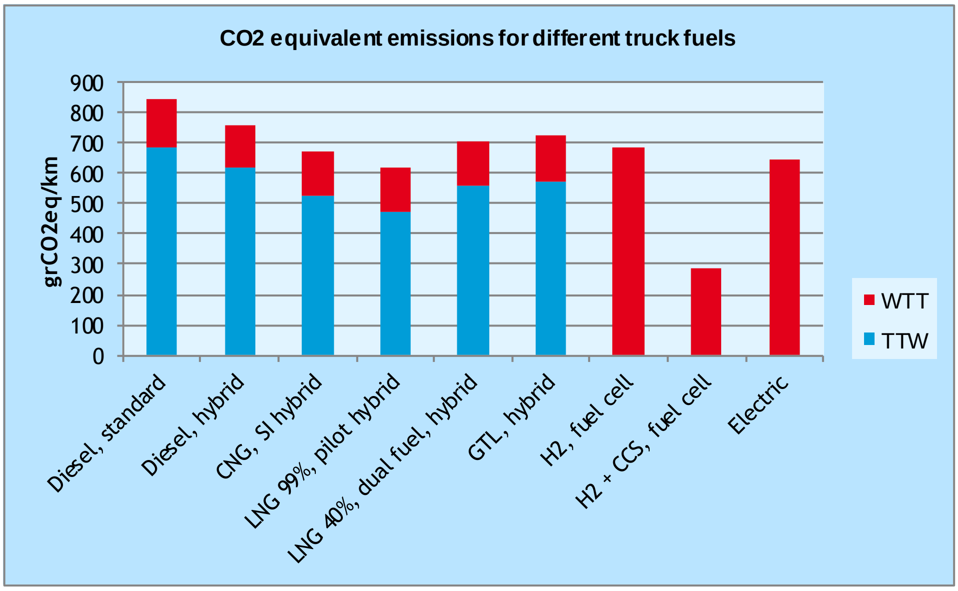
From an energy efficiency point of view, the natural gas routes do not seem to offer any benefits compared to a hybrid diesel truck, and both GTL and H_2 score significantly worse.

Figure 34 WTW energy use for different NG-based energy carriers - rigid trucks



The GHG emissions show a different picture, though, as the CNG hybrid, LNG pilot (99% LNG), and electric vehicle achieve about 10-20% reduction WTW compared to the standard diesel vehicle. The hydrogen route with CCS is found to reduce CO_2 emissions by about 60%. The dual fuel hybrid (40% LNG), GTL hybrid and H_2 without CCS options have WTW GHG emissions that are quite comparable to the diesel hybrid.

Figure 35 WTW GHG emissions for different NG-based energy carriers - rigid trucks



NO_x emissions are comparable to the diesel hybrid except for the H_2 and electric routes, where these emissions are significantly reduced. Well-To-Wheel PM_{10} emissions are negligible in case H_2 or electricity from natural gas is used. The differences between the other options are limited.

Figure 36 NO$_x$ emissions for different NG-based energy carriers - trucks

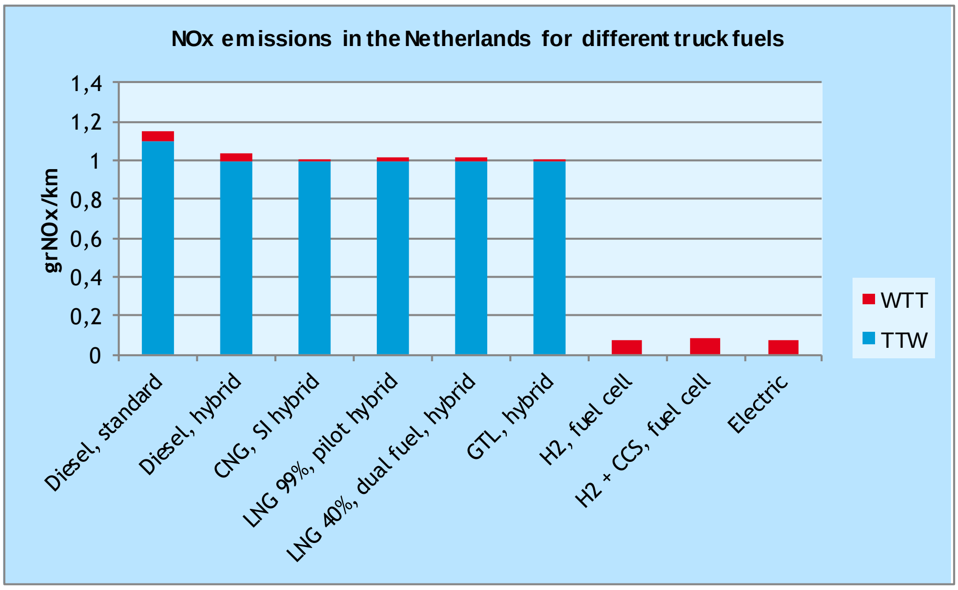
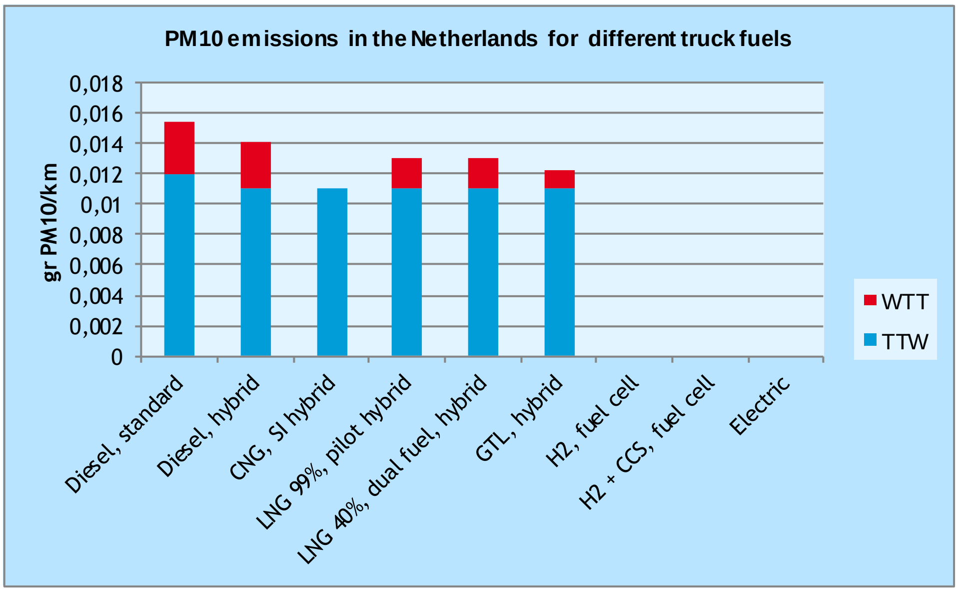


Figure 37 PM$_{10}$ emissions for different NG-based energy carriers - trucks



The cost results (in €/km) are shown in Figure 38 (high NG price) and Figure 39 (low NG price), again with the lower two bars (blue and red) the cost without taxes, and the upper two bars representing the (current) taxes.

With the assumptions used in this report, if we look at cost without taxes, the cost of natural gas routes are comparable (LNG pilot, GTL) to, somewhat higher (CNG and LNG dual fuel) or significantly higher (H_2) than that of diesel hybrid trucks. However, the relatively low taxes on LNG result in an overall cost advantage for LNG pilot. The lower taxes on CNG, LNG and H_2 do not compensate the higher vehicle cost in these routes.

Figure 38 Cost for different NG-based energy carriers - trucks, high NG price

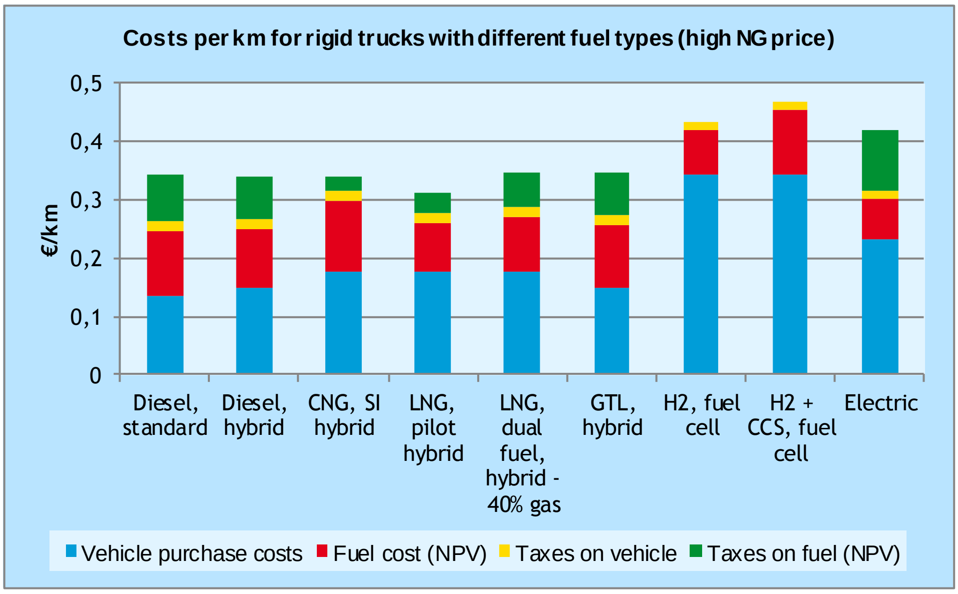
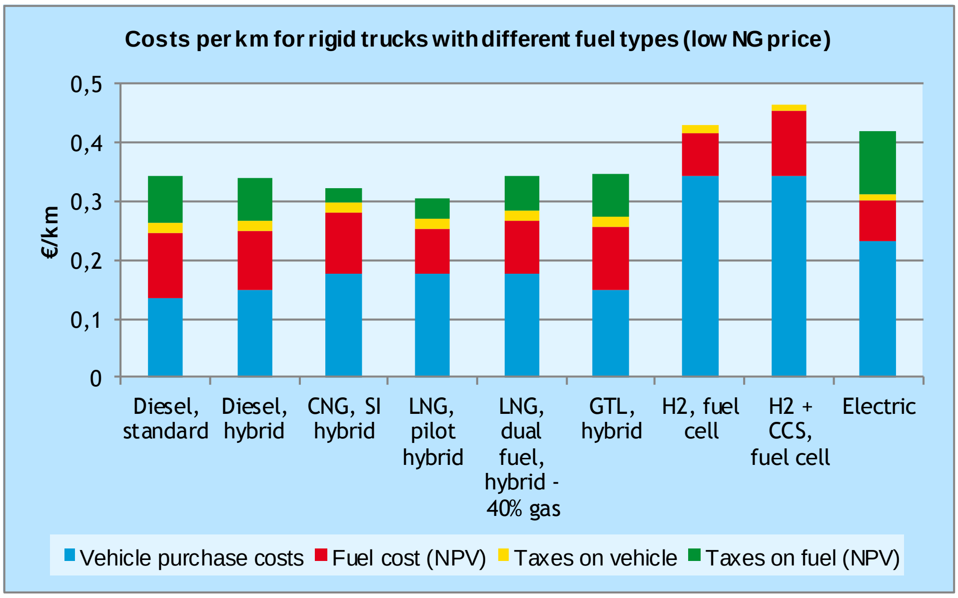


Figure 39 Cost for different NG-based energy carriers - trucks, low NG price



7.3.2 Tractor-trailer

The results for the truck trailer combination show the same trends as the results for the rigid truck, as shown in the following graphs of WTW energy use and GHG emissions. The same conclusions apply.

Figure 40 WTW energy use for different NG-based energy carriers - tractor-trailers

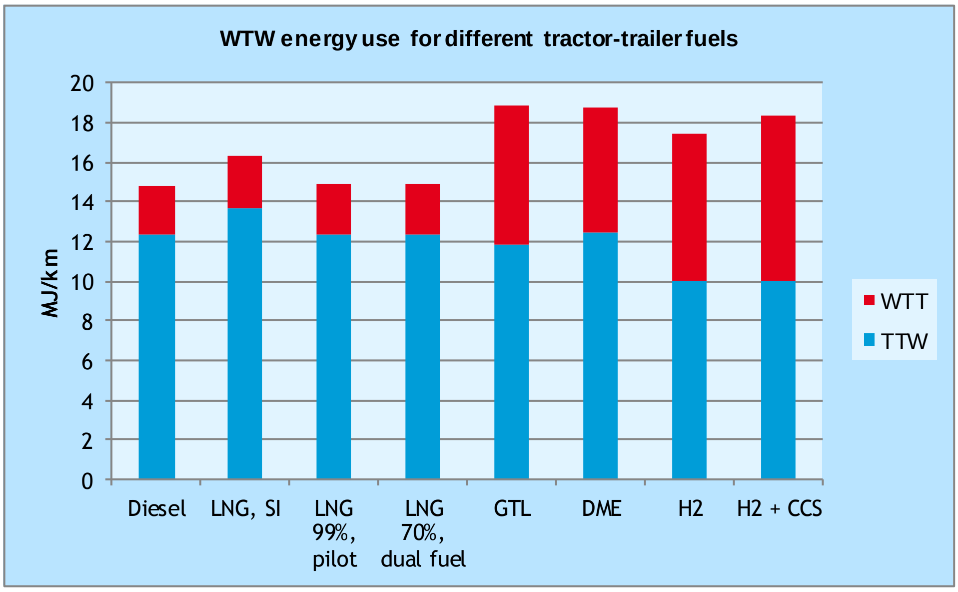
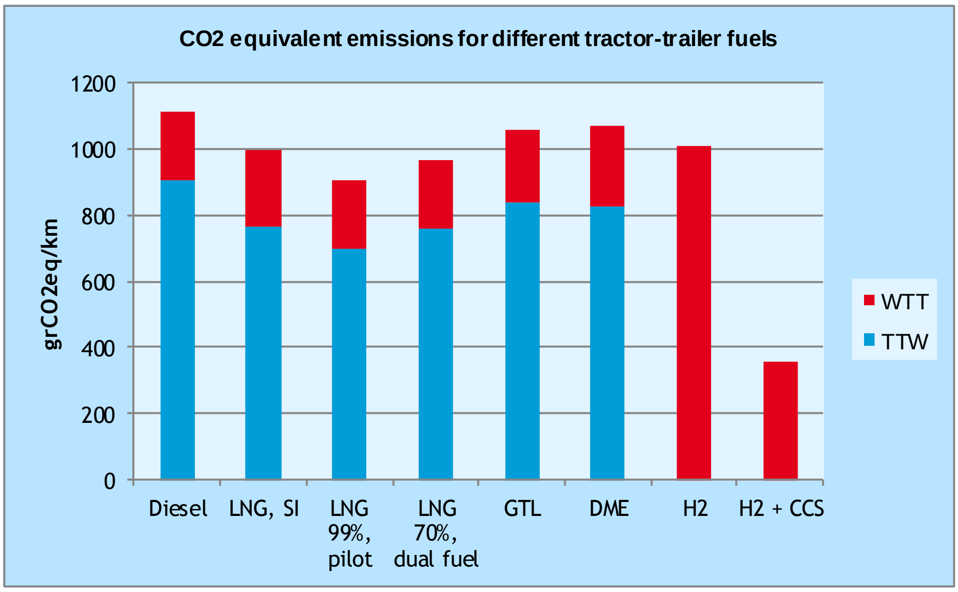


Figure 41 WTW GHG emissions for different NG-based energy carriers - tractor-trailers



The Well-To-Wheel energy use and GHG emissions for DME (only considered in this vehicle category) are quite comparable to that of diesel and GTL, offering no clear benefit compared to the diesel hybrid. DME does score significantly better regarding NO_x and PM_{10} emissions though, as shown in the following figures.

Figure 42 NO_x emissions for different NG-based energy carriers - tractor-trailer

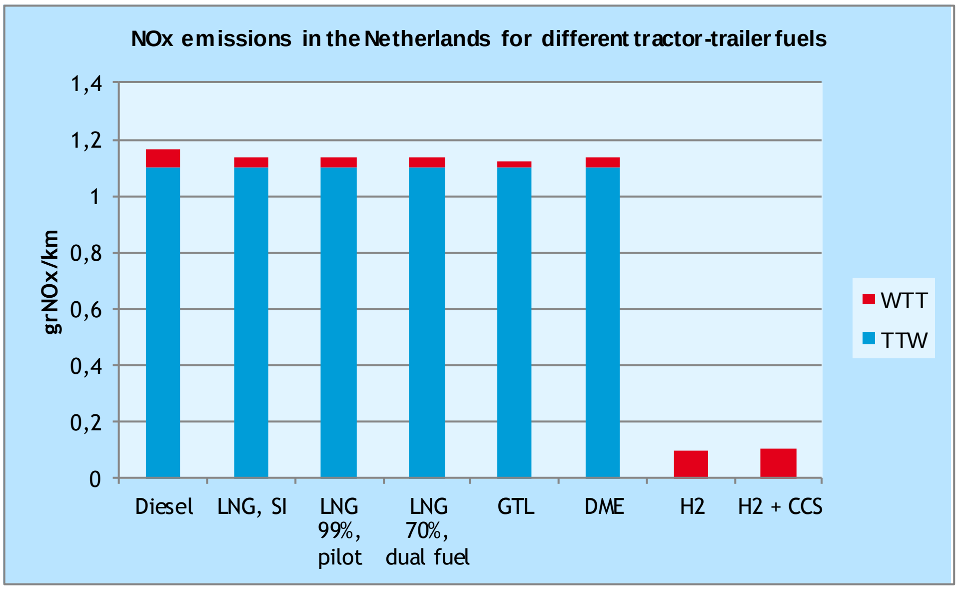
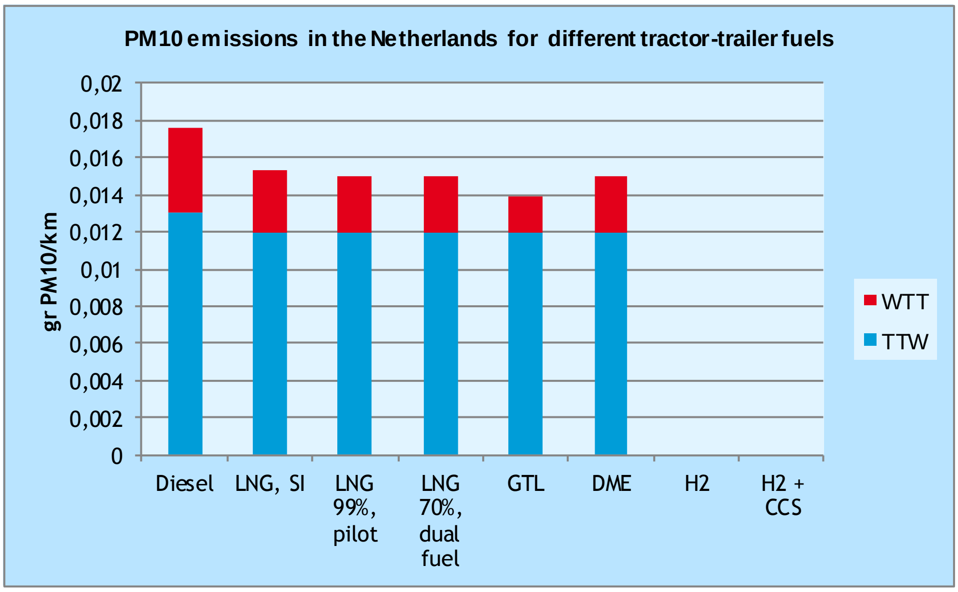


Figure 43 PM_{10} emissions for different NG-based energy carriers - tractor-trailer



The results of the cost calculations are shown in the following Figure 44 (high NG price). Costs without taxes are found to be comparable to that of diesel, with the exception of the hydrogen truck, which clearly results in higher cost per kilometre. If taxes are included, the LNG and DME options are found to reduce cost by up to 20%. Only GTL and H_2 remain more costly than the reference (diesel) vehicles.

Figure 44 Cost for different NG-based energy carriers - tractor-trailer, high NG price

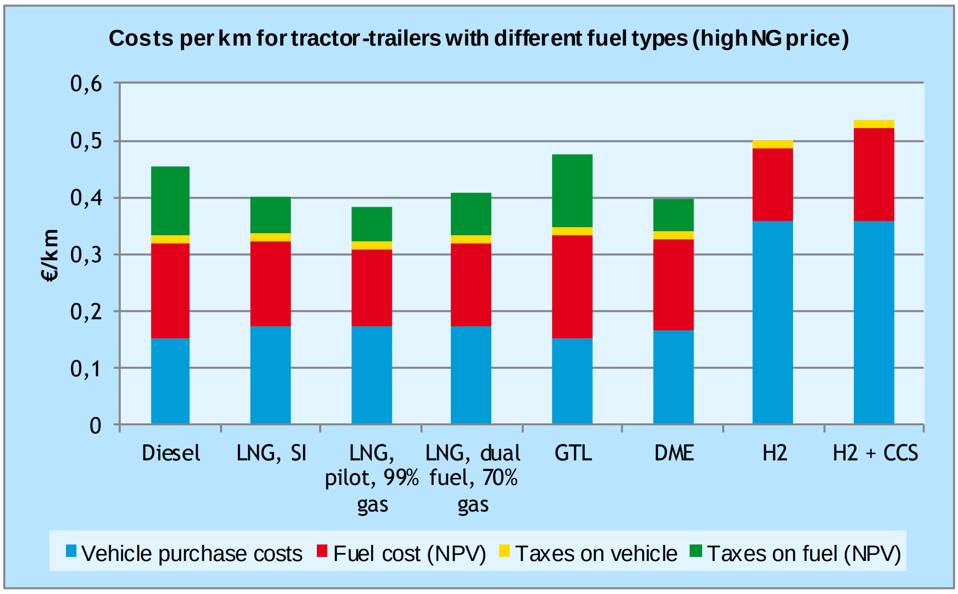
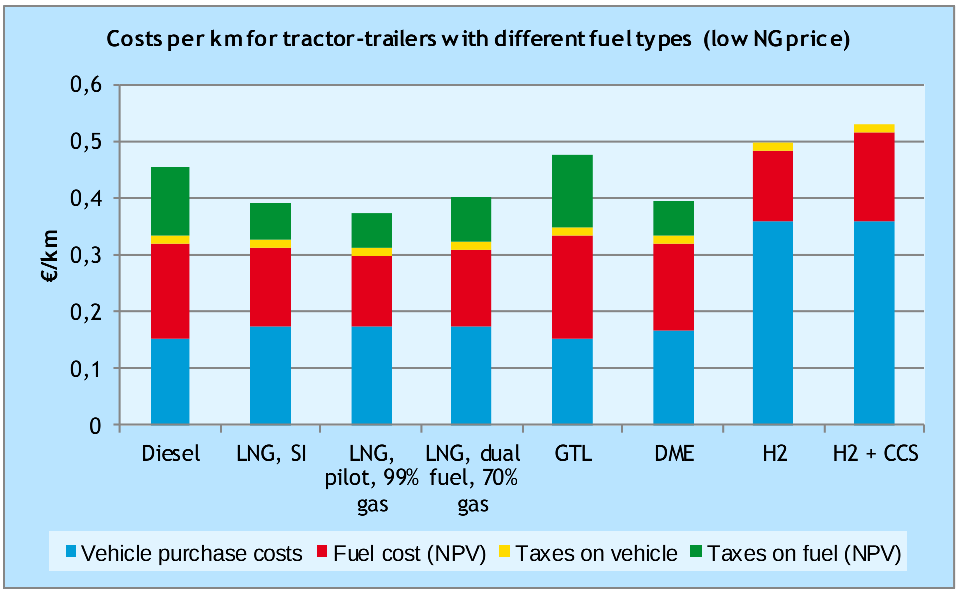


Figure 45 Cost for different NG-based energy carriers - tractor-trailer, low NG price



7.3.3 City bus

Next the results for the city bus are shown. The trends in these graphs are quite similar to that of the other heavy duty vehicles. Compared to diesel hybrid city busses, the natural gas routes (except for electricity) have higher WTW energy use (although in most cases still lower than the conventional diesel bus). Most routes do have somewhat lower CO_2 emissions compared to the diesel hybrid bus – with the exception of the H_2 bus with CCS, which achieves a very significant CO_2 reduction of 70% and of the electric bus, which achieves a reduction of 25%. Pollutant emissions are typically comparable to those of the diesel hybrid, only the hydrogen and electric routes score very well on these criteria.

Figure 46 WTW energy use for different NG-based energy carriers - city bus

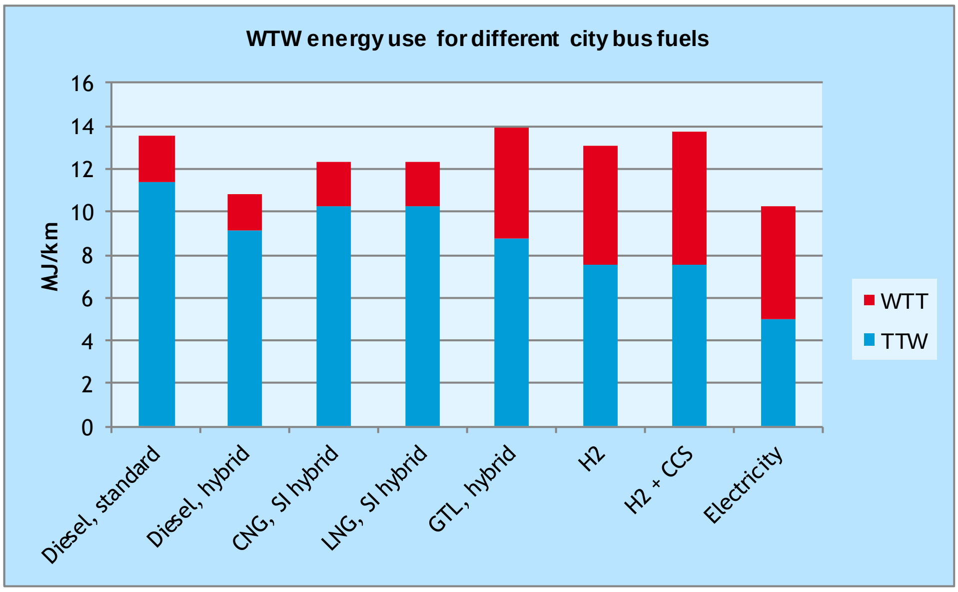


Figure 47 WTW GHG emissions for different NG-based energy carriers - city bus

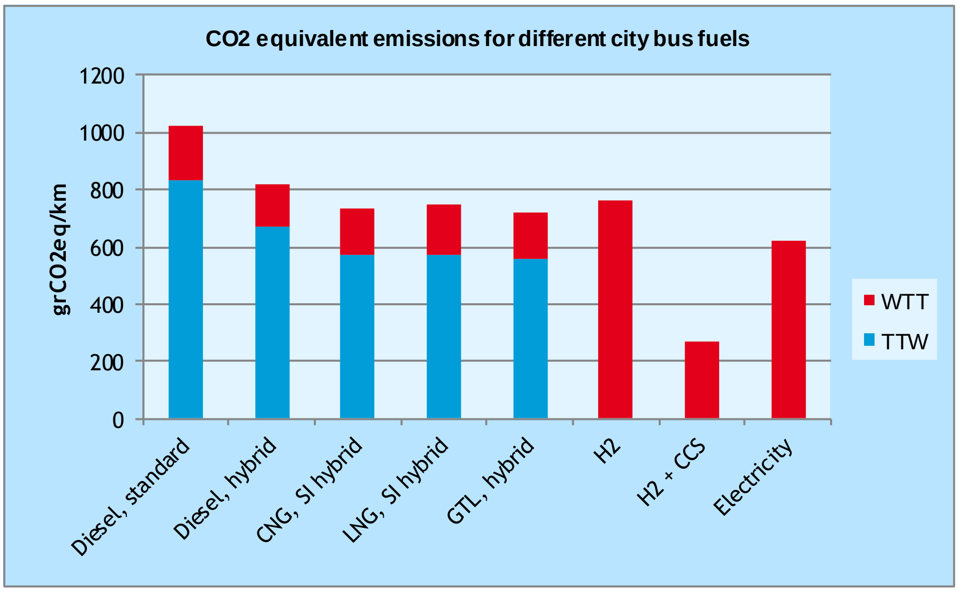


Figure 48 NO$_x$ emissions for different NG-based energy carriers - city bus

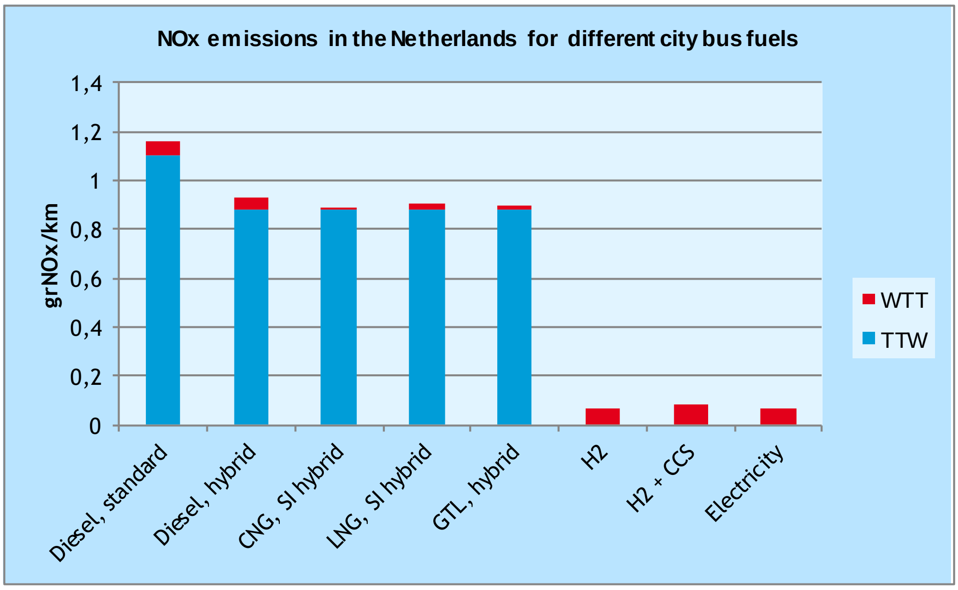
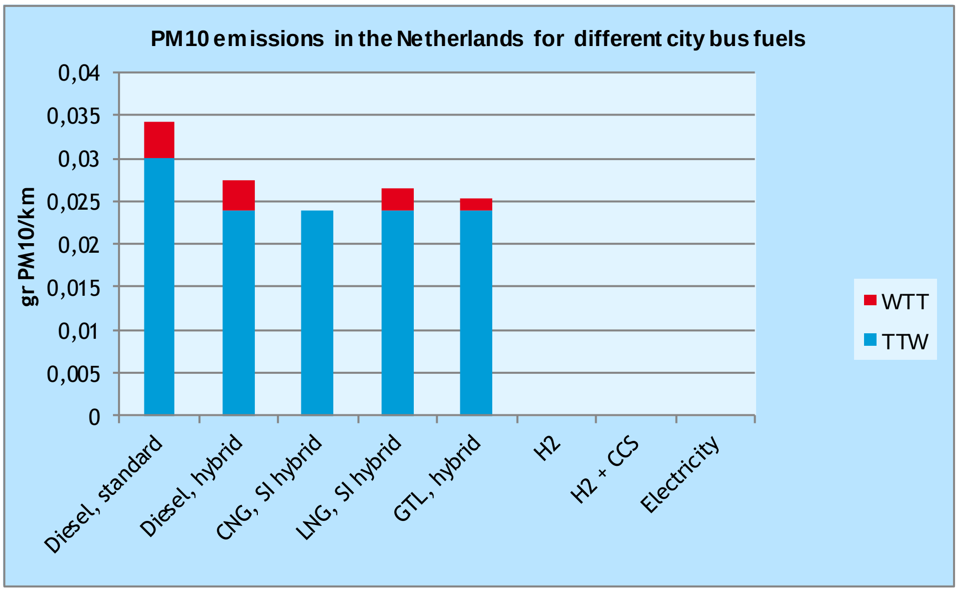


Figure 49 PM$_{10}$ emissions for different NG-based energy carriers - city bus



When looking at the cost per kilometre, the lower taxes on CNG and LNG (compared to diesel and GTL) are found to compensate the higher vehicle cost. Costs without taxes are somewhat higher for these fuels, but with taxes they are lower than those of the diesel (both standard and hybrid).

Figure 50 Cost for different NG-based energy carriers - city-bus, high NG price

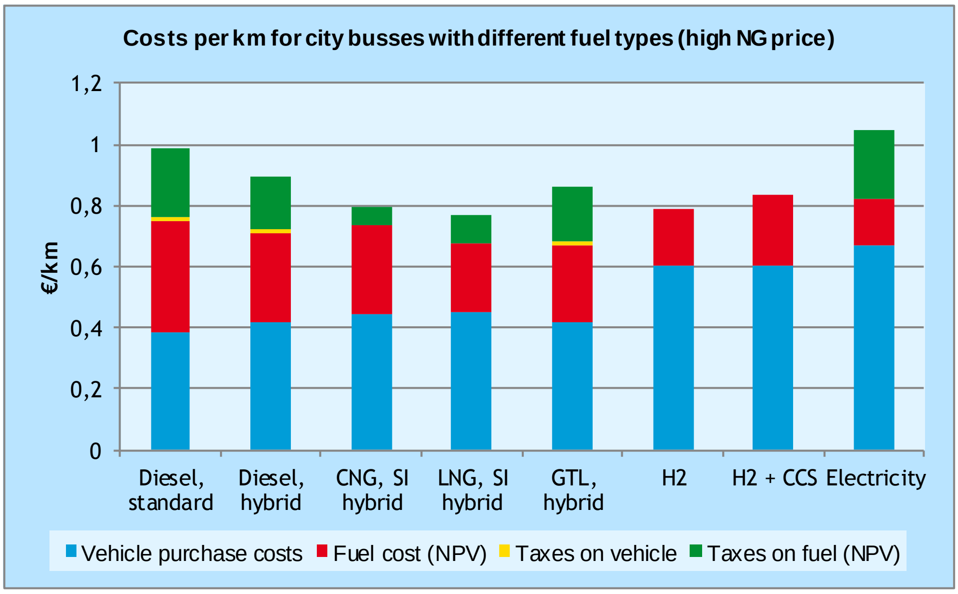
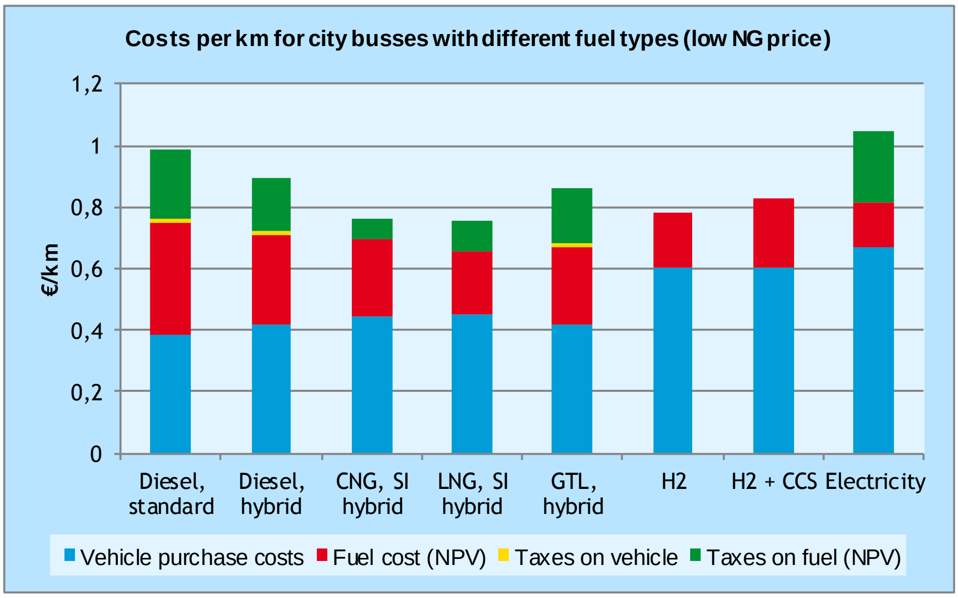


Figure 51 Cost for different NG-based energy carriers - city-bus, low NG price



7.4 Natural gas in shipping

Four different types of ships were assessed. Overall results regarding the potential environmental effects of the natural gas options are the following:

- LNG was found to increase Well-To-Wheel energy use to some extent (3-9%) in all ship types;
- WTW GHG emissions of LNG are comparable to those of the reference fuel (diesel, MGO and HFO respectively); the change in GHG emissions varies from a 4% decrease to a 1% increase compared to the reference fuel, with the exception of the LNG dual fuel route for a deep sea ship of 15,000 TEU, which results in a 20% decrease of GHG emissions;

- GTL in inland ships increases WTW energy use by about 35% and has a neutral effect on GHG emissions, it does reduce NO_x emissions by about 10% (GTL in other ships was not investigated);
- in inland and short sea ships NO_x emissions of the LNG options are comparable to or slightly higher than of the reference fuels;
- significant NO_x reductions can be achieved by using LNG in sea ships, especially for the LNG pilot technology;
- LNG reduces PM_{10} emissions significantly in all ship types;
- SO_2 emissions of short and deep sea ships are strongly reduced if LNG is used to replace the reference fuel.

These findings are Illustrated in the following graphs of the inland ship fuels. In Verbeek (2011), it was concluded that LNG sea ships would have a significant GHG reduction of some 10% compared to the diesel fuels. This advantage is lost, due to a higher WTT energy consumption and CO_2 emission (refer to Section 4.2) and also due to a more accurate estimation of the energy efficiency of the ship. In this analysis both a loss in engine efficiency as well as a loss in cargo space has led to a higher energy consumption of the ship.

Figure 52 WTW energy use for different NG-based energy carriers - inland shipping

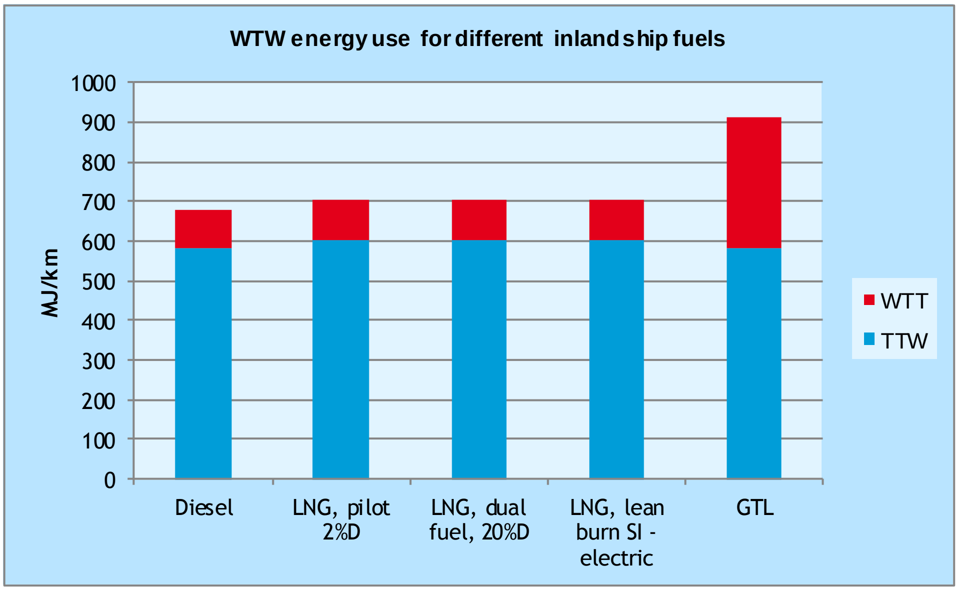


Figure 53 WTW energy use for different NG-based energy carriers - short sea shipping

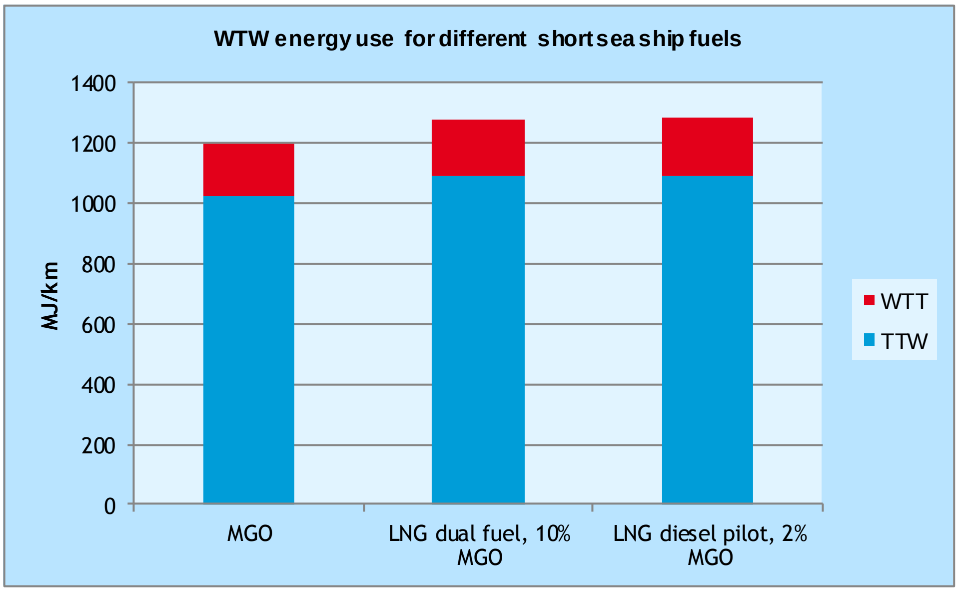


Figure 54 WTW GHG emissions for different NG-based energy carriers - inland shipping

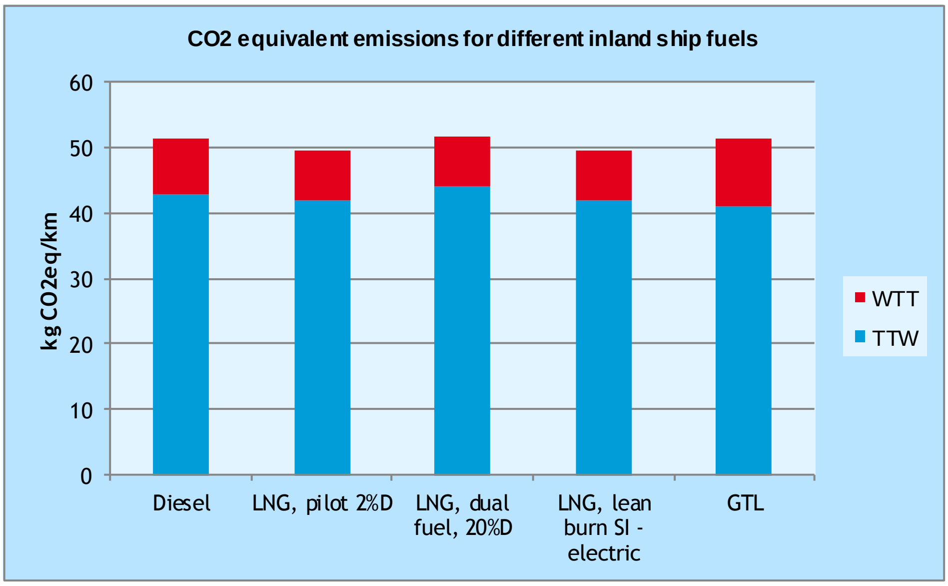


Figure 55 WTW GHG emissions for different NG-based energy carriers - short sea shipping

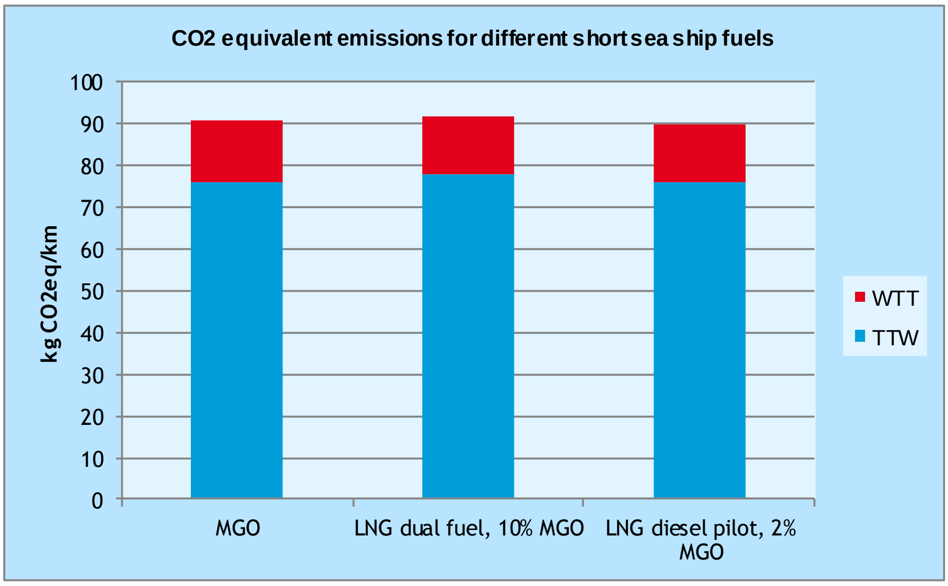


Figure 56 NO_x emissions for different NG-based energy carriers - inland shipping

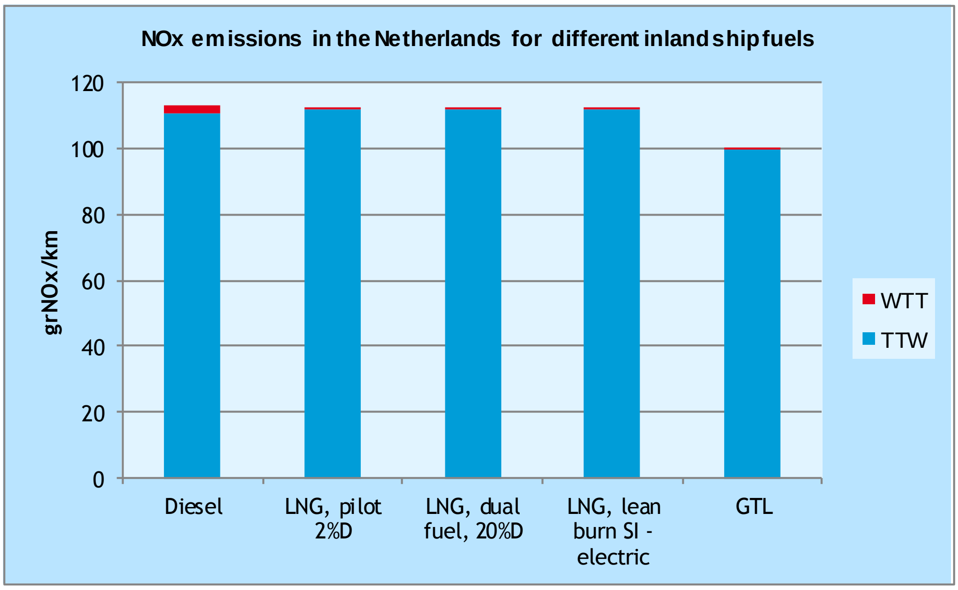


Figure 57 NO$_x$ emissions for different NG-based energy carriers - short sea shipping

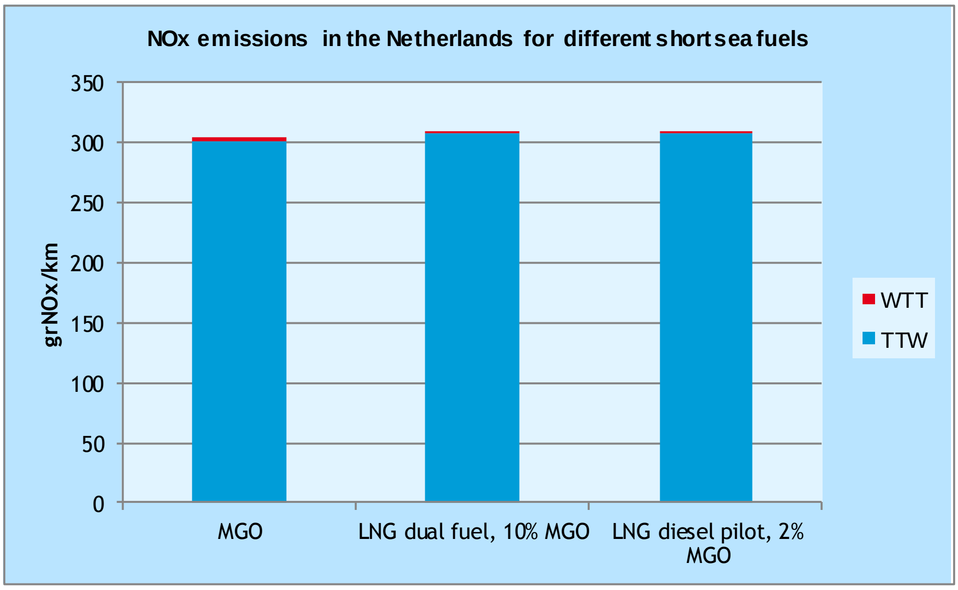


Figure 58 PM$_{10}$ emissions for different NG-based energy carriers - inland shipping

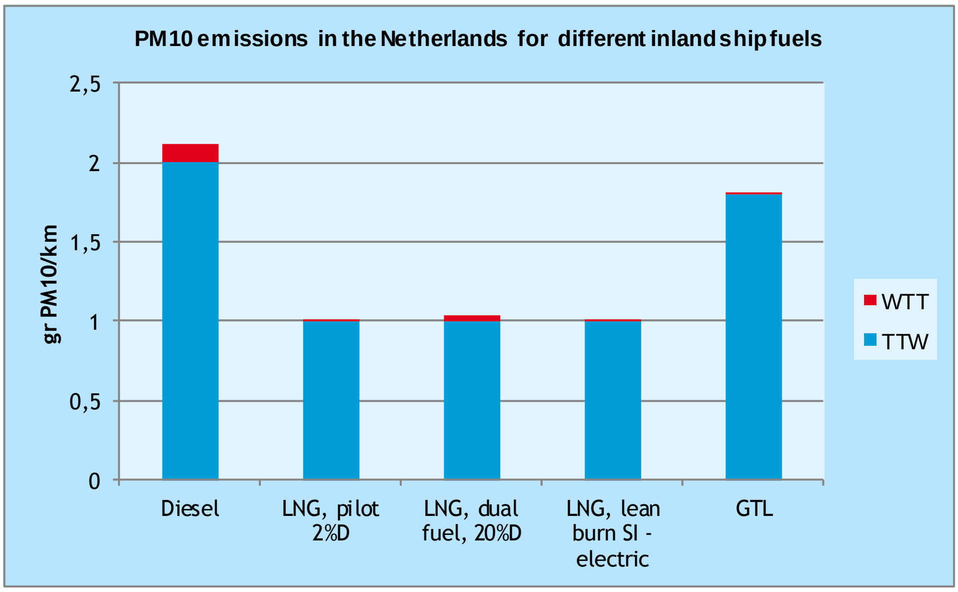


Figure 59 PM_{10} emissions for different NG-based energy carriers - short sea shipping

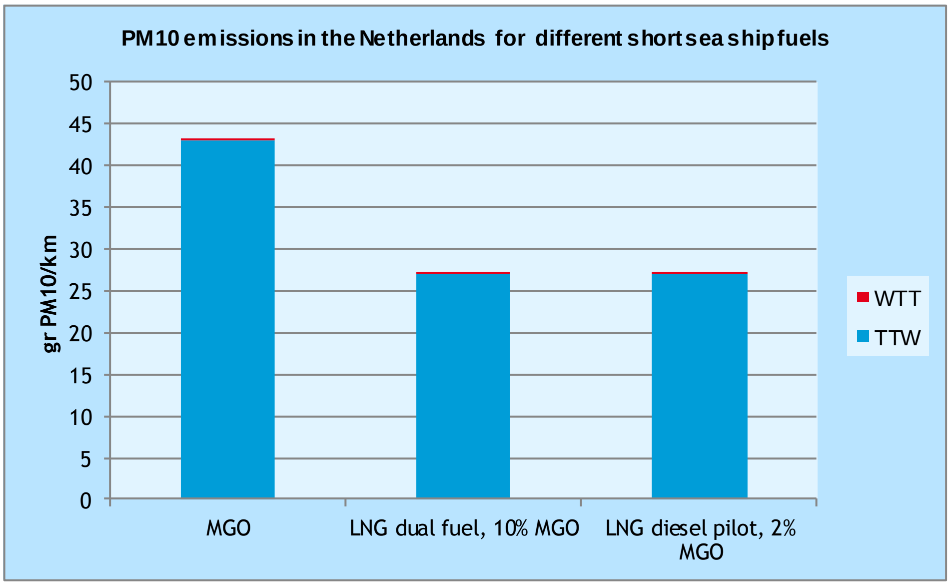


Figure 60 SO_x emissions for different NG-based energy carriers - inland shipping

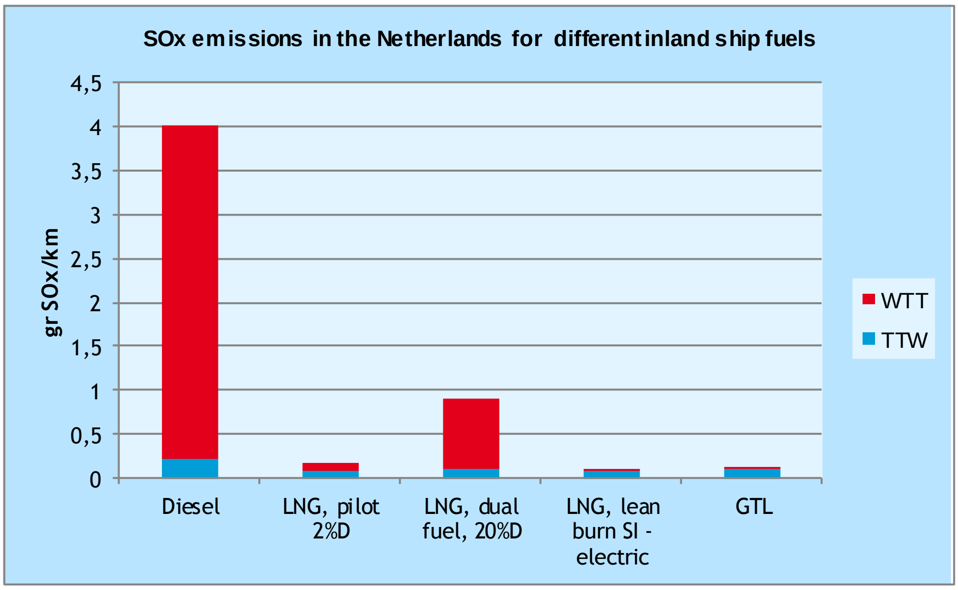


Figure 61 SO$_x$ emissions for different NG-based energy carriers - short sea shipping

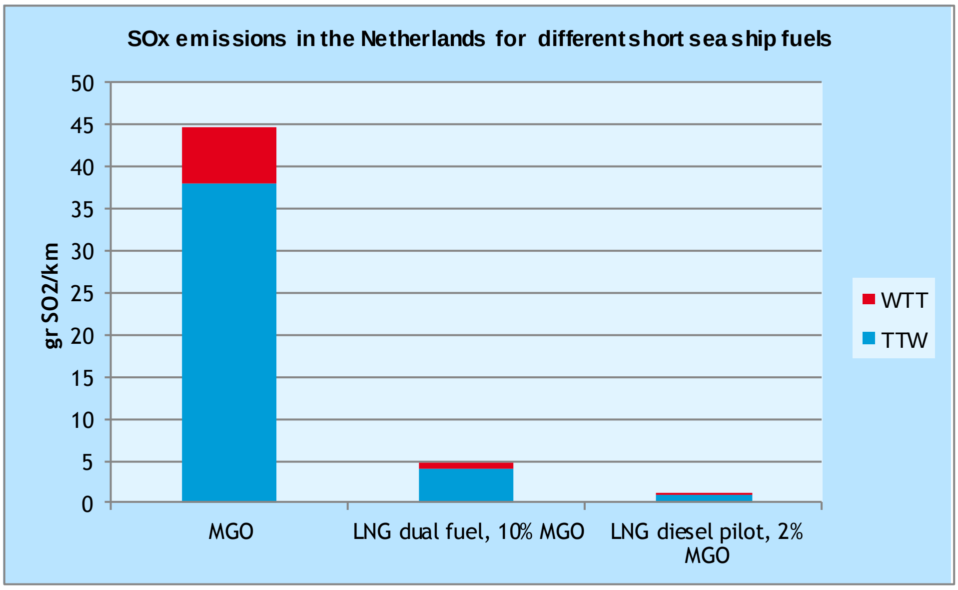


Figure 60 and Figure 61 show the impacts on SO_2 emissions and need some explanation. All road fuels are almost sulphur free. Also diesel for inland shipping contains less than 10 ppm sulphur. To reach this level, more than 99.9% of the sulphur has to be removed in the refinery. In the refinery about 99% of the removed sulphur is converted into a solid yellow pure sulphur product. But if the resulting 1% is emitted as SO_2 the refinery emission from diesel production are ten times bigger than the SO_2 emissions from using the diesel, causing the WTT emission to be larger than the TTW emission. In case of MDO of HFO for sea ships, which contain much more sulphur the TTW emissions are much higher than the WTT emissions.

The strong impact of LNG on CO_2, NO_x, PM_{10} and SO_2 emissions of deep sea ships is shown in Figure 63 up to and including Figure 66.

Figure 62 WTW energy use for different NG-based energy carriers - deep sea shipping

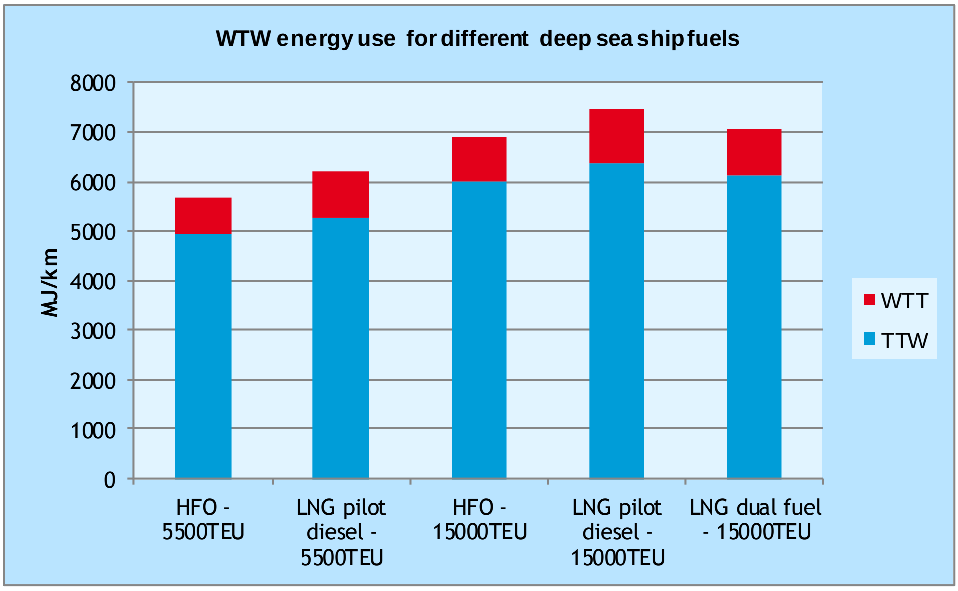


Figure 63 GHG emissions for different NG-based energy carriers - deep sea shipping

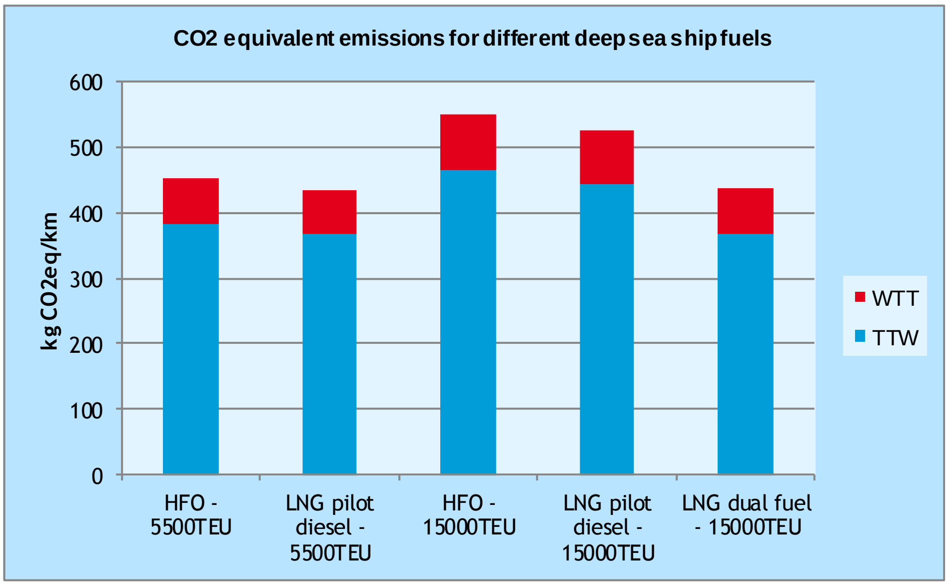


Figure 64 NO_x emissions for different NG-based energy carriers - deep sea shipping

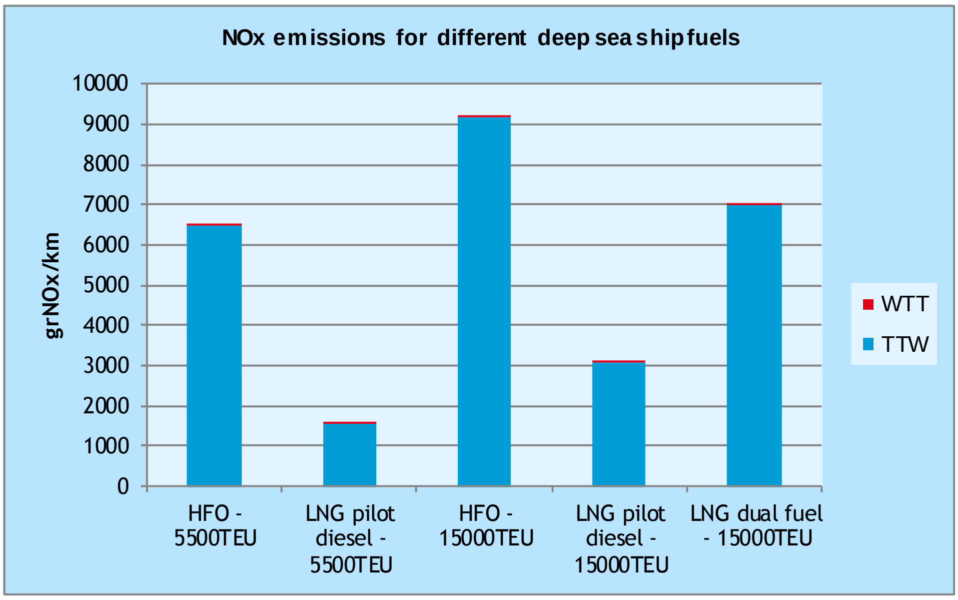


Figure 65 PM_{10} emissions for different NG-based energy carriers – deep sea shipping

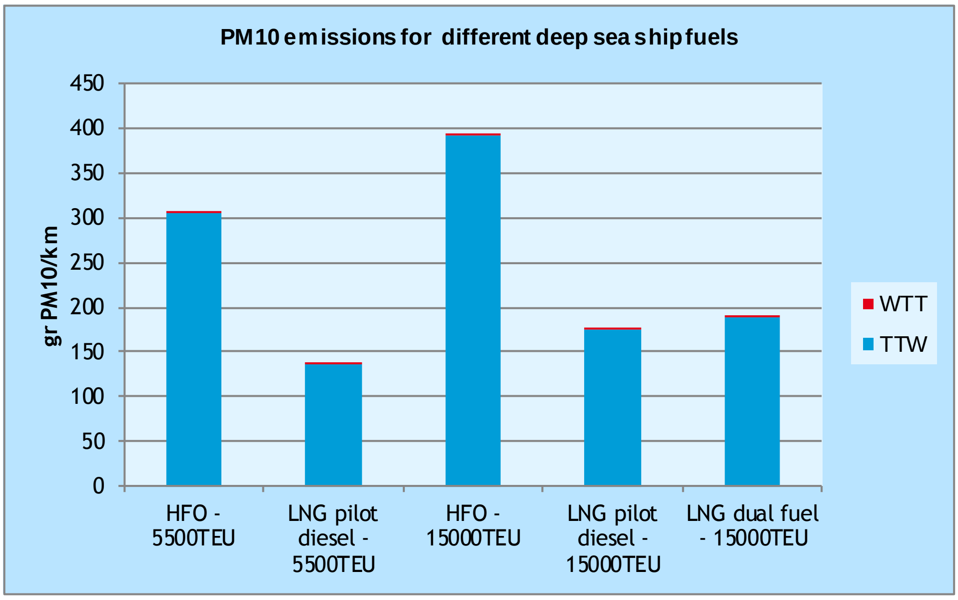
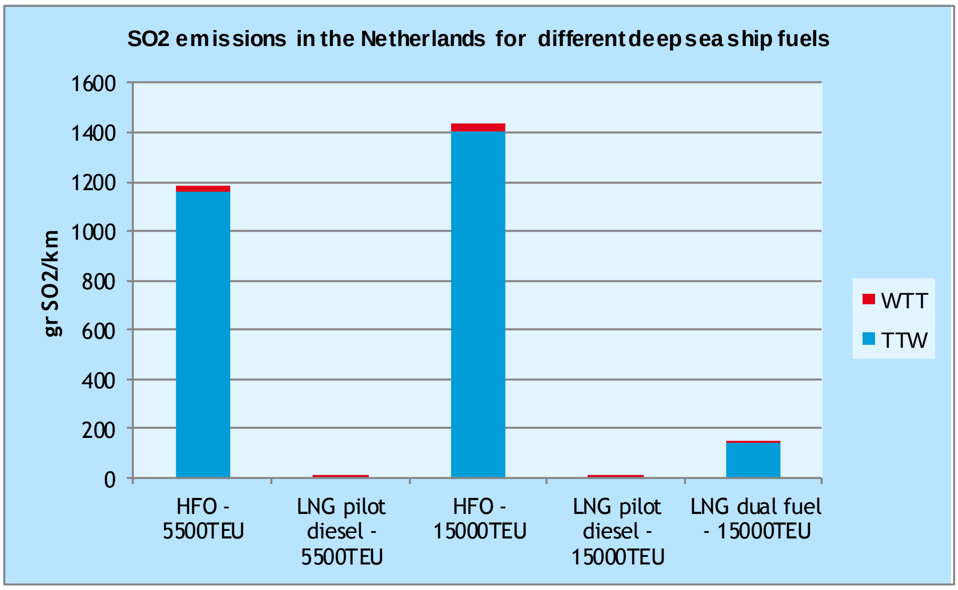


Figure 66 SO_2 emissions for different NG-based energy carriers – deep sea shipping



Regarding cost per kilometre, it was found that:
- LNG in inland ships reduces cost by up to 10%, mainly due to lower fuel cost (per kilometre), see Figure 67.
- LNG use in short sea ships results in slightly lower (comparable) cost compared to the reference fuel MGO. Fuel cost are somewhat lower, but the LNG ships are more expensive.
- LNG in deep sea ships was found to increase cost quite significantly, compared to the reference fuel HFO. Both fuel and vessel costs are higher in the deep sea ship categories investigated here.

Note that no taxes are levied on ships or their fuels.

Figure 67 Cost for different NG-based energy carriers - inland shipping, high NG price

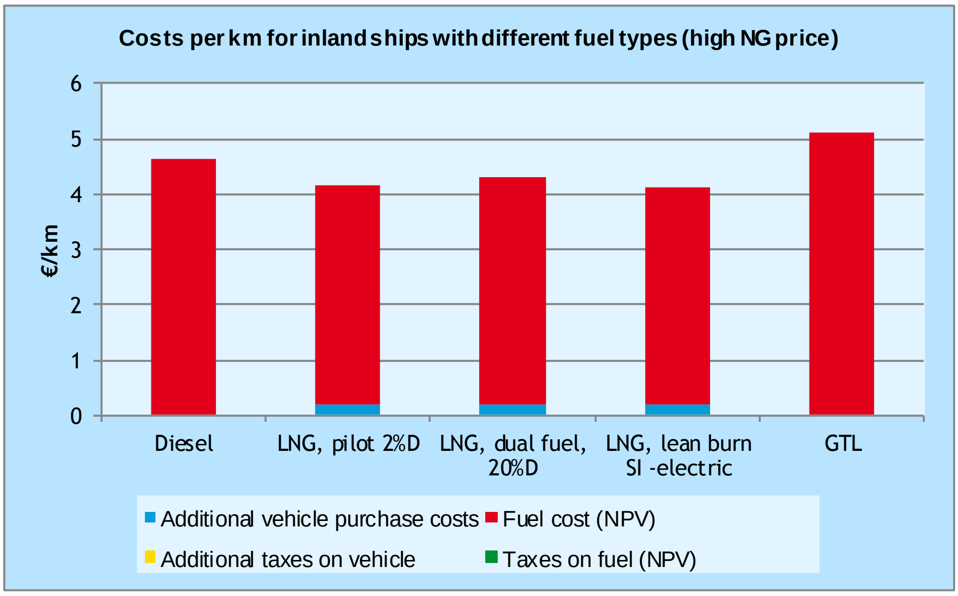


Figure 68 Cost for different NG-based energy carriers - short sea shipping, high NG price

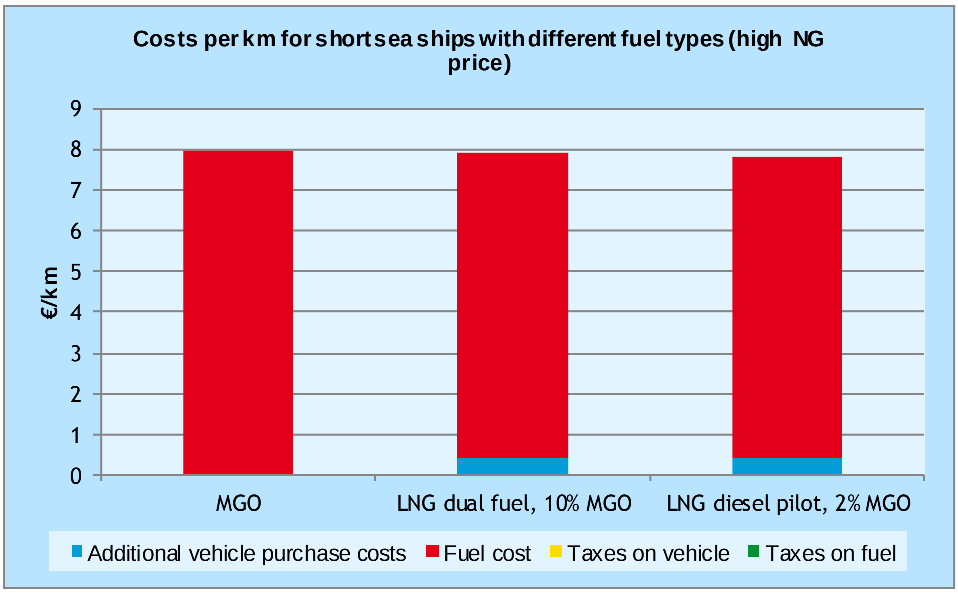
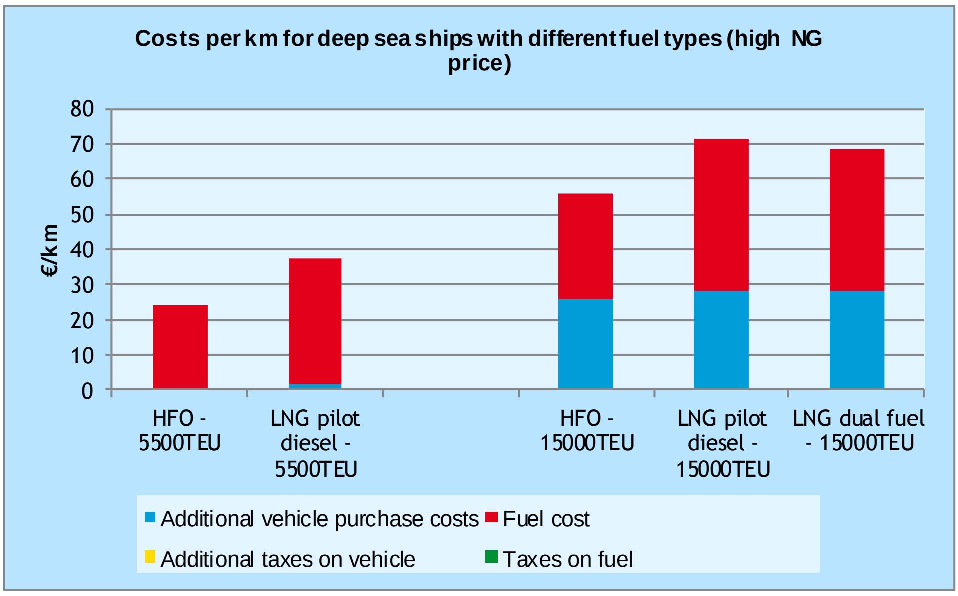


Figure 69 Cost for different NG-based energy carriers – deep sea shipping, high NG price



7.5 Natural gas in aviation

The two natural gas routes investigated for aviation increase the WTW energy use significantly, GTL by 35% (due to higher energy use during conversion of the gas to the GTL) and LNG by 10% (due to higher energy use both in the TTW and the WTT part of the life cycle). For LNG, the increased Tank-To-Wheel energy consumption is due to a projected loss in energy efficiency of 10%, due to increased weight and loss of space for the LNG tanks.
Refer to Section 3.7.
GHG emissions also increase when GTL is used, albeit to a lesser extent (5%). LNG results in about 10% GHG emission reduction, but this does not include the effects of the strong increase in water vapour emission with LNG. This would almost certainly lead to wider contrails, which would probably have a direct effect on ambient temperature. It is recommended to further investigate this. Impacts on NO_x and PM_{10} emissions are negligible.

Figure 70 WTW energy use for different NG-based energy carriers - aviation

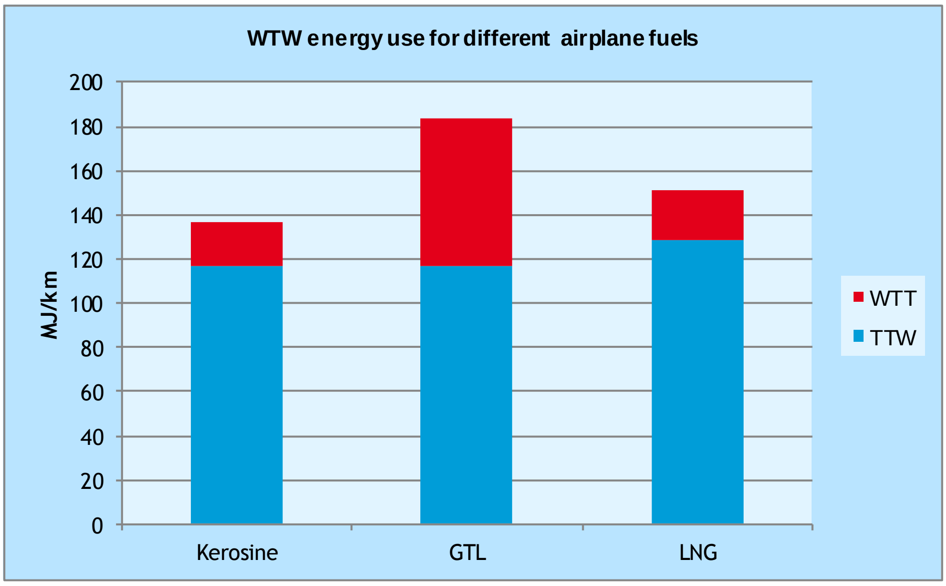
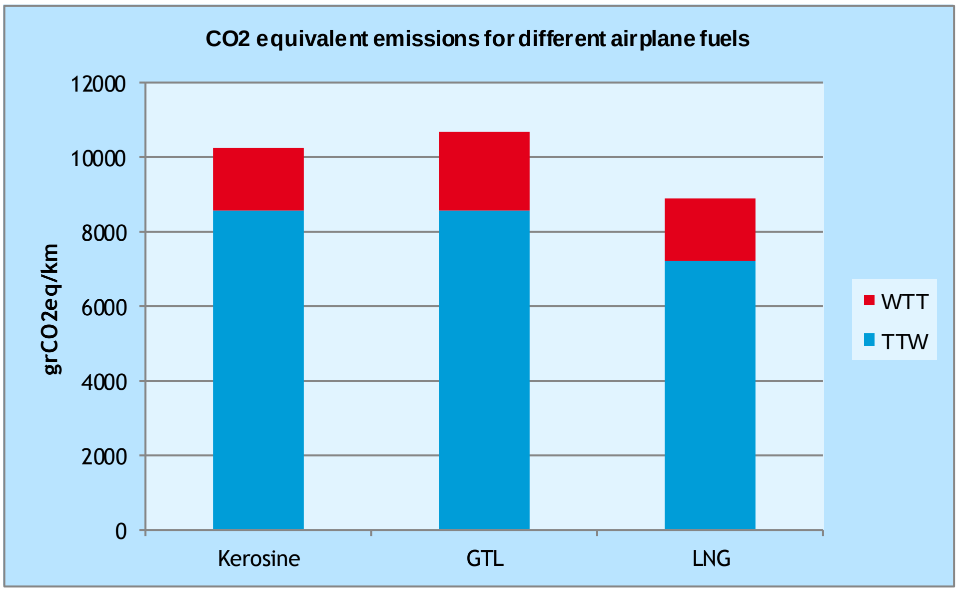


Figure 71 WTW GHG emissions for different NG-based energy carriers - aviation



7.6 Sensitivities: the potential impact of uncertainties

The results of this assessment are clearly dependent on the assumptions described in the previous chapters. For example, if methane slip will be lower in reality than assumed, the Well-To-Tank GHG emissions of the CNG and LNG routes will reduce. If the lifetime of an electric passenger car turns out to be lower on average than that of the other cars, its cost will be less favourable than given here.

As there are so many variables, it is not feasible to explore the potential effect of all the uncertainties in this report. In most cases, however, these effects can be estimated quite easily from the figures that are presented here.

- Taking Figure 54 as an example (WTW GHG emissions of inland shipping), the effect of reduced methane emissions in LNG dual fuel engines can be estimated quite easily: if the TTW GHG emissions could be reduced by 10% (about 4 kg CO_2 eq./km), the overall emissions of this route will reduce from about 52 to 48 kg/km. This application will then result in a (limited) GHG reduction, compared to both the reference and the other natural gas routes.
- With the data in Figure 27 (cost per kilometre for passenger cars 30,000 km/y), for example, it can be concluded that if the CNG passenger cars would be 10% more expensive than expected in this report, the cost per kilometre would increase by almost 0.005 €/km which would hardly affect the overall cost of these vehicles.
- On the other hand, from the same graph we can derive what will happen to the cost if the owner of an electric passenger car charges his batteries at home rather than at public or company charging points. He would then have to pay 32.4 €/GJ tax rather than the 3.1 €/GJ assumed in this study (see section 4.4). This would increase the energy taxes by a factor 10, from 0.004 €/km to 0.021 €/km.
  Total cost would increase from 0.085 €/km to 0.102 €/km – a 20% increase of cost per kilometre for these cars.

7.7 Scenario assessment: effects of using 2.5 million ton LNG p.a. in the Dutch transport sector in 2025

To assess what these findings mean for the total impact of LNG in the Dutch transport sector, the potential impacts of the LNG-scenario used in the safety calculations (Chapter 6) were estimated.

7.7.1 Scenario definition

Starting point is the assumption that in 2025 a total of 2.5 million tons of LNG is used in the transport sector in the Netherlands. 40% of this volume is used in heavy duty road vehicles (trucks and tractor-trailers), 22% in inland shipping, 12% in short sea ships and the remaining 26% in deep sea shipping.

To estimate the effects of this shift to LNG, these volumes need to be distributed in more detail over the various vehicle and ship types used in this report. The following assumptions were used for this:

- the volume used in road transport is distributed over trucks and tractor-trailers in line with their share in diesel use;
- the volume for deep sea shipping is equally distributed over 5,500 and 15,000 TEU ships.

The scenario definition is shown in Table 85.

Table 85 Scenario: 2.5 million ton LNG in 2025

Vehicle	mln ton LNG/y in NL	mln MJ LNG/y
Rigid truck	0.36	17,583
Tractor-trailer	0.64	31,417
Inland ship	0.55	26,950
Short sea ship	0.31	15,190
Deep sea ship 5,500 TEU	0.32	15,680
Deep sea ship 15,000 TEU	0.32	15,680
Total	***2.50***	***122,500***

The share of LNG vehicle technologies in 2025 (pilot, dual fuel and spark ignition) was based on TNO expert opinion, and shown in Table 86.

Table 86 **Scenario: market shares of the various LNG engine technologies**

2017-2025 Vehicle (and ship) sales	Pilot	Dual fuel	Spark ignition
Rigid truck	20%	80%	0%
Tractor-trailer	20%	40%	40%
Inland ship	30%	50%	20%
Short sea ship	50%	50%	0%
Deep sea ship 5,500 TEU	100%	0%	0%
Deep sea ship 15,000 TEU	50%	50%	0%

7.7.2 Impacts

Using the data presented earlier, the total impacts on WTW energy use, GHG emissions and NO_x and PM_{10} emissions were calculated. Results are shown in Table 87. Key findings are:

- This shift to LNG would reduce WTW GHG emission by about 654 kton CO_2. NO_x and PM_{10} emissions in the Netherlands would reduce by about 26 and 1.3 kton respectively. SO_x emissions will reduce by almost 7.7 kton per year.
- Overall energy use would increase, though, by about 6.8 million GJ, 5.5% of the total LNG energy content.
- The main GHG reduction benefits are achieved with LNG use in road transport and for the heaviest deep sea ship type.
- NO_x and PM_{10} emission reductions are mainly due to LNG use in maritime transport (short sea and deep sea), SO_x reductions are solely due to shipping.

What this means in terms of relative reduction is shown in Table 88. Note that this table shown effects on emission of the vehicles and ships that run on LNG, these percentages are not related to overall emissions of the transport mode.

Table 87 **Scenario calculations, effects on emissions of the shift from the reference fuels to LNG**

	Effect on WTW energy use (mln MJ primary)	Effect on WTW GHG emissions (kton CO_2 eq.)	Effect on NO_x emissions (kton)	Effect on PM_{10} emissions (ton/year)	Effect on SO_{10} emissions (ton/year)
Rigid truck	189	-293	0	-2	
Tractor-trailer	1,698	-361	-0.1	-6	
Inland ship	1,200	0	0	-49	-156
Short sea ship	1,192	0	0.1	-225	-580
Deep sea ship 5,500 TEU	1,500	0	-15	-515	-3,510
Deep sea ship 15,000 TEU	968	0	-11	-542	-3,409
Total	**6,747**	**-654**	**-26**	**-1,264**	**-7,655**

Table 88 **Scenario calculations, relative effects on emissions**

	Relative change in WTW energy use	Relative change in WTW GHG	Relative change in NO_x for the Netherlands	Relative change in PM for the Netherlands	Relative change in SO_x for the Netherlands
Rigid truck	1%	-19%	-2%	-8%	
Tractor-trailer	5%	-13%	-3%	-14%	
Inland ship	4%	-1%	-1%	-52%	-87%
Short sea ship	7%	0%	1%	-37%	-93%
Deep sea ship 5,500 TEU	9%	-4%	-77%	-57%	-100%
Deep sea ship 15,000 TEU	6%	-12%	-46%	-55%	-95%

Looking at the impacts on cost, results are found to depend quite strongly on whether the taxes are included in the calculations or not. The LNG price also plays a role, of course. An overview of the results is shown in Table 89. Summarising, we find that in the ‘high LNG price’ calculations, the shift to LNG will cause an overall increase of cost of transport (excl. taxes), although cost savings are achieved in some of the vehicle categories. If taxes are included, the LNG users in road transport benefit from the relatively low excise duty on LNG, resulting in a net benefit on average.

In the ‘low LNG price’ calculations, the overall cost was found to reduce also if taxes are excluded. This is due to a net cost reduction in the tractor-trailer category and the inland and short sea ships. Including the taxes will further increase this cost advantage.

Table 89 **Scenario calculations: overall impacts on cost (million €/yr)**

	Excluding taxes with high NG price	Including taxes with high NG price	Excluding taxes with low NG price	Including taxes with low NG price
Rigid truck	38	-2	32	-9
Tractor-trailer	-1	-129	-24	-152
Inland ship	-19	-19	-31	-31
Short sea ship	-1	-1	-7	-7
Deep sea ship 5,500 TEU	38	38	30	30
Deep sea ship 15,000 TEU	36	36	28	28
Total	91	-77	27	-140

The difference between the net cost effect with and without taxes is the impact on the government revenues of this shift to LNG – assuming the taxes are kept at current levels: almost € 170 million, in 2025.

8 Conclusions and recommendations

8.1 Emissions and energy efficiency

In Chapter 7 we have seen that GHG emissions, energy consumption and pollutant emissions of fuels are very much influenced by the type of vehicle or ship, the type of engine and driveline technology and the type of use.
An overview of the key results for the main vehicle and ship types is given in Table 90.

Table 90 **WTW GHG emission, energy consumption and pollutant emissions of alternative fuels produced from natural gas for year 2020/2025, compared to the reference (negative value = emission reduction)**

Transport segment	GHG emission	Energy consumption	Pollutant emissions	Reference	Remark/Issues
CNG in passenger cars	-17% -12%	3% 11%	o +	Petrol Diesel	
CNG in vans	-12%	11%		Diesel	
Electric passenger cars	≈ -45%	≈ -35%	++	Petrol	Maturity & efficiency to be demonstrated; CCS may further reduce GHG emissions
H_2 fuel cell passenger cars	≈ -30%	≈ -10%	++	Petrol/ Diesel	Indicative, maturity & efficiency to be demonstrated; CCS may reduce improve GHG emissions.
GTL in trucks, cars, DME in trucks	0 to -5%	30 - 35%	o	Diesel	As pure fuel or blend
Electric trucks and buses	≈ -15% to -25%	≈ -5% to 5%	++	Diesel	Maturity & efficiency to be demonstrated; CCS may further reduce GHG emissions.
H_2 fuel cell trucks and buses	≈ -8%	≈ 20%	++	Diesel	Indicative, maturity & efficiency to be demonstrated; CCS may further reduce GHG emissions.
Natural gas in trucks and buses	0 to -19%	0 to 14%	o	Diesel	Dual-fuel or pilot engines may not be sufficiently available
GTL inland ships	0	35%	+	Diesel	
LNG inland ships	≈ 0	4%	o	Diesel	Potentially GHG ≈ -20% with low methane emission

Transport segment	GHG emission	Energy consumption	Pollutant emissions	Reference	Remark/Issues
LNG in sea ships	≈ 0 to -20%	≈ 5%	++	MGO or HFO	GHG -20% for ships with low methane emission
LNG in airplanes	≈ -13%	11%	o	Kerosene	Indicative/no commercial application by 2025
GTL in airplanes	≈ 4%	≈ 35%	o	Kerosene	Synthetic kerosene 100% compatible with kerosene

Greenhouse gas emissions

With a fossil fuel, the combination of energy efficiency and hydrogen to carbon ratio determines to a large extent the WTW GHG emissions. Methane and nitrous oxide emissions then add GHG emission to that. Natural gas has a very favourable hydrogen to carbon ratio, compared to crude oil. This should lead to a reduction in GHG emissions of some 25% if similar energy efficiencies would be achieved and if no substantial methane emissions takes place. Actual benefits are often lower in practice, as energy efficiencies of gas powered engines are typically less favourable than that of the reference fuels.

The results of this study show that for 2025 greenhouse gas emission savings for many transportation modes are possible if natural gas is used as fuel or feedstock for fuel. GHG savings of up to 30-45% are expected if natural gas is used for the electricity and H_2 production, to be used in passenger cars.

In a number of cases these savings are conditional upon expected vehicle or ship technology developments between now and 2020/2025. It is important to monitor these developments and if necessary develop policies to secure them. The following improvements are expected and necessary to secure GHG savings:

- H_2 fuel cell cars demonstrate the expected fuel efficiency in practise.
- Engine efficiency of natural gas spark ignition truck engines is increased up to 90% of fuel efficiency of diesel engines.
- Diesel-pilot or dual-fuel truck engines with high shares of natural gas and very low methane emission (< 1 g/kWh) become available. In the latter case WTW GHG savings of up to 20% are possible.

For ships, gas engines are already very efficient (close to or comparable with diesel engines), but methane emissions are still substantial for most engine types. For that reason the WTW GHG savings are limited to some 5%. Only the biggest engines, used for large sea ships, show a low methane emission, resulting in GHG savings of up to some 20%[22]. It is important that industry and authorities agree on a path to gradually lower methane emissions of all engine types in order to secure a long term 20% GHG benefit for the entire sector.

Energy efficiency

Both the energy efficiency of both the fuel production and the driveline of the vehicle or ship are important in determining the overall energy efficiency of a fuel.

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[22] Large scale fleet penetration of such ships in 2025 is, however, unlikely, as low-methane engines are not yet available, whereas implementation of methane emission regulation and replacement of ships and ships engines is slow. Full potential (-20%) will be achieved if methane emission is gradually reduced for all engine types.

When natural gas is used in combustion engines, generally some deterioration in engine efficiency occurs, of up to 10 or 15%. Only for large engines such as for ships and for dual-fuel or pilot diesel engines, the efficiency difference with diesel engines is often very small or even absent. A difference of 10 to 15% does offer a scope for further improvement after 2020/2025.

For some fuels such as for H_2 fuel cell vehicles, we see a large difference between application in passenger cars and application in trucks and buses. The WTW energy consumption with passenger cars is some 10% lower than for diesel cars, while for heavy duty (HD) vehicles, the energy consumption is some 20% higher. The relatively higher energy consumption with HD vehicles is caused by the much less favourable engine efficiency of the HD diesel engine.

Pollutant emissions

The pollutant emissions of the electric and H_2 fuel cell vehicles are the lowest of all options investigated here because these vehicles are truly zero emission vehicles. There are, however, still some emissions for the electricity and H_2 production in the Netherlands.

When natural gas is used in combustion engines, pollutant emissions are very much dependent on the pollutant emission standards that the vehicles and ships meet, and the type of fuel used. For passenger cars, pollutant emissions are expected to reduce if CNG is used instead of diesel, however, emission of petrol cars will be even lower (for diesel cars, higher pollutant emissions are allowed). For HD vehicles and inland ships, the emission standards will be tight in the near future. As a consequence we expect little difference between emissions of natural gas and diesel fuel. Diesel engines will be equipped with SCR deNO_x catalysts and trucks will also have diesel particulate filters installed. When older inland ship engines are replaced with new LNG engines, there will be a large improvement in pollutant emissions, but benefits are more limited if LNG ships are compared with newer (2020) diesel ship engines - PM_{10} emissions will be halved in that case, but NO_x emission will be similar.

For sea ships, substantial reduction of NO_x, PM and SO_x emissions can be achieved by shifting from the standard fuels (MGO and HFO) to LNG, mainly because of the lower quality fuel which is used in this transport mode.

8.2 Cost

Apart from the effects on the environmental indicators discussed above, a shift to natural gas-based fuels and energy carriers will also impact on cost of the vehicles and ships, on fuel cost and taxes that need to be paid.

Whether the natural gas options can reduce cost for vehicle and ship owners in 2025 depends strongly on
- the developments in vehicle and ship costs for the various fuels and energy carriers;
- the cost of the fuels and energy;
- the energy efficiency of the vehicles and ships;
- the taxes on the various vehicle types and the fuels/energy carriers.

As oil and gas prices are quite dynamic, taxes tend to change over time, and many of the vehicles types assessed in this study are currently only being produced on a relatively small scale (some are still in the R&D phase), the cost estimates for 2020/2025 are still quite uncertain.

In 2025, it is expected that all natural gas options, except GTL, require vehicles and ships that are more expensive than the reference. In some cases, but not all, these higher cost are sufficiently compensated by lower fuel cost and/or taxes to result in lower overall cost (expressed in cost per kilometre, from user perspective).

Cost savings (for users) are expected when LNG is applied in trucks and buses, inland ships and short sea ships. For trucks, attractiveness is dependent on fuel tax level. Government (tax) revenues will, however, reduce with increasing market penetration of the natural gas options, if current tax levels would remain in place. For sea ships outside of emission control areas (ECAs), operation on HFO is probably the most cost effective options. Ships with dual-fuel, pilot diesel engines may run on HFO outside ECA and on LNG within ECAs.

In road transport, CNG, LNG, hydrogen and electricity benefit from a lower tax per unit energy content compared to diesel and petrol. Cost comparisons including taxes therefore show that in some cases, overall cost per kilometer of the natural gas alternatives are lower than the references, even though costs excluding taxes are higher. This effect does not occur in shipping and aviation, where no taxes are applied.

Comparison of 2025 with current situation

The conclusions in this report apply to the 2020/2025 situation, the focus of this study. The current situation was not investigated, but the main differences between now and 2025 can be identified without detailed study:

- Pollutant emissions with natural gas (CNG, LNG) are now substantial lower than with diesel, but this will diminish over time for several modalities, especially for NO_x and PM for trucks, inland ships and ships in Emission Control Areas. This is a consequence of the entering into force of (much) more stringent pollutant emissions legislation in the future. Only SO_x emission advantages for sea ships will be maintained. Also GTL has some advantages in the current situation, but these will mostly disappear (for trucks) over time.
- GHG advantages with LNG are smaller now than in 2025, especially for trucks and ships. It is expected that efficiencies with natural gas engines will further improve and methane emission will be lowered which both lead to lower GHG emissions in the future.
- Additional vehicle and ship costs for drivetrains for alternative fuels are higher now than in 2020/2025 (with GTL as the only exception, as it is used in conventional diesel engines). Production volumes of CNG and LNG vehicles and ships, and electric and hydrogen vehicles are still very limited, resulting in relatively high cost. Increasing production volumes and further R&D, for example in batteries for electric cars, are likely to significantly reduce cost of these vehicles in the future.

8.3 Impacts of 2.5 mln ton LNG in Dutch transport in 2025

The potential overall impact of LNG in the Dutch transport sector was estimated for a concrete LNG-scenario – the same scenario that was also used in the assessment of the potential impact on safety of large scale roll-out of LNG in the Netherlands. This scenario assumes an annual volume of 2.5 mln tonnes of LNG in Dutch road transport in 2025 (about 122 million GJ), of which 40% will be used in heavy duty road vehicles (trucks and tractor-trailers), 22% in inland shipping, 12% in short sea ships and the remaining 26% in deep sea shipping. The main findings are:

- This shift to LNG would reduce WTW GHG emission by about 654 kton CO_2, NO_x and PM_{10} emissions in the Netherlands would reduce by about 26 and 1 kton respectively, SO_x emissions by more than 7.5 kton per year. Overall energy use would increase, though, by about 11 million GJ.

- The main WTW GHG reduction benefits are achieved with LNG use in road transport.
- NO_x and PM_{10} emission reductions are mainly due to LNG use In maritime transport (short sea and deep sea), SO_x reductions are solely due to shipping.
- The overall cost to vehicle and ship owners was found to decrease compared to the reference fuels. Annual savings of € 77 million (high NG price assumption) to € 140 million (low NG price assumption) were found - see Table 91. However, a large part of these savings are due to lower taxes, as tax revenues would reduce by about € 168 million – all values assuming current taxes levels will remain in place. Cost without taxes were thus found to increase in the high NG price scenario, and decrease in the low price scenario.
- The cost advantages are not evenly distributed over the various applications, as can be seen in Table 91: cost will increase in some applications (tractor-trailer, inland and short sea ship mainly) and reduce in others.

Table 91 Scenario calculations: overall impacts on cost (million €/yr)

	Excluding taxes with high NG price	Including taxes with high NG price	Excluding taxes with low NG price	Including taxes with low NG price
Rigid truck	38	-2	32	-9
Tractor-trailer	-1	-129	-24	-152
Inland ship	-19	-19	-31	-31
Short sea ship	-1	-1	-7	-7
Deep sea ship 5,500 TEU	38	38	30	30
Deep sea ship 15,000 TEU	36	36	28	28
Total	**91**	**-77**	**27**	**-140**

The LNG platform expects a use of LNG for the transport sector of 1 to 1.25 mln ton in 2025. The LNG platform explained that, in addition to the LNG use for transport in the Netherlands, LNG landed at the GATE terminal could be further transported to the Nordic countries.

8.4 Main conclusions per transport mode

8.4.1 Light Duty vehicles – main conclusions

- The pollutant emissions of the various NG-routes are positive in most cases, with only few exceptions.
- WTW GHG emissions improve in most cases, or stay the same (GTL).
- Well-To-Wheel energy use is found to increase somewhat with CNG, and significantly with GTL. The other routes (H_2 and electricity) have similar or better WTW energy efficiency. In this study H_2 and electricity are made from natural gas. Making them from wind or sun energy would lead to additional cost.
- The impact on cost depends on whether or not taxes are included. Without taxes, some routes can be expected to increase cost (namely the hydrogen and some of the CNG and electricity options). With fuel and vehicle taxes included, however, most of the passenger car alternatives result in positive impacts on cost - with the cost assumptions used in this report.

8.4.2 Heavy Duty vehicles - main conclusions

- Energy use is found to increase in most cases, with some routes by more than 15%.
- GHG emissions reduce in most routes, only GTL has a neutral impact here.
- Pollutant emissions were also found to reduce in most options.
- When looking the cost per kilometre, cost without taxes are somewhat higher for CNG. However, with taxes included they are lower than that of the diesel reference.
- Except for the city bus, the hydrogen routes increase cost significantly.

8.4.3 Ships - main conclusions

- LNG was found to increase Well-To-Wheel energy use to some extend (≈ 5%), in all ship types. WTW GHG emissions of LNG are uncertain, due to uncertainty of methane emissions. Currently we predict comparable GHG emissions to those of the reference fuels. If methane emissions can be well controlled, GHG emission savings up to 20% are possible.
- GTL in inland ships increases WTW energy use by about 30% and has a neutral effect on GHG emission. It reduces NO_x emissions by about 10%.
- The effect on pollutant emissions varies:
  - in inland and short sea ships, NO_x emissions of the LNG options are comparable to that of the reference fuels;
  - significant NO_x reductions can be achieved by using LNG in sea ships, especially for the LNG pilot technology;
  - LNG reduces PM_{10} emissions significantly in all ship types;
  - SO_2 emissions of short and deep sea ships are strongly reduced if LNG is used to replace the reference fuel.

8.4.4 Aviation - main conclusions

- Both LNG and GTL were found to increase the WTW energy use of aviation significantly (by 10 and 35% respectively).
- GHG emissions also increase when GTL is used, albeit to a lesser extent, but LNG result in about 10% GHG emission reduction.
- Impacts on NO_x and PM_{10} emissions are negligible.

8.5 Potential for decarbonisation

A range of options exist to decarbonise the various natural gas routes in the future, an important step in the context of overall climate policy.
For example, CNG and LNG can be gradually replaced by biomethane produced by anaerobic digestion and perhaps, in the future, gasification of biomass. GTL can be replaced by biodiesels such as HVO and BTL and various renewable electricity options exist that can replace the natural gas-based electricity production.

When comparing these options, the main issue is that the biomass based routes are faced with a limited overall amount of biomass. Furthermore, the transport sector is not the only sector interested in these feedstocks.
Power plants can use it as fuel, the chemical industry as a feedstock and the build environment as source of green gas.

The use of waste is a preferred and more sustainable option, but this resource is rather small. It is possible to grow additional biomass on farmland, but discussion about food versus fuel, land use change and other sustainability issues is on-going. For the first generation of biofuels the amount of fuel produced per hectare of farmland and the GHG reduction is often limited, and costs may be high. The route of small scale digestion is relatively costly and is not very energy efficient. Non food (lignocellulosic) biomass used for gasification of chemical/biological conversion has a greater potential and causes less discussion about food versus fuel. More waste is available, but it has to be collected (for instance forest residues) and care needs to be taken that undesired impacts on, for example, carbon stock and biodiversity are limited. In general lignocellulosic feedstock costs are lower but the conversion processes are more expensive, and not as far developed as first generation processes.

The use of electricity from wind and sun as a source for transport fuels has less limitations compared to biomass, especially because these options require less surface area. Sun and wind are, however, sources with intermittency, as they depend on the fluctuating intensity of wind and solar radiation. With growing penetration of sustainable electricity, additional storage/consumption options are needed. Car batteries or hydrogen are such an option. Direct use of electricity is more efficient than conversion to hydrogen.

Many of these renewable options are already being promoted by existing policies, namely the biofuels obligation, the FQD and the SDE+ subsidies. However, the incentives differ strongly between the various routes, and a number of routes, namely all sea shipping options, are not yet included in any renewable energy policy. Although there is some attention for methane emissions in the FQD directive, reduction of methane in other parts of the Well-To-Wheel route (for instance from tank storage) is important as well.

8.6 Safety

Part of this study was an assessment of the external safety impacts of the intended LNG distribution chain and infrastructure for road and sea transport and the identification of possible safety issues. From the safety assessment it can be concluded that LNG bunkering stations and transport over water seem to pose no problem with respect to external safety although attention needs to paid to the societal risk around the bunkering stations.
However, LNG filling stations have fairly large risk contours, but different options are available to reduce the risks, creating probably sufficient possibilities for safe locations for these filling stations. The transport of LNG over the road needs detailed attention. Since LNG will replace diesel and not LPG as a transport fuel, the projected LNG transport volume over the road (‘basisnet weg’) will be additional to LPG and will pose a problem due to exceeding the risk level for a large number of the road segments. Without any actions, the expected volume of LNG cannot be absorbed by the ‘basisnet weg’. This requires further investigation.
Adjusting the risk calculation model for road transport (RBM II) to accommodate LNG properly is proposed (a rough approximation for the LNG risk calculations was used in the underlying study). Identification of specific LNG incident and effect scenario’s, assessing specific failure frequencies for critical LNG installation parts and improving current effect models will all lead to more realistic risk levels of LNG and should also be subject to further study.

8.7 Recommendations

Monitor efficiency and emissions of new technologies

In many cases, projections of driveline efficiencies and emissions had to be made with very little (real-world) information which leads to substantial uncertainties. It is therefore recommended to monitor the following parameters in the future:

- efficiencies of fuel cell and battery electric vehicles;
- energy efficiencies and methane emissions of HD natural gas engines;
- methane emissions of ship engines.

LNG fuel quality

A standardisation process for CNG and LNG is currently on-going within CEN/Technical Committee TC408: ‘Project Committee – Natural gas and biomethane for use in transport and injection in the natural gas grid’.
The current plans allows for a relatively wide range specification for CNG and LNG. It also allows for a narrow range, higher quality LNG.

It is recommended to closely monitor advantages and disadvantages of both options. This can be done by participation in the CEN standardisation process and by participation in engine test and development programs. It is recommended to monitor weathering[23] issues in the tanks of HD vehicles and at LNG fuel stations. Lower LNG quality (methane number) may delay the development of higher efficiency engines and lead to additional GHG emissions (and fuel cost).

Methane emission of natural gas engines (CNG and LNG)

Combustion engines, depending on the technology, can have a relatively large methane emission. Methane emissions are generally low with stoichiometric running gas engines and also with lean-burn gas engines with oxidation catalyst. Higher methane emissions can easily ruin the advantages in GHG emissions of potentially some 20%. It is recommended to gradually lower these methane emission in a dialog between industry and governments.
It could well take ten years or more to effectively reduce methane emissions of all engine types. It is nevertheless recommended to take this time, otherwise availability of low emission engines will be strongly compromised.
In addition to methane emission from the engine, there can be methane emission from boil-off of LNG tanks (if the vehicle is not used for a number of days) or when a tank is deliberately blown-off (for example after weathering). It is recommended to monitor this in the future and to consider installations at garages and/or fuel stations to empty LNG tanks in an environmentally friendly way.

Continue evaluation of liquid and gaseous biofuels

Biomass will likely be an important source for both liquid and gaseous biofuels. It is recommended to compare the Well-To-Wheel and Well-To-Propeller of both options quantitatively, and to assess the potential future availability of sustainable liquid biofuels and biogas in more detail, taking demand from other sectors into account.

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[23] Weathering is the accumulation of non-methane hydrocarbons which is in varying percentages present in LNG. This can lead to unusable fuel, especially when the vehicle or fuel station is used less frequently.

It is also recommended to further investigate if the liquid biofuel routes such as biodiesel, HVO and BTL would be the preferred alternative to the gaseous options from a practical and technical point of view, for example because of their easy handling and storage.

External Safety of LNG

The following recommendations can be made to address and/or minimise the safety issues related to the LNG installations and LNG transport:

- apply as much as possible a modal shift for the LNG transport from road to water, since the ‘basisnet water’ can more easily absorb the required LNG volumes without exceeding the accepted risk levels than the ‘basisnet weg’;
- create a LNG specific substance category in RBM II to be able to more realistically calculate the risk of LNG transport, including description of the LNG specific scenarios;
- validate effect models applied in RBM II and SafetiNL for LNG phenomena like evaporation and dispersion;
- collect available failure data for LNG equipment and establish specific LNG failure rates for critical components;
- apply the latest technology for LNG installations and safety measures to ensure optimal safety from a design point of view.

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