The role of natural gas and biomethane in the transport sector

Final Report

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Glossary

AD	Anaerobic digestion
CBM	Compressed bio methane
CI	Compression ignition engine
C&I	Commercial and industrial (waste)
CNG	Compressed natural gas
CO_2	Carbon dioxide
CH_4	Methane
ECA	Emission Control Areas
EEDI	Energy Efficiency Design Index
EU	European Union
GER	Gas Energy Ratio
GHG	Greenhouse Gas
GVW	Gross Vehicle Weight
HC	Hydrocarbons
HFO	Marine Fuel Oil
IMO	International Maritime Organization
LBM	Liquefied biomethane
LNG	Liquefied natural gas
MGO	Marine Gas Oil
MSW	Municipal solid waste
N_2O	Nitrous oxide
NMHC	Non methane hydro carbons
NO_X	Oxides of nitrogen
PM	Particulate matter
Ro-Ro	Roll-on/roll-off
SEEMP	Ship Energy Efficiency Management Plan
SI	Spark ignition engine
SNG	Syngas
SO_x	Oxides of sulphur
THC	Total hydrocarbon
WHTC	World Harmonised Test Cycle
WTT	Well-to-Tank (road transport); Well-To-Wake (shipping)

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Appendx 1 - Definition of scope of the study

1 Introduction

The transport sector is a significant contributor to economy-wide greenhouse gas (GHG) emissions in Europe, and accounted for more than 20% of total GHG emissions in the EU in 2012 (European Commission, 2015).

The Commission's 2011 Transport White Paper (European Commission, 2011) sets a high level objective to reduce emissions from transport by 60% against 1990 levels by 2050. In order to achieve this, EU legislation for road transport vehicles has either been introduced or is planned, including binding emission targets for cars and vans, CO_2 labelling for new passenger cars, fuel quality legislation which requires the reduction of the GHG intensity of fuels, and plans to develop a strategy to reduce GHG emissions from heavy duty vehicles (HDVs).

The Transport White Paper also includes a high-level target to reduce EU CO_2 emissions from maritime bunker fuels by 40% by 2050 (50% if feasible). Steps have also been taken to develop a strategy to progressively integrate maritime emissions into the EU's domestic GHG reduction policy.

The required reductions in emissions are anticipated to be achieved through a range of technologies and fuels, improved energy efficiency in the transport sector and demand management. There is currently strong interest in the use of natural gas and biomethane as a means to reduce GHG emissions from transport. However, there is uncertainty regarding the potential costs, environmental benefits and environmental impacts of using these fuels in the transport sector.

With this in mind, T&E has commissioned Ricardo Energy & Environment to review the latest evidence on the costs, GHG benefits, resource availability and wider environmental impacts associated with increasing the use of natural gas and biomethane in the transport sector. This study draws together evidence from a range of published studies on this topic, and covers the key modes of transport where natural gas and/or biomethane could be deployed – namely the road transport and shipping sectors.

The report is structured as follows:

- Chapter 2 compares GHG emissions performance of ships and road vehicles powered by natural gas and biomethane with equivalent vessels and vehicles powered by conventional oil-based fossil fuels;
- Chapter 3 reviews the impacts of ships and road vehicles powered natural gas and biomethane on emissions of air pollutants
- Chapter 4 presents an analysis of the costs and benefits to society of methane-fuelled shipping and road transport, taking into account capital costs, operating costs and environmental external costs
- Chapter 5 places this assessment of natural gas and biomethane in the context of Europe's capacity for biomethane production in Europe between now and 2030.

The final chapter (Chapter 6) presents the conclusions and recommendations based on the findings from the study.

2 Well-to-wheels GHG emissions performance of transport powered by natural gas and biomethane

This chapter focuses on the environmental impacts of natural gas and biomethane use in transport throughout the entire lifecycle compared to conventional fossil fuels. It uses the following, common abbreviations to refer to the different types of emissions produced during this lifecycle:

- *WTT – 'Well to tank' emissions.* Also known as indirect emissions, these are the emissions 'upstream' from the point of use of the fuel resulting from the transport, refining, purification or conversion of primary fuels to fuels for direct use by end-users and the distribution of these fuels;
- *TTW – 'Tank to wheel' emissions.* Also known as direct, or 'in use' emissions, these are the emissions from the direct use of driving a road vehicle. For the shipping sector, these in-use emissions can also be referred to as *'tank to wake'* emissions; and;
- *WTW – 'Well to wheels' emissions* describes the full lifecycle emissions, i.e. WTT plus TTW emissions. For the shipping sector, the term *'well-to-wake'* emissions is often used.

2.1 Well-to-tank GHG emissions

2.1.1 Oil and natural gas

This section considers the WTT GHG impacts of different fossil fuels, including petrol, diesel, shipping fuels and natural gas. This has been carried out by estimating GHG emissions throughout the various stages of the various fuels' production and distribution process, referred to as 'pathways'.

For oil and fossil gas based pathways, the results are presented according to the five generic steps below:

1. **Production and conditioning at source -** Includes all operations required to extract, capture or cultivate the primary energy source. In most cases, the extracted or harvested energy carrier requires some form of treatment or conditioning before it can be conveniently, economically and safely transported.
2. **Transformation at source** - Used for those cases where a major industrial process is carried out at or near the production site of the primary energy.
3. **Transportation to market** - Relevant to energy carriers which are produced outside the EU and need to be transported over long distances.
4. **Transformation near market** - Includes the processing and transformation that takes place near the market place in order to produce a final fuel according to an agreed specification (e.g. oil refineries or hydrogen reformers).
5. **Conditioning and distribution** - Relates to the final stages required to distribute the finished fuels from the point of import or production to the individual refuelling points (e.g. road transport) and available to the vehicle tank (e.g. compression in the case of natural gas).

Data in this section have been obtained from the JEC 'Well to Wheel study' (JEC, 2013) where a breakdown of emissions into standardised steps is provided. A new study titled "Study on actual data for diesel, petrol, kerosene and natural gas" has been released (Exergia et al., 2015) and is also reviewed further on to provide comparison with JEC estimates.

Table 2-1 to Table 2-4 present GHG emissions per step and by pollutant for oil-based pathways. GHG emissions related to methane leakage are included.

Table 2-1: Oil based pathways: GHG emissions split by process step

Pathway	GHG emissions for each step in pathway ($kgCO_2eq/GJ$ of delivered fuel)					Total
	Production & conditioning at source	Transformation at source	Transportation to market	Transformation near market	Conditioning & distribution	
Crude oil to petrol	4.60	0.00	0.95	7.01	1.20	13.76
Crude oil to diesel	4.68	0.00	0.97	8.60	1.10	15.34
Crude oil to HFO	4.64	0.00	0.96	7.80	1.15[1]	14.55
Crude oil to MGO	4.68	0.00	0.97	8.60	1.10[2]	15.34

Source: (JEC, 2013)
1: Ricardo Energy & Environment assumption: Equal to average of petrol and diesel pathway (in line with approach used in Defra, 2015)
2: Ricardo Energy & Environment assumption: Equal to diesel (in line with approach used in Defra, 2015)

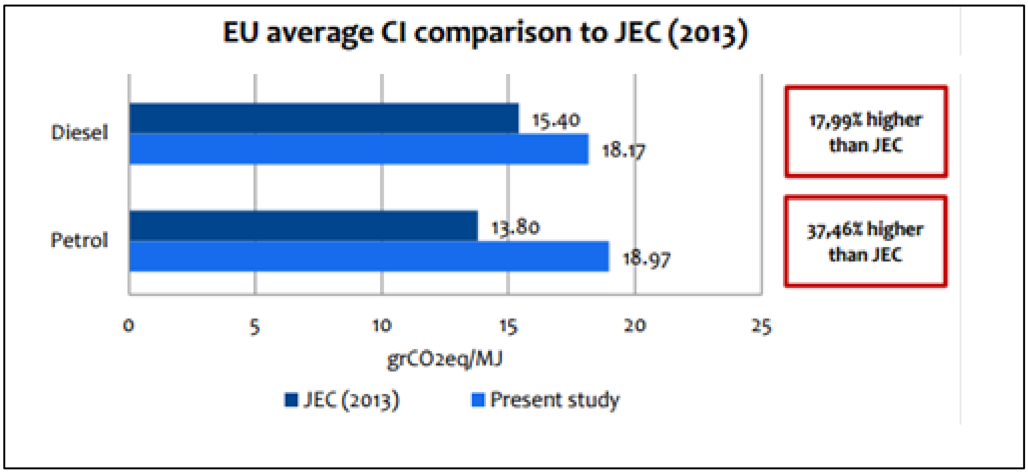
Table 2-2: Oil based pathways: GHG emissions split by pollutant

Pathway	Well to tank (WTT) emissions data ($kgCO_2eq/GJ$ of delivered fuel)				Source/Notes
	CO_2 emissions	CH_4 emissions	N_2O emissions	Total GHG emissions	
Crude oil to petrol	13.05	0.70	0.01	13.76	(JEC, 2013)
Crude oil to diesel	14.62	0.72	0.00	15.34	(JEC, 2013)
Crude oil to HFO	13.83	0.71	0.00	14.55	Assumed equal to average of petrol and diesel
Crude oil to MGO	14.62	0.72	0.00	15.34	Assumed to be equal to diesel

Source: **(JEC, 2013)**

Figure 2-1 below compares the JEC figures set out in the tables above with those from the more recent study by Exergia. As illustrated below, the latter study suggests that GHG intensities could be up to 37% higher than those quoted by JEC.

Figure 2-1: Comparison of average GHG intensity of oil products with JEC values



Source: (Exergia et al., 2015)

Table 2-3 and Table 2-4 present GHG emissions per step and by pollutant for gas-based pathways. GHG emissions related to methane leakage are included.

Table 2-3: Fossil gas based pathways: GHG emissions split by process step

Pathway	GHG emissions for each step in pathway ($kgCO_2eq$/GJ of delivered fuel)					
	Production & conditioning at source	Transform-ation at source	Transport-ation to market	Transform-ation near market	Conditioning & distribution	TOTAL
EU-mix natural gas supply	4.02	0.00	5.14	0.00	3.87	**13.03**
Shale gas	3.90	0.00	0.00	0.00	3.86	**7.76**
Imported LNG (overseas)	4.02	6.17	4.78	0.00	4.42	**19.38**
Imported NG from Russia	4.45	0.00	14.26	0.00	3.86	**22.57**

Source: JEC, 2013

*GHG emissions for the shale gas transportation are covered in the conditioning & distribution step

Table 2-4: Fossil gas based pathways: GHG emissions split by pollutant

Name	Well to tank (WTT) data			
	CO_2 emissions	CH_4 emissions	N_2O emissions	Total GHG emissions
	$kgCO_2eq$/GJ of delivered fuel	$kgCO_2eq$/GJ of delivered fuel	$kgCO_2eq$/GJ of delivered fuel	$kgCO_2eq$/GJ of delivered fuel
EU-mix natural gas supply	8.48	4.46	0.09	**13.03**
Shale gas	4.84	2.87	0.05	**7.76**
Imported LNG (overseas)	13.46	5.82	0.10	**19.38**
Imported NG from Russia	15.03	7.36	0.18	**22.57**

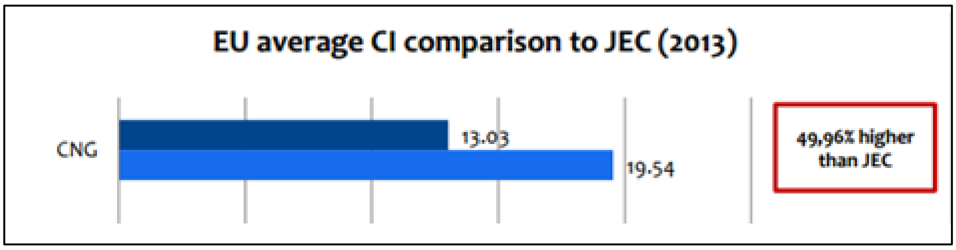
Source: JEC, 2013

As can be seen from the tables, fossil shale gas has the lowest well-to-tank GHG emissions with just over 7.7 kg CO_2e emitted for every GJ delivered. By contrast, imported CNG (from Russia) has the highest WTT GHG emissions of any production route for natural gas or biomethane. The high WTT emissions are primarily due to the long distances involved in transporting this fuel to market. For example piped natural gas from Russia is transported over a distance of approximately 7,000 km during this step. This highlights the importance of domestically produced natural gas which has over 73% lower emissions than natural gas from Russia across the WTT phase.

Imported LNG is another carbon intensive fuel in terms of its WTT GHG emissions. This is again largely the result of the distances travelled from source to market (as LNG is generally transported from overseas) as well as the liquefaction (transformation) stage which is also a carbon intensive process relative to the other pathways.

As before, JEC figures are compared to the recent estimates by Exergia (Exergia et al., 2015) below and are significantly lower.

Figure 2-2: Comparison of average GHG intensity of gas products with JEC values



Source: (Exergia et al., 2015)

The Exergia study also details the large differences in the GHG intensity of natural gas production by European region, as presented in Table 2-5 below. Most strikingly, WTT emissions from natural gas supplied to the EU South East region are more than twice those from natural gas supplied to the EU North region. Differences in WTT emissions for different supply routes are primarily due to (a) the amount of transportation required to deliver the gas (i.e. routes with longer pipeline transportation requirements have higher levels of emissions) and (b) whether the gas is supplied from an LNG stream or not (LNG streams have higher WTT emissions due to the energy intensive nature of the liquefaction process) **(Exergia et al., 2015)**.

Table 2-5: Average GHG intensities of CNG production and distribution for selected EU regions

Reference scenario	EU average	EU North	EU Central	EU South East	EU South West
CNG			**$kgCO_{2eq}/GJ$**		
Fuel dispensing	3.82	3.52	4.11	4.22	2.79
Gas distribution, transmission and storage	2.96	1.25	2.80	6.62	1.16
Feedstock transportation (pipeline, LNG)	6.63	2.44	8.29	9.12	5.14
Fuel production and recovery	5.39	4.82	3.35	7.89	9.56
CO_2, H_2S removed from NG (gas processing)	0.37	0.24	0.20	0.77	0.52
TOTAL	**19.18**	**12.26**	**18.76**	**28.58**	**19.17**

Source: (Exergia et al., 2015)

Table 2-6: Average GHG intensities of LNG production and distribution for selected EU regions

Reference scenario	EU average	EU North	EU Central	EU South East	EU South West
LNG	$kgCO_{2eq}/GJ$				
Fuel dispensing	N/A	1.97	1.98	1.98	1.96
Gas distribution, transmission and storage	N/A	0.59	0.62	0.62 to 0.66	0.59 to 0.63
Feedstock transportation (pipeline, LNG)	N/A	4.39	0.36 to 4.48	1.98 to 4.06	0.74 to 4.21
Fuel production and recovery	N/A	11.27	8.61 to 11.27	11.27 to 37.81	8.73 to 37.86
CO_2, H_2S removed from NG (gas processing)	N/A	1.38	0.00 to 1.38	0.99 to 1.38	0.00 to 1.38
TOTAL	N/A	**19.60**	**11.58 to 19.74**	**19.32 to 43.42**	**12.01 to 43.45**

Source: (Exergia et al., 2015)

The implications of this newly published report are crucial to this study as these large differences will greatly impact on the cost-effectiveness of each fuel. In order to reflect these variations, the following three scenarios are proposed with regards to WTT emission impacts for LNG:

1. Low emission factor scenario, using lower estimates from the JEC Well-to-Wheels study (EU-mix for natural gas;
2. Central emission factor scenario, using central estimates for all fuels from the JEC Well-to-Wheels study (EU-mix for natural gas);
3. High emission factor scenario, EU average emissions factors for petrol, diesel and CNG from (Exergia et al., 2015) and the mean of emissions factors for small-scale production of LNG from (Exergia et al., 2015)

The emissions factors for these scenarios are presented in the table below.

Table 2-7: Low, central and high scenarios for WTT greenhouse gas emissions associated with fuel production

Fuel type	Total WTT GHG emissions ($kgCO_2eq/GJ$ of delivered fuel)		
	Low	Central	High
Petrol	12.2	13.8	18.2
Diesel	13.8	15.3	17.4
HFO	13.0	14.6	17.8
MGO	13.8	15.3	17.4
CNG	11.8	13.0	19.2
LNG	18.8	19.4	24.6

Note that all of the above datasets include methane leakage emissions. Methane leakage is a term given to the level of methane emissions that are released to the atmosphere during fuel production. Methane has a 100 year global warming potential 30 times greater than CO_2[1] (IPPC, 2014), and hence,

[1] Based on 5th Assessment Report under Kyoto Protocol

in terms of climate change impacts, 1 kg of methane released to the atmosphere is equivalent to 30 kg of CO_2. Significant amounts of methane leakage could therefore outweigh the CO_2 reduction benefits of using natural gas or biomethane in place of conventional transport sector fossil fuels.

For oil based pathways, the level of methane leakage is low (almost negligible) and occurs during the process of venting emissions from crude oil refineries.

Table 2-8: Methane leakage associated with the production of oil-based fuels

Process	Methane leakage (% of final amount of fuel produced)
Production & conditioning at source	0.1%
Transportation to market	0.0%
Transformation near market	0.0%
Conditioning and distribution	0.0%

However during the production of natural gas and biomethane, the levels of methane leakage emissions are much greater. For natural gas pathways, the extraction and processing step is the main generator of methane emissions during production as shown in Table 2-9. There are also some methane emissions as a result of transporting the gas, with imported gas from Russia being a large contributor to methane emissions (0.8% leakage) because of the long distances involved. The table below provides some information on the levels of methane leakage associated with different production steps for natural gas production; however, these figures are only indicative as there is a significant level of uncertainty in the levels of methane leakage associated with natural gas production processes, due to the difficulty in accurately quantifying leakage rates from the different steps involved. The table below gives methane leakage rates of up to 1.2% depending on the source of the gas and whether it is dispensed as CNG or LNG. However, other estimates indicate that methane leakage can range from less than 1% to as high as 9% (Carbon Brief, 2014).

Table 2-9: Natural gas pathways, methane leakage (%) by process

Process	Methane leakage %
EU-mix natural gas	
Extraction & Processing	0.4%
Transport	0.3%
Distribution	0.0%
Compression	0.0%
LNG	
Extraction & Processing	0.4%
Liquefaction	0.2%
Transport (shipping)	0.0%
Unloading terminal	0.0%
Road transport	0.4%
Shale gas	
Extraction & Processing	0.5%
Distribution	0.0%
Compression and CNG dispensing at retail site	0.0%
Natural gas from Russia	
Extraction & Processing	0.4%
Transport	0.8%
Distribution	0.0%
Compression	0.0%

Source: (Ricardo-AEA, 2014)

However, there is significant uncertainty in the levels of methane leakage associated with natural gas extraction, processing and distribution. There are two main methods of quantifying leakage rates: bottom-up approaches and top-down approaches (Carbon Brief, 2014). Bottom-up approaches focus on estimating leakage emissions at the source. However, it is not feasible for researchers to measure emissions at every point in the production and distribution chain, and hence there is a risk that this approach can underestimate or overestimate leakage rates. For example, it is possible that researchers could miss a big leak in a pipeline simply because that section of the pipeline is not covered in their measurements. This would lead to an underestimate in overall leakage rates. Alternatively, if researchers take measurements from wells that have particularly high leakage rates but that are not representative of the wider population of gas well, then the bottom-up approach could lead to systematic overestimates of methane leakage rates.

By contrast, top-down approaches try to avoid the problems associated with bottom-up approaches by taking measurements of the total amount of methane in the atmosphere for a particular area. This can be achieved by taking measurements above ground level – for example, from a tall building or from an aeroplane. The major limitation associated with top-down approaches is that it is difficult to relate the levels of methane measured in the atmosphere with particular sources; emissions may be due to leakage from gas production and distribution, or they may be due to other sources such as wetlands and landfill sites. Hence, top-down approaches tend to result in higher estimates than bottom-up approaches because there is a risk of systematically overestimating methane leakage rates.

2.1.2 Biomethane

To produce biomethane, there are two primary production pathways, namely (i) anaerobic digestion and (ii) landfill degradation. After either of these initial production steps has been completed, there are various common production and distribution processes to obtain biomethane that can be used for transport sector applications. The key production and distribution steps are presented in Table 2-10.

Table 2-10: Description of key biomethane production processes

Process	Equivalent step in JEC WTT pathway analysis	Description
Anaerobic digestion	Production and conditioning at source	This includes: • Reception and storage of source separated food waste, • Pre-processing including heat treatment, • Digestion to produce biogas, • On site biogas storage
Landfill degradation	Production and conditioning at source	No emissions are assumed to be associated with production of landfill gas, as landfill gas is a by-product of disposal of waste to landfill i.e. the primary purpose of the operation is waste disposal.
Cleaning (CO_2 removal)	Production and conditioning at source	In this step CO_2 is removed from biogas produced in the anaerobic digester. Various technologies can be used, membrane separation, chemical scrubbing, water scrubbing and pressure swing adsorption.
Injection to grid	Production and conditioning at source	In this step biomethane, having had CO_2 and other impurities removed, is compressed, metered, and odourised. Its calorific value is adjusted by propane addition typically 3%, by volume. The gas is then compressed from 10 bar to 20 bar for injection into the grid

Process	Equivalent step in JEC WTT pathway analysis	Description
Liquefaction	Transformation at source	Here the gaseous form of methane produced from anaerobic digestion is reduced to a liquid via a cooling process. In liquid form the biomethane occupies only 1/600th of its gaseous volume, while for it to be in liquid form a temperature of around -162°C is required. This liquefied biomethane is then stored in large insulated tanks, prior to transportation to the dispensing point
Distribution	Conditioning & distribution	Domestic transportation of gas from source to market whether through pipelines or road tankers.
Dispensing as CNG/LNG (from CBM/LBM)	Conditioning & distribution	Relates to the final stages required to distribute the finished fuels from the point of import or production to the individual refuelling points.

Table 2-11 and Table 2-12 present a summary of the GHG emissions per WTT process step for biomethane based pathways. The GHG emissions data presented in this section include emissions of CO_2, CH_4 and N_2O. However the level of detail available in the original literature source does not allow for a breakdown by individual GHG species. As for fossil gas pathways, the well-to-tank GHG emissions data for biomethane include estimates for methane leakage. In the case of biomethane produced from anaerobic digestion, methane leakage rates can be very significant (see Table 2-14).

Table 2-11: WTT emissions for biomethane from source separated food waste produced via anaerobic digestion (kgCO$_2$eq/GJ of delivered fuel)

	WTT greenhouse gas emissions	
Process step	**CBM transported via pipeline**	**LBM transported via road tanker**
Anaerobic digestion	9.87	9.72
Cleaning, CO_2 removal	5.28	5.23
Injection to grid	0.50	2.46
Distribution (Pipeline transport)	3.87	3.73
Dispensing as CNG / LNG*		0.00
TOTAL	**19.51**	**21.33**

Source: Ricardo-AEA, 2014; JEC, 2013

* Trace emissions

Table 2-12: WTT emissions for biomethane from residual municipal solid waste (MSW) produced via landfill degradation (kgCO$_2$eq/GJ of delivered fuel)

	WTT greenhouse gas emissions	
Process step	**CBM transported via pipeline**	**LBM transported via road tanker**
Landfill degradation*	0.00	0.00
Cleaning, CO_2 removal	5.28	5.28
Injection to grid	0.50	2.46
Distribution (Pipeline transport)	3.87	3.73
Dispensing as CNG / LNG**		0.00

Source: Ricardo-AEA, 2014; JEC, 2013

* Landfill gas is considered to be a waste resource, so only emissions from cleaning, upgrading and liquefaction are included when quantifying GHG emissions associated with the biomethane production process.

** Trace emissions

Table 2-13: WTT greenhouse gas emissions for biomethane production pathways

Name	Total WTT GHG emissions kgCO$_2$eq/GJ of delivered fuel
CBM from food waste (AD)	19.51
LBM from food waste (AD)	21.33
CBM from MSW (LFG)	9.64
LBM from MSW (LFG)	11.47

Key: Food waste (AD) = Anaerobic digestion of source separated food waste; **MSW (LFG) =** Landfill gas derived biofuel from municipal solid waste

Producing biomethane from anaerobic digestion of food waste or from landfill gas results in fuels that contain only biogenic carbon, and hence the combustion of these fuels releases biogenic CO_2 emissions. Biogenic CO_2 emissions are defined as those emissions related to the natural carbon cycle, as well as emissions associated with the combustion, harvest, digestion, fermentation decomposition or processing of biologically-based materials. The CO_2 emissions released from the combustion of biogenic carbon are not considered to contribute to climate change because the carbon in the fuel was assumed to be absorbed during the growth of the original biological material.

Table 2-14: Biomethane pathways, methane slip (%) by process

Process	Methane leakage %
Anaerobic digestion	1.2%
Landfill gas production	0.0%
Upgrading	0.5%
Injection to grid	0.1%
Transmissions in pipeline	0.0%
Dispensing as CNG (from CBM)	0.0%
Liquefaction	0.0%
Dispensing as LNG (from LBM)	0.0%

Ricardo-AEA, 2014

As can be seen from the above tables, the WTT emissions factors for the production of biomethane vary significantly depending on the production route used. For the purposes of this study, we have developed three scenarios (low, central and high) as follows:

1. **Low emission factor scenario:** assumes that CBM and LBM are produced solely from landfill gas
2. **Central emission factor scenario:** assumes that production of CBM and LBM is split 50:50 between landfill gas derived production and anaerobic digestion
3. **High emission factor scenario:** assumes all CBM and LBM is produced via anaerobic digestion.

Table 2-15: Low, central and high scenarios for WTT greenhouse gas emissions associated with biomethane production

Fuel type	Total WTT GHG emissions (kgCO$_2$eq/GJ of delivered fuel)		
	Low	Central	High
CBM	9.64	14.58	19.51
LBM	11.47	16.40	21.33

2.1.3 Summary of pathways results

The previous sections have shown that the WTT greenhouse gas emissions associated with the production of fossil fuels and biomethane are highly dependent on the specific production mechanisms and on the amount of transportation required to bring the fuels to market. Furthermore, the most recent analysis of WTT greenhouse gas emissions associated with the production of fossil fuels (Exergia et al, 2015) indicates that these emissions could be very significantly higher than previously thought. In particular, for CNG, WTT emissions could be up to 50% higher than previous estimates and for LNG, emissions could be more than 100% higher than previous estimates in the worst case scenario. Given the very high levels of uncertainty with respect to WTT emissions, and the fact that these emissions can vary very significantly depending on the source of the fuels, a scenario-based approach has been applied so that a range of estimates can be used to support the analysis in this study. A summary of the WTT emissions data is presented in the table below.

Table 2-16: Summary of low, central and high estimates of the WTT greenhouse gas emissions factors for fossil fuels and biomethane

Fuel type	Total WTT GHG emissions (kgCO$_2$eq/GJ of delivered fuel)		
	Low	Central	High
Petrol	12.2	13.8	18.2
Diesel	13.8	15.3	17.4
HFO	13.0	14.6	17.8
MGO	13.8	15.3	17.4
CNG	11.8	13.0	19.2
LNG	18.8	19.4	24.6
CBM	9.6	14.6	19.5
LBM	11.5	16.4	21.3

As can be seen from this table, in some scenarios, the WTT emissions associated with biomethane are lower than the equivalent WTT emissions factors for comparator fossil fuels, whilst in other cases, the factors for biomethane are higher than for some of the fossil fuels. In all cases, WTT emissions for LNG are higher than for CNG, and similarly WTT emissions are always higher for LBM than for CBM. This is primarily due to the additional energy required for the liquefaction process. The data presented in the above table have been used in combination with tailpipe, tank-to-wheel (TTW) GHG estimates (see Section 2.2) in order to develop overall well-to-wheel GHG emissions factors for each fuel.

2.2 Tailpipe GHG emissions performance for each transport mode

This section assesses the in-use tailpipe GHG emissions performance for each mode of transport using (a) natural gas and (b) biomethane (road transport only) and covering emissions of CO_2, methane (CH_4) and nitrous oxide (N_2O) for each mode of transport. For natural gas and biomethane, details on methane slip emissions are also included, where such data are available.

2.2.1 Tank-to-wake emissions for the shipping sector

2.2.1.1 Policy context

Due to the international nature of the shipping industry (i.e. emissions from shipping cannot be the responsibility of a specific country) it has been considered too complex for emissions to be regulated under the United Nations Convention on Climate Change (Kyoto Protocol). As such, regulations covering shipping emissions were not proposed at the UN Climate Change Conference in 2011.

However, there is increasing pressure on the shipping sector to reduce GHG emissions. In 2011, the IMO adopted two mandatory mechanisms intended to implement minimum energy efficiency standards for ships in 2011. These were:

(1) The Energy Efficiency Design Index (EEDI), for new ships; and
(2) The Ship Energy Efficiency Management Plan (SEEMP) for all ship owners.

The EEDI is a design-based mechanism that requires a certain minimum energy efficiency in new ships. Ship designers and builders are free to choose the technologies they include to satisfy the EEDI requirements in a specific ship design. The SEEMP establishes a mechanism for operators to improve the energy efficiency of ships. The Regulations apply to all ships of and above 400 gross tonnage and entered into force on 1st January 2013.

In addition, in 2013 the EC set out a strategy which aims to progressively integrate maritime emissions into the EU's policy for reducing its domestic GHG emissions. This includes monitoring, reporting and verification (MRV) of CO_2 emissions from large ships using EU ports; GHG reduction targets for the maritime transport sectors and further measures, including market based measures (MBMs) in the medium to long term (European Commission, 2013). As the first step in implementing this strategy, EC Regulation (2015/757/EC) was adopted in 2015 requiring the MRV of CO_2 from maritime transport (European Commission, 2015a). Measures to reduce GHG emissions and fuel consumption from shipping are often difficult to implement due to the existence of a number of market barriers, including the lack of reliable information on the fuel efficiency of ships or of technologies available for retrofitting ships. The Regulations establish an EU-wide legal framework which requires the collection and publication of verified annual data on CO_2 emissions and energy efficiency for all large ships (in excess of 5,000 gross tons) using EU ports (regardless of where ships are registered). Companies will therefore have to monitor and report verified CO_2 emission data from their ships on voyages to, from and between EU ports from January 2018.

In this context, there is increasing interest in the potential of natural gas and biomethane to be used as one of the means for the shipping sector to reduce its GHG emissions.

2.2.1.2 Methodology

This section presents the approach we have used to compare the TTW GHG emissions performance of ships using LNG compared to conventional marine fossil fuels (HFO and MGO). In order to carry out this analysis, we have drawn on previous research carried out by the Danish Maritime Authority (2012). This research investigated the costs and emissions benefits associated with using LNG instead of HFO or MGO for four different types of ships. For each vessel type and fuel type combination, the study included estimates of typical annual fuel consumption. For HFO-fuelled vessels, the Danish Maritime Authority study accounted for the additional fuel consumption associated with exhaust gas scrubbers (fuel consumption typically increases by 2.5%). It is worth noting that CE Delft has recently carried out work on this topic and their research indicates that for freshwater scrubbers, fuel consumption increases by approximately 1% and for seawater scrubbers, fuel consumption increases by 3% (CE Delft, 2015); these figures are broadly in line with the Danish Maritime Authority study which focused on sea-going vessels.

We have used these datasets and then combined the fuel consumption data with emission factor data (in units of kg of emission per GJ of fuel consumed) to quantify the tailpipe emissions performance of each vessel type. Emissions of CO_2, methane (CH_4) and nitrous oxide (N_2O) were all taken into account and then converted into total CO_2 equivalent (CO_2e) emissions using the latest Global Warming Potential values for CH_4 and N_2O (IPPC, 2014). For LNG-fuelled vessels, methane slip emissions were included in this analysis.

Table 2-17: Annual fuel consumption for selected case study vessels (derived from (Danish Maritime Authority, 2012))

Ship type	Annual fuel consumption (tonnes per year and GJ per year)		
	HFO + scrubber	MGO	LNG
RoRo	3,101 tonnes (126,224 GJ)	2,891 tonnes (123,146 GJ)	2,700 tonnes (129,303 GJ)
Coastal tanker / bulk carrier	3,676 tonnes (149,599 GJ)	3,426 tonnes (145,940 GJ)	3,200 tonnes (153,248 GJ)
Container ship	5,179 tonnes (210,374 GJ)	4,818 tonnes (205,243 GJ)	4,500 tonnes (215,505 GJ)
Large RoRo	11,257 tonnes (458,148 GJ)	10,492 tonnes (446,973 GJ)	9,800 tonnes (469,322 GJ)

Table 2-18: Shipping fuel and LNG emission factors (assuming complete combustion and methane slip emissions during vessel operation)

Fuel	Emissions per GJ of fuel consumed - Net CV			
	kg CO_2	kg CH_4	kg N_2O	kg CO_2e
Marine fuel oil	79.19	0.001	0.002	79.81
Marine gas oil	74.94	0.001	0.002	75.53
LNG	51.13	0.003	0.000	51.24

Source: (DEFRA, 2015)

The above emission factors do not take into account methane slip emissions due to unburnt LNG being released to the atmosphere from the engine/exhaust tailpipe. It is necessary to take these emissions into account because they can counteract the CO_2 benefits associated with LNG compared to conventional marine fossil fuels.

Research carried out by ICCT indicates that methane slip emissions are currently around 10.6 kgCO_2e/GJ (ICCT, 2013), which equates to approximately 1.8% of the fuel being lost to the atmosphere. (Thomson, Corbett, & Winebrake, 2015) estimate methane slip emissions of up to 659.4 grams of methane per mmBtu of LNG consumed (equivalent to 20.9 kgCO_2e/GJ, based on a GWP for methane of 28, or a methane loss rate of approximately 3.5%). The large variations in estimates for methane slip emissions indicate that this is an area where there is a significant amount of uncertainty.

Table 2-19: Estimates for methane slip emissions from LNG-fuelled vessels

Data source	Methane slip emissions from vessel operation (kgCO_2e/GJ	Methane slip rate
ICCT (2013)	10.6 kgCO_2e/GJ	1.8%
Thomson et al (2015)	20.9 kgCO_2e/GJ	3.5%

Drawing all of this information together, we have been able to estimate total annual tank-to-wake GHG emissions for each vessel type and fuel type combination, using the two different assumptions for the level of methane slip emissions associated with vessel operation. These estimates are presented in the table below.

Table 2-20: Annual tank-to-wake greenhouse gas emissions associated with the use of different types of vessels

Ship type	Annual CO_2e emissions (tonnes per year)			
	HFO + scrubber	MGO	LNG (1.8% methane slip)	LNG (3.5% methane slip)
RoRo	9,996	9,228	8,146	9,312
Coastal tanker / bulk carrier	11,847	10,937	9,655	11,037
Container ship	16,659	15,381	13,577	15,520
Large RoRo	36,280	33,496	29,568	33,800
Percentage difference in TTW emissions between LNG and HFO			-19%	-7%
Percentage difference in TTW emissions between LNG and MGO			-12%	+1%

As can be seen from the table, once methane slip emissions are taken into account, using LNG results in a reduction of between 9% and 19% in tailpipe GHG emissions compared to an equivalent HFO-fuelled vessel equipped with exhaust gas scrubbers, and between a 1% increase and 12% reduction compared to MGO-fuelled vessels, depending on which assumptions are used for the levels of methane slip emissions. Hence it is clear that any tailpipe GHG emissions impacts are highly sensitive to the levels of methane slip emissions associated with operating LNG-fuelled vessels. If there were no methane slip emissions, then total annual tailpipe GHG emissions from LNG vessels would be around 30% lower than from MGO-fuelled vessels and around 35% lower than from HFO-fuelled vessels equipped with exhaust gas scrubbers. Engine manufacturers are currently working on preventing methane slip in order to improve the GHG reduction potential of LNG. Technologies such as oxidation catalysts and exhaust gas recirculation (EGR) are being used to achieve this.

2.2.2 Tank-to-wheel emissions for passenger cars

2.2.2.1 Methodology assumptions

The use of natural gas and biomethane in passenger road vehicles has not been widely adopted in Europe and currently, only around 0.4%[2] of cars registered in Europe are gas fuelled. Many cars currently using CNG are converted from petrol vehicles whilst some are manufactured as bi-fuel vehicles, with two fuel tanks. For this study, only mono-fuel CNG and CBM powered vehicles have been investigated. LNG technologies were not included in the analysis for passenger cars, as this technology is generally only deployed in the heavy goods vehicle market.

2.2.2.2 Emissions analysis

In general, methane-powered passenger cars have spark ignition engines and therefore fuel efficiency (on a fuel energy content basis) is very similar to an equivalent petrol-powered vehicle[3].

Table 2-21 sets out the initial parameters used to assess the difference in GHG emissions performance between cars powered by CNG and CBM and those powered by petrol and diesel.

[2] NGVA statistics - http://www.ngvaeurope.eu/cars

[3] In some instances, gas vehicles can exhibit greater or lower energy efficiency when compared to a petrol counterpart. In this study they are assumed to be equal.

Table 2-21: Vehicle characteristics used in this study for LDVs

Vehicle type	Engine type	Annual mileage (km)	Lifetime age	2015 NEDC tailpipe emissions (gCO_2/km	2015 real-world tailpipe emissions (gCO_2/km	2020 real-world tailpipe emissions (gCO_2/km)	Notes
CNG passenger car	SI engine	13,000	14	93	112	88	For real-world driving of a lower medium sized 1.4 litre CNG-powered vehicle
CBM passenger car	SI engine	13,000	14	0	0	0	For real-world driving of a lower medium sized 1.4 litre CNG-powered vehicle using bio-methane
Petrol passenger car	SI engine	13,000	14	118	142	111	For real-world driving of a lower medium sized 1.4 litre petrol-powered vehicle
Diesel passenger car	CI engine	13,000	14	89	107	84	For real-world driving of a lower medium sized 1.6 litre diesel-powered vehicle

Source: Ricardo-AEA, 2014

These figures have been developed based on the current performance of typical C-segment passenger cars for each powertrain type that are available on the market today. The NEDC test cycle CO_2 emissions performance figures for each current vehicle have been uplifted by 20% to provide an approximate real-world emissions figure. The resulting data have then been scaled to develop real-world CO_2 emissions estimates for equivalent 2020 vehicles based on the gap between current fleet-wide average new car performance and projected 2020 fleet-wide performance needed to meet the forthcoming EU 95 gCO_2/km target.

For CNG-fuelled vehicles, the different fuel composition leads to a 21% reduction in TTW tailpipe CO_2 emissions compared to petrol-fuelled cars, assuming complete combustion of the fuel (i.e. no methane slip). However, compared to diesel cars, tailpipe CO_2 emissions performance is around 5% worse in the example above. With regards to CBM, tailpipe emissions of CO_2 are reported as zero. This is because for this study, we have focused only on biomethane produced from waste biological materials such as landfill gas and anaerobic digestion of organic wastes. For biomethane produced from these types of wastes, the tailpipe CO_2 emissions released on combustion are treated as biogenic and not considered to contribute to climate change. However, it is possible to produce biomethane from other waste feedstocks where not all of the carbon is biogenic in nature. For example, the gasification process can be applied to residual municipal solid waste (MSW) or to solid recovered fuel (SRF – a fuel prepared from residual waste, which is more homogeneous and has a higher energy content). However, these feedstocks contain waste of both a biological origin (e.g. paper, card, food waste) and of fossil origin (e.g. plastics). Based on the typical composition of waste streams, it is assumed that 50% of the carbon in solid recovered fuels and 70% of the carbon in MSW are from biogenic sources. Hence, if biomethane is produced from these feedstocks, tailpipe CO_2 emissions would not be reported as zero, but would be 50% (for SRF-derived biomethane) and 30% (for MSW-derived biomethane) respectively of the tailpipe emissions of a CNG-powered car (i.e. 44 gCO_2/km and 26 gCO_2/km respectively).

Additionally, biomethane can also be produced from energy crops or from wood resources. The CO_2 emissions released on combustion of biogas and biomethane produced from energy crops are not considered to contribute to climate change because they are part of the short-term carbon cycle (i.e. the CO_2 emitted on combustion was absorbed from the atmosphere up to around one year earlier). However, energy crops can potentially lead to undesirable environmental impacts such and indirect land use change, putting pressure on the amount of land available for growing food crops. Furthermore, it is also possible to produce biomethane from wood which could have net impacts on climate change in terms of CO_2 emissions released on combustion of the resulting biomethane, as wood is not part of the short-term carbon cycle.

2.2.2.3 Methane slip and emissions of nitrous oxide

As well as CO_2 emissions, emissions of methane (CH_4) and nitrous oxide (N_2O) are especially relevant for vehicles running on methane fuels because of the much higher global warming potential (GWP) of methane and nitrous oxide compared to CO_2 (GWP values of 30 and 265 respectively (IPPC, 2014). As was discussed in Section 2.2.1 on shipping, small amounts of these gases leaving the exhaust and the engine crankcase may significantly increase the overall GHG emissions impacts of the vehicle. Methane emissions are in theory controlled by exhaust gas recirculation (EGR) technology. There are no specific regulatory limits for tailpipe (TTW) emissions of methane or N_2O, but typical emission factors are given in the latest version of the EEA/EMEP emission factor guidebook, as given in Table 2-21[4].

Table 2-22: EMEP/EEA emission factors for CH_4 and N_2O for transport fuels for Euro 5/6 petrol and diesel passenger cars

	Emissions of CH_4 and N_2O per km travelled for typical 2020 passenger cars	
Fuel type	**CH_4 (mg/km)**	**N_2O (mg/km)**
Petrol	3	1.3
Diesel	0.6	4

Source: (EMEP/EEA, 2014). Note that emission factor for methane has been derived based on Tier 2 and Tier 3 emission factor data included in (EMEP/EEA, 2014)

Table 2-23 presents data on the tailpipe emissions performance for the same model of passenger car equipped with petrol, diesel and natural gas engines. As can be seen from the data, methane emissions for the vehicle running on CNG and CBM are significantly higher than the emissions for petrol and diesel vehicles.

Table 2-23: Comparison of the tailpipe GHG emissions performance of cars powered by different types of fuels

Vehicle type	Total CO_2e (g/km)	CO_2 (g/km)	CH_4 (mg/km)	N_2O (mg/km)	% CO_2e reduction versus petrol/diesel counterpart
CNG passenger car	89.0	88	27.6	0.64	20.8% reduction compared to petrol
CBM passenger car	1.0	0	27.6	0.64	99.3% reduction compared to petrol, when using CBM produced from biogenic feedstocks
Petrol passenger car	111.4	111	3	1.3	N/A
Diesel passenger car	85.1	84	0.6	4	N/A

From the table it is seen that relative to its petrol counterpart, an OEM built CNG vehicle generates a 20.8% saving in GHG emissions.

2.2.3 Tank-to-wheel emissions for heavy-duty vehicles

2.2.3.1 Methodology

For the purpose of this study the HGV fleet has been split into two categories: urban and long-haul. “Urban” describes smaller rigid trucks carrying loads between 3.5 tonnes and 16 tonnes (e.g. Iveco Eurocargo), and “long haul” describes large articulated trucks typically carrying up to 44 tonnes (e.g., Volvo FM13 truck chassis).

[4] See EMEP EEA Guidebook, 2013 versions, Chapter on Exhaust emissions from Road Transport, available from: http://www.eea.europa.eu/publications/emep-eea-guidebook-2013/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-road-transport-annex-hdv-files.zip

The methane fuelled vehicles that are assumed to replace these conventional diesel comparators are a dedicated methane fuelled SI engine in the smaller rigid truck, and a dual fuel CI engine in the articulated trucks. Whilst these are the current technologies being evaluated, it may be that dedicated methane engines of higher rated power become available for use in articulated vehicles, or dual fuel smaller engine vehicles are used. In both cases, the generalities described below apply.

2.2.3.2 Analysis

Typical GHG emissions performance figures for these types of vehicles are presented below, comparing diesel-powered trucks with equivalent versions using natural gas and biomethane. These figures assume complete combustion of the fuels (i.e. methane slip is not taken into account for vehicles powered by natural gas or biomethane).

Table 2-24: Comparison of the tailpipe GHG emissions performance of HGVs powered by different types of fuels

Vehicle type	Fuels	gCO_2e/km	gCO_2/km	gCH_4/km	gN_2O/km
HGV (urban)	Diesel	601.2	600	0.0030	0.0040
HGV (urban)	CNG	663.9	600	1.25	0.109
HGV (urban)	CBM	63.9	0	1.25	0.109
HGV (long distance)	Diesel	831.2	830	0.0030	0.0040
HGV (long distance)	Dual fuel (Diesel and LNG)	778.5	760	0.5020	0.0179
HGV (long distance)	Dual fuel (Diesel and LBM)	418.8	400*	0.4910	0.0179

Source: VehTechData for DfT Gaseous Fuel Project (Built on estimates in line with the new EC regulations

* Assumptions made regarding the gas substitution ratio: CO_2 emissions are not zero because fossil diesel fuel continues to be used alongside the LBM.

Natural gas vehicles are typically up to 15% less fuel efficient than their diesel counterparts, and that fuel efficiency gap tends to be higher for older vehicles (ICCT, 2015). Spark ignition methane-powered vehicles are typically less efficient than vehicles equipped with dual-fuel compression ignition engines, which have fuel efficiency characteristics that are much closer to diesel-powered vehicles. ICCT reported the results of research that indicated that there are significant opportunities for improving the fuel efficiency of methane-powered heavy duty vehicles, which may mean that it is possible for reductions in the fuel efficiency gap between methane-powered and diesel-powered heavy duty vehicles to be achieved in future years. However, improvements in the fuel efficiency of conventional diesel-powered vehicles may also be achieved in future years, and ICCT's analysis assumed methane-powered vehicles remain 10% less fuel efficient than equivalent diesel vehicles in the future. It is important to note the lower fuel efficiency of methane-powered vehicles does not automatically mean that the CO_2 emissions from methane-powered vehicles are higher than from equivalent diesel-powered vehicles, although obviously it is also important to consider other non-CO_2 greenhouse gases in this context, as discussed in the next section.

2.2.3.3 Methane slip emissions

A recent study for the UK's Department for Transport (DfT): "Waste and gaseous fuels in transport" (Ricardo-AEA, 2014) estimated that, for a typical dual-fuel HGV, a 2% level of methane leakage could completely negate the greenhouse gas savings offered by using methane as a vehicle fuel in place of diesel (Ricardo-AEA, 2014). Recent research carried out by ICCT indicates that leakage levels as low as 1% could be sufficient to offset the GHG benefits of natural gas vehicles (ICCT, 2015).

Additional conclusions drawn from this study that are relevant to quantifying methane leakage from heavy duty vehicles are as follows:

- Methane slip emissions, particularly from diesel/methane dual fuel vehicles, are currently very variable, ranging from less than 1 gCH_4/kWh to over 10 gCH_4/kWh (0.036 gCH_4/GJ to 0.36

gCH4/GJ). This is equivalent to 28 – 280 g CO_2e/kWh (1 – 10 gCO_2e/GJ). CO_2 emissions from a diesel comparator vehicle are around 600 g/kWh.

- Methane fuelled vehicle technology is at a relatively early stage of development, particularly in the context of more than 100 years of diesel engine development, and the level of methane slip emissions from current vehicles may be a poor representation of the methane slip emissions that technically could be achieved by vehicles that will be available in 2020. However, in order to achieve future improvements in European particular, in Europe further regulatory action in this area may be needed (see discussion below).

The potential level of methane leakage from new gas vehicles in 2020 is shaped by current European regulations on hydrocarbon emissions. Euro VI is the most recent standard for HGVs, as set out in EC Regulation 595/2009 (European Commission, 2009) and its implementing regulation, Regulation 582/2011 (European Commission, 2011) which came into force for all type approvals from January 2013 and for all new registrations from January 2014[5]. Using the World Harmonized Stationary Cycle (WHSC) test and the World Harmonized Transient Cycle (WHTC) test (for gas and diesel vehicles), emission limits are enforced for all new vehicles, as set out in Table 2-25.

Table 2-25: Euro VI emission standards for HGVs

Test / g per kWh	CO	NMHC	HC	CH_4	NOx	PM
WHSC (HD diesel engines)	1.5	-	0.13	-	0.4	0.01
WHTC (diesel and gas engines)	4.0	0.16*	-	0.5	0.46	0.01

**THC for diesel vehicles*

Source: (European Commission, 2009)

These regulations set limits for methane emissions from gas engines. A more recent amending regulation, Regulation 133/2014/EC, also specifies methane emission limits for dual fuel vehicles. These values are consistent with the emissions from diesel only and dedicated methane vehicles specified in the earlier EC Regulation (582/2011). Based on these values, we have assumed that in 2020, the maximum level of methane slip emissions from gas-powered heavy duty vehicles will be 0.5 gCH_4/kWh (0.018 gCH_4/GJ); this equates to 14 gCO_2e/kWh (0.5 gCO_2e/GJ) based on a GWP of 28 for methane.

Given that there is scope to improve the methane slip emissions performance of vehicles, there is an argument that more stringent methane emissions limits may be required in future years. In particular, the current European limit value of 0.5 gCH_4/kWh for heavy-duty vehicles is significantly less stringent than the current US limit of 0.13 gCH_4/kWh.

Dual-fuel vehicles

The impacts of methane slip emissions on the overall TTW emissions performance of gas-powered vehicles can be assessed using data on the relative emissions performance of HGVs from a recent demonstration project. The UK Government's Low Carbon Truck Demonstration Trial (Atkins, Cenex, 2015) indicates that the TTW CO_2 emissions from a dual-fuel diesel/methane truck were 7% compared to a diesel comparator vehicle. However, these figures do not take into account methane slip emissions. Accounting for methane slip levels of 14 gCO_2e/kWh, as described above, the overall improvement in TTW GHG emissions performance of the dual fuel truck compared to the conventional diesel truck would decline from 7% to just 4.9%.

Dedicated mono-fuel vehicles

The TTW CO_2 emissions performance of mono-fuelled gas-powered trucks have in the past been worse than for equivalent conventional diesel vehicles. In a trial conducted in 2012 it was found that a dedicated mono-fuel methane vehicle had 103% of the CO_2 emissions of a diesel comparator during laboratory testing – i.e. its emissions were higher, even before taking into account methane slip emissions (Cenex, 2012). However, since then several of the heavy-duty engine manufacturers have made significant progress in improving the overall efficiency of dedicated methane vehicles relative to

[5] http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:31991L0542

their diesel comparators (Transport Engineer, July 2015). If it is assumed that by 2020, dedicated methane vehicles on the road deliver 7% lower CO_2 emissions, and that they have methane slip emissions of 0.5 gCH_4/kWh (i.e. 14 gCO_2e/kWh) then this would lead to an overall GHG saving of 4.90% relative to the diesel comparator. For a 2020 mono-fuelled rigid truck, 0.5 gCH_4/kWh is equivalent to 1.22 gCH_4/km (34.2 gCO_2e/km).

To conclude, there is clear evidence that there is an energy efficiency gap between methane-powered vehicles and conventional diesel vehicles, and that there are likely to be improvements in gas vehicle technology in the coming years. However, improvements in diesel vehicle efficiency are also likely and hence an efficiency gap may remain in future years. Furthermore, overall tailpipe GHG benefits are highly dependent on the levels of methane slip emissions. At present some of the vehicles currently available on the market have relatively high levels of methane slip which reduces (or eliminates) the TTW greenhouse gas benefits of gas-powered vehicles. Whilst it is technically feasible to reduce methane slip emissions in future years, there may be a need for regulatory action to ensure that such improvements occur in the EU market.

2.3 Well-to-wake and well-to-wheels GHG emissions performance

Drawing on the findings from the previous sections, we have produced estimates of the total well-to-wake and well-to-wheels GHG emissions for, respectively, the case study ships and road vehicles analysed. For both shipping and road transport, we have used the low, central and high scenarios for well-to-tank GHG emissions, and hence for each vessel and vehicle type, we have generated three estimates for the total annual GHG emissions impacts.

2.3.1 Well-to-wake emissions for shipping

The following tables present the annual well-to-wake GHG emissions estimates for shipping, based on the analysis carried out in Sections 2.1 and 2.2.1. Each scenario uses different estimates for the well-to-tank emissions associated with each fuel, as explained in Section 2.1.1 (Page 9); furthermore, the analysis also takes into account uncertainty in the levels of methane slip emissions from ship engines and exhaust systems for LNG-powered vessels.

Table 2-26: Annual well-to-wake GHG emissions for selected ship types (low WTT greenhouse gas emissions scenario)

Ship type	Annual well-to-wake CO_2e emissions (tonnes per year)			
	HFO + scrubber	MGO	LNG (1.8% methane slip)	LNG (3.5% methane slip)
RoRo	11,714	11,001	10,591	11,757
Coastal tanker / bulk carrier	13,884	13,038	12,552	13,934
Container ship	19,524	18,334	17,652	19,595
Large RoRo	42,519	39,928	38,441	42,672
Percentage difference in well-to-wake emissions between LNG and HFO			-9.6%	+0.3%
Percentage difference in well-to-wake emissions between LNG and MGO			-3.7%	+6.8%

Table 2-27: Annual well-to-wake GHG emissions for selected ship types (central WTT greenhouse gas emissions scenario)

Ship type	Annual well-to-wake CO_2e emissions (tonnes per year)			
	HFO + scrubber	MGO	LNG	LNG
RoRo	11,910	11,190	10,666	11,832
Coastal tanker / bulk carrier	14,116	13,263	12,641	14,023
Container ship	19,850	18,651	17,777	19,719
Large RoRo	43,229	40,617	38,713	42,945
Percentage difference in well-to-wake emissions between LNG and HFO			-10.4%	-0.6%
Percentage difference in well-to-wake emissions between LNG and MGO			-4.7%	+5.7%

Table 2-28: Annual well-to-wake GHG emissions for selected ship types (high WTT greenhouse gas emissions scenario)

Ship type	Annual well-to-wake CO_2e emissions (tonnes per year)			
	HFO + scrubber	MGO	LNG	LNG
RoRo	12,320	11,444	11,344	12,509
Coastal tanker / bulk carrier	14,602	13,563	13,444	14,826
Container ship	20,534	19,073	18,906	20,849
Large RoRo	44,718	41,537	41,173	45,404
Percentage difference in well-to-wake emissions between LNG and HFO			-7.9%	+1.5%
Percentage difference in well-to-wake between LNG and MGO			-0.9%	+9.3%

As can be seen from the tables, the impacts on well-to-wake GHG emissions depends on the WTT emissions scenario and also on the levels of TTW methane slip emissions. In the best-case scenario, well-to-wake GHG emissions from LNG ships are 10.4% lower than from an HFO-fuelled ship and 4.7% lower than from an MGO-fuelled ship. However, if the high TTW methane slip emissions scenario is used, any GHG benefits associated with LNG are either very low or completely wiped out (in particular, under the high emissions scenario, the WTW emissions are 1.5% higher for LNG ships compared to HFO-fuelled ships). When LNG ships are compared to MGO-fuelled vessels, any emissions benefits are much lower; in the best-case scenario, LNG ships have well-to-wake GHG emissions that are 4.7% lower than an equivalent MGO-fuelled ship, and in the worst-case scenario, GHG emissions are 9.3% higher for LNG ships.

Other studies also indicate that the well-to-wake GHG impacts of LNG ships are highly dependent on various factors relating to WTT emissions for LNG, including levels of methane leakage/slip. ICCT has examined eight different LMG marine fuel bunkering pathways to compare and assess the well-to-wake GHG emissions impacts for each pathway in comparison to conventional marine fossil fuels. Their research indicated that well-to-wake GHG emissions for LNG-fuelled vessels can range from being 18% lower than conventional distillate and residual fuels to being 4.8% higher, depending on the specific fuel pathway. The pathway with the lowest total WTW emissions also had the lowest levels of methane leakage/slip emissions (leakage rate of 2.7%), and the pathway with the highest total WTW emissions also had the highest levels of methane leakage/slip (leakage rate of 5.4%). Six of the eight LNG pathways had lower well-to-wake GHG emissions than conventional marine fuels, and only two had higher emissions. As part of the same study, ICCT also investigated best practice methods that could be applied for controlling methane leakage/slip emissions for each of the eight pathways. The findings from this research indicated that overall leakage rates could be reduced from a range of 2.7% - 5.4% to 0.9% - 1.9%. Overall, applying these best practice approaches would reduce total WTW emissions for the LNG pathways by between 10% and 16%. If best practice approaches for controlling methane leakage are applied, then all eight pathways would give significant overall WTW emissions benefits compared to conventional marine fuels (12% to 27% lower WTW emissions for LNG compared to conventional marine fuels).

(Thomson, Corbett, & Winebrake, 2015) also investigated the GHG emissions impacts of using LNG compared to conventional fuels and found similar results in that overall GHG impacts are highly dependent on methane leakage rates in LNG production/distribution and methane slip rates associated with fuel combustion. However, they also used the Technology Warming Potential (TWP) metric as a way to investigate the long-term climate impacts of switching the shipping fleet to LNG. The TWP quantifies the time period it would take for a technological intervention to be climate neutral compared to a comparator incumbent technology. In this case, Thomson et al investigated the TWP values for replacing ships fuelled by HFO and MGO with LNG-fuelled vessels. They found that using LNG as a fuel for the shipping sector could achieve climate neutrality within 30 years for ships powered by compression ignition, dual-fuel LNG engines, but that for mono-fuel spark ignition LNG ships, it could take up to 190 years to achieve climate parity with conventional marine fuels. As with other research on this topic, their work indicated a need for further interventions to control both upstream and downstream methane leakage emissions to avoid net increases in GHG emissions if LNG is to be used in the shipping sector.

2.3.2 Well-to-wheels emissions for road transport

We have also carried out similar analysis for the road transport sector, again using the three scenarios for the well-to-tank GHG emissions associated with fuel production and distribution.

Table 2-29: Annual well-to-wheels GHG emissions for selected types of road vehicles (low WTT greenhouse gas emissions scenario)

Vehicle type	Annual well-to-wheels CO_2e emissions (tonnes per year)			Percentage change in WTW emissions	
	Petrol/diesel	Natural gas	Biomethane	Natural gas vs petrol/diesel	Biomethane vs petrol/diesel
Passenger car (petrol)	1.70	1.39	0.20	-18%	-88%
Passenger car (diesel)	1.31	1.39	0.20	+6%	-85%
LCV	3.98	4.28	0.82	+8%	-79%
Small rigid truck	18.07	20.43	4.91	+13%	-73%
Large rigid truck 26 t	48.21	55.94	10.61	+16%	-78%
Articulated truck (>32 t)	135.38	136.23	82.00	+1%	-39%
Bus	57.53	60.96	10.10	+6%	-82%
Coach	46.14	53.12	9.60	+15%	-79%

Note: for passenger cars, the baseline comparator vehicle is petrol powered; for all other vehicles, the baseline vehicles are diesel powered.

Table 2-30: Annual well-to-wheels GHG emissions for selected types of road vehicles (central WTT greenhouse gas emissions scenario)

Vehicle type	Annual well-to-wheels CO_2e emissions (tonnes per year)			Percentage change in WTW emissions	
	Petrol/diesel	Natural gas	Biomethane	Natural gas vs petrol/diesel	Biomethane vs petrol/diesel
Passenger car (petrol)	1.74	1.42	0.31	-18%	-82%
Passenger car (diesel)	1.34	1.42	0.31	+6%	-77%
LCV	4.05	4.36	1.12	+8%	-72%
Small rigid truck	18.39	20.76	6.25	+13%	-66%
Large rigid truck 26 t	49.06	56.36	14.20	+15%	-71%
Articulated truck (>32 t)	137.76	140.63	86.22	+2%	-37%
Bus	58.54	62.05	14.49	+6%	-75%
Coach	46.95	53.53	13.03	+14%	-72%

Table 2-31: Annual well-to-wheels GHG emissions for selected types of road vehicles (high WTT greenhouse gas emissions scenario)

Vehicle type	Annual well-to-wheels CO_2e emissions (tonnes per year)			Percentage change in WTW emissions	
	Petrol/diesel	Natural gas	Biomethane	Natural gas vs petrol/diesel	Biomethane vs petrol/diesel
Passenger car (petrol)	1.83	1.55	0.41	-15%	-78%
Passenger car (diesel)	1.37	1.55	0.41	+13%	-70%
LCV	4.14	4.73	1.42	+14%	-66%
Small rigid truck	18.81	22.43	7.58	+19%	-60%
Large rigid truck 26 t	50.19	60.17	17.78	+20%	-65%
Articulated truck (>32 t)	140.94	147.47	91.08	+5%	-35%
Bus	59.90	67.51	18.87	+13%	-68%
Coach	48.04	57.18	16.47	+19%	-66%

As can be seen from the tables, for all types of road vehicles except for petrol cars, there are no net GHG benefits associated with shifting from conventional liquid fossil fuels to fossil-based natural gas. Under all three WTT emissions scenarios, total GHG emissions from natural gas vehicles are higher than for the equivalent conventional diesel-powered vehicles. For articulated trucks, the emissions penalty is smaller than for other diesel vehicles because these vehicles have dual-fuel engines. Only petrol passenger cars, where the conventional comparator vehicles is powered by petrol, demonstrate consistent benefits from shifting to natural gas. However, even these benefits could be lost if there are significant improvements in petrol engine efficiency (e.g. wider uptake of hybrid petrol-electric vehicles which already have significantly better CO_2 emissions than conventional petrol cars).

For biomethane, the picture is very different; for all vehicle types and under all three scenarios, there are very large WTW emissions benefits associated with shifting from petrol or diesel to biomethane. This difference is wholly due to the biogenic nature of the CO_2 emissions released when biomethane produced from organic waste materials is combusted; biogenic CO_2 emissions from renewable fuels do not contribute to climate change and hence from an accounting perspective, they are reported as zero. Note that the CO_2 emissions from combustion of biomethane produced from energy crops would also be zero-rated as these emissions are part of the short-term carbon cycle, and hence are not considered to contribute to climate change. However, the use of energy crops can lead to increases in indirect land use change. The issue of CO_2 emissions from the combustion of wood-derived biomethane is less clear-cut as forestry resources are not part of the short-term carbon cycle, and hence these emissions may be net contributors to climate change.

In summary, the results of this analysis for the road transport sector indicate that there are very limited WTW greenhouse gas emissions benefits associated with using fossil-based natural gas in road vehicles (i.e. there are only benefits when replacing a non-hybrid petrol car with a CNG-powered car), but that there are large WTW emissions benefits associated with using biomethane.

3 Impacts of natural gas and biomethane use in the transport sector on air pollution

3.1 Overview

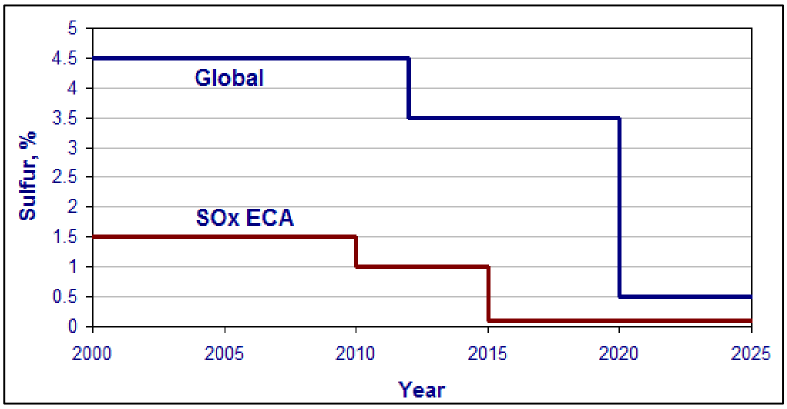
One of the anticipated benefits of using natural gas and biomethane in transport applications is a reduction in air pollutants, specifically oxides of sulphur (SOx), oxides of nitrogen (NOx) and particulate matter (PM). This chapter describes the impacts of using these fuels in the shipping sector and for road transport applications, compared to conventional fossil fuels.

3.2 Impacts on air pollution of natural gas and biomethane use in the shipping sector

3.2.1 Policy context

In 2005, regulations for the prevention of air pollution from ships (MARPOL Annex VI) came into force. These regulations include a requirement from 2015 that only bunker fuels with a maximum sulphur content of 0.1% can be used in Emission Control Areas (ECAs[6]) (see Figure 3-1). Outside of the ECAs, ships, bunker fuels with a maximum sulphur content of 3.5% can be used; the limit value for sulphur content will be reduced to 0.5% in either 2020 or 2025 (depending on the outcome of an ongoing review due to be completed in 2018).

Figure 3-1: MARPOL Annex VI fuel sulphur content limits



Source: (DieselNet, 2015)

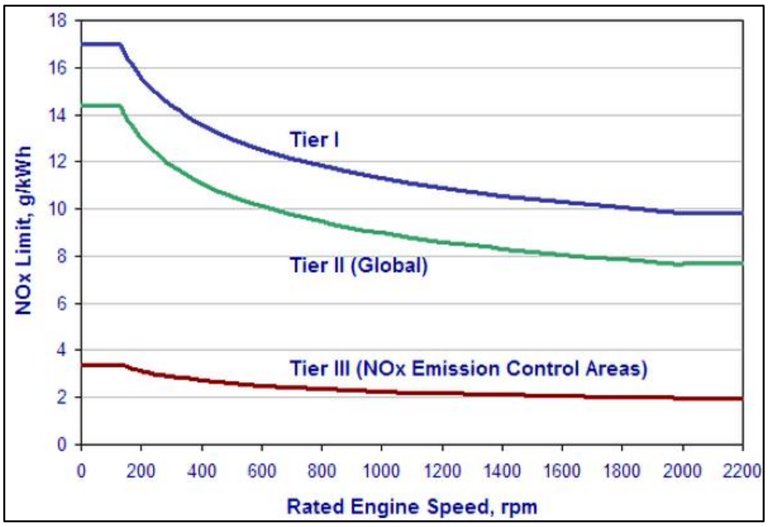
Emission standards will apply for NOx emissions in 2020 with emissions expected to be around 2-3 g/kWh inside ECAs (Tier III - from 2016 onwards) and around 8-14 g/kWh in other areas (current regulations) (see Figure 3-2). No regulations apply, or are currently planned, for emissions of particulate matter (PM) from shipping.

There are three main technical solutions that are expected to be applied to ensure compliance with the ECAs and forthcoming emissions limits. These are as follows:

- HFO-fuelled ships equipped with exhaust gas scrubbers
- MGO-fuelled ships
- LNG-fuelled ships

[6] There are currently four “emission control areas”: the North and Baltic seas, North America, and the US Caribbean

Figure 3-2: MARPOL Annex VI NOx Emission Limits



Source: (DieselNet, 2015)

3.2.2 Impacts analysis

Calculating sulphur dioxide (SO_2) emission factors is straightforward, since they are directly related to the sulphur content of the fuel, and are defined by the following formula;

$$EF_{SOx} = (\%sulphur\ content / Fuel\ calorific\ value)$$

For example, Maritime Gas Oil (MGO) has a net calorific value of 42.57 MJ/kg and so for a fuel sulphur content of 0.1%, the SO_x emission factor is 0.024 g/MJ.

For NO_x and PM emission factors, the situation is more complex, as they are not directly related to the composition of the fuel used. Hence, actual emissions can vary significantly depending on the engine type, the level of emissions control applied and the typical operating conditions. However, for the purposes of this study it was deemed appropriate to apply general emission factors on an energy basis as these will give a reasonable overall approximation of typical air pollutant emission levels in relation to the fuel consumed.

LNG is expected to be one of the options used to ensure compliance with ECA requirements. It is a significantly cleaner fuel than MGO or HFO, producing negligible sulphur or particle emissions and drastically lower NOx emissions per unit of fuel. With this in mind, the data in Table 3-1 has been sourced from the Third IMO study (IMO, 2015). Taking into account the Regulations in place, projected 2030 emission factors for the different fuel types in question are presented in the table below in grams of pollutant per gram of fuel consumed[7]. We have then converted these factors to kg of pollutant per GJ of fuel consumed to enable comparisons on an equivalent energy basis to be made[8].

[7] Page 136, taken from low LNG scenario for NOx factors. Page 291 for PM factors.
[8] Energy content (net calorific value) of fuels taken from (DEFRA, 2015); HFO = 40.70 GJ/tonne; MGO = 42.57 GJ/tonne; LNG = 47.89 GJ/tonne

Table 3-1: NOx, SO_2 and PM Emission factors for 2030 (IMO, 2015)

Fuel	Grams of pollutant per gram of fuel consumed			kg of pollutant per GJ of fuel consumed		
	NO_x	SO_2	PM	NO_x	SO_2	PM
HFO (0.5% sulphur content)	0.0825	0.005	0.00385	2.027	0.123	0.095
MGO (0.1% sulphur content)	0.0877	0.001	0.00097	2.060	0.023	0.023
LNG	0.0140	0	0.00018	0.292	0.000	0.004
LNG: change versus HFO (%)				-85.6%	-100%	-96.0%
LNG: change versus MGO (%)				-85.8%	-100%	-83.5%

As can be seen from the table, the use of LNG gives reductions in NOx emissions of more than 85%, reductions in SO_2 emissions of 100% and reductions in PM emissions of 83.5% compared to MGO and 96% compared to HFO. Hence, it is clear that a shift to LNG in the shipping sectors would have very significant benefits in terms of reductions in air pollutant emissions even in future years.

Using these emissions factors, we have estimated the annual air pollutant emissions impacts for a selection of vessel types drawing on analysis of typical annual fuel consumption data for HFO, MGO and LNG-powered ships from a study carried out by the Danish Maritime Authority (Danish Maritime Authority, 2012). The results of this analysis are presented in the table below. Note that each LNG-powered vessel is assumed to be a dual-fuel vessel operating on HFO and LNG, and hence SO_2 emissions for these ships are not completely eliminated.

Table 3-2: Annual emissions of air pollutants for selected HFO-fuelled vessels fitted with exhaust gas scrubbers

	Emissions (tonnes per year)		
Sea region	NO_x	SO_2	PM
RoRo	235.9	1.6	3.1
Coastal tanker / bulk carrier	279.6	1.9	3.6
Container ship	393.2	2.6	5.1
Large RoRo	856.2	5.8	11.1

Derived from (Danish Maritime Authority, 2012)

Table 3-3: Annual emissions of air pollutants for selected MGO-fuelled vessels

	Emissions (tonnes per year)		
Sea region	NO_x	SO_2	PM
RoRo	266.4	3.0	2.9
Coastal tanker / bulk carrier	315.7	3.6	3.5
Container ship	444.0	5.1	4.9
Large RoRo	966.9	11.0	10.7

Derived from (Danish Maritime Authority, 2012)

Table 3-4: Annual emissions of air pollutants for selected LNG-fuelled vessels

	Emissions (tonnes per year)		
Sea region	**NO_x**	**SO_2**	**PM**
RoRo	37.8	0.2	0.1
Coastal tanker / bulk carrier	44.8	0.2	0.1
Container ship	63.0	0.3	0.2
Large RoRo	137.2	0.6	0.4

Derived from (Danish Maritime Authority, 2012)

As can be seen from the tables, shifting to LNG-powered vessels from either HFO or MGO fuel types gives very significant annual improvements in air pollutant emissions for each type of ship. Compared to HFO-fuelled vessels equipped with exhaust gas scrubbers, shifting to LNG reduces emissions of NOx by 84%, emissions of SO_2 by 90% and emissions of PM by 96%. Compared to MGO-fuelled vessels, LNG ships have NOx emissions that are 86% lower, SO_2 emissions that are 95% lower and PM emissions that are 96% lower. These are very substantial improvements in emissions and demonstrate that that the use of LNG in shipping can provide very substantial reductions in emissions of the key air pollutants.

3.3 Impacts on air pollution of natural gas and biomethane use in the road transport sector

3.3.1 Impacts analysis

For road transport, the air pollutant emissions performance of gas-powered vehicles has been compared to current Euro 6 (light duty) and Euro VI (heavy duty) vehicles. These standards are assumed to still be relevant for new 2020 vehicles given that currently no new standards have been proposed. Typical Tier 2 emission factors, derived from the current limit values, have been obtained from the EMEP/EEA emissions inventory guidebook for road transport emissions (EMEP/EEA, 2014). These datasets are presented in the table below.

Table 3-5: Emission factors (Tier 2 factors predominantly for Euro 6/VI (EMEP/EEA, 2014)

Vehicle type	NO_x (mg/km)	SO_2 (mg/km)	PM (mg/km)
Passenger car (petrol)	59	0.31	1.4
Passenger car (diesel)	210	0.46	1.5
Light commercial vehicle (diesel)	221	0.93	0.9
Small rigid truck (diesel)	291	1.91	16.1
Large rigid truck (diesel)	422	2.99	23.9
Articulated truck (diesel)	507	3.66	26.8
Bus (diesel)	600	4.3	23.1
Coach (diesel)	500	3.31	35.4

An assessment of the impacts on air pollutant emissions performance was carried out by drawing on evidence from the 2014 EMEP emissions inventory guidebook to quantify the likely impacts of shifting from petrol and diesel to methane.

NOx emissions

The EMEP/EEA guidebook gives little contemporary advice on NOx emissions for methane-powered vehicles. However, some information is provided on Euro III CNG-powered coaches, and this has been used as the basis for determining the impacts of switching to methane on NOx emissions. The NOx emission factor for a Euro III CNG coach is given as 2.5 g/km, which is very similar to the figure for conventional diesel Euro III buses. Evidence from a study carried out for Transport for London in 2014 (Ricardo-AEA, 2014) also backs up this assumption, as this research indicates that NOx emissions for methane-powered vehicles are very similar to diesel vehicles. Other research gives mixed results; independent real-world emission tests indicate that NOx emissions from Euro VI CNG buses can be marginally higher than for equivalent Euro VI diesel buses (LowCVP, 2015), whilst other research shows that CNG heavy duty vehicles give lower NOx emissions. Similarly, for passenger cars and light commercial vehicles (Atkins and Cenex, 2015). As the regulatory standard for NOx emissions from Euro VI heavy duty vehicles is engine based, is the same for both diesel and methane fuelled vehicles, and is challenging to meet, we have assumed that there is no change in NOx emission factor per km on switching from conventional diesel to methane fuelled vehicles. For light-duty vehicles, we have assumed that the NOx emissions performance of methane-powered vehicles is the same as for petrol-engined vehicles, in line with the Euro 6 regulation.. By implication, this means that when switching from diesel-powered passenger cars and vans to equivalent methane-fuelled vehicles, there are significant emissions benefits as NOx emissions from diesel cars and vans are significantly higher than equivalent petrol-fuelled vehicles. In practice, this means that we have assumed that NOx emissions for methane-fuelled cars and vans are 72% lower than for equivalent diesel vehicles.

SO_2 emissions

SO_2 emissions are directly proportional to the sulphur content of the fuel. Conventional petrol and diesel vehicles have to use sulphur-free petrol and diesel respectively (i.e. <10 ppm sulphur content), and methane generally contains no sulphur. Hence, switching from petrol/diesel to methane results in a 100% reduction in SO_2 emissions. For dual-fuel vehicles, we have assumed that SO_2 emissions are 80% lower than for an equivalent diesel vehicle.

PM emissions

Methane-fuelled vehicles emit very little PM relative to their diesel comparators. However, diesel particulate filters, and careful calibration of the engines, has meant that modern diesel engines also emit only very low levels of PM. The EMEP EEA emissions inventory guidebook (EMEP/EEA, 2014) indicates that PM emissions from a CNG bus are 5 mg/km, whilst for a Euro VI bus, PM emissions are 23.1 mg/km. Based on these data, switching from diesel to a dedicated mono-fuelled methane vehicle results in an 80% reduction in PM emissions. For dual fuel vehicles, where around 50% of the energy is supplied by methane replacing diesel, it is assumed that a 40% reduction in PM occurs.

Using the above information in combination with the EEA EMEP emissions factors for Euro 6 and Euro VI vehicles, we have generated a set of air pollutant emissions factors for methane-fuelled road vehicles (see Table 3-6).

Table 3-6: Emission factors for methane-powered vehicles (derived from (EMEP/EEA, 2014)

Vehicle type	NO_x (mg/km)	SO_2 (mg/km)	PM (mg/km)
Passenger car (CNG)	59	0	0.3
Light commercial vehicle (CNG)	62	0	0.2
Small rigid truck (dedicated CNG)	291	0	1.6
Large rigid truck (dedicated LNG)	422	0	2.4
Articulated truck (dual fuel diesel-LNG/LBM)	507	0.75	8.0
Bus (dedicated CNG)	600	0	4.6
Coach (dedicated LNG)	500	0	3.5

In summary, it can be seen that there is a mixed picture for the impacts of methane-fuelled vehicles on air pollutant emissions. Whilst methane-fuelled vehicles emit lower levels of PM and SO_2 emissions than conventional vehicles, for NOx emissions, the main benefits are associated with shifting from diesel cars to CNG/CBM-fuelled vehicles. Furthermore, PM and SO_2 emissions are already effectively controlled through existing emissions and fuel quality standards, and hence any further reductions in these pollutants due to a switch to methane-fuelled vehicles would only provide marginal air quality benefits. By contrast, NOx emissions are currently the main focus of European regulators and national governments, primarily because many Member States around the EU are not in compliance with the pollutant concentration limits for nitrogen dioxide (NO_2). This is primarily due to NOx and NO_2 emissions from road transport. For typical vehicles, the annual reductions in air pollutants associated with shifting to natural gas or biomethane are presented in the table below.

Table 3-7: Change in annual emissions of air pollutants associated with a shift from petrol/diesel-fuelled vehicles to methane-fuelled vehicles

	Change in annual emissions of air pollutants (grams per vehicle per year)			
Vehicle type	**Average annual mileage (km)**	**NO_x**	**SO_2**	**PM**
Passenger car (CNG compared to petrol)	13,000	0	-7	-15
Passenger car (CNG compared to diesel)	13,000	-1,963	-12	-16
Light commercial vehicle (CNG)	16,000	-2,546	-15	-12
Small rigid truck (dedicated CNG)	35,000	0	-67	-225
Large rigid truck (dedicated LNG)	60,000	0	-179	-574
Articulated truck (dual fuel diesel-LNG/LBM)	130,000	0	-476	-697
Bus (dedicated CNG)	50,000	0	-215	-924
Coach (dedicated LNG)	52,000	0	-172	-736

As can be seen from the table above, there would be no reduction in NO_X emissions for most vehicle types, although there would be benefits in replacing diesel passenger cars with CNG-powered cars as NOx emissions from diesel cars are significantly higher than for CNG cars. Annual reductions in SO_2 range from just 7 grams per vehicle per year for petrol cars to 476 grams per vehicle per year for dual-fuel articulated trucks. For PM emissions, annual reductions range from 12 grams per vehicle per year for light commercial vehicles to 736 g per vehicle per year for coaches.

These reductions in emissions can be placed in the context of total emissions of air pollutants from road transport in Europe to understand whether a wide-scale shift to methane-fuelled vehicles would give any significant air quality benefits. Data from the European Environment Agency (EEA, 2015) provides estimates of total air pollutant emissions from the road transport sector for 2013 (latest available year). These data are presented in the table below.

Table 3-8: Total EU emissions of key air pollutants from road transport sources

2013 EU emissions from road transport (kilotonnes)		
NOx	**SO_2**	**PM**
3,805	6	240

However, most of these emissions are due to older vehicles and the impact of any shift to methane-fuelled vehicles will only initially affect the new vehicle fleet. In order to assess the potential impacts on EU-wide emissions of air pollutants from road transport, we have examined a hypothetical scenario for increased penetration of methane-fuelled vehicles across the new vehicle fleet in Europe. Total new vehicle sales by vehicle type in the EU for 2015 are presented in the table below (ACEA, 2016).

Table 3-9: Total new vehicle registrations in the EU in 2015

Vehicle type	Total new registrations
Passenger car	13,713,526
Light commercial vehicles	1,713,850

Vehicle type	Total new registrations
Medium trucks (HGVs from 3.5 tonnes to 16 tonnes)	325,689
Heavy trucks (HGVs over 16 tonnes)	260,135
Buses/coaches	39,783

Italy is currently the leading European market for sales of methane-fuelled vehicles, with around 5% of new vehicles sold there powered by this fuel. If we assume that this level of market penetration was replicated across the whole of Europe, we can estimate the air pollution impacts by comparing this scenario to a baseline scenario where the new vehicle fleet consists only of petrol and diesel vehicles. This is a simplification of the actual baseline situation as there are currently some limited sales of methane, LPG, electric and plug-in hybrid-electric vehicles as well as petrol/diesel vehicles today. However, for the purposes of this illustrative scenario, this simplification is appropriate. We have assumed that 50% of new passenger cars are equipped with petrol engines and the remaining 50% with diesel engines. All other vehicles in the baseline scenario are equipped with diesel engines. Using the emission factors presented earlier in this report, we can quantify the total annual emissions impacts associated with 5% of new vehicles across the EU being equipped with methane-fuelled engines in place of petrol/diesel engines. These figures are presented in the table below.

Table 3-10: Impacts on annual emissions of air pollutants from new vehicles of a 5% market penetration of methane-fuelled vehicles in the new vehicle fleet

	NOx (tonnes)		SO_2 (tonnes)		PM (tonnes)	
Vehicle type	Petrol/ diesel	Methane	Petrol/ diesel	Methane	Petrol/ diesel	Methane
Passenger cars (petrol)	5,259	5,259	28	26	125	120
Passenger cars (diesel)	18,719	18,046	33	31	134	128
Light commercial vehicles	6,060	5,842	25	24	25	24
Small rigid trucks	3,317	3,317	21	20	92	88
Large rigid trucks	3,295	3,295	23	22	93	90
Articulated trucks	8,568	8,568	64	61	226	222
Buses	1,193	1,193	8	8	46	44
Coaches	1,034	1,034	7	6	37	35
TOTAL	**47,447**	**46,555**	**207**	**198**	**777**	**751**
Absolute and percentage change in annual emissions	**-891 tonnes -1.9%**		**-10 tonnes -4.7%**		**-27 tonnes -3.4%**	
Change in environmental damage costs	**-€9.48 million**		**-€0.10 million**		**-€1.87 million**	

As can be seen from the figures, the impacts of 5% market penetration of methane-fuelled vehicles in the new fleet has a limited impacts on emissions of air pollutants; NOx emissions from new vehicles would reduce by just under 2%, SO_2 emissions by 4.7% and PM emissions by 3.4%. The annual emissions reductions associated with this scenario can be monetised using the damage cost figures presented earlier in this section. As can be seen from the table, the reductions in NOx emissions give the greatest monetised benefits, reducing damage costs by just under €9.5 million per year. Overall, the combined monetised benefits of this scenario would be approximately €11.45 million per year.

As can be seen from the data above, the overall air pollution benefits associated with increased market penetration of methane-fuelled vehicles would be small but not insignificant. Increasing the market penetration of methane-fuelled vehicles would lead to further reductions in air pollution, scaling in line with the numbers of new petrol/diesel vehicles displaced.

4 Economic analysis of the costs and benefits of deploying natural gas and biomethane in the transport sector

4.1 Overview

The previous sections have focused on analysing the environmental impacts and benefits of using natural gas and biomethane in the transport sector. This chapter explores the economic impacts of such a choice, in terms of the costs and benefits of these fuels compared to conventional liquid fossil fuels.

This assessment has been carried out by taking into account the costs of each fuel, the costs of vehicles and vessels that can use natural gas / biomethane compared to the costs of conventional vehicles and vessels, and by accounting for the monetised environmental benefits of switching from conventional liquid fossil fuels to natural gas or biomethane.

The rest of this chapter is structured as follows:

- Section 4.2: High-level view of fuel costs for natural gas and biomethane
- Section 4.3: Economic analysis of the costs and benefits of using LNG in the shipping sector
- Section 4.4: Economic analysis of the costs and benefits of using methane in the road transport sector

4.2 High-level view of fuel costs for natural gas and biomethane

4.2.1 Natural gas

Over the last few years, the prices for natural gas have been subject to a high level of variability, which has had impacts on how attractive it is as a fuel for the transport sector. In particular, the wholesale and spot prices of natural gas have been affected by a wide range of factors and events recently:

- The Russian-Ukraine conflict created and served to heighten European uncertainty regarding the longer term costs of natural gas, which led to a decline in wholesale prices and a degree of uncertainty in forecasts.
- Additionally, a mild winter in 2013-2014 and 2014-2015 also affected the wholesale and spot prices for pipeline natural gas.

The average reported *wholesale price* of European natural gas during 2014 ranged between €4.4 per GJ in the summer to €7.2 per GJ over the winter months according to the European Commission's *Quarterly Report on European Gas Markets* (European Commission, 2014) (European Commission, 2015).

Medium term forecasts for natural gas were revised during and at the end of 2014 in order to take into account the uncertainty and changes that came into effect during the period. In addition, the sanctions imposed due to the Russian-Ukraine conflict resulted in less impact on the natural gas markets than originally anticipated and so prices reduced as concerns were eased (World Bank, 2015). Overall, the spot price of natural gas is expected to fall by 8% by 2020 – to €6.5 per GJ. Table 4-1 overleaf gives the forecasts from 2014 to 2020 ((World Bank, 2015).

Table 4-1: Forecasts for natural gas in pipeline from 2014 – 2020 (€/GJ)

Year	Actual and forecast prices for pipeline natural gas	
	€/GJ	€/tonne
2014	€7.2 per GJ	€353 per tonne
2015	€6.0 per GJ	€294 per tonne
2016	€6.1 per GJ	€299 per tonne
2017	€6.3 per GJ	€308 per tonne
2018	€6.3 per GJ	€308 per tonne
2019	€6.5 per GJ	€318 per tonne
2020	€6.5 per GJ	€318 per tonne

Notes: Average European import border price, including the UK - includes a spot price component.

Liquefied natural gas

The Fukushima Nuclear disaster has had a profound impact on the trade in LNG, with new trade routes strengthening as LNG imports to Asia increased, diverting LNG from the European market and raising prices for European buyers.

The spot price of LNG in Europe during 2014 varies according to location and ranged from €5.7 per GJ for the UK and Spain, to €7.1 per GJ Europe-wide. The wholesale price of LNG in Europe in 2014 is estimated to have been €9.2 per GJ. LNG prices fell during 2014 for the first time since the aftermath of Fukushima, and continued to fall in early 2015. Since February 2015, spot LNG prices have been relatively stable, moving in the €6.2-7. 3 per GJ range.

Table 4-2 (below) demonstrates the range of spot price for LNG reported for Europe. Comparing the 2014 European spot prices with the Asian commodity price for 2014 at €12.1 per GJ helps to understand the way in which the Fukushima disaster and changes to the Asian market have had an impact on the relative price of this commodity.

Table 4-2: Delivered price of LNG in 2014

Delivered price (€/GJ)	Delivered price (€/tonne)	Area	Notes	Source
€5.7 per GJ	€279 per tonne	UK & Spain	LNG Spot Price	(European Commission, 2014) (European Commission, 2015)
€6.4 per GJ	€313 per tonne	Europe	LNG Spot Price	(European Commission, 2014)
€6.4 to €7.1 per GJ	€313 to €348 per tonne	Europe	LNG Spot Price	(DECC, 2014)
€9.2 per GJ	€450 per tonne	Europe	Wholesale Price (Exc Tax)	(Gasnam, 2014)

In the aftermath of Fukushima and the changes it wrought in the global LNG market, many previous forecasts for global trading of LNG have been amended (Platts, 2015). From 2014, medium-term forecasts predict that the costs of LNG will continue to fall as the market is flooded with new supplies from fresh global sources of stocks which could increase supplies by up to 45% (IEA, 2015). Moreover, new infrastructure developments and technologies will come into play in the medium term, further reducing the spot price of LNG on the European market (European Commission, 2014a) (Gasnam, 2014).

Short term (<1 year) forecasts for LNG prices on the European market are available – however medium term projections for the European market are scarce. The International Monetary Fund (IMF) provides a medium term prediction for the Japanese market which projects that prices will reduce by 50% between 2014 and 2020 (see Table 4-3 below).

Table 4-3: Spot price of LNG – medium term forecasts from the Asian market.

Year	Actual and forecast prices for pipeline natural gas	
	€/GJ	€/tonne
2014	€7.3 per GJ	€357 per tonne
2015	€6.1 per GJ	€299 per tonne
2016	€6.1 per GJ	€299 per tonne
2017	€6.1 per GJ	€299 per tonne
2018	€6.1 per GJ	€299 per tonne
2019	€6.1 per GJ	€299 per tonne
2020	€6.1 per GJ	€299 per tonne

Source: IMF Commodity price of Indonesian LNG in Japan

The fluctuations that have been observed in recent years may explain the paucity of forecasts for the European markets with LNG projections focusing on the Asian market whilst the European markets have been dominated by pipeline natural gas predictions.

For shipping, even taking into account the significant reductions in the price of crude oil since 2014, and the impacts this has had on bunker fuel prices for HFO and MGO, in 2015, LNG remains cheaper than either of these fuels. In November 2015, the price of LNG on the spot market was €5.7 per GJ (€280 per tonne); in the same month, HFO and MGO were €225 per tonne and €429 per tonne respectively.

4.2.2 Biomethane

Data on the production costs of biomethane were taken from a recent study that we carried out for the UK Department for Transport to assess the costs and benefits of gaseous and waste-derived fuels for the transport sector (Ricardo-AEA, 2014). A number of different fuel pathways were analysed in detail, and cost data were collected for each production step. For the purposes of this study, we have aggregated the cost data for CBM and LBM for each of the two primary production routes, namely (i) anaerobic digestion and (ii) processing of landfill gas.

Table 4-4: Production costs for compressed and liquefied biomethane produced via anaerobic digestion and from landfill gas

Production pathways	Total costs of production (€/GJ)
Compressed biomethane produced via anaerobic digestion	€7.28 to €10.20
Compressed biomethane produced from landfill gas	€7.19
Liquefied biomethane produced via anaerobic digestion	€12.86 to €15.76
Liquefied biomethane produced from landfill gas	€12.77

Source: Ricardo-AEA, 2014

The data on wholesale prices for natural gas and production costs for biomethane do not take into account the costs of delivery and dispensing required in order for methane to be used as a transport fuel. In our work for the UK Department for Transport, we gathered data on these costs for each type of fuel (see Table 4-5).

Table 4-5: Delivery and dispensing costs for natural gas and biomethane used in the transport sector

Production pathways	Total costs of delivery and dispensing (€/GJ)
Compressed natural gas	€2.77 to €5.72
Liquefied natural gas	€2.73
Compressed biomethane produced via anaerobic digestion	€2.77 to €5.72
Compressed biomethane produced from landfill gas	€2.77 to €5.72
Liquefied biomethane produced via anaerobic digestion	€2.73
Liquefied biomethane produced from landfill gas	€2.73

Source: (Ricardo-AEA, 2014)

4.3 Economic analysis of the costs and benefits of using LNG in the shipping sector

For the shipping sector, the economic analysis needs to take into account the fact that there are already ECAs in place that require ship operators to reduce their emissions of sulphur dioxide, and that by 2025, these requirements will be expanded globally. With this in mind, the economic analysis needs to compare the costs and benefits of using LNG in the shipping sector against the costs and benefits of the alternatives – namely HFO-powered ships fitted with scrubbers, or shifting to low sulphur MGO.

4.3.1 Capital costs of LNG ships

A number of studies have investigated the capital costs of equipping different types of vessels with LNG technology. The additional costs primarily relate to the dual-fuel engine and on-board LNG storage tanks, as well as on-vessel pipelines, gas alarm systems and additional safety systems.

Key studies include research by the Danish Maritime Authority (Danish Maritime Authority, 2012), analysis carried out by Germanischer Llloyd and MAN on LNG-powered container ships (Germanischer Lloyd & MAN, 2011), analysis conducted by Lloyds Register Marine (Lloyd's Register Marine, UCL, 2014), and work carried out by Ricardo-AEA (Ricardo-AEA et al, 2013). We have drawn from these studies to provide estimates for the additional costs of this technology.

Previous research carried out by Ricardo-AEA (Ricardo-AEA et al, 2013) indicated that the additional costs of equipping a vessel with LNG propulsion technology are around 10% of the new-build cost of an equivalent conventional vessel, plus a further US$2 million (€1.8 million). A selection of new-build cost data for conventional ships and their LNG-fuelled equivalents is presented in the table below. It also includes figures based on Lloyd’s Register data (Lloyd's Register Marine, UCL, 2014) which estimates that the additional unit procurement costs of an LNG-fuelled vessel are US$1.65 million (€1.49 million) per MW of installed power. Using the baseline capital cost data from the Ricardo-AEA study (2013) for conventionally-fuelled vessels, we have calculated estimated new-build costs and total incremental costs for a selection of ship types using this estimate from (Lloyd's Register Marine, UCL, 2014). The findings are summarised in the table below. More detailed tables are available in Appendix, Section A.1.1.5.

Table 4-6: Additional capital cost estimate for LNG-fuelled ships compared to conventional HFO-fuelled ships

Ship type	Load capacity	Ricardo-AEA	Lloyds' Register Marine
Dry bulk – hand-size	15,000 to 35,000 DWT	€3.3 million	€10.0 million
General cargo ship	Up to 15,000 DWT	€2.4 million	€2.4 million
Container ship	3,000 to 5,500 TEU	€6.2 million	€55.2 million
RoRo	Up to 15,000 DWT	€3.5 million	€7.5 million
RoRo	15,000 to 35,000 DWT	€6.1 million	€21.2 million
Crude oil tanker	45,000 DWT	€4.5 million	€13.6 million
Chemical tanker	15,000 to 40,000 DWT	€4.6 million	€11.6 million

As illustrated above, using the Lloyds Register Marine unit cost estimates gives much higher new build costs for LNG-fuelled ships than were found in the Ricardo-AEA study. The significant level of variability in the cost estimates presented in the literature reflects the fact that the technology is not yet a mainstream application in the shipping sector. .

DNV GL has also published information on the costs of LNG vessels (DNV GL, 2014). In this example, costs are quoted for a 50,000 DWT oil tanker; DNV GL estimates that the additional cost of equipping such a vessel with a duel-fuel engine and LNG storage system would be US$5.8 million (€5.2 million). This cost comprises US$0.9 million (€0.8 million) for the dual fuel engine, US$4.4 million (€4.0 million) for the LNG storage system and US$0.5 million (€0.45 million) for yard costs.

Other research (IHS CERA, 2011) confirms that the costs of equipping ships to run on LNG are highly variable and can be linked to the installed engine power on the vessel, with unit costs declining per MW of engine power. These incremental unit cost estimates are based on demonstration and commercial projects where dual-fuel LNG systems were installed on actual vessels (see Table 4-7 below).

Table 4-7: Incremental unit capital costs for LNG dual-fuel installation

Ship type	Installed engine power (MW)	Unit additional costs (€/MW installed power)	Estimated total additional costs per ship
Port tug	1 MW	€0.56 million	€0.56 million
General cargo ship	4 MW	€0.99 million	€3.96 million
Inland ship	5 MW	€0.27 million	€1.35 million
Ro-Ro	7 MW	€0.32 million	€2.84 million
Short sea ship	8 MW	€0.41 million	€2.59 million
Cruise ship	15 MW	€0.41 million	€6.08 million
Ro-Ro	20 MW	€0.29 million	€5.76 million
Ro-Pax	48 MW	€0.14 million	€6.91 million

Source: (IHS CERA, 2011)

The Danish Maritime Authority carried out research on LNG for the shipping sector (Danish Maritime Authority, 2012), and as part of this study, the capital costs of equipping different types of ships with LNG technology were investigated in detail. A summary of the findings from this research is presented below in Table 4-8 and Table 4-9. The LNG vessels are assumed to be equipped with dual-fuel engines.

Table 4-8: Incremental capital cost estimates for retrofitting different types of ships with (a) scrubber technology; (b) MGO technology; and (c) LNG technology

Ship type	Engine power and DWT	HFO + scrubber	MGO	LNG
RoRo	5.4 MW; 4,200 DWT	€2.3 million	€0.5 million	€3.2 million
Coastal tanker / bulk carrier	8.5 MW; 10,000 to 25,000 DWT	€3.7 million	€0.7 million	€5.1 million
Container ship	8.0 MW; 9,000 DWT	€3.4 million	€0.6 million	€4.8 million
Large RoRo	21 MW	€9.0 million	€1.5 million	€12.6 million

Table 4-9: Incremental capital cost estimates for different types of new-build ships with (a) scrubber technology; (b) MGO technology; and (c) LNG technology

Ship type	Engine power and DWT	HFO + scrubber	MGO	LNG
RoRo	5.4 MW; 4,200 DWT	€3.3 million	€1.6 million	€4.3 million
Coastal tanker / bulk carrier	8.5 MW; 10,000 to 25,000 DWT	€5.1 million	€2.5 million	€6.8 million
Container ship	8.0 MW; 9,000 DWT	€4.8 million	€2.4 million	€6.4 million
Large RoRo	21 MW	€12.6 million	€6.0 million	€16.7 million

As can be seen from the tables, the capital investment costs are significantly greater for all ship types than the incremental capital expenditure required for equipping HFO-fuelled ships with scrubbers or the incremental costs of an MGO-fuelled ship over and above a conventional HFO-fuelled ship. However, these additional investment costs are offset by significantly lower operating costs, which are primarily due to bunker fuel prices for LNG being much lower than for HFO and MGO.

Overall it can be seen that the estimates for the capital costs of building LNG-fuelled ships are very varied and depend on ship type, installed engine capacity and the size of the on-board LNG storage tanks required. Most of the cost estimates indicate that the unit incremental costs are lower than €1 million per MW of installed engine power, and on average unit costs are around €0.5 million per MW. The data from Lloyds Register Marine are an exception as their research gives a figure of €1.65 million per MW of installed power. Given that all other datasets indicate much lower capital costs for building LNG ships, we believe that the Lloyds Register data is likely to be an overestimate.

For the purposes of this study, we have chosen to use the data from the Danish Maritime Authority study as the basis for carrying out further analysis on the costs and benefits associated with using LNG in the shipping sector. This is because the analysis presented in this study is very comprehensive and transparent, and includes estimates of both capital and operating costs for ships equipped with scrubbers and ships that operate on MGO as well as LNG-powered vessels. These data have allowed us to carry out a more complete assessment of the costs and benefits of LNG-powered vessels compared to the alternative options.

4.3.2 Infrastructure costs

Widespread uptake of LNG fuelled ships would require the development of infrastructure, including terminals, and LNG storage facilities (with or without liquefaction capabilities). Currently, most production plants and LNG import terminals are designed to service full sized LNG carriers and are not equipped to serve smaller vessels, or to frequently receive ships. Existing LNG terminals would therefore require modification to refuel ships. LNG can also be supplied by trucks, provided the volumes required are relatively small; for example, this is common in Norway. The costs of LNG terminals for ship refuelling can be high, and the EU is supporting four new studies in an attempt to address this barrier.

A study by the Danish Maritime Authority (Danish Maritime Authority, 2012), which focussed on the LNG supply chain, assessed the costs to establish three different sizes of LNG terminals. The three LNG ports assessed during the study would be suitable for refuelling ships. Their characteristics and costs are summarised in the table below.

Table 4-10: LNG infrastructure costs from Danish Maritime Authority

LNG Terminal	Description/Characteristics	NPV total investment cost (million €)	NPV total operational cost (million € / year)
Port Case I LNG import terminal	No separate storage – draws LNG directly from import terminal Throughput LNG (m^3/year): 204,000	€76 million	€208 million
Port Case II Medium-sized intermediary terminal	20,000 m^3 tank storage Throughput LNG (m^3/year): 343,000	€151 million	€419 million
Port Case III Small LNG intermediary terminal	Two 700 m^3 storage tanks Throughput LNG (m^3/year): 52,000	€16 million	€39 million

Source: (Danish Maritime Authority, 2012)

Using these scenarios, the study calculates infrastructure costs of €120 per tonne to €200 € per tonne of LNG, and used an average figure of €170 per tonne for their cost analysis. The same study estimates a cost of 10 €/tonne for existing HFO and MGO infrastructure. These infrastructure costs have been added to the respective fuel prices for the cost/benefit analysis carried out in this study (see following sections).

Table 4-11: Unit infrastructure costs per tonne of fuel

Fuel	Infrastructure cost (per tonne of fuel)
HFO	€10 per tonne
MGO	€10 per tonne
LNG	€170 per tonne

4.3.3 Operating costs for LNG ships

In order to assess the net costs and financial benefits associated with using LNG in the shipping sector, it is necessary to compare the net capital and operational costs of LNG-fuelled ships against alternative options. The Danish Maritime Authority study (2012) referred to earlier included a detailed analysis of the payback periods for alternative strategies for complying with the current ECA requirement on sulphur emissions (i.e. comparing the capital and operating costs of HFO-fuelled vessels fitted with scrubbers, MGO-fuelled vessels and LNG-fuelled vessels). The capital cost estimates have already been reviewed in Section 4.3.1; in this section we outline the findings from the payback analysis, taking into account fuel costs and other operational costs as well as the capital costs. Three fuel price scenarios that were included in the study as set out in the table below.

Table 4-12: Fuel price scenarios for payback analysis of ECA compliance strategies

	Price scenarios for each fuel type		
	HFO	MGO	LNG
Scenario 1	€520 per tonne	€875 per tonne	€315 per tonne
Scenario 2	€520 per tonne	€875 per tonne	€440 per tonne
Scenario 3	€520 per tonne	€875 per tonne	€570 per tonne

Adding the fuel infrastructure costs to the basic fuel prices provides the on-board delivered fuel prices that would be faced by ship operators. These delivered fuel price scenarios are presented in the table below.

Table 4-13: On-board delivered fuel price scenarios (including fuel infrastructure costs) for payback analysis of ECA compliance strategies

	Price scenarios for each fuel type (including infrastructure costs)		
	HFO	MGO	LNG
Scenario 1	€530 per tonne	€885 per tonne	€485 per tonne
Scenario 2	€530 per tonne	€885 per tonne	€610 per tonne
Scenario 3	€530 per tonne	€885 per tonne	€740 per tonne

Source: (Danish Maritime Authority, 2012)

Fuel consumption and total annual fuel costs for each ship type are presented in the table below.

Table 4-14: Annual fuel and infrastructure costs for ECA compliance strategies based on (a) HFO+scrubbers; (b) MGO fuel; and (c) LNG fuel

	Annual fuel costs for each vessel type/fuel type combination				
	HFO + scrubber	MGO	LNG		
Ship type	€530/tonne	€885/tonne	€485/tonne	€610/tonne	€740/tonne
RoRo	€1.64 million	€ 2.56 million	€ 1.31 million	€ 1.65 million	€ 2.00 million
Coastal tanker / bulk carrier	€1.95 million	€ 1.82 million	€ 1.55 million	€ 1.95 million	€ 2.37 million
Container ship	€2.74 million	€ 2.55 million	€ 2.18 million	€ 2.75 million	€ 3.33 million
Large RoRo	€5.97 million	€ 5.56 million	€ 4.75 million	€ 5.98 million	€ 7.25 million

Source: (Danish Maritime Authority, 2012)

4.3.4 Payback periods and comparison of capital and operating costs

The study compared the payback period for HFO+scrubber and LNG-based ECA compliance strategies against a counterfactual scenario of shifting to MGO fuel. The payback period defines how many years would be required for the respective investments to generate cost savings that add up to the same amount as the capital investment required. The study found that payback times are typically between two and four years compared to a strategy based on shifting to MGO fuel. Payback periods are primarily determined by the relationship between fuel consumption and installed engine power. High fuel consumption per unit power output reduces the payback period. If the LNG price is high (as in Scenario 3), the payback period for LNG is greater than for the alternative strategy of using HFO with scrubbers. However, overall the payback periods for both strategies are short due to the large difference in prices between MGO and LNG/HFO.

The study also investigated what the payback periods would be if the counterfactual was assumed to be the business-as-usual situation of continuing to use HFO but without scrubbers. The results of this analysis indicated that shifting to LNG would have a payback period of 8 to 15 years with the fuel prices from Scenario 1, 50 to 80 years for Scenario 2, and there would not be any payback with the fuel prices from Scenario 3.

The economics of operating LNG-powered ships depend to a large extent on the price of LNG compared to conventional bunker fuels. Even with the significant reductions in the price of oil since 2014, LNG is still a cheaper fuel. At the beginning of 2015, the price of natural gas was more than 13% lower than the price of HFO, and almost 50% lower than the price of low sulphur (0.1%) MGO. This is not expected to change in the short term, as the supply of gas remains strong, and new production streams (e.g. shale gas) are becoming more common. Furthermore, if oil producers reduce their production output in the future because of the current very low oil prices, then prices of HFO and MGO could increase, thereby giving natural gas even more of an advantage. However, it must be stressed that there has been a high level of variability in fuel prices in recent years which makes it difficult to accurately predict how prices may change in the future.

As a sensitivity analysis, we have re-calculated the payback periods associated with each type of vessel, based on current (November 2015) fuel prices for HFO, MGO and LNG (Bunkerworld, 2015). The prices used for this analysis are presented in Table 4-15, and the annual fuel costs using these prices for each vessel type are presented in Table 4-16.

Table 4-15: November 2015 prices for maritime bunker fuels

	Price scenarios for each fuel type		
	HFO	MGO	LNG
November 2015 fuel prices	€225 per tonne	€429 per tonne	€280 per tonne
Infrastructure costs	€10 per tonne	€10 per tonne	€170 per tonne
On-board delivered fuel prices	€235 per tonne	€439 per tonne	€450 per tonne

Source: (Bunkerworld, 2015)

Table 4-16: Annual fuel costs for ECA compliance strategies using November 2015 bunker fuel prices (and including fuel infrastructure costs)

	Annual fuel costs for each vessel type		
	HFO + scrubber	MGO	LNG
Ship type	€235/tonne	€439/tonne	€450/tonne
RoRo	€ 0.71 million	€ 1.27 million	€ 1.22 million
Coastal tanker / bulk carrier	€ 0.84 million	€ 0.80 million	€ 1.44 million
Container ship	€ 1.19 million	€ 1.13 million	€ 2.03 million
Large RoRo	€ 2.58 million	€ 2.47 million	€ 4.41 million

Using current fuel prices has a very significant impact on the payback analysis. For most vessel types, the annual fuel costs for LNG-powered ships are higher than the fuel costs for HFO and MGO vessels, which means that from the operator's perspective, there is never any payback. The exception to this finding is for small RoRo vessels, where annual LNG fuel costs would be lower than the costs of powering an equivalent ship with MGO. However, the marginal fuel cost savings are very small (approximately €50,000 per year) and would be outweighed by the additional capital costs of the vessel.

4.3.4.1 Comparison of annualised capital and operating costs

In addition to examining payback periods, which take into account investment decisions from an operator's perspective, we can also look at the annualised capital and operating costs associated with LNG-powered ships compared to the other ECA compliance options, to provide the societal perspective. For this analysis, capital costs for each ship type have been annualised over a 25 year lifetime using the European Commission's recommended 4% social discount rate.

Table 4-17: Total annualised capital and operating costs for ECA compliance strategies (based on Danish Maritime Authority, 2012)

Ship type	Total annualised capital and operating costs for each vessel type				
	HFO + scrubber	MGO	LNG		
	€530/tonne	€885/tonne	€485/tonne	€610/tonne	€740/tonne
RoRo	€1.85 million	€2.66 million	€1.58 million	€1.92 million	€2.27 million
Coastal tanker / bulk carrier	€2.27 million	€1.98 million	€1.99 million	€2.39 million	€2.80 million
Container ship	€3.05 million	€2.71 million	€2.59 million	€3.15 million	€3.74 million
Large RoRo	€6.77 million	€5.95 million	€5.82 million	€7.05 million	€8.32 million

As can be seen from the data in this table, if the price of LNG is at €485 per tonne, the total annual costs are significantly lower for LNG ships than either HFO-fuelled or MGO-fuelled ships. However, at higher LNG fuel prices, assuming now change in HFO or MGO prices, a shift to LNG is not cost effective. It is important to note that this analysis is based on a societal perspective where capital costs have been annualised over the full life-time of a vessel.

As a sensitivity analysis, we have re-calculated the total annualised (capital and operating) costs associated with each type of vessel, based on current (November 2015) fuel prices for HFO, MGO and LNG (with infrastructure costs added to these prices). The prices used for this analysis are presented in the table below.

Table 4-18: Total annualised capital and operating costs for ECA compliance strategies based on November 2015 fuel prices (based on data from Danish Maritime Authority, 2012)

	Total annualised capital and operating costs for each vessel type		
	HFO + scrubber	MGO	LNG
Ship type	€235/tonne	€439/tonne	€450/tonne
RoRo	€0.94 million	€1.41 million	€1.49 million
Coastal tanker / bulk carrier	€1.19 million	€0.97 million	€1.88 million
Container ship	€1.52 million	€1.29 million	€2.43 million
Large RoRo	€3.45 million	€2.85 million	€5.48 million

As can be seen from the table, using current (November 2015) fuel prices, the total annualised capital and operating costs associated with LNG-powered vessels are significantly higher than for all HFO-fuelled vessels equipped with scrubbers and for all MGO-fuelled vessels.

4.3.5 Monetised environmental impacts

4.3.5.1 Methodological approach

In order to assess the full societal costs of LNG-powered ships, it is necessary to assess the impacts of this technology on environmental external costs as well as the impacts on capital costs and operating costs. The environmental externalities are those that relate to the emissions of air pollutants and greenhouse gases, and for this study we have used the latest values from the European Commission's "Update of the Handbook on External Costs of Transport" (Ricardo-AEA, 2014). These environmental externalities are not borne by transport operators or users, but by society as a whole. For air pollutants, these costs are damage costs that represent the impact that emissions have on human health, crops, ecosystems, and on economic activity. In the Commission's Handbook, human health costs are quantified using the Value of a Life Year (VOLY) approach. For greenhouse gases, the costs taken into account are the abatement costs associated with achieving a given amount of emission reduction; in theory it would be preferable to use damage costs for GHG emissions, but abatement costs are used in the Commission's updated handbook because there is an extremely high level of uncertainty with respect to the damage costs of climate change.

4.3.5.2 Environmental externalities for the shipping sector

The updated EC Handbook on External Costs of Transport includes emissions-related externalities that are specific to the shipping sector. The values of these externalities are presented in the table below.

Table 4-19: External costs of main air pollutants and greenhouse gases, by sea area, in € per tonne (2010) (Ricardo-AEA et al, 2014)

	External costs (€ per tonne)			
Sea region	**NO_x**	**SO_2**	**PM**	**CO_2e**
Baltic Sea	4,700	5,250	13,800	90
Black Sea	4,200	7,950	22,500	90
Mediterranean Sea	1,850	6,700	18,500	90
North Sea	5,950	7,600	25,800	90
Remaining North-East Atlantic	2,250	2,900	5,550	90

Annual emissions of each pollutant for the different vessel and fuel combinations are presented in the following tables. Note that for the LNG-fuelled ships, the emissions of greenhouse gases (presented in tonnes of CO_2e) include both CO_2 emissions from fuel production and combustion as well as methane leakage/slip emissions (the range of values for LNG ships reflects lower and upper estimates for methane slip of 1.8% and 3.5% respectively, as discussed previously).

Table 4-20: Annual emissions of air pollutants and greenhouse gases for ships equipped with HFO+scrubber technology (derived from (Danish Maritime Authority, 2012))

	Emissions (tonnes per year)			
Sea region	**NO_x**	**SO_2**	**PM**	**CO_2e**
RoRo	226.1	1.5	3.3	12,505
Coastal tanker / bulk carrier	268.0	1.8	3.9	14,821
Container ship	376.8	2.5	5.4	20,842
Large RoRo	820.6	5.5	11.8	45,390

Table 4-21: Annual emissions of air pollutants and greenhouse gases for MGO-fuelled ships (Danish Maritime Authority, 2012)

	Emissions (tonnes per year)			
Sea region	**NO_x**	**SO_2**	**PM**	**CO_2e**
RoRo	253.7	2.9	6.9	11,001
Coastal tanker / bulk carrier	300.7	3.4	8.2	13,038
Container ship	422.8	4.8	11.5	18,334
Large RoRo	920.8	10.5	25.0	39,928

Table 4-22: Annual emissions of air pollutants and greenhouse gases for LNG-fuelled ships (Danish Maritime Authority, 2012)

	Emissions (tonnes per year)			
Sea region	**NO_x**	**SO_2**	**PM**	**CO_2e**
RoRo	40.1	0.2	0.1	10,591 to 11,757
Coastal tanker / bulk carrier	47.5	0.2	0.2	12,552 to 13,934
Container ship	66.8	0.3	0.2	17,652 to 19,595
Large RoRo	145.5	0.6	0.5	38,441 to 42,672

The annual external costs associated with each vessel type / fuel type combination can be calculated by using the emissions data in conjunction with the unit external cost data from the EC's Handbook of External Costs. The unit external costs vary by sea region and hence we have included the highest and lowest values, which relate to the North Sea and the remaining North East Atlantic Ocean, in order to demonstrate the range of external costs associated with shipping. Furthermore, to demonstrate the benefits of the technologies for achieving compliance with the ECAs, we have also quantified the external costs associated emissions from conventional ships operating on HFO **without** exhaust gas scrubbers.

Table 4-23: Annual external costs associated with emissions of air pollutants and GHGs for each vessel type / fuel type combination – North Sea

	Fuel/equipment type			
Ship type	**Conventional HFO (no scrubber)**	**HFO + scrubber**	**MGO**	**LNG**
RoRo	€ 2.95 million	€ 2.50 million	€ 2.61 million	€ 1.19 million
Coastal tanker / bulk carrier	€ 3.49 million	€ 2.96 million	€ 3.09 million	€ 1.41 million
Container ship	€ 4.91 million	€ 4.16 million	€ 4.35 million	€ 1.98 million
Large RoRo	€ 10.69 million	€ 9.06 million	€ 9.48 million	€ 4.32 million

Table 4-24: Annual external costs associated with emissions of air pollutants and GHGs for each vessel type / fuel type combination – North East Atlantic Ocean

	Fuel/equipment type			
Ship type	**Conventional HFO (no scrubber)**	**HFO + scrubber**	**MGO**	**LNG**
RoRo	€ 1.72 million	€ 1.60 million	€ 1.60 million	€ 1.05 million
Coastal tanker / bulk carrier	€ 2.03 million	€ 1.89 million	€ 1.90 million	€ 1.24 million
Container ship	€ 2.86 million	€ 2.66 million	€ 2.67 million	€ 1.74 million
Large RoRo	€ 6.23 million	€ 5.80 million	€ 5.81 million	€ 3.80 million

As can be seen from the tables, the external costs associated with emissions of air pollutants and greenhouse gases are significantly lower for ships powered by LNG than for all other options. In the North Sea, the external costs for LNG ships range from being €1.42 million lower than MGO-fuelled RoRo vessels to €5.16 million lower than for large MGO-fuelled RoRo vessels. Compared to HFO-fuelled ships equipped with exhaust gas scrubbers, the external costs for LNG ships are €1.31 million lower for small RoRo vessels and €4.74 million lower for large RoRo vessels. For ships operating in the North East Atlantic Ocean, the differences in external costs between LNG-fuelled ships and other options are lower (due to the much lower levels of population exposure), but in all cases, LNG-fuelled ships have the lowest external costs.

4.3.6 Analysis of total costs and benefits

The findings from the analysis of capital costs, operating costs and the external costs of emissions can be combined to estimate the overall monetised costs and benefits of each of the ECA compliance options. In this way, we can assess, from an economic perspective, whether shifting to LNG-fuelled ships generates net costs or net benefits to society.

For this analysis we have taken the annualised capital costs and combined these with the annual fuel costs and annual external emissions costs for each vessel type / fuel type combination. Given the differences in external emissions costs by sea area, we have carried out this assessment for the North Sea region and for the North East Atlantic Ocean to demonstrate the upper and lower estimates for total costs and benefits.

The results of this analysis are presented in the tables below. Table 4-25 and Table 4-26 present the total annualised costs to society for each option, using fuel price data from the Danish Maritime Authority (2012) study, and for (a) vessels operating in the North Sea and (b) in the North East Atlantic Ocean.

Table 4-25: Total annual costs to society for ECA compliance strategies for vessels operating in the North Sea (based on CAPEX and OPEX data from Danish Maritime Authority, 2012)

	Total annual costs to society for each vessel type (CAPEX, OPEX and external costs)				
	HFO + scrubber	MGO	LNG		
Ship type	€530/tonne	€885/tonne	€485/tonne	€610/tonne	€740/tonne
RoRo	€ 4.31 million	€ 5.27 million	€ 2.77 million	€ 3.11 million	€ 3.46 million
Coastal tanker / bulk carrier	€ 5.18 million	€ 5.07 million	€ 3.40 million	€ 3.80 million	€ 4.21 million
Container ship	€ 7.14 million	€ 7.06 million	€ 4.57 million	€ 5.14 million	€ 5.72 million
Large RoRo	€ 15.68 million	€ 15.42 million	€ 10.16 million	€ 11.39 million	€ 12.66 million

Table 4-26: Total annual costs to society for ECA compliance strategies for vessels operating in the North East Atlantic Ocean (based on CAPEX and OPEX data from Danish Maritime Authority, 2012)

	Total annual costs to society for each vessel type (CAPEX, OPEX and external costs)				
	HFO + scrubber	MGO	LNG		
Ship type	€530/tonne	€885/tonne	€485/tonne	€610/tonne	€740/tonne
RoRo	€ 3.41 million	€ 4.26 million	€ 2.63 million	€ 2.97 million	€ 3.32 million
Coastal tanker / bulk carrier	€ 4.12 million	€ 3.87 million	€ 3.23 million	€ 3.63 million	€ 4.04 million
Container ship	€ 5.64 million	€ 5.38 million	€ 4.34 million	€ 4.90 million	€ 5.48 million
Large RoRo	€ 12.43 million	€ 11.76 million	€ 9.62 million	€ 10.84 million	€ 12.12 million

Under all scenarios, LNG vessels incur lower total costs to society than HFO-fuelled ships equipped with scrubbers and MGO-fuelled ships. For ships operating in the North Sea, the total costs to society for LNG-fuelled vessels are between €0.85 million per year and €5.52 million per year lower than either of the other ECA compliance options, depending on the price of LNG. For ships operating in the North East Atlantic, the total societal costs for LNG-fuelled ships are between €0.07 million and €2.81 million per year lower than HFO-fuelled vessels equipped with exhaust gas scrubbers, again depending on the price of LNG. Compared to MGO-fuelled vessels, the total costs to society associated with LNG ships are only lower for the €485 per tonne and €610 per tonne LNG price scenarios; annual costs are between €0.25 million and €2.14 million lower under these scenarios. If the LNG price is assumed to be €740 per tonne, then the total costs to society are higher for all LNG ships except for small RoRo vessels. Societal costs for other vessels are between €0.11 million and €0.36 million per year higher.

We repeated the analysis described above using current (November 2015) fuel prices to examine what effect this has on the net costs and benefits to society (see Table 4-27 and Table 4-28 below).

Table 4-27: Total annual costs to society for ECA compliance strategies for vessels operating in the North Sea (based on CAPEX data from Danish Maritime Authority, 2012 and November 2015 fuel price data)

	Total annual costs to society for each vessel type		
	HFO + scrubber	MGO	LNG
Ship type	€235/tonne	€439/tonne	€450/tonne
RoRo	€ 3.42 million	€ 3.98 million	€ 2.68 million
Coastal tanker / bulk carrier	€ 4.13 million	€ 4.06 million	€ 3.28 million
Container ship	€ 5.65 million	€ 5.64 million	€ 4.42 million
Large RoRo	€ 12.44 million	€ 12.33 million	€ 9.79 million

Table 4-28: Total annual costs to society for ECA compliance strategies for vessels operating in the North East Atlantic Ocean (based on CAPEX data from Danish Maritime Authority, 2012 and November 2015 fuel price data)

	Total annual costs to society for each vessel type		
	HFO + scrubber	MGO	LNG
Ship type	€235/tonne	€439/tonne	€450/tonne
RoRo	€ 2.52 million	€ 2.97 million	€ 2.54 million
Coastal tanker / bulk carrier	€ 3.06 million	€ 2.86 million	€ 3.12 million
Container ship	€ 4.16 million	€ 3.96 million	€ 4.18 million
Large RoRo	€ 9.19 million	€ 8.66 million	€ 9.28 million

The results of this analysis show that even with much lower fuel prices, there are still net economic benefits to society associated with LNG-fuelled ships compared to other options. For vessels operating in the North Sea, total societal costs for LNG-fuelled are between €0.74 million per year and €2.64 million per year lower than for the other options. However, in the North East Atlantic, total societal costs for LNG ships are, in most cases, higher than for HFO and MGO-fuelled vessels. Total societal costs are between €0.02 million per year and €0.61 million per year higher for LNG ships; the exception to this is for small RoRo vessels where the total societal costs for LNG ships are around €0.44 million per year lower than for equivalent MGO-fuelled ships.

4.3.7 Summary

The analysis presented in the previous sections shows that whilst LNG-fuelled ships have higher capital costs than HFO-fuelled ships equipped with scrubbers and MGO-fuelled ships, there can be economic benefits to operators but these benefits are very sensitive to shifts in fuel prices. In particular, at current (November 2015) fuel prices, for most vessel types there would not be any economic benefits to operators in shifting to LNG because the annual fuel costs for LNG ships would be higher than for HFO and MGO-fuelled vessels.

However, from a societal perspective, under many scenarios there are clear net economic benefits in using LNG-fuelled ships in place of HFO-fuelled ships equipped with scrubbers or MGO-fuelled ships. This is primarily because the external costs of air pollutant and GHG emissions from LNG-fuelled ships are lower than for the other options. The net economic benefits are greater in environmentally sensitive areas such as the North Sea, but even for ships operating in the North East Atlantic Ocean, there can still bet net benefits for LNG-fuelled ships compared to the alternatives. However, at current (November 2015) fuel prices, there are no net economic benefits associated with using LNG for ships operating in the North East Atlantic; total annual costs to society for such vessels are in most cases greater for LNG ships than for conventional HFO and MGO-fuelled ships.

4.4 Economic analysis of the costs and benefits of using natural gas and biomethane in the road transport sector

4.4.1 Capital costs for methane-powered road vehicles

For road vehicles, the literature review identified a number of data sources for capital costs, but we felt that it was important to use a consistent set of data for all vehicle types, and that took into account likely cost differentials between conventional petrol and diesel vehicles and methane-powered vehicles by 2020. In order to provide this type of data, we drew on work carried out by AEA in 2012 for the UK Committee on Climate Change to review efficiency and cost assumptions for road transport vehicles for the period between 2010 and 2050 (AEA, 2012). As part of this research, AEA developed cost estimates for a very wide range of vehicle types and technologies covering the years 2010, 2020, 2030, 2040 and 2050. These estimates drew on a very broad range of sources, including detailed vehicle teardown studies that analysed the costs of individual components and vehicle systems. The estimates developed in this study were used to inform analysis of the future costs and cost effectiveness of GHG abatement technologies in the road transport sector for the UK Government, and subsequently they were used to support the Ricardo-AEA study for the UK Department for Transport on waste and gaseous transport fuels (Ricardo-AEA, 2014). Consequently, these cost data have been peer-reviewed a number of times and are widely considered to be robust estimates. A summary of the 2020 capital costs for each vehicle type from this study is presented in the table below.

Table 4-29: Capital costs for petrol, diesel and methane-powered road vehicles

Vehicle type	Fuel type			
	Petrol vehicle	Diesel vehicle	Dedicated (mono-fuel) gas vehicle	Dual-fuel gas vehicle
Passenger car	€ 19,500	€ 20,400	€ 20,550	
Light commercial vehicle	€ 15,700	€ 17,000	€ 17,700	
Small rigid truck		€ 45,000	€ 55,600	€ 58,000
Large rigid truck		€ 73,900	€ 85,400	€ 89,450
Articulated truck		€ 97,200	€ 112,750	€ 118,500

Source: (AEA, 2012)

As can be seen from the table, dual-fuel vehicles (which are only available for heavy duty vehicles) are significantly more costly than dedicated mono-fuel gas vehicles, even in 2020. In all cases, methane-fuelled vehicles will continue to have higher capital costs than equivalent conventional petrol and diesel vehicles in 2020, although the cost differential between diesel-powered and methane-powered passenger cars and LCVs is likely to be very small by 2020 (€150 and €700 respectively).

For heavy duty vehicles, the capital cost differential between conventional diesel-fuelled vehicles and dedicated methane-fuelled vehicles is likely to still be substantial by 2020. AEA (2012) estimates that for small rigid trucks, large rigid trucks, articulated trucks, this cost differential will remain above €10,000 in 2020 (the cost differential ranges from just under €10,600 for small rigid trucks to more than €15,500 for articulated trucks). .

Table 4-30: Marginal capital costs of gas vehicles versus petrol/diesel fuelled vehicles

Vehicle type		Marginal capital cost of methane-fuelled vehicle compared to conventional petrol or diesel vehicle
LDV	Dedicated passenger cars vs petrol	€ 1,050
	Dedicated passenger car vs diesel	€ 150
	Dedicated LCV vs petrol	€ 2,000
	Dedicated LCV vs diesel	€ 700
HDV	Dedicated small rigid truck vs diesel	€ 10,600
	Dual fuel small rigid truck vs diesel	€ 13,000
	Dedicated large rigid truck vs diesel	€ 11,500
	Dual fuel large rigid truck vs diesel	€ 15,550
	Dedicated articulated truck vs diesel	€ 15,550
	Dual fuel articulated truck vs diesel	€ 21,300
	Dedicated bus vs diesel	€ 8,700
	Dual fuel bus vs diesel	€ 11,400
	Dedicated coach vs diesel	€ 12,700
	Dual fuel coach vs diesel	€ 16,450

4.4.2 Operating costs for methane-fuelled road vehicles

In this section we have analysed the annual operating costs associated with methane-fuelled vehicles, focusing on the dominant cost element, namely fuel costs. One of the key challenges associated with carrying out this analysis is the volatility of fuel prices. This can be seen from the table below which presents pre-tax fuel prices for petrol and diesel for selected points in time in 2012, 2014 and 2015.

Table 4-31: Petrol and diesel fuel costs (without tax or duty)[9]

	Petrol (€/1000 l)	Diesel (€/1000 l)	Petrol €/GJ	Diesel €/GJ
Sept 2012	€772	€811	€23.47	€24.65
Average throughout 2014	€643 ± €36	€680 ± €31	€19.54 ± €1.10	€18.80 ± €0.86
Sept 2015	€455	€475	€13.82	€13.12

Comparative prices for natural gas and biomethane are presented in the following table (Ricardo-AEA, 2014).

Table 4-32: 2014 methane fuel costs (without tax or duty)

Fuel	Cost for compressed methane (€/GJ)	Cost for liquefied methane (€/GJ)

[9] Economic analysis of societal costs and benefits does not include taxes or duties as these are typically treated as transfers within the economy. Furthermore, taxation levels for fuels and vehicle vary significantly across the European Union.

Biomethane from AD food	€ 13.00	€ 15.60
Biomethane from landfill	€ 12.91	€ 15.51
Average biomethane cost	€ 12.96	€ 15.56
Natural gas	€ 14.54	€ 13.16

The fuel cost data for methane are taken from previous research for the UK Department for Transport (Ricardo-AEA, 2014) indicates that for compressed biomethane has lower costs than compressed natural gas, whilst liquefied biomethane has higher costs than liquefied natural gas. These data are based on a comprehensive review of each step in the production and distribution process for each type of fuel, but we are aware that there is very significant variability in fuel costs and prices over time.

Fuel consumption and total annual fuel costs for each vehicle type are presented in Table 4-33 for conventionally petrol and diesel vehicles, and in Table 4-33 for the gas vehicles based on the prices tabulated above. Whilst it is appropriate to consider constant engine energy requirements for ship engines, this does not apply to road transport. The methodology adopted was to use typical CO_2 emissions of a methane fuelled vehicle (gCO_2/km), and to work backwards, using the CO_2 emissions to determine the average fuel consumption (litres per 100 km) for the vehicle and use the fuel's energy characteristics to determine fuel usage in units of MJ/km. Annual fuel costs were then calculated using the fuel price data and information on the average annual distances travelled by vehicles of each type. The typical CO_2 emissions performance data for the methane-fuelled vehicles were taken from previous research carried out for the UK Department for Transport (Ricardo-AEA, 2014). In the calculated annual energy consumption column, beside the total is either the legend (C) or (L) to denote whether it is assumed the vehicle uses compressed, or liquefied methane fuel.

Table 4-33: Annual fuel consumption and fuel costs for conventional liquid fuels (costs exclude taxes and duties)

Vehicle type	Average vehicle lifetime (years)	Average annual mileage (km)	Average new vehicle consumption (l/100km)	Annual fuel consumption (litres)	Annual fuel consumption (GJ)	Average annual liquid fuel costs (€)
Passenger car (petrol)	14	13,000	4.7	611	20.1	€ 391
Passenger car (diesel)	14	13,000	3.2	412	14.8	€278
Light commercial vehicle (diesel)	14	16,000	7.8	1,248	45.2	€ 844
Small rigid truck	11[10]	35,000	16.0	5,600	202.7	€ 3,789
Large rigid truck	11	60,000	25.0	15,000	543	€ 10,149
Articulated truck	11	130,000	32.5	42,250	1,521	€ 28,587
Bus	15	50,000	36.0	18,000	651.6	€ 12,179
Coach	15	52,000	27.7	14,404	506.9	€ 9,746

Sources: (Ricardo-AEA, 2014) (AEA et al, 2011) (EMEP/EEA, 2014)

Table 4-34: Annual fuel consumption and fuel costs for methane fuelled vehicles (costs exclude taxes and duties)

[10] Lifetime of trucks and coaches taken from Section 4.2.2 of EC HGV LOT1 report (Ricardo-AEA 2011)

Vehicle type	Average annual mileage (km)	Average CO_2 emissions (g CO_2/km)	Energy consumption (MJ/km)	Annual gaseous fuel consumption (GJ)	Average annual methane fuel costs (€)	
					Natural gas	Bio-methane
Passenger car	13,000	87.5	1.590	20.67 (C)	€ 301	€ 268
Light commercial vehicle	16,000	208.0	3.777	60.43 (C)	€ 879	€ 783
Small rigid truck	35,000	426.7	7.748	271.18 (C)	€ 3,943	€ 3,513
Large rigid truck	60,000	666.7	12.106	726.35 (L)	€ 9,559	€ 11,298
Articulated truck (dual fuel)*	130,000	747.2	13.567	1873.26* (L)	€ 27,822	€ 30,962
Bus	50,000	978.7	17.772	888.59 (C)	€ 12,920	€ 11,512
Coach	52,000	738.7	13.413	697.49 (L)	€ 9,179	€ 10,850

* Dual-fuel truck assumed to operate 65% on methane and 35% on diesel

As can be seen from the tables, annual fuel costs for cars are lower for methane-fuelled vehicles than they are for equivalent petrol/diesel vehicles. For all other vehicle types, the fuel cost differential is highly dependent on whether the vehicle uses biomethane or natural gas, and on whether it uses compressed methane or liquefied methane. For light commercial vehicles, using natural gas leads to an overall increase in annual fuel costs, whilst for biomethane there would be a reduction, based on the fuel cost data from previous research (Ricardo-AEA, 2014). Similar results can be seen for small rigid trucks and buses, all of which are assumed to use compressed natural gas or compressed biomethane. For large rigid trucks, articulated trucks and coaches, it has been assumed that they use LNG or LBM, and as the costs of LBM are higher than LNG, annual fuel costs are higher. For all of the vehicles except passenger cars, the conventional comparator vehicles use diesel, and the overall energy efficiency of diesel vehicles is much higher than dedicated methane-fuelled vehicles; this factor offsets much or, in some cases, all of the savings due to the lower prices of natural gas and biomethane compared to petrol and diesel.

4.4.3 Infrastructure costs

In order for methane-powered road vehicles to be a viable mainstream option for the transport sector, the availability of sufficient refuelling infrastructure is critically important. There are two main options for road vehicle refuelling infrastructure, namely (i) CNG and (ii) LNG refuelling stations.

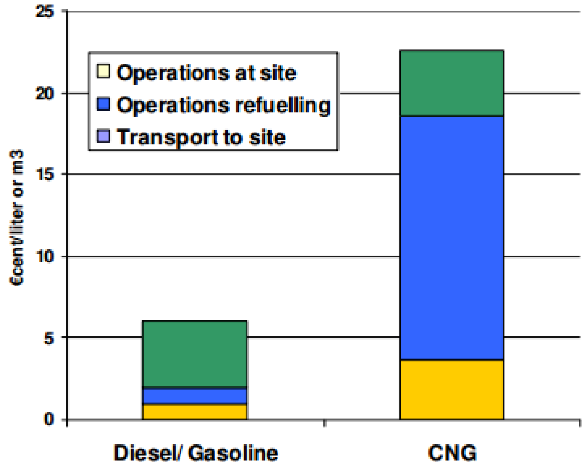
CNG stations have pressurised dispeners and use a compressor that can deliver methane to vehicles at a pressure of 200 bar (Oxford Institute for Energy Studies, 2014). These stations are connected to the gas grid via a pipeline connection. The costs of such systems depend on the overall pressure of the relevant gas grid (i.e. higher gas grid pressures mean that the amount of additional compression required is reduced, thereby reducing costs). In cases where it is not possible to establish a grid connection, or where the costs of such a connection are prohibitively expensive, a so-called "mother-daughter" configuration can be used as an alternative. This consists of a mobile trailer-mounted CNG tank (the "daughter" station) that is delivered from the mother CNG station by road transport. A second trailer is used in conjunction with the first trailer to ensure that the mobile daughter station always has sufficient fuel to meet demand (Oxford Institute for Energy Studies, 2014).

LNG stations consist of leak-tight dispensers and a cryogenic tank for storing the LNG fuel. LNG is delivered to these stations by road tanker. On average, LNG stations can refuel 40 to 50 vehicles per hour. LNG stations can also be configured as L-CNG stations which can dispense both CNG and LNG (Oxford Institute for Energy Studies, 2014).

According to the Natural and bio Gas Vehicle Association (NGVA Europe), in September 2014 there was a total of 3,280 CNG refuelling stations, 29 LNG stations and 36 L-CNG stations across the EU28. At that point in time, 2,619 of the CNG stations were publicly accessible and there were plans to build a further 210 CNG stations (NGVA Europe, 2014)

The costs of refuelling stations have been analysed in separate studies carried out by IGU and TTR. (IGU, 2012) compared the unit costs of refuelling stations for petrol/diesel vehicles and CNG vehicles on a cost per litre basis. These costs included the direct costs of fuelling (equipment on site, costs of gas/electric grid), and the indirect costs of fuelling (costs for building structures, land, or provisions for automatic payment). This analysis indicated that costs for petrol/diesel stations are approximately €0.06 per litre, whilst for CNG the costs are around €0.23 per litre.

Figure 4-1: Comparison of European fuelling costs for petrol/diesel vehicles and CNG vehicles



Source: (IGU, 2012)

The study also found that a dedicated CNG station would need an annual capacity of around 1 million kg of CNG (equivalent to 1.46 million litres of diesel) and would need to achieve sales volumes of 30% of this annual capacity in order to be efficient.

TTR (TTR, 2011) developed unit cost estimates for CNG, LNG and L-CNG refuelling infrastructure based on different levels of annual throughput. The capital and civil engineering costs from this study for each type of refuelling infrastructure are presented below, converted from UK Sterling prices to Euros, using the 2011 average exchange rate of £1 = €1.15 (the study was carried out in 2011).

Table 4-35: CNG refuelling station costs

Station size (kg/day)	Capital costs	Civil engineering costs
500	€ 184,000	€ 57,500
1000	€ 230,000	€ 69,000
2000	€ 287,500	€ 92,000
5000	€ 402,500	€ 138,000
10000	€ 805,000	€ 161,000

Source: derived from (TTR, 2011)

Table 4-36: LNG refuelling station costs

Station size (kg/day)	Capital costs	Civil engineering costs
500	€ 83,950	€ 11,500
1000	€ 106,950	€ 13,800
2000	€ 218,500	€ 23,000
5000	€ 299,000	€ 34,500
10000	€ 402,500	€ 46,000

Source: derived from (TTR, 2011)

Table 4-37: L-CNG refuelling station costs

Station size (kg/day)	Capital costs	Civil engineering costs
500	€ 172,500	€ 34,500
1000	€ 230,000	€ 34,500
2000	€ 402,500	€ 69,000
5000	€ 575,000	€ 115,000
10000	€ 920,000	€ 138,000

Source: derived from (TTR, 2011)

As can be seen from the tables, the capital and civil engineering costs scale up as the capacity of the station increases. However, the unit infrastructure costs per kg of methane delivered are lower for stations with higher overall capacity. TTR calculated these unit costs for each station type and size combination; we have presented these costs in the tables below, converting from £ per kg to € per GJ.

Table 4-38: Unit costs of CNG refuelling stations (€/GJ)

Station size (kg/day)	Capital payback (€/GJ)	Operating costs (€/GJ)	Total infrastructure costs €/GJ)
500	€ 6.48	€ 5.76	€ 12.25
1000	€ 4.08	€ 3.36	€ 7.44
2000	€ 2.64	€ 2.40	€ 5.04
5000	€ 1.68	€ 1.92	€ 3.60
10000	€ 1.44	€ 1.68	€ 3.12

Source: derived from (TTR, 2011)

Table 4-39: Unit costs of LNG refuelling stations (€/GJ)

Station size (kg/day)	Capital payback (€/GJ)	Operating costs (€/GJ)	Total infrastructure costs €/GJ)
500	€ 2.64	€ 3.60	€ 6.24
1000	€ 1.68	€ 2.16	€ 3.84
2000	€ 1.68	€ 1.20	€ 2.88
5000	€ 0.96	€ 0.72	€ 1.68
10000	€ 0.72	€ 0.72	€ 1.44

Source: derived from (TTR, 2011)

Table 4-40: Unit costs of L-CNG refuelling stations (€/GJ)

Station size (kg/day)	Capital payback (€/GJ)	Operating costs (€/GJ)	Total infrastructure costs €/GJ)
500	€ 5.52	€ 5.76	€ 11.29
1000	€ 3.60	€ 3.36	€ 6.96
2000	€ 3.12	€ 2.88	€ 6.00
5000	€ 1.92	€ 2.88	€ 4.80
10000	€ 1.44	€ 2.16	€ 3.60

Source: derived from (TTR, 2011)

The TTR study also estimated the infrastructure costs for petrol/diesel fuel stations at £0.032 per litre (€0.037 per litre based on 2011 exchange rate of €1.15 = £1). These datasets from the TTR study have been used to calculate the per-vehicle annual costs associated with refuelling infrastructure for each vehicle type of interest, based on the average amount of fuel used per year for each vehicle type. In each case, we have presented the high and lower cost estimates for each vehicle type, which are based on the smallest and largest station sizes respectively. Marginal annual infrastructure costs are also presented in these tables; these figures are the additional annual costs associated with refuelling infrastructure on a per-vehicle basis compared to conventional petrol/diesel refuelling infrastructure costs.

Table 4-41: Annual and marginal refuelling infrastructure costs for CNG stations on a per vehicle basis (marginal costs compared to conventional petrol/diesel refuelling stations)

Vehicle type	Annual infrastructure costs (LOW)	Annual infrastructure costs (HIGH)	Marginal annual infrastructure costs (LOW) (relative to petrol/diesel)	Marginal annual infrastructure costs (HIGH) (relative to petrol/diesel)
Passenger car (relative to diesel)	€ 65	€ 253	€ 47	€ 235
Passenger car (relative to diesel)	€65	€253	€51	€240
Light commercial vehicle	€ 189	€ 740	€ 149	€ 700
Small rigid truck	€ 847	€ 3,321	€ 667	€ 3,142
Large rigid truck	€ 2,267	€ 8,896	€ 1,787	€ 8,416
Articulated truck	N/A	N/A	N/A	N/A
Bus	€ 2,774	€ 10,882	€ 2,198	€ 10,306
Coach	N/A	N/A	N/A	N/A

Table 4-42: Annual and marginal refuelling infrastructure costs for LNG stations on a per vehicle basis (marginal costs compared to conventional petrol/diesel refuelling stations)

Vehicle type	Annual infrastructure costs (LOW)	Annual infrastructure costs (HIGH)	Marginal annual infrastructure costs (LOW) (relative to petrol/diesel)	Marginal annual infrastructure costs (HIGH) (relative to petrol/diesel)
Passenger car	N/A	N/A	N/A	N/A
Light commercial vehicle	N/A	N/A	N/A	N/A
Small rigid truck	€ 391	€ 1,693	€ 212	€ 1,514
Large rigid truck	€ 1,047	€ 4,535	€ 567	€ 4,055
Articulated truck	€ 2,699	€ 11,696	€ 1,347	€ 10,344
Bus	N/A	N/A	N/A	N/A
Coach	€ 1,005	€ 4,355	€ 544	€ 3,894

Source: derived from (TTR, 2011)

Table 4-43: Annual and marginal refuelling infrastructure costs for L-CNG stations on a per vehicle basis (marginal costs compared to conventional petrol/diesel refuelling stations)

Vehicle type	Annual infrastructure costs (LOW)	Annual infrastructure costs (HIGH)	Marginal annual infrastructure costs (LOW) (relative to petrol/diesel)	Marginal annual infrastructure costs (HIGH) (relative to petrol/diesel)
Passenger car (relative to diesel)	€ 74	€ 233	€ 57	€ 215
Passenger car (relative to diesel)	€ 74	€ 233	€ 61	€ 220
Light commercial vehicle	€ 218	€ 682	€ 178	€ 642
Small rigid truck	€ 977	€ 3,061	€ 798	€ 2,881
Large rigid truck	€ 2,616	€ 8,198	€ 2,136	€ 7,718
Articulated truck	€ 6,747	€ 21,142	€ 5,395	€ 19,790
Bus	€ 3,201	€ 10,029	€ 2,625	€ 9,453
Coach	€ 2,512	€ 7,872	€ 2,051	€ 7,411

Source: derived from (TTR, 2011)

It can be seen from the tables that depending on the type of vehicle and the size and type of infrastructure, the marginal costs associated with refuelling infrastructure for methane-powered vehicles can be very significant. In summary, the ranges of marginal annual refuelling infrastructure costs for each vehicle type are as follows:

- Passenger cars: €47 to €240 per year
- Light commercial vehicles: €149 to €700 per year
- Small rigid truck: €212 to €3,142 per year
- Large rigid truck: €567 to €8,416 per year
- Articulated truck: €1,347 to €19,790 per year
- Bus: €2,198 to €10,306 per year
- Coach: €544 to €7,411 per year

In all cases, there is a significant difference in refuelling infrastructure costs between low capacity and high capacity refuelling stations, with high capacity stations always giving lower costs per vehicle. It is particularly notable that refuelling infrastructure costs for buses and articulated trucks are extremely expensive if the capacity of the refuelling infrastructure is low (the upper cost figures of €19,790 per vehicle per year for articulated trucks and €10,306 per vehicle per year for buses relate to refuelling stations with a capacity to deliver up to 500 kg of methane per day. Overall, these findings on refuelling infrastructure costs are in line with the outputs from the IGU study (IGU, 2012) discussed earlier which showed that there are minimum annual capacity and utilisation levels that are necessary in order to ensure that methane refuelling facilities are cost effective.

4.4.4 Payback periods and comparison of capital and operating costs

The marginal capital and operating costs of gas vehicles versus petrol/diesel fuelled vehicles can be converted into annualised costs for the seven vehicle types of interest using the identical approach to that described in the analogous section on shipping. These results are given in Table 4-44. Note that in every case the capital cost of the methane fuelled vehicle is higher than for the conventional vehicle. As can be seen from the table, in most cases, the annualised marginal capital and operating costs for gas-powered vehicles are higher than for conventional petrol and diesel vehicles, meaning that from the vehicle user's perspective, it may not be economically attractive to switch to methane. These results are obviously very sensitive to the differential in fuel costs between oil-based fuels and methane fuels, but other factors that affect the economic attractiveness of switching are (a) the additional capital costs associated with methane-fuelled vehicles and (b) the overall energy efficiency of these vehicles compared to conventional petrol/diesel vehicles. However, we stress that these data do not take into account fuel taxes and duties, and in many countries there are significant differences between taxation rates for petrol/diesel and for methane used in transport, which can have a very significant positive impact on the cost effectiveness of gas-powered vehicles from the user's perspective.

Table 4-44: Total annualised marginal vehicle capital and operating costs for methane-fuelled vehicles compared to conventional petrol and diesel vehicles

Vehicle type	Annualised marginal capital and operating costs relative to conventional petrol/diesel vehicles (€ per year)			
	CNG	LNG	CBM	LBM
Passenger car (compared to petrol)	+€9		-€24	
Passenger car (compared to diesel)	+€36		+€3	
Light commercial vehicle (compared to diesel)	€101		+€5	
Small rigid truck	+€1,364		+€934	
Large rigid truck 26 t		+€722		+€2,462
Articulated truck (>32 t)		+€1,666		+€4,807
Bus	+€1,524		+€115	
Coach		+€575		+€2,246

The above costs are from the vehicle user's perspective and hence do not take into account the costs associated with providing and operating refuelling infrastructure for methane-powered vehicles. Total annualised marginal costs that take into account all three elements (i.e. vehicle capital costs, refuelling infrastructure costs and fuel costs) are presented in the table below and include low and high estimates that take into account the variation in refuelling infrastructure costs depending on the size and type of the infrastructure.

Table 4-45: Total annualised marginal vehicle capital costs, refuelling infrastructure costs and fuel costs

Vehicle type	Annualised marginal vehicle, refuelling infrastructure and fuel costs relative to conventional petrol/diesel vehicles (€ per year)			
	CNG/LNG		CBM/LBM	
	Low	High	Low	High
Passenger car (CNG/CBM compared to petrol)	€ 56	€ 244	€ 23	€ 211
Passenger car (CNG/CBM compared to diesel)	€ 88	€ 276	€ 55	€ 243
Light commercial vehicle (CNG/CBM compared to diesel)	€ 249	€ 801	€ 153	€ 705
Small rigid truck (CNG/CBM)	€ 1,575	€ 4,245	€ 1,146	€ 3,815
Large rigid truck 26 t (LNG/LBM)	€ 1,289	€ 9,138	€ 3,029	€ 10,877
Articulated truck (>32 t) (LNG/LBM)	€ 3,013	€ 21,456	€ 6,154	€ 24,597
Bus (CNG/CBM)	€ 3,721	€ 10,976	€ 2,313	€ 9,568

Vehicle type	Annualised marginal vehicle, refuelling infrastructure and fuel costs relative to conventional petrol/diesel vehicles (€ per year)			
	CNG/LNG		CBM/LBM	
	Low	High	Low	High
Coach (LNG/LBM)	€ 1,119	€ 7,986	€ 2,790	€ 9,657

The data clearly indicate that once the costs of refuelling infrastructure are taken into account, the total combined costs to vehicle operators and infrastructure providers are, in all cases, higher than for conventional petrol and diesel vehicles. In some cases, the additional annual costs are very significantly higher.

4.4.5 Monetised environmental impacts

4.4.5.1 Methodological approach

The general approach used for monetising the environmental impacts for road vehicles is the same as for shipping, as described in Section 4.3.5.

The annual emissions of key emissions species (NOx, SO_2, PM and GHGs (expressed as CO_2e)) were calculated firstly for conventional vehicles, and then for their methane-fuelled counterparts. Again the environmental externalities are monetised using the latest values from the European Commission's "Update of the Handbook on External Costs of Transport" (Ricardo-AEA, 2014).

To quantify the annual emissions released by a vehicle, the average annual distance travelled (in km) and the emissions factors per km travelled are required. For the shipping sector, a Tier 1 approach was used. This is appropriate for a slowly changing fleet and emissions profile, but ceases to be appropriate for road transport. Instead, a Tier 2 approach is better because this uses average emission factors (per km) for vehicles built to meet different emission standards, but stops short of using speed related emission factors. For the 2020 time horizon, Euro 6 (light duty) and Euro VI (heavy duty) factors should be used for air pollutants. These are taken from EEA/EMEP emissions inventory guidebook for road transport emissions (2014 update), as described in Section 3.3.

4.4.5.2 Monetised environmental impacts for petrol and diesel road vehicles

As for shipping these were calculated by combining data on each vehicle's annual emissions performance with the environmental damage cost per unit mass of emissions. These emission factors (per km), taken from the EMEP EEA emissions inventory guidebook for road transport emissions (2014 update), are tabulated below, in

Table 4-46 for the conventionally fuelled vehicles.

Table 4-46: Emission factors (Tier 2 factors predominantly for Euro 6/VI from EMEP EEA guidebook, 2014)

Vehicle type	Average annual mileage (km)	NO_x (g/km)	SO_2 (mg/km)	PM (mg/km)	CO_2e (g/km)	CH4 (g/km)	N_2O (g/km)
Passenger car (petrol)	13,000	0.059	0.31	1.4	111	0.003	0.0013
Passenger car (diesel)	13,000	0.210	0.46	1.5	84	0.0006	0.004

Vehicle type	Average annual mileage (km)	NO_x (g/km)	SO_2 (mg/km)	PM (mg/km)	CO_2e (g/km)	CH4 (g/km)	N_2O (g/km)
Light commercial vehicle (diesel)	16,000	0.221	0.93	0.9	208.0	0.0006	0.004
Small rigid truck	35,000	0.291	1.91	16.1	426.7	0.030	0.030
Large rigid truck	60,000	0.422	2.99	23.9	666.7	0.090	0.030
Articulated truck	130,000	0.507	3.66	26.8	816	0.09	0.030
Bus	50,000	0.6	4.3	23.1	960	0.03	0.030
Coach	52,000	0.5	3.31	35.4	738.7	0.03	0.030

For greenhouse gases, in addition to the tank-to-wheel (TTW) emissions tabulated above, the well-to-tank (WTT) emissions were also taken into account, drawing in the research from Section 2.2. The WTT factors used for each fuel are presented in the table below.

Table 4-47: Well-to-tank GHG emissions factors for each fuel type

Fuel type	Total WTT GHG emissions ($kgCO_2eq/GJ$ of delivered fuel)		
	Low	Central	High
Petrol	12.20	13.76	18.20
Diesel	13.80	15.34	17.40
CNG	11.80	13.03	19.18
LNG	18.80	19.38	24.62
CBM	9.64	14.58	19.51
LBM	11.47	16.4	21.33

Using all of these datasets, the total annual emissions of air pollutants and greenhouse gases were calculated for each vehicle/fuel type combination.

Environmental damage costs of these main pollutants were taken from the "Update of the Handbook on External Costs" (Ricardo-AEA et al. , 2014). These are given in Table 4-48.

Table 4-48: Damage costs of main pollutants from transport in € per tonne

	External costs (€/tonne)			
	$PM_{2.5}$	NO_x	SO_2	CO_2e
EU Average	70,258[1]	10,640	10,241	90

[1] Suburban figure

The annual environmental external costs for each vehicle type were then calculated using the annual emissions data and unit external cost data. Note that on a per vehicle basis, the annual external damage costs for some pollutants are small, because the actual levels of emissions per vehicle are small. For example, for an urban bus, travelling 50,000 km a year its annual NOx and PM emissions are 30 kg and 1.15 kg, respectively. Given the damage costs above, these convert into annual damage costs of €319 and €81 for NOx and PM emissions respectively.

Table 4-49: Annual damage costs caused by key emissions from the conventional vehicles (central WTT GHG emissions scenario)

Vehicle type	Average annual mileage (km)	NO_x (€/veh/yr)	SO_2 (€/veh/yr)	PM (€/veh/yr)	CO_2e (€/veh/yr)	Total damage costs (€/veh/yr)
Passenger car (petrol)	13,000	€ 8	€ 0.04	€ 1	€ 155	€ 165
Passenger car (diesel)	13,000	€ 29	€ 0.05	€ 1	€ 121	€ 151
Light commercial vehicle (diesel)	16,000	€ 38	€ 0.15	€ 1	€ 364	€ 403
Small rigid truck	35,000	€ 108	€ 0.66	€ 20	€1,655	€ 1,784
Large rigid truck	60,000	€ 269	€ 1.78	€ 50	€4,415	€ 4,737
Articulated truck	130,000	€ 701	€ 5.02	€ 122	€12,398	€ 13,227
Bus	50,000	€ 319	€ 2.14	€ 81	€ 5,269	€ 5,671
Coach	52,000	€ 277	€ 1.71	€ 65	€ 4,226	€ 4,569

The key point from the above table is that the vast majority of the external environmental costs for road transport arise from the GHG emissions. This is because over the past 20 years there have been significant reductions in emissions of air pollutants from road vehicles due to the progressively stringent Euro standards introduced since 1992.

The total annual environmental external costs (taking into account both air pollutants and greenhouse gases) for the different petrol and diesel conventional vehicles are presented in the table below for the three WTT emissions scenarios referred to in Table 4-47.

Table 4-50: Total annual damage costs caused by key emissions from the conventional vehicles for the three WTT GHG emission scenarios

Vehicle type	Average annual mileage (km)	Total damage costs (€/veh/yr)		
		Low	Central	High
Passenger car (petrol)	13,000	€ 162	€ 165	€ 174
Passenger car (diesel)	13,000	€ 149	€ 151	€ 154
Light commercial vehicle (diesel)	16,000	€ 397	€ 403	€ 411
Small rigid truck	35,000	€ 1,755	€ 1,784	€ 1,821
Large rigid truck	60,000	€ 4,661	€ 4,737	€ 4,838
Articulated truck	130,000	€ 13,013	€ 13,227	€ 13,513
Bus	50,000	€ 5,580	€ 5,671	€ 5,793
Coach	52,000	€ 4,496	€ 4,569	€ 4,666

4.4.5.3 Monetised environmental impacts for gas fuelled road vehicles

For the methane-fuelled equivalents of the seven vehicle types described above, changes in the four key emissions were assessed, as described in Sections 2.2.2, 2.2.3 and 3.3.

Relative to the conventional petrol and diesel vehicles where three sets of environmental damage costs were calculated, corresponding to the three WTT GHG emission scenarios, there are twice as many datasets for the methane-fuelled vehicles, depending on whether they are fuelled with natural gas or biomethane. The damage costs analogous to those given for conventional vehicles in Table 4-50 are given in Table 4-51 for natural gas fuelled vehicles and Table 4-52 for biomethane fuelled vehicles.

Table 4-51: Total annual damage costs caused by key emissions from the gas vehicles when fuelled with natural gas for the three WTT GHG emission scenarios

Vehicle type	Average annual mileage (km)	Total damage costs (€/veh/yr)		
		Low	Central	High
Passenger car	13,000	€ 134	€ 136	€ 148
Light commercial vehicle	16,000	€ 396	€ 403	€ 436
Small rigid truck	35,000	€ 1,951	€ 1,981	€ 2,131
Large rigid truck	60,000	€ 5,314	€ 5,352	€ 5,695
Articulated truck	130,000	€ 13,254	€ 13,432	€ 14,048
Bus	50,000	€ 5,821	€ 5,920	€ 6,412
Coach	52,000	€ 5,070	€ 5,107	€ 5,436

Table 4-52: Total annual damage costs caused by key emissions from the gas vehicles when fuelled with bio-methane for the three WTT GHG emission scenarios

Vehicle type	Average annual mileage (km)	Total damage costs (€/veh/yr)		
		Low	Central	High
Passenger car	13,000	€ 28	€ 37	€ 46
Light commercial vehicle	16,000	€ 85	€ 112	€ 139
Small rigid truck	35,000	€ 554	€ 674	€ 795
Large rigid truck	60,000	€ 1,235	€ 1,557	€ 1,879
Articulated truck	130,000	€ 8,155	€ 8,535	€ 8,973
Bus	50,000	€ 1,244	€ 1,640	€ 2,034
Coach	52,000	€ 1,153	€ 1,463	€ 1,772

As can be seen from the above two tables, there are significant differences in damage costs between natural gas powered vehicles and those running on biomethane. These differences are wholly due to the biogenic CO_2 released when biomethane is combusted, which does not contribute to climate change, and hence there are no damage costs associated with these emissions. Again, we stress that biomethane produced from energy crops can contribute to indirect land use change, which can have negative impacts on full fuel-cycle GHG emissions.

Using the above datasets, the marginal environmental external costs of methane-fuelled vehicles compared to conventional petrol and diesel vehicles can be calculated. These data are presented in Table 4-53 and Table 4-54 respectively.

Table 4-53: Marginal total annual damage costs for gas vehicles when fuelled with natural gas relative to the conventionally fuelled comparator vehicles for the three WTT GHG emission scenarios

Vehicle type	Gas comparator vehicle	Total damage costs (€/veh/yr)		
		CO_2e Low	CO_2e Central	CO_2e High
Passenger car (petrol)	Dedicated CNG passenger cars	-€ 28	-€ 29	-€ 26
Passenger car (diesel)	Dedicated CNG passenger cars	-€ 15	-€ 15	-€ 6
Light commercial vehicle (diesel)	Dedicated CNG LCV	€ 0	€ 0	+€ 25
Small rigid truck	Dedicated CNG small rigid truck	+€ 196	+€ 197	+€ 309
Large rigid truck	Dedicated LNG large rigid truck	+€ 654	+€ 615	+€ 856
Articulated truck	Duel fuelled diesel/LNG articulated truck	+€ 241	+€ 206	+€ 534

Vehicle type	Gas comparator vehicle	Total damage costs (€/veh/yr)		
		CO_2e Low	CO_2e Central	CO_2e High
Bus	Dedicated CNG bus	+€ 241	+€ 249	+€ 618
Coach	Dedicated LNG coach	+€ 575	+€ 538	+€ 769

The results in the table above indicates that for passenger cars there are reductions in environmental damage costs associated with a shift from petrol/diesel cars to CNG-powered vehicles, but that for heavy duty vehicles, the environmental damage costs are higher for CNG and LNG vehicles than for conventional diesel vehicles. This is because (a) methane-powered vehicles are less efficient than diesel vehicles and (b) the WTT emissions associated with CNG and LNG are significantly higher than for diesel.

Table 4-54: Marginal total annual damage costs for gas vehicles when fuelled with bio-methane relative to the conventionally fuelled comparator vehicles for the three WTT GHG emission scenarios

Vehicle type	Gas comparator vehicle	Total damage costs (€/veh/yr)		
		CO_2e Low	CO_2e Central	CO_2e High
Passenger car (petrol)	Dedicated CNG passenger cars	-€ 135	-€ 129	-€ 128
Passenger car (diesel)	Dedicated CNG passenger cars	-€ 121	-€ 114	-€ 108
Light commercial vehicle (diesel)	Dedicated CNG LCV	-€ 312	-€ 291	-€ 273
Small rigid truck	Dedicated CNG small rigid truck	-€ 1,201	-€ 1,109	-€ 1,027
Large rigid truck	Dedicated LNG large rigid truck	-€ 3,426	-€ 3,180	-€ 2,959
Articulated truck	Dual-fuelled diesel/LNG articulated truck	-€ 4,857	-€ 4,692	-€ 4,540
Bus	Dedicated CNG bus	-€ 4,336	-€ 4,032	-€ 3,760
Coach	Dedicated LNG coach	-€ 3,343	-€ 3,106	-€ 2,894

All the numbers in the above table are negative, indicating that biomethane fuelled vehicles have lower annual environmental damage costs relative to equivalent petrol/diesel vehicles.

4.4.6 Analysis of total costs and benefits

The findings from the analysis of vehicle capital costs, fuel costs, refuelling infrastructure costs and the external costs of emissions can be combined to estimate the overall annual monetised costs and benefits for each of the seven vehicle types. In this way, we can assess, from an economic perspective, whether shifting to methane-fuelled vehicles generates net costs or net benefits to society. The analysis has been carried out separately for (a) natural gas and (b) biomethane and in each case we present total monetised costs and benefits for low and high estimates of refuelling infrastructure costs and for the three different scenarios on WTT GHG emissions performance. Table 4-55 and Table 4-56 present the results of this analysis for natural gas whilst Table 4-57 and Table 4-58 present the results for biomethane. Positive costs indicate that there are net additional costs to society associated with shifting from conventional petrol/diesel vehicles to methane-fuelled vehicles, whilst negative costs indicate that there are net benefits to society.

Table 4-55: Total annual marginal costs to society caused by replacing a conventionally fuelled vehicle with a natural gas fuelled vehicle for seven different road transport vehicle types (LOW refuelling infrastructure costs scenario)

Vehicle type	Gas comparator vehicle	Total marginal costs (€ per vehicle per year) LOW refuelling infrastructure costs		
		Low	Central	High
Passenger car (petrol)	Dedicated methane passenger car vs petrol passenger car	+€ 27	+€ 27	+€ 30
Passenger car (diesel)	Dedicated methane passenger car vs diesel passenger car	+€ 73	+€ 73	+€ 82
Light commercial vehicle (diesel)	Dedicated methane LCV vs diesel LCV	+€ 249	+€ 249	+€ 274
Small rigid truck	Dedicated small rigid truck vs diesel truck	+€ 2,227	+€ 2,228	+€ 2,341
Large rigid truck 26 t	Dedicated large rigid truck vs diesel truck	+€ 1,942	+€ 1,904	+€ 2,145
Articulated truck (>32 t)	Duel-fuel articulated truck vs diesel truck	+€ 3,254	+€ 3,219	+€ 3,548
Bus	Dedicated methane bus vs diesel bus	+€ 3,963	+€ 3,970	+€ 4,340
Coach	Dedicated methane coach vs diesel coach	+€ 1,694	+€ 1,657	+€ 1,889

Table 4-56: Total annual marginal costs to society caused by replacing a conventionally fuelled vehicle with a natural gas fuelled vehicle for seven different road transport vehicle types (HIGH refuelling infrastructure costs scenario)

Vehicle type	Gas comparator vehicle	Total marginal costs (€ per vehicle per year) HIGH refuelling infrastructure costs		
		Low	Central	High
Passenger car (petrol)	Dedicated methane passenger car vs petrol passenger car	+€ 216	+€ 215	+€ 218
Passenger car (diesel)	Dedicated methane passenger car vs diesel passenger car	+€ 261	+€ 262	+€ 270
Light commercial vehicle (diesel)	Dedicated methane LCV vs diesel LCV	+€ 800	+€ 801	+€ 826
Small rigid truck	Dedicated small rigid truck vs diesel truck	+€ 4,701	+€ 4,703	+€ 4,815
Large rigid truck 26 t	Dedicated large rigid truck vs diesel truck	+€ 9,094	+€ 9,056	+€ 9,296
Articulated truck (>32 t)	Duel-fuel articulated truck vs diesel truck	+€ 21,697	+€ 21,662	+€ 21,991
Bus	Dedicated methane bus vs diesel bus	+€ 12,071	+€ 12,078	+€ 12,448
Coach	Dedicated methane coach vs diesel coach	+€ 8,561	+€ 8,525	+€ 8,756

Table 4-57: Total annual marginal costs to society caused by replacing a conventionally fuelled vehicle with a biomethane fuelled vehicle for seven different road transport vehicle types (LOW refuelling infrastructure costs scenario)

Vehicle type	Gas comparator vehicle	Total marginal costs (€ per vehicle per year) LOW refuelling infrastructure costs		
		Low	Central	High
Passenger car (petrol)	Dedicated methane passenger car vs petrol passenger car	+€ 134	+€ 141	+€ 142
Passenger car (diesel)	Dedicated methane passenger car vs diesel passenger car	-€ 45	-€ 38	-€ 31
Light commercial vehicle (diesel)	Dedicated methane LCV vs diesel LCV	-€ 35	-€ 14	+€ 4
Small rigid truck	Dedicated small rigid truck vs diesel truck	+€ 952	+€ 1,044	+€ 1,127
Large rigid truck 26 t	Dedicated large rigid truck vs diesel truck	-€ 2,696	-€ 2,450	-€ 2,229
Articulated truck (>32 t)	Duel-fuel articulated truck vs diesel truck	-€ 3,454	-€ 3,289	-€ 3,137
Bus	Dedicated methane bus vs diesel bus	-€ 688	-€ 384	-€ 112
Coach	Dedicated methane coach vs diesel coach	-€ 2,760	-€ 2,523	-€ 2,312

Table 4-58: Total annual marginal costs to society caused by replacing a conventionally fuelled vehicle with a biomethane fuelled vehicle for seven different road transport vehicle types (HIGH refuelling infrastructure costs scenario)

Vehicle type	Gas comparator vehicle	Total marginal costs (€ per vehicle per year) HIGH refuelling infrastructure costs		
		Low	Central	High
Passenger car (petrol)	Dedicated methane passenger car vs petrol passenger car	+€ 323	+€ 329	+€ 330
Passenger car (diesel)	Dedicated methane passenger car vs diesel passenger car	+€ 144	+€ 151	+€ 157
Light commercial vehicle (diesel)	Dedicated methane LCV vs diesel LCV	+€ 516	+€ 537	+€ 555
Small rigid truck	Dedicated small rigid truck vs diesel truck	+€ 3,427	+€ 3,519	+€ 3,601
Large rigid truck 26 t	Dedicated large rigid truck vs diesel truck	+€ 4,456	+€ 4,702	+€ 4,922
Articulated truck (>32 t)	Duel-fuel articulated truck vs diesel truck	+€ 14,989	+€ 15,154	+€ 15,306
Bus	Dedicated methane bus vs diesel bus	+€ 7,421	+€ 7,724	+€ 7,997
Coach	Dedicated methane coach vs diesel coach	+€ 4,107	+€ 4,344	+€ 4,556

For all natural gas powered vehicles, the net costs to society are greater than for conventional petrol or diesel vehicles regardless of whether it is assumed that refuelling infrastructure costs are low or high (low infrastructure costs relate to high capacity infrastructure). Whilst there are additional costs to society for all vehicle types, the additional costs are particularly large for heavy duty vehicles. Additional annual costs for cars and light commercial vehicles are much lower than for other vehicle types.

If we assume that refuelling infrastructure costs are high (i.e. low capacity infrastructure and/or L-CNG facilities where appropriate), then the net costs to society associated with natural gas vehicles are potentially very high. In the worst cases, total costs to society for natural gas powered large rigid trucks are more than €9,000 per year higher than for equivalent diesel trucks, more than €21,000 per year higher for articulated trucks, more than €12,000 per year higher for buses and more than €8,000 per year higher for coaches.

For vehicles fuelled with biomethane, the situation is also highly dependent on assumptions around refuelling infrastructure costs, but if these costs are assumed to be low (i.e. we assume that high capacity refuelling infrastructure is in place) then there are potentially significant net benefits for some vehicle types. For large rigid trucks, articulated trucks and coaches, net benefits of between €2,229 per year and €3,454 per year are possible compared to conventional diesel vehicles, depending on vehicle type and WTT emissions scenario. For diesel cars, LCVs and buses, there are also net benefits, but these are much smaller. By contrast, if the infrastructure costs are assumed to be high, then total costs to society associated with biomethane-fuelled vehicles are higher than for conventional petrol/diesel vehicles for all vehicle types and under all WTT emissions scenarios.

The difference in total societal costs between natural gas and biomethane is due to the fact that as a renewable fuel, the tailpipe CO_2 emissions released on combustion of biomethane are treated as biogenic emissions which do not contribute to climate change. Consequently, these emissions do not incur any damage costs. As the CO_2 emissions from fuel combustion dominate the environmental external costs for all road vehicles, removing these costs has the effect of making biomethane more attractive from the point of view of reducing total costs to society. However, we reiterate that biomethane produced from energy crops can contribute to indirect land use change, which can have negative impacts on full fuel-cycle GHG emissions.

In summary, the economic analysis shows that for all vehicle types, there are no economic benefits to society associated with using fossil-based natural gas in the road transport sector instead of conventional petrol or diesel. For biomethane, there are potentially significant net economic benefits to society for some vehicle types, but only if the refuelling infrastructure costs are assumed to be low. If the refuelling infrastructure costs are assumed to be high, there are no net economic benefits to society associated with using biomethane in the transport sector.

5 Biomethane resource availability

5.1 Overview

Biomethane is produced by removing impurities from biogas. The term biogas usually refers to a mixture if gases that are formed when organic materials break down in the absence of oxygen, and anaerobic digestion is one of the main production routes for this fuel. Biogas comprises methane, CO_2, hydrogen sulphide and may also contain siloxanes and moisture. Biogas can be used for power and/or heat generation. In particular, it can be used in generators and in combined heat and power (CHP) systems. However, raw biogas cannot be used in road vehicles without removing the non-methane components as these are not compatible with modern engine and vehicle exhaust after-treatment technologies. Hence, the need to process biogas to remove these impurities, thereby producing biomethane.

The use of biomethane has a number of benefits when compared to natural gas. In particular, there are significant well-to-wheel GHG emissions benefits, and the use of biomethane can help reduce EU countries' reliance on imports of natural gas. However, current resources of biomethane are limited and there is strong competition from the heat and power sectors for these limited resources. This chapter considers (a) the sources of biogas and biomethane (including future production potentials and supply); and (b) competition for the use of biomethane from other sectors.

In the literature reviewed for this task, there are a variety of different units used. In this study we cite the value as given in the reference documents, but for comparison and consistency adopt the unit of millions of tonnes of oil equivalence, Mtoe, because this is the unit used in International Energy Agency (IEA) publications. The conversion factors used are given in the box below.

Box 5-1: Energy conversion factors for methane

1 PJ = 0.023885 Mtoe

For methane, 1.0 billion m3 (bcm) = 35.17 PJ = 0.840 Mtoe

For biogas, 1.0 billion m3 (bcm) = 19 PJ = 0.454 Mtoe

cm = billion cubic metres

5.2 Sources of biogas and biomethane

The main sources of biogas and biomethane are landfill gas and anaerobic digestion (AD) plants (including crops, domestic food waste; commercial and industrial waste; and agricultural materials and sewage sludge digestion). At this point in time, the majority of biogas and biomethane fuels in the EU are produced from crops rather than waste materials, although a number of countries in Europe have, or are planning to introduce measures to reduce or restrict biogas produced from energy crops. The CO_2 emissions released on combustion of biogas and biomethane produced from energy crops are not considered to contribute to climate change because they are part of the short-term carbon cycle (i.e. the CO_2 emitted on combustion was absorbed from the atmosphere up to around one year earlier). However, energy crops can potentially lead to undesirable environmental impacts such and indirect land use change, putting pressure on the amount of land available for growing food crops. Furthermore, it is also possible to produce biomethane from wood which could have net impacts on climate change in terms of CO_2 emissions released on combustion of the resulting biomethane, as wood is not part of the short-term carbon cycle. With respect to waste-derived biogas and biomethane, as EU Member States move towards more sustainable and efficient practices of waste management, landfill gas production will slowly decline, reducing its availability as a resource. Therefore anaerobic digestion will be the primary source of biomethane. This section considers the EU production and consumption of biogas and biomethane; domestic EU biogas supply (including its potential and threats); and EU imports of natural gas.

5.2.1 EU production and consumption of biogas and biomethane

The number of production plants for biogas and biomethane is increasing in the EU (see Table 5-1). In 2013, the number of plants stood at 14,563 and 282 respectively (EurObserv'ER, 2014). In line with the increasing amounts of installed production capacity[11], the amount of biogas and biomethane being produced in the EU is also increasing. Production increased by 10.2% in 2013 compared to 2012 to just under 13.4 Mtoe of biogas. The majority of this biogas was produced in Germany (>50%), followed by the UK and Italy (<14% each). EurObserv'ER also provides high-level information on the feedstocks and processes used to produce biogas in the EU, classifying three main production routes: (a) landfill gas, (b) sewage sludge gas and (c) “other” biogas. Other biogas comprises decentralised agricultural plant, municipal solid waste methanisation plants, centralised co-digestion plant, and it is this group or processes that currently dominates biogas production in the EU. In 2013, 69% of biogas production was produced via these “other” biogas processes, and information from the European Biogas Association indicates that 55% of all biogas produced in the EU in 2013 was derived from agricultural crops. However, whilst other biogas processes are the main production routes for the EU as a whole, different processes can dominate in different countries. Other biogas routes are dominant in Germany, Italy, Austria and the Czech Republic; these are all countries that have a well-developed industrial methanisation sector. In other countries such as the UK, France, Portugal, Ireland and Spain, landfill gas is the main source of biogas. Information on biogas and biomethane production capacity as well as biogas and biomethane production levels for 2012 and 2013 are presented in Table 5-1.

Table 5-1: EU production of biogas and biomethane

Year	No of biogas plants	Installed capacity (GW)	Biogas production (Mtoe)	No of biomethane plants	Biomethane production (Mtoe)
2012	13,800	7.4	12.14		
2013	14,563	7.86	13.38	282	1.09 Mtoe (1.303 bcm)

Source: (EurObserv'ER, 2014)

As can be seen from the table, in 2013 13.38 Mtoe of biogas and 1.09 Mtoe of biomethane were produced. To put these figures into context, the gross inland energy consumption for the EU28 in 2013 was 1,666 Mtoe (European Commission, 2015). The production of biogas and biomethane in the EU was therefore 0.80%, and 0.07% of total EU energy consumption respectively. In the same year, consumption of natural gas (methane) was 386.9 Mtoe (European Commission, 2015), meaning that biomethane produced in the EU accounted for 0.29% of total methane consumption.

5.2.2 Domestic EU biogas supply, its potential and trends

Current and future (2020) biofuel production potential estimates from a variety of sources were collated and presented in a 2014 study for the UK Department for Transport (E4Tech, 2014). A summary of the data for the feedstocks which produce biogas is shown in Table 5-2. The table also indicates whether any expansion in production is likely after 2020, i.e. whether each feedstock supply potential is expected to increase significantly between now and 2030 (↑), whether it is close to a maximum/not expected to expand further (↔), or if it is likely to decrease between now and 2030 (↓).

[11] There was an increase of 6.2% installed capacity between 2012 and 2013.

Table 5-2: Summary of biogas production potentials (i.e. without conversion plant capacity constraints)*

	Data quality	Current biogas production potential (PJ/year)	2020 biogas production potential (PJ/year)	Estimated expansion post 2020 (to 2030)
Bio-fraction of MSW	Medium	491	460	↓
Bio-fraction of C&I waste	Medium	460	359	↔
Animal manure	Medium	969	853	↑
Sewage sludge	High	161	165	↑
Macro-algae	High	0	0.24	↑↑↑
Total		2,081 PJ/year 49.7 Mtoe/year	1,837 PJ/year 43.9 Mtoe/year	

* Before any competing uses for the feedstocks are considered

Source: (E4Tech, 2014)

The reasons behind some of the expected trends for particular feedstocks are not always made clear in the source literature. For example, the production potential for animal manure is projected to decrease between now and 2020, but between 2020 and 2030, it is projected to increase. However, based on these datasets, it appears that between now and 2020, Europe biogas production potential will decrease 12%. It should also be noted that for some biogas feedstocks, there is very significant competition from the heat and power sectors. In particular, both animal manures and sewage sludge are in high demand in these sectors, and this is likely to continue in future years.

The above figures indicate the production **potentials** for biogas, both now and in the future (i.e. the figures take into account feedstock supply and the availability of production facilities); they do not reflect actual levels of production. By contrast to the above figures, it has been estimated that the level of biogas production expected in 2020, as set out in EU Member States' National Renewable Energy Action Plans is expected to double from 2012 production levels of 12 Mtoe to about 23.5 Mtoe (28 bcm/year) in 2020 (European Biogas Association, 2015). It is worth noting that alternative more optimistic scenarios also exist. For example, the European Biomass Organisation estimate 40 Mtoe/year (48 bcm/year) biomass production by 2020, whereas the Institute for Energy and Environment estimates production could be as high as 168 Mtoe/year (200 bcm/year) (Oxford Institute for Energy Studies, 2012), which is significantly higher than the E4tech projection for production potential. However, the achievement of these alternative scenarios depends on a number of factors, including the availability of continued financial support for the development of biogas and biomethane production facilities; and the effect of competition on cultivated land between biomass production and food and feed production and deforestation.

5.2.3 EU imports of natural gas

The IEA projects that overall EU demand for natural gas will increase to 412 Mtoe (491 bcm) in 2020 and to 443.5 Mtoe (528 bcm) in 2030 (IEA, 2015). The EU currently relies heavily on imports of natural gas. In 2013, imports of natural gas from non-EU countries totalled 309 Mtoe[12] representing 80% of all EU gas consumption, (European Commission, 2015) an increase of 2% from 2012 (see Table 5-3). 39% of imports are from Russia, and a further 29.5% of imports are from Norway.

[12] 12,408,433 TJ (GCV)

Table 5-3: EU Imports of Natural Gas – 2013 (from non-EU suppliers)

Import country of origin (non-EU)	Volume of gas imported		Percentage (%) of gross final energy consumption
	Mtoe	TJ (GCV)	
Russia	115.6	4,840,727	39%
Norway	87.6	3,665,682	29.5%
Algeria	38.0	1,593,028	12.8%
Not specified	19.9	831,925	6.7%
Qatar	19.8	828,946	6.7%
Nigeria	5.3	223,039	1.8%
Libya	5.2	217,361	1.8%
Trinidad and Tobago	2.3	94,606	0.8%
Other non-EU suppliers	15.5	648,125	0.9%
Total imports	**309.2**	**12,408,433**	**100%**

Source: Derived from (European Commission, 2015)

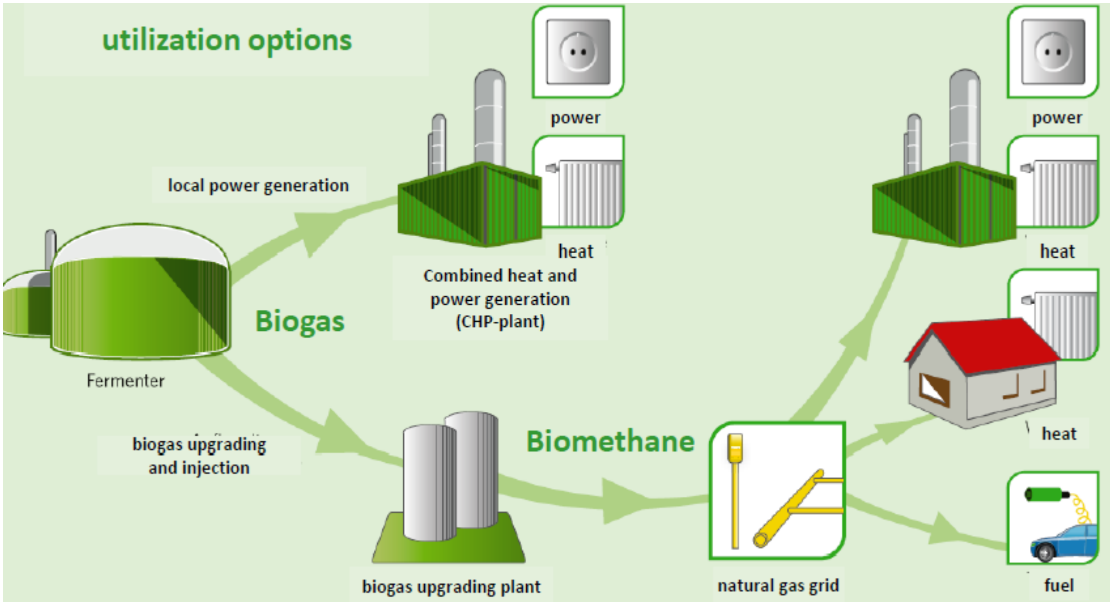
We can compare the current and projected levels of demand for natural gas with projections for biomethane production potentials and estimated levels of future supply discussed in Section 5.2.2. Given that the maximum production potential for biomethane is projected to be 43.9 Mtoe by 2020 (E4Tech, 2014), it is clear that biomethane could make a useful contribution to reducing the EU's reliance on imports of natural gas. The 2020 production potential for biomethane equates to 11% of total 2020 EU projected demand for natural gas and 13% of projected imports (assuming that imports remain at 80% of total demand in 2020). If Russian imports of natural gas were to remain at 39% of total EU imports in 2020, this would equate to 161 Mtoe. Increasing biogas production from 13.4 Mtoe (2013 levels) to 43.9 Mtoe would potentially allow the EU to reduce its natural gas imports from Russia (or elsewhere) by up to 30.5 Mtoe – equal to 19% of possible 2020 Russian imports. However, if by 2020 there is considerable extra demand for natural gas in the EU's transport sector, then potentially the percentage reduction in Russian imports of natural gas would be lower. Furthermore, if all of the potential future 2020 biogas production (i.e. 43.9 Mtoe) was used in the road transport sector, this would only account for around 15% of total energy demand based on 2013 total road transport energy demand of 285 Mtoe (European Commission, 2015).

The EU's total demand for natural gas is not spread evenly across its Member States; six countries are responsible for 75% of total EU28 gas demand (E3G, 2015), and all six of these countries (Germany, UK, France, Italy, Netherlands and Spain) are in Western Europe. However, not all of these countries are major importers of natural gas from Russia; in particular, UK and Spanish imports of Russian gas are close to 0% of total national gas demand. By contrast, 46% of Germany's and 34% of Italy's demand for gas are met by Russian imports (the figures for France and the Netherlands are 18% and 5% respectively) (E3G, 2015). Consequently, the location of any future biogas production facilities is also important in determining the extent to which Russian imports of natural gas could be reduced in future years.

5.3 Competition for biomethane from other sectors

There are a number of uses for biogas and biomethane (see Figure 5-1). Biogas can be used in local power generation, or it can be upgraded (by the removal of impurities, e.g. nitrogen, carbon dioxide, sulphur compounds etc) to produce biomethane which can then be injected into the gas grid and subsequently used in the heat, power or transport sectors. The choice as to which sector will benefit most from the use of biomethane depends on commercial and logistical factors, i.e. which outlet brings the higher return, and the location of the biomethane facility relative to the gas grid or transport refuelling infrastructure.

Figure 5-1: Utilisation options for biogas (including biomethane)



Source: (AEE, 2013)

At the EU level there is a binding target to achieve 20% final energy consumption from renewable sources by 2020, as set by the Renewable Energy Directive. Each EU Member State has committed to reaching their own national renewables target in order to achieve this. Member States are also each required to have at least 10% of their transport fuels come from renewable sources by 2020.

The use of biomethane often relies on relatively high subsidies, and individual countries determine the levels of subsidies that apply. This support can vary substantially from country to country. Power supply in Sweden (and Switzerland) can be almost completely covered by hydroelectric and nuclear power, negating the need to incentivise biomethane use to generate electricity from the climate and energy policy perspectives. The focus is therefore on biomethane as a fuel to reduce transport sector dependence on imports of oil and natural gas based fuels (Grope, 2012).

However, this is not the case in all other EU Member States. In the UK, incentives available include the Renewable Heat Incentive (RHI), which provides a fixed income (per kWh) to generators of renewable heat, and producers of renewable biogas and biomethane[13]. Incentives do exist in the transport sector under the Renewable Transport Fuel Obligation (RTFO), which requires suppliers of fossil fuels to ensure that a specified percentage of road fuel that they supply in the UK is made up of renewable fuels. Renewable Transport Fuel Certificates (RTFCs) can be claimed for every litre of sustainable fuel supplied, or in the case of biogas, every kilogram of biomethane supplied. Suppliers can then meet their obligation by redeeming these certificates (or by paying a fixed sum for each litre of fuel for which they wish to buy-out) (DfT, 2015). However, the reward per kWh is much lower for biomethane used in the transport sector compared to that offered under other incentives including the RHI. This means that there is currently little incentive to use biomethane in the UK's transport sector.

Like the UK, the focus on subsidies and incentives for biomethane use in Germany is primarily on combined heat and power (CHP), rather than the transport sector. The main legislation/incentive driving the uptake and use of biomethane in Germany is the Renewable Energy Act (EEG), which enables electricity generated from biomethane (in CHP) to receive feed-in tariffs guaranteed for 20 years (Grope, 2012). There is also the Renewable Energy Heat Act ("Erneuerbare-Energien-Wärmegesetz" - EEWärmeG) whereby the use of biomethane in CHP for pure heat supply is incentivised, specifying the pro rata use of renewable energy for the supply of heat in new buildings and existing public buildings. For the transport sector, the Biofuel Quota Act (BiokraftQuG) aims to increase the share of biofuels,

[13] Ranges from 2.2 to 7.5 pence/kWh

and currently allows biomethane to be used to fulfil the quota. However, other obstacles exist relating to the uptake and use of biomethane in German transport sector, including limited number of gas vehicles/filling infrastructure, and a political focus on electric vehicles (Grope, 2012). Furthermore, for use in the transport sector, biogas has to be upgraded to remove impurities and convert it into biomethane, whereas there are opportunities for using biogas without the need to upgrade it for local power generation.

It is clear that the main competition for biomethane use comes from the heat and power sectors in Europe where the highest financial incentives exist; there is currently less incentive for economic operators to pursue biomethane use in the transport sector.

5.4 Summary

The EU is a world leader in the production of biogas, producing around 13.4 Mtoe in 2013, a 10.2% increase from 2012 production. This was produced from a number of feedstocks, including crops, landfill gas, the bio-fraction of municipal and C&I solid waste, from animal manure and from sewage sludge ((EurObserv'ER, 2014).

In 2013 Europe produced 1.1 Mtoe of biomethane. This biomethane production was around 0.29% of Europe's total methane consumption (387 Mtoe). Therefore, there is a clear market if higher volumes of biomethane were produced. However, the cost of producing biomethane is currently a barrier to increasing its supply as it is significantly more expensive to produce than natural gas. Incentives and subsidies exist to support the production and supply of biomethane in many EU Member States, but in the main, these are currently more favourable to producers who supply the heat and power sectors, meaning that it is often not economically viable to produce biomethane for the transport sector. In order to make biomethane more attractive as a fuel for the transport sector, it would be necessary for the incentives and subsidies available to be equivalent to those available to producers supplying biogas/biomethane to the heat and power sectors. Without additional support of this nature, it is unlikely that biomethane will be adopted to any significant extent in the transport sector. It should be noted that in addition to the organic waste-derived biomethane considered in this study, this fuel can also be produced from energy crops and potentially from wood. Whilst the CO_2 emissions released on combustion of biomethane produced from energy crops would not be considered to contribute to climate change, because these emissions are part of the short-term carbon cycle, the issue of CO_2 emissions from combustion of wood-derived biomethane is less clear-cut as forestry resources are not part of the short-term carbon cycle. Furthermore, energy crops can lead to other undesirable environmental impacts such as indirect land use change.

The EU currently relies heavily on imports of natural gas in order to meet its increasing demand for gas. This dependence on imports was nearly 80% in 2013, with 39% of that coming from Russia, and a further 29% from Norway. It is anticipated that total gas consumption in Europe will continue to increase between now and 2020, in line with projected increases in demand. However, by increasing the production and supply of biogas and biomethane in the EU, it would be possible to reduce the levels of natural gas imported into Europe, depending on the locations of any future biogas production plants. Based on estimates for 2020 production potential for biogas, in theory it could be possible to reduce the EU's imports of natural gas by 30.5 Mtoe, which would equate to 19% of projected future natural gas imports from Russia. However, if there is additional demand for natural gas from the transport sector between now and 2020, the potential reductions in gas imports from Russia could be lower.

6 Conclusions and recommendations

6.1 Overview

In this study we have investigated the role that natural gas and biomethane can play as fuels in the transport sector. We have examined the well-to-wheels emissions impacts of these fuels, taking into account different production routes and end uses, and we have also assessed the air pollution impacts of using methane in the transport sector. Bringing the outputs from all of this research together, along with information on capital and operating costs, we have carried out an economic analysis to quantify the costs and benefits to society of using natural gas and biomethane in the transport sector compared to conventional oil-based fossil fuels. Finally, we have also assessed the current and future availability of biogas/biomethane resources, including analysing the potential for these fuels to displace future imports of natural gas.

In the following sections, we summarise the findings of the study and make recommendations based on these findings.

6.2 Impacts on greenhouse gas emissions

From the analysis we have carried out, there is some potential for reducing GHG emissions from the transport sector through the use of natural gas and biomethane, but any reductions achieved are very sensitive to assumptions on (a) well-to-tank GHG emissions associated with the production of these fuels (including levels of methane leakage during production/distribution) and (b) the levels of methane slip that occur when the fuel is used in road transport or shipping.

For the shipping sector, well-to-wake greenhouse gas emissions are highly dependent on the levels of methane slip emissions that are assumed to occur during vessel operation. In this study, we have assumed two rates of methane slip: 1.8% and 3.5%. If methane slip occurs at a rate of 1.8%, then the well-to-wake GHG emissions associated with LNG ships are between 1% and 10% lower than for equivalent MGO and HFO-fuelled ships. However, if methane slip emissions are assumed to occur at a rate of 3.5% then in most cases, total well-to-wake emissions are higher for LNG ships than for MGO and HFO ships (between 0.3% and 9% higher, depending on the specific assumptions used for WTT emissions). These findings indicate that in the best-case scenario LNG may only give relatively marginal GHG emissions benefits compared to conventional marine fuels, and that these benefits can be completely wiped out of the levels of methane slip are high. However, there are best-practice techniques that can be applied to reduce both upstream methane leakage emissions associated with LNG production/distribution and downstream methane slip emissions associated with vessel operations that can significantly improve total well-to-wake emissions performance. If such techniques are applied, the overall well-to-wake GHG emissions performance for LNG could be between 12% and 27% better than conventional marine fuels. Wider research (Thomson, Corbett, & Winebrake, 2015) has shown that the overall long-term impacts of a fleet-wide shift to LNG could be significant in terms of the length of time it might take for LNG vessels to achieve climate neutrality compared to conventional vessels powered by HFO and MGO. This research found that using LNG as a fuel for the shipping sector could achieve climate neutrality within 30 years for ships powered by compression ignition, dual-fuel LNG engines, but that for mono-fuel spark ignition LNG ships, it could take up to 190 years to achieve climate parity with conventional marine fuels.

In the road transport sector, there are no WTW greenhouse gas emissions benefits associated with replacing diesel vehicles with natural gas vehicles; in each case, the WTW emissions are higher for natural gas vehicles, particularly once methane slip emissions are taken into account. However, there are emissions benefits associated with replacing a petrol car with a CNG-powered car (although these emissions benefits would not occur if comparing a CNG car with a hybrid petrol-electric car). For biomethane, the situation is different. In this study we considered biomethane produced from landfill gas and from anaerobic digestion of organic wastes. The biogenic nature of the carbon in biomethane from these sources means that tailpipe emissions of CO_2 from the combustion of this fuel are officially reported as zero and hence there are significant WTW emissions reductions associated with using this fuel in place of petrol and diesel for all vehicles types. These reductions range from 39% for dual-fuel articulated trucks to 88% for cars under the low WTT emissions scenario. WTW emissions savings are lower under the central and high WTT emissions scenarios, but still very significant (reductions of 35% for dual fuel articulated trucks (compared to diesel) and 78% for cars (compared to petrol) under the high WTT emissions scenario. However, it should be noted that in addition to the organic waste-derived biomethane considered in this study, this fuel can also be produced from energy crops and potentially from wood. Whilst the CO_2 emissions released on combustion of biomethane produced from energy crops would not be considered to contribute to climate change, because these emissions are part of the short-term carbon cycle, the issue of CO_2 emissions from combustion of wood-derived biomethane is less clear-cut as forestry resources are not part of the short-term carbon cycle. Furthermore, energy crops can lead to other undesirable environmental impacts such as indirect land use change.

For both biomethane and CNG, it is necessary to account for the methane leakage and methane slip emissions. Evidence gathered during this study indicates that there is a high level of uncertainty in the amount of methane leakage that occurs during the natural gas production process. Studies indicate that leakage rates could be as low as 1% or as high as 9%; the uncertainty relates to the different approaches used to quantify methane leakage and the limitations associated with each of these approaches. Methane slip emissions occur during vehicle use and relate to emissions released from the engine crankcase or via the exhaust tailpipe. Studies indicate that methane slip emissions as low as 1% from natural gas powered vehicles could completely offset any TTW tailpipe GHG benefits associated with this fuel.

6.3 Air pollution impacts

With respect to air pollution, our analysis has shown that shifting to LNG would have very significant benefits in the shipping sector in terms of reducing emissions of NOx, SO_2 and particulate matter. Using LNG in a dual-fuel engine ship would reduce emissions of NOx by at least 84%, emissions of SO_2 by at least 90% and emissions of PM by at least 96% compared to either HFO or MGO. From this perspective alone, there are sound environmental reasons for using LNG in the shipping sector in place of conventional marine bunker fuels.

For the road transport sector, the picture is very different, primarily because much action has already been taken to reduce emissions of air pollutants from road vehicles. Since 1992, the Euro standards for light duty and heavy duty vehicles have dramatically reduced emissions of NOx and PM, and fuel quality standards mean that all road vehicles already use ultra-low sulphur fuels with a maximum sulphur content of 10 ppm. These factors mean that shifting to natural gas or biomethane in the road transport sector does not yield any tangible emissions benefits. In particular, the one area where road transport emissions are still a problem relates to NOx and NO_2 emissions. Many areas across the EU are struggling to comply with existing European legislation on NO_2 pollutant concentrations. These air quality problems are primarily due to emissions of NOx from road transport; however, the evidence gathered during this study indicates that there would be no reduction in NOx emissions associated with switching from diesel to natural gas or biomethane for heavy-duty road vehicles, but that there would be reductions associated with switching from diesel cars to CNG or CBM-fuelled cars. Overall, the impacts on air pollution associated with switching to methane-fuelled vehicles are small, but not insignificant. However, it would not be possible to justify a switch to natural gas or biomethane in the road transport sector on air quality grounds.

6.4 Economic analysis

The analysis of net costs and benefits indicates that for the shipping sector there are potentially large economic benefits to society associated with using LNG-fuelled ships in place of either HFO-fuelled ships equipped with exhaust gas scrubbers or in place of MGO-fuelled ships. These benefits are mainly due to the very significant reductions in air pollutant emissions associated with shifting to LNG. Even at today's (November 2015) very low fuel prices, there are still net economic benefits ranging from societal cost savings of between €0.74 million and €2.64 million per vessel per year for ships operating in the North Sea. However, for vessels operating in the North East Atlantic, total costs to society would be higher for LNG ships compared to HFO and MGO-fuelled vessels at today's fuel prices.

For road transport, there are no economic benefits associated with shifting from petrol or diesel to fossil natural gas. For all vehicle types, the total costs to society are higher for natural gas powered vehicles than for conventional vehicles, and hence from a societal perspective it does not make sense to encourage the use of this fuel. However, the situation for biomethane is very different, and for all types of road vehicles, there can be very significant net economic benefits to society compared to equivalent petrol and diesel vehicles (these benefits are dependent on assumptions with respect to the cost of refuelling infrastructure). The key difference between natural gas and biomethane is the fact that the CO_2 emissions released on combustion of the fuel are biogenic in nature for biomethane produced from waste organic materials and from energy crops. This means that these CO_2 emissions do not contribute to climate change and consequently, the environmental external costs of these emissions are zero. However, we stress that biomethane produced from energy crops can contribute to indirect land use change, which can have negative impacts on full fuel-cycle GHG emissions. Given that the CO_2 emissions associated with fuel combustion dominate the environmental external costs of road vehicles, the use of waste-derived biomethane in this sector could play an important role in helping to reduce the impacts of road transport on climate change. However, we stress that it is possible for biomethane to be produced from non-biogenic resources, or from organic sources that are not part of the short-term carbon cycle, where the combustion CO_2 emissions would contribute to climate change.

6.5 Biogas and biomethane resource availability

Our analysis indicates that there is significant potential to increase production levels of biogas and biomethane in future years, and any increase in production levels will help to improve the EU's energy security by reducing the region's reliance on imports of natural gas. Whilst increases in biogas and biomethane production cannot completely displace the need for gas imports, our analysis indicates that by 2020 it could be possible to reduce the EU's imports of natural gas by 30.5 Mtoe, which would equate to 19% of projected 2020 natural gas imports from Russia into the EU. However, if there is additional EU demand for natural gas to support the transport sector, then reductions in 2020 natural gas imports could be lower than this. Furthermore, the extent to which Russian natural gas imports would reduce depends on which countries any new biogas production facilities are located in. For example, Germany and Italy import significant natural gas from Russia to meet 46% and 34% respectively of their total demand. By contrast, imports from Russia to the UK and Spain are very low.

Competition for biogas and biomethane from the heat and power sectors is a significant issue now likely to continue in future years, and means that at the moment, the resources available for the transport sector are very limited. In particular, the incentives and subsidies available in a number of EU Member States favour the use of biogas and biomethane in the heat and power sectors, and hence it is not economically attractive for producers to supply biomethane to the transport sector.

6.6 Recommendations

Based on the analysis that we have carried out in this study and our findings, there are a number of key recommendations:

- There are clear air pollution benefits associated with using LNG in the shipping sector, but any GHG emissions benefits are highly dependent on the well-to-tank emissions performance associated with LNG production and distribution processes (including levels of upstream methane leakage), and also on the levels of methane slip emissions released during vessel operation. Further research may be required to more fully understand (a) the overall environmental impacts of shifting from conventional marine fuels to LNG and (b) the techniques that can be applied to control upstream and downstream methane leakage.
- For the road transport sector, the use of fossil-based natural gas does not generate net environmental benefits, primarily because in most cases there are no reductions in WTW greenhouse gas emissions and any reductions in air pollutant emissions are very limited. Furthermore, it is clear that methane leakage emissions can significantly erode the GHG

emissions benefits associated with natural gas compared to petrol and diesel. Given that our analysis of net costs and benefits to society indicates that societal costs would be higher with natural gas, it is difficult to justify supporting the use of this fuel in the road transport sector.

- Given that very small amounts of methane slip emissions from the engine crankcase and the exhaust tailpipe during vehicle use can completely offset the tailpipe GHG reductions associated with natural gas, further efforts to control methane slip may be required. In particular, it may be necessary to introduce more stringent regulations on the levels of methane emissions that road vehicles can release.
- It is also clear that increased use of biogas and biomethane can help to reduce the EU's reliance on imports of natural gas. It may therefore be appropriate to provide additional support to encourage the development of new production capacity for biomethane in the coming years. However, consideration needs to be given to the production routes used to generate biogas and biomethane. There are sustainability issues associated with crop-derived biogas and biomethane, including issues related to indirect land use change. It may be appropriate to introduce measures to disincentivise or restrict the production of biogas and biomethane from crops and promote the production of these fuels from waste biogenic materials.
- Given the potential (albeit limited) role that biomethane could play in helping to reduce the climate change impacts of the road transport sector, it may also be appropriate for EU Member States to consider introducing incentive schemes that encourage fuel producers to supply biomethane to the transport sector. In particular, this may require incentives to be broadly consistent across the three sectors. However, the costs associated with using biomethane in the transport sector are potentially very high due to the need for new refuelling infrastructure. Hence, developing a more comprehensive understanding of the cost effectiveness of using biomethane in the transport sector as a means of reducing GHG emissions compared to using it in the heat and power sectors is necessary before Member States introduce measures to support the use of biomethane in transport.

7 Appendix 1

A.1 Definition of scope of the study

Table 7-1 sets out the vehicle, engine and fuel types for which data was gathered, assessed and analysed.

Table 7-1: Vehicles considered in study

Vehicle type	Engine type	Fuels
Passenger car	Spark ignition (SI)	Petrol
Passenger car	Spark ignition (SI)	CNG
Passenger car	Spark ignition (SI)	CBM
Passenger car	Compression ignition (CI)	Diesel
HGVs (urban)	Compression ignition (CI)	Diesel
HGVs (urban)	Spark ignition (SI)	CNG
HGVs (urban)	Spark ignition (SI)	CBM
HGVs (long run)	Compression ignition (CI)	Diesel
HGVs (long run)	Spark ignition (SI)	LNG
HGVs (long run)	Spark ignition (SI)	LBM
HGVs (long run)	Compression ignition (CI)	Dual fuel (LNG/Diesel)
HGVs (long run)	Compression ignition (CI)	Dual fuel (LBM/Diesel)
Maritime ships	2 stroke, low speed main engine	Marine fuel oil (HFO) (0.5% Sulphur)
Maritime ships	2 stroke, low speed main engine	Low sulphur marine gas oil (MGO) (0.1% Sulphur)
Maritime ships	Bi-fuelled engine	LNG / Diesel
Inland ships	2 stroke, low speed main engine	Marine fuel oil (HFO) (0.5% Sulphur)
Inland ships	2 stroke, low speed main engine	Low sulphur marine gas oil (MGO) (0.1% Sulphur)
Inland ships	Bi-fuelled engine	LNG / Diesel

A.1.1.1 Definition of fuels

Table 7-2: Fuel types considered in study

Fuel type	Definition
Petrol	100% mineral petrol used in road vehicles
Diesel	100% mineral diesel used in road vehicles
Marine fuel oil	Also known as heavy fuel oil (HFO) or residual oil. This is the most commonly used ship fuel currently by some distance. After 2020 (or by 2025 depending on the outcome of an ongoing review due to be

	completed in 2018) MARPOL regulations Annex VI[14] will require the sulphur content of this fuel to be 0.5% in all regions.
Low sulphur marine gas oil	Also known as MGO or distillate oil. The more expensive of the shipping fuel and therefore less widely used. From 2015, MARPOL regulations Annex VI required the sulphur content of this fuel to be 0.1% within Emission Control areas (ECAs).
CNG	Compressed natural gas. CNG is made by compressing natural gas (which is mainly composed of methane, CH_4), to less than 1% of the volume it occupies at standard atmospheric pressure. CNG is used in traditional SI engine vehicles that have been modified or in vehicles which were manufactured for CNG use, either alone ('dedicated'), with a segregated petrol system to extend range (bi- fuel) or in conjunction with another fuel such as diesel (dual fuel).
LNG	Liquefied natural gas. LNG is natural gas that has been converted to liquid form for ease of storage or transport. It takes up about 1/600th the volume of natural gas in the gaseous state. LNG achieves a higher reduction in volume than CNG so that the energy density of LNG is 2.4 times greater than that of CNG. This makes LNG cost efficient to transport over long distances. From LNG is used in traditional CI engine vehicles and is common in the HGV industry where its added range potential (versus a diesel HGV) is an attractive option for road hauliers. The fuel is also starting to be used in shipping as alternative to fuel/gas oil due to its air quality pollutants reduction potential (which will address MARPOL regulations)
CBM	Compressed biomethane. Biofuel sourced equivalent to CNG.
LBM	Liquefied biomethane. Biofuel sourced equivalent to LNG.

A.1.1.2 Definition of engine type

Table 7-3: Engine types considered in study

Engine type	Definition
SI road vehicles	Standard, conventional spark-ignition (SI) petrol engine.
CI road vehicles	Standard, conventional compression-ignition (CI) diesel engine.
Dedicated methane vehicles (CNG/LNG/CBM/LBM)	Vehicles either modified or manufactured to run off natural gas as its sole fuel.
Dual-fuelled HGVs	HGVs designed for natural gas to be used in conjunction with another fuel (diesel generally).
2 stroke, low speed main engine	Standard engine used in shipping. A 2 stroke engine is more commonly used (rather than a 4 stroke) as the main engine despite slower speeds due to their ability to burn lower grade fuel which reduces fuel costs.
Bi-fuelled engine (LNG for ships)	A marine LNG engine is a dual fuel engine that uses natural gas and any ship fuel (also known collectively as bunker fuel). The gas is stored as LNG and the boil-off gas is routed to and burned in a dual fuel engine

A.1.1.3 Fuel pathways considered in study

Fuel production

For conventional transport sector fossil fuels only crude oil based sources were considered. Crude oil[15] is assumed to be produced and conditioned at source, and then transported to market where it is refined into petrol/diesel variants and distributed and dispensed at a retail site.

For fossil gaseous fuels, four sources were considered, which are:

1. EU, domestically sourced natural gas;
2. Shale gas from hydraulic fracturing in the EU;
3. Imports of liquefied natural gas (LNG) from overseas and;

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[14] MARPOL Annex VI states a progressive reduction globally in emissions of SOx, NOx and particulate matter and the introduction of emission control areas (ECAs) to reduce emissions of those air pollutants further in designated sea areas. Under the revised MARPOL Annex VI, the global sulphur cap will be reduced from current 3.50% to 0.50%, effective from 1 January 2020, subject to a feasibility review to be completed no later than 2018. The limits applicable in ECAs for SOx and particulate matter were reduced to 0.10%, from 1 January 2015.
[15] Crude oil from typical EU supply, transport by sea, refining in EU (marginal production), typical EU distribution and retail.

4. Imports of compressed natural gas (CNG) specifically from Russia.

Natural gas, whether obtained via (i) conventional extraction and production processes in the EU, (ii) hydraulic fracturing in the EU or (iii) imports is assumed to be injected into the natural gas grid for distribution to filling stations, where it is dispensed as compressed natural gas (CNG). LNG is loaded onto road tankers for distribution to vehicle refuelling stations as LNG.

Biomethane can either be injected in to the gas grid for distribution and dispensing as compressed biomethane (CBM) in the same way as natural gas, or can be liquefied and distributed by road tanker like LNG (LBM). Production routes for biomethane considered in this study were (i) anaerobic digestion and (ii) production from landfill gas. In both cases, the biogas produced by the initial conversion process has to be upgraded to biomethane in order to remove impurities. Without upgrading, biogas cannot be used for transport sector applications.

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