CO_2 EMISSION ABATEMENT COSTS OF GAS MOBILITY AND OTHER ROAD TRANSPORT OPTIONS

Report for NGVA Europe

April 2021

Dr. David Bothe
+49 221 3371-3106
david.bothe@frontier-economics.com

Dr. Matthias Janssen
+49 221 3371-3117
matthias.janssen@frontier-economics.com

Amber Gorzynski
+44 20 7031 7018
amber.gorzynski@frontier-economics.com

Julian Bauer
+49 175 954 65 31
julian.bauer@frontier-economics.com

CONTENTS

ABBREVIATIONS

BEV	Battery Electric Vehicle
CAPEX	Capital Cost Expenditures
CBM	Compressed Biomethane (bio-CNG)
CCS	Carbon Capture and Storage
CNG	Compressed Natural Gas
CO2	Carbon dioxide
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse gas
gmobility	Gas mobility
H2	Hydrogen
HPDI	High Pressure Direct Injection
ICEV	Internal Combustion Engine Vehicle
LBM	Liquefied Biomethane (bio-LNG)
LCA	Life-Cycle Analysis
LNG	Liquefied Natural Gas
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
OPEX	Operating Cost Expenditures
PI	Positive Ignition
SMR	Steam Methane Reforming
TTW	Tank-To-Wheel
WTT	Well-To-Tank
WTW	Well-To-Wheel

EXECUTIVE SUMMARY

Context & motivation

Road transport greenhouse gas emissions need quick and strong reduction

Road transport emissions are significant. They account for around 70% of greenhouse gas (GHG) emissions in the mobility sector and 20% of total GHG emissions in the EU. Addressing these is a vital part of reaching the EU's ambitious near term climate target of cutting emissions by at least 55% below 1990 levels by 2030, which was recently accelerated in light of the EU Green Deal.

Road transport decarbonisation requires a mix of technologies

There are many potential routes to reduce emissions in road transport by switching fuels away from today's dominating fossil oil and petroleum fuels, and towards renewable and low-carbon fuels. Current EU policy and debate primarily focuses on battery-electric vehicles (BEV) as the technology to reduce road emissions. For example, the EU legislative framework on CO_2 emission standards for new road vehicles focuses on tailpipe emissions in a "tank-to-wheel" approach. This approach favours electric vehicles because it assigns them zero emissions, irrespective of the CO_2 emissions that occur during the production of the electricity. Renewable fuels such as biomethane have positive tailpipe emissions, however most of these emissions are bound during the production of the fuels.[1] The current "tank-to-wheel" approach does not compare the different technologies appropriately because it ignores emissions associated with the production of the fuel. It does not recognise the positive contribution of renewable fuels such as biomethane to climate protection, and thus biases one technology over others without a climate protection rationale.

Instead of focusing on a single technology such as electrification, a range of technological solutions is required to achieve significant emission reductions in the near term.

In this study we provide a comparison of carbon abatement costs for different road transport technologies considering emissions and costs along the value chain

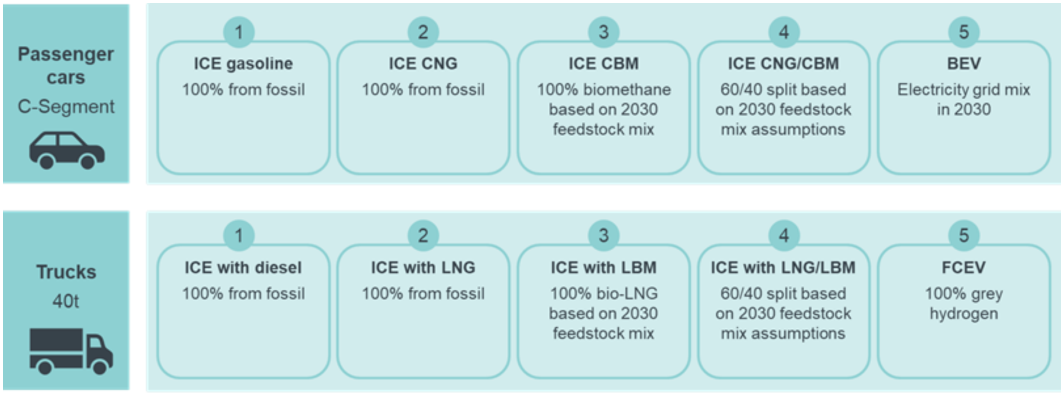
When comparing technology options and their contribution to climate protection, a comprehensive approach is needed that takes emissions and costs along the value chain into account, rather than an approach focussing narrowly on tailpipe emissions. This will ensure that emissions targets are achieved in a cost-effective way ("value for money") when policymakers are deciding which technology options to support.

[1] Some biomethane production methods can have negative emissions. This is because biomethane can be produced from feedstocks such as manure, which otherwise would release methane directly into the atmosphere as it decomposes in fields. By using the feedstock to produce biomethane, the overall GHG emissions impact is reduced.

Comparing options is complex due to the different emission and cost profiles of vehicles. One comparison method is to calculate the cost of carbon abatement for each option. This is defined as the additional cost associated with one tonne of CO_2 abatement relative to a counterfactual option, for example a conventional fossil-fuelled vehicle.

In this study we analyse CO_2 emission abatement costs of key road transport vehicles to illustrate the potential contribution of gas mobility (gmobility) alongside other technologies. We focus our analysis on the near term up to 2030 using two example vehicle types (passenger cars and trucks), set out in Figure 1. Within each vehicle type, we compare a range of low-carbon options including gas mobility to a fossil counterfactual.

Figure 1 Fuel/powertrain combinations considered



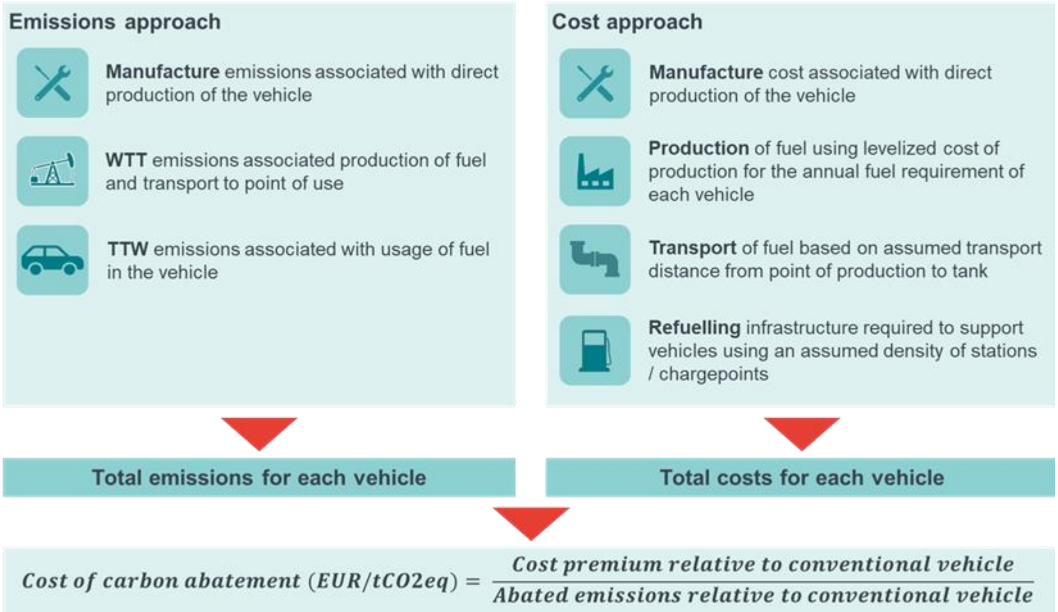
Source: Frontier Economics. For FCEV we also do sensitivity calculations with blue and green hydrogen.

Rather than limiting to tailpipe emissions in a Tank-to-Wheel (TTW) approach, our calculations take into account emissions and costs across the supply chain including vehicle manufacture, fuel production, fuel transport and refuelling, as shown in Figure 2.[2]

Throughout the calculations we use economic costs rather than user cost. This allows us to compare the cost of CO_2 emission abatement to society, excluding all taxes, levies and subsidies (which are policy-driven). For example, while biomethane and CNG may have similar costs for the user at the point of use (due to subsidies for biomethane), they have different production costs. Accordingly, the fuel production cost that we consider deviates from cost that readers may be familiar with from their experience at filling stations, as the main part of prices at filling stations (for fossil fuels such as gasoline and diesel) constitutes taxes.

[2] Ultimately, a full Life Cycle analysis (LCA) should be used to compare vehicles including emissions from as widely across the value chain as is possible, also including emissions for manufacturing of assets along the supply chain (e.g. renewable power plants or pipeline or electricity transport infrastructure) as well as vehicle end-of-life costs and emissions. As a simplification, we do not use a LCA approach here because it adds significant complexity and data requirements for cost calculations across different options.

Figure 2 CO_2 emission abatement calculation approach across the value chain



Source: *Frontier Economics*

Note: *All costs are based on economic costs rather than end user costs*

We acknowledge that significant uncertainty exists around the development of costs and emissions associated with some areas of the value chain, particularly for BEVs which are a less mature technology than combustion engine vehicles. This makes the comparison between technologies sensitive to the input assumptions. Therefore, our calculation includes a range of sensitivities to illustrate how the cost of CO_2 emission abatement varies under different assumptions.

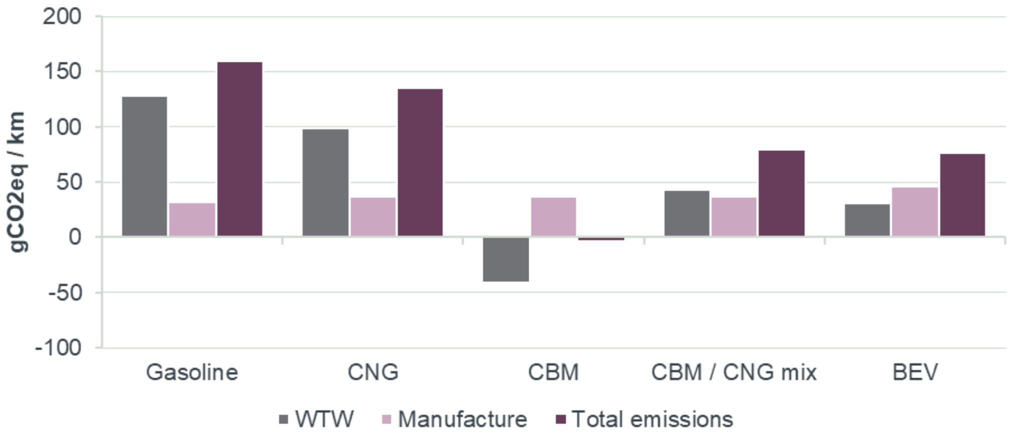
Please note that we do not conduct a similar sensitivity analysis for trucks, but raise the challenge that today there are limitations on the availability of FCEV vehicles and low-carbon hydrogen supply. Consequently, while FCEV trucks are a promising decarbonisation option in the medium-to-long term, there is significant uncertainty around availability and cost of the vehicles and the fuel supply in the time horizon 2030.

Key results

Passenger vehicles: Emissions

Figure 3 shows total emissions for passenger vehicles in 2030. Gas mobility running on a 40/60 mix of CBM and CNG has similar total emissions to BEV on a combined Well-to-Wheel (WTW) and manufacturing emissions basis.

Figure 3 Passenger vehicles: Total emissions in 2030 (under baseline assumptions)

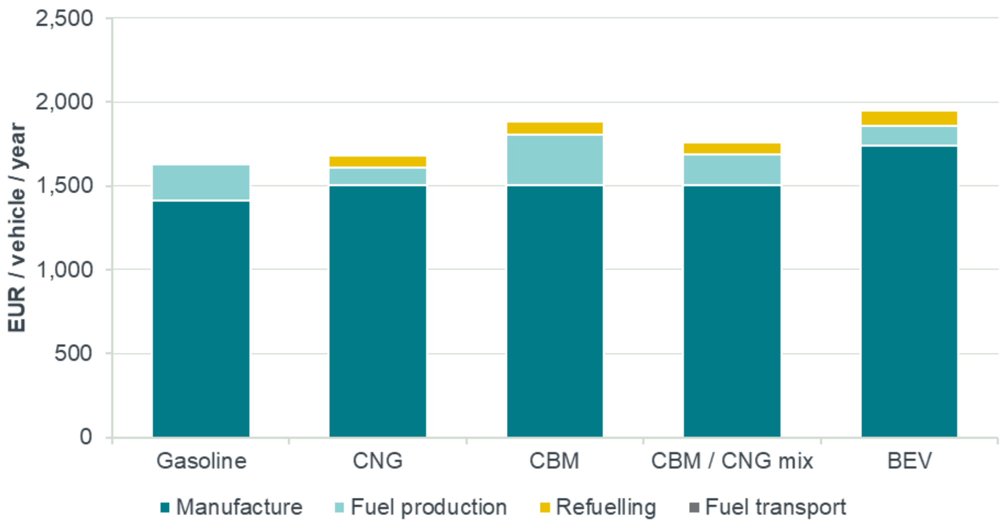


Source: Frontier Economics based on JEC WTW v5 for WTW emissions and a literature review for manufacturing emissions, see Section 3 for details

Passenger vehicles: Costs

Figure 4 shows total costs of each vehicle type in 2030. These are primarily driven by manufacturing and fuel production costs. Gas mobility tends to be cheaper than BEV due to lower vehicle manufacturing cost. However, higher biomethane production costs mean that an ICEV running on pure biomethane has a comparable overall cost to BEV.

Figure 4 Passenger vehicles: Total annualised costs in 2030 (under baseline assumptions)

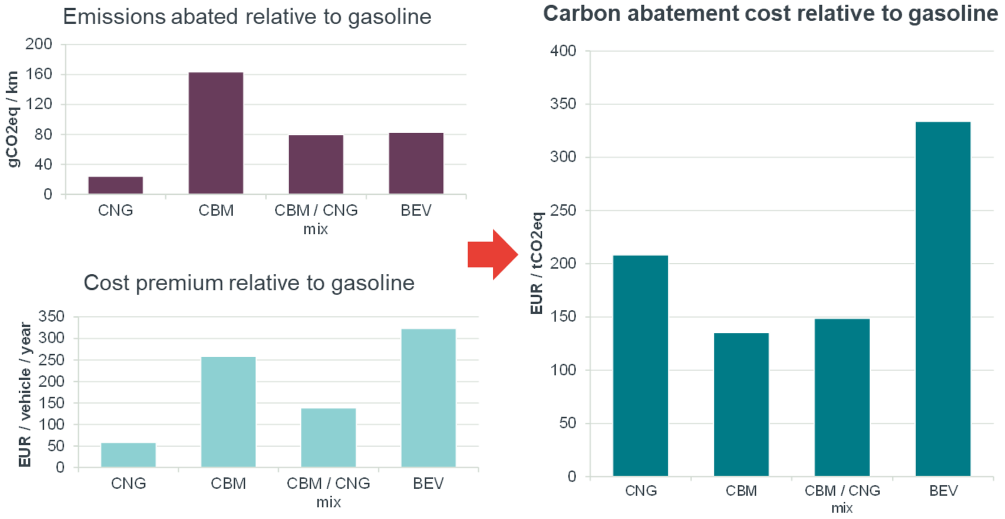


Source: Frontier Economics based on literature review

Passenger vehicles: Carbon abatement costs (baseline)

Figure 5 shows the abated emissions, cost premium above gasoline, and CO_2 emission abatement cost[3] for each vehicle under our baseline assumptions. Gas mobility has a lower abatement cost than BEVs for all CNG and biomethane fuel mixes.

Figure 5 Passenger vehicles: CO_2 emission abatement cost (under baseline assumptions)



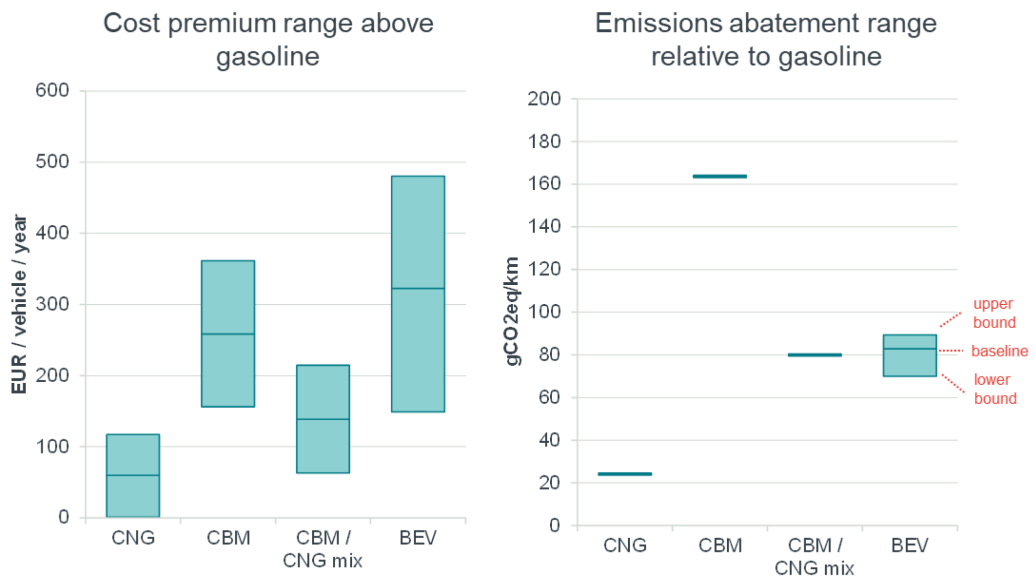
Source: Frontier Economics based on literature review

Passenger vehicles: Carbon abatement costs (sensitivities)

Figure 6 shows the aggregate impact of varying different parameters across the supply chain on the cost premium and abated emissions for each vehicle. Gas mobility has a lower range of estimated costs and emissions than BEV, which reflects the greater certainty around CNG vehicles' costs and emissions as a more mature technology. BEVs have a substantial cost abatement upside risk. This is mainly driven by the uncertainty associated with the future development of vehicle (i.e. mainly battery) manufacture cost. Similarly, BEV has a greater emissions abatement range than gas mobility, which is driven by uncertainty around how (battery) manufacturing emissions will evolve over the next decade.

[3] Carbon abatement costs (EUR/t CO2) = Cost premium (EUR / vehicle / year) / Emissions abated (tCO2eq/km * annual mileage).

Figure 6 Sensitivity range of costs and emissions relative to gasoline

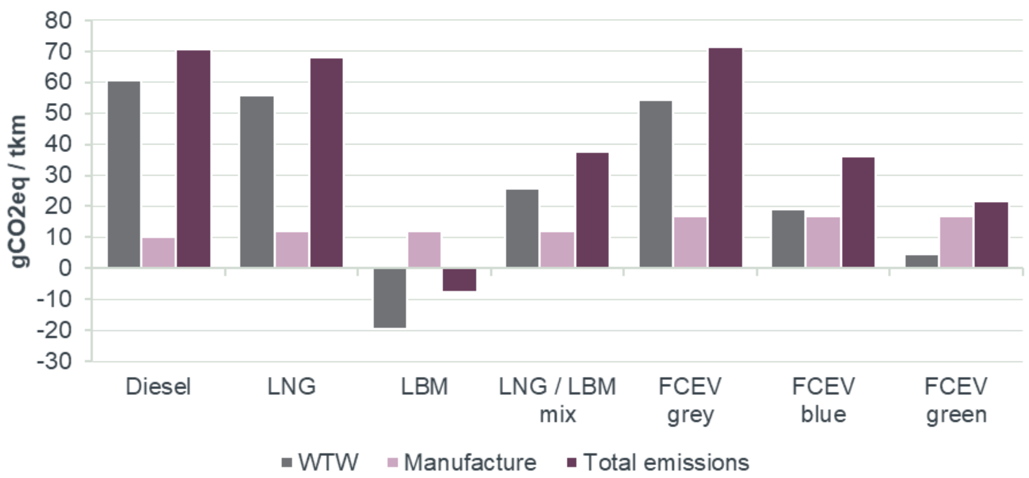


Source: Frontier Economics based on literature review
Note that under some cost parameter assumptions, CNG have even a lower overall cost than gasoline i.e. they have a negative cost premium.

Trucks: Emissions

Figure 7 shows the total WTW and manufacturing emissions for trucks. Conventional diesel trucks, LNG trucks, and FCEV running on grey hydrogen all have similar overall emissions. Gas mobility using a mix of LNG and bio-LNG has half as many total emissions as diesel and FCEV running on grey hydrogen.

Figure 7 Trucks: Total emissions in 2030

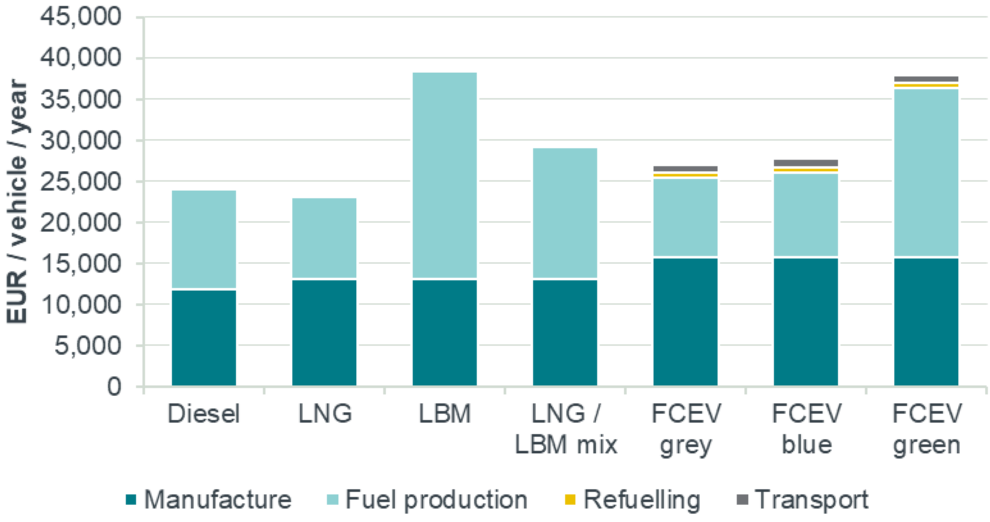


Source: Frontier Economics based on JEC WTW v5 for WTW emissions and Ricardo (2020) for manufacturing emissions
Note that in the near term there is limited availability of blue and green hydrogen for use in transport, although supply is expected to ramp up over the coming decade

Trucks: Costs

Figure 8 shows total costs for one truck on an annualised basis. The numbers show that FCEV using green hydrogen and LBM are the most expensive in 2030, which is largely driven by manufacturing costs for FCEV and fuel production costs.

Figure 8 Trucks: Total annualised costs in 2030



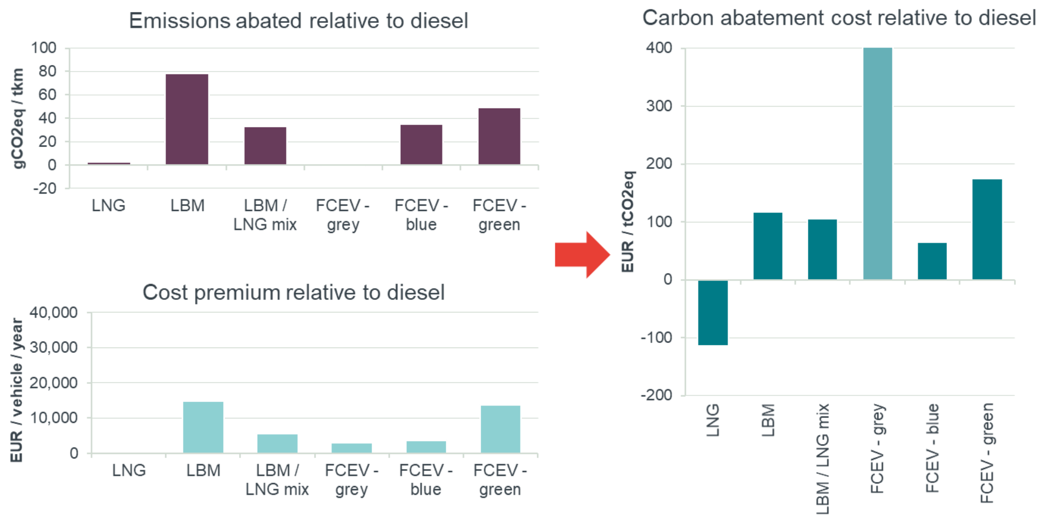
Source: Frontier Economics based on literature review

Trucks: Carbon abatement costs

Figure 9 shows the CO_2 emission abatement cost against a diesel reference. Both the pure bio-LNG and the 40/60 LNG/bio-LNG mix have similar costs of CO_2 emission abatement, however the pure bio-LNG vehicle offers significantly higher levels of emissions savings. FCEV running on blue hydrogen has the lowest cost of carbon abatement, although the availability for blue hydrogen to be used in transport is relatively uncertain in the near term.

These results support the deployment of multiple technological options in the near term to decarbonise heavy duty transport. LNG and bio-LNG mobility able to offer near term decarbonisation at a low cost of carbon abatement, and FCEV using blue and green hydrogen are likely to play an important role in the future.

Figure 9 Trucks: CO_2 emission abatement costs



Source: Frontier Economics
Note that LNG vehicles have a lower total cost than diesel due to lower fuel production costs. This leads to a negative carbon abatement cost because they reduce both costs and emissions.
Note also that FCEV fuelled by grey hydrogen do not abate any emissions relative to diesel, and thus have prohibitively high abatement costs (which we capped at 400 EUR/tCO2eq in the graph).

Roadmap to 2030

ACEA (2021) reports a total stock of 1.2 million natural gas passenger vehicles and 25,000 natural gas trucks in the European Union in 2019. NGVA Europe expects that gas mobility could account for close to 10 million passenger vehicle and 500,000 truck sales between 2020 and 2030.[4]

- For **passenger vehicles**, NGVA Europe expects that in 2030 over 1.6 million passenger cars and LCVs will be sold (new registrations) that are powered by gaseous fuels. Over their lifetime, these vehicles would be associated with abated emissions of over 24 million tonnes compared to a similar number of conventional gasoline vehicles,[5] at an additional system cost of 2.8 billion EUR. A similar number of BEVs would be associated with similar emissions reductions, but system costs would be much higher at around 6.0 billion EUR above gasoline.
- For **trucks**, NGVA Europe estimates that in 2030 around 52,000 LNG trucks will be sold in the EU. Relative to a similar number of diesel trucks, these LNG vehicles would save over 25.1 million tonnes of CO_2 over their lifetime at an additional system cost of around 2.6 billion EUR. In comparison, FCEV running on grey hydrogen do not offer emissions savings relative to diesel trucks and will have a significant additional cost.

[4] This is broadly in line with the assumptions of the European Commission's Impact Assessment (2020d), which predicts that gas fuelled vehicles could make up 5% of total passenger demand in 2030, or 7.6 million vehicles.

[5] Based on the assumption that CNG cars are powered by a fuel mix of 60% CNG and 40% biomethane.

Policy implications: The regulatory framework must provide a level-playing-field and allow for gas mobility to contribute to emissions reductions in the near term

Our analysis shows that gas mobility can help to contribute to reducing GHG emissions in road transport at comparably low system cost. As gas mobility – in contrast to other drivetrain technologies which are less mature – is readily available on vehicle, infrastructure and fuel supply levels and thus quickly scalable now, it can contribute to ambitious early GHG emission reduction by 2030 at low cost.

It is therefore key to ensure that the regulatory framework allows for further drivetrain options such as gas mobility to contribute to emission reductions.

Today's fragmented regulatory approach, which is limited to tailpipe emissions for fleet targets, does not reflect the system-wide overall costs and benefits of different low-carbon vehicles. While suggestions for concrete adjustments of the wide field of regulation are beyond the scope of this study, future adjustments should be built on various principles which would allow gas mobility – as any other low-carbon technology option – to become part of a wide technology mix to achieve carbon neutral mobility:

- **Technological diversification.** The immense challenge and high urgency for the mobility sector to achieve emissions reductions does not allow for cherry picking of individual technologies. Rather, we have to go "all-in" by enabling as many options to contribute as possible
- **Freedom of choice and competition of technologies.** The heterogeneity of mobility applications with many individual factors determining the most efficient technology in each case rules out any central planning approach – there is no "one size fits all" solution.
- **Keeping options open.** There is a high degree of uncertainty around the optimal technology options in the future. Regulation therefore should avoid prematurely ruling out any pathway (e.g. by banning combustion engines which may in the future be fuelled by renewable or low-carbon fuels or gases).

Various areas of the policy landscape could be adjusted in accordance with these principles to further support the EU's ambitious climate targets:

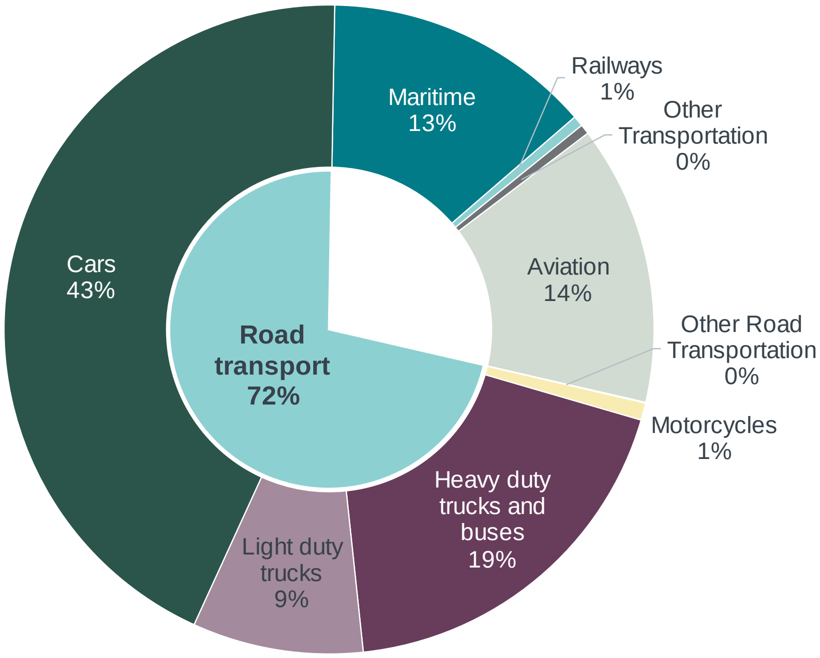
- **Transport and Climate policy.** Leveraging on the CO_2 emissions reduction only at tailpipe level is not sufficient to ensure the ambitious shift to carbon neutral mobility. EU fleet targets should recognise the contribution from sustainable renewable fuels beyond a tailpipe emission only focus.
- **Infrastructure support.** The development of gas refuelling infrastructure should be supported to facilitate a homogeneous market throughout Europe.
- **Sector specific regulations.** Such as the Renewable Energy Directive (RED II / III), the Energy Tax Directive (ETD) or fleet targets, many of which are currently or will be soon under revision.
- **Technical standards.** An implementation of harmonised EU standards at national levels may help to increase interoperability among European countries.

1 INTRODUCTION

Greenhouse gas emissions of road transport are significant and road transport volume is growing

Road transport accounts for 70% of greenhouse gas (GHG) emissions in the transport sector (Figure 10) and around 20% of total GHG emissions in the EU.

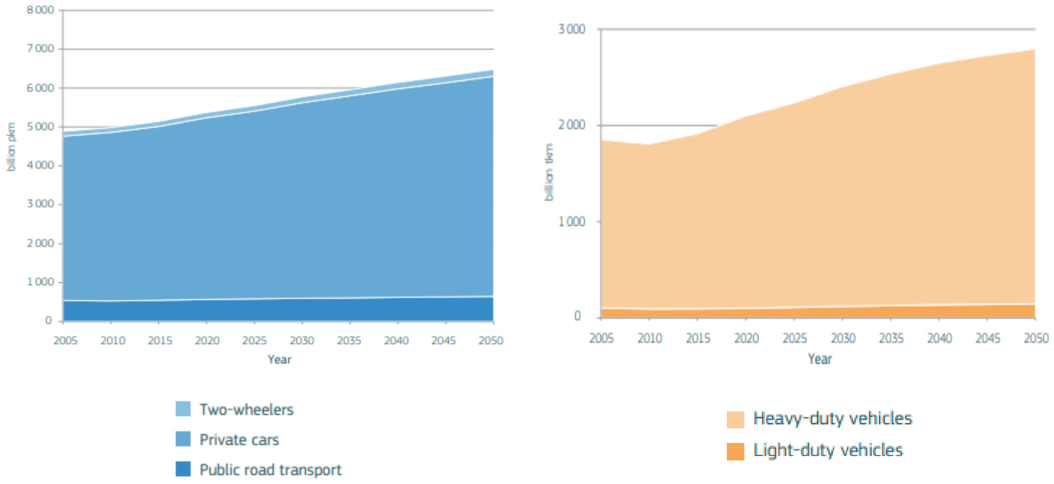
Figure 10 Split of greenhouse gas emissions in mobility sector in the EU (2019)



Source: Illustration by Frontier Economics, based on data from https://www.eea.europa.eu/data-and-maps/daviz/share-of-transport-ghg-emissions-2

In addition, demand for passenger and (particularly heavy) duty transport is predicted to increase substantially going forward (Figure 11).

Figure 11 Forecasted growth in passenger road transport (left) and light and heavy-duty transport (right)



Source: JRC (2019)

Near term action is needed to reduce road transport GHG emissions

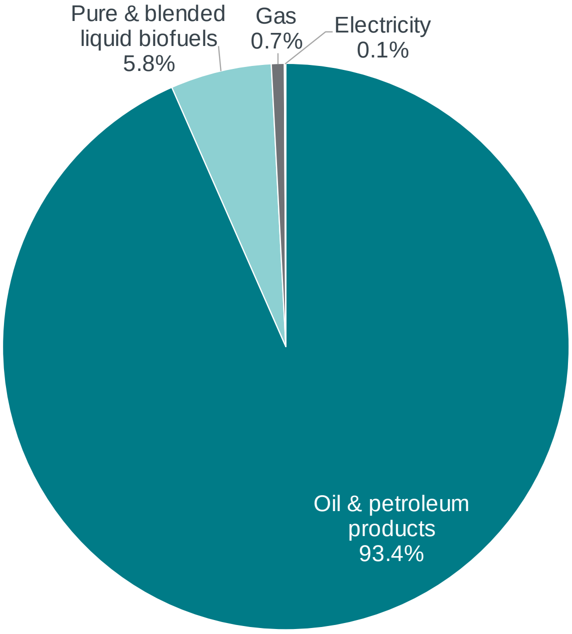
At the same time, the EU has set ambitious targets to reduce GHG emissions, which were recently accelerated in the light of the Green Deal to a target of cutting emissions by at least 55% below 1990 levels by 2030. As road transport is one of the key greenhouse gas emitters in the EU, near term action is needed to reduce road transport emissions significantly.

There are many potential routes to reduce GHG emissions in road transport. The potential to reduce the volume of road transport (in passenger km or tonne km) by shifting transport from road to rail or public transport is limited (see also Figure 11), as is the potential for further reducing specific (fossil) fuel consumption per passenger km or tonne km, for example by reducing the average weight of vehicles or increasing the efficiency of combustion engines.[6]

As a consequence, a fuel switch away from today's dominating fossil oil and petroleum fuel (see Figure 12) towards renewable and low-carbon fuels is required. These can include, for example, liquids such as biofuels or renewable or low-carbon hydrogen-based e-fuels in conventional Internal Combustion Engine Vehicles (ICEV), natural gas, biomethane, hydrogen or hydrogen-based synthetic methane in gas combustion vehicles (gas mobility), electricity in battery electric vehicles (BEV), or hydrogen in fuel cell electric vehicles (FCEV).

[6] While specific fuel consumption has indeed been decreasing for a given vehicle type due to improved efficiency, there is an ongoing trend for higher shares of high-weight passenger cars that is countervailing improved efficiencies.

Figure 12 Split of fuels in EU27 road transport (2019)



Source: Frontier Economics based on Eurostat

Current EU policy has a strong focus on electric mobility

The current debate on climate change in road transport primarily focusses on battery-electric vehicles as the technology to reduce emissions, and policy actions are mainly directed to facilitate electrification.

For example, the EU legislative framework on CO_2 emission standards for new road vehicles ('fleet targets') focuses on tailpipe emissions in a so-called "tank-to-wheel" approach. This assigns zero emissions to electric vehicles, irrespective of the actual CO_2 intensity of the electricity mix that is fuelling the vehicles. For renewable fuels such as biomethane, the CO_2 tailpipe emissions are bound during the production of the fuels. The current "tank-to-wheel" approach does not reward this positive contribution of these renewable fuels to climate protection, and thus biases one technology over others without a climate protection rationale.

Heterogeneity of road transport requires a technology mix, therefore there is no "one-size-fits-all" solution

To allow for a timely and significant reduction in GHG emissions in road transport, multiple different technological solutions are required. There is no such thing as standardised road transport. Instead, a heterogeneous mix of different vehicle types, transport purposes and personal preferences exists. This results in a wide range of transport patterns, for example with regards to weight of vehicles and freight, yearly mileage, distances per trip or refuelling patterns. Different technology solutions have characteristics which are more or less suited to particular uses, therefore there is no "one-size-fits-all" solution to CO_2 emission abatement in road transport.

Gas mobility is available now and quickly scalable, and could add to the technology mix

Gas mobility is available and scalable now, and might consequently – in contrast to other drivetrain technologies on a less mature level – be able to contribute to achieving ambitious early GHG emission reduction in the short term already. Key advantages of this technology include:

- **Availability and maturity of vehicles**: Gas-fuelled vehicles are readily available and mature in all relevant transport categories, including all levels of passenger and light duty transport as well as heavy duty transport or busses.[7]
- **Building on existing infrastructure**: Gas mobility can build on existing infrastructure such as (LNG and pipeline) import, transport, distribution and storage infrastructure with sufficient capacity also for providing further demand from transport (see for example Figure 13 and Figure 14). This is an important advantage over other decarbonisation options in the mobility sector such as electrification or hydrogen, where the infrastructure would require significant additional investment and retro-fitting to cope with the additional demand from mobility.[8]
- **Available fuel supply**: Gas mobility can leverage on substantial fuel supply potentials in the near-term. Existing natural gas supply might be used as a bridging fuel (reducing GHG in comparison to gasoline or diesel vehicles). In addition, biomethane or synthetic methane – which are compatible with natural gas infrastructure , gas refuelling stations and vehicles at zero extra switching cost and thus allow for a straightforward transition – could be used on an increasing scale.

  NGVA Europe predicts that EU biomethane demand from gas mobility will increase from 5 TWh today to 117 TWh by 2030, corresponding to

  - a biomethane share in gas demand for gas mobility of 40% and
  - a gas mobility share of new registrations in 2030 of 12% in passenger and light-duty transport, 25% in heavy duty transport, and 34% in bus transport.

  Biomethane supply potential is able to meet this demand. Navigant (2019) predicts that biomethane supply within Europe could increase from 20 TWh in 2020 to 370 TWh by 2030. CERRE (2019) also estimates the potential for large increases in biomethane production based on feedstock availability. For example, it estimates that Germany produced just under 10 TWh of biomethane in 2017, but could produce up to 116 TWh today from available manure and crop residues.[9]

  Beyond Europe, the global supply of biomethane is also expected to increase in the near-term. The IEA (2020) estimates that more than 8,140 TWh of

---

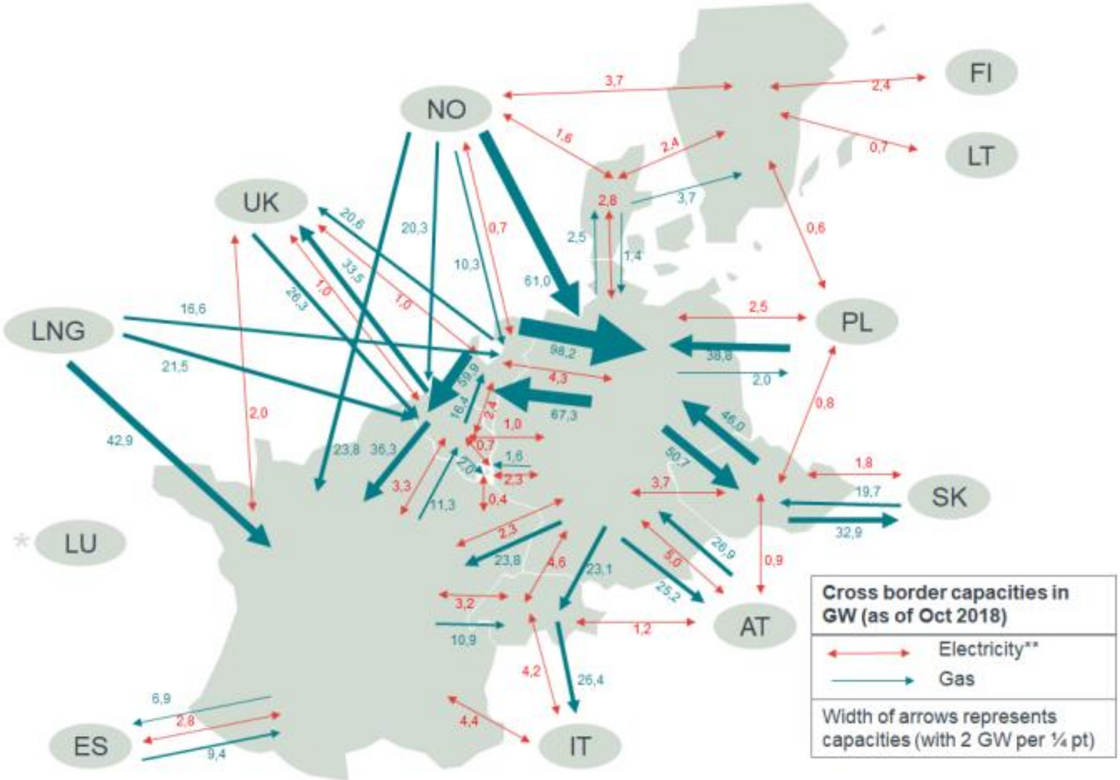
[7] See for example NGVA Europe (2019), the g-mobility vehicle catalogue provided by NGVA Europe.

[8] Refuelling infrastructure for g-mobility needs further development. However, there are already existing CNG and LNG stations across Europe. In addition, building new CNG refuelling stations or retrofitting existing refuelling stations comes at comparably low cost and is relatively straightforward because it can rely on the existing transport and storage infrastructure.

[9] CERRE (2019) also estimates a potential scale up for the following countries: Belgium from negligible amounts in 2017 to 8.8 TWh, France from 0.5 TWh to 143 TWh, Italy from 0.25 TWh to 53 TWh, Netherlands from 1.3 TWh to 12. 7TWh, UK from 4.2 to 63.6 TWh.

biomethane could be produced sustainably today, rising to 11,630 TWh by 2040. This is equivalent to about 19% and 27% of global natural gas demand today respectively.[10]

Figure 13 Cross-border transport capacities for gas exceed those of electricity by far

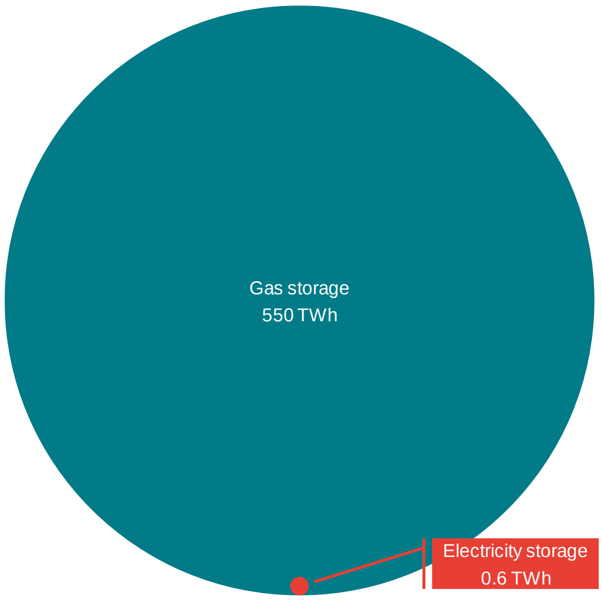


Source: Frontier Economics and IAEW (2019) based on Entso-E and Entso-G

Note: The study focuses on eight European countries, so does not include flows between the countries labelled in circles. In some cases published capacities vary slightly between flow directions. In that cases, the higher figures are depicted.

[10] IEA (2020), https://www.iea.org/reports/natural-gas-information-overview

Figure 14 Energy storage capacity as gas is almost 1000 times as large as electricity storage in eight analysed European countries[11]



Source: Frontier Economics and IAEW (2019)

The purpose of this study is to analyse emission savings and corresponding CO_2 emission abatement costs of key road transport technologies along the supply chain

Multiple technological options exist to reduce GHG emissions in the mobility sector, including gas mobility. These options should be compared comprehensively, taking both emissions and costs into account, rather than through a narrow focus on tailpipe emissions. This will ensure that emissions targets are achieved in a cost-effective way ("value for money") when policymakers are deciding which technology options to support.

The Natural and bio Gas Vehicle Association (NGVA Europe) has commissioned Frontier Economics for a study to apply a holistic approach to estimating the CO_2 emission abatement cost of several key road transport technologies.

In the remainder of this report, we

- set out our methodology (Section 2);
- describe key assumptions and calculations for carbon emissions (Section 3) and costs (Section 4);
- summarise the resulting CO_2 emission abatement costs (Section 5);
- conclude with high-level policy recommendations (Section 6).

[11] Analysed countries consist of Belgium, Czech Republic, Denmark, France, Germany, Sweden, Switzerland and the Netherlands.

2 METHODOLOGY

Comparing road transport technology options is complex due to the different emission and cost profiles of vehicles. One comparison method is to calculate the cost of carbon abatement for each option. This is defined as the additional cost associated with one tonne of CO_2 abatement relative to a counterfactual option, for example a conventional fossil-fuelled vehicle.

We compare cost of CO_2 emission abatement for a range of example fuel/powertrain combinations, to illustrate the potential contribution of gas mobility alongside other technologies.

In this section, we set out

- the scope of our analysis (Section 2.1);
- our CO_2 emission abatement cost methodology (Section 2.2); and
- the selection of calculation sensitivities (Section 2.3).

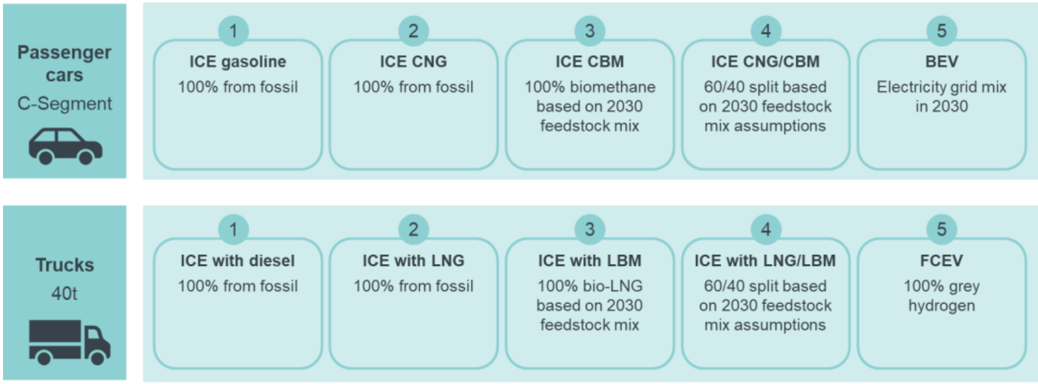
2.1 Scope of the analysis

We focus our analysis as follows:

- on a **2030 time horizon** to reflect the near term;
- on two example vehicle types, a compact class **(C-segment) passenger car** to reflect passenger transport and a **40 tonne truck** to reflect heavy duty transport; and
- for each vehicle type, we consider **three example fuel/powertrain combinations** that reflect those combinations that can be expected to have a high penetration in 2030. These are:
  - For passenger cars:
    - An Internal Combustion Engine Vehicle (**ICEV**) fuelled by fossil **gasoline** as a reference,
    - A Compressed Natural Gas (**CNG**) vehicle fuelled by compressed fossil natural gas, compressed biomethane (CBM) or a 60/40 split of the two, and
    - A Battery Electric Vehicle (**BEV**) powered by an average EU grid electricity mix;
  - For trucks:
    - An **ICE** fuelled by fossil **diesel** as a reference,
    - An **LNG** vehicle fuelled by LNG, liquified biomethane (LBM) or a 60/40 split of the two, and
    - A Fuel Cell Electric Vehicle (**FCEV**) supplied by grey hydrogen.

Figure 15 sets out the vehicles considered in our assessment.

Figure 15 Fuel/powertrain combinations considered



2.2 Well-to-Wheel plus manufacturing approach to calculate CO_2 emission abatement costs

EU emissions standards for new road vehicles use a Tank-to-Wheel (TTW) approach. This focuses on tailpipe emissions and therefore does not distinguish between renewable fuels and fossil fuels. In our calculation we use a Well-To-Wheel (WTW) approach plus manufacturing, which includes emissions and costs associated with vehicle manufacture, fuel production, fuel transport and refuelling.[12]

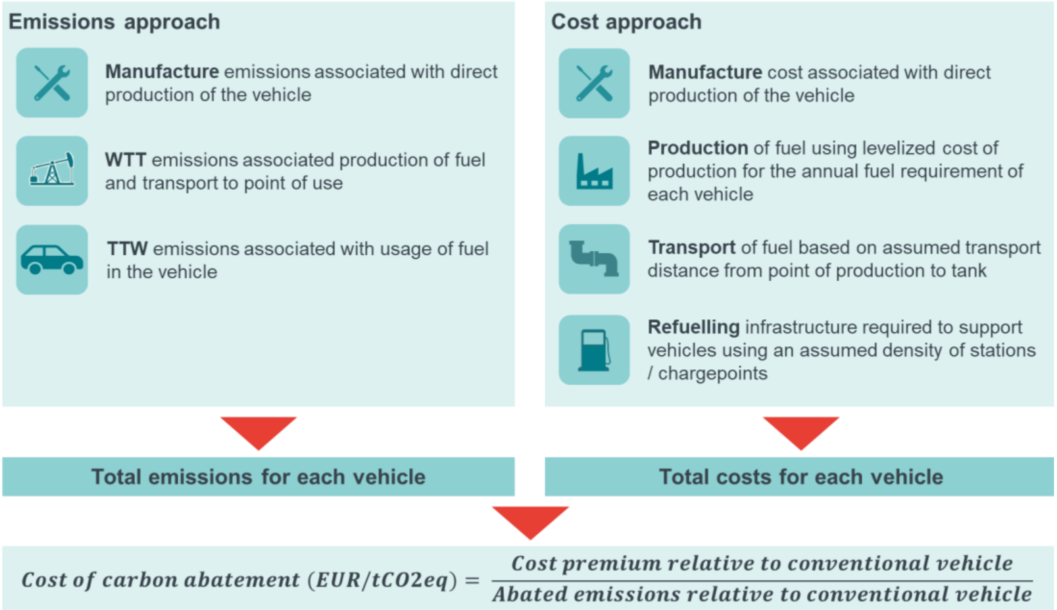
Figure 16 sets out our approach across the value chain. First, we estimate the total emissions and costs associated with each vehicle, where we draw as much as possible on published third-party studies. For each segment, we use economic costs rather than user costs which allows us to compare the cost of CO_2 emission abatement to society, excluding all taxes, levies and subsidies.

Next, we calculate the abated emissions and cost premiums for each alternative vehicle relative to the conventional vehicle (gasoline for passenger cars and diesel for trucks).

Finally, we divide the cost premium by the abated emissions to give the cost of CO_2 emission abatement in EUR/tCO2eq abated.

[12] Ultimately, a full Life Cycle analysis (LCA) should be used to compare vehicles including emissions from as widely across the value chain as is possible, also including emissions for manufacturing of assets along the supply chain (e.g. renewable power plants or pipeline or electricity transport infrastructure) as well as vehicle end-of-life costs and emissions. As a simplification, we do not use a LCA approach here because it adds significant complexity and data requirements for cost calculations across different options.

Figure 16 CO_2 emission abatement calculation approach across the value chain



2.3 Sensitivities to capture key uncertainties over how costs and emissions will evolve

Passenger vehicles

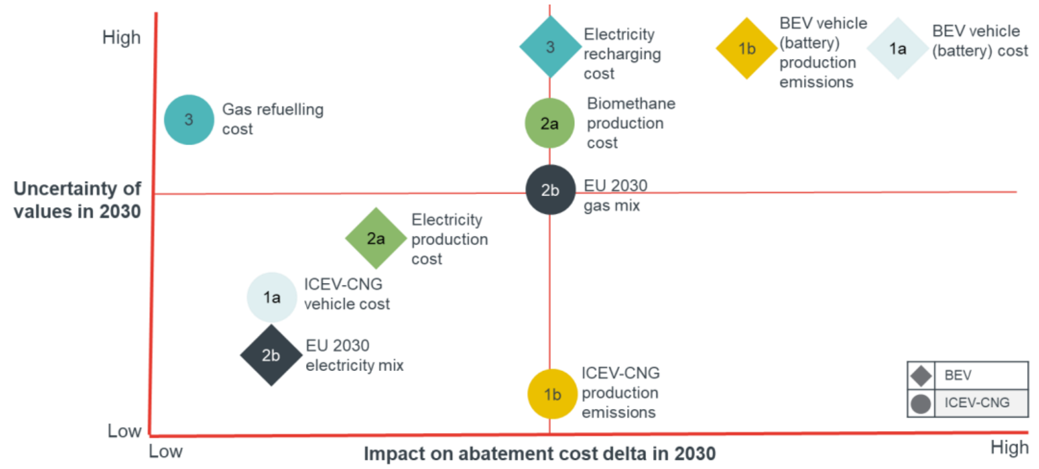
Gas mobility and BEVs can both make contributions to decarbonisation in the 2020s. However, significant uncertainty exists around the development of costs and emissions associated with some areas of the value chain. This makes the comparison between gas mobility and BEVs sensitive to the input assumptions. Therefore, our calculation includes a range of sensitivities to illustrate how the cost of CO_2 emission abatement varies under different assumptions.

For each area of the value chain, we qualitatively assess the uncertainty over costs and emissions and map them in Figure 17 and Figure 18. The mapping illustrates the clustered risk associated with BEVs whereby multiple parameters are highly uncertain. Gas mobility is relatively more certain because the technology is well-established. However, some parameters such as biomethane production cost are more uncertain, and we reflect this in our calculations. See our detailed descriptions on parameter variations in third-party studies in Sections 3, 4 and 5.

Figure 17 Uncertainty parameter mapping

		Gasoline	CNG	CBM	CNG/CBM mix	BEV
1. Manufacture	a. Cost	Well established with no uncertain cost changes expected up to 2030.	CNG vehicles are relatively well established with no major manufacturing changes expected to 2030, although some reduction in costs is expected as production scales up.			Major reductions are expected in the cost of battery pack production, however the technology development path is highly uncertain.
	b. Emissions	Well established with no major emissions changes expected up to 2030.	Well established with no major emissions changes expected up to 2030.			Major reductions are expected for BEV manufacturing emissions (mainly driven by battery manufacturing), however the technology development path is highly uncertain.
2. Fuel production	a. Cost	Well established with no major cost changes expected up to 2030.	Well established with no major cost changes expected up to 2030.	Production cost of biomethane is expected to decrease over the next decade. The extent of the decrease is uncertain as it relies on technological changes.		Cost of generation will change over time as the renewable share increases. Generation cost of renewables is expected to decrease, but the magnitude is uncertain.
	b. Mix	Well established with no major fuel composition changes expected up to 2030.	Well established with no major changes in supply expected up to 2030.	The volume of biomethane supply is uncertain as it depends on an increase in production. Constraining factors exist such as feedstock availability.		Increased share of renewables (as per ambitious EU targets) will affect the EU electricity generation mix. The impact depends on the development of the cost of renewables, which is uncertain.
3. Refuelling	a. Cost	Well established with no major changes expected up to 2030.	Station level costs are well understood however cost per vehicle depends on the density of the EU network. EU-wide gas transportation network is already in place to support refuelling network development.			Grid reinforcement costs associated with charging infrastructure are highly uncertain and depend on the scale of BEV take-up, as well as other distributed energy resources connected to the grid.

Figure 18 Parameter uncertainty mapping



Source: *Frontier Economics*

Trucks

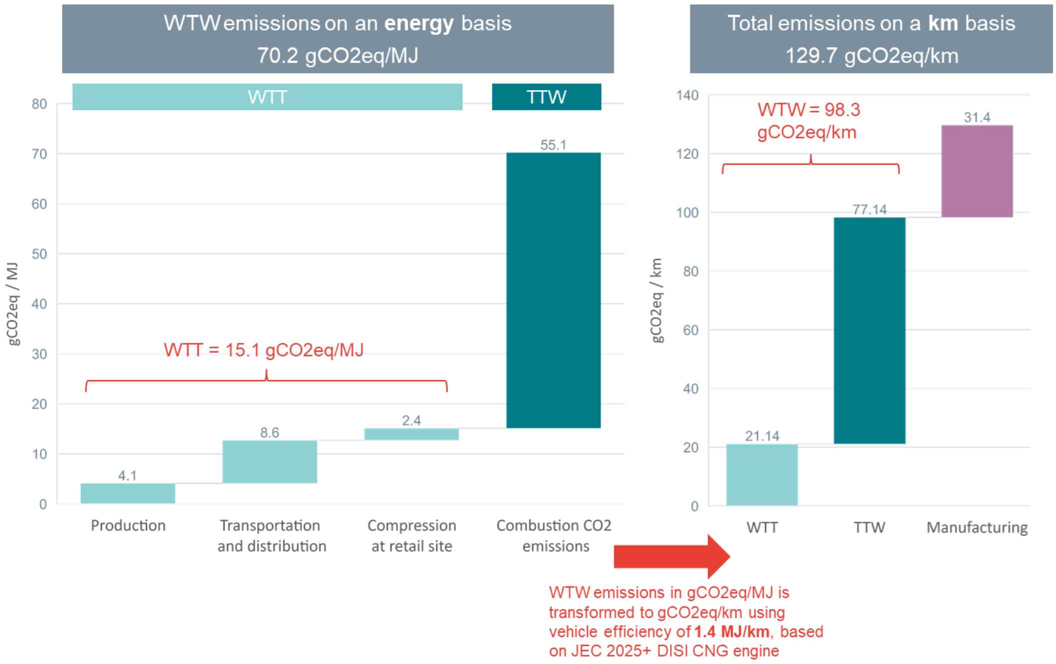
The comparison between alternative low-carbon trucks is more clear. While FCEVs may be a promising decarbonisation option in the longer term, large scale ramp up in the 2020s will be challenging. This is because in the near term, there is significant uncertainty around the widespread availability of FCEV trucks as well as low-carbon hydrogen to fuel them. Therefore, we only use baseline assumptions for trucks and do not calculate sensitivities.

3 EMISSIONS

Current EU legislation for Original Equipment Manufacturers (OEMs) focuses on tailpipe 'TTW' emissions. However, this measure does not take into account the emissions associated with other aspects of the value chain and therefore does not give a meaningful comparison between vehicles. We extend the emissions approach to a 'WTW' calculation to take into account emissions across the fuel production and usage value chain. In addition, we include emissions associated with direct manufacturing because this is an area where emissions vary significantly across vehicles.

Figure 19 demonstrates our calculation approach, using a passenger vehicle running on fossil CNG as an example. We calculate the WTW emissions on an energy basis for the relevant fuel, and then convert this to a gCO2eq/km basis using the relevant vehicle efficiency. Finally, we add the manufacturing emissions on a gCO2eq/km basis using an assumed 175,000 km passenger vehicle lifetime mileage.

Figure 19 Example emissions calculation for CNG vehicle in 2030



Source: Frontier Economics

Notes: WTW figures taken from JEC v5; manufacturing figures based on several studies converted to km using a 175,000km vehicle lifetime assumption

Ultimately, a full life-cycle analysis (LCA) should be used to compare vehicles including emissions from as widely across the value chain as is possible, also including emissions for manufacturing of assets along the supply chain (e.g. renewable power plants or pipeline or electricity transport infrastructure) as well as vehicle end-of-life costs and emissions.

As a simplification, we do not use a LCA approach here because it adds significant complexity and data requirements for cost calculations across different options.[13] End-of-life emissions are particularly uncertain and tend to be low relative to the rest of the value chain,[14] so adding these would be unlikely to change the overall picture significantly.

In this section we set out the emissions associated with each vehicle:

- **WTW** emissions including WTT and TTW, which is the area where the majority of vehicle emissions are incurred (Section 3.1); and
- **Manufacturing** emissions associated with direct production of vehicles (Section 3.2).

3.1 Well-to-Wheel (WTW) emissions

WTW includes WTT and TTW emissions (see Figure 20):

- WTT are the emissions associated with fuel production and transport to the point of use, and is mainly driven by the fuel type and its origin (e.g. renewable or fossil);
- TTW are the emissions associated with fuel combustion within the vehicle, and is driven by two factors: fuel type and assumptions on vehicle efficiency.

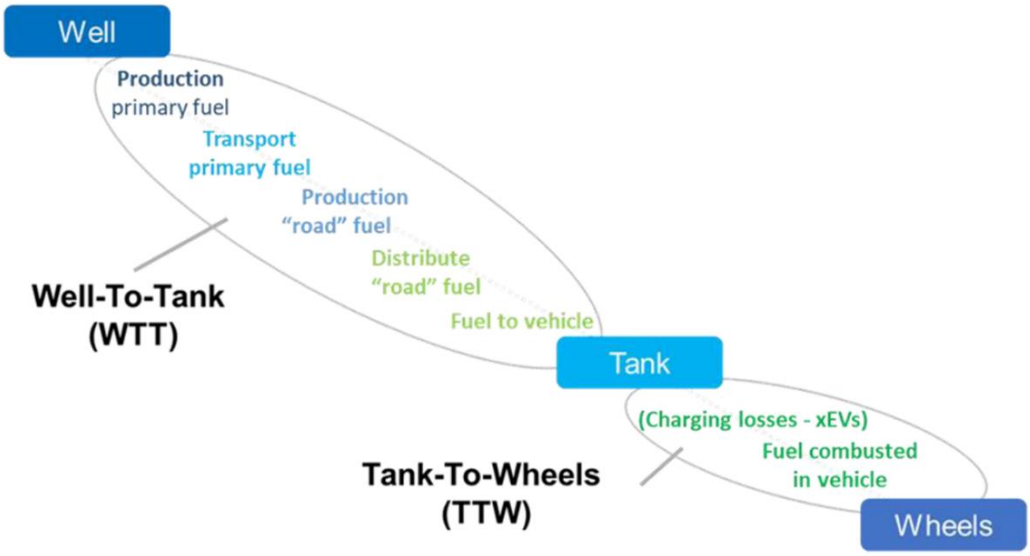
Our WTW emissions figures are taken from the JEC WTW v5 study,[15] see ANNEX A for further details.

[13] For example, the literature takes different views on the assumptions regarding battery recycling which affects emissions: see (Ahmadi et al., 2014; Canals Casals et al., 2017; Hall and Lutsey, 2018).

[14] For example, Ricardo (2020) estimates passenger vehicle end-of-life emissions in 2030 to be -8 gCO2eq/km for gasoline, -9 gCO2eq/km for CNG, and -9.5 gCO2eq/km for BEV based on a 225,000 km lifetime. This is in comparison to overall LCA emissions of 239 gCO2eq/km, 184 gCO2eq/km, and 67 gCO2eq/km respectively.

[15] European Commission (2020c).

Figure 20 Components considered in WTW approach



Source: JEC (2020)

3.1.1 Passenger vehicles

Figure 21 shows the WTT, TTW, and resulting WTW emissions associated with each passenger vehicle. Conventional gasoline vehicles have the highest overall emissions, while gas mobility and BEV offer lower emissions.

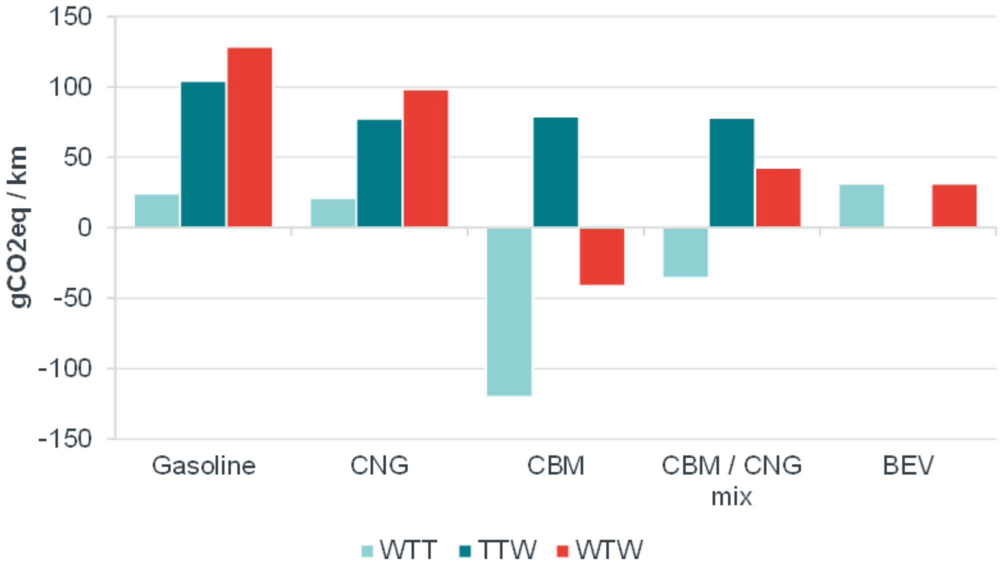
Vehicles running on pure biomethane have negative WTW emissions. This is driven by the strongly negative WTT emissions associated with the biomethane production from manure (assumed to be 35% of the feedstock mix, see).[16] Gas mobility using a 60/40 mix of CNG and CBM offers a comparable level of total WTW emissions to BEV.

BEV have zero TTW emissions because electricity does not emit GHG at the point of use, however it is important to note that the WTT emissions associated with electricity production are positive, and are higher than those associated with gasoline, natural gas or biomethane based fuels.[17]

16 Liquid manure is assigned emission credits when the emissions are calculated because burning produced biomethane releases lower GHG emissions than would otherwise be released from raw manure or slurry management since this releases methane. See ANNEX A for further details, based on the JEC WtW report.

17 In the longer term as the renewable share of generation increases, electricity production emissions will decrease. However, in 2030 it is expected that more than 50% of generation will still be non-renewable. IRENA (2018) forecasts that 41% of power generation will be from renewables in 2030, while EC (2019) forecasts that 45% of power generation will be from renewables in 2030. The JEC WtW report uses a 2030 electricity mix of 45% renewables.

Figure 21 WTW emissions for passenger vehicles in 2030



Source: *Frontier Economics based on JEC WTW v5.*
The electricity mix for BEV is based on the predicted EU electricity mix in 2030, which consists of 45% renewables.

Figure 22 outlines our assumptions on the fuel type and vehicle efficiency for each vehicle.

Figure 22 Passenger vehicle WTW assumptions

	Gasoline	CNG	CBM	CNG/CBM mix	BEV
Fuel mix	Conventional fossil gasoline	Fossil CNG	Biomethane produced from feedstock mix: 45% waste, 35% manure, 10% gasification, 10% power	60% CNG mixed with 40% biomethane using assumed feedstock mix	EU 2030 grid electricity, composed of 45% renewables
Vehicle efficiency (MJ/km)	1.42	1.4	1.4	1.4	0.42

Source: *Frontier Economics based on NGVA Europe and JEC WTW v5*

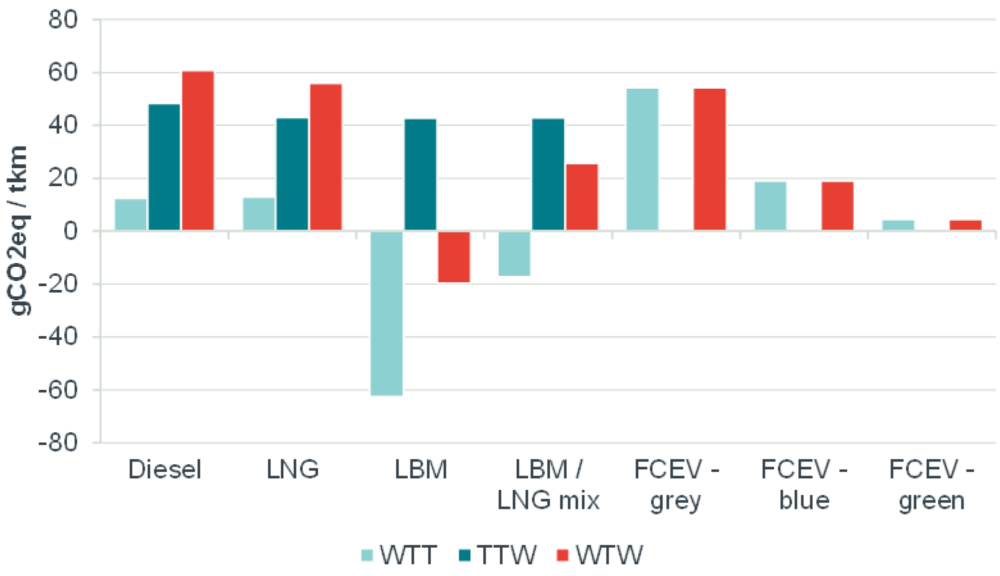
Note: *Efficiency is defined as the amount of energy required to power a vehicle for one kilometer. Therefore, a higher numerical value in MJ/km represents a less efficient vehicle because more energy is required to power it for a given distance.*

3.1.2 Trucks

Figure 23 shows the WTT, TTW, and WTW emissions associated with each truck. Diesel, LNG, and FCEV running on grey hydrogen all have similar levels of emissions. While LNG has a lower carbon intensity than diesel, LNG trucks have a lower vehicle efficiency which results in marginally lower overall TTW emissions for LNG compared to diesel (see ANNEX A for further details). Similarly to compressed biomethane in cars, bio-LNG production has negative WTW emissions which are mainly driven by the avoided methane emissions for manure feedstocks. The LBM / LNG mix vehicle has the lowest WTW emissions from the baseline vehicles that we consider.

Analogously to BEV in passenger cars, FCEV have zero TTW emissions, because neither the fuel cell that produces electricity from hydrogen nor the electric engine does emit at the point of use. However, the WTT fuel production emissions associated with grey hydrogen are significant, as this hydrogen is produced from fossil fuels (such as natural gas) via Steam Methane Reformation (SMR). Production emissions associated with blue and green hydrogen are much lower: for blue hydrogen, the emissions arise from natural gas production and transportation and residual emissions during the SMR and the Carbon Capture and Storage (CCS) process, while for green hydrogen, i.e. hydrogen produced by electrolysis based on renewable electricity, the only emissions come from the road transportation of the fuel. However, it is important to note that the availability of blue and green hydrogen is uncertain over the next decade, therefore we use grey hydrogen as our main comparator, while we include the effects of fuelling FCEV trucks with blue and green hydrogen here as an illustration.

Figure 23 WTW emissions for trucks in 2030



Source: Frontier Economics based on JEC WTW v5

Figure 24 sets out our baseline assumptions on fuel mix and vehicle efficiency for each truck that we use in our analysis based on the JEC WTW study. For LNG and LBM trucks, we assume a 2030 vehicle mix of 66% PI engines and 33% HPDI, which gives an overall efficiency of 0.78.[18] The JEC study forecasts that FCEV will achieve a 28% reduction in fuel consumption relative to diesel, which may be optimistic given that today there are no 40T FCEV trucks in existence. We use the

[18] A PI engine refers to Positive Ignition. A High Pressure Direct Injection Compression Ignition (HPDI) engine, also referred to as dual fuel LNG–Diesel engine, uses the Direct Injection Compression Ignition (CI) combustion principle and can hence combine the compared to a PI combustion higher efficiencies of the diesel combustion process with the lower C/H-ratio of methane compared to diesel.

JEC figure in our analysis for consistency across vehicles, however other studies suggest that this is a conservative upper bound for FCEV efficiency.[19, 20, 21]

Figure 24 Truck WTW assumptions in 2030

	Diesel	LNG	LBM	LNG/LBM mix	FCEV grey H2	FCEV blue H2	FCEV green H2
Fuel mix	Conventional fossil diesel	Fossil LNG	Bio-LNG produced from feedstock mix: 45% waste, 35% manure, 10% gasification, 10% power to gas	60% LNG mixed with 40% bio-LNG using assumed feedstock mix	Grey hydrogen produced from SMR without CCS	Blue hydrogen produced from SMR with CCS	Green hydrogen produced via electrolysis from renewable electricity
Vehicle efficiency (MJ/tkm)	0.66	0.78	0.78	0.78	0.48	0.48	0.48

Source: Frontier Economics based on NGVA Europe and JEC WTW v5

Note: Efficiency is defined as the amount of energy required to power a vehicle for one kilometer. Therefore, a higher numerical value in MJ/km represents a less efficient vehicle because more energy is required to power it for a given distance.

3.2 Manufacturing emissions

3.2.1 Passenger vehicles

We estimate the emissions stemming from vehicle manufacturing by looking at a range of studies. To combine one-off vehicle manufacturing emissions – that occur per manufactured vehicle irrespective of how many kilometres the vehicle drives in its lifetime – and WTW emissions (in gCO2eq/km), we transform vehicle manufacturing emissions to gCO2eq/km by assuming 175,000 km lifetime mileage for each vehicle type.[22]

Published studies vary significantly in their approach and the assumptions used. Therefore, we only consider studies which compare CNG or BEV emissions to a gasoline baseline to ensure the delta is based on the same underlying assumptions. Figure 25 summarises the study deltas for CNG and BEV above the

[19] Burk and Zhao (2017) estimate that FCEV efficiency is likely to be 21% higher than diesel for long haul trucks in 2030

[20] Nikola Corporation (2020) claims fuel consumption for FCEV of 7.5 miles / kg of H2 which is similar to future diesel consumption of 8.4 miles per gallon

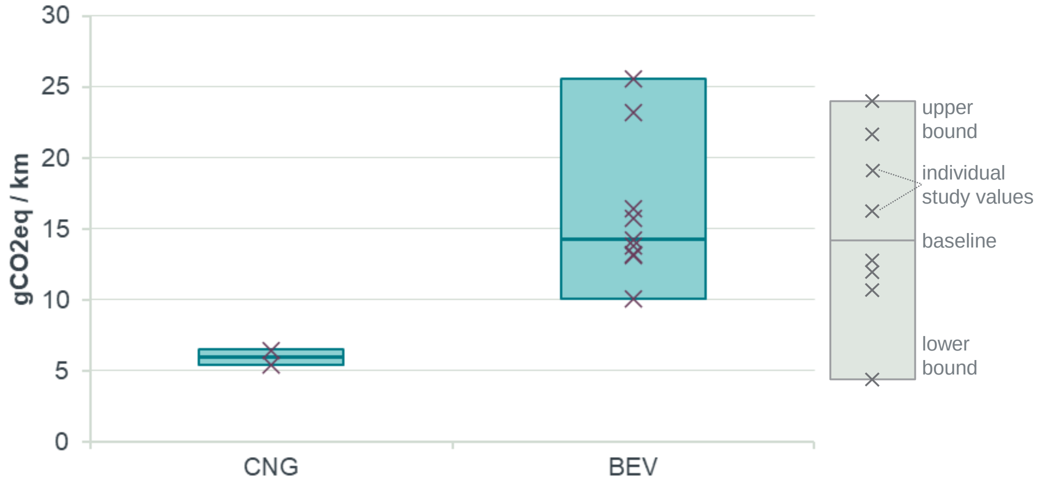
[21] The Hyundai Xcient truck is currently the only operational FCEV truck in Europe. It has a range of 400km per 32kg of Hydrogen (https://fuelcellsworks.com/news/worlds-first-fuel-cell-heavy-duty-truck-hyundai-xcient-fuel-cell-heads-to-europe-for-commercial-use/). Based on an assumption of 120 MJ/kg for hydrogen and 35 MJ per litre for diesel fuel, this is equivalent to 27.4 diesel litres equivalent per 100km. The Hyundai is only rated to 36 tonnes in trailer pull mode, therefore this further supports a maximum 1.2x efficiency factor for FCEV vs diesel.

[22] Whenever studies have diverging assumptions we amend their values by adjusting them using our mileage assumption to ensure consistency across studies.

gasoline baseline within each study.[23] Our baseline delta is the median of the studies.

For CNG there are relatively few studies, which give similar deltas above gasoline: Ardey (2018) which gives a delta of 5gCO2eq/km above gasoline, and Ricardo (2020) which gives a delta of 6gCO2eq/km above gasoline. For BEV, the studies give a much wider range of emission estimates. This reflects the uncertainty associated with the relatively less mature technology and the need to forecast the electricity mix used in producing batteries and its related carbon intensity. There is also some uncertainty around CNG vehicle manufacturing emissions as production scales up, however this is a more established technology than batteries. To account for the uncertainty we include sensitivity ranges around our baseline values using the upper and lower bounds from our literature review.

Figure 25 Manufacturing emissions above gasoline in 2030 based on literature review



Source: Own illustration based on literature review. CNG: Ardey (2018) and Ricardo (2020). BEV: Agora (2018), Ardey (2018), Baumann et al. (2019), Del Pero et al. (2018), FFE (2019), ICCT (2018), Joanneum Research (2019), Kawamoto et al. (2019), Zapf et al. (2019), Ricardo (2020).
Note that we assume 175,000 lifetime mileage for each vehicle type.
The manufacturing emissions for CNG, CBM and CNG/CBM mix are the same, as there are no extra emissions associated with installing a vehicle tank that can fuel a gas blend.

To construct our parameter ranges, we then add the deltas to a gasoline baseline of 31gCO2eq/km which is the median value resulting from a meta-analysis of 12 LCA studies.[24] Figure 26 provides a table overview of the absolute value of manufacturing emission assumptions we use.

---

23 Note that most studies look at 2020 rather than 2030. To obtain emissions figures for 2030, we reduce study values from 2020 by a technology-specific emissions reduction factor. For CNG, the reduction factor is 5% based on Ricardo (2020) which estimates emissions in 2020 and 2030. For BEV, the reduction factor is 24% based on an average of Ricardo (2020), UNITI (2019), and VDI (2020). VDI (2020) predicts a 9% reduction in emissions, while Ricardo (2020) and UNITI (2019) are more optimistic and predict 30% reductions.

24 As the meta-analysis is analysing current vehicle manufacturing emissions, we adjust the values to 2030 values by applying the assumption of a ~12% emission reduction between 2020 and 2030 in Ricardo (2020).

Figure 26 Passenger vehicle manufacturing emissions in gCO2eq/km

Scenario	Gasoline	CNG/CBM	BEV
Baseline	31.4	37.3	45.6
Lower bound		36.8	41.5
Upper bound		37.8	54.6

Source: Frontier Economics calculations based on literature review.

3.2.2 Trucks

We calculate the vehicle manufacturing emissions for trucks by taking the values of Ricardo (2020) for each vehicle type and dividing them by their assumed lifetime mileage of 1,605,672 tonne-kilometres. FCEV trucks have the highest emissions with 17 gCO2eq/t-km. Diesel and LNG vehicles have lower emission with 10 and 12 gCO2eq/t-km respectively. We use Ricardo (2020) for consistency across vehicles, however note that other studies find that LNG vehicles have manufacturing emissions at a similar level to diesel.[25]

Figure 27 shows our assumptions on the emissions related to manufacturing of heavy duty vehicles in 2030. Manufacturing emissions are the same for each blend of LNG and bio-LNG because there is no difference in the tank required for various levels of bio-LNG.

Figure 27 Truck vehicle manufacturing emissions in gCO2e/(t)km

Scenario	Diesel	LNG	FCEV
Baseline	10	12	17

Source: Frontier Economics calculations based on literature review.

[25] Carbone 4 (2020) shows similar manufacturing emissions for LNG and diesel trucks

4 COSTS

We calculate annual system costs across the value chain associated with one vehicle in 2030 (EUR per vehicle per year). Some costs are variable and incurred on a per-km basis (such as fuel production costs), while others are one-off fixed costs (such as manufacturing and infrastructure). To make these costs comparable, we annualise any one-off costs over the lifetime of the relevant investment.[26] For variable costs, we calculate total yearly costs based on an assumed annual mileage for each vehicle.

Throughout the calculations we use economic costs rather than user cost. This allows us to compare the cost of CO_2 emission abatement to society, excluding all taxes, levies and subsidies (which are policy-driven). For example, while biomethane and CNG are likely to have similar costs for the user at the point of use (due to subsidies for biomethane), they have different production costs.

In this section we set out our approach to each segment of the value chain in 2030:

- **Manufacturing** of vehicles, which is the largest cost component in the value chain (Section 4.1);
- **Fuel production** based on the levelized cost of production (Section 4.2);
- **Fuel transport** within Europe, taking into account the extent to which existing infrastructure can be utilised for natural gas and electricity transportation and distribution (Section 4.3);
- **Refuelling** network expansion for fuels where the current network is more limited today (Section 4.4).

4.1 Manufacturing costs

Vehicle manufacturing costs are the largest component of annual overall costs for both passenger vehicles and trucks. Therefore, they have a big impact on the CO_2 emission abatement costs. Manufacturing costs are one-off Capital Expenditure (CAPEX) investments which we annualise over a 15 year lifetime for passenger cars and a 9 year lifetime for trucks.[27]

4.1.1 Passenger vehicles

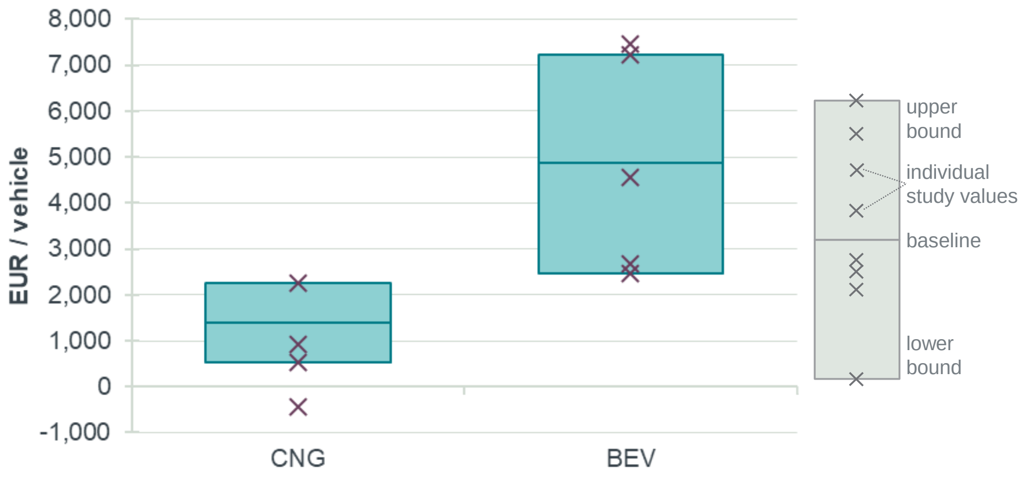
We use assumptions on the total cost for each vehicle based on a range of published studies, and then calculate the cost premium for each alternative fuel vehicle relative to the gasoline baseline. Figure 28 shows the results for passenger vehicle manufacturing costs premiums in 2030. This includes a sensitivity range for each vehicle to reflect uncertainty associated with how manufacturing costs will develop over the next decade.

[26] For example, vehicle manufacture costs are annualised over the assumed vehicle lifetime which is 15 years for passenger cars and 9 years for trucks. Refuelling station investments are annualised over the assumed lifetime of the station which is 30 years.

[27] The difference in lifetime between passenger cars and trucks comes from their different use profiles. Trucks tend to have a higher yearly mileage and therefore shorter lifetime in year terms.

BEV manufacturing has a significantly higher cost premium to gasoline than CNG, with a baseline cost premium of 4,900 EUR per vehicle (BEV vs. gasoline) and 1,400 EUR per vehicle (CNG vs. gasoline) respectively. Note that the costs for CNG, CBM and the CNG/CBM mix are the same, as there are no costs associated with using a blend in the vehicle tank. CNG vehicles have lower cost uncertainty range than BEV because they are a well-established technology today, while battery production technology is less mature and consequently future developments of battery production technologies and associated costs are less foreseeable (see text box on battery cost developments below).

Figure 28 Passenger vehicle manufacturing cost premiums above gasoline in 2030

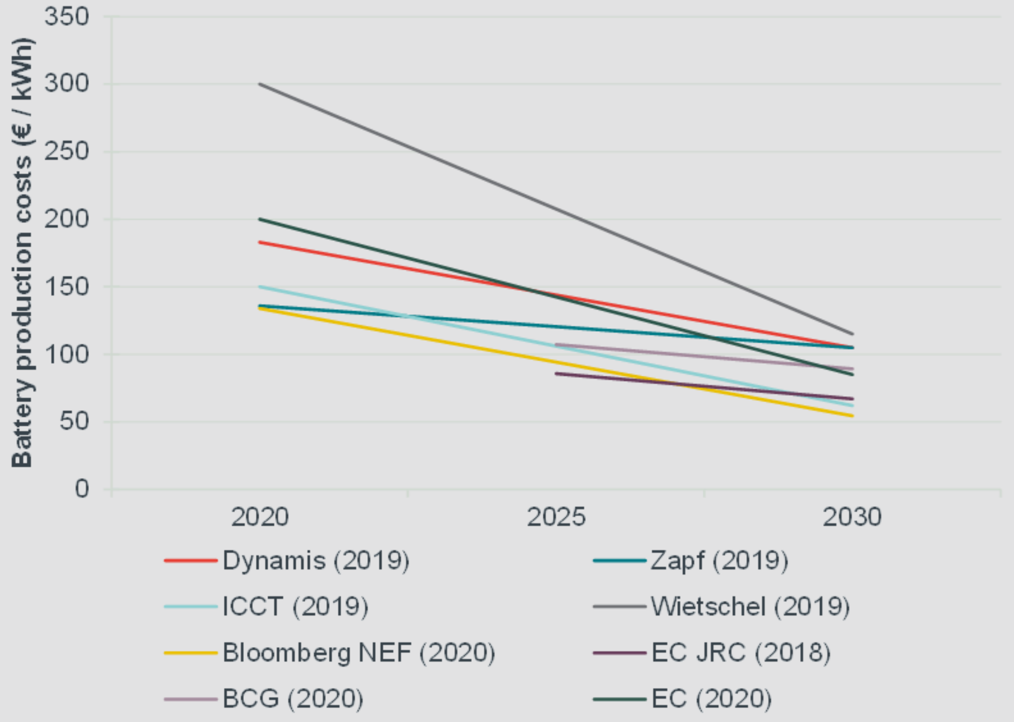


Source: Frontier Economics based on literature review (see below for details)

BATTERY MANUFACTURING COSTS

One of the main components for the BEV manufacturing costs are the battery capacity and battery manufacturing cost assumptions. While all studies we looked at agree that battery manufacturing costs will decline in the future, the cost estimates vary substantially across studies. The 2030 estimates still range from 54 to 115 EUR/kWh. Figure 29 shows the level and trajectory of battery manufacturing cost assumptions across the reviewed studies.

Figure 29 Battery manufacturing cost assumptions

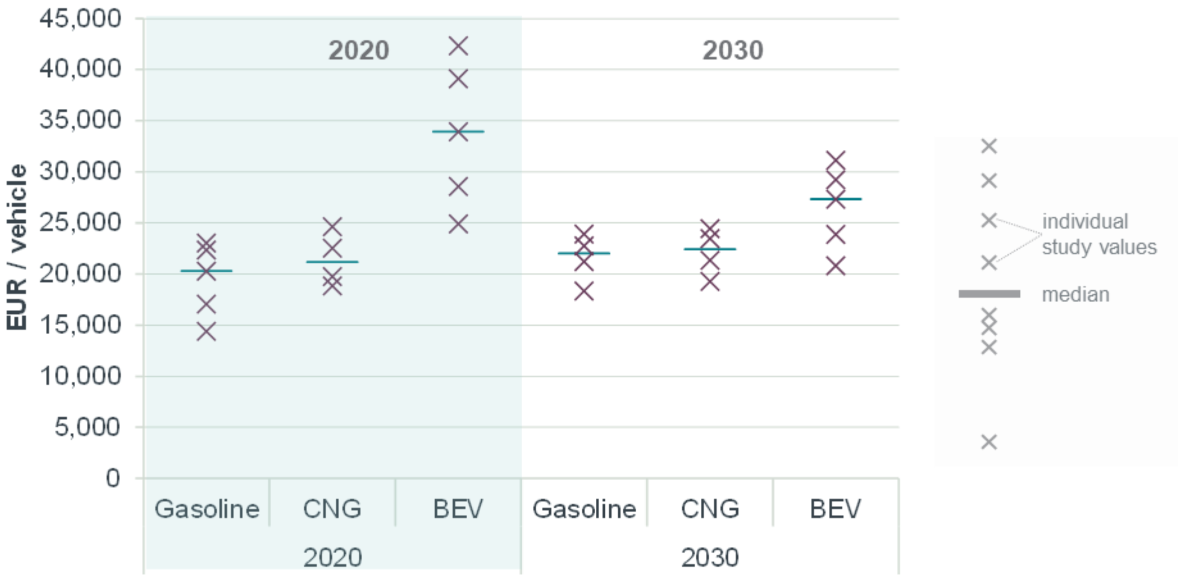


Source: Frontier Economics based on literature review.

Passenger vehicle manufacturing cost inputs

We calculate vehicle manufacturing costs by taking a range of studies into account. Figure 30 shows the costs estimates of all the studies we considered, and the corresponding median value. Cost estimates vary widely across studies, which is most pronounced for BEVs, due to the different assumptions taken on vehicle characteristics including weight, power, battery size and battery production costs. This means that the studies have different starting points for gasoline vehicles and so are not easily directly comparable.

Figure 30 Median passenger car manufacturing costs in 2020 and 2030



Source: Frontier Economics based on literature review of Dynamis (2019), Dena (2018), ICCT (2019), Wietschel (2019), Zapf (2019).
Please note that we consider economic cost here and not end customer prices, i.e. prices do not include taxes or subsidies.

Figure 31 shows the cost premium for CNG and BEV in 2030 within each study.[28] Using this measure, the studies give a more consistent picture of the additional cost of CNG and BEV above gasoline. Cost estimates for CNG are relatively homogeneous across studies, with a small premium above gasoline. In contrast, the costs premium of BEVs is still estimated to be much greater than gasoline and more uncertain than CNG across studies.

We define our cost ranges by combining the approaches of several studies.[29] For the upper bound, we use the study with the highest cost premium above gasoline for CNG and BEV respectively. For CNG this is gives a cost premium of around 2,200 EUR (Dynamis (2019)), while for BEV it gives a cost premium of 7,200 EUR above gasoline (Dena (2018)).[30] For the lower bound, we use the study with the lowest cost premium above gasoline which gives 500 EUR for CNG (Dena (2018))[31] and 2,400 EUR for BEV (Zapf (2019)). Our baseline is the mid-point between the upper and lower bounds for each vehicle.

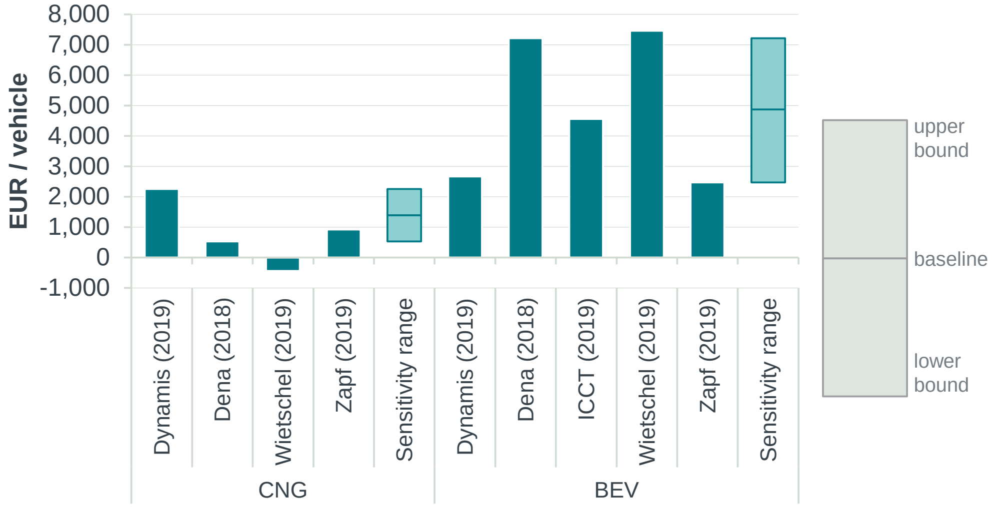
28 For example, the values for Dynamis (2019) show the cost difference between a CNG and a gasoline vehicle as they are given in Dynamis (2019).

29 We adjust the cost estimates for BEV to have comparable battery sizes. See ANNEX A for further details.

30 Note we do not use the Wietschel (2019) value because it compares BEV to diesel rather than gasoline. In any case it is a similar figure to Dena (2018).

31 We exclude Wietschel (2019) from our sensitivity range because it compares CNG to diesel rather than gasoline and therefore gives a negative cost premium, i.e. CNG is cheaper than diesel.

Figure 31 Vehicle manufacturing costs in 2030



Source: Frontier Economics based on a range of published studies
Dynamis (2019) has been adjusted for BEV to reflect a battery consistent with a 500km range rather than 300km.
Wietschel (2019) compares CNG and BEV to diesel, so we do not include it in our sensitivity range

To obtain our parameter estimates for vehicle manufacturing costs, we add the deltas for CNG and BEV to a baseline gasoline figure taken from Dynamis (2019).[32] The vehicle manufacturing costs are shown in Figure 32.

Figure 32 Passenger vehicle manufacturing costs in 2030

	Gasoline	CNG	BEV
Baseline	21,212	22,605	26,084
Lower bound	-	21,741	23,678
Upper bound	-	23,468	28,426

Source: Frontier Economics calculations based on literature review.

4.1.2 Trucks

There are fewer studies available that estimate the production costs of heavy-duty vehicles. Figure 33 shows the total production costs for the three vehicle types we consider in our study in 2030. The values are derived by adjusting current Dynamis (2019) figures to 2030 using the relative cost increases from different studies for LNG and FCEV:

- **Diesel 107,228 EUR/vehicle:** We take the production costs of a diesel ICEV in 2030 from Dynamis (2020).
- **LNG 117,950 EUR/vehicle:** We take the diesel production costs in 2030 and add the relative increase in Wietschel (2019) from diesel ICEV to LNG in 2030.[33]

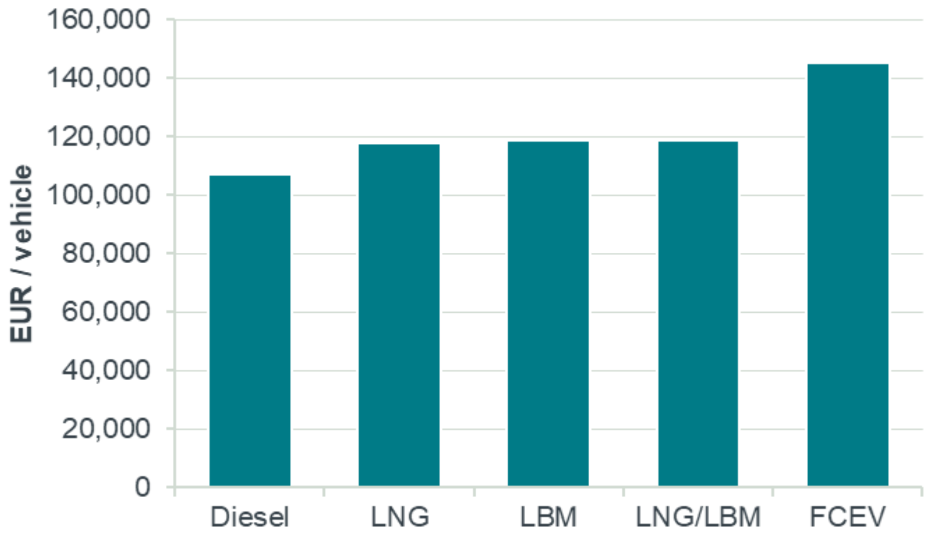
[32] We adjust the Dynamis figure from a purchase price to a manufacture price using an assumed margin of 20% based on Roland Berger (2016).

[33] We use the Wietschel (2019) relative change, as Dynamis (2019) predicts a very high premium above diesel of 52% for LNG (significantly higher than the 2020 premium of 7%), which we do not deem plausible.

- **FCEV 141,667 EUR/vehicle:** We take the production costs of a FCEV in 2030 from Dynamis (2020), noting that there is significant uncertainty about the development of FCEV costs over the next decade.[34]

In summary, the costs of LNG trucks are projected to be similar to diesel, while FCEV trucks are expected to be more costly in 2030. Further, there is uncertainty around when FCEV trucks will enter the market at scale over the next decade.

Figure 33 Heavy-duty vehicle manufacturing costs



Source: Own illustration based on literature review of Dynamis (2019) and Wietschel (2019). Please note that we consider economic cost here and not customer prices, i.e. prices do not include taxes or subsidies.

4.2 Fuel production costs

We use estimated levelized cost of fuel production in 2030. This measure of costs includes CAPEX and OPEX on a per-MWh basis for each fuel, which allows us to compare the full cost of production across each fuel type.[35] Note that the costs used here are lower than those faced by end users, because they do not include fuel duties and taxes.

The EUR/MWh fuel costs are transformed into annual vehicle costs using an assumed vehicle efficiency in MWh/(t)km and yearly mileage in (t)km.

4.2.1 Passenger vehicles

Figure 34 shows the fuel production cost in 2030 for each vehicle on a per MWh basis and a total annual cost basis. Electricity has the highest production cost in

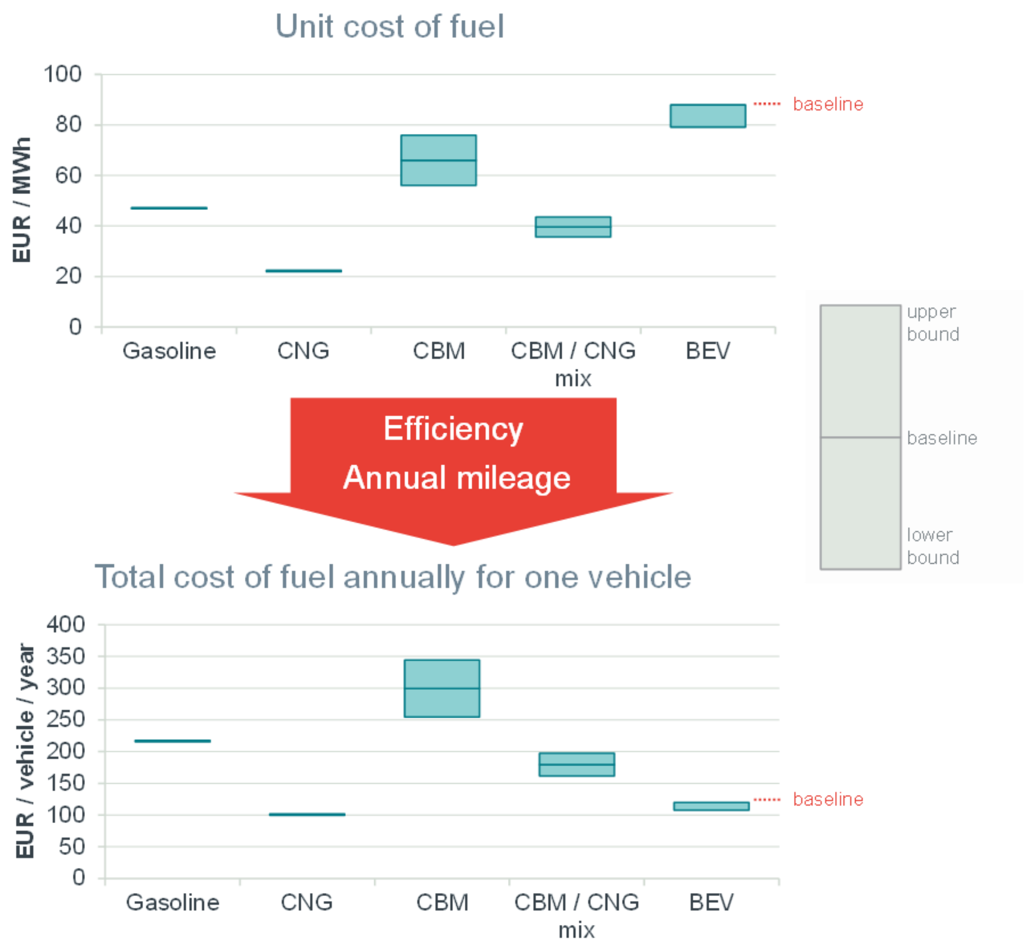
[34] Dynamis (2019) predicts an large cost decrease from 2020 to 2030: from 257% premium above diesel in 2020 to 48% premium in 2030. Other sources predict less significant cost reductions, for example ICCT (2017) predicts that a FCEV truck will cost around 217,000 EUR in 2030. Oko (2018) gives FCEV truck costs of 121,000 EUR in 2030.

[35] Biomethane, hydrogen, and renewable electricity production will need to be scaled up over the next decade, therefore it is appropriate to take into account the CAPEX associated with these investments. Investment in conventional fuels will also be required due to ongoing O&G exploration and increasing transport demand.

EUR/MWh based on the EU generation mix in 2030. However, this translates into a relatively low total cost of fuel, because BEVs are more efficient than ICE vehicles. CNG vehicles have low unit and total fuel costs, while vehicles running on biomethane have relatively high fuel production costs. Note that for end users, the cost of CNG and bio-CNG at the pump may be similar due to subsidies for biomethane, which we do not include in our calculations as we look at economic costs (and not user costs).

Biomethane fuel cost in 2030 is uncertain due to feedstock mix assumptions and potential technological improvements in the production process as supply is scaled up. In addition, there is some uncertainty about the cost of renewable electricity production which we include in our sensitivity range for BEV.

Figure 34 Passenger vehicle fuel production cost in 2030



Source: Frontier Economics based on literature review, see ANNEX B for details
Please note that we consider economic cost here and not end customer prices, i.e. prices do not include taxes or subsidies. For ease of reference, the 46.8 EUR/MWh fuel production cost for gasoline (equivalent to 13 EUR/GJ based on JEC WTTv5) are equivalent to 0,42 €/l gasoline (based on an energy density of gasoline of 8,88 kWh/l or 32 MJ/l), which is only a fraction of what end customers have to pay at filling stations where substantial taxes have to be paid on top of production and distribution cost.

We calculate two sensitivities around the fuel production baseline by varying the following parameters:

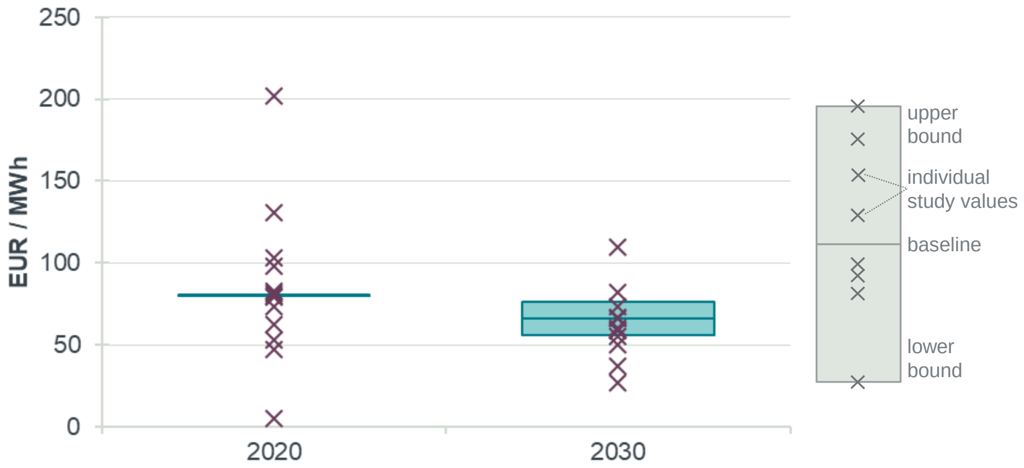
- Fuel production cost for biomethane and renewable electricity

- Renewable electricity share of generation

Sensitivity analysis: Fuel production cost

Figure 35 shows a range of studies which estimate the cost of biomethane production today, and forecasts to 2030. Our baseline of 66 EUR/MWh comes from Navigant (2019) based on their predicted EU feedstock mix.[36] Navigant (2019) gives a range estimate of 58 – 75 EUR/MWh, which is roughly +/- 10%. To be conservative, we widen this range to +/- 15% for our sensitivity which gives a lower bound of 58 EUR/MWh and an upper bound of 76 EUR / MWh.

Figure 35 Biomethane production costs in 2020 and 2030



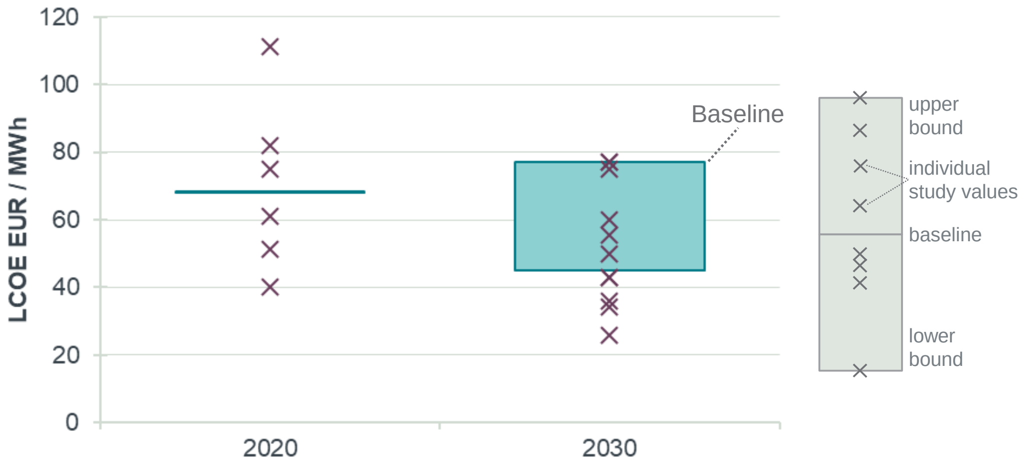
Source: Frontier Economics based on literature review, see ANNEX B for details
Note that for 2020 some of the costs were estimates for biogas and are adjusted by purification costs of 8,5 EUR/MWh (Navigant 2019 give a range of 5-12 EUR/MWh).

In addition to varying the biomethane production cost, we also vary the levelized cost of electricity generation from wind. We use a baseline overall generation mix cost in 2030 of 88 EUR/MWh which is taken from European Commission (2019). Of this mix, 20% is wind with a cost of 77 EUR/MWh. Figure 36 shows several other studies which look at wind costs in 2030. In our sensitivity we vary this cost downwards to 45 EUR/MWh which is an average of the 2030 onshore wind cost estimates. We hold the cost of the remaining sources of generation constant.

This has a relatively small downward impact on the overall cost of electricity because wind generation accounts for around 20% of EU electricity generation in 2030.

[36] Due to the limited availability of published costs on feedstock-specific biomethane production, we use Navigant (2019)'s assumed mix for the costs. This is a different approach to emissions, where we are able to construct an emission value which reflects our assumed feedstock mix due to the data granularity in the JEC WTW report.

Figure 36 Wind generation costs in 2020 and 2030

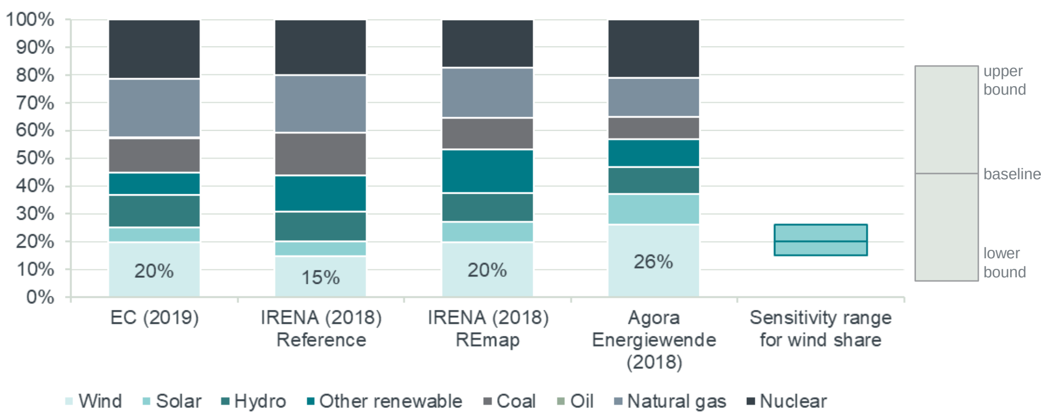


Source: Frontier Economics based on literature review, see ANNEX B for details

Sensitivity analysis: Fuel mix

Renewable electricity generation in the EU is expected to increase as a share of the overall generation mix from 30% today to around 45% - 54% in 2030, as shown in Figure 37. Wind makes up a significant part of this, accounting for 15% - 26% of overall generation in 2030. We therefore vary the 2030 wind share based on forecast values from a baseline of 20% to a lower bound of 15% and an upper bound of 26%.

Figure 37 2030 EU power mix



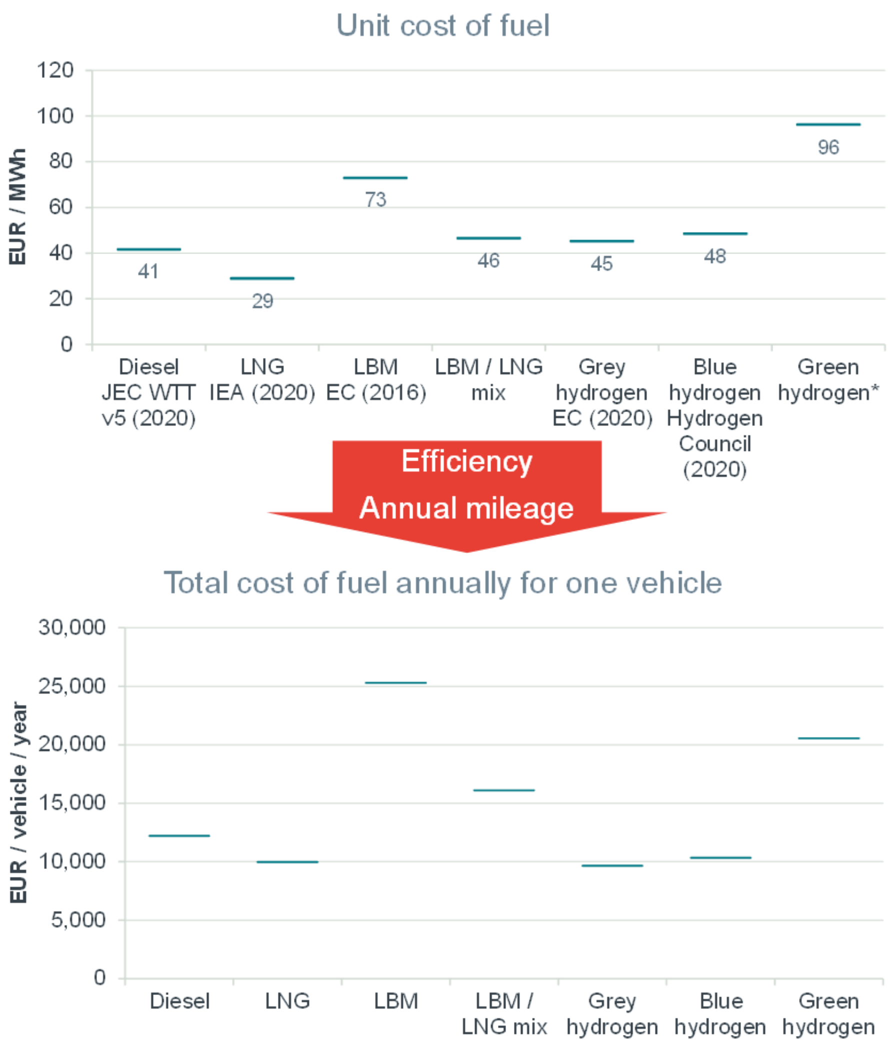
Source: Frontier Economics based on literature review

There is also uncertainty around the level of biomethane in the CNG/CBM mix in 2030. We reflect this uncertainty throughout the report by showing gas mobility results for 100% CNG, 100% CBM, and a 60%/40% CNG/CBM mix.

4.2.2 Trucks

Figure 38 shows the total cost of fuel for one truck per year based on published studies. LNG and grey hydrogen are the cheapest fuels, while bio-LNG is relatively more expensive.[37] Green hydrogen is the most expensive fuel due to the technological immaturity of electrolysis in 2030, although significant cost reductions are expected relative to today.[38]

Figure 38 Truck fuel production cost in 2030



Source: Frontier Economics based on literature review
**Note that green hydrogen costs in particular are uncertain, and depend on the scale of deployment over the next decade. It is possible that significant cost reductions could materialise if green electrolysers are deployed at a large scale.*

[37] The bio-LNG cost is taken from the same source as the biomethane cost for passenger vehicles, plus a liquefaction cost of 6.7 EUR/MWh taken from Agora Energiewende and Frontier Economics (2018)

[38] Sources for green hydrogen costs vary significantly. We take an average of the following studies which estimate green hydrogen levelized costs for 2030: CERRE (2019) 67 EUR/MWh, IRENA (2020) 93 – 107 EUR/MWh, IEA (2019) 117 EUR/MWh. The actual cost of green hydrogen will depend on several factors including the definition of 'green' electricity and whether new-build dedicated renewables must be co-located geographically with electrolysers and used for hydrogen production.

Please also note that we consider economic cost here and not customer prices, i.e. prices do not include taxes or subsidies.

4.3 Fuel transport costs

We calculate the cost of transporting fuel within Europe to the point of use for each vehicle.[39] This includes transportation and distribution costs.

4.3.1 Passenger vehicles

Significant transportation and distribution infrastructure exists today for natural gas, therefore we assume no additional transport CAPEX investment is required to supply CNG vehicles. The cost of compressing natural gas is included in the refuelling station cost (see Section 4.4).

For electricity, it is expected that increasing BEV demand will necessitate grid reinforcement and new transmission and distribution lines. The magnitude of this reinforcement is complex to model and requires many assumptions around the evolution of wider electricity demand. For simplicity, we only look at O&M costs here, and include some grid reinforcement costs in our refuelling estimate (see Section 4.4). This is a conservative assumption with respect to BEV costs: it is likely that the cost of expanding electricity grid infrastructure will be substantial.[40,41]

Figure 39 shows the cost of fuel transportation for CNG vehicles and BEV. biomethane is blended into the natural gas network and therefore has the same fuel transportation costs as CNG. Transport costs are higher for CNG than BEV. This is because CNG fuel demand is higher than BEV due to its lower vehicle efficiency. In addition, we have not included electricity grid reinforcement costs here, so the electricity transport cost is a lower bound estimate.

Figure 39 Passenger vehicle fuel transport costs

	End vehicle fuel demand per year (MWh / vehicle / year)	Fuel transport O&M cost (EUR / MWh)	Total fuel transport O&M cost (EUR / vehicle / year)
CNG	4.5 MWh	1.3 EUR	5.9 EUR
BEV	1.4 MWh	0.2 EUR	0.3 EUR

Source: *Frontier Economics based on literature review, see ANNEX C for details*

Note: *Calculations are only based on O&M costs for fuel transported 400 km within Europe. Costs do not include grid reinforcement for electricity and are therefore conservative.*

---

[39] We do not model costs for gasoline or diesel as a simplifying assumption, because costs are small for these technologies and the focus of the study is a comparison between g-mobility and BEV.

[40] ENTSO-E's Ten-Year Network Development Plan forecasts that an additional 50GW of cross-border transmission capacity reinforcements will be required at a cost of 1.3bn EUR/year up to 2030. Note that this will clearly support all electricity demand, not just demand from transport. Allocating EU-wide grid reinforcement to transport is complex and beyond the scope of this study.

[41] Brinkel et al (2020) find that cost and emission savings arising from more flexible EV charging are smaller than the costs and emissions incurred from installing grid reinforcement assets.

4.3.2 Trucks

We assume that LNG and hydrogen transport takes place via road tanker in 2030, with an average transport distance of 400 km within the EU for each fuel.[42] Figure 40 shows that LNG has lower fuel transport costs than hydrogen. This is driven by the characteristics of each fuel:

- **Higher energy density of LNG pushes LNG transport costs down.** LNG, cooled at minus 160°C has a substantially higher energy density than compressed gases (e.g. hydrogen). This means that LNG road tankers have a higher transport capacity than hydrogen tube trailers. Typical LNG road tankers can transport around 20,000 kg of LNG per trip, while the largest H2 tube trailers are only able to transport around 1,100 kg.[43] Therefore, even when taking into account the approximately twice as high gravimetric energy density of H2, LNG road tankers are able to supply significant more fuel per trip than hydrogen tube trailers, which results in lower costs for LNG transport.
- **Lower end vehicle efficiency of LNG pushes LNG transport costs up.** FCEV trucks have an efficiency of 0.13 kWh/tkm, while LNG trucks have an efficiency of 0.22 kWh/tkm. This means that the overall end fuel demand for hydrogen is lower than for LNG. As a result, less hydrogen needs to be transported to supply end vehicles, which lowers transport costs relative to LNG.

The higher energy density of LNG dominates the calculation. It outweighs the better efficiency of FCEV relative to LNG trucks, and results in an overall lower cost of fuel transportation for LNG. In addition, hydrogen tube trailers are slightly more expensive than LNG transportation trucks.

Figure 40 Truck fuel transport costs

	End vehicle fuel demand per year	Capacity of road tanker on one trip	Number of tankers needed for 1 vehicle per year	Cost of tanker (EUR)	Transport CAPEX (EUR/vehicle/ year)	Transport OPEX (EUR/vehicle/ year)
LNG	347 MWh 22,771 kg	20,000 kg	0.01 road tanker	120,000	121	76
H2	214 MWh 6,423 kg	1,100kg	0.05 road tankers	163,000	867	88

Source: Frontier Economics based on literature review, see ANNEX C for details

We include CAPEX and OPEX fuel transportation costs. CAPEX is the cost of the road tankers required to supply one LNG truck or FCEV, annualised over the

[42] In 2030, hydrogen may be transported a shorter distance if it is mostly used for local transport located close to production sites. For comparability, we use the same transport distance assumption for both LNG and hydrogen. Reducing the average hydrogen transport distance would reduce overall transport costs, however for most distances it is still more costly to transport than LNG due to the effects described here.

[43] Hydrogen Europe https://hydrogeneurope.eu/hydrogen-transport-distribution.

lifetime of the road tanker. OPEX is the annual fuel cost of the road tanker based on an assumed annual mission profile and payload.

Our hydrogen fuel transportation cost assumptions are conservative. We assume that there is no dedicated EU-wide hydrogen pipeline network by 2030. Due to the limited number of hydrogen production sites expected to be online in the 2020s, use of hydrogen in heavy goods transport is likely to be limited to fleets with established routes. Including the cost of a hydrogen transmission system would increase the cost of FCEV significantly. Guidehouse (2020) estimate the cost of establishing a ‘Hydrogen Backbone’ pipeline network in the EU by 2040 will range between 27bn – 64bn EUR, which includes the capital cost of building and retrofitting pipelines.

4.4 Refuelling costs

We assume that sufficient refuelling infrastructure is in place for conventional vehicles (gasoline and diesel) and no expansion is required to meet 2030 demand.

4.4.1 Passenger vehicles

Refuelling stations for CNG vehicles already exist today, with around 4,000 across Europe.[44] However, further expansion of the refuelling network is required to increase geographic coverage across Europe and support a greater number of vehicles. Similarly for BEV, public charging points already exist today but more will be needed as the number of BEVs increases.

Figure 41 shows the refuelling costs for each vehicle. CNG / CBM vehicles have much lower refuelling costs than BEV. This is because the required station density is lower since gas-fuelled vehicles have a greater range than BEV (and therefore need to refuel less often), and they are quicker to refuel. CNG and CBM refuelling stations have the same costs; there are no additional costs associated with supplying biomethane blends or pure biomethane compared to natural gas.

[44] https://www.ngva.eu/stations-map/.

Figure 41 Passenger vehicle refuelling cost assumptions

	CNG / CBM	BEV
# stations : vehicle in 2030	1 station per 1,000 vehicles [45]	1 private charging point per vehicle plus 1 public charging point per 130 vehicles
Cost of infrastructure	Invest: 350,000 – 450,000 EUR per station O&M: 3% of invest p.a.	1,400 EUR per vehicle Includes 1,050 for private charger and 350 for public network[46]
Cost per vehicle annualised	25 EUR/vehicle/year	93 EUR/vehicle/year

Source: CNG / CBM numbers based on NGVA Europe assumptions; EV cost values (that include equipment, installation, and grid upgrade) based on Transport & Environment (2020)

We assume incremental costs are linear with each additional vehicle in 2030 as a simplification. But it is important to note that initially the refuelling network will be underutilised because it must provide sufficient geographic coverage to support vehicle uptake, therefore in the longer term these investment costs will be spread over a larger number of vehicles.

As a sensitivity, we vary the refuelling density for each fuel type to reflect the uncertainty around how extensively the refuelling networks will be out by 2030. For CNG vehicles we vary the network density by +/- 25% from the baseline of 1 station per 1,000 vehicles. For BEV, we vary the public network component of overall recharging costs by +/- 25% (since each BEV will still require an individual charger).

4.4.2 Trucks

Today there is limited refuelling infrastructure in place for LNG[47] and hydrogen powered trucks. Similarly to passenger vehicles, we assume incremental costs are linear as a simplification.

Hydrogen refuelling stations are significantly more expensive than LNG due to onerous storage and compressor requirements.[48]

[45] The Alternative Fuels Infrastructure Directive (2014) contains an objective of 1 CNG refuelling station at least every 150km on TEN-T Core Network and one CNG refuelling point per estimated 600 CNG vehicles, which is currently under revision upwards to 1 CNG refuelling station every 50km for CNG.

[46] This cost represents 1,050 EUR for a private charger, and is based on the assumption that every BEV requires its own private charger. In addition, 350 EUR represents the per-vehicle cost for the public charging network (at a density of 1 charger per 130 vehicles), including the network connection costs required to accommodate this. Charger type assumptions are based on Transport & Environment (2020). 45% of charging is done at home, while public chargers account for 16% of charging based on a 11-22kW charger and 11% of charging on large 50kW or 150kW chargers. The remaining charge is assumed to be at work or on small public chargers.

[47] Around 400 LNG refuelling stations exist across Europe https://www.ngva.eu/stations-map/

[48] Hydrogen refuelling station costs vary based on the volume of hydrogen that is stored and dispensed. We use hydrogen refuelling station costs for 2030 from ICCT (2019) which are based on a throughput of 1,700kg of hydrogen per day. IEA (2020) estimates station costs in 2050 will be around 2.1 million EUR for a throughput of 1,300 kg of hydrogen per day.

Figure 42 Truck refuelling cost assumptions in 2030

	LNG	Hydrogen
# stations : vehicle in 2030	~ 1 station per 240 vehicles	~ 1 station per 240 vehicles
Cost of infrastructure	Invest: 1,200,000 EUR per station O&M: 3% of invest p.a.	Invest: 2,600,000 EUR per station O&M: 3% of invest p.a.
Cost per vehicle	317	686

Source: LNG station cost based on NGVA Europe assumptions; Hydrogen station cost based on ICCT (2019)

5 CO_2 EMISSION ABATEMENT COST: RESULTS

In this section we first set out the total emissions and costs associated with each vehicle, based on the parameters outlined in Sections 3 and 4. Next, we present the CO_2 emission abatement cost under baseline assumptions. Finally, we show the effect of the sensitivity analysis on the CO_2 emission abatement cost. We start with passenger cars (Section 5.1), followed by trucks (Section 5.2). Ultimately we aggregate numbers on assumptions with regards to a roadmap of road transport development by 2030 (Section 5.3).

5.1 Passenger vehicles

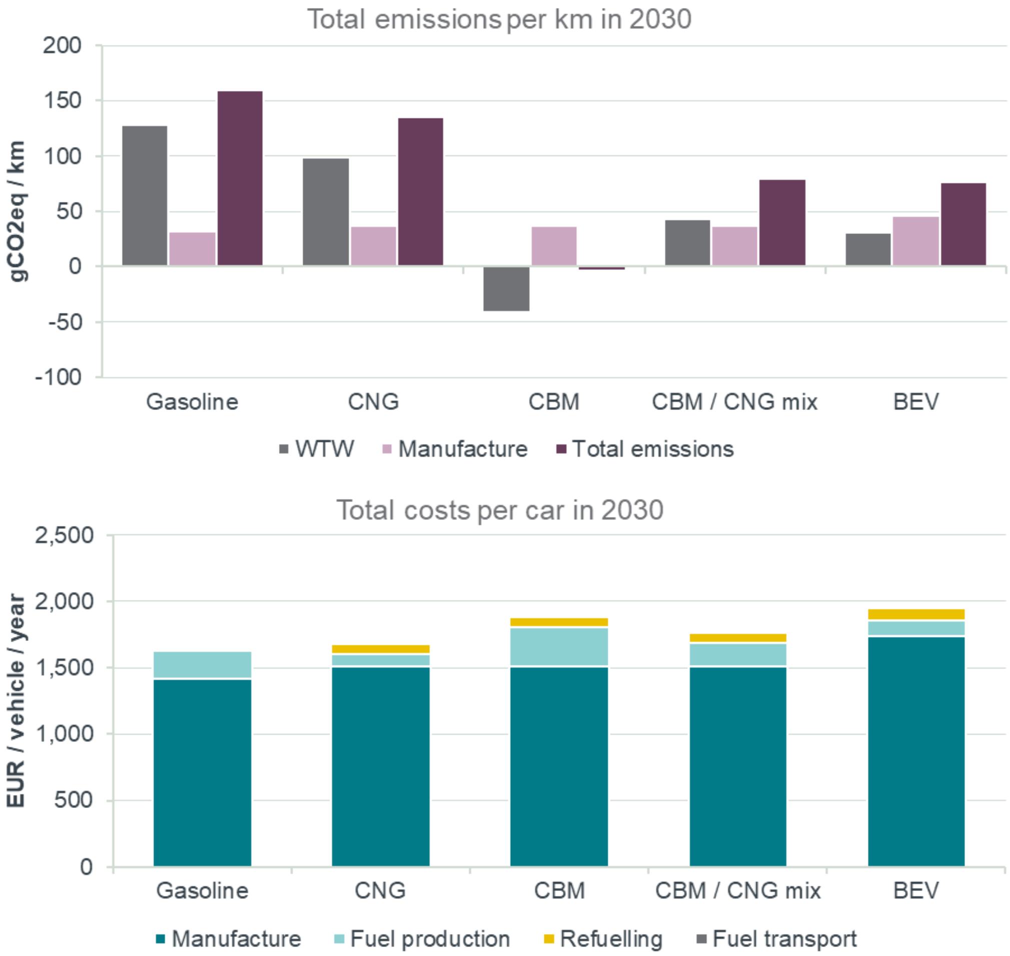
Total emissions and costs

Figure 43 shows total emissions and costs for passenger vehicles in 2030. Gas mobility running on a mix of CBM and CNG has similar total emissions to BEV on a combined WTW and manufacturing emissions basis. Many emissions comparisons in the literature are limited to TTW, which does not give the full picture of GHG emissions associated with different vehicles. Our approach emphasises the importance of taking the full value chain into account.

The total costs of each vehicle type are mainly driven by manufacturing and fuel production costs. Gas mobility tends to be cheaper than BEV, however because of higher biomethane production costs an ICEV running on pure biomethane has a comparable overall cost to BEV.

Gas mobility offers a lower cost of CO_2 emission abatement than BEV under our baseline assumptions (see Figure 5 and Figure 44). This is mainly driven by vehicle manufacturing costs, where gas mobility is expected to retain a significant cost advantage over BEVs in the next decade.

Figure 43 Passenger vehicles: Total emissions and costs



Source: *Frontier Economics based on literature review*

Note: *Costs are presented on an annualised basis. Note that the fuel transport and refuelling costs are overall conservative for BEV, because they take into account one-off localised grid connection upgrade costs but not the wider system electricity network upgrades that are likely to be required.*

CO_2 emission abatement costs

We calculate CO_2 emission abatement cost in EUR/tCO2eq by relating the total annual cost premium of one (gas mobility or BEV) vehicle over the fossil gasoline reference to the total annual CO_2 emission abated by the respective vehicle compared to the fossil gasoline reference.[49] This gives the annualised cost associated with an emissions reduction of one tonne of CO2-equivalent for the system components included in this study.[50]

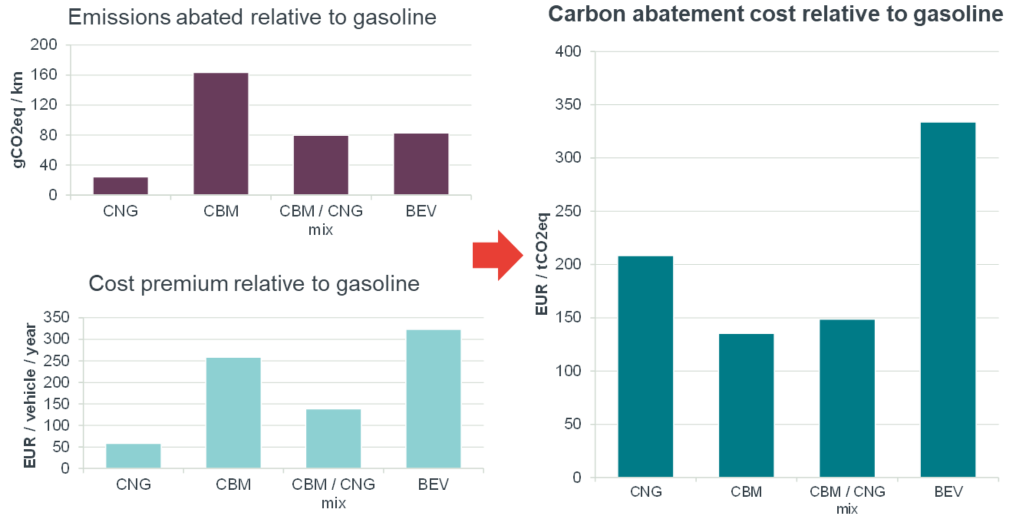
Figure 44 summarises the baseline results for passenger cars. It shows each component of the vehicle comparison relative to gasoline:

[49] Carbon abatement costs (EUR/t CO2) = Cost premium (EUR / vehicle / year) / Emissions abated (tCO2eq/km * annual mileage).

[50] Note that a full LCA could take into account a wider range of costs and emissions (e.g. end-of-life emissions and costs), however for the purposes of this study we have limited the scope to a WTW plus manufacturing approach.

- **Emissions abated relative to gasoline.** CBM vehicles offer the highest absolute level of emissions savings, with 168 gCO2eq/km savings relative to conventional gasoline vehicles.[51] BEV and CBM/CNG mix have similar emissions savings at around 80 gCO2eq/km. CNG has the lowest emissions savings, although it still offers around 24 gCO2eq/km which supports its role as a transitional fuel.
- **Cost premium above gasoline.** BEV has the highest cost premium relative to gasoline, at 323 EUR / vehicle / year above gasoline. CBM also has a relatively high cost premium due to the production cost of biomethane. CBM / CNG mix gas mobility has a lower cost premium of 139 EUR / vehicle / year, and CNG has the lowest cost premium of 59 EUR / vehicle / year.
- **Carbon abatement cost.** Gas mobility has a lower abatement cost than BEVs for all CNG and biomethane fuel mixes. CBM and CBM / CNG mixes offer a similar cost of carbon abatement, despite having different cost and emission profiles. This is because CBM is relatively expensive but also offers a high level of emissions savings. Therefore the cost per tonne of CO_2 abated is similar to a CBM / CNG mix, which offers a lower level of emissions savings but is also less costly. BEV has a high cost of carbon abatement relative to gas mobility. While BEV offers a similar level of emissions savings to CBM / CNG mix vehicles (around 80 gCO2eq/km), its cost premium is much higher. This gives a higher cost of carbon abatement. In other words, BEV offers less “value for money” than gas mobility for the time horizon of this study (i.e. 2030).[52]

Figure 44 Passenger vehicles: CO_2 emission abatement cost



Source: Frontier Economics based on literature review

Note: Emissions abated and cost premium above gasoline show the difference to conventional gasoline for each technology. The cost premium is defined as the additional annualised cost of each vehicle compared to the gasoline baseline.

[51] Note that this is driven by the negative CBM emission assumption associated with the CBM feedstock mix we have used. However, the overall emissions savings are more than double that associated with BEV. So even under a more conservative assumption, CBM is likely to offer greater emissions abatement.

[52] Note that in the longer run this may change, particularly if the electricity mix becomes increasingly renewable and if battery production costs come down significantly.

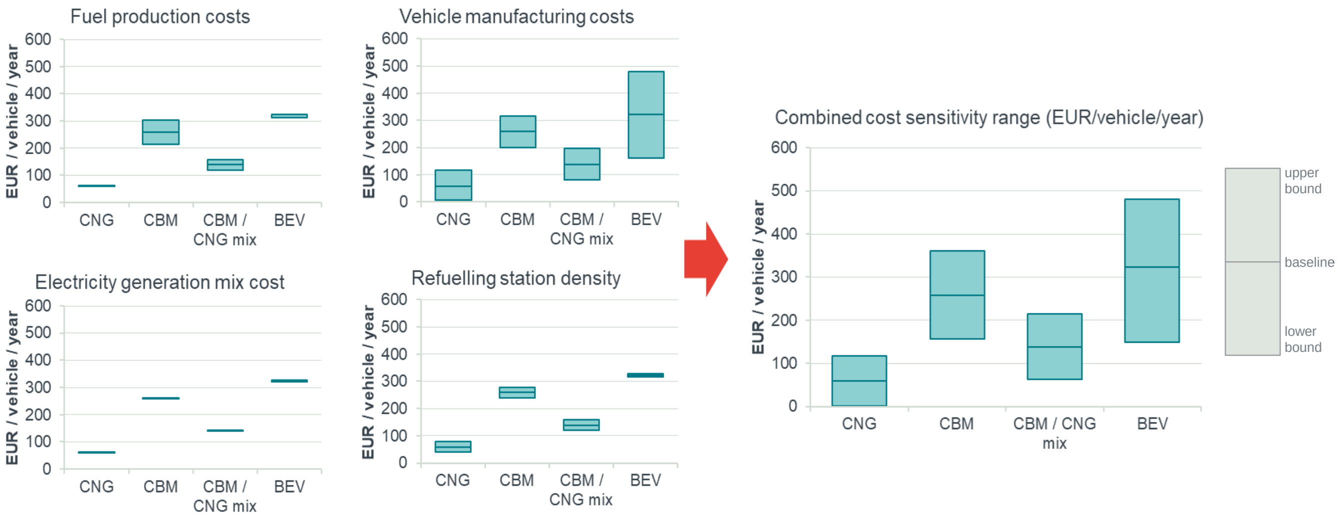
Sensitivity analysis: Costs

Figure 45 summarises impact of varying each parameter on the cost premium for each vehicle above gasoline. We also show the combined impact of the sensitivities to give an overall compound cost range for 2030.

Carbon abatement costs of gas mobility are relatively more certain than those of BEV. The main sources of abatement cost uncertainty are vehicle manufacturing costs and emissions, particularly for BEVs which have a significant upside cost risk in addition to having a higher baseline cost.

Variations in the number of refuelling stations per vehicle do not have a big impact on costs. This suggests that the lack of an existing widespread refuelling network for CNG cars should not be considered as a significant barrier to scaling up alternative vehicles, since the cost on a per-vehicle basis is relatively low.

Figure 45 Impact of varying different parameters on total cost premium above gasoline

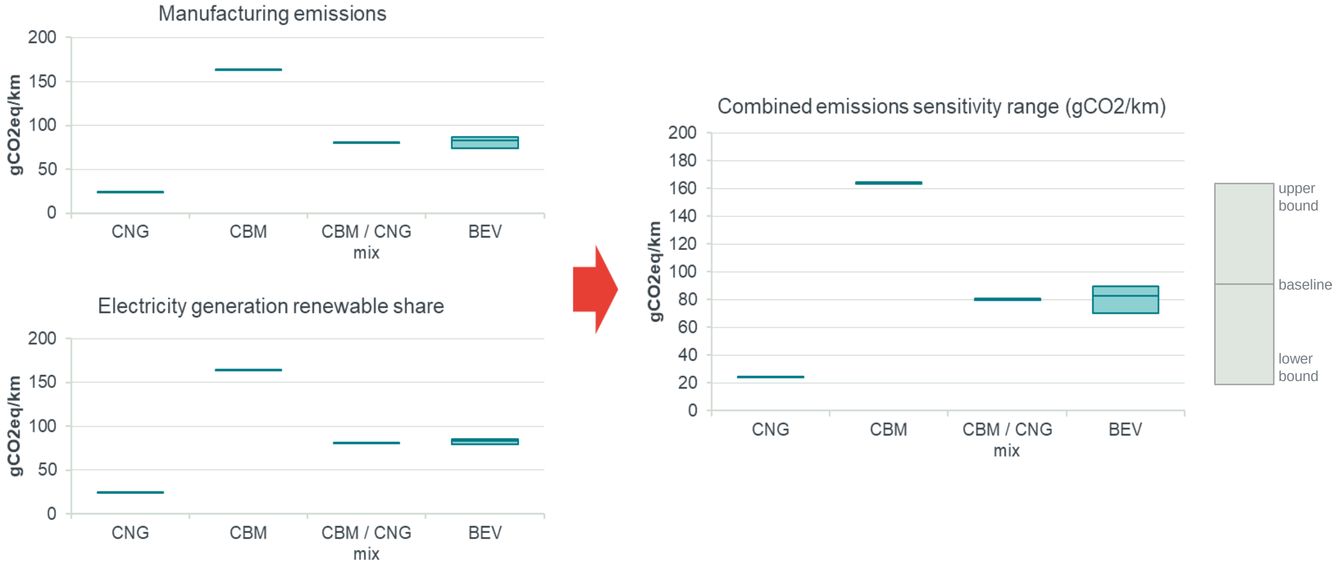


Source: Frontier Economics based on literature review

Sensitivity analysis: Emissions

Figure 46 shows the impact on abated emissions of varying manufacturing emissions and the electricity generation mix assumptions. BEV has relatively more uncertain emissions than gas mobility.

Figure 46 Impact of varying different parameters on abated emissions relative to gasoline



Source: Frontier Economics based on literature review

5.2 Trucks

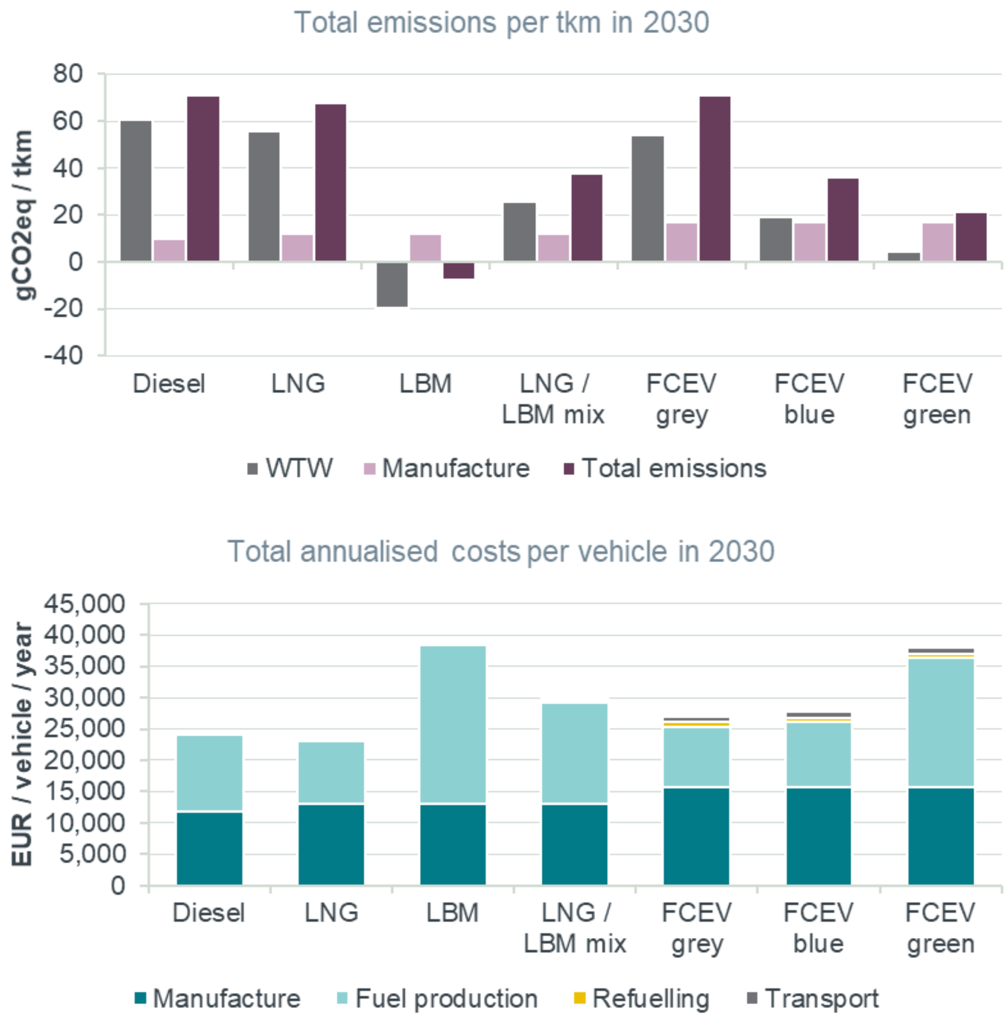
Total emissions and costs

Figure 47 shows the total WTW and manufacturing emissions and total costs for trucks. Conventional diesel trucks, LNG trucks, and FCEV running on grey hydrogen all have similar overall emissions. Gas mobility using a mix of LNG and bio-LNG has lower total emissions than FCEV running on grey hydrogen.

Total costs for one truck on an annualised basis are largely driven by manufacturing and fuel production costs.[53] Figure 47 show that diesel and LNG trucks have similar overall costs. Gas mobility running on a mix of LNG and bio-LNG has slightly higher total costs, while gas mobility fuelled by pure bio-LNG is more expensive due to the higher fuel production costs. FCEV fuelled by grey or blue hydrogen have comparable overall costs to an LNG / LBM mix truck. Green hydrogen has relatively high fuel production costs and therefore is one of the more expensive decarbonisation options in 2030.

53 Trucks have high annual mileage and fuel requirements, so fuel production costs make up a more significant proportion of their overall costs than for passenger vehicles.

Figure 47 Trucks: Total emissions and costs



Source: Frontier Economics based on literature review

CO_2 emission abatement costs

Similarly to the approach taken for passenger vehicles, we combine the abated emissions and costs to calculate the cost of CO_2 emission abatement.[54] Figure 48 shows the emissions, costs, and costs of carbon abatement for each vehicle relative to diesel:

- **Emissions abated relative to diesel.** Bio-LNG vehicles offer the highest absolute level of emissions savings, with 78 gCO2eq/tkm savings relative to conventional diesel vehicles.[55] LBM / LNG mix vehicles also offer emissions savings of around 33 gCO2eq/tkm, while vehicles running on fossil LNG offer minor emissions savings relative to diesel. FCEV fuelled by grey hydrogen emits slightly more CO_2 than diesel, so this vehicle does not offer any

[54] Carbon abatement costs (EUR/t CO2) = Cost premium (EUR / vehicle / year) / Emissions abated (tCO2eq/tkm * annual tkm)

[55] Note that this is driven by the negative LBM emission assumption associated with the LBM feedstock mix we have used.

opportunity for emissions abatement unless low-carbon hydrogen is used. Blue hydrogen offers emissions abatement of 35 gCO2eq/tkm which is similar to the abatement of the LBM / LNG mix truck, and green hydrogen offers slightly higher emissions savings of 49 gCO2eq/tkm.

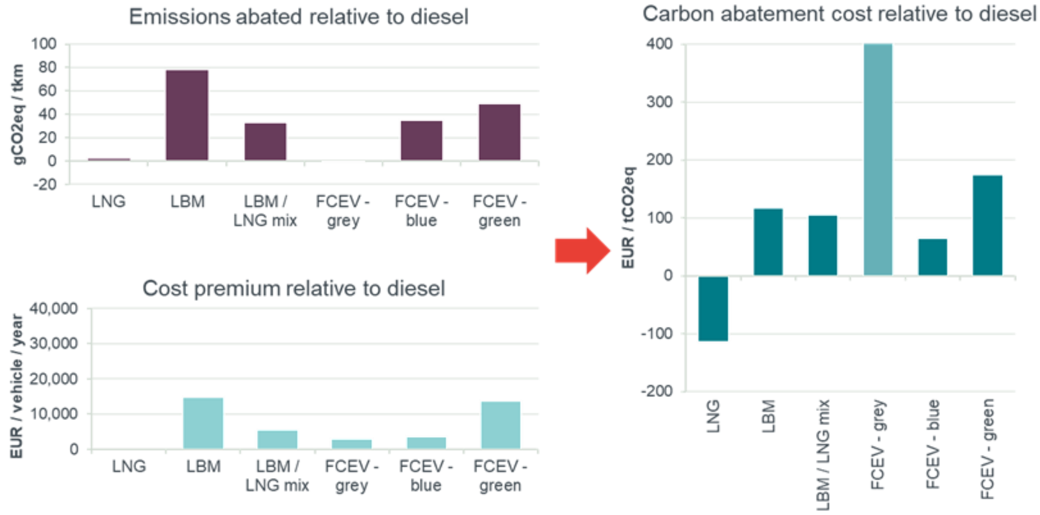
- **Cost premium above diesel.** FCEV using green hydrogen and ICEV fuelled by pure bio-LNG have the highest cost premium relative to diesel, however we note that the green hydrogen cost is very uncertain (particularly expected cost reductions over the next decade). LNG / LBM mix vehicles and FCEV fuelled by grey or blue hydrogen all have comparably low cost premiums above diesel in 2030.
- **Carbon abatement cost.** Gas mobility using LNG offers emissions savings and cost savings relative to diesel, which means that it has a negative carbon abatement cost and can be a useful transitional fuel. FCEV fuelled by blue hydrogen offers a low cost of carbon abatement of 65 EUR/tCO2eq. However, there may be some limitations to the supply of blue hydrogen available for use in transport.[56] Note that cost of carbon abatement for FCEV running on grey hydrogen are prohibitively high because it does not offer any emissions savings relative to diesel.[57] Both the pure bio-LNG and LNG/bio-LNG mix have similar costs of CO_2 emission abatement, despite having different cost and emission profiles. This is because pure bio-LNG offers very high emissions savings, but is also relatively high cost. LNG/bio-LNG mix vehicles offer lower emissions savings but are also lower cost. FCEV running on green hydrogen has the highest cost of carbon abatement which is driven by the relatively high fuel production costs.

These results support the deployment of multiple technological options in the near term to decarbonise heavy duty transport. LNG and bio-LNG gas mobility is able to offer near term decarbonisation at a low cost of carbon abatement, and FCEV using blue and green hydrogen are likely to play an important role in the future.

[56] The supply ramp up of hydrogen in general is uncertain at the moment, particularly for blue hydrogen which faces social and political opposition to CCS in some EU states. For example, the German National Hydrogen Strategy (2020) considers ‘only hydrogen that has been produced using renewable hydrogen (green hydrogen) to be sustainable in the long term’. In addition, it is possible that early hydrogen projects could be used in other sectors such as blending into the natural gas grid or as dedicated supply for industrial clusters.

[57] For illustrative purposes we capped these cost at 400 EUR/tCO2eq in Figure 48.

Figure 48 Trucks: CO_2 emission abatement costs

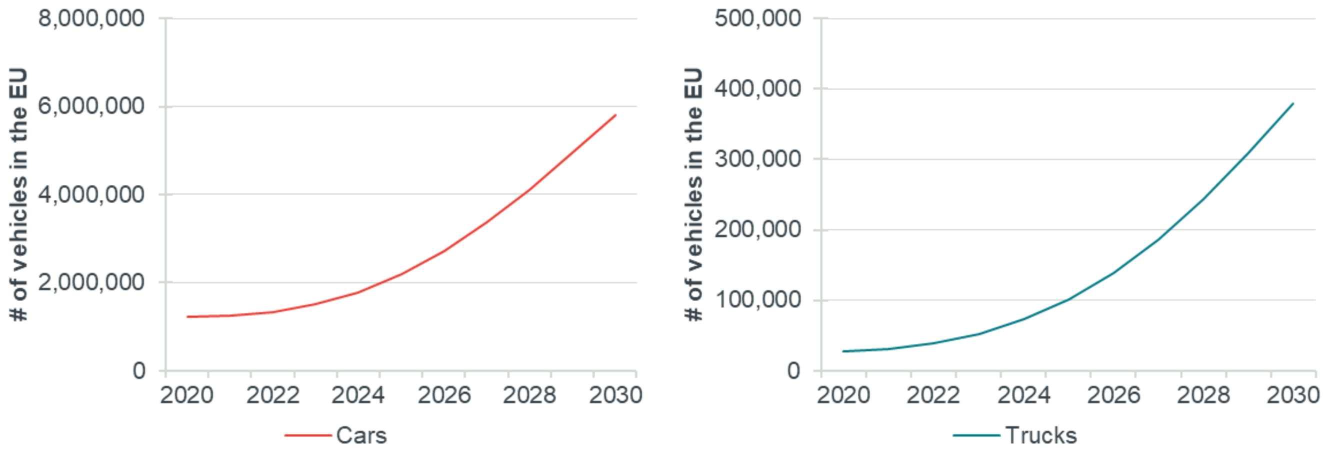


Source: Frontier Economics based on literature review
Note that LNG vehicles have a lower total cost than diesel due to lower fuel production costs. This leads to a negative carbon abatement cost because they reduce both costs and emissions.
Note also that FCEV fuelled by grey hydrogen do not abate any emissions relative to diesel, and thus have prohibitively high abatement costs (which we capped at 400 EUR/tCO2eq in the graph).

5.3 Roadmap towards near-term decarbonisation

ACEA (2021) reports a total stock of 1.2 million natural gas passenger vehicles and 25,000 natural gas trucks in the European Union in 2019. NGVA Europe expects that gas mobility could account for close to 10 million passenger vehicle and 500,000 truck sales between 2020 and 2030 (Figure 49). This is broadly in line with the assumptions of the European Commission's Impact Assessment,[58] which predicts that gas fuelled vehicles could make up 5% of total passenger demand in 2030, or 7.6 million vehicles.

Figure 49 Stock of natural gas vehicles in the EU between 2020 and 2030



Source: Frontier Economics based on NGVA Europe assumptions and ACEA (2021)
Note: Note that we assume a vehicle lifetime of 15 years for cars and of 9 years for trucks.

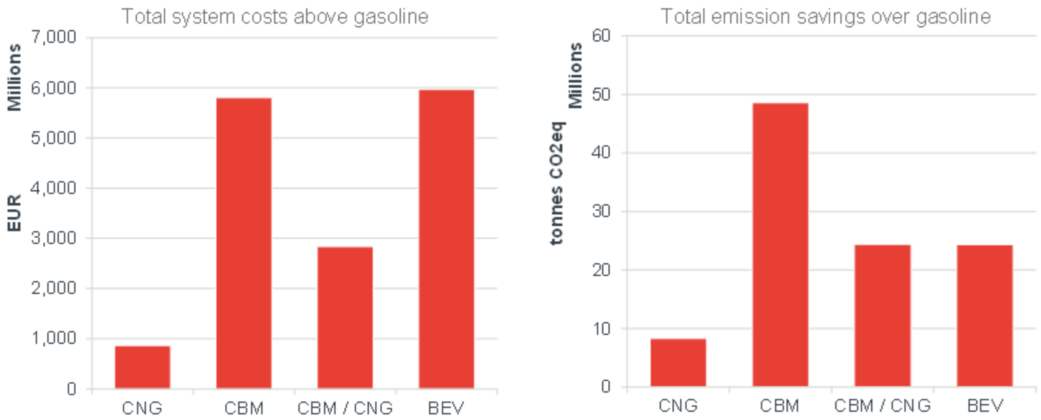
[58] See European Commission (2020d).

Passenger vehicles

NGVA Europe expects that in year 2030 over 1.6 million passenger cars and light duty vehicles will be sold that are powered by gaseous fuels (new registrations in 2030). Assuming that these vehicles will all be powered by a 40/60 mix of CBM / CNG, the total amount of GHG lifetime emissions saving associated with those sales in 2030 would be over 24 million tonnes of CO_2 (this is compared to the emissions of the same number of conventional gasoline passenger vehicles over the lifetime of the vehicles). We estimate the additional system costs for the CBM / CNG vehicles to be 2.8 billion euros relative to gasoline vehicles. This translates into abatement costs of around 116 EUR/tCO2eq.

If we assume that these vehicles would be BEV rather than the 40/60 biomethane / natural gas gas mobility mix, the emissions savings would be roughly equal, but system costs (even not considering the additional investment costs on electricity infrastructures such as new transmission and distribution lines) would be more than double the size and amount to 6.0 billion euros. Figure 50 shows the additional system costs and emission savings relative to gasoline vehicles for each fuel type.

Figure 50 Passenger car additional system costs and emission savings relative to gasoline of the full lifetime for vehicles sold in 2030



Source: Frontier Economics based on literature reivew

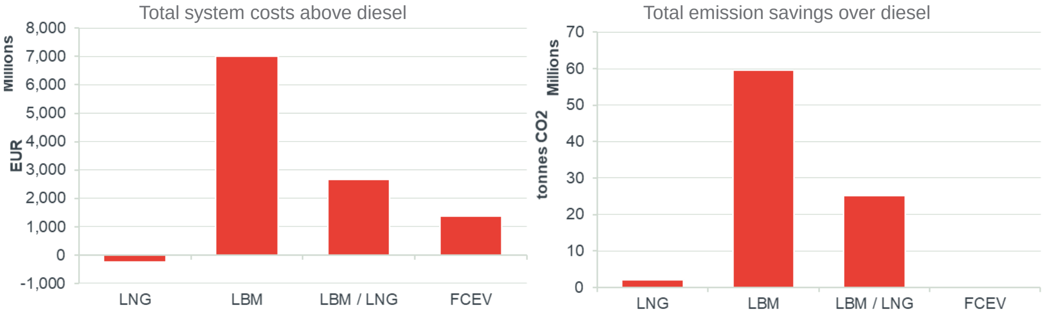
Trucks

Figure 51 shows the additional system costs and emission savings relative to gasoline trucks for their full lifetime for vehicles sold in 2030. In this timeframe LBM and LBM/LNG-mix trucks have sizeable emission savings potentials, while LNG trucks only have a small positive impact and FCEV trucks fuelled by grey hydrogen generate the same (or even more) emissions as diesel trucks.

NGVA Europe estimates that in 2030 around 52,000 LNG trucks will be sold in the EU. If we assume that those vehicles would all be fuelled by a 60/40 LBM / LNG mix, there would be over 25.1 million tonnes of CO_2 abatement associated with it. We estimate the additional system costs for the LBM / LNG vehicles to be around

2.7 billion euros relative to diesel vehicles. This translates into abatement costs of around 106 EUR/tCO2eq. Under an assumption of FCEV fuelled by grey hydrogen in 2030, there would be an additional 1.4 billion EUR with no emissions savings relative to diesel (noting that this picture would be different if blue or green hydrogen was used).

Figure 51 Trucks additional system costs and emission savings relative to gasoline of the full lifetime for vehicles sold in 2030



Source: Frontier Economics based on literature review

6 CONCLUSIONS

Our analysis shows that gas mobility is a readily available and is would be an attractive addition to the technology mix in 2030 required to effectively and efficiently migrate towards a low-carbon mobility sector in Europe. It is therefore key to ensure that the regulatory framework allows for further drivetrain options such as gas mobility to contribute to emission reductions.

Gas mobility can contribute to an effective technology mix on the path towards carbon neutral mobility

In this study we highlighted that the heterogeneity of road transport requires a broad technology mix. Gas mobility contributes to this mix with distinct advantages:

- It adds an additional fuel path towards the drive-train options based on existing infrastructure and value chains;
- It combines a readily available reduced-carbon option (partly based on natural gas) with long-term carbon neutral options (based on bio- and synthetic gas sources); and thereby
- could potentially accelerate the decarbonisation of mobility particularly over the next decade.

Our quantitative analysis demonstrates the fact that drivetrain-technologies based on LNG and CNG offer attractive low- carbon-abatement-cost pathways, which provide efficient emission reductions. This can help Europe to achieve a given climate protection target at lower costs (higher “value for money”).

In order to harness the potential of gas mobility it will be necessary to re-adjust the current regulatory framework

While suggestions for concrete adjustments of this wide field of regulation are beyond the scope of this study, we believe any future adjustments should be built on various **principles**, which would allow gas mobility – as any other low-carbon technology option – to become part of a wide technology mix to achieve carbon neutral mobility:

- In order to allow for an optimal mix of technologies, any regulation should be built on the principle of **technology diversification** – the immense challenge and high urgency for the mobility sector to achieve emissions reductions does not allow for the cherry picking of individual technologies. Rather, we have to go “all-in” by enabling as many options to contribute as possible in the near term.
- The heterogeneity of mobility applications with many individual factors determining the most efficient technology in each case rules out any central planning approach – there is no “one size fits all” solution. Maintaining the **freedom of choice** between options for individuals and a vivid **competition of technologies** should therefore be a key objective.
- Finally, the currently high degree of uncertainty both regarding the ultimate challenges the mobility transition is going to face as well as regarding the technology options available in the future provides a high **value of keeping**

options open. Regulation therefore should strive to maintain opportunities in all directions and not to prematurely rule out any pathway (e.g. by banning combustion engines which may in the future be fuelled by renewable or low-carbon fuels or gases).

The advantages of gas mobility become particularly evident based on a systemic view, as it combines the benefits of an already existing upstream infrastructure ("Well-to-Tank"), low production-emissions and a lower carbon intensity in driving emissions compared to e.g. gasoline or diesel ("Tank-to-Wheel").

Today's fragmented regulatory approach – with e.g. a limitation to tailpipe emissions for fleet targets – does not reflect these system-wide overall benefits in corresponding competitive advantages from a customer perspective compared to other low-carbon options. In order to harness the full potential of gas mobility (as part of a technology mix), the current regulatory framework should be revised based on the principles set out above. Many policy instruments which span across a range of policy areas are potentially of relevance:

- **Transport and Climate policy** - Focusing on the CO_2 emissions reduction only at tailpipe level might not be sufficient to ensure the ambitious shift to carbon neutral mobility. Without a wider focus, the contribution of renewable fuels in the CO_2 emissions from the EU fleet may not be increased fast enough to meet the target in 2030 or the net-zero objective in 2050. Recognising the contribution from renewable fuels in the CO_2 fleet target would support the path towards net-zero mobility. The recognition should happen through a new mechanism that encompasses the contribution of sustainable renewable fuels when determining manufacturers compliance with their CO_2 emission targets.[59] It should also avoid technological distortions to allow the maximum number of options to support a reduction in the transportation carbon footprint
- **Infrastructure support** – the development of gas refuelling infrastructure may be supported to facilitate a homogeneous market throughout Europe. The support to infrastructure should be develop for those fuels that have a potential of a high renewable share on a well-to-wheel approach. Restricting the selection of fuels eligible as alternative fuels would simply prevent Europe and Member States from reaching climate goals in an effective way.
- **Sector specific regulations** – Such as RED II / III, the Energy Tax Directive (ETD), many of which are currently or will be soon under revision could support through a carbon signal to internalise the societal costs of carbon emissions, thus enhancing profitability of low carbon options such as renewable and low-carbon gas vs. fossil mineral oil products. On the other hands, a more careful assessment of the role of users' costs alongside the economic costs.
- **Technical standards** – An implementation of harmonised EU standards at national levels may help to increase interoperability among European countries.

[59] See for example our suggestions for the German Ministry of Economics and Energy (BMWi; http://www.frontier-economics.com/uk/en/news-and-articles/news/news-article-i7325-accounting-for-renewable-fuels-in-eu-fleet-targets-path-to-lower-co2-emissions/), further developed for Neste (http://www.frontier-economics.com/uk/en/news-and-articles/news/news-article-i7905-how-does-a-crediting-system-for-renewable-fuels-work-and-what-are-the-benefits/).

REFERENCES

ACEA (2021), ACEA Report: Vehicles in use Europe, European Automobile Manufacturers' Association (ACEA), January 2021, https://www.acea.be/uploads/publications/report-vehicles-in-use-europe-january-2021.pdf

ADAC (2019), Rund ums Fahrzeug – Autokatalog, https://www.adac.de/rund-ums-fahrzeug/autokatalog/

Agora Energiewende and Frontier Economics (2018), The Future Cost of Electricity-Based Synthetic Fuels, study by Frontier Economics, commissioned by Agora Verkehrswende and Agora Energiewende, September 2018, https://www.agora-energiewende.de/fileadmin2/Projekte/2017/SynKost_2050/Agora_SynKost_Study_EN_WEB.pdf

Ardey (2018), Future Technology Mix for Emission-Free Mobility, Nikolai Ardey, AUDI AG, 27th Aachen Colloquium Automobile and Engine Technology 2018, October 2018

BCG (2020), Who Will Drive Electric Cars to the Tipping Point?, Boston Consulting Group, Mosquet et al., January 2020, https://www.bcg.com/publications/2020/drive-electric-cars-to-the-tipping-point

BloombergNEF (2020), Electric Vehicle Outlook 2020, https://about.bnef.com/electric-vehicle-outlook/

Brinkle et al (2020), Should we reinforce the grid? Cost and emission optimization of electric vehicle charging under different transformer limits, October 2020, https://reader.elsevier.com/reader/sd/pii/S0306261920307972?token=2279AA5288691C8432D455515D8792E19DD1D11F49398A7778E3EBF506719F940B982BB3896C1814DA8B8E438436B0A3&originRegion=eu-west-1&originCreation=20210415104352

Burk and Zhao (2017), Fuel Cells and Hydrogen in Long-Haul Trucks, May 2017

BMWi (2020), The National Hydrogen Strategy, June 2020, https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6

Carbone 4 (2020), Transport routier : quelles motorisations alternatives pour le climat ? Comparaison des émissions en cycle de vie, France et Europe, Pôle Mobilité, Amant, Meunier and de Cossé Brissac, November 2020, http://www.carbone4.com/publication-transport-routier-motorisation-alternatives/

CERRE (2019), Future markets for renewable gases and hydrogen: What would be the optimal regulatory provisions?, Centre on Regulation in Europe, Muraga, Mulder and Perey, September 2019, https://cerre.eu/wp-content/uploads/2020/05/cerre_report_future_markets_for_renewable_gases_and_hydrogen.pdf

Dena (2018), dena-Leitstudie Integrierte Energiewende: Impulse für die Gestaltung des Energiesystems bis 2050 - Ergebnisbericht und Handlungsempfehlungen, Deutsche Energie-Agentur GmbH (dena), July 2018, https://www.dena.de/themen-projekte/projekte/energiesysteme/dena-leitstudie-integrierte-energiewende/

Dynamis (2019), Dynamische und intersektorale Maßnahmenbewertung zur kosteneffizienten Dekarbonisierung des Energiesystems – Datenanhang, Dynamis project coordinated by Forschungsstelle für Energiewirtschaft (FfE), November 2019, https://www.ffe.de/die-themen/ressourcen-und-klimaschutz/628-dynamis

Element Energy (2019), Hy-Impact Series Study 2: Net-zero hydrogen - Hydrogen production with CCS and bioenergy, study by Element Energy, on behalf of Equinor, November 2019, http://www.element-energy.co.uk/wordpress/wp-content/uploads/2019/11/Element-Energy-Hy-Impact-Series-Study-2-Net-zero-Hydrogen.pdf

ENTSO-E (2020), Ten-Year Network Development Plan – Completing the map: Power system needs in 2020 and 2040, November 2020, https://eepublicdownloads.azureedge.net/tyndp-documents/IoSN2020/200810_IoSN2020mainreport_beforeconsultation.pdf

European Commission (2016), Optimal use of biogas from waste streams - An assessment of the potential of biogas from digestion in the EU beyond 2020, CE Delft, Eclareon and Wageningen Research, on behalf of the European Commission, December 2016, https://ec.europa.eu/energy/sites/ener/files/documents/ce_delft_3g84_biogas_beyond_2020_final_report.pdf

European Commission (2017a), Building up the future, cost of biofuel - Sub group on advanced biofuels: sustainable transport forum, Directorate-General for Mobility and Transport, Maniatis, Landälv, Waldheim et al., March 2017, https://op.europa.eu/en/publication-detail/-/publication/13e27082-67a2-11e8-ab9c-01aa75ed71a1

European Commission (2017b), Renewable technologies in the EU electricity sector: trends and projections - Analysis in the framework of the EU 2030 climate and energy strategy, Joint Research Centre (JRC) Science for Policy Report, Banja and Jégard, 2017, https://core.ac.uk/download/pdf/146996696.pdf

European Commission (2018), Li-ion batteries for mobility and stationary storage applications - Scenarios for costs and market growth, Joint Research Centre (JRC) Science for Policy Report, Tsiropoulos, Tarvydas and Lebedeva, 2018, https://op.europa.eu/en/publication-detail/-/publication/e65c072a-f389-11e8-9982-01aa75ed71a1/language-en

European Commission (2019), Energy prices and costs in Europe, Brussels, January 2019, https://ec.europa.eu/energy/sites/default/files/epc_report_final_1.pdf

European Commission (2020a), Questions and answers: A Hydrogen Strategy for a climate neutral Europe, press corner: Questions and answers, Brussels, July 2020, https://ec.europa.eu/commission/presscorner/detail/en/QANDA_20_1257

European Commission (2020b), Deliverable 3.6 – Strategic Research Agenda for Batteries, European Technology and Innovation Platform on Batteries – Batteries Europe, December 2020, https://ec.europa.eu/energy/topics/technology-and-innovation/batteries-europe/news-articles-and-publications/sra_de

European Commission (2020c), JEC Well-To-Wheels report v5, Well-to-Wheels analysis of future automotive fuels and powertrains in the European context, JRC Science for Policy Report; Joint Research Centre, EUCAR and Concawe; 2020, https://ec.europa.eu/jrc/en/jec/publications/reports-version-5-2020

European Commission (2020d), Impact Assessment: Stepping up Europe's 2030 climate ambition - Investing in a climate-neutral future for the benefit of our people, September 2020, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020SC0176

Financial Times (2020), Electric car costs to remain higher than traditional engines, Joe Miller, Frankfurt, August 2020, https://www.ft.com/content/a7e58ce7-4fab-424a-b1fa-f833ce948cb7

Fraunhofer ISE (2018), Levelized cost of electricity renewable energy technologies, Fraunhofer Institute for Solar Energy Systems ISE, March 2018, https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/EN2018_Fraunhofer-ISE_LCOE_Renewable_Energy_Technologies.pdf

Frontier Economics (2020a), Crediting system for renewable fuels in EU emission standards for road transport – Report for the German Federal Ministry for Economic Affairs and Energy (BMWi), May 2020, https://www.frontier-economics.com/media/3937/crediting-systems-for-renewable-fuels-in-eu-emission-standards-for-road-transport-en.pdf

Frontier Economics (2020b), Crediting system for renewable fuels: Functionality & benefits – Report prepared for Neste, November 2020, https://www.frontier-economics.com/media/4347/crediting-system-for-renewable-fuels.pdf

Frontier Economics and IAEW (2019), The value of gas infrastructure in a climate-neutral Europe - A study based on eight European countries, study by Frontier Economics and the Institute of Power Systems and Power Economics (IAEW) at RWTH Aachen University on behalf of Green Gas Initiative (GGI) and Net4Gas, April 2019, https://www.frontier-economics.com/media/3113/value-of-gas-infrastructure-report.pdf

Frontier Economics and FVV (2020), Cradle-to-Grave Life-Cycle Assessment in the Mobility Sector - A Meta-Analysis of LCA Studies on Alternative Powertrain Technologies, a study by Frontier Economics on behalf of Forschungsvereinigung Verbrennungskraftmaschinen (FVV), June 2020, https://www.fvv-net.de/fileadmin/user_upload/medien/pressemitteilungen/FVV_LCA_Life-cycle_analysis_Frontier_Economics_R595_final_2020-06_EN.pdf

Guidehouse (2020), European Hydrogen Backbone, How a dedicated Hydrogen Infrastructure can be created, July 2020, https://guidehouse.com/-/media/www/site/downloads/energy/2020/gh_european-hydrogen-backbone_report.pdf

Hydrogen Council (2020), Path to hydrogen competitiveness - A cost perspective, supported by McKinsey & Company and E4tech, January 2020, https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

ICCT (2017), Transitioning to zero-emission heavy-duty freight vehicles, 2017

ICCT (2019), Update on electric vehicle costs in the United States through 2030, International Council on Clean Transportation (ICCT), working paper 2019-06, Lutsey and Nicholas, https://theicct.org/sites/default/files/publications/EV_cost_2020_2030_20190401.pdf

ICCT (2019), Estimating the infrastructure needs and costs for the launch of zero-emission trucks, August 2019, https://theicct.org/sites/default/files/publications/ICCT_EV_HDVs_Infrastructure_20190809.pdf

IEA (2019), The Future of Hydrogen - Seizing today's opportunities, report prepared by the International Energy Agency for the G20 in Japan, June 2019, https://www.iea.org/reports/the-future-of-hydrogen

IEA (2020a), World Energy Outlook 2020, flagship report, International Energy Agency, October 2020, https://www.iea.org/reports/world-energy-outlook-2020

IEA (2020b), Outlook for biogas and biomethane: Prospects for organic growth, World Energy Outlook special report, International Energy Agency, March 2020, https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth

IRENA (2018), Renewable Energy Prospects for the European Union, International Renewable Energy Agency, February 2018, https://www.irena.org/publications/2018/Feb/Renewable-energy-prospects-for-the-EU

IRENA (2019), Future of Wind: Deployment, investment, technology, grid integration and socio-economic aspects, International Renewable Energy Agency, October 2019, https://www.irena.org/publications/2019/Oct/Future-of-wind

IRENA (2020), Green Hydrogen Cost Reduction – Scaling up electrolysers to meet the 1.5C climate goal, 2020, https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

JEC (2020), JEC, (2020), Well-To-Wheels report v5 - https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/jec-well-wheels-report-v5

JRC (2019), The future of road transport - Implications of automated, connected, low-carbon and shared mobility, https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/future-road-transport

Navigant (2019), Gas for Climate - The optimal role for gas in a net-zero emissions energy system, Navigant Netherlands B.V., March 2019, https://gasforclimate2050.eu/wp-content/uploads/2020/03/Navigant-Gas-for-Climate-The-optimal-role-for-gas-in-a-net-zero-emissions-energy-system-March-2019.pdf

Navigant (2021), Setting a binding target for 11% renewable gas, A Gas for Climate policy paper, Guidehouse (former Navigant), January 2021, https://gasforclimate2050.eu/?smd_process_download=1&download_id=633

NGVA Europe (2019), Vehicle Catalogue 2019, Natural & bio Gas Vehicle Association Europe, September 2019, https://www.ngva.eu/medias/vehicle-catalogue-2019/

Nikola Corporation (2020), Investor roadshow presentation, April 2020, https://d32st474bx6q5f.cloudfront.net/nikolamotor/uploads/investor/presentation/presentation_file/5/NikolaInvestorRoadShowPresentation042720.pdf

Öko-Institut (2018), Oberleitungs-Lkw im Kontext weiterer Antriebs- und Energieversorgungsoptionen für den Straßengüterfernverkehr, 2018

Ørsted (2019), Making green energy affordable: How the offshore wind energy industry matured – and what we can learn from it, Denmark, June 2019, https://orsted.com/-/media/WWW/Docs/Corp/COM/explore/Making-green-energy-affordable-June-2019.pdf

Ricardo (2020), Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA, Final Report for the European Commission, DG Climate Action, Ricardo Energy & Environment, E4tech and ifeu, July 2020, https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/docs/2020_study_main_report_en.pdf

Roland Berger (2016), Integrated Fuels and Vehicles Roadmap to 2030+, April 2016

Sustainable Gas Institute (2017), A greener gas grid: What are the options?, white paper, Sustainable Gas Institute (SGI), Imperial College London, July 2017, https://www.imperial.ac.uk/media/imperial-college/research-centres-and-groups/sustainable-gas-institute/SGI-A-greener-gas-grid-what-are-the-options-WP3.pdf

Transport & Environment (2020), Recharge EU: How many charge points will EU countries need by 2030, European Federation for Transport and Environment AISBL, January 2020, https://www.transportenvironment.org/sites/te/files/publications/01%202020%20Draft%20TE%20Infrastructure%20Report%20Final.pdf

UNITI (2019), Die CO2-Gesamtbilanz für Antriebstechnologien im Individualverkehr heute und in Zukunft – Lebenszyklusanalysen als Basis für zielführende Klimapolitik und Regularien, Frontier Economics, report on behalf of UNITI Bundesverband mittelständischer Mineralölunternehmen e. V., November 2019, https://www.uniti.de/images/PDF/publikationen/Aktuelle%20Studien/RPT-Frontier-Uniti-LCA-26-11-2019.pdf

VDI (2020), Ökobilanz von Pkws mit verschiedenen Antriebssystemen, a study by Verein Deutscher Ingenieure (VDI) October 2020, https://www.vdi.de/fileadmin/pages/vdi_de/redakteure/vor_ort/bv/braunschweiger-bv/news/News_BV/VDI-Studie_Oekobilanz-Pkw_Internet.pdf

Wietschel et al. (2019), Klimabilanz, Kosten und Potenziale verschiedener Kraftstoffarten und Antriebssysteme für Pkw und Lkw, final report, Fraunhofer-Institut für System- und Innovationsforschung ISI, in cooperation with Technische Universität Hamburg (TUHH) and IREES GmbH – Institut für Ressourceneffizienz und Energiestrategien, study funded by Biogasrat+ e.V., September 2019.

Zapf et al. (2019), Kosteneffiziente und nachhaltige Automobile: Bewertung der realen Klimabelastung und der Gesamtkosten – Heute und in Zukunft, Springer Vieweg

ANNEX A EMISSION ASSUMPTIONS

A.1 WTW emission assumptions

We use the JEC WTW report[60] for our assumptions on emissions.

A.1.1 WTT emissions

Figure 52 shows the specific fuels used in our study, along with the WTT emissions associated with each.

Figure 52 WTT emissions

Fuel	Code	Description	Combustion CO2 emissions g CO2eq/MJ	Combustion CO2 emissions (renewable) g CO2eq/MJ	Total WTT g CO2 eq/MJ
Gasoline	COG1	Crude oil from typical EU supply	73.4	0.0	17.0
CNG	GPCG1b	Imported natural gas, transport to EU by pipeline	55.1	0.0	15.1
CBM	OWCG1	Upgraded biogas from municipal organic waste as CBM	56.7	-56.7	9.5
CBM	OWCG21	Upgraded biogas from wet manure as CBM	56.7	-56.7	-102.9
SNG	WWCG2	Synthetic methane (as CNG) via gasification of waste wood and methanation	56.7	-56.7	21.0
SNG	RECG1	Synthetic methane (as CNG) from renewable electricity and CO2 from flue gas	55.0	-55.0	2.4
Electricity	WWLG2	Synthetic methane (as LNG) via gasification of waste wood and methanation	54.9	-54.9	25.3
Electricity	RELG1a	Synthetic methane (as LNG) from renewable electricity, CO2 from flue gases	55.0	-55.0	6.7
Diesel	COD1	Crude oil from typical EU supply	73.2	0.0	18.9
LNG	GRLG1	Remote natural gas liquified at source	55.1	0.0	16.6
LBM	OWLG1	Upgraded biogas from municipal organic waste as LBM	54.9	-54.9	13.8
LBM	OWLG21	Upgraded biogas from wet manure as LBM	54.9	-54.9	-98.7
SLNG	WWLG2	Synthetic methane (as LNG) via gasification of waste wood and methanation	54.9	-54.9	25.3
SLNG	RELG1a	Synthetic methane (as LNG) from renewable electricity, CO2 from flue gases	55.0	-55.0	6.7
Hydrogen	GPCH1b	H2 produced via steam methane reformation without CCS	0.0	0.0	113.0
Hydrogen	GPCH2bC	H2 produced via steam methane reformation with CCS	0.0	0.0	39.7
Hydrogen	WDEL 1/ CH2	Electrolysis from 100% wind energy	0.0	0.0	9.5

Source: JEC WTTv5, (2020), Appendix 1 - https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/jec-well-tank-report-v5

[60] JEC, (2020), *Well-To-Wheels report v5* - https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/jec-well-wheels-report-v5.

A.1.2 TTW emissions

Figure 53 shows the vehicle efficiency figures used to calculate TTW emissions for each vehicle.

Figure 53 Energy expended TTW

Powertrain	Engine	Fuel	TTW Energy expended MJ/(t)km	Source graph (JEC WTW)
ICE	DISI	Gasoline	1.42	Figure 21 - Gasoline & Diesel - DISI & DICI - 2025+
ICE	DISI	CNG/CBM	1.4	Figure 33 - CBM and SNG - DISI - 2025+
BEV	Range 400	Electricity	0.42	Figure 35 - Electricity- BEV 400 - 2025+
ICE	CI	Diesel	0.66	Figure 66 - Diesel - CI & CI hybrid - 2025+
ICE	PI	LNG/LBM	0.83	Figure 74 - LBM and LSNG - PI - 2025+
ICE	HPDII	LNG/LBM	0.68	Figure 74 – LBM and LSNG – HPDI – 2025+
ICE	PI / HDPI mix	LNG/LBM	0.78	Weighted average based on 1/3 vehicles using HPDI engines and 2/3 using PI
FCEV	FC	Hydrogen	0.48	Figure 78 - Hydrogen - FCEV - 2025+

Source: JEC WTW v5, (2020) https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/jec-well-wheels-report-v5

A.1.3 WTW emissions

We calculate the WTT and TTW emissions to give a WTW emission figure for each vehicle. We use the following formulae:

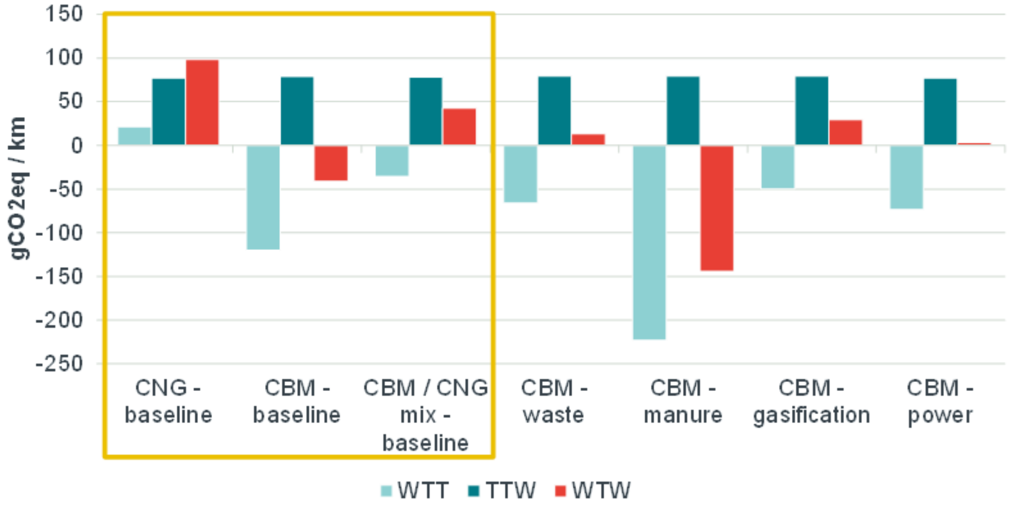
WTT *(g CO2eq / km) = (Combustion CO2 emissions of which renewable (g CO2 eq / MJ) + Total WTT emissions (g CO2 eq / MJ)) * (Efficiency factor (MJ/(t)km)*

TTW *(g CO2eq / km) = Combustion CO2 emissions (g CO2 eq / MJ) * Energy expended (MJ/(t)km)*

WTW *(g CO2eq / km) = WTT emissions (g CO2eq / km) + TTW emissions (g CO2eq / km)*

Figure 54 shows the WTW emissions for each of the CBM feedstocks which are used in the 2030 fuel mix.

Figure 54 CBM WTW emissions

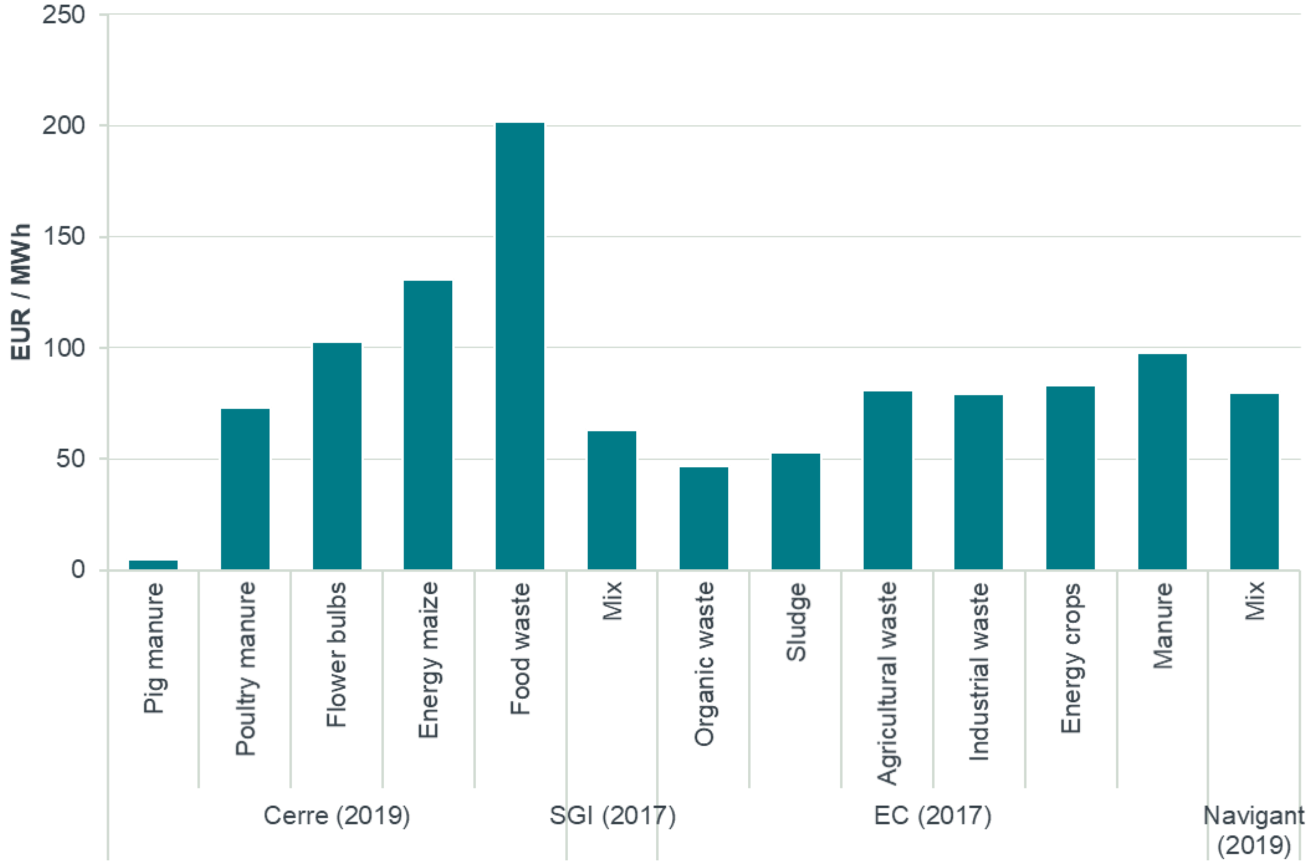


Source: Frontier Economics based on JEC WTW and NGVA Europe fuel mix assumptions

ANNEX B FUEL PRODUCTION COST

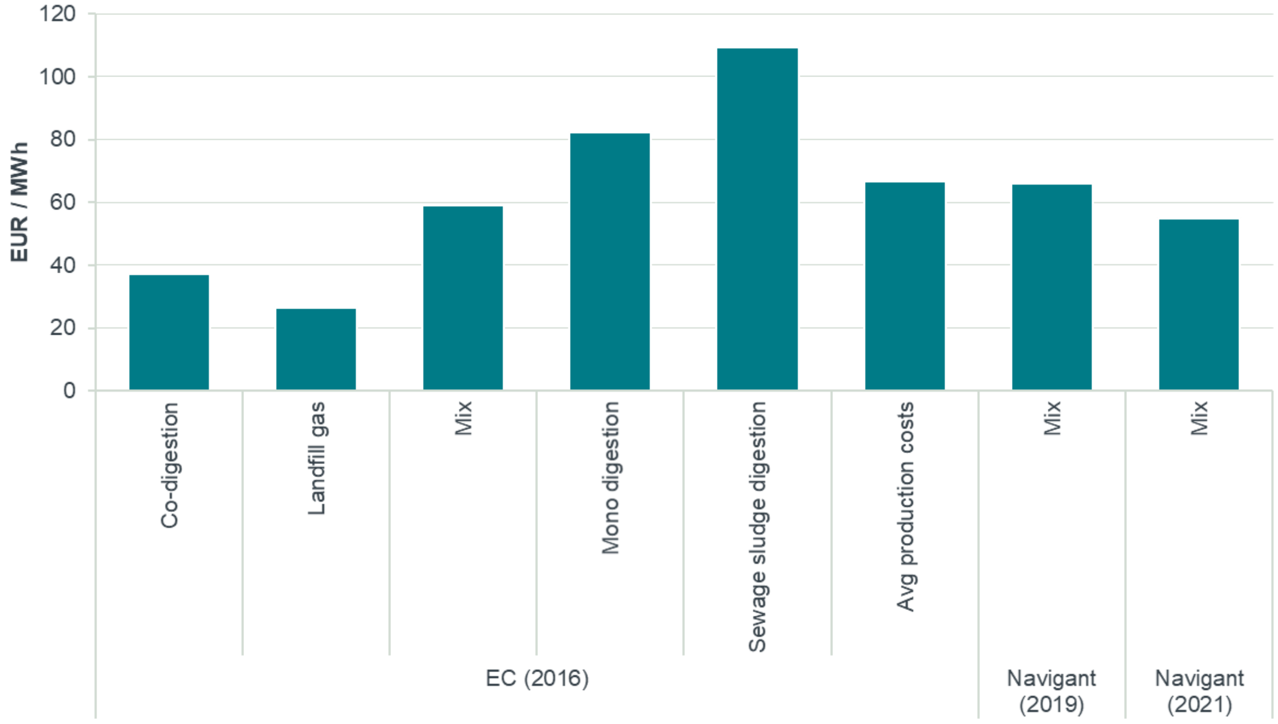
B.1 Passenger vehicles

Figure 55 Biomethane production costs in 2020



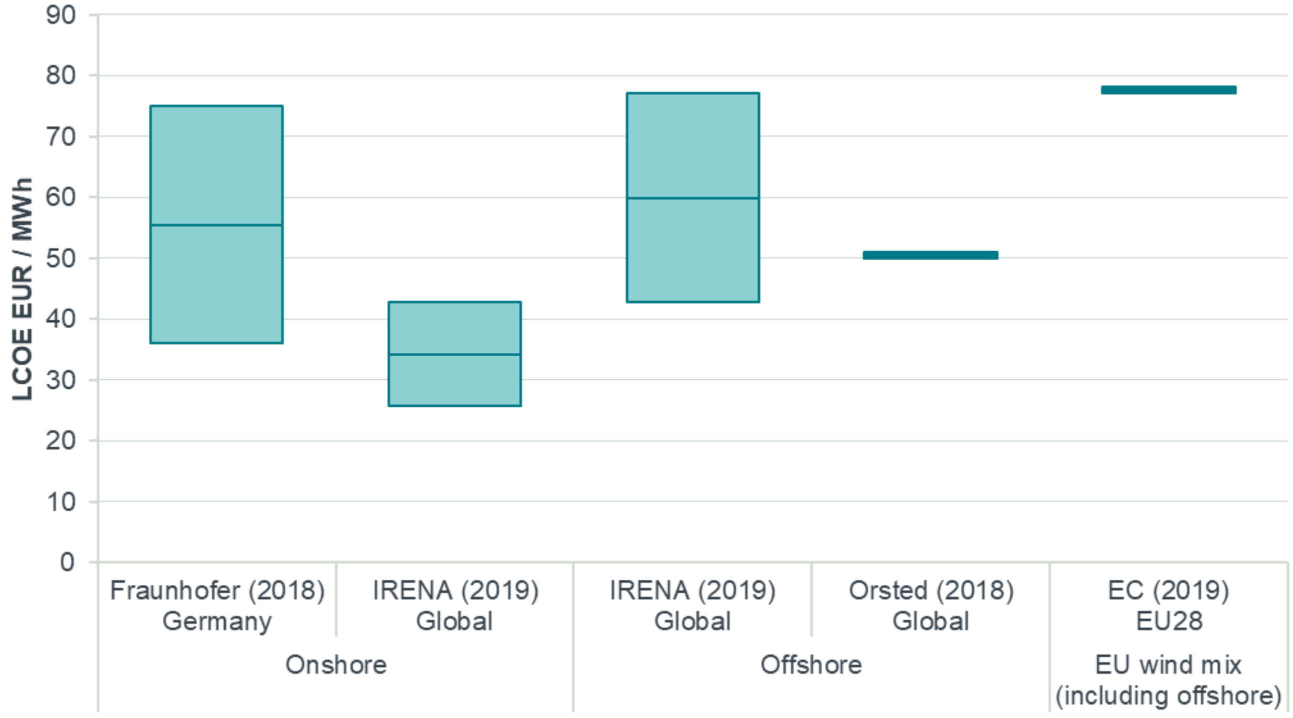
Source: Frontier Economics based on literature review
Note that the EC (2017) costs were estimates for biogas and are adjusted by purification costs of 8,5 EUR/MWh (Navigant 2019 gives a range of 5-12 EUR/MWh for purification).

Figure 56 Biomethane production costs in 2030



Source: Frontier Economics based on literature review

Figure 57 Wind production costs in 2030



Source: Frontier Economics based on literature review

ANNEX C FUEL TRANSPORT COST

C.1 Passenger vehicles

Figure 58 sets out the assumptions used for transmission and distribution pipelines used for the transportation of natural gas.

Figure 58 Methane transport costs

	Parameter	Unit	Investment cost (2030 EUR/unit)	O&M cost % investment	O&M cost (EUR/km/year)
Transmission	Transmission pipelines	km	2,000,000	4%	80,000
Distribution	Distribution pipelines	km	380,000	4%	15,200
	LNG trucks	#	120,000		

Source: Pipeline cost estimates based on https://www.nep-gas-datenbank.de/app/#!/ausbaumassnahmen for transmission and https://sari-energy.org/oldsite/PageFiles/What_We_Do/activities/GEMTP/CEE_NATURAL_GAS_VALUE_CHAIN.pdf for distribution

Figure 59 sets out the assumptions on transmission and distribution investment costs used for electricity transportation.

Figure 59 Electricity transport costs

	Parameter	Unit	Investment cost (2030 EUR/unit)	O&M cost % investment	O&M cost (EUR/km/year)	Operating life
Transmission	AC overhead lines	km	2,200,000	1%	22,000	20
Distribution	HVDC cables	km	2,000,000	1%	20,000	20
	HS	km	1,050,000	1%	10,500	20
	MS	km	110,000	1%	1,100	20
	NS	km	80,000	1%	800	20

Source: Costs based on NEP and https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/technologieuebersicht.pdf?__blob=publicationFile&v=12

C.2 Trucks

Figure 60 sets out the main assumptions used for LNG and hydrogen transport, which is done via road tanker in 2030.

Figure 60 Truck transport cost

Parameter	Unit	LNG	H2	Source
Road tanker transport capacity	kg	20,475	1,100	LNG: https://www.shell.de/medien/shell-publikationen/shell-lng-studie/_jcr_content/par/toptasks.stream/1570447648817/3cb7ff696a24326140f5b19765408059c494ca88/lng-study-uk-18092019-einzelseiten.pdf
Fuel transport distance (one way)	km	400	400	H2: https://hydrogeneurope.eu/hydrogen-transport-distribution
Road tanker yearly km	km	98,000	98,000	
Road tanker yearly tkm	tkm	1,096,498	242,060	FE assumption
Cost of truck	EUR	120,000	163,760	Mileage for 4-LH: HDV fleet target regulation Annex I

Source: Frontier Economics based on literature review

www.frontier-economics.com