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Department of Transport,
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Report on Diesel-and Alternative-Fuel Bus Trials

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EXECUTIVE SUMMARY

The National Development Plan commits Ireland to stop purchasing diesel-only buses for the urban public fleet by July 2019. To assist the Department of Transport, Tourism and Sport (DTTAS) with understanding the available alternative technologies and, importantly, the emissions generated under real-world conditions, trials were carried out on fifteen buses over a five-month period (December 2018 to April 2019) in Dublin and Cork using a portable emissions measuring system (PEMS). A mix of diesel, diesel hybrid, gas and electric buses were tested. Two of the diesel buses tested were retrofitted with selective catalytic reduction (SCR) technology, which is primarily aimed at reducing emissions of nitrogen oxides (NO_X).

Legislative & Policy Context

There are several underlying drivers for examining the alternatives to diesel buses in the urban public fleet. The commitment in the National Development Plan to stop purchasing diesel-only buses for the urban public fleet by July 2019 stems from many national and EU low-carbon and renewable energy commitments, obligations and strategies, including Ireland's national energy policy, as set out in the Energy White Paper, the Government's 2013 National Policy Position on Climate Action and Low-Carbon Development, the forthcoming Clean Air Strategy, the Alternative Fuels Infrastructure Directive, the Renewable Energy Directive, and the National Mitigation Plan.

Another important driver is the recast Clean Vehicles Directive, which sets various binding targets for 'clean vehicles' and 'zero-emission heavy duty vehicles' when procuring public buses (and other public transport vehicles) from 2021 onwards.

The Irish Transport Market & Urban Public Bus Fleet

Transport accounts for 43% of national final energy consumption, of which 97% is supplied by oil. There are very few other fuels in use in the transport sector; biofuels account for the majority at around 4% of road transport energy. There is also liquified petroleum gas (LPG), electricity, and there are plans for compressed natural gas (CNG) as part of the Causeway Project, which aims to pilot 14 fast-fill CNG stations by 2020. Transport accounted for one-fifth of Ireland's total greenhouse gas (GHG) emissions in 2017 and 40% of NO_X emissions. In 2017, public passenger services, which includes buses and taxis, accounted for 2.7% of national final energy consumption and GHG emissions.

Dublin Bus is the main bus operator in the Greater Dublin Area, along with Bus Éireann and Go-Ahead Ireland. Almost half of the buses operated by the three companies conform to the latest Euro standard (Euro VI) with the remainder being Euro V, IV and III (Euro V buses account for the smallest portion of the fleet).

The efficiency of the public urban bus fleet was 16.6 MJ/km (46 l/100km) in 2018. When the entire public fleet (urban, regional and intercity) is considered, the overall efficiency improves to 14.7 MJ/km (41 l/100km).

DTTAS bus trials

In general, the findings from the PEMS testing and testing on the electric buses are in keeping with the findings from other similar trials and studies.

1. Electric buses are the most energy efficient (on a final energy basis), followed by hybrid and diesel buses – CNG buses are the least efficient.

2. Electric buses emit no tailpipe CO_2 emissions. Of the remaining technologies, diesel hybrid buses emit the lowest quantities of CO_2 per kilometre. Even though the carbon intensity of natural gas is less than that of diesel, the energy efficiency of the CNG buses is such that the CO_2 emitted per kilometre is greater than the Euro VI diesel bus and the hybrid bus.

3. Based on lifecycle GHG emissions, electric buses perform the best, when compared with diesel hybrid buses and CNG buses run on fossil fuels. If the diesel hybrid and CNG buses were run on 100% biofuel (i.e. biodiesel and biomethane), the hybrid buses would achieve the lowest lifecycle GHG emissions followed by CNG buses and then electric.

4. The performance of CNG buses and diesel buses vary with respect to NO_X emissions. In some cases, the data indicate that, relative to diesel buses, NO_X emissions can be marginally higher for CNG buses; in other cases, NO_X emissions from CNG buses are lower.

5. In general, the buses operated more efficiently in Dublin, and thus, had lower CO_2 emissions. CO emissions were similar in both cities. NO_X emissions were marginally higher in Dublin because the buses stopped more frequently, which reduced the exhaust temperature and the effectiveness of the SCR systems. The results show that the particulate emissions for diesel and diesel hybrid buses observed at both locations (excluding cold starts) were significantly below the particulate limit for passenger cars.

6. NO_X and particulate emissions were typically higher for the diesel hybrid buses relative to the Diesel 3 Euro VI bus (the baseline bus). This maybe because the SCR on the diesel hybrid buses may not operate as effectively when combined with the stop / start operation of the hybrid engine, i.e. the exhaust may not reach a high enough temperature to operate the SCR effectively, because the engine is not always running. In addition, the Diesel 3 Euro VI bus has been procured and optimised for city-centre driving in Ireland, whereas the diesel hybrids tested were demonstration buses.

Contribution to Renewable Energy and Emissions Reductions

The overall EU targets for renewable energy are 20% by 2020 and 27% by 2030. Member States have different national targets for 2020, although all have a mandatory target of 10% for transport (by 2020), as set out in the Renewable Energy Directive (RED). Ireland's overall renewable energy target for 2020 is 16%. The recast Renewable Energy Directive (RED II) sets a 14% renewable energy target in transport for 2030.

The public urban bus fleet accounts for approximately 1% of road transport energy demand. Consequently, the potential contribution towards renewable energy targets by increasing renewable energy in the public bus fleet is limited, as is reducing emissions. Notwithstanding this, increasing renewables in the public urban bus fleet will support achieving renewable energy and emissions reduction targets, as well as demonstrating leadership in the transport sector.

We examined several technology penetration scenarios (10% electric buses to 100% electric buses, 10% bioCNG to 100% bioCNG, and 10% HVO[1] to 100% HVO in hybrid buses). The largest contribution to the 2030 renewable energy target would be delivered by gas buses run on 100% bioCNG: 1.4%. An entirely electric fleet would contribute, at most, 0.44%, and running a hybrid fleet

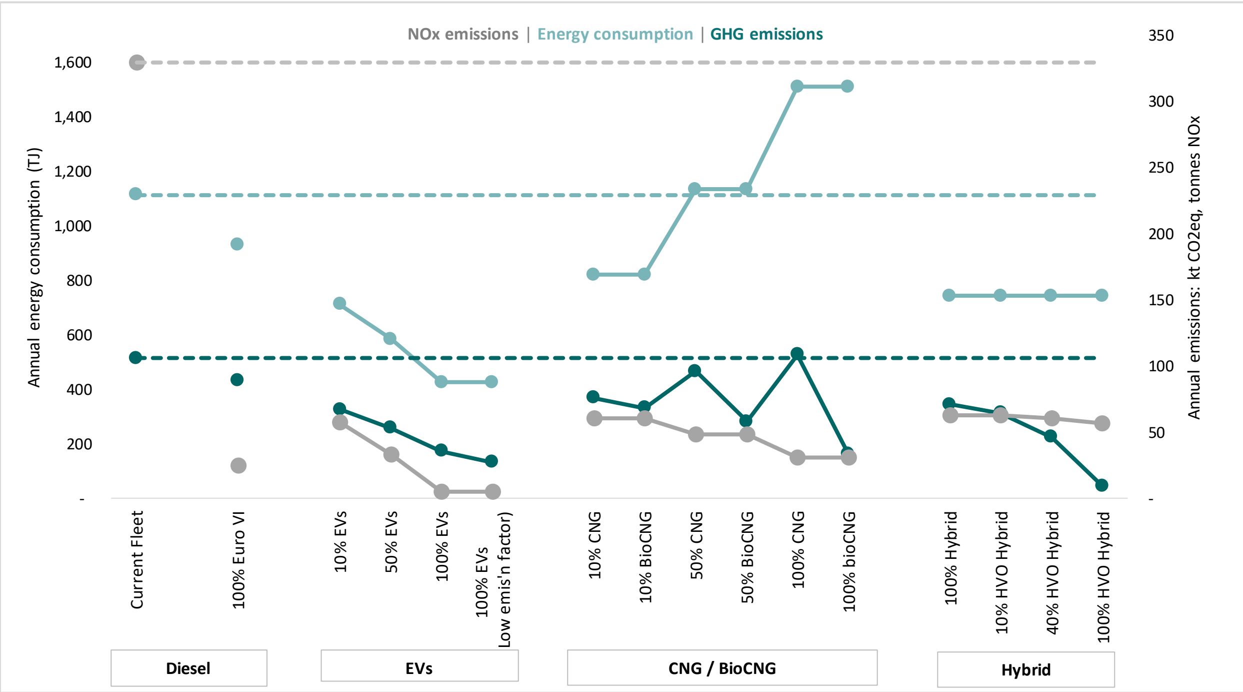
[1] Hydrotreated Vegetable Oil – a type of biodiesel that can be blended with diesel at high rates.

entirely on HVO (or biodiesel) would contribute 0.74%. These results are, however, deceptive. Electric buses are the most energy efficient (on a final energy basis); thus, they consume less energy to perform the same work – gas buses are the least energy efficient. Therefore, gas buses, by virtue of consuming more renewable energy than the electric buses or the HVO hybrid buses, would contribute more to the 2030 renewable energy target.

We estimate that the national pubic urban bus fleet emits approximately 0.7% of Ireland's transport related NO_X. Under all the scenarios examined, there will be significant reductions in NO_X emissions by 2030 (greater than 80%). This reduction is being driven to a large extent by transitioning the fleet away from older Euro IV and V engines to Euro VI hybrids. While moving to a 100% electric fleet would eliminate tailpipe emissions of NO_X, there would be NO_X emissions associated with generating the electricity, which still relies on burning fossil fuels.

A plot comparing the estimated performance of various technology and fuel scenarios in 2030 is presented in Figure 1. For the electric and CNG scenarios, we assume as new buses are purchased the number purchased reflects the scenario description with the balance of the buses purchased being diesel hybrids. For the HVO scenarios, all the new buses purchased are hybrids with the scenario description reflecting the percentage of those new buses being run on HVO.

Figure 1: Comparison of options in 2030



Cost Benefit Analyses

Two costs benefit analysis have been carried out. In both, we adopt a benefit cost ratio (BCR) approach which compares the present value costs and benefits. In a typical net present value (NPV) assessment, if the sum of the net cash flows over the lifetime of the project are positive, then it indicates the investment may be justifiable. However, in the case of an investment to reduce or eliminate potential environmental damage or improve human health, there should be a bias towards the benefits to be gained. There are several guidelines comparing what level of cost can be incurred to justify environmental and health benefits. In this assessment we assume a level of bias (i.e. a proportion factor) of greater than 2 indicates that the costs maybe disproportionate to the benefits gained.

In the first cost benefit analysis, we examine the merits of an SCR system installed on two diesel buses (Euro IV and Euro V). The estimated proportion factor for installing the SCR on the Euro IV bus was 2.1, which suggests the investment is close to being justifiable. The proportion factor for the Euro V bus was 3.8, suggesting the costs may be disproportionate to the benefits gained.

The sensitivity analysis shows that the lifetime of the SCR system has the greatest influence on the proportion factor. For the Euro IV, a lifetime of greater than 4 years will drop the proportion factor to below 2; for the Euro V, the lifetime of the SCR would need to increase to 12 years for the proportion factor to reduce to below 2.

Apart from the length of time the SCR is installed, the magnitude of the NO_X damage costs and the efficiency of the SCR system also have significant impacts on the proportion factor. For the Euro IV bus, if the damage costs of NO_X emissions were to rise above €11,500 per tonne (central value is €10,000 per tonne) or the SCR system was to save in excess of 7 gNO_X/km (central value is 6 gNO_X/km), the proportion factor would drop below 2 indicating the investment may be justifiable. Varying the capital cost, the operating cost and the discount rate will have little influence on the decision to invest in SCR for Euro IV or Euro V buses.

The second cost benefit analysis was carried out on the four different bus technologies trialled (electric, CNG, diesel and hybrid) and incorporated several different fuel inputs. In total, fourteen investment options were assessed relative to a baseline fleet comprised entirely of Euro VI diesel buses. The objective was to assess various technology and fuelling options in various combinations. The analysis found that none of the options returned a proportion factor of less than 2, indicating the investments may not be justifiable. However, given that it is national policy to transition the urban pubic bus fleet away from diesel only buses, the proportion factors calculated indicate that the following priority should be given to the technology and fuel options: electric, HVO diesel hybrid, bioCNG, diesel hybrid and CNG.

CNG buses (fuelled by natural gas) perform poorly relative to the baseline fleet because lifecycle GHG emissions are high as a consequence of poor energy efficiency. Although bioCNG buses also suffer from poor energy efficiency, bioCNG has a much lower GHG emission factor than CNG and consequently is a more attractive option.

Three of the fourteen investment options assessed did not provide environmental benefits greater than the baseline fleet comprised entirely of Euro IV diesel buses:

1. 50% CNG / 50% diesel hybrid mix
2. 65% CNG / 35% bioCNG mix
3. 100% CNG

In terms of achieving the Climate Action Plan's GHG reduction target of 45% to 50% by 2030, five of the investment options assessed reduced GHG emissions by greater than the target:

1. 100% electric
2. 50% electric / 50% diesel hybrid
3. 100% HVO hybrid
4. 40% HVO hybrid / 60% diesel hybrid
5. 100% bioCNG

A sensitivity analysis carried out on three of the investment options (100% electric, 100% HVO hybrid and 100% BioCNG) shows that for the electric buses, the biggest influences on the proportion factor are the efficiency of the vehicles and the CO_2 damage costs. Using central values, a proportion factor of 5.9 was calculated for the 100% electric fleet, which is lower than the 6.5 calculated for the 100% HVO hybrid fleet and 8.2 for the 100% bioCNG fleet (the lower the proportional factor, the closer the benefits are to matching the costs). The proportion factor for the 100% electric option could be reduced to 4.7 if the bus maintenance costs, including battery maintenance, are approximately half of the equivalent ICE maintenance costs. A similar proportion factor could be achieved for electric buses, and hybrid buses fuelled by HVO, if the CO_2 damage cost increased to approximately €140 per tonne by 2030.

To achieve a similar proportion factor for the 100% bioCNG fleet, the lifecycle GHG emission factor for the biomethane would have to reduce to approximately 0 gCO_{2eq}/MJ. This reflects a very low carbon intensive fuel, which, even though achievable, may not be available. Increasing the CO_2 damage costs to €140 per tonne or reducing the fuel cost to €1.70 / 100 MJ (central value is €1.98 / 100 MJ) would also reduce the proportion factor, but they would only reduce it to approximately 6.5.

In reducing GHG emissions, HVO and bioCNG are viable alternatives to a fully electric fleet, particularly if the price of carbon rises and the cost of these fuels reduce; however, fuel availability is a concern and while buses run on HVO and bioCNG could be classified as ‘clean vehicles’, they could not be considered to be ‘zero-emission heavy duty vehicles’, as defined in the Clean Vehicles Directive.

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ABBREVIATIONS

AFID	Alternative Fuels Infrastructure Directive
B20	Diesel with 20% biodiesel
BCR	Benefit-cost ratio
BOS	Biofuels Obligation Scheme
CAF	Common appraisal framework
CCS	Carbon capture & storage
CH_4	Methane
CNG	Compressed natural gas
bioCNG	Biomethane used in a CNG vehicle
CO_2	Carbon dioxide
CO_{2eq}	Carbon dioxide equivalent
CRU	Commission for Regulation of Utilities
CVD	Clean Vehicles Directive
DPF	Diesel particulate filter
DTTAS	Department of Transport, Tourism and Sport
EA	Emissions Analytics
EEA	European Environment Agency
EPA	Environmental Protection Agency
EU	European Union
EV	Electric vehicle
FAME	Fatty acid methyl ester
FID	Flame ionisation detection
GDF	Gross disproportion factor
GHG	Greenhouse gas
NH_3	Ammonia
HSE	UK Health and Safety Executive
HVO	Hydrogenated vegetable oil
ICE	Internal combustion engine
kt	Kilo tonne (1×10^9 grams)
kWh	Kilowatt hour. Equal to 3.6×10^6 joules
LNG	Liquified natural gas
LPG	Liquefied petroleum gas
MJ	Mega Joule (1×10^6 joules)
NDP	National Development Plan
NH_3	Ammonia
NMP	National Mitigation Plan
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_X	Nitrogen oxides
NPF	National policy framework
NPV	Net present value
NTA	National Transport Authority

PEMS	Portable emissions measurement system
PJ	Peta Joule (1×10^{15} joules). Equal to 278 GWh.
PM	Particulate matter
PN	Particulate number
PSC	Public Spending Code
PSO	Public service obligation
PV	Present value
RED	Renewable Energy Directive
RED II	Recast Renewable Energy Directive
SCR	Selective catalytic reduction
SEAI	Sustainable Energy Authority of Ireland
SMR	Steam methane reformation
SO_2	Sulphur dioxide
SOC	State of charge
TJ	Tera Joule (1×10^{12} joules)
TRL	Transport Research Laboratory
UCO	Used cooking oil
ULEV	Ultra-low emission vehicle
WHO	World Health Organisation

1 INTRODUCTION

The Department of Transport, Tourism and Sport (DTTAS) appointed Byrne Ó Cléirigh in November 2018 to assist the Climate Change Unit with project managing, administering and assuring the quality of trials carried out on diesel and alternatively fuelled buses. The primary reason for conducting the trials is the commitment in the National Development Plan (1) to stop purchasing diesel-only buses for the urban public fleet by July 2019. With diesel-only buses no longer permitted, DTTAS needs to understand the available alternative technologies and, importantly, the emissions generated under real-world conditions.

The trials were carried out on fifteen buses over a five-month period (December 2018 to April 2019) in Dublin and Cork. Emissions Analytics (EA) was appointed by DTTAS to measure the emissions from the buses using a portable emissions monitoring system (PEMS). Two of the diesel buses tested were retrofitted with selective catalytic reduction (SCR) technology, which is primarily aimed at reducing emissions of nitrogen oxides (NO_X).

BÓC were appointed to carry out several tasks:

1. Prepare and plan for the trials;
2. Oversee the trials;
3. Review the PEMS data;
4. Analyse the emissions and fuel economy data;
5. Examine the well-to-wheel performance of the different fuels;
6. Compare the findings with other bus studies;
7. Examine the likely infrastructure requirements;
8. Assess the contribution to renewable energy targets;
9. Examine the broader costs and benefits of the fuels and technologies;
10. Prepare a report on the trials.

In Section 2 of this report we set out the legislative and policy context for the trials. In Section 3 we provide an overview of energy consumption and emissions from the transport sector in Ireland and the contribution of the public bus fleet. Section 4 summarises the impact of transport emissions on human health and the environment, and provides examples of the actions other countries and cities are taking to reduce transport emissions.

In Section 5 we describe the bus trials, the methodology employed for the PEMS testing and for testing the electric buses, and report on the energy efficiency and emissions findings. In Section 6 we report on similar tests and experiences from elsewhere and compare the findings with those from this trial.

In Section 7, we calculate the contribution alternative fuels and technologies could make to renewable energy targets and emissions reductions under several scenarios. Section 8 describes our approach to the cost benefit analysis and sets out the findings for several different alternative fuels and technology adoption scenarios, and for the SCR system. Finally, in Section 9, we provide our conclusions on the trials and make recommendations on actions that could be taken in the coming years to comply with policy requirements and improve the performance of the national bus fleet.

2 LEGISLATIVE & POLICY CONTEXT

2.1 Overview

There are several underlying drivers for examining the alternatives to diesel buses in the public transport fleet. The most relevant is the commitment in the National Development Plan (1) to stop purchasing diesel-only buses for the urban public fleet by July 2019. This requirement stems from many national and EU low-carbon and renewable energy commitments, obligations and strategies, including Ireland's national energy policy, as set out in the Energy White Paper (2), the Government's 2013 National Policy Position on Climate Action and Low-Carbon Development (3), the forthcoming Clean Air Strategy, the Alternative Fuels Infrastructure Directive (4), the Renewable Energy Directive (5), and the National Mitigation Plan (6). In the following sub-sections, we briefly describe these important drivers for decarbonising the public bus fleet in Ireland and incorporating renewable energy into the transport fuel mix.

2.2 National Development Plan

The National Development Plan 2018 – 2027 (NDP) (1) sets out the investment priorities for implementing the National Planning Framework (7). The objective of the Plan is to guide national, regional and local planning and investment decisions. There are ten national strategic outcomes identified in the Plan, one of which is *sustainable mobility*.

One of the sustainable transport investment actions in the Plan is the primary driver for the DTTAS's bus trials: *transition to low emission buses, including electric buses, for the urban public bus fleet, with no diesel-only buses purchased from July 2019, while promoting commercial bus services and small public service vehicle industry to pursue low emission fleet*.

A complementary action set out in the NDP aimed at reducing transport emissions and increasing the share of renewable energy is to replace *existing diesel buses for the urban public bus fleet with lower emitting alternatives under the BusConnects programme, while promoting commercial bus services and small public service vehicle industry to use low-emission fleet*.

2.3 Energy White Paper

The long-term vision set out in the White Paper (2) is for greenhouse gas (GHG) emissions from the energy sector to be reduced by 80-95% by 2050. In the longer term, it is envisaged that renewable energy sources will largely replace fossil fuels. The White Paper expresses Ireland's intention to transition to a low-carbon economy by 2050 and it is the DTTAS's vision that only zero-emissions cars (or zero-emission-capable cars) will be sold in 2030, with a view to decarbonising transport by 2050. In the context of alternative fuels, the Paper envisages transitioning to electric and hydrogen vehicles, which have no tailpipe emissions (other than water with hydrogen vehicles). However, producing electricity and hydrogen requires energy, which has associated carbon emissions. Therefore, rather than just shifting the point at which the GHG emissions are generated from the car to generating station, reducing the lifecycle GHG emissions will require a reduction in emissions from electricity and hydrogen generation.

The White Paper acknowledges that transitioning to low-carbon fuels will take some time and that oil and natural gas will remain significant elements of Ireland's energy supply between now and 2035. Transitioning the public bus fleet away from fossil fuels will assist with moving towards a low-carbon economy and will also demonstrate leadership in this area.

2.4 Renewable Energy Directive (RED)

Article 3 of the RED (5) sets out mandatory national targets and measures for using energy from renewable sources for EU Member States. Ireland's target for the share of gross final energy consumption to come from renewable sources is 16%, by 2020

Although Member States may set individual targets for heat and electricity, item 4 of Article 3 places the following obligation on all Member States.

> *Each Member State shall ensure that the share of energy from renewable sources in all forms of transport in 2020 is at least 10 % of the final consumption of energy in transport in that Member State.*

It is in this context that Ireland has implemented the Biofuel Obligation Scheme (the BOS), which was given effect in law under the Energy (Biofuel Obligation and Miscellaneous Provisions) Act 2010 (8). The Scheme is one aspect of a two-part approach to meeting the EU target for the use of renewable energy in transport; the second part is to encourage the accelerated development and usage of electric vehicles (EVs). The National Oil Reserves Agency is the body charged with administering the BOS.

The RED also established the 'sustainability criteria' for biofuels. These set the GHG savings requirement and the requirements for conserving carbon stock and biodiversity. In short, only biofuels that meet the sustainability criteria can be counted towards the RED targets. Biofuels that are produced from wastes and residues may be double-counted[2].

The RED is the cornerstone of renewable energy policy in Ireland's transport sector. RED II (9) is the successor to the RED. The objectives of the RED II are to give regulatory certainty to industry, to promote investment, enable cost-effective renewables to be incorporated into the electricity sector, decarbonise the transport sector, promote advanced biofuels, and incorporate more renewables into the heating and cooling sectors. The RED II was published in December 2018 and will need to be transposed into Irish law by 2021. It sets a 14% renewable energy target in transport for 2030.

2.5 Alternative Fuels Infrastructure Directive (AFID)

More than 90% of the energy used in transport within Europe is derived from crude oil, most of which is imported – in 2011, 84% of Europe's oil was imported[3] (10). The AFID (4) requires each Member State to develop a sustainable alternative fuels strategy, to support the development of appropriate refuelling infrastructure and associated standards.

The AFID sets out the main alternative fuel options that could act as a substitute to oil in transport (road and maritime). These include electricity, hydrogen, biofuels, natural gas (in the forms of compressed natural gas (CNG) and liquified natural gas (LNG)), liquid petroleum gas (LPG), and synthetic and paraffinic fuels. Infrastructural targets are only required for electricity and natural gas (in the form of CNG/LNG).

The AFID requires Member States to prepare a national policy framework (NPF) on alternative fuels infrastructure. Ireland's NPF (11), which was published in June 2017, states that reducing reliance on fossil fuels and switching to alternatives will be an integral part of the transport sector's efforts to decarbonise. The NPF represents a first step in communicating a longer-term vision for transport to

[2] As a means of promoting biofuels derived from waste, residues and other advanced feedstocks, the RED permits Member States to count each litre of such biofuels twice towards the 10% target.

[3] Costing up to one billion euro per day.

2050. While a multi-faceted set of measures (energy efficiency, demand management, modal shift, spatial planning, behavioural change and fiscal incentives) aimed at helping decarbonise transport over this period are proposed in other policy initiatives and plans, the focus of the framework is on reducing transport's dependency on oil through the provision of infrastructure and common standards for alternative fuels.

To meet climate targets and air quality objectives, the NPF envisages the transport sector transitioning from oil over the next two decades, moving predominantly to electricity for passenger cars, taxis and commuter rail in the greater Dublin area by 2030. It proposes that natural gas, along with some electrification, will provide an interim alternative solution for larger vehicles such as freight and buses, and that biofuels, including biomethane, will play an important role over the period up to 2030. Post-2030, it envisages that hydrogen will likely increase its penetration across the entire fleet, with a correlated decline in the predominance of vehicles run solely on fossil fuels. It states that Ireland's ambition is for all new cars and vans sold from 2030 to be zero-emission (or zero-emission-capable) and that the freight and bus sectors will continue on a positive trajectory towards full penetration of low-emissions vehicles.

2.6 National Mitigation Plan

Ireland's first National Mitigation Plan (NMP) (6) was published in July 2017. The objective of the NMP is to set out a 'pathway' to decarbonising the economy so that Ireland meets its international commitments under the Paris Agreement, as well the more immediate EU obligations. Thus, it considers the 2020 and 2050 horizons. The NMP contains five sections, one of which addresses decarbonising transport.

The NMP states that *advances in battery technology, increasing competition in the market and lower vehicle costs would suggest that electrification will be the predominant low carbon choice for transport, particularly for the private car, taxis and commercial vans. We can expect freight to be fuelled by a range of fuel types or combinations of such types as biogas, biofuels, electricity, hydrogen, CNG and LNG.*

2.7 Air quality & vehicle emission standards

In addition to the climate impact of transport emissions, the impact on air quality and human health is also of concern. There is EU and Irish legislation that seeks to limit and reduce emissions. Air quality standards (AQS) are set out in a series of EU directives which establish ambient air concentration limits for individual pollutants and target dates for compliance by Member States. An initial framework directive (96/62/EC) was followed by a series of 'daughter directives' which were introduced between 1999 and 2004. The sequence in which the standards for different pollutants were introduced reflected the urgency attached by the EU to specific pollutants. The first daughter directive (1999/30/EC) dealt with SO_2, NO_X, PM_{10} and lead, and was introduced amid concern over the impact of acid rain in the Nordic countries. The second daughter directive (2000/69/EC) set standards for benzene and carbon monoxide. The latest standards for a wide range of pollutants, including those covered in the first and second daughter directives, are now contained in the fourth daughter directive (2004/107/EC) and the Clean Air for Europe (CAFE) Directive (2008/50/EC).

The EPA's Air Quality in Ireland 2015 report (12) references a 2014 report by the European Environment Agency (EEA) which estimates *that around 1,200 deaths in Ireland in 2012 were directly linked to air pollution'.* It also states that increased *'economic activity will likely be mirrored by increases in NO_X emissions, particularly in urban areas. City centre and urban monitoring sites in*

Ireland are approaching EU limit values for NO_2, and it is probable that we will see limit value exceedances in the near future unless mitigation steps are taken.

The Department for Communications, Climate Action and the Environment is preparing a National Clean Air Strategy[4] with the aim of promoting policies to enhance and protect air quality. Core to the strategy will be a national approach to implementing and delivering on the 2020 and 2030 targets set out in the National Emissions Ceiling Directive (13) for NO_X, non-methane volatile organic compounds (NMVOCs), SO_2, ammonia (NH_3) and fine particulate matter ($PM_{2.5}$). The Directive was transposed by SI 232 of 2018 and requires the preparation of a national air pollution control programme.

NO_X is of concern because it reacts with water to produce nitric acid, which is harmful to human health. There are several recently published studies and reports on the impacts on human health from air pollution, and transport emissions in particular, including, for example:

- *Impact of excess NO_X emissions from diesel cars on air quality, public health and eutrophication in Europe* (14), published in 2017[5].
- *Air Quality in Europe* (15), published by the EEA.
- *Air Pollution Marginal Damage Values Guidebook for Ireland* (16), published as part of an EPA-funded IMP[6] project.

The transport sector is a large contributor to NO_X emissions. The recent well-publicised cases of fraudulent manipulation of vehicle exhaust emissions during testing has given rise to new test requirements that more accurately measure emissions during real-world driving conditions.

NO_X emissions from vehicles in Europe are regulated through the Euro standards, which were introduced in the 1990s. Since introducing the standards, the allowable limits have been progressively lowered. While it was acknowledged that there would be a difference between emissions measured during testing and real-world emissions (i.e. emissions under every-day driving conditions), as the compliance limits have been reduced, the gap between NO_X measurements in laboratory tests and the emissions generated under real-world conditions has been increasing for diesel vehicles. A technical working group on real driving emissions was set up in 2011, which has informed the development of several pieces of legislation:

- Commission Regulation EU 2016/427 introduced on-road testing with PEMS to complement the laboratory testing for the type approval of light-duty vehicles. The PEMS integrates gas analysers, exhaust mass flow meters, ambient weather condition measurement and global positioning systems, and can be connected to vehicles' engine control units. There are no 'standard' PEMS, and equipment manufactured by different suppliers may deliver marginally different results.

[4] https://www.dccae.gov.ie/en-ie/environment/topics/air-quality/national-clean-air-strategy/Pages/default.aspx

[5] Prepared by the Norwegian Meteorological Institute in cooperation with the International Institute for Applied Systems Analysis (IIASA) in Austria, and the Dept. Space, Earth & Environment at Chalmers University of Technology in Sweden.

[6] IMP (integrated modelling project) Ireland is a critical research capacity programme designed to develop and direct integrated assessment modelling tools and expertise for applied use within Ireland and the broader international community for cross sectoral integrated modelling of transboundary and greenhouse gas (GHG) emissions.

- Commission Regulation EU 2016/646 introduced not-to-exceed limits which are emission limits for laboratory tests multiplied by 'conformity factors' that take account of the measurement uncertainty of the PEMS.
- Both regulations were consolidated in the World Harmonised Light Duty Test Procedure Commission Regulation EU 2017/1151 and further developed by Commission Regulation EU 2017/1154, which also introduced a real driving emissions conformity factor for the on-road testing of particulate emissions.

There are also several regulations specific to PEMS testing of heavy-duty vehicles. Regulation EC 595/2009 established the requirement for PEMS testing to verify in-use tailpipe emissions as part of the vehicle type-approval process. Regulation EU 582/2011 laid down measures for implementing various aspects of the 2009 Regulations, including specific requirements on using PEMS.

The bus trials used PEMS to measure real-world emissions data, which is an established means of measuring tailpipe emissions.

2.8 Exemplary role of public bodies

SI 426 of 2014 (as amended) requires all public bodies, including the semi-state transport companies, to *fulfil an exemplary role with regard to energy efficiency*. Public bodies are expected to fulfil this obligation through, *inter alia,* energy efficient procurement, including with respect to the procurement of vehicles.

2.9 Clean Vehicles Directive (CVD)

The recast Directive on promoting clean and energy-efficient road transport vehicles (Clean Vehicle Directive) (17) aims to stimulate the market for clean and energy-efficient vehicles, and requires lifetime operational energy consumption, CO_2, NO_X, non-methane hydrocarbons and PM to be taken into account by contracting authorities and public transport authorities purchasing vehicles, including buses.

The recast CVD sets out minimum procurement targets for 'zero emission heavy duty vehicles' and 'clean vehicles' and includes purchased, leased, hire-purchased and rented road transport vehicles. Targets are set for two distinct time periods, to reflect the rate of development in clean vehicle technology:

- 45% of M3 category (urban) public buses purchased between August 2021 and December 2025 must be 'clean vehicles';
- between January 2026 and December 2030, 65% of public buses must be 'clean vehicles'.

A clean bus is defined as one that uses 'alternative fuels', as defined in the AFID, i.e. electricity, hydrogen, sustainable biofuels, synthetic and paraffinic fuels, CNG, BioCNG, LNG, BioLNG and LPG. In the case of vehicles using liquid biofuels and synthetic and paraffinic fuels, they cannot be blended with conventional fossil fuels. Additional zero emission sub-targets also apply for urban public buses:

- 50% of 'clean' buses must be zero-emission vehicles, i.e. buses without an internal combustion engine (ICE), or with an ICE that emits less than 1 gCO_2/kWh;
- If more than 80% of buses covered by Member State contracts are double-deck, the 50% requirement reduces to 25% for the first compliance period (2021 to 2025).

Complying with this Directive will have a significant impact on Ireland's urban public bus fleet.

2.10 Climate Action Plan

Ireland's Climate Action Plan (18), published in June 2019, aims to reduce transport emissions by 45-50% by 2030, with a significant acceleration in the second half of the decade. It proposes to increase the use of public transport, cycling and walking, reduced reliance on private cars, and to reduce the carbon intensity of travel by mandating increases in the biofuel mix. It sets out 2030 targets to increase the number of electric vehicles: 1,200 low-emission buses, 95,000 electric vans and trucks, and 840,000 electric cars. Converting fleets to electricity is identified as a central element of future mandates given to all public bodies and a commitment is made to establish a roadmap for all public urban bus fleets to transition to low emission vehicles by 2035.

The Climate Action Plan states that battery prices have fallen by 79% in the last 7 years and a further 67% fall is predicted by 2030. This will significantly reduce the costs of purchasing electric buses and electric vehicles. BloombergNEF estimates that batteries account for approximately 33% of the cost of an EV in 2019 (19).

In addition, a commitment is made to add 500,000 public transport and active travel journeys daily by 2035. Over the lifetime of the BusConnects project, a 50% increase in bus passenger numbers is targeted in the major Irish cities. This is estimated to reduce the emissions from using private cars, which consume the greatest amount of energy in transport at over 40%. The plan also includes for legislation to enable local authorities to introduce low- and zero-emission driving zones.

The EU's 2020 target for GHG emissions reductions is 20% below 1990 levels. Each Member State has been allocated a binding national target in accordance with an effort-sharing agreement (Ireland's target, which applies to the non-Emission Trading Scheme[7] sector only, is a 20% reduction by 2020, compared to 2005 levels). The Climate Action Plan cites the EPA's National Emissions Projections, which estimates that Ireland will exceed its compliance obligations by between 16.3 – 17 Mt CO_{2eq}.

The Effort Sharing Regulation (20) adopted in 2018 is part of the EU's strategy for implementing the Paris Agreement (21). It sets national emission reduction targets for 2030 for all Member States, ranging from 0% to 40% from 2005 levels – Ireland's emission reduction target is 30%.

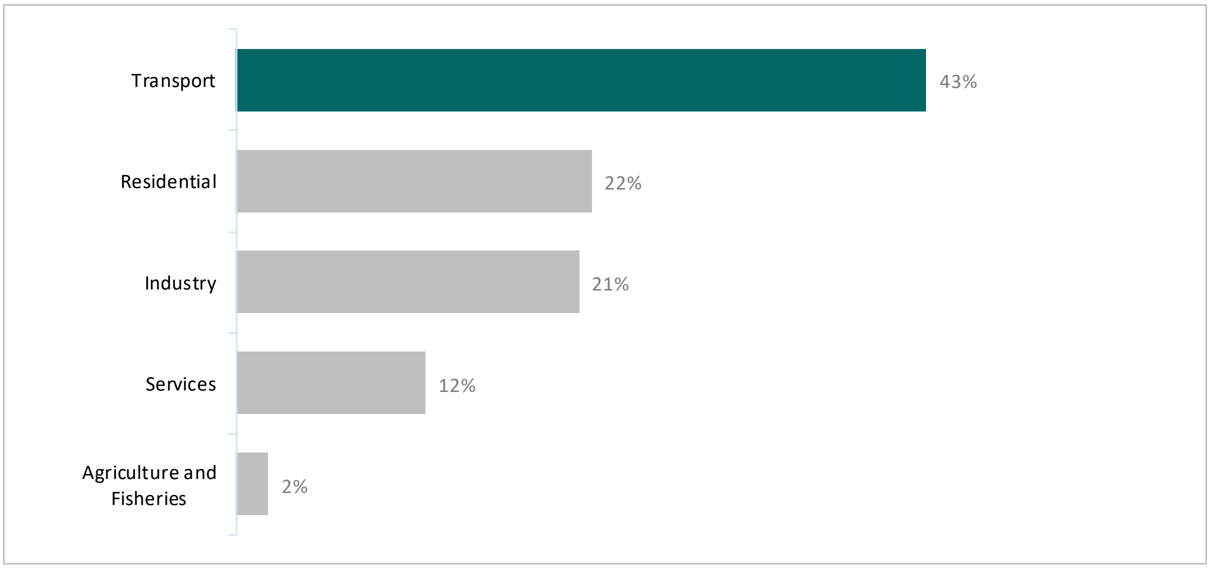
[7] The non-Emission Trading Scheme sector is dominated by transport, agriculture, commercial businesses, the public sector, small industry and households. It accounts for approximately 70% of Ireland's national emissions, which is high compared to most other European jurisdictions.

3 The Irish Transport Sector

3.1 Energy consumption and CO_2 emissions

In total, Ireland consumed almost 500 PJ of energy in 2017, of which 43% was in the transport sector, as shown in Figure 2.

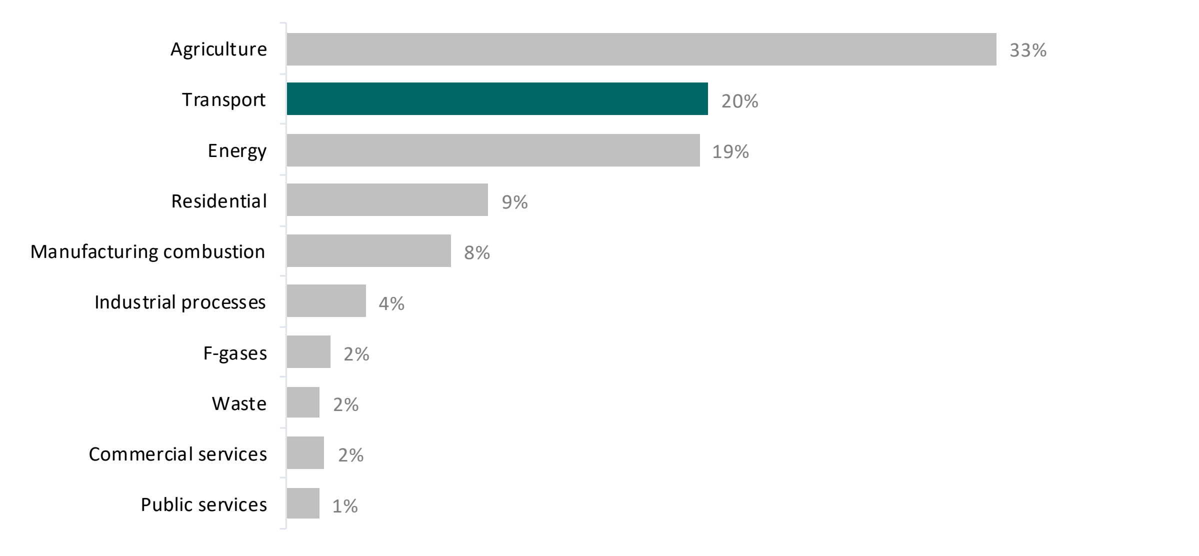
Figure 2: Ireland's total final energy consumption 2017 (source: SEAI)



Oil remains the largest single fuel source (48%) because, although it accounts for less than 2% of power generation, it dominates transport (97%) and supplies 43% of residential heating. There are very few other fuels in use in the transport sector; biofuels account for the majority at around 4% of road transport energy. There is also LPG, electricity for EVs, and there are plans for CNG as part of the Causeway Project, which aims to pilot 14 fast-fill CNG stations by 2020 (the first of these stations became operational in Dublin Port in early 2019).

Transport accounted for one-fifth – approximately 12,000 kt CO_{2eq} – of Ireland's total GHG emissions in 2017, as shown in Figure 3. Road transport was the biggest contributor, accounting for almost 96% of all transport GHG emissions (excluding aviation). GHG emissions in transport decreased for the first time in 2017 after four consecutive years of increases, primarily because of a 10% reduction in petrol use and an increase of 36% in biofuels consumption.

Figure 3: Breakdown of Ireland's GHG emissions 2017 (source: EPA)



GHG emissions[8] from the transport sector from 1990 to 2017 are shown in Figure 4. Transport emissions peaked in 2006 (14,407 kt CO_{2eq}) and then decreased following the economic downturn. In 2017, GHG emission were 17% below the 2007 peak.

Figure 4: GHG emissions[9] from the transport sector 1990 – 2017 (source: EPA)

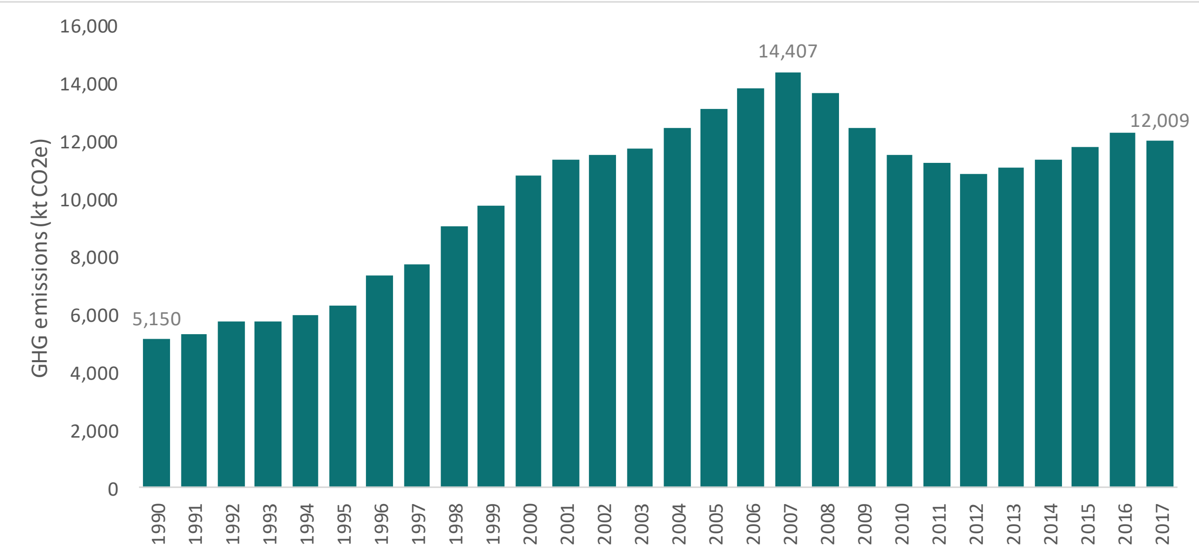
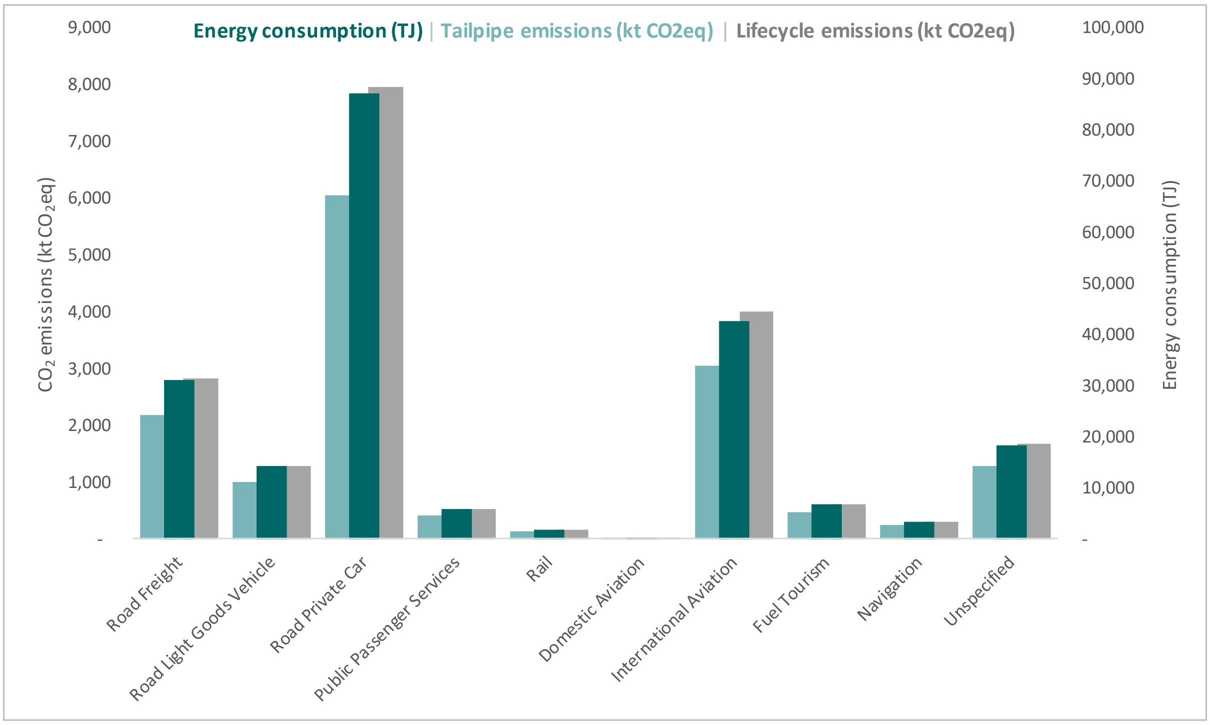


Figure 5 provides a breakdown of energy consumption and CO_{2eq} emissions by mode of transport. The largest contributor to emissions in transport are private cars (41%), followed by international aviation (20%) and road freight (15%). Public passenger services, which includes buses and taxis, account for just 2.7% of energy consumption and CO_{2eq} emissions.

[8] GHG emissions from transport, as presented by the EPA in its annual emissions inventory, refers to 'tailpipe' emissions i.e. emissions from the vehicle's exhaust. Another method of reporting emissions is on a lifecycle basis. Both methods are described in Section 5.3.2.

[9] International aviation emissions are not reported by the EPA emissions inventory, but can be derived from SEAI's Energy Balance.

Figure 5: Energy consumption and $CO2_{eq}$ emissions 2017, by mode of transport (source: SEAI Energy Balance)



Of the total energy consumed in public passenger services in 2017, diesel accounted for 86%, petrol 10% and biofuels 4%. There was no contribution from electricity, LPG or CNG.

As public transport services account for less than 3% of transport energy and emissions, switching to alternative-fuel vehicles will have a limited impact on emissions and renewable energy targets (this is discussed further in Section 7); however, it promotes the use of these technologies and allows public bodies to '*fulfil an exemplary role with regard to energy efficiency*'[10].

3.2 NO_X Emissions

NO_X refers to two pollutants: nitric oxide (NO) and nitrogen dioxide (NO_2). They are produced during combustion at high temperatures; the main sources in Ireland are vehicles and power stations. The EPA reported 108.3 kt of NO_X emissions in Ireland in 2017 – the transport sector was responsible for 44.4 kt (22). While NO_X is not a GHG, and thus does not contribute to climate change, exposure to elevated NO_2 levels can damage human health and impact ecosystems. This is discussed further in Section 4.

3.3 Urban public bus services

3.3.1 Overview of existing Bus Éireann and Dublin Bus urban fleet

A breakdown of the Bus Éireann and Dublin Bus urban public bus fleet, by Euro exhaust emissions standard, is provided in Table 1.

[10] SI 426 of 2014 (as amended): *European Union (Energy Efficiency) Regulations 2014*

Table 1: Bus fleet by Euro exhaust emissions standard (source: DTTAS[11])

Operator	Euro III	Euro IV	Euro V	Euro VI	Total
Dublin Bus	283	174	148	402	1,007
Bus Eireann	6	77	21	100	204
Total (%)	**289 (24%)**	**251 (21%)**	**169 (14%)**	**502 (41%)**	**1,211 (100%)**

Dublin Bus is the main bus operator of PSO buses in the Greater Dublin Area. It covers 136 routes with over 1,000 buses. Bus Éireann has fewer urban services than Dublin Bus; however, it also works with around 1,250 school transport contractors and bus hire companies that support peak demand (23).

Go-Ahead began operating in September 2018 after being awarded a contract for 24 routes in the outer Dublin/Kildare area under the Bus Marketing Opening initiative. We have not included the Go-Ahead fleet in our analysis in Sections 7 and 8 because data was not available for the whole of 2018.

Since 2014, PSO buses were purchased to the highest Euro standard (currently Euro VI). Table 2 sets out the highest Euro standard at the time of procuring the existing bus fleet.

Table 2: Euro standard at time of procurement

Procurement period	Euro standard
2003 – 2006	III
2007 – 2009	IV
2012 – 2013	V
2014 – present	VI

Almost half of the urban public buses operated by the three companies conform to the latest Euro standard (Euro VI); however, around 45% of buses are Euro III or Euro IV. Euro V buses account for the smallest portion of all buses. This is as a result of a shorter time period during which Euro V standards were applicable, relative to other Euro standards, as well as reduced investment between 2009 and 2013.

The reduced investment in buses between 2009 and 2013 has seen the average age of the Dublin Bus and Bus Éireann fleet rise, relative to 2010, as shown in Table 3.

[11] Internal analysis completed by DTTAS in August 2018.

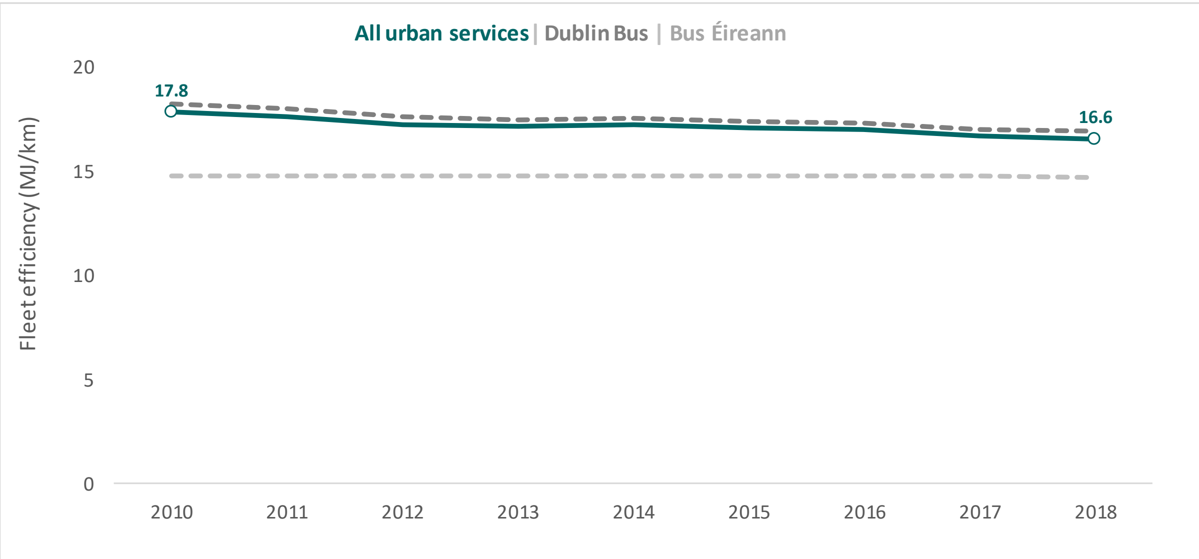
Table 3: Average age of operator's fleet (source: NTA Bus & Rail Statistics 2018)

Year End	Dublin Bus	Bus Éireann (city fleet)	Bus Éireann (services fleet)
2010	6.8	4.8*	4.8*
2011	7.7	6.4*	5.5
2012	7.5	5.6*	5.4
2013	7.5	5.4*	6.1
2014	7.6	6.4*	7.4
2015	7.5	6.3*	6.7
2016	7.5*	6.3*	7.4
2017	7.2*	7.3*	7.3*
* PSO fleet only			

3.3.2 Efficiency of Bus Éireann and Dublin Bus urban fleet

Bus Éireann provides urban public bus services as well as regional and intercity services; Dublin Bus only operates urban public services in the Greater Dublin Area. The efficiency of the urban public bus fleet is shown in Figure 6. Overall efficiency improved by approximately 7% during this period, mainly because of efficiency improvements by Dublin Bus[12].

Figure 6: Efficiency of public bus service, 2010 – 2017 (source: Dublin Bus and Bus Éireann)



The efficiency of the urban public bus fleet was 16.6 MJ/km in 2018. When the entire fleet (urban, regional and intercity) is considered, the overall efficiency improves to 14.7 MJ/km.

[12] While fuel consumption and distance travelled are tracked by Bus Éireann, it operates a 'top-down' reporting system, which makes it difficult to differentiate between urban, regional and intercity services. The figures provided by Bus Éireann are a best estimate of its urban operation.

4 Human Health & the Environment

4.1 Overview

In addition to the climate impact of transport emissions, the impact on air quality and human health is an important consideration. There are many pieces of EU and Irish legislation aimed at limiting and reducing harmful emissions, but rather than having a goal of reducing the effects of climate change, the focus is on reducing emissions that directly impact on human health as a consequence of poor air quality, particularly in urban areas.

The following is an extract from the EPA's report *Air Quality in Ireland 2015* (12).

> *The links between poor air quality and human health are well understood with the 2014 report by the European Environment Agency (EEA) estimating that around 1,200 deaths in Ireland in 2012 were directly linked to air pollution, while for Europe the figure was approximately 400,000 deaths. It is now apparent that the EU limit value levels are inadequate to protect people from the harmful effects of air pollutants and the WHO has intimated that there is no safe limit for air pollution. Along with the clear health benefits in improving air quality in Ireland, there is also an economic saving in doing so, highlighted by the recent OECD report on the economic cost of air pollution (OECD 2016).*
>
> *As the improvement in our economy continues we will also face challenges to comply with EU legislation for pollutants emitted from car exhausts. Economic activity will likely be mirrored by increases in NO_X emissions, particularly in urban areas. City centre and urban monitoring sites in Ireland are approaching EU limit values for NO_2, and it is probable that we will see limit value exceedances in the near future unless mitigation steps are taken.*
>
> *With regard to vehicle exhaust emissions, although it is hoped that technological advances will go some way to addressing this issue, this approach cannot be solely relied upon and complimentary measures to mitigating the problem will be needed such as the transition of individuals from private fossil fuel powered motor cars to alternative modes of transport such as walking, cycling and public transport and policy incentives to promote a transition to more environmentally friendly and sustainable options such as electric motor powered vehicles.*

In the following sections we have summarised the main pollutants of concern (NO_X and PM) and the actions other Member States and cities are implementing to reduce emissions.

4.2 NO_X

NO_X refers to two pollutants: nitric oxide (NO) and nitrogen dioxide (NO_2). They are produced during combustion at high temperatures; the main sources in Ireland are vehicles and power stations. The industrial sector is also a significant contributor to NO_X levels in Ireland, particularly the cement industry. Most NO_X emissions are comprised of NO, with typically 5 - 10% being directly emitted as NO_2.

NO_2 concentrations are closely associated with traffic volumes because diesel engines tend to emit a high percentage of NO_2. As a result, 'sensitive' individuals (asthmatics, elderly people and children) are more susceptible to NO_2 exposure closer to busier roads. Exposure to elevated NO_2 levels can lead to health impacts including respiratory related problems and liver damage. Unlike GHGs, it is the build-up of pollution in a particular location that increases the concentration in the air and the associated risks. According to the UK Department for Transport (24), road vehicles contribute about 80% of NO_2 pollution at the roadside and growth in the number of diesel cars has exacerbated this problem.

Elevated NO_X concentrations can also impact on ecosystems. High NO_X levels can contribute to the acidification and eutrophication[13] of soils and water, which can lead to changes in biodiversity. NO_X also acts as a precursor to tropospheric ozone and influences the production of secondary organic aerosols.

The EPA has stated that, because of Ireland's continued reliance on fossil fuels in transport, NO_X levels will remain a problem in Irish towns and cities (12). It forecasts that it is likely the problem will be exacerbated with the increase in economic activity, as NO_X concentrations would be expected to rise, and it is probable that the NO_2 limit will be exceeded in the near future.

The EPA also states that although technological advances in the future may lead to lower NO_X emissions from individual cars, via the adoption of the various Euro 6 emissions standards, this technology will take time for the benefits to make an impact (25). It advises that a more certain route to mitigating the problem of NO_X is for individuals to prioritise public transport and alternative modes of transport over private motor cars, and that transport policy in Ireland should go further to tackle the problem of air pollution, whether using alternative modes of transport or alternative fuels.

4.3 Particulate Matter (PM_{10} & $PM_{2.5}$)

The main source of PM in Ireland is solid fuel consumption in the residential sector. Other sources include road transport, particularly diesel vehicles, and agriculture.

'Primary' PM is produced by combustion. There are two main categories: PM_{10} (diameter less than 10 µm) and $PM_{2.5}$ (diameter less than 2.5 µm). $PM_{2.5}$ tends to be a better signifier of man-made pollution, whereas PM_{10} can have a greater contribution from natural sources

'Secondary' PM is formed by the chemical reaction of other pollutants, such as NO_X, sulphur dioxide or ammonia. Agriculture is a significant source of secondary PM, primarily through the formation of aerosols from ammonium nitrates, for example.

According to the EPA, PM_{10} and $PM_{2.5}$ levels in Ireland are above the World Health Organisation (WHO) air quality guidelines values and reducing the levels below the WHO guideline values will be a challenge, requiring co-operation across several sectors (25; 12). Fine PM can penetrate deep into the lungs and research in recent years has strengthened the evidence that both short-term and long-term exposure to $PM_{2.5}$ are linked with a range of adverse health outcomes including, *inter alia*, respiratory and cardiovascular effects.

The EPA states that '*overall, air quality in Ireland is expected to remain good, due largely to the prevailing clean westerly airflow from the Atlantic and the relative absence of large cities and heavy industry… Levels of particulate matter are highest in towns with no ban on bituminous coal and traffic influenced sites in cities. Efforts are required to address both these sources, including extending the ban on bituminous coal to other areas of the country and reducing traffic emissions in cities. The Clean Air for Europe Directive (2008/50/EC) requires Member States to reduce urban background concentrations of $PM_{2.5}$. Ireland will need to reduce its average $PM_{2.5}$ levels by 10 per cent by the year 2020'* (25).

[13] The enrichment of the environment with nutrients.

4.4 Examples from other countries and cities

4.4.1 UK & London

Following a legal case, the UK High Court ordered the British Government to produce new plans to deal with illegal levels of nitrogen dioxide. The plan (24) was published in July 2017 and the UK Government announced that it will *'end the sale of all new conventional petrol and diesel cars and vans from 2040'*. A £225m fund to help tackle emissions from diesel vehicles, as part of a £3 billion package on air quality spending, was also announced.

In London, the mayor ordered the replacement of the capital's current diesel bus fleet with cleaner alternatives. In addition, from October 2017, there is a £10 toxicity charge, or T-charge, on the highest-polluting cars entering the city centre. The measures are part of a wider plan to create an ultra-low-emission zone in central London from April 2019.

In addition, the UK Government has established a plug-in taxi grant scheme giving owners a £7,500 grant to buy new electric taxis. Any licensed taxi driver purchasing an ultra-low emissions vehicle (ULEV) purpose-built taxi is eligible. A ULEV purpose-built taxi is a vehicle which meets Transport for London's Conditions of Fitness for motor taxis in London as well as meeting the definitions of either category 1 or category 2 of the existing plug-in car grant. A category 1 vehicle must emit less than 50 g/km of CO_2 and have a zero emission capable range of at least 70 miles. A category 2 vehicle must have CO_2 emissions of less than 50 g/km and have a zero emission capable range of between 10 and 69 miles.

The plug-in taxi grant amounts for category 1 and category 2 purpose-built ULEV taxis are £7,500 and £3,000 respectively. In March 2017, the London Taxi Company opened a new manufacturing plant in Coventry to produce the TX5[14] (the TX5 is one of two purpose-built ULEV taxis expected on the market in the UK). Non purpose built ULEV taxis and private hire vehicles may attract grant funding under the existing plug-in car grant.

4.4.2 Other locations

Table 4 summarises some of the actions being taken in a variety of other countries and cities around the world.

[14] https://www.gov.uk/government/news/1000-jobs-created-at-new-300-million-factory-for-electric-taxis

Table 4: Examples of initiatives in other countries

Locations	Actions
Germany	Several German cities (e.g. Cologne, Bonn and Stuttgart) have banned older diesel cars (e.g. Euro 4 and older) from certain parts of the city. Berlin has bans in place on Euro 5 and older diesel cars for certain parts of the city.
Spain	There are restrictions on older cars entering parts of Madrid.
South Korea	There is a ban in Seoul on all diesels made before 2006 from a city-centre low emission zone.
Mexico City	Ban diesel completely by 2025.
France	The Environment Minister announced that there would be a ban on petrol and diesel vehicles by 2040. The French Climate Plan (26) states that … *the Government will take the initiative to propose an ambitious Euro 7 standard at European level and set the goal of ending the sale of cars emitting greenhouse gases in 2040*.
Norway	A national target of 100% electric or plug-in hybrid car sales by 2025. Since August 2019, Trondheim has been operating 189 buses on biogas and biodiesel.

5 DTTAS Bus Trials

5.1 Overview

Fifteen[15] buses were trialled:

- 3 x double-deck diesel buses, from the Dublin Bus fleet (a Euro IV, Euro V and Euro VI)
- 1 x single-deck diesel bus, from the Bus Éireann fleet (Euro VI)
- 1 x single-deck micro-hybrid bus
- 2 x double-deck hybrid buses
- 1 x single-deck CNG bus
- 1 x double-deck CNG bus
- 4 x single-deck battery-electric buses
- 2 x diesel buses fitted with SCR systems (Euro IV and Euro V)

A detailed description of each bus, and the definitions of the different bus technologies as set out by the Low Carbon Vehicle Partnership (27), are provided in Appendix 1. (For the purposes of the analysis, we do not differentiate between the different types of hybrid bus technologies i.e. hybrids and micro-hybrids are grouped into the 'hybrid' category.)

Emissions testing was carried out on eleven of the buses by Emissions Analytics (EA) with its PEMS equipment – PEMS testing was not required on the electric buses because they have no tailpipe emission.

The trials were carried out in Dublin and Cork over a period of 5 months (December 2018 to April 2019). The two primary objectives of the trials were to:

1. Prepare and implement a method of testing the buses that would be repeatable and provide a fair means of comparing different technologies; and
2. Gather emission and fuel economy data that reflects real-world operating conditions.

5.2 Methodology

5.2.1 Test conditions

Several parameters were agreed with the Bus Working Group[16] in November 2018 prior to commencing the trial.

1. The trials would be carried out in Dublin and Cork. The two cities have distinctly different terrains[17]: Cork is relatively hilly whereas Dublin is quite flat. Dublin also has higher traffic volumes, services larger passenger numbers and is predominantly serviced by double-deck buses (Cork is currently predominately single-deck).

[15] A double-deck fuel cell (hydrogen) electric bus was also due to be tested. Due to several technical and logistical issues, this was not possible in the project timeframe.

[16] The Bus Working Group consists of DTTAS, the National Transport Authority, Dublin Bus and Bus Éireann.

[17] The Dublin route had a total elevation gain of 78 m and a maximum gradient of 6.5%. The Cork route had a total elevation gain of 143 m and a maximum gradient of 11.5%.

2. The test routes would be representative of the 'typical' routes serviced in both cities. The routes were nominated by Dublin Bus and Bus Éireann and are set out in Table 5.

Table 5: Summary of test routes

Location	Bus route	Start and end location	Test cycle distance (km)	No. of stops
Dublin	Dublin Bus No. 9 (Southern half)	Broadstone Depot, Phibsborough Road, Dublin 7	19.8	58
Cork	Bus Éireann No. 207a (modified)	Merchant's Quay, Cork	21.4[Note]	44

Note: The Cork test route was approximately half the distance of the Dublin test route (10.7 km) and, therefore, the test cycle distance represents two complete journeys along the route.

3. The tests would be carried out over the typical operating cycle of a bus, i.e. during rush hour and off-peak.

4. Cold start testing would be carried out to capture fuel consumption and emissions data prior to the engines reaching their optimum operating temperature. Cold start tests were carried out along a 1.4 km loop in the vicinity of Broadstone depot (Dublin) and a 1.9 km loop in the vicinity of Capwell depot (Cork).

5. The trials would simulate operating conditions so the buses would be loaded to simulate 30 passengers (2,000 kg) and the buses would stop for 20 seconds at each designated bus stop along the route.

6. The drivers would, in so far as possible, drive in a consistent manner to reduce the influence of driver style and behaviour on the results.

Each bus completed six test loops over two days at each location (12 loops in total). At least one rush hour test was completed each day.

5.2.2 PEMS Testing

5.2.2.1 Overview

PEMS facilitates direct measurement of tailpipe emissions and fuel consumption for vehicles operating under real world driving conditions. The PEMS is fitted to the vehicle exhaust and the exhaust gas is analysed using a range of analysers.

5.2.2.2 Measurement parameters

Eleven buses were tested using PEMS equipment; the following tailpipe emissions were measured:

- Carbon dioxide (CO_2)
- Carbon monoxide (CO)
- Nitric oxide (NO)
- Nitrogen dioxide (NO_2)

- Nitrogen oxides (NO_x)
- Particulate number (PN) (not measured on CNG buses[18])
- Methane (CH_4) approximated by Total Hydrocarbons (THC) (measured on CNG buses only)

5.2.2.3 Test equipment

The following PEMS equipment was used (a selection of photographs are provided in Appendix 2):

1. Gaseous emission measurement system (CO_2, CO, NO, NO_2 and NO_X);
2. Particulate number counter, including a heated line;
3. Vacuum flame ionisation detection unit (FID) for measuring total hydrocarbons (including methane);
4. Weather station, mounted to the side of the bus, for measuring ambient temperature, pressure and humidity; and
5. Flow tube, mounted at the end of the tailpipe, for measuring exhaust gas flow rates.

The PEMS equipment was also used to measure fuel economy using the carbon balance method[19].

Two of the diesel buses (Euro IV and Euro V) were tested with and without SCR technology, which was fitted by Eminox in January 2019. SCR technology is primarily aimed at reducing NO_X emissions from diesel vehicles. Due to space restrictions on the underside of the bus following the installation of the SCR systems, the PEMS contractor fitted its equipment onto the back of the two buses; heat shielding and warning signs were provided.

A full list of the vehicles tested is provided in Appendix 1.

5.2.3 Electric Bus Testing

5.2.3.1 Overview

PEMS testing was not carried out on the battery-electric buses because there are no tailpipe emissions. The battery-electric buses were tested using a procedure similar to the approach set out in the guidance note *UITP Project E-SORT Cycles for electric vehicles* (28). The same test conditions as set out in Section 5.2.1 were implemented, i.e. the bus was loaded with 2,000 kg of weights, the same routes were travelled, etc.

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[18] EA's PEMS setup does not allow it to measure particulate number (PN) and total hydrocarbons simultaneously. Since PN is generally only present in minute quantities once a CNG engine has sufficiently warmed up, methane was considered to be the more important measurement parameter for CNG buses; thus, the flame ionisation detection unit was used for CNG buses, while the particulate number counter was used for diesel and hybrid buses.

[19] The 'carbon balance method' is an indirect method for calculating fuel consumption. The total carbon mass is measured at the vehicle exhaust and, assuming that the carbon emitted comes from the fuel, the quantity of fuel used can be calculated.

5.2.3.2 Additional services

Neither Dublin Bus nor Bus Éireann operate electric buses, so their depots are not set-up to charge electric buses. Consequently, several additional supporting activities were carried out. The following were hired specifically for the trial:

1. Two diesel generators, one in Dublin and another in Cork[20];
2. Energy metering equipment;
3. A 10-ft storage container for storing the distribution boxes, cabling, and energy metering equipment (just in Dublin);
4. Lifting services for transferring the buses and bus chargers between Dublin and Cork[21].

5.2.3.3 Bus charging systems

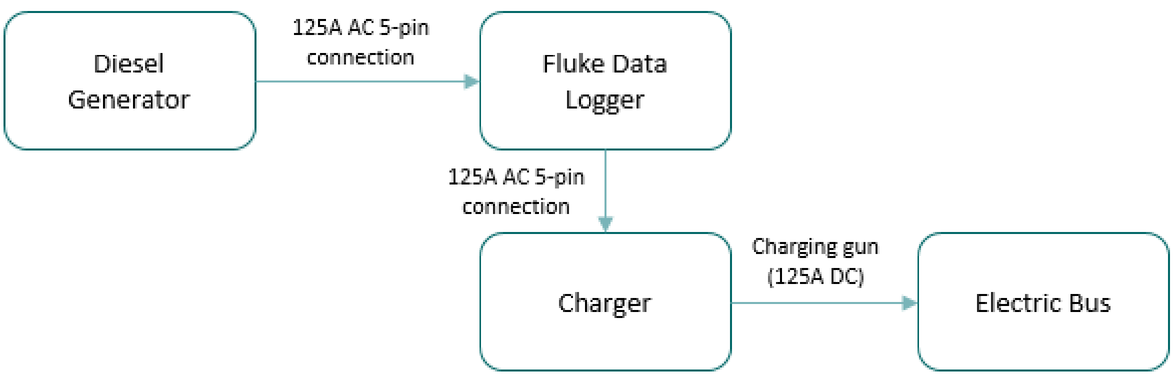
An electric bus relies on a series of battery packs to power its electric motors. External power is required to re-charge the batteries after use and a charger is required to control the power supplied to the bus to prevent overheating and imbalance[22] among the battery packs; in some cases, it is also used to convert AC to DC. Bus Éireann's depots were not equipped to supply the required power for charging within a practical timeframe; consequently, diesel generators were used.

The specifications and charging cycles for each charging system used is detailed in Appendix 3.

5.2.3.4 Energy measurement

To measure the energy supplied during charging, a data logger was connected between the generator and the charger. The general charging arrangement is illustrated in Figure 7 (photographs of the setup are provided in Appendix 2).

Figure 7: Charging equipment and setup



[20] The highest rated power sockets at the bus depots were 32A, which was not sufficient to charge the electric buses.

[21] The buses did not have the battery capacity to drive between Dublin and Cork without requiring an additional charge.

[22] Imbalance refers to battery packs charging at different rates. During charging, the state of charge should be consistent across all battery packs.

We have used the energy supplied to the buses, as measured by the data logger, for the energy consumption calculations. However, in some cases, the state of charge (SOC) lost during a trial was different from the SOC gained during the subsequent charge (for logistical reasons, the bus was never charged to 100%). This was primarily due to energy losses while the buses were idle; on average, the difference was approximately 1%. In other words, not all energy supplied during charging could be attributed to the previous trial. To account for this, the following formula was used to correct for the loss in charge:

$$Energy\ consumed\ during\ trial = Energy\ supplied\ during\ charge * \left(\frac{SOC\ lost\ during\ trial}{SOC\ gained\ during\ charge}\right)$$

5.2.3.5 Other data

In addition to the data captured by the data logger, the following information was also gathered:

- start and end time of each test;
- SOC before and after each test;
- odometer reading before and after each test;
- weather conditions;
- traffic conditions.

5.3 Comparing energy efficiency and emissions results

5.3.1 Energy efficiency

The energy efficiency of an internal combustion engine (ICE) is typically reported in litres consumed per 100 km, whereas the efficiency of an electric vehicle is reported in kWh/km. To enable a direct comparison between the technologies, the data have been converted to MJ/km. Table 6 summarises the conversion factors.

Table 6: Energy content of fossil fuels

Fuel	Energy content by weight (MJ/kg)	Energy content by volume (MJ/l)	Source of Data
Diesel	43	36	Annex III of Directive 2018/2001
Biogas purified to natural gas quality	50	-	Annex III of Directive 2018/2001

When considering the energy efficiency of the electric buses, the data can be presented on final energy or a primary energy basis.

- **Final energy** is the energy (e.g. electricity, diesel or natural gas) that is consumed directly by the buses.
- **Primary energy** includes the consumption, distribution and conversion losses in transforming energy from one form to another (e.g. burning coal at Moneypoint to generate electricity). The efficiency of electricity supply in 2017 was 49.1% (29), i.e. on a national basis, 2 MJ of energy was required to supply an electric bus with 1 MJ of electrical energy.

This is important in the context of supplying energy to electric buses from a national perspective, where the primary energy requirement needs to be considered.

5.3.2 Comparing GHG emissions

There are two main ways of reporting GHG emissions: lifecycle and tailpipe.

1. **Tailpipe emissions** are the CO_2, N_2O and CH_4 emissions resulting from combusting the fuel, reported in CO_{2eq}. In the case of diesel and petrol, the CO_2 emissions account for the vast majority of the total CO_{2eq} emissions (more than 99%).
2. **Lifecycle emissions** include the tailpipe emissions (i.e. fuel in use), and the emissions generated by extracting or cultivating raw materials[23], annualised emissions from carbon stock changes caused by land-use change, processing, transport and distribution, soil carbon accumulation via improved agricultural management, carbon capture and geological storage, carbon capture and replacement, and savings from excess electricity from cogeneration (as per RED).

Table 7 summarises the lifecycle and tailpipe emission factors gathered from literature for the fuels considered in this assessment.

Table 7: Lifecycle and tailpipe emissions

Fuel	Lifecycle (gCO_{2eq}/MJ)	Tailpipe (gCO_{2eq}/MJ)	Data Sources
Diesel	95.1	73.3	Annex I, Part 2 of Directive 2015/652 & SEAI emission factors.
Biodiesel	12	0	Based on data contained in BOS Sustainability Statements 2018[24].
CNG	69.3	56.9	Annex I, Part 2 of 2015/652 & SEAI emission factors.
BioCNG	20.4	0	Maximum carbon intensity allowed in order to comply with RED II GHG emissions savings criteria for biomethane used for heat (it is more stringent than the transport criteria).
Electricity	121[Note 1]	0	SEAI's carbon emission factor (in gCO_2/kWh) × conversion to gCO_{2eq}/MJ (0.2778).
Note 1: The carbon intensity of grid electricity provided by SEAI does not include the emissions associated with producing the fuel used to generate the electricity.			

While the tailpipe emissions for biofuels are listed as zero, there are physical emissions. It is assumed that the carbon emitted from combustion is re-absorbed by the crops and trees that are used to produce biomass fuels and so the carbon remains in a 'closed loop' and does not contribute to increased global carbon emissions.

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[23] This includes emissions from the collection of raw materials, wastes and leakages, and from producing chemicals or products used to extract or cultivate.

[24] http://www.nora.ie/biofuels-obligation-scheme/bos-annual-reports.225.html

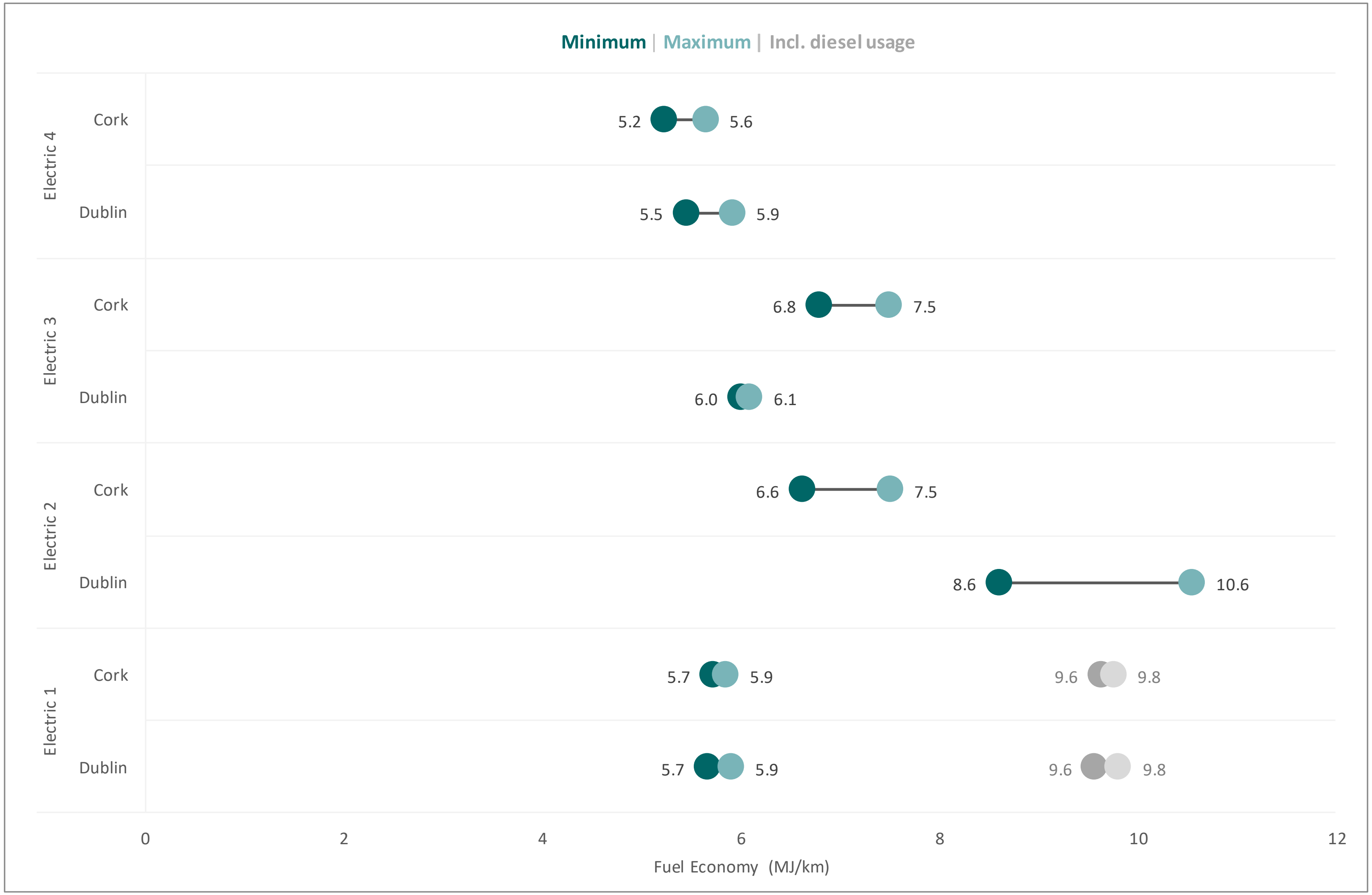
5.4 Electric Bus Test Results

5.4.1 Energy efficiency

The energy efficiency of each electric bus is shown in Figure 8 (on a final energy basis[25]).

[25] Electric bus consumption data captured during the bus trials includes for charger losses (refer to Section 5.2.3.4 for further detail). This is a more appropriate measurement for bus fleet operators as it provides a better indication of the amount of energy that needs to be supplied.

Figure 8: Energy efficiency of electric buses (final energy)



The following are the key findings:

- The average energy consumption across all electric buses was 7.5 MJ/km, which includes the diesel consumed by the heating system on the Electric 1 bus. Excluding the Electric 1 bus, the average energy consumption was 6.8 MJ/km.
- The Electric 4 bus was the most efficient electric bus, averaging 5.6 MJ/km across the two cities; the Electric 1 bus, when the energy consumed by the diesel heating system is considered, is the least efficient electric bus (average for Dublin and Cork is 9.7 MJ/km).
- The Electric 2 bus was approximately 35-40% less efficient in Dublin compared to Cork. The test results were compared with Met Éireann data and a relationship between the two variables (R^2 = 0.6) was found, with colder temperature corresponding to higher energy usage.
- On average, the buses were marginally more efficient in Cork than in Dublin (7.3 MJ/km versus 7.8 MJ/km).
- When idle:
    - the Electric 2 bus lost a significant amount of charge. Over two different periods (30th to 31st January 2019, and 2nd to 4th February 2019), the bus was observed to lose approximately 0.6% charge per hour or 14.4% per day, and the energy supplied to recharge the bus to 'full' corresponded to losses of 6.5 – 8.7 MJ/h. According to the manufacturer, the significant loss in charge is because the bus consumes energy keeping its batteries at a minimum temperature.
    - the Electric 1 bus lost 0.04% per hour and Electric 4 bus lost 0.02% per hour over separate weekend periods; the Electric 3 bus was not observed to lose any charge during the trials, although the bus was not retained over a weekend.

Table 8 shows the range of final energy and primary energy consumption for the electric buses.

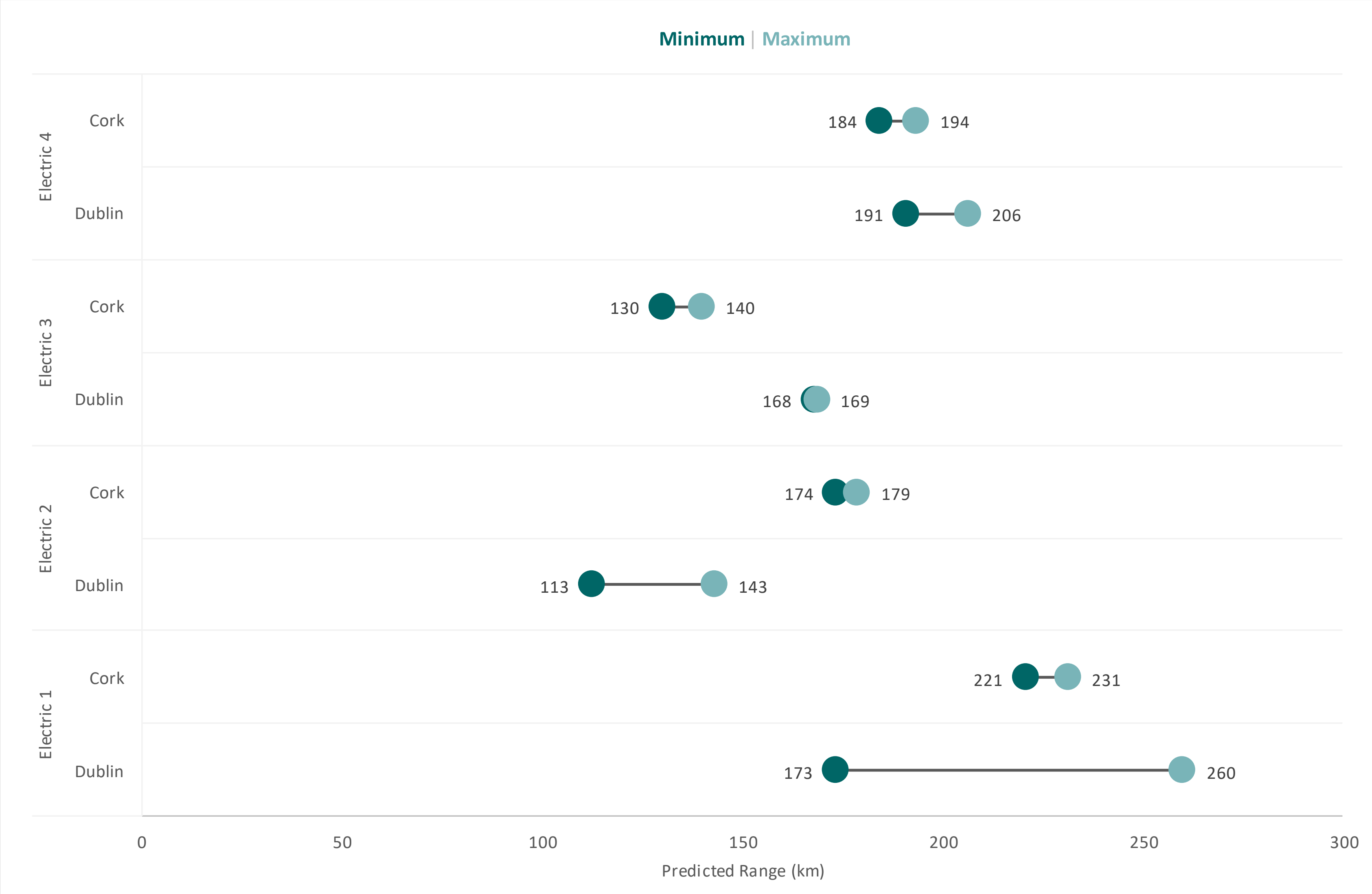
Table 8 Energy efficiency of electric buses

Bus	Electrical consumption (MJ/km)	Diesel consumption (MJ/km) Note	Final energy consumption (MJ/km)	Primary energy consumption (MJ/km)
Electric 1	5.7 – 5.9	3.9	9.6 – 9.8	15.4 – 15.9
Electric 2	6.6 – 10.6	-	6.6 – 10.6	13.5 – 21.5
Electric 3	6.0 – 7.5	-	6.0 – 7.5	12.2 – 15.3
Electric 4	5.2 – 5.9	-	5.2 – 5.9	10.7 – 12.1
Note: The Electric 1 bus has a diesel-powered climate control system. The other three buses are fully electric.				

5.4.2 Driving Range

The estimated driving range of the electric buses is shown in Figure 9. These results were obtained by taking the SOC lost over a given distance during testing and extrapolating based on the battery capacity to find the maximum range. It should be noted that these results are an indication of range in an urban setting and account for the stop/start nature of operation.

Figure 9: Predicted range of electric buses



The following are the key findings:

- The Electric 1 bus achieved the highest average range (221 km). It also achieved the longest predicted range (260 km in Dublin). This is because its diesel heating system reduced the space heating load on the batteries.
- The highest average range for an electric bus with an electric climate control system was achieved by the Electric 4 bus (194 km).
- The Electric 2 and Electric 3 buses both achieved an average range of approximately 150 km.
- The average range of the four electric buses was 177 km. The range was similar across both cities, albeit the Electric 3 and Electric 4 achieved marginally higher ranges in Dublin.

5.4.3 Time to charge

The estimated time to charge each bus from empty to full, which is a function of the estimated battery capacity (derived from the energy supplied to each bus and the corresponding change in SOC), the capacity of the power supply, and maximum power output of the bus charger, is shown in Table 9.

Table 9: Average time to charge electric buses

Bus	Maximum Power Output (kW)	Average time to charge (hours)
Electric 1 [Note]	21	15.4
Electric 2	80	4.5
Electric 3	50	5.2
Electric 4	60	4.9
All buses	-	**7.4**
All buses (excl. Electric 1)	-	**4.9**
Note: A temporary, down-rated charger was provided with this bus. Consequently, this bus took longer to charge. The specifications, and charging cycles, for each charging system used is detailed in Appendix 3.		

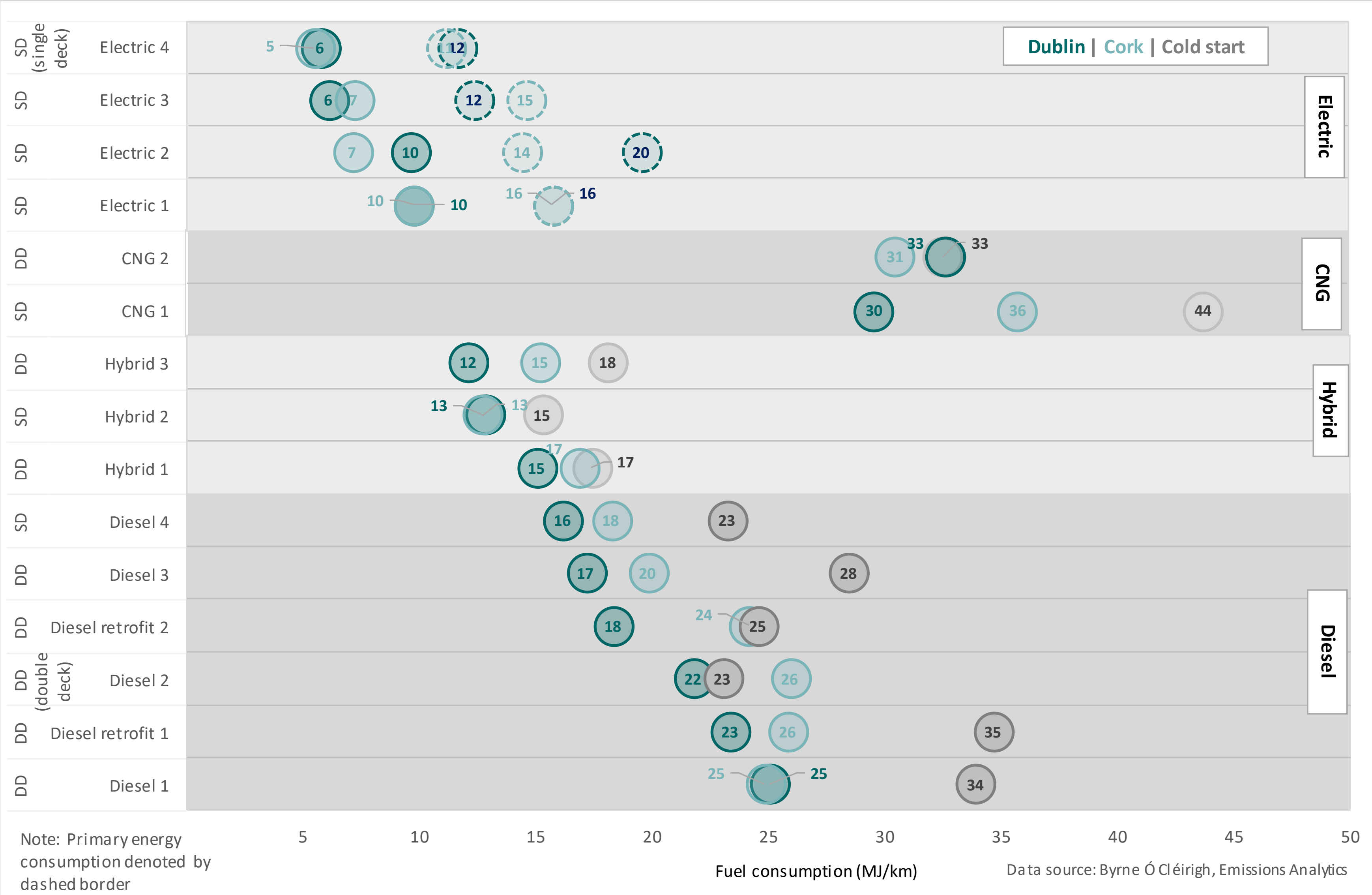
The Electric 2 bus charger had the highest maximum power output (80 kW) and took the shortest time to charge (4.5 hours on average). The Electric 3 and Electric 4 buses took a similar time to charge. The time taken to charge the buses could be reduced by increasing the capacity of the power supply and the batteries.

5.5 PEMS Test Results

5.5.1 Energy efficiency

The energy efficiencies of all the buses, including the electric buses, are shown in Figure 10.

Figure 10: Energy efficiency of trial buses



The following are the key findings:

- On a final energy basis, the electric buses are the most efficient with an average energy consumption of 7.5 MJ/km achieved during the trials. However, when compared on a primary energy basis, the electric buses were comparable with the diesel hybrids.
- All the electric buses trialled were single deck buses, so it is not certain whether double deck electric buses would achieve similar energy efficiencies. The findings from this trial suggest that there is little difference between the energy efficiency of single deck and double deck buses.
- With increasing renewable energy penetration on the electricity grid, it would be expected that the overall efficiency of electricity production will improve and thus the primary energy efficiency of the electric buses will also improve.
- The CNG buses are the least efficient achieving 32.1 MJ/km (excluding cold start tests).

5.5.2 Tailpipe emissions

5.5.2.1 Comparison with Diesel 3 Euro VI bus

Tailpipe emissions for each technology (diesel, hybrid and CNG), relative to the baseline bus (the Diesel 3 Euro VI bus) are shown in Table 10. There are no tailpipe emissions from electric buses, so there is no comparison to make for this technology.

Table 10: Comparison of emissions by technology relative to Diesel 3 Euro VI bus

Parameter	Technology type	Dublin	Cork	Cold start
CO_2	Diesel (Euro IV & V)	+ 38%	+ 28%	+ 1%
	Diesel retrofit [Note 1]	+ 21%	+ 25%	+ 3%
	Hybrid [Note 5]	- 22% / - 21%	- 25% / -19%	- 40% / -37%
	CNG	+ 35%	+ 25%	0%
NO_X	Diesel (Euro IV & V)	+ 1,951%	+ 2,454%	+ 53%
	Diesel retrofit [Note 2]	+ 1,159%	+ 576%	+ 71%
	Hybrid [Note 5]	+ 166% / + 95%	+ 195% / + 184%	- 54% / - 56%
	CNG	+ 40%	+ 53%	- 91%
PN	Diesel (mix) [Note 3]	+ 412%	+ 224%	+ 1,278%
	Hybrid [Note 5]	+ 5% / + 13%	- 5% / + 23%	+ 211% / + 348%
	CNG	Note 4		
CO	Diesel (Euro IV & V)	+ 438%	+ 165%	+ 346%
	Diesel retrofit	+ 51%	+ 96%	+ 167%
	Hybrid [Note 5]	- 58% / - 78%	- 69% / -77%	- 49% / - 65%
	CNG	- 9%	- 46%	+ 29%

Note 1: The difference in CO_2 emissions pre- and post-retrofit are discussed in Section 5.5.2.2.

Note 2: The Diesel 2 Euro V retrofit bus was tested by EA in February 2019 following the installation of the Eminox SCR system. The primary purpose of the system was to reduce NO_X emissions. The initial tests carried out by EA showed that the NO_X emissions increased relative to the pre-retrofit tests. Our analysis demonstrated that this unexpected result was caused by the exhaust temperature not reaching 200ºC and, thus, the SCR could not function correctly. Eminox subsequently adjusted the urea dosing rate to better suit city driving conditions and this gave rise to reduced NO_X emissions relative to the pre-retrofit tests, which are the data presented here.

Note 3: The results provided are the average of the Diesel 1 Euro IV bus (pre-retrofit) and the Diesel 2 Euro V bus (post-retrofit). The other data was not considered because:

1. EA identified a problem with its equipment after testing the Diesel 1 Euro IV bus post-retrofit which meant that it could not guarantee the validity of the results obtained for the tests carried out on this bus. It's also unclear if the results for the Diesel 1 Euro IV bus pre-retrofit are valid as the data shows very low values relative to other bus technologies. We queried the Diesel 1 Euro IV bus pre-retrofit results with EA, but no reason was provided for the low values.
2. High PN results were recorded for the Diesel 2 Euro V bus prior to installing the SCR system. It is likely that the diesel particulate filter (DPF), a device which removes the vast majority of particulates from the exhaust gas, was not functioning correctly during the test runs.

Note 4: EA's PEMS setup does not allow it to measure PN and total hydrocarbons simultaneously. Since PN is generally only present in minute quantities once a CNG engine has sufficiently warmed up, methane was considered to be the more important measurement parameter for CNG buses; thus, the flame ionisation detection unit was used for CNG buses, while the particulate number counter was used for diesel and hybrid buses.

Note 5: The second value shown excludes the Hybrid 2 bus, which is a 'micro hybrid' (see definition in Appendix 1).

The findings for each emission type are shown in Figure 11 (CO_2), Figure 12 (NO_X), Figure 13 (PN) and Figure 14 (CO).

Figure 11: CO_2 emissions

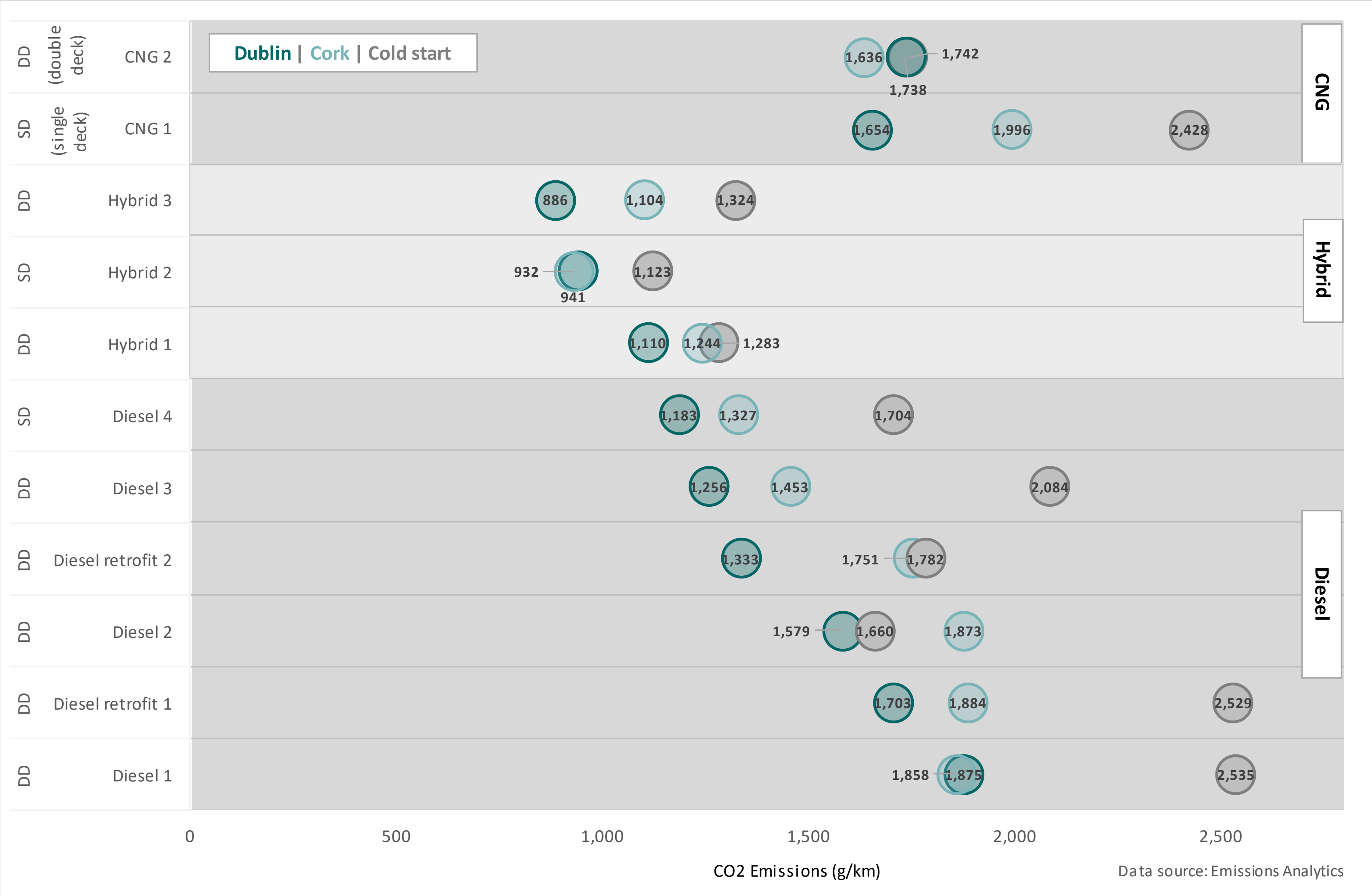


Figure 12: NOx emissions

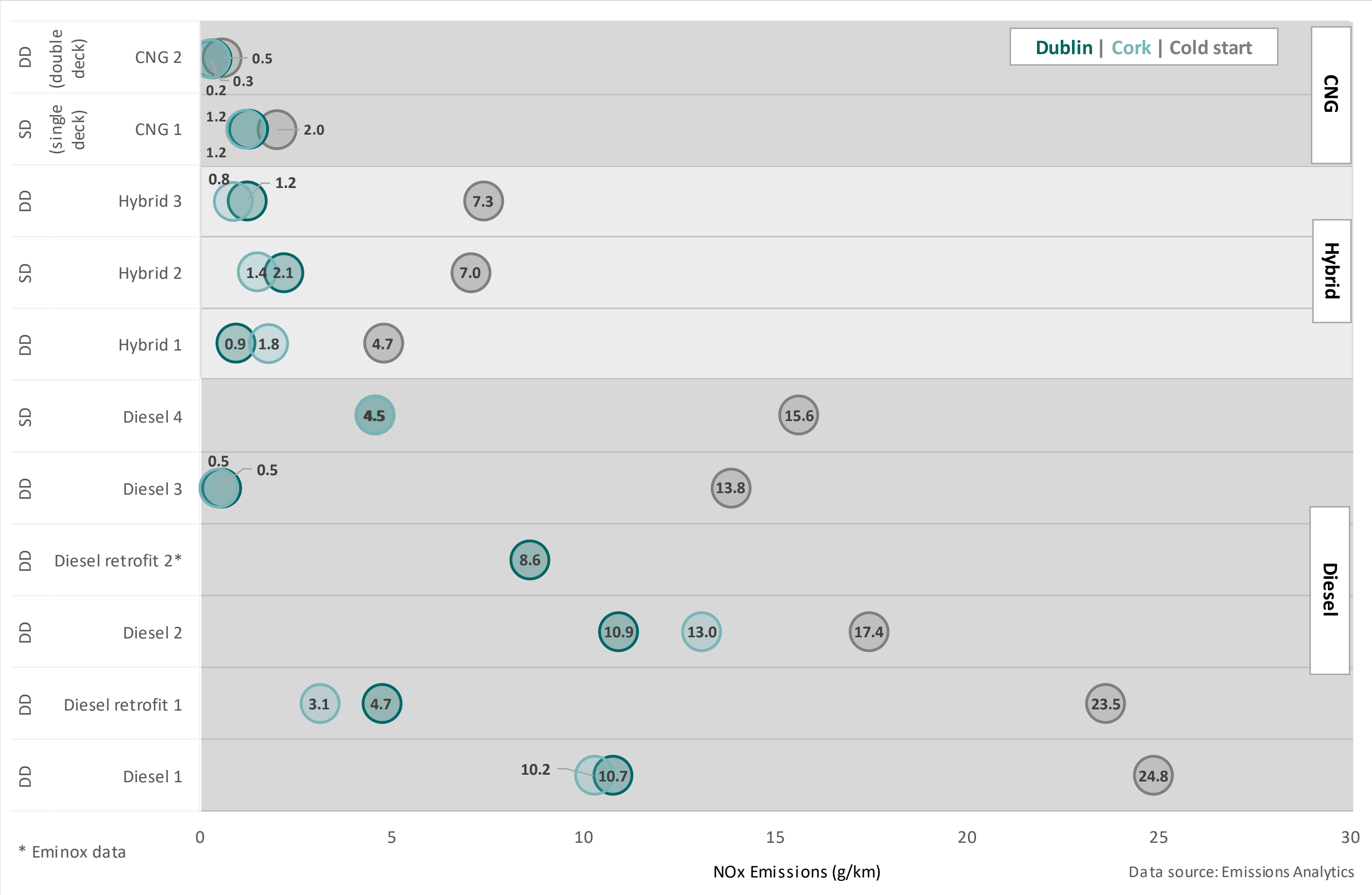


Figure 13: PN emissions

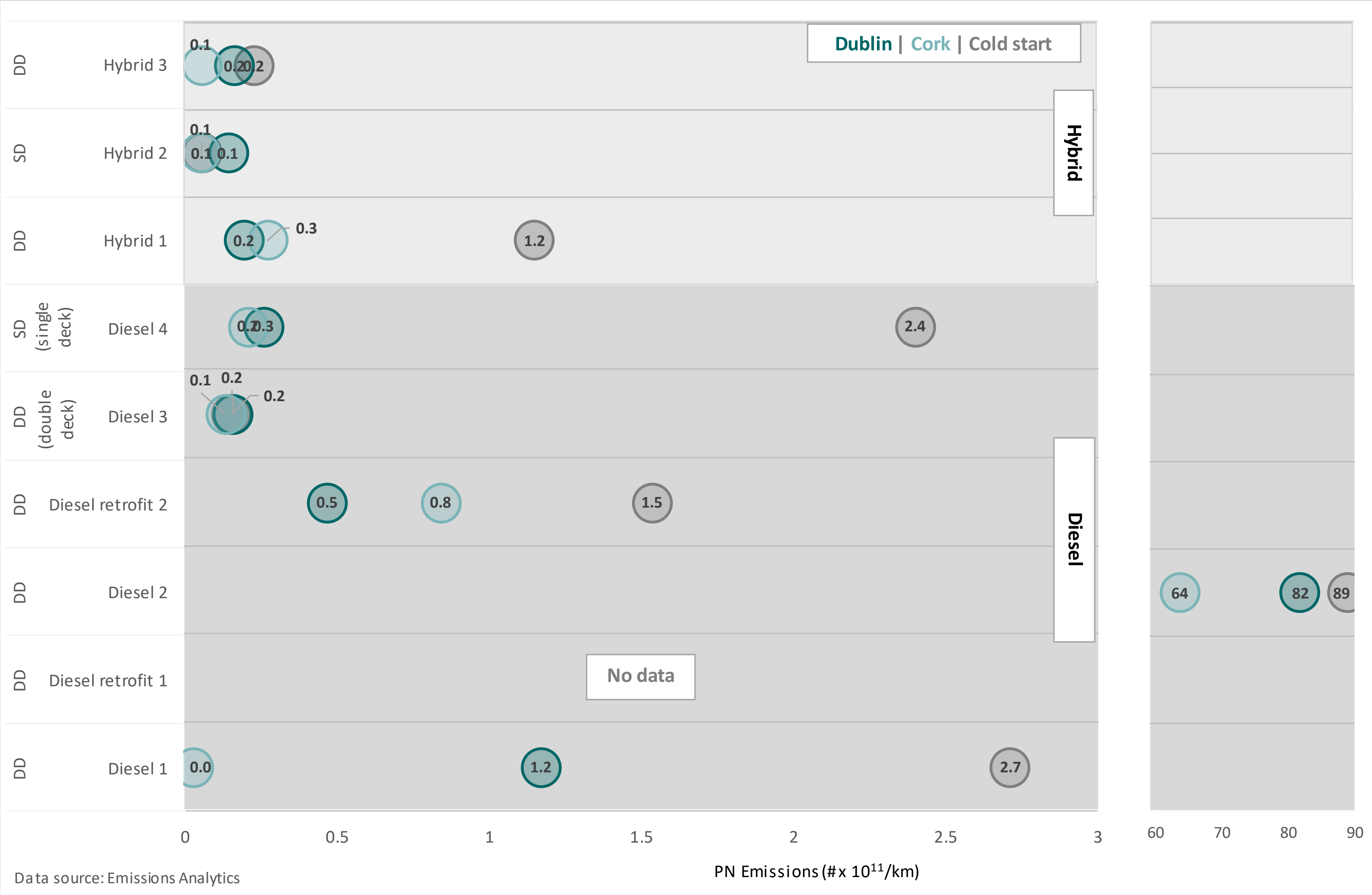
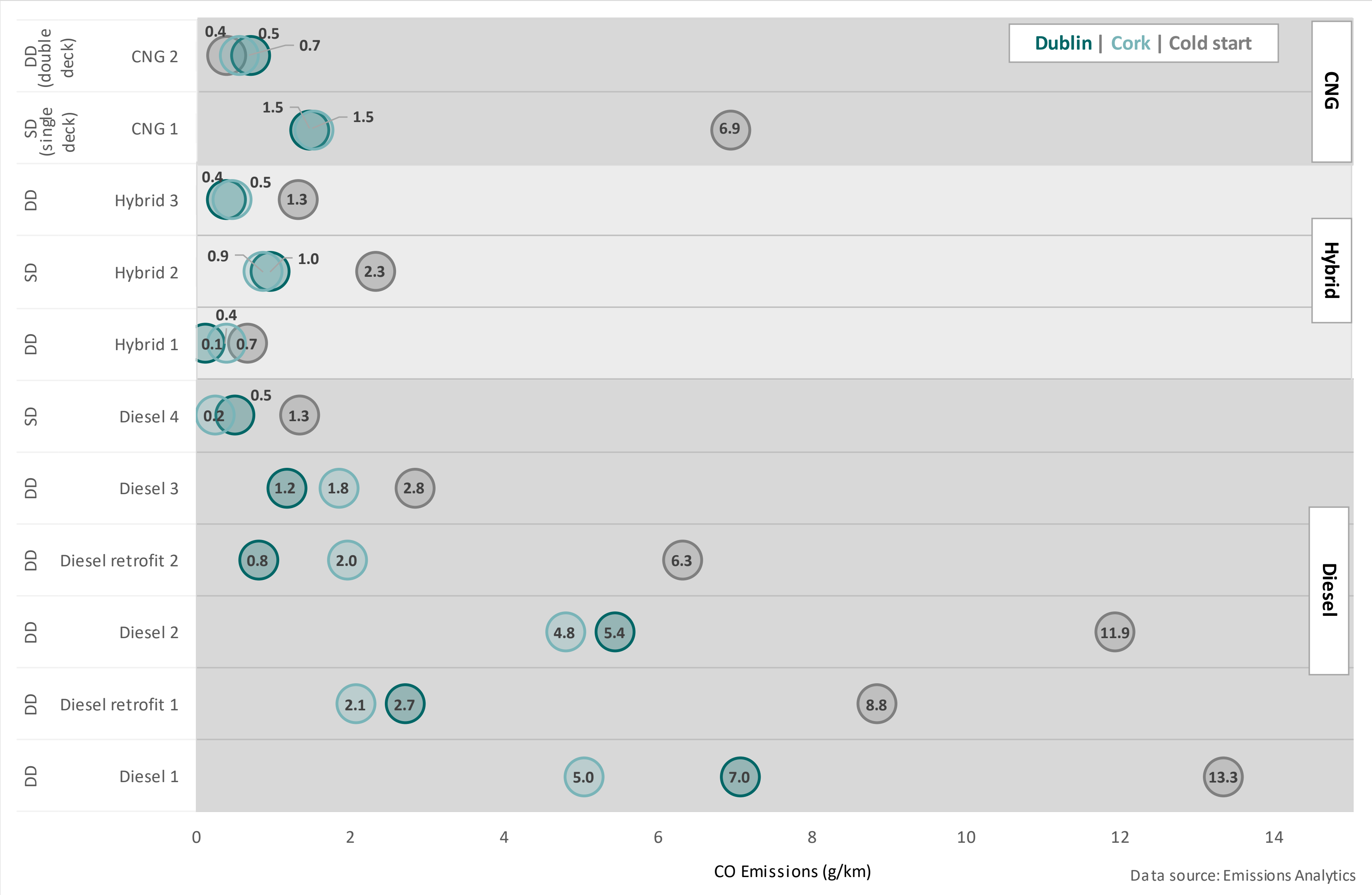


Figure 14: CO emissions



The main findings from the PEMS testing in relation to tailpipe emissions are set out in the following paragraphs.

<u>CO_2</u>

- CO_2 emissions are directly correlated with the type of fuel and the energy efficiency of the vehicle.
- Natural gas will emit less CO_2 per MJ than diesel, but because the CNG buses are less energy efficient than the diesel buses, more CO_2 is emitted per kilometre travelled.
- The Diesel 3 Euro VI bus emitted less CO_2 than the older diesel buses (including those fitted with SCR technology), and the CNG buses.
- The CO_2 emissions from the hybrid buses were on average 20-25% lower than the Diesel Euro VI 3 bus. The Hybrid 2 and Hybrid 3 buses were the best performers in both cities.
- Lower CO_2 emissions were observed during post-retrofit tests on the Diesel 1 Euro IV and Diesel 2 Euro V buses, relative to the pre-retrofit tests.
- The average CO_2 emissions measured during the trials of all the CNG buses was approximately 62.1 gCO_2/MJ of gas consumed, which is higher than the carbon intensity of natural gas (56.9 gCO_2/MJ) provided in Table 7. This can be explained by the fact that the composition of natural gas varies (methane 90% – 98%, ethane 0.5% – 5%, CO_2 0% – 2%, etc), which will give rise to changes in the quantity of CO_2 produced when it is combusted (methane will produce 55 gCO_2/MJ whereas propane will produce 65 gCO_2/MJ) and it will also give rise to a variance in the energy content of the fuel (NCV of methane is 50 MJ/kg whereas propane is 46.4 MJ/kg).

<u>NO_X</u>

- Even when the Diesel 1 Euro IV and Diesel 2 Euro V buses were fitted with SCR, they still emitted significantly higher quantities of NO_X than the Diesel 3 Euro VI bus.
- NO_X emissions during the initial tests on the Diesel 2 Euro V bus were higher with the SCR system installed compared with the pre-retrofit tests. During a subsequent investigation, Eminox adjusted the urea dosing rate which gave rise to an improvement relative to the pre-retrofit tests. This suggests the standard settings on the Eminox SCR system are not suited to city-centre driving.
- The CNG buses showed improved (lower) emissions than hybrid buses but were higher than the Diesel 3 Euro VI bus. On an individual basis, the CNG 2 bus was the top performing bus in terms of NO_X emissions (this was the only bus with lower NO_X emissions in both cities compared with the Diesel 3 Euro VI bus).
- On average across all buses, NO_X emissions were marginally higher (10%) in Dublin than in Cork. This may be explained by the fact that there were 2.9 stops per kilometre in Dublin whereas there were only 2.1 stops per kilometre in Cork. Stopping more frequently reduces the average temperature of the exhaust and thus lessens the effectiveness of the SCR system to reduce NO_X emissions.
- The average NO_X emissions from the hybrid buses were higher than the Diesel 3 Euro VI bus. This maybe because the SCR on the hybrid buses may not operate as effectively when combined with the stop / start operation of the hybrid engine, i.e. the exhaust may not reach a high enough temperature to effectively operate the SCR, because the engine is not always running.

PN

- The Diesel 3 Euro VI bus emitted approximately similar quantities of particulates to the hybrid buses, and significantly fewer than the older diesel buses. As shown in Figure 13, emissions of particulates for all buses were low except for the Diesel 2 Euro V pre-retrofit. It is likely that the DPF for this bus was not functioning correctly during these tests, which highlights the importance of regular DPF maintenance on diesel buses.
- Particulate emissions for the Diesel 3 Euro VI bus and hybrid buses were approximately 90% higher in Dublin than Cork, albeit the emissions observed (not including cold starts) were significantly below the PN limit for passenger cars (6 x 10^{11}/km).

CO

- All hybrid buses showed reduced CO emissions relative to the Diesel 3 Euro VI bus, as did the CNG 2 bus.
- The Hybrid 1 bus was the top performing bus.
- The SCR system contributed to reducing CO emissions on the Diesel 1 Euro IV and Diesel 2 Euro V buses.
- The Diesel 3 Euro VI bus has significantly lower CO emissions than the older diesel buses, both pre- and post-retrofit.

5.5.2.2 Impact of driver behaviour and congestion on CO_2 tailpipe emissions

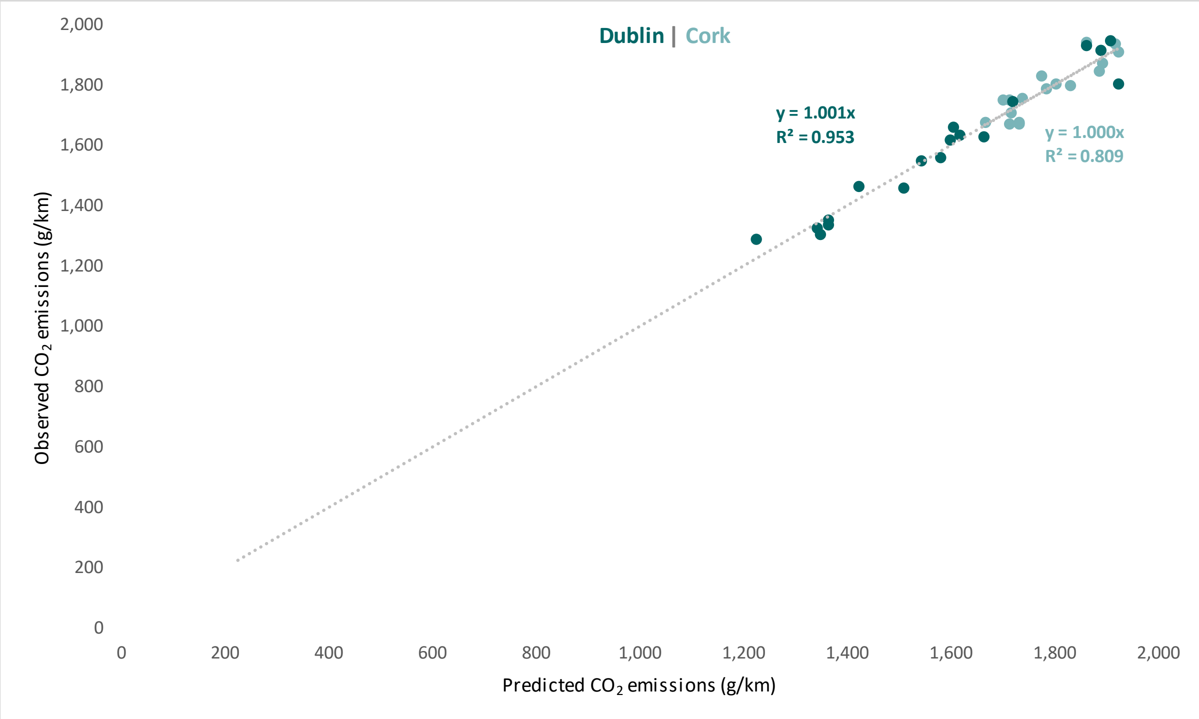
During an initial analysis of results for the two retrofit buses, unexpected differences in CO_2 emissions were observed between the pre- and post-retrofit tests. As shown in Figure 11, lower CO_2 emissions were observed during the post-retrofit tests (relative to the pre-retrofit tests). Since the SCR system has little or no impact on CO_2 emissions, and no other alterations were made to the bus, this potential discrepancy was examined in further detail.

The main reasons for the difference in emissions are:

- driver behaviour, which is captured quantitatively in the data by an *average positive acceleration* variable; and
- traffic congestion, which is captured quantitatively in the data by the *average speed of the bus*.

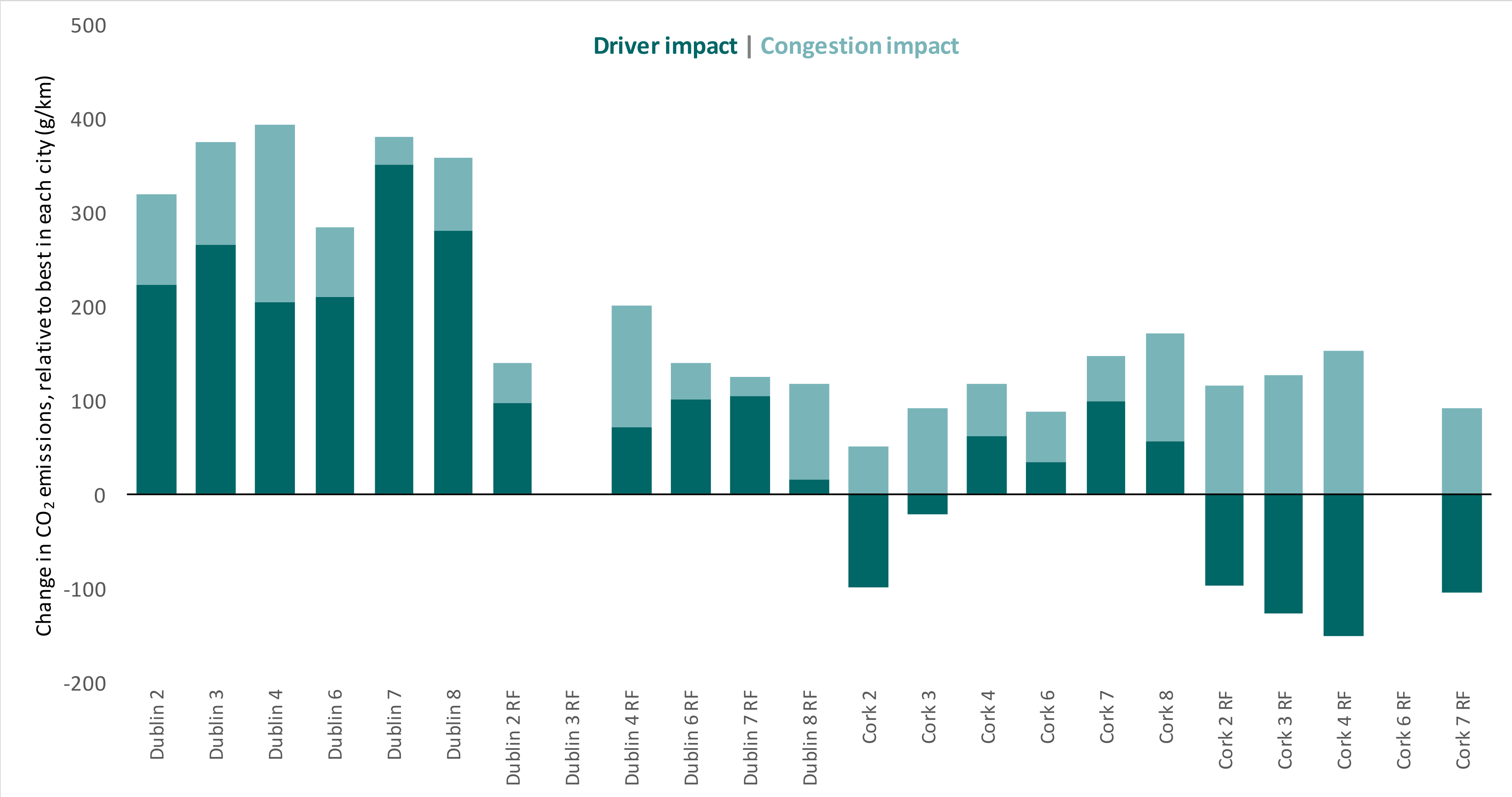
We applied a regression model to predict CO_2 emissions using average positive acceleration and average speed data obtained for the Diesel 1 Euro IV and Diesel 2 Euro V buses. The predicted CO_2 emissions were calculated using separate regression models for each city and were then plotted against the observed CO_2 values – the results are shown in Figure 15.

Figure 15: Predicted vs observed CO_2 emissions



The high coefficient of determination (R^2) for each city suggests that the two variables (driver behaviour and traffic congestion) can explain the difference in CO_2 emissions. In general, changes in driver behaviour has a greater impact (approximately 60-80% more for the Diesel 2 Euro V bus) on CO_2 emissions than traffic congestion, as shown in Figure 16.

Figure 16: Changes in CO_2 emissions



The data shows that accelerating (and braking) at a more gradual rate, and/or reducing traffic congestion (as measured by increased average speeds) can assist with reducing CO_2 emissions. This is because these measures improve the energy efficiency of the bus. The analysis also illustrates the large potential for improving energy efficiency (and thus reducing CO_2 emissions) by changing driver behaviour.

5.5.2.3 Spatial analysis of tailpipe emissions

To identify the worst affected areas along a given route, we have analysed the emissions by location. We compare emissions of three pollutants (NO_X, CO and CO_2) on randomly selected test cycles of four buses:

- Diesel 3 Euro VI bus (baseline) – cycle 7
- Diesel 1 Euro IV bus (least efficient diesel bus tested) – cycle 3
- Hybrid 2 bus (micro-hybrid) – cycle 7
- CNG 2 bus (most efficient gas bus tested) – cycle 4

Emission maps are presented in Appendix 4; an example is shown in Figure 17. The map shows the variance in NO_X emissions along the test route for the Diesel 3 Euro VI and Diesel 1 Euro IV buses.

Figure 17: NOx emissions along test route for Diesel 3 Euro VI bus (left) and Diesel 1 Euro IV bus (right)

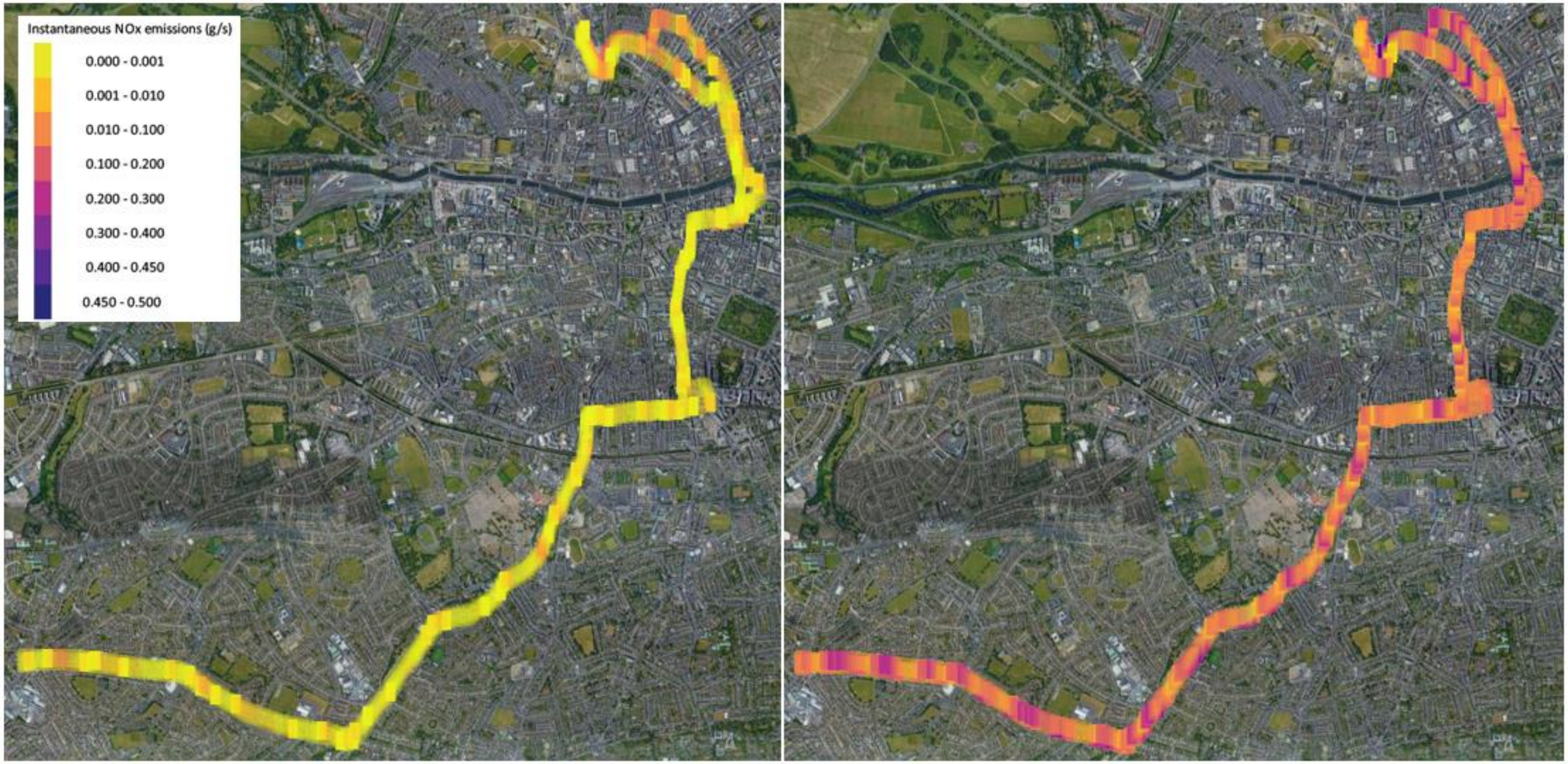


Figure 17 illustrates that, in general, the Diesel 3 Euro VI bus emits less NO_X along the entire route. For both buses, the highest emissions of NO_X were observed at Broadstone garage and the immediate surrounds, usually corresponding with the start of a test cycle. While it is beyond the scope of this study to identify strategies for minimising the impact on local air quality, these maps are very informative and present, in an readily understandable way, the locations where measures could be taken to reduce emissions or where particular technologies may be more effective than others.

5.5.2.4 Methane emissions

Total hydrocarbons (THC) were measured on the CNG buses to approximate methane (CH_4) emissions during the trials (there are no methane emissions from the diesel or electric buses). The results are presented in Table 11.

Table 11: THC emissions

Parameter	Bus	Dublin	Cork	Cold start
THC (g/km)	CNG 1	0.2	0.2	2.3
	CNG 2	9.9	Note	3.0
Note: Because of the significant quantities of water vapor generated by the CNG buses during the trials, EA had difficulty in consistently measuring THC. This was because the flame produced by the FID equipment was regularly extinguished; thus, the equipment could not function as designed and the emissions could not be measured. In the case of the CNG 2 bus, it was not possible to gather any data in Cork.				

The incomplete combustion of natural gas in CNG engines can result in emissions of methane via the exhaust system (referred to as 'methane slip'). The CNG vehicles tested during the trials emitted, on average, 4.3 g/km of methane (excluding cold start tests). Based on the trial efficiencies achieved by the CNG buses and a global warming potential[26] of 25 for methane, this equates to an equivalent CO_2 emission factor of 3.3 gCO_{2eq}/MJ (GHG emission factors are discussed in detail in Section 7.2.2).

[26] Global Warming Potential (GWP) is a measure of how much heat a GHG traps in the atmosphere relative to CO_2.

6 Other Bus Studies and Reports

6.1 Introduction

In this section, we report on various international studies and data on alternative-fuel bus fleets, including the UK Low Emission Bus Scheme, the UK Transport Energy Model and the Swedish public transport fleet. We also review the use CNG in transport and the use of electric buses in Iceland's public bus fleet. Finally, we compare the findings and data (fuel consumption and emissions) from these sources with the findings from the DTTAS bus trials.

6.2 The UK Low Emission Bus Scheme

The Low Emission Bus Scheme is being funded by the UK Department for Transport to obtaining data on alternative-fuel buses and to allow the UK Government to make informed decisions on future investments to meet CO_2 emission targets and reduce air pollution.

The scheme is testing electric, diesel-hybrid, biomethane and hydrogen fuel cell buses; funding is being provided over a three-year period and covers 326 buses. The performance of each bus – fuel consumption, emissions, running costs and reliability – will be monitored for a continuous 12-month period.

The £30.4m funding has been distributed amongst thirteen successful bidders to fund the buses and the associated infrastructure. Approximately £22.7m has been allocated to the buses and £7.7m to the supporting infrastructure.

The Department for Transport appointed Transport Research Laboratory (TRL) to monitor and evaluate the performance of the buses. Quarterly results for five bus fleets were released by TRL in January 2019 and Table 12 shows the average energy efficiency of each technology.

Table 12: Comparison of energy efficiency

Technology	Energy efficiency (MJ/km)
Diesel baseline	14.3
Hybrid	11.2
CNG	23.5
Electric	3.4[Note]
Note: Fuel consumption for electric buses is on a final energy basis.	

Based on these results, battery-electric buses are the most energy efficient of the three technologies, being three times more efficient than the hybrid buses and seven times more efficient than CNG.

The lifecycle GHG emissions of each technology will be proportional to the energy efficiency of the vehicle and the carbon intensity of the fuel. Based on the data in Table 12 and the lifecycle carbon intensity of the fuels, Table 13 sets out the lifecycle carbon emissions for each technology. For comparison, we have included an estimate of the lifecycle emission from diesel and hybrid buses run on liquid biofuel and CNG buses run on biomethane (bioCNG).

Table 13: Lifecycle GHG emissions

Technology	Energy efficiency (MJ/km)	Carbon Intensity (gCO_{2eq}/MJ)	GHG emissions (gCO_{2eq}/km)	Source of carbon intensity data
Diesel baseline	14.3	95.1	1,360	Directive 2015/652 Annex I, Part 2
Diesel baseline (100% biodiesel)	14.3	12	172	BOS Sustainability Statements 2018 (http://www.nora.ie/biofuels-obligation-scheme/bos-annual-reports.225.html).
Hybrid (100% diesel)	11.2	95.1	1,065	Directive 2015/652 Annex I, Part 2
Hybrid (100% biodiesel)	11.2	12	134	BOS Annual Report 2018
CNG (100% natural gas)	23.5	69.3	1,629	Directive 2015/652 Annex I, Part 2
CNG (100% biomethane)	23.5	20.4	479	Maximum carbon intensity allowed to comply with RED II GHG emissions savings criteria for biomethane used for heat (20.4 gCO_{2eq}/MJ), which is more stringent than the criteria used for transport.
Electric	3.4[Note 1]	121	411	Irish electricity grid emission factor in 2017.
Note 1: Fuel consumption for electric buses is on final energy basis.				

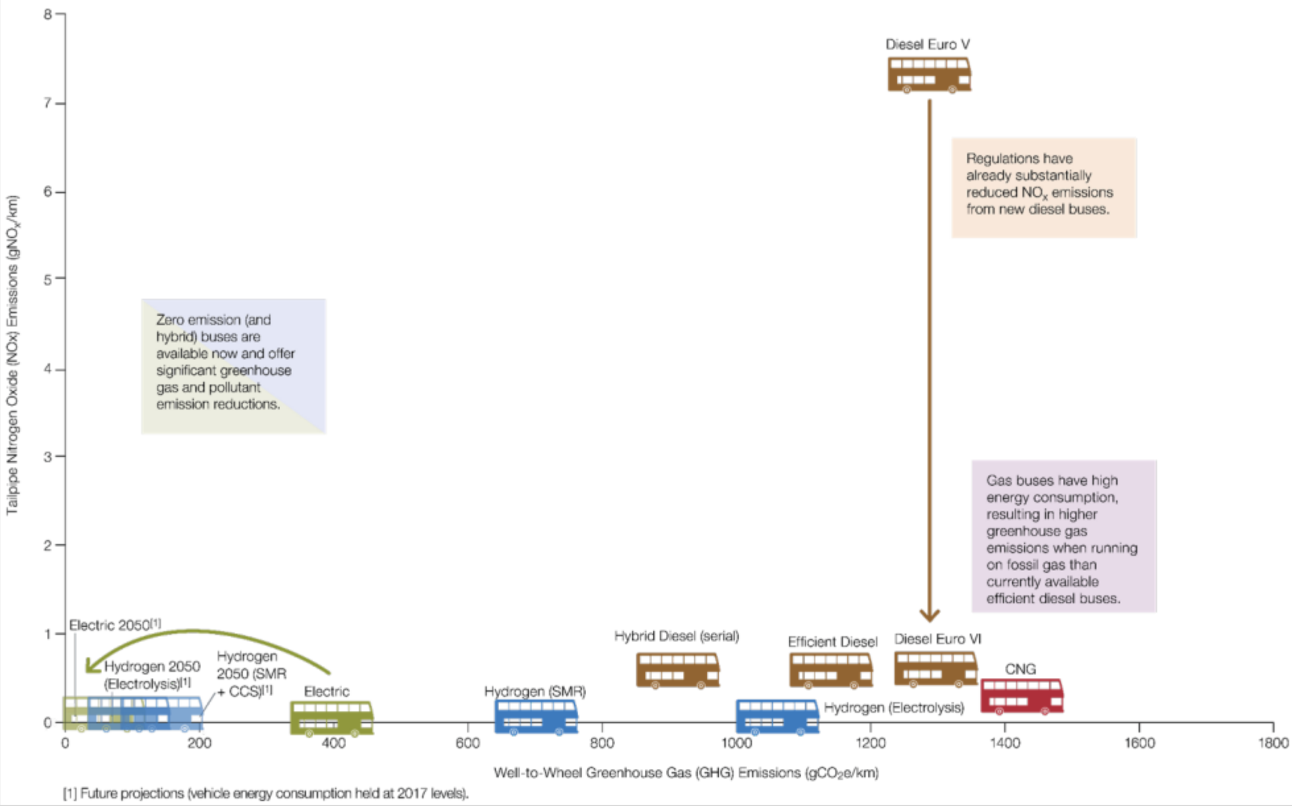
6.3 UK Transport Energy Model

A Transport Energy Model report[27] was published by the UK Department for Transport in 2018. The report examines the emissions from currently available energy sources and vehicle technologies, as well as estimates of future performance. The model compares a range of different energy sources in several different vehicle types. The model includes GHG emissions from the production and use (lifecycle emissions) of a range of energy sources – including liquid fossil fuels, biofuels, natural gas, electricity and hydrogen – and tailpipe emissions of NO_X and PM for five vehicle types, ranging from a medium car to a 44-tonne heavy goods vehicle.

The following extract from the report compares the emissions of NO_X and CO_{2eq} across a range of bus technologies.

27 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/739462/transport-energy-model.pdf

Figure 18: Estimated GHG and NOx emissions for a double deck bus on the LowCVP Urban Bus test cycle (average speed 22.4 km/h)



The plot highlights several interesting findings from the study:

1. there has been a very large improvement in NO_X emissions between Euro V and Euro VI diesel buses;
2. CNG buses, while performing well on NO_X emissions, are the poorest performers on GHG emissions (the report also illustrated that as the average speed decreases, the performance of the CNG bus deteriorates relative to the other technologies);
3. based on current UK electricity grid performance, electric buses are the best performer;
4. electric and hydrogen buses have significant capacity to reduce GHG emissions.

However, this plot does not show the potential GHG emission for CNG buses run wholly or partially on biomethane, which could significantly reduce the GHG emission, or how diesel or hybrid buses would perform if run on various biofuel blends.

In Figure 18 it is assumed that the diesel consumed is a 98.3% fossil and 1.7% biodiesel blend. One third of the London bus fleet are running on B20 (diesel with 20% biodiesel)[28]. If the biodiesel was produced from used cooking oil (UCO) or tallow, the GHG emissions for the diesel Euro VI bus would move from between 1,200 – 1,400 gCO_{2eq}/km to 1,000 – 1,200 gCO_{2eq}/km, a 16% reduction in GHG emission; the diesel hybrid would move into the 600 – 800 gCO_{2eq}/km bracket, which is comparable to a hydrogen bus where the hydrogen is produced from steam methane reformation (SMR)[29].

[28] https://www.london.gov.uk/questions/2017/2662

[29] SMR is a typical commercial production pathway for bulk hydrogen which uses methane produced from fossil fuels as a feedstock.

If the diesel buses were run on 100% biodiesel or hydrogenated vegetable oil (HVO)[30] (again assuming UCO or tallow as the feedstock), the GHG emissions would reduce by around 80% and make a diesel hybrid bus run on 100% biodiesel comparable to the buses at the lower left corner of Figure 18 (i.e. electric 2050, hydrogen 2050 (electrolysis) and hydrogen (SMR + CCS[31])).

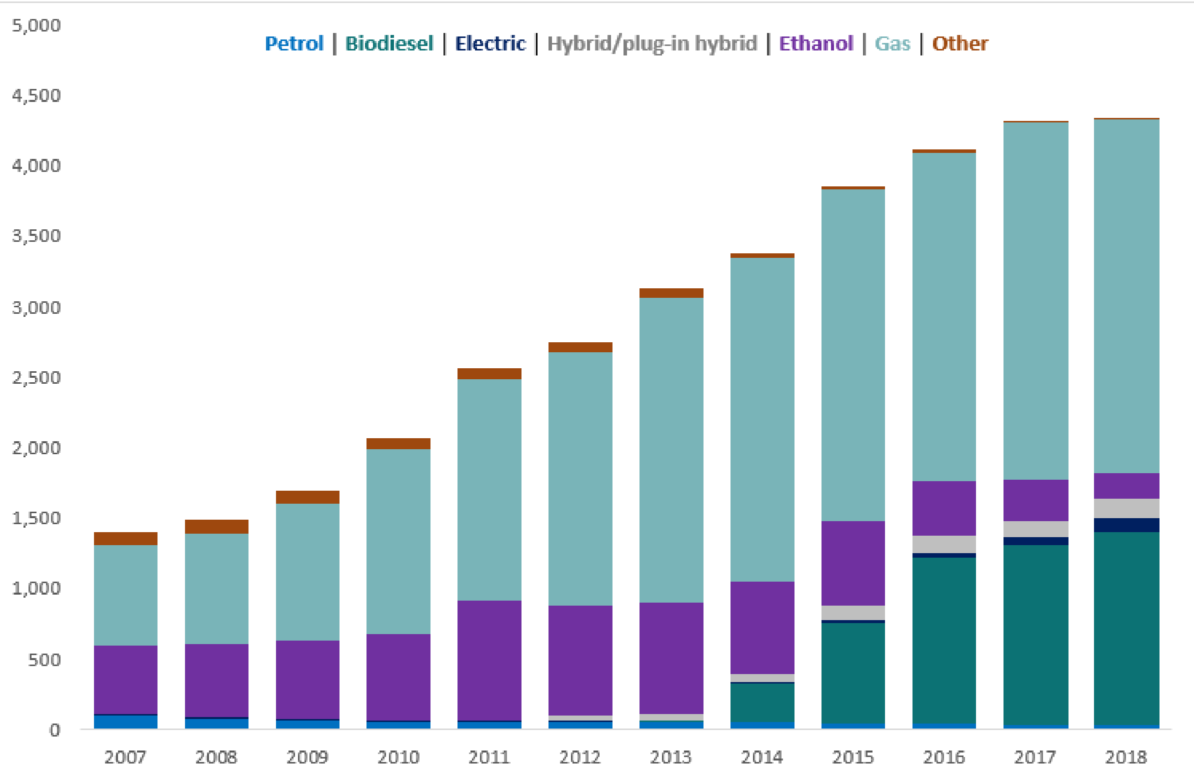
6.4 Trends in Swedish public bus transport

Bus-travel accounts for most of the public travel in Sweden (approximately 80%). Sweden has made significant progress with increasing the penetration of renewable fuels in its transport fleet (including buses) and thus we have examined in some detail the trends and developments in this country.

6.4.1 Bus fleet

There are approximately 14,500 buses in Sweden, according to Trafikanalys[32] vehicle statistics, of which 94% are used in public service. The bus fleet has seen a significant shift away from diesel-only powered vehicles (reducing from 89% of all buses in 2007 to 70% in 2018). The growth of alternative-fuel technology buses in Sweden is illustrated in Figure 19.

Figure 19: Buses in use, by fuel (excluding diesel)



[30] HVO is a form of biodiesel that is chemically identical to diesel.

[31] Carbon capture and storage, CCS, is a technology that captures and stores CO_2 production emissions.

[32] Trafikanalys (or Transport Analysis in English) is a government agency responsible for providing support to transport policy makers (https://www.trafa.se/en).

In 2018, gas buses were the second largest group by fuel-type (17.5%), followed by biodiesel (9.5%). Ethanol buses have decreased year-on-year since 2012, accounting for just 1.2% of buses in 2018.

The data shows that there is a trend towards electric and biogas buses. There were approximately 120 electric buses at the end of 2018, with less than ten at the start of 2014. Recent data also shows that there are approximately 2,500 gas buses. Initiatives such as the EU-funded Baltic Biogas Bus project (2007-2013) have supported Sweden, and other Member States, with introducing hybrid biogas-electric buses. Biodiesel buses are also becoming more popular, accounting for approximately 1,400 buses in 2018.

6.4.2 Fuel usage by public buses

While 70% of Sweden's buses are classified as being diesel buses, these buses can be run on biodiesel and HVO, as well as fossil diesel. The public transport sector aims to run 90% of its total vehicle-kilometres on renewable fuels by 2020. Data from the Swedish Public Transport Association (FRIDA[33]) shows that between 2006 and 2018 the use of renewables in public transport increased from 6% to 87% (buses achieved 85% renewable penetration in 2018). In 2018, twelve of the twenty-one counties, which include the two largest cities (Stockholm and Gothenburg), achieved greater than 90% penetration of renewables in public bus transport.

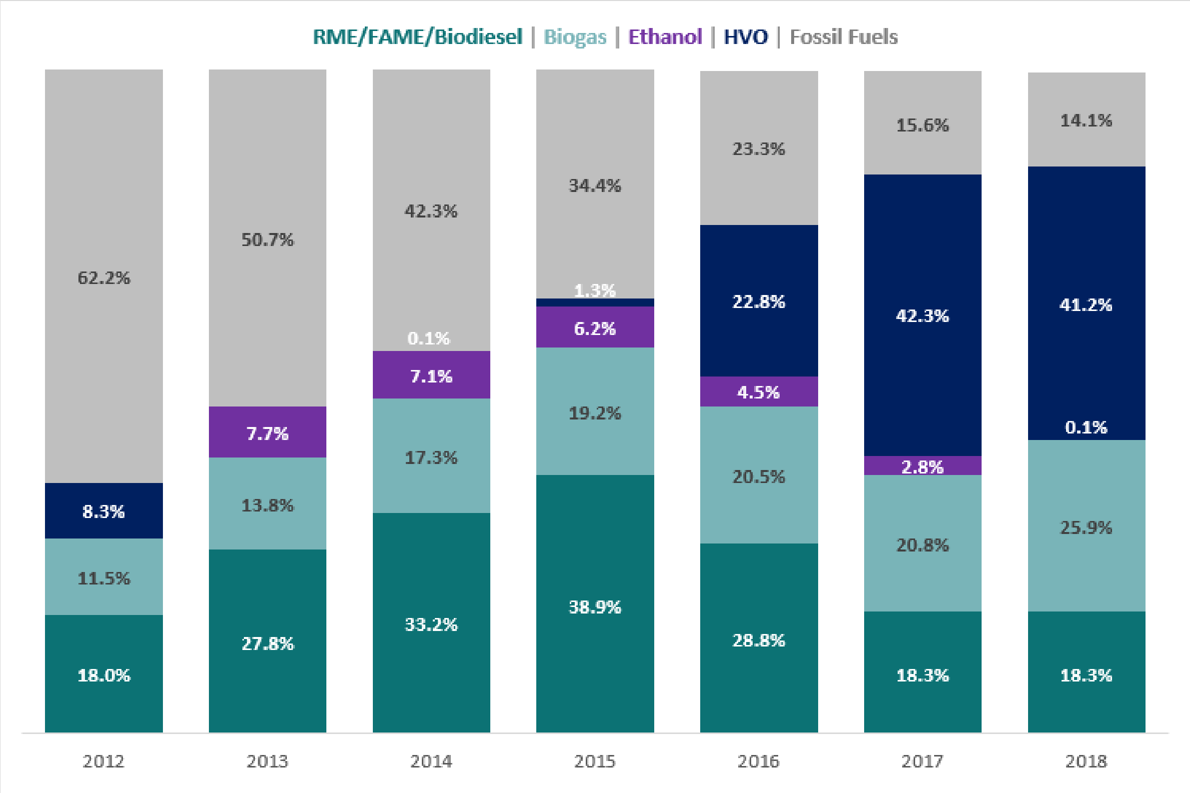
In 2018, HVO[34] was the most popular choice of renewable fuel, followed by biogas, biodiesel, electricity and ED95[35], as illustrated in Figure 20.

[33] Swedish Public Transport environment and vehicle database (FRIDA): http://www.frida.port.se/hemsidan/default.cfm

[34] HVO is a form of biodiesel that is chemically identical to diesel and is not restricted by the EN 590 biodiesel blend wall; thus, it can be blended with diesel to much higher blends than traditional biodiesel. Blending above 40% impacts on the density of the diesel and causes it to exceed the EN590 density limits. Therefore, blending above 40% would also need to be approved by vehicle manufacturers.

[35] ED95 is an ethanol-based biofuel used in modified diesel engines. It is 95% ethanol, with the remainder composed of an ignition improver, lubricant and corrosion inhibiter.

Figure 20: Percentage[36] share of total vehicle-kilometres for public buses (source: FRIDA)



There has been a large increase in the use of HVO in public buses from 2016; it is now providing energy for approximately 40% of the distance travelled by public buses in Sweden. The significant increase in HVO use can be attributed to tax incentives and additional production capacity. While the increase has reduced diesel consumption, it has also resulted in reduced biodiesel use in the public bus fleet.

There is one HVO producer in Sweden (Preem), which co-processes HVO and fossil fuels. In 2015, Preem increased its production of HVO at its Gothenburg refinery from 160m to 220m litres[37].

Biogas usage has also been increasing year-on-year in line with increased numbers of biogas buses, and in 2018 was used in over 25% of all vehicle kilometres travelled by the public bus fleet.

6.4.3 Energy efficiency

The energy efficiency of the Swedish bus fleet in 2018 is provided in Table 14. The energy consumption data was sourced from the FRIDA database, which is used by most Swedish transport authorities for compiling data on energy consumption.

[36] In some instances, a full dataset was not available and so the totals in some years fall marginally short of 100%.

[37] The Swedish Knowledge Centre for Renewable Transport Fuels: https://f3centre.se/sv/faktablad/hefa-hvo-hydroprocessed-esters-and-fatty-acids/

Table 14: Energy efficiency of buses in Sweden in 2018

Fuels	Energy consumption (TJ)	Distance travelled ('000 km)	Energy Efficiency (MJ/km)
Diesel (fossil & bio)	4,657	383,598	12.1
Gas (fossil & bio)	3,171	162,445	19.5
Electricity	11	2,280	4.8
Ethanol (for buses running on ED95)	3	570	11.1

On average over the last four years, the energy efficiency of the bus fleet in Sweden has been as follows:

- Diesel (fossil & bio) – 12.4 MJ/km
- Gas (fossil & bio) – 19.4 MJ/km
- Electricity – 5.8 MJ/km
- Ethanol (for buses running on ED95) – 14.2 MJ/km

6.4.4 Emissions from the bus fleet

The shift towards more sustainable fuels in public transport has resulted in a significant reduction in emissions. Lifecycle emissions of CO_2 decreased by 71% between 2012 and 2018 (as shown in Table 15).

Table 15: Net emissions of CO_{2eq} and kilometres travelled for public buses (source: FRIDA)

Transport	2012	2013	2014	2015	2016	2017	2018
CO_2 emissions (tonnes)	466,309	407,739	376,437	337,242	257,752	187,926	133,072
Kilometres travelled ('000 km)	618,366	635,354	670,422	684,306	702,578	707,859	569,981

There is a strong negative correlation between vehicle-kilometres and net emissions of CO_{2eq}, between 2012 and 2017[38], with an even stronger negative correlation between bus-kilometres and emissions on a per kilometre basis[39]. From 2012 to 2017, net emissions reduced by 57% while vehicle kilometres increased by 13%, i.e. for every 1% increase in vehicle kilometres there was a 4.4% reduction in emissions.

The average emissions of NO_X and PM have also improved since 2012 (reducing by 33% and 51%, respectively), as shown in Table 16.

[38] The 2018 results were ignored due to an unexplained sharp drop in bus kilometres.

[39] R^2 of between -0.94 and -0.96. The closer the R^2 value is to +/- 1, the greater the relationship between values.

Table 16: Emission levels for public buses, 2012 to 2018 (source: FRIDA)

Emission	2012	2013	2014	2015	2016	2017	2018
NO_X (g/km)	4.27	3.82	3.46	3.04	2.71	2.48	2.09
PM (g/km)	0.03	0.03	0.03	0.02	0.02	0.02	0.02
CO_2 (g/km)	755	643	564	493	368	275	244

Table 17 shows the NO_X emission rate for each fuel type.

Table 17: NO_X emissions by fuel type

Fuel	2016	2017	2018
Diesel (bio & fossil) (g/km)	2.62	2.47	2.02
Ethanol (g/km)	3.63	3.95	2.28
Gas (bio & fossil) (g/km)	2.87	2.77	2.61

6.5 Gas for transport

The trend in Sweden in recent years has been towards HVO and biogas buses. According to the Swedish Energy Agency (30), biogas has been produced in Swedish sewage treatment plants since the 1940's. The energy crisis of the 1970's led to large-scale construction of biogas plants supported by major investments backed by national programmes. The total amount of biogas produced in Sweden 2010 amounted to 1.4 TWh (5 PJ). In 2016, there were 279 biogas facilities which produced just over 2 TWh (7.2 PJ) of biogas.

While the Swedish experience points to a role for gas and biogas in transport, a recent Transport & Environment report (31) does not support gas or biogas for transport. It states that fossil gas used in transport has no meaningful climate benefits compared to petroleum-based fossil fuels. The authors did not find any evidence supporting the theoretical savings of gas vehicles, which are based on the lower carbon content of the fuel and noted that the poor efficiency of the vehicles often offset the tailpipe emission benefit of the lower carbon content of the fuel.

In relation to biomethane, the report concludes that a *shift to methane use in transport would require the build-up of new infrastructure, a transition in the manufacturing sector and continued fiscal support, in particular through subsidies and tax breaks. EU domestic fossil gas production is declining (rapidly in the case of the Netherlands) and the EU is increasingly dependent on imports in particular from Russia. Creating a new market for fossil gas in transport will increase the EU's dependence on energy imports. Based on the available evidence the role of fossil but also renewable methane in decarbonising transport will be extremely limited and continued support for the expansion of methane as a transport fuel does not appear to be justified.*

Biomethane in transport can play a niche role in local projects, with vehicles running on 100% biomethane, refuelling at local biomethane production sites. A wider shift to methane will almost certainly lead to a transport sector powered by fossil gas, not renewable methane.

Another study carried out in the USA in 2013 comparing CNG, diesel and diesel hybrid buses (32) states that: *Diesel and CNG buses emit very similar levels of CO_2 from their tailpipes (g/mi); while natural gas has lower carbon content than diesel fuel this advantage is eroded by generally higher fuel economy for diesels… Hybrid buses generally emit lower CO2 (g/mi) than diesel or CNG buses due to their higher fuel economy… Total wells-to-wheels GHG emissions are generally lower from hybrid* *buses than from diesel or CNG buses due to their higher fuel economy. The reduction in total annual GHG emissions from operating new hybrid buses instead of new CNG buses could be as high as 54.5 tons CO2-e per bus.*

The analysis was carried out using two different tests. The fuel economy test was carried out on a test track and the emission test was carried out on a large-roll chassis dynamometer. Both tests were carried out over a series of specific tests cycles to simulate real-world driving. The results from the tests carried out six buses (x2 diesel, x2 hybrid & x2 CNG) over the 'Manhattan cycle' are set out in Table 18. The 'Manhattan cycle' recorded an average speed of 11 kph, which is similar to the average speeds recorded in Dublin (12.7 kph) and Cork (13.4 kph) during the trials.

Table 18: Manhattan test cycle results

Fuel	Average Fuel Economy (MJ/km)	NO_X (g/km)	CO_2 (g/km)	CH_4 (g/km)
Diesel	23.93	1.68	1,770	-
Hybrid	17.98	1.09	1,340	-
CNG	30.23	0.36	1,752	0.34

6.6 Electric buses in Iceland

Following trials of electric buses in March 2018, fourteen electric buses were put into service in Reykjavik. The buses are managed by Strætó, the main bus company in Reykjavík, and account for around 10% of buses operating in the capital.

Each bus has a stated range of approximately 300 km. In general, the buses are operated in the mornings, charged, then operated again in the afternoon. Initially, the buses completed 5,000 km/month; this has since increased to 8,000 km/month.

The average fuel economy of the buses is between 3.6 - 4 MJ/km; however, this does not include the energy used by the heating system, which is diesel-powered.

As well as purchasing new buses, infrastructure improvements were required at the bus depot: a 750 kW charging station was installed, consisting of five outlets, each with two plugs. Each outlet is rated to 150 kW, which is split equally between the two plugs. The cost of installing the charging station was 54 million ISK (~€400k).

6.7 Compare DTTAS bus trials with other studies & data

The purpose of this sub-section is to compare the findings and data from the other sources discussed in the proceeding sub-sections with the findings from the bus trials, to determine if, in general, they are in keeping with the experiences from elsewhere. We first compare the energy efficiency data followed by the CO_2 and NO_X data.

6.7.1 Energy efficiency

Based on 2018 data, the energy efficiency of the urban public bus fleet is 16.6 MJ/km. This appears contrary to the findings from the bus trials which recorded higher average energy consumption data, as set out in Table 19.

Table 19: Energy efficiency of diesel buses trialled

Bus	Efficiency (MJ/km)
Euro IV	24.9
Euro V	23.8
Euro VI	18.5

The difference between the energy efficiencies recorded during the trials and the actual energy efficiency is because the actual figure is based on data from hundreds of routes of varying distance and conditions whereas the trial data is for specific routes and under specific conditions. Thus, it would be expected that the trials would give rise to less energy efficient buses.

If we apply the energy efficiency figures set out in Table 19 to the national urban fleet, the 'calculated' energy efficiency is 22.1 MJ/km[40]. The 'calculated' energy efficiency provides a reference against which all the bus technologies trialled can be measured. For example, the energy efficiency of the Diesel 3 Euro VI bus was measured at 18.5 MJ/km during the trials, which is 16% less than the 'calculated' efficiency of the fleet (22.1 MJ/km). Therefore, it is reasonable to assume that if the national fleet was comprised entirely of Euro VI buses, the energy efficiency of the fleet would improve by 16% and reduce to 13.8 MJ/km from 16.6 MJ/km. Table 20 sets out the estimated energy efficiency of the fleet if it was comprised entirely of Euro VI, hybrid, electric or CNG buses.

Table 20: Estimated energy efficiency

Bus	Estimated energy efficiency (MJ/km)
Euro VI	13.8
Hybrids	10.6
Electric [Note]	5.1
CNG	24.1
Note: This excludes the Electric 1 bus, because it is unlikely that electric buses with separate diesel space heating would be purchased.	

Table 21 sets out the results from the trials and provides a direct comparison with data from other sources.

[40] Assumes the Euro III buses achieve the same fuel efficiency as the Euro IV.

Table 21: Comparison of energy efficiency data

Bus	Trial data Note 1	Irish fleet (estimated)	UK TRL (33)	Iceland	Sweden	USA Note 5
	(MJ/km)					
Euro IV	24.9	16.6 Note 3	-	-	12.1 Note 4	23.9
Euro IV (post retrofit)	24.6					
Euro V	23.8					
Euro V (post retrofit)	21.2					
Euro VI	18.5					
Hybrids	14.1	10.6	11.6	-		18
Electric	6.8 Note 2	5.1	3.4	3.4 - 4	4.8	-
CNG	32.1	24.1	25.2	-	19.5	30.2

Note 1: Does not include cold starts.

Note 2: This excludes the Electric 1 bus, because it is unlikely that electric buses with separate diesel space heating would be purchased. Also, energy consumption was measured between the power source and bus charger (see Section 5.2.3) – this may not be the case for the other data sources.

Note 3: This is the recorded fuel efficiency of the combined Dublin Bus and Bus Éireann urban fleets.

Note 4: All Sweden's diesel, biodiesel and HVO fuelled buses.

Note 5: The buses were all manufactured between 2010 and 2012

The data in Table 21 demonstrates a level of consistency across the technologies in terms of the relative performance. The electric buses are the most efficient (on a final energy basis), followed by the hybrids and the diesel buses – the least efficient were the CNG buses.

6.7.2 CO_2 emissions (tailpipe)

CO_2 emissions are directly correlated with the type of fuel used and the energy efficiency of the vehicle. When 1 MJ of diesel (0.0278 litres) is combusted (assuming complete combustion), it emits 73.3 gCO_2 – this is the tailpipe carbon intensity of diesel[41]. Therefore, the more efficient a bus is, the less CO_2 will be emitted per km travelled.

While the carbon intensity of natural gas is 56.9 gCO_2/MJ, which is less than that of diesel, the CNG buses are less energy efficient, i.e. they require more energy to travel the same distance. Thus, to compare the CO_2 performance of both technologies, it is appropriate to do so based on distance travelled.

[41] The CO_2 emissions from all the diesel buses measured by the PEMS equipment were approximately equal to 73.3 gCO_2/MJ of diesel consumed.

Table 22: Comparison of tailpipe CO_2 emissions during the trials

Bus type	Emission factor (gCO_2 /MJ)	Trial energy efficiency (MJ/km)	Trial emissions (gCO_2/km)	UK (gCO_2/km)	Sweden (gCO_2/km)	USA (gCO_2/km)
Euro VI (diesel)	73.3	18.5	1,356			
Hybrid (diesel)	73.3	14.1	1,034	818	887	1,340
CNG	62.1[Note]	32.1	1,993	1,433	1,110	1,752
Note: The tailpipe emission factor set out for natural gas is 56.9 gCO_{2eq}/MJ. However, the trials recorded average tailpipe emissions of 62.1 gCO_2/MJ, which is discussed in Section 5.5.2.1.						

Even though the tailpipe emission factor for natural gas is less than that of diesel, the energy efficiency of the CNG buses is such that the CO_2 emitted per kilometre travelled is greater than the Euro VI diesel bus and the hybrid bus. While there is a variance between the magnitude of the emissions recorded during the trial, which can be attributed to the poor energy efficiency recorded during the trials, and those from the UK and Sweden, these data support the findings from the trials: CNG buses emit more CO_2 per kilometre than diesel buses and in the case of diesel hybrid buses, considerably more.

The preceding analysis does not include electric buses because there are no tailpipe emissions.

6.7.3 CO_{2eq} emissions (lifecycle)

The same principles applied to assessing tailpipe CO_2 emissions apply to lifecycle emissions.

Table 23: Comparison of lifecycle CO_{2eq} emissions

Bus type	Emission factor (gCO_{2eq}/MJ)	Trial efficiency (MJ/km)	Trial emissions (gCO_{2eq}/km)	UK emissions (gCO_{2eq}/km)
Euro VI (diesel)	95.1	18.5	1,760	1,300
Hybrid (diesel)	95.1	14.1	1,340	900
CNG	77.8[Note]	32.1	2,497	1,400
Electric	121	6.2	750	400
Note: The default emission factor set out in Directive 2015/652 for natural gas is 69.3 gCO_{2eq}/MJ, which is composed of tailpipe (56.9 gCO_{2eq}/MJ) and upstream emissions (12.4 gCO_{2eq}/MJ). However, the trials recorded average tailpipe emissions of 62.1 gCO_{2eq}/MJ (5.2 gCO_{2eq}/MJ higher than the default value) and 3.3 gCO_{2eq}/MJ of methane slip. Thus, the lifecycle emission of CNG is 77.8 gCO_{2eq}/MJ (69.3 + 5.2 + 3.3).				

While the data from the trials show higher emissions, the general findings are the same: emissions from the electric buses are the lowest, followed by the hybrids with the CNG buses emitting the most CO_2.

Both diesel and CNG can be blended or replaced with biofuels. Thus, on a lifecycle basis, both technologies can achieve lower emissions. Biodiesel sold in Ireland has an average lifecycle carbon intensity of approximately 12 gCO_{2eq}/MJ; the carbon intensity of biomethane produced from dry manure is 15.1 gCO_{2eq}/MJ. Given the potential lifecycle carbon intensities of the two fuels are very similar, the relative performance of the two technologies will remain the same if the fossil fuels are replaced with biodiesel and bioCNG (biomethane).

6.7.4 NOx emissions

Table 24 compares the findings from the trials with the data gathered from other studies and sources.

Table 24: Comparison of NOx emissions

<table>
<tr><th rowspan="2">Bus</th><th>Trial emissions Note</th><th>Irish Fleet (estimated)</th><th>UK transport energy model (from COPERT)</th><th>Sweden</th><th>USA</th></tr>
<tr><th colspan="5">(gNO_X/km)</th></tr>
<tr><td>Euro IV</td><td>10.5</td><td>7.8</td><td>6.2</td><td rowspan="5">2</td><td rowspan="4">1.7</td></tr>
<tr><td>Euro IV retrofit</td><td>3.9</td><td>2.9</td><td>-</td></tr>
<tr><td>Euro V</td><td>11.9</td><td>9</td><td>5.5 – 7.5</td></tr>
<tr><td>Euro VI</td><td>0.5</td><td>0.4</td><td>0.5</td></tr>
<tr><td>Hybrids</td><td>1.4</td><td>1.0</td><td>-</td><td>1.1</td></tr>
<tr><td>CNG</td><td>0.7</td><td>0.5</td><td>0.2</td><td>2.6</td><td>0.4</td></tr>
<tr><td colspan="6">Note 1: Does not include cold start data.</td></tr>
</table>

The results from the trials indicate that, in comparison to the Euro VI bus, on average, NOx emissions are marginally higher for CNG buses – this is similar to the operational data from Sweden. The UK data gives the opposite result: NOx emissions from CNG buses are lower than from Euro VI buses.

While, on average, the results from the trials indicate that NOx emissions are marginally higher for CNG buses, the results for each CNG bus show how the conclusion differs depending on the bus:

- The average NOx emissions for the CNG 2 bus, for both Dublin and Cork, was 0.2 gNO_X/km, which is less than the Diesel 3 Euro VI bus.
- The average NOx emissions for the CNG 1 bus, for both Dublin and Cork, was 1.2 gNO_X/km, which is greater than the Diesel 3 Euro VI bus.

A 2016 Ricardo report (34) compares the NO_X emissions of methane powered buses and modern Euro VI buses – it found the emissions to be the same. It stated that '*Evidence from a study carried out for Transport for London in 2014 (Ricardo-AEA, 2014) also backs up this assumption, as this research indicates that NOx emissions for methane-powered vehicles are very similar to diesel vehicles. Other research gives mixed results; independent real-world emission tests indicate that NOx emissions from Euro VI CNG buses can be marginally higher than for equivalent Euro VI diesel buses (LowCVP, 2015), whilst other research shows that CNG heavy duty vehicles give lower NOx emissions*'.

7 CONTRIBUTION TO RENEWABLE ENERGY AND EMISSIONS REDUCTIONS

7.1 Introduction

The overall EU targets for renewable energy are 20% by 2020 and 27% by 2030. Member States have different national targets for 2020, although all have a mandatory target of 10% for transport (by 2020), as set out in the Renewable Energy Directive (RED) (5). Ireland's overall renewable energy target for 2020 is 16%. The recast Renewable Energy Directive (RED II) (9) sets a 14% renewable energy target in transport for 2030.

Oil remains the largest single fuel source (48%) in Ireland because, although it only accounts for <2% of power generation, it dominates transport (97%) and supplies 43% of residential heating. There are very few other fuels in use in the transport sector; biofuels account for the majority at around 4% of road transport energy. There is also LPG, electricity for EVs, and there are plans for CNG as part of the Causeway Project, which aims to pilot 14 fast-fill CNG stations by 2020.

Dublin Bus and Bus Éireann consume approximately 55m litres of diesel per annum – the urban public services consume approximately 31m litres. Ireland’s road transport market is approximately 4.7 billion litres (73% diesel, 22% gasoline and 5% biofuel). The public bus fleet account for approximately 1% of road transport energy demand.

Consequently, the potential contribution towards renewable energy targets by increasing renewable energy in the urban public bus fleet is limited, as is reducing emissions. Notwithstanding this, increasing renewables in the urban public bus fleet will support achieving renewable energy and emissions reduction targets, as well as demonstrating leadership in the transport sector.

In our analysis of the contribution renewable energy consumed in Ireland’s public buses could make to national renewable energy targets in 2030, we assume the demand for road and rail energy is 200 PJ in 2030, which is a 20% increase on the 2018 value, but the size of the urban public bus fleet and the distance travelled by the buses remains the same. We also assume that the urban public bus fleet is turned over once every 14 years[42]. Therefore, approximately 14% of the buses from 2018 will still be in the fleet in 2030.

7.1.1 Electricity

To estimate the amount of renewable electricity that could be consumed by electric buses, we have used the formula provided in Annex I (3)(c)(iii) of Directive 2015/652, which lays down the calculation methods and reporting requirements for the Fuel Quality Directive (35).

Electricity consumed = distance travelled (km) × electricity consumption efficiency (MJ/km)[43]

We have used the average consumption efficiency achieved by the electric buses trialled, adjusted for the urban fleet operating under normal conditions (5.2 MJ/km), and data from Dublin Bus and Bus Éireann on annual mileage. Table 25 sets out four scenarios and details the contributions that could be made by electric buses, depending on the uptake of electric buses and the renewable

[42] Dublin Bus vehicles typically travel 57,000 km each year. The original Clean Vehicles Directive (2009/33/EC) suggests a lifetime mileage of 800,000 km for buses; thus, we’ve assumed that the current fleet will be turned over every 14 years i.e. 1/14th of the fleet will be replaced with newer buses each year. This is in keeping with the data for the Dublin Bus fleet which has an average age of approximately 7 years.

[43] Electric bus consumption data captured during the bus trials includes for charger losses. This is a more appropriate measurement for bus fleet operators as it provides a better indication of the amount of energy that needs to be supplied.

energy penetration on the electricity grid. Each scenario reflects the percentage of new buses purchased each year that are electric. For example, under the 10% electric scenario, 10% of the new buses purchased each year will be electric – the remainder are assumed to be diesel hybrid run on fossil diesel. This means that at a replacement rate of approximately 90 buses per year, some diesel buses from 2018 and 2019 will still be in the fleet in 2030. It is not until 2032 that all the buses in the fleet will match the scenario[44].

In addition, RED II allows for renewable electricity consumed by EVs to be considered to be 4-times its energy content – this is included in the contribution towards the renewable energy target set out in Table 25[45].

Table 25: Contribution of renewable electricity to 2030 renewable energy targets

Scenario	Distance travelled ('000 km)		Energy consumption (PJ)		% Renewable Electricity	Contribution towards target (percentage points)
	Diesel	Elec	Diesel	Elec		
10% electric	61,454	5,795	0.68	0.03	57%[Note 1]	0.03pp
50% electric	38,275	28,973	0.44	0.15	57%	0.17pp
100% electric	9,302	57,946	0.13	0.30	57%	0.34pp
100% electric	9,302	57,946	0.13	0.30	75%[Note 2]	0.44pp

Note 1: Eirgrid's renewable energy forecast for renewable energy penetration on the grid in 2030 under its 'Steady Evolution' scenario (36).

Note 2: Eirgrid's renewable energy forecast for renewable energy penetration on the grid in 2030 under its 'Low Carbon Living' scenario (36).

Under the optimistic conditions, urban public electric buses could contribute 0.44pp towards the renewable energy targets in 2030.

7.1.2 BioCNG

To contribute the to the renewable energy targets in 2030, the CNG supplied to the buses must be produced from biomass and it must be sustainable[46]. As was the case for renewable electricity, bioCNG (i.e. biomethane) produced from wastes and residues can be double counted and each scenario reflects the percentage of new buses purchased each year that are CNG – the remainder of new buses purchased each year are diesel hybrid. Double counting is included in the contribution towards the renewable energy target set out in Table 26.

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[44] This reflects a fleet turnover rate of once every fourteen years equating to a bus life of c. 800,000 km (57,000 km per year).

[45] Articles 25 to 29 of RED II set out how compliance with the 2030 renewable energy target is calculated.

[46] RED II stipulates that, for biomethane used in transport, GHG saving greater than 60% must be achieved relative to fossil fuel comparator of 94 gCO_{2eq}/MJ, i.e. the lifecycle carbon intensity of biomethane must be less than 37.6 gCO_{2eq}/MJ. However, biomethane used for heat production must achieve greater GHG savings: the carbon intensity must be less than 20.4 gCO_{2eq}/MJ. Because biomethane injected to the national gas grid could be used for either heat or transport, we assumed that biomethane producers will supply product that meets the more stringent GHG emission saving criteria of 20.4 gCO_{2eq}/MJ.

Table 26: Contribution of bioCNG to renewable energy targets in 2030

Scenario	Distance travelled ('000 km)		Energy consumption (PJ)		% Renewable Energy	Contribution towards target (percentage points)
	Diesel	BioCNG	Diesel	BioCNG		
10% BioCNG	61,454	5,795	0.68	0.14	10%	0.14pp
50% BioCNG	38,275	28,973	0.44	0.70	50%	0.70pp
100% BioCNG	9,302	57,946	0.11	1.40	100%	1.40pp

At 100% bioCNG, the urban public buses could contribute 1.4pp towards the 2030 renewable energy target. This is far greater than the electric buses; however, the result is somewhat misleading.

One of the findings from bus trials, which is confirmed by results from other studies, is that CNG buses are not as energy efficient as the diesel or electric buses, so more energy is required to travel the same distance. This has a somewhat paradoxical impact on achieving renewable energy targets: even though more energy is required, which is inefficient, if it is renewable energy, this contributes more to achieving the renewable energy target.

The important thing to realise is that to achieve this significant contribution, the energy consumption of the bus fleet increases, because CNG buses are less energy efficient than the current bus fleet.

7.1.3 Biofuels – HVO

Hydrotreated vegetable oil (HVO) is a form of biodiesel that is chemically identical to diesel and is not restricted by the EN 590 biodiesel blend wall[47]. While buses could be run on traditional FAME-type (fatty acid methyl ester) biodiesel, the 7% biodiesel blend wall means that high blend rates could not be achieved without taking additional measures to manage the fuel's properties, putting in place facilities to supply higher blends and engaging with the vehicle manufactures to ensure they are satisfied that high blends can be used. While this is a viable option and is being pursued in London where one-third of the bus fleet is running on B20[48] (diesel with a 20% biofuel blend), HVO can be blended to around 40% without impacting the EN 590 specification. Blending above 40% impacts on the density of the diesel and causes it to exceed the EN590 density limits. Therefore, blending above 40% would also need to be approved by vehicle manufacturers.

Table 27 sets out three scenarios and details the contributions that could be made by HVO towards renewable energy targets. In these scenarios we assume that all the buses are diesel hybrid, to reflect a bus fleet that has been renewed with diesel hybrids rather than CNG or electric vehicles and that each year the new hybrids purchased are run on the percentage HVO described in the scenario.

[47] The European specification for road diesel is EN 590 and it specifies a biodiesel blend limit of 7%.

[48] Even though the EN 590 standard is ubiquitous in Europe, there are other specifications for higher blends, such as EN 16709 for B20 and B30 blends for use by captive fleets and EN 16734 covers B10 for use in vehicles compatible with a 10% biodiesel blend.

Table 27: Contribution of HVO to renewable energy targets

Scenario	Distance travelled ('000 km)	Energy consumption (PJ)	% Renewable Energy	Contribution towards target (percentage points)
10% HVO	67,248	0.74	10%	0.07pp
40% HVO			40%	0.37pp
100% HVO			100%	0.74pp

7.2 Comparison of Technologies

7.2.1 Renewable energy targets

Comparing the impact on achieving renewable 2030 renewable energy targets of the three technologies examined in the preceding sub-sections is complicated by the different bus efficiencies. As set out in Figure 10 in Section 5.5.1, on a final energy basis, the electric buses are the most energy efficient and the CNG the least efficient. This means that the potential contribution electric buses could make to renewable energy targets is minimised because electric buses consume 25% of the energy consumed by CNG buses. Table 28 summarises the potential contribution each fuel could make to renewable energy targets under the various scenarios detailed in Table 25, Table 26 and Table 27.

Table 28: Estimate contribution towards 2030 renewable energy targets

Scenario	Estimated contribution (percentage points)
10% Electric	0.03
50% Electric	0.17
100% Electric (57% renewable grid)	0.34
100% Electric (75% renewable grid)	0.44
10% BioCNG	0.14
50% BioCNG	0.70
100% BioCNG	1.40
10% HVO	0.07
40% HVO	0.37
100% HVO	0.74

7.2.2 GHG emissions

Table 29 compares the energy efficiency of the fuels when consumed in buses, and their lifecycle and tailpipe carbon intensities. Again, the comparison is complicated by the variance between the energy efficiency of the technologies. Thus, to provide a fair comparison, we have done so on a per kilometre basis and included both lifecycle and tailpipe emissions. To provide context for the scale of emissions, data for the Diesel 3 Euro VI bus is also included.

Table 29: Comparison of GHG emissions in 2030

Fuel	Consumption efficiency (MJ/km) Note 1	Carbon Intensity – lifecycle (gCO_{2eq}/MJ)	Carbon intensity – tailpipe (gCO_{2eq}/MJ)	Lifecycle emissions (gCO_{2eq}/km)	Tailpipe emissions (gCO_{2eq}/km)	Source of carbon intensity data
Electricity	5.1	78	0	398	0	Linear interpolation between 2017 (SEAI – 121 gCO_2/MJ) and a 2050 projection of 11 gCO_2/MJ, which is required to achieve the goal of an 80% decarbonisation of the energy system. The ESB report *Ireland's low carbon future – Dimensions of a solution* references a UCC modelling report (37) which states that generation carbon intensity needs to fall to 38 gCO_2/kWh (11 gCO_2/MJ) by 2050.
CNG	24.1	77.8	65.4	1,875	1,576	Lifecycle = default value (69.3 gCO_{2eq}/MJ, Annex I, Part 2 of 2015/652), plus variation because of natural gas composition (5.2 gCO_{2eq}/MJ, see section 5.5.2.1), plus methane slip (3.3 gCO_{2eq}/MJ)[Note 2]. Tailpipe = measured during trials (62.1 gCO_{2eq}/MJ), plus methane slip measured during trials (3.3 gCO_{2eq}/MJ).
BioCNG	24.1	23.7	0	571	0	Lifecycle = maximum carbon intensity allowed to comply with RED II GHG emissions savings criteria for biomethane used for heat (20.4 gCO_{2eq}/MJ), which is more stringent than the criteria used for transport, plus methane slip measured during trials (3.3 gCO_{2eq}/MJ) [Note 2].
HVO	10.6 [Note 3]	12.6	0	134	0	BOS Annual Report, 2015
Biodiesel (average)	10.6 [Note 3]	12	0	127	0	BOS Sustainability Statements (http://www.nora.ie/biofuels-obligation-scheme/bos-annual-reports.225.html)
Diesel (Euro VI)	13.8	95.1	73.3	1,312	1,012	Annex I, Part 2 of Directive 2015/652 & SEAI emission factors

Note 1: As per Table 20.

Note 2: Incomplete combustion in CNG engines can result in emissions of methane via the exhaust system (referred to as 'methane slip'). The CNG vehicles tested during the trials emitted, on average, 4.3 g/km of methane, which is equivalent to 3.3 gCO_{2eq}/MJ.

Note 3: Consumption efficiency when used in a hybrid bus.

In terms of reducing the GHG emissions from the transport fleet, biodiesel (produced from waste) currently achieves the largest reduction per kilometre travelled. Even though bioCNG has a very low carbon intensity, because CNG buses require approximately 50% more energy to travel the same distance, the GHG emissions per kilometre are almost four-times those emitted by buses powered by biodiesel.

The GHG emissions from electric buses are also greater than those emitted by biodiesel-powered buses. However, as the penetration of renewables increase on the electricity grid, the carbon intensity of electricity will reduce. However, to achieve similar GHG emissions reductions as biodiesel, the grid emission factor will need to reduce to approximately 26 gCO_{2eq}/MJ (assuming the consumption efficiency of the buses remain static)[49].

It should be noted that the lifecycle carbon intensity values provided in Table 33 for bioCNG, HVO and biodiesel are calculated in accordance with the methodology set out in RED and RED II. The methodology stipulates that while tailpipe emissions do arise from combusting these fuels, they are counted as zero because it is assumed that as plants (biomass) grow, they sequester the same quantity of CO_2 from the atmosphere that is generated during combustion.

7.2.3 NO_X Emissions

The results from the PEMS testing provides data on NO_X emissions (detailed in Section 5.5). However, as detailed in the introduction to this section, the fleet is more energy efficient than recorded during the trials and assuming NO_X emissions are directly proportional to the amount of energy consumed, we have calculated NO_X emission factors for a bus fleet comprised entirely of Euro VI, Hybrid or CNG buses (there are no <u>tailpipe</u> NOx emission from electric buses).

Table 30: NO_X emission factors

Bus	Trial emissions (gNO_X/km)	Relative to calculated fleet emission factor of 6.5 gNO_X/km	Estimated emissions (gNO_X/km)
Euro VI	0.5	-92%	0.4
Hybrids Note 1	1.4	-79%	1.0
CNG	0.7	-89%	0.5

Using this data, we have estimated the likely tailpipe NO_X emissions for the bus fleet for different technology penetration scenarios.

[49] To achieve the goal of an 80% decarbonisation of the energy system by 2050, as set out in the National Development Plan, an ESB report (*Ireland's low carbon future – Dimensions of a solution)* references a UCC modelling report (37) which states that generation carbon intensity needs to fall to 38 gCO_2/kWh by 2050.

Table 31: Estimated tailpipe NOx emissions in 2030

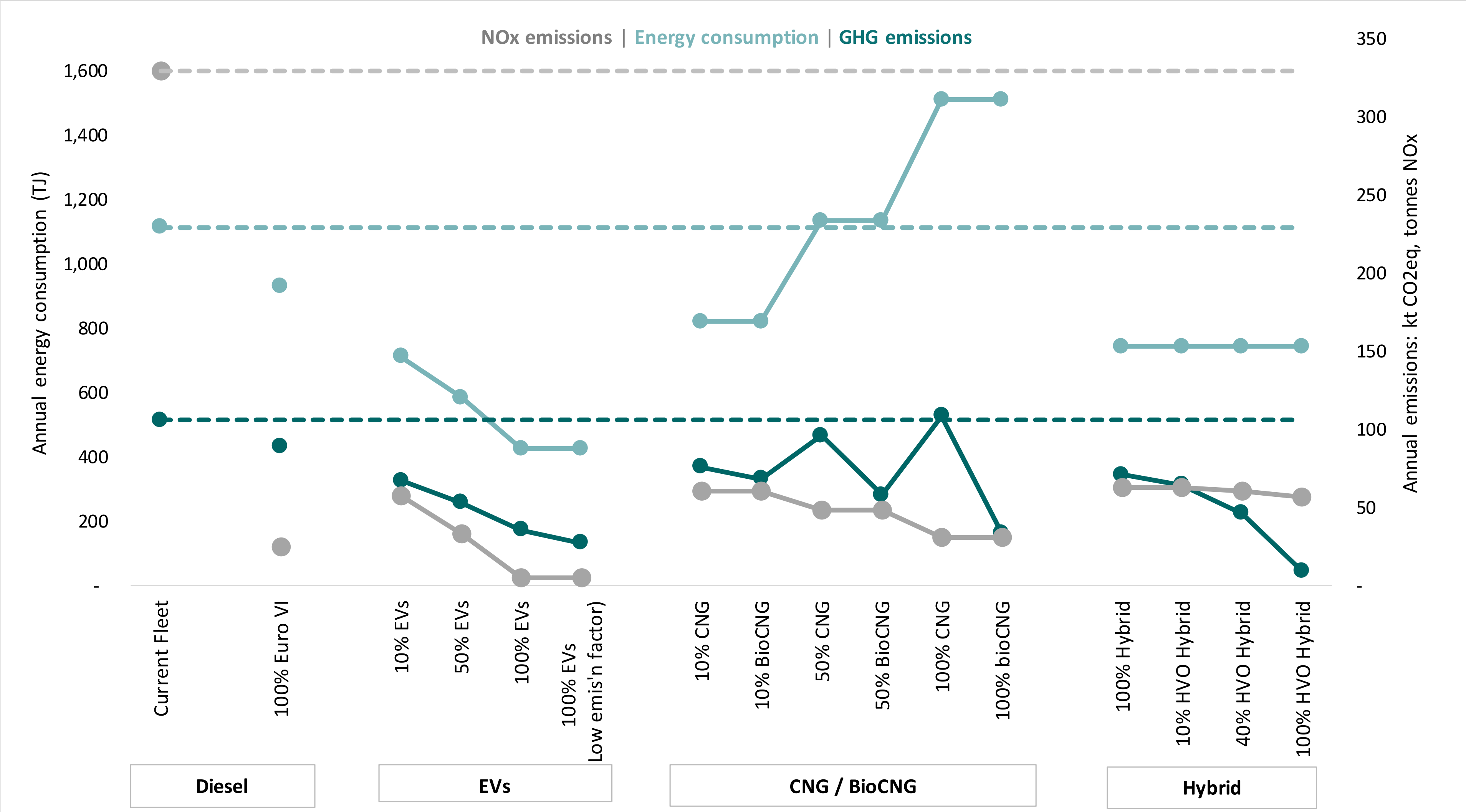
Scenario	NOx emissions (tonnes)
Existing fleet	329
10% electric	57
50% electric	33
100% electric	5
10% CNG/BioCNG	60
50% CNG/BioCNG	48
100% CNG/BioCNG	30
10% HVO	62
40% HVO	60
100% HVO	57

The EPA reported 108.3 kt of NO_X emissions in Ireland in 2017 – the transport sector was responsible for 44.4 kt (22). We estimate the existing bus fleet emit approximately 0.7% of Ireland's NO_X transport emissions. This would reduce substantially under all the scenarios presented. If all the buses were electric, tailpipe NO_X emissions would be eliminated. There would, however, be NO_X emissions arising from generating the electricity, which are not included in this analysis because we have only examined tailpipe NO_X emissions.

7.2.4 Combined comparison

Figure 21 compares the technologies on the basis of fuel consumption, lifecycle GHG emission and NO_X emissions, summarising the data presented in the preceding sub-sections. It shows how each fleet option would perform in 2030.

Figure 21: Comparison of options in 2030



8 Cost Benefit Analysis

8.1 Approach to Cost Benefit Analysis

8.1.1 Purpose

The purpose of a cost-benefit analysis is to examine a potential investment decision by comparing the investment cost, including capital outlays, sustaining capital investment and annual operating and maintenance costs, and the benefits that accrue from that investment. For an investment that provides a monetary return, it is relatively straightforward to estimate the benefit and to identify the beneficiary. However, in the case of an investment to reduce or eliminate potential environmental damage, quantifying the benefit in monetary (value) terms such that it can be compared against the cost of the investment is not straightforward. Furthermore, the benefit to the environment is unlikely to be confined to the investor, but rather to the public.

Two cost benefit analyses have been undertaken:

1. Installing an SCR system on Euro IV and Euro V buses (Section 8.2).
2. Comparing alternative- and diesel-fuel bus technologies under a range of deployment scenarios (Section 8.3).

8.1.2 Appraisal Methods

Several methods that can be used to compare the costs and benefits of a project are described in both the Department of Public Expenditure and Reform's Guide to Economic Appraisal: Carrying out a cost benefit analysis (38) and the UK Treasury's Green Book – Central Government Guidance on Appraisal and Evaluation (39). These include:

- Internal rate of return
- Net present value (NPV)
- Benefit-cost ratio (BCR)

The **internal rate of return** is the maximum rate of interest that a project can afford to pay for resources which allows the project to cover the initial capital outlay and ongoing costs. It can also be described as the rate of return that equates the present value of future benefits to the investment costs.

The **net present value** (NPV) expresses the sum of the net cash flows over the lifetime of the project (i years, $n = i_{max}$), including capital costs, discounted at a rate (r):

$$NPV = \sum_{i=1}^{n} \frac{cash\ flow_i}{(1+r)^i}$$

$$NPV = \sum_{i=1}^{n} \frac{(benefit_{ANNUAL} - cost_{ANNUAL})_i}{(1+r)^i}$$

A positive NPV indicates that there is an overall benefit from the project and it may be justifiable to proceed with the investment. Conversely, a negative NPV indicates that the overall costs of the project outweigh the benefits and, therefore, it may not be justifiable to proceed with the investment.

The **benefit-cost ratio** (BCR) follows a similar form to the NPV, with present values for both the benefits and the costs calculated over the lifetime of the project (including capital costs):

$$PV_{BENEFIT} = \sum_{i=1}^{n} \frac{(benefit_{ANNUAL})_i}{(1+r)^i}$$

$$PV_{COST} = \sum_{i=1}^{n} \frac{(cost_{ANNUAL})_i}{(1+r)^i}$$

The ratio of the present values of the benefits to the present value of the costs yields the BCR. In general, a BCR greater than one indicates that the project may be justifiable, with the benefits outweighing the costs. Conversely, a BCR less than one indicates that the project may not be justifiable.

We have applied the BCR approach as it facilitates comparisons to be made with the ratios calculated by regulatory authorities.

8.1.3 Proportion Factors

The approaches adopted by authorities in Ireland and the UK to assigning BCRs and proportion factors (the inverse of BCRs) are outlined in the following sub-sections.

8.1.3.1 UK Health & Safety Authority

The UK Health and Safety Executive (HSE) sets out its decision-making process in relation to managing risk in its guidance: Reducing risks, protecting people (40). Although the HSE's approach is primarily related to managing health and safety risks, it also applies to environmental risks.

One of the key elements of the HSE's approach to managing risk is the concept of gross disproportion when comparing the risk against the cost of minimising (or eliminating) the risk. The HSE guidance states:

> *For duty holders, the test of 'gross disproportion' implies that, at least, there is a need to err on the side of safety in the computation of health and safety* [and environmental] *costs and benefits.*

In all cases, this proportion factor must be greater than 1, otherwise, there is an implication of a bias against health and safety and / or the environment. While the HSE does not provide guidance on the level that would be considered *gross* when assessing mitigation measures for different scenarios, it does refer to the Nuclear Safety Directorate's approach which applies the following proportion factors:

- a factor of 2 for low risks to members of the public;
- a factor of up to 3 for risks to workers;
- a factor of 10 for high risks.

For risks that are considered intolerable or unacceptable, the proportion factor should be at least 10. In other words, proportion factors greater than 10 are considered to be grossly disproportionate and would not justify expenditure on a mitigation measure.

8.1.3.2 Commission for Regulation of Utilities

As part of its functions under the Petroleum Safety Framework and the Gas Safety Regulatory Framework, the Commission for Regulation of Utilities (CRU) published guidance[50] on the concepts of gross disproportion and as low as reasonably practicable (ALARP) (originally in 2015 and updated in 2016). The guidance describes applying these concepts in assessing risk, noting:

> *… the ALARP principle arises from the fact that boundless time, effort and money could be spent in the attempt to reduce a risk to zero, but that some limit must be placed on how far a duty holder must go to discharge their duty, otherwise economic activity would cease, and this limit is defined to be one of reasonable practicability. What is reasonably practicable in any given situation will be determined by the facts of the case.*

Once an assessment has been carried out, reasonable practicability may be shown by demonstrating that the residual risk is negligible, or by means of a cost benefit analysis showing the balance between the cost and the benefit. As in the case of the UK HSE's guidance, the CRU also utilises the concept of gross disproportion and the gross disproportion factor (GDF) when assessing the outputs from a cost benefit analysis.

> *A value of at least 2 for the GDF is required, with a robust justification required to use a GDF of less than 10.*

8.1.3.3 Other Member States

The focus of the HSE and CRU guidance is typically on single-point (acute) events, albeit they can also be applied to risks to people and the environment where there may be a long delay between first exposure and the manifestation of undesirable symptoms, e.g. developing chronic respiratory issues due to long-term inhalation of toxic pollutants emanating from buses.

Proportion factors are also used by Integrated Pollution Control licensed operators undertaking cost-benefit analysis as part of a request for derogation[51] from certain emission limit values. A report for the European Commission on applying derogations to Article 15(4) of the Industrial Emission Directive (41) summarises the approaches that several Member States have adopted to determine the disproportionality between benefits and costs.

Overall, the report noted that Member States use different approaches to assess disproportionality, with fixed cut-off values used to give a direction of the disproportionality and to make a final decision on the derogation request in certain jurisdictions. Such cut-off values can be useful as they can ensure consistency in decision-making over time, between sectors and regions. However, the report also noted that a range of additional factors are important to consider in the final decision, such as local socio-economic conditions, the operator's history of investment, consistency with other operators in the sector and compliance with other relevant European and National legislation and environmental quality standards.

Detailed information on methodologies were provided by Czechia, France, Poland, Slovakia and the UK.

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[50] *ALARP Guidance: Part of the Petroleum Safety Framework and the Gas Safety Regulatory Framework* (CRU, 2017)

[51] Article 15(4) of the *Industrial Emissions Directive* allows, under certain conditions, setting a less stringent emission limit value (ELV) that exceeds proposed, or existing, EU best available techniques guidance.

- In the UK, Natural Resources Wales indicate that a BCR of less than 0.75 is considered disproportionate[52], while the Environment Agency and the Scottish Environmental Protection Agency acknowledge that monetising costs and benefits have high uncertainty, and that disproportionality should only be partially assessed by cost benefit analysis tools and should include a sensitivity analysis.
- The approach developed by Poland for the evaluation of derogations refers to a fixed cut-off value (a benefit to cost ratio of 0.7[53]). This value is used as a reference value only. If clear arguments exist or other factors are to be considered, a different cut-off value could be applied.

The European Commission Directorate-General's report also noted that in its response, Ireland advised that "it is recommended that the operator should use standardised methodologies e.g. cost benefit analysis".

8.1.4 Discount Rate

The DTTAS Common Appraisal Framework for Transport Projects and Programmes (CAF) (42) refers to Section E of the Department of Public Expenditure and Reform's (DPER) Public Spending Code[54], which specifies a discount rate of 5%. The Public Spending Code has been recently amended by new DPER guidance (38), which specifies a discount rate of 4%. The underlying methodology[55] for calculating the discount rate uses the social rate of time preference[56] to derive the discount rate, but it makes no reference to changes in spending preferences when there is a risk to an individual's health.

Guidance published by the UK Treasury (39) recommends that future costs and benefits are discounted by the social rate of time preference (3.5%); however, it considers that individuals place an increased value on health and safety benefits as their living standards increase (which could also be applied to environmental benefits) and thus consider that an effective annual discount rate of 1.5% should be applied for evaluating the risk to health and life. We have applied this value in our analysis.

8.1.5 Capital Costs

There are two broad approaches to representing the capital costs. The first is to assume the capital costs are incurred in the first year; the second is to assume the capital costs are incurred over the lifetime of the project (or a proportion of the project), to reflect how the project may be financed. The former yields a higher present value cost compared to the latter and is applied in this analysis.

[52] Equivalent to a proportion factor of (approximately) 1.33.

[53] Equivalent to a proportion factor of (approximately) 1.43.

[54] https://publicspendingcode.per.gov.ie/

[55] The underlying methodology is set out in the *How can we improve evaluation methods for public infrastructure* (ESRI Economic Renewal Series No. 2, 2011)

[56] The social rate of time preference is a core principle used to develop the discount rate. It is a measure of society's willingness to postpone private consumption now in order to consume later.

8.1.6 Damage costs

8.1.6.1 Air Quality

For certain environmental parameters there are published data on the 'damage cost' associated with emissions to atmosphere. We have examined three data sources:

1. An EU-commissioned report: *Damages per tonne emission of $PM_{2.5}$, NH_3, SO_2, NO_X and VOCs from each EU25 Member State (excluding Cyprus) and surrounding seas,* prepared by AEA Technology Environment in 2005 as part of the Clean Air for Europe Programme (43).
2. *Public Spending Code: Central Technical References and Economic Appraisal Parameters (PSC),* DPER, 2019[57] (38).
3. A study supported by the EPA's STRIVE program: *Air Pollutant Marginal Damage Values: Guidebook for Ireland* (16).

The European Commission funded report provides damage cost estimates per tonne of emissions and distinguishes between the impacts on different countries, sea areas, and between urban and rural emissions, considering both health and environmental (crop damage) impacts. The estimated damage costs for Ireland for each pollutant are outlined in Table 32.

Table 32: Marginal damage costs for Ireland

Pollutant	Range of marginal damage costs (€ per tonne)
NH_3	2,767 – 7,876
NO_X	4,044 – 11,707
$PM_{2.5}$	15,964 – 44,699
SO_2	5,108 – 14,900
Note: Escalated from 2010 values to March 2019 values using the Consumer Price Index.	

The DPER PSC report sets out guidance on monetising the impact of emissions; the damage costs are set out in Table 33.

[57] This publication supersedes elements of the *Common Appraisal Framework for Transport Projects and Programmes* (CAF) published by DTTAS in 2016.

Table 33: Cost of emissions

Pollutant	Location	Damage cost (€ per tonne)
NMVOCs	All Areas	1,398
NO_X		5,688
SO_X		6,959
$PM_{2.5}$	Urban	194,660
	Suburban	47,420
	Rural	16,512

The EnvEcon report considers a comprehensive range of factors when calculating damage costs and is intended specifically for use in Ireland. The damage values account for the following and are set out in Table 34:

- direct health damage (mortality and morbidity) caused by particulates, NO_X and ozone;
- biomass loss caused by ozone (crops, coniferous forests, deciduous forests and semi-natural lands);
- eutrophication and acidification of natural areas by NO_X, NH_3 and SO_2;
- secondary PM health impacts for NO_X, NH_3, SO_2 and VOC.

Table 34: Aggregate marginal damage values

Location	NO_X	$PM_{2.5}$	NH_3	SO_2	NMVOC
Ireland all	1,064	7,982	878	5,135	931
Ireland rural	984	7,024	692	5,135	905
Urban large (Dublin)	9,951	71,998	14,022	10,962	2,847
Urban medium (population ≥ 15,000)	1,650	24,292	3,512	5,055	1,650
Urban small (population 10,000 - 15,000)	1,463	15,751	1,596	5,614	1,437
Small towns (population < 10,000)	1,224	10,270	1,117	5,029	1,091
Note 1: Escalated from 2010 values to March 2019 values using the Consumer Price Index.					

As the trials were carried out in urban areas, we consider the 'Urban large (Dublin)' values used in the EnvEcon report to be the most appropriate damage values and have applied these in this analysis. We have used the values provided in the two other reports in a sensitivity analysis (carried out in Sections 8.2.6 and 8.3.6), in order to compare the impact of changing the damage values on our findings.

8.1.6.2 Greenhouse Gases

The DPER PSC report sets out guidance on monetising the impact of GHG emissions; the damage costs for the period 2019 to 2032 are set out in Table 35 for the non-emission trading sector.

Table 35: Damage costs

	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
€/tCO_{2eq}	20	32	39	46	52	59	66	73	80	86	93	100	105	110

8.1.7 Shadow Prices

The DTTAS's CAF includes for shadow pricing when assessing transport projects. A shadow price is a monetary value assigned to resources (labour, public funds and carbon) on projects that don't have a known or easily identifiable market value. The estimated value of the shadow price of public funds is 130%; the shadow price of carbon is set out in Section 8.1.6.2.

8.2 Cost-Benefit Analysis: SCR system

8.2.1 Overview

Two diesel buses were retrofitted by Eminox with SCR technology and tested under the same conditions before and after the retrofit. The purpose of doing so was to examine the performance of the buses under real-world driving conditions and determine if SCR should be installed on some of the Dublin Bus fleet. In this first cost-benefit analysis, we examine the merits of installing the SCR system on buses operating in Dublin.

8.2.2 Costs

8.2.2.1 Capital Costs

Based on data provided by Eminox, the cost of purchasing an SCR system, including installation, is approximately €26,720 (£23,500 – March 2019 conversion). We have assumed that the capital costs are incurred in the first year.

8.2.2.2 Operating Costs

The system converts NO_X into nitrogen and water by adding urea (AdBlue) to the exhaust gas in the presence of a catalyst. Data from the *Eminox Telemetry Hub*[58] for the period 21st March 2019 to 25th April 2019 recorded average AdBlue consumption of 0.042 l/km for the Diesel 1 Euro IV bus and 0.035 l/km for the Diesel 2 Euro V bus[59].

[58] As part of its contract with DTTAS, Eminox facilitates real-time performance monitoring of the retrofitted vehicles via the *Eminox Telemetry Hub.*

[59] To put this in context, the average AdBlue consumption for Dublin Bus's Euro VI fleet is 0.019 l/km (53 km/l).

Dublin Bus advised that AdBlue costs €0.18/litre (excluding VAT). Therefore, based on annual mileage of approximately 57,000 km each year, the annual cost of supplying AdBlue for a Euro IV bus is €426 and is €356 for a Euro V.

8.2.2.3 Maintenance Costs

The SCR system will give rise to additional routine maintenance and there will be non-routine equipment breakdowns. The Eminox SCR training manual advises that low temperature operation, which was observed during the bus trials (discussed in Section 5.5.2.1), leads to more frequent filter servicing and faster degradation of catalyst performance.

While we did not gather data on the likely additional costs, it will be seen in Section 8.2.6 that unless these costs are extremely high, it is likely they will have little impact on the findings.

8.2.2.4 Shadow Price of Public Funds

As there is only one product being considered in this assessment, and DTTAS has an approximate unit price, shadow pricing has not been applied in this instance.

8.2.3 Benefits

The environmental benefits of installing an SCR system arise primarily from reduced NO_X emissions. Table 36 details the findings from the trials and compares the NO_X emission pre-and post-retrofit.

Table 36: Environmental benefit of installing SCR system (NO_X emissions)

Case	Unit	Euro IV	Euro V	Source
Business as usual Note 1	g/km	10.72	10.87	EA Final Report – average Dublin emissions, excluding cold starts, for the Diesel 1 Euro IV and Diesel 2 Euro V buses
SCR system installed	g/km	4.69	8.56 Note 2	Euro IV: EA Final Report (as above) Euro V: Eminox Telemetry Hub – average Dublin emissions for additional tests carried out on 24th & 25th April 2019 on the Diesel 2 Euro V bus Note 3
Environmental benefit Note 4	g/km	6.03	2.30	-
	t/y	0.39	0.15	Buses travel approximately 57,000 km per year

Note 1: The Diesel 1 Euro IV and Diesel 2 Euro V buses use a diesel oxidation catalyst and SCR system to reduce CO, HC and NO_X emissions (PM and PN are not controlled). These systems were removed prior to installing the Eminox SCR system on the two buses.

Note 2: The Eminox SCR system, under current system settings, was not as effective at reducing NO_X emissions on the Diesel 2 Euro V bus in comparison to the Diesel 1 Euro IV bus. Following the trials, further data was gathered from the Eminox telemetry hub: for the period 13th May 2019 to 20th May 2019, the SCR system on the Diesel 1 Euro IV bus emitted 5.9 g NO_X/km on average, whereas the Diesel 2 Euro V bus averaged 7.5 g NO_X/km.

Note 3: The NO_X sensors on the Eminox SCR system activate once the system reaches 200°C. In general, a period of approximately 10-minutes elapses before this occurs; thus, there is limited data captured during the 'cold start' phase.

Note 4: The NO_X emission reductions claimed by Eminox on the *Telemetry Hub* will differ from those shown because Eminox savings are based on the difference between the inlet and outlet measurements of its SCR system whereas the NO_X savings in this table are based on the difference between the pre- and post-retrofit tests (in both cases, the buses operated with emission reduction systems – see Note 1).

If the SCR system was installed, the annual NO_X emissions would reduce by approximately 0.4 tonnes per year for a Euro IV bus, and approximately 0.15 tonnes for a Euro V. These reductions represent the environmental benefit of installing the SCR system.

It is possible that the NO_X emissions could be further reduced on Euro V buses by adjusting the AdBlue dosing rate. It is evident from Eminox's telemetry data that the Diesel 1 Euro IV bus is consuming more AdBlue than the Diesel 2 Euro V bus (0.042 l/km versus 0.035 l/km), and the NO_X emissions are notably lower. We have examined the impact of varying the NO_X emission rate on the findings from the cost benefit in a sensitivity analysis (set out in Section 8.2.6).

8.2.4 Appraisal Period

The CAF advises that road and rail infrastructure projects should be evaluated over a thirty-year period whereas shorter-lived projects should be appraised over the life-time of the asset.

Dublin Bus has 721 buses that do not meet the Euro VI standard (shown in Table 1). Based on a replacement rate of 100 buses per year and assuming the older buses will be replaced first, we have assumed a lifetime of four years for operating the SCR system on a Euro IV bus, and six years for a Euro V bus.

8.2.5 Analysis

Based on the estimated costs and benefits described in Sections 8.2.2 and 8.2.3, and the system lifetime set out in Section 8.2.4, the net present value for both the costs and benefits can be estimated using the BCR approach set out in Section 8.1.2. Table 37 summarises the inputs to the cost benefit analysis.

Table 37: Cost Benefit Analysis for SCR system

Input variable		Euro IV	Euro V
Capital cost (€)		26,720	26,720
Operating cost (€/year)		426	356
NO_x emissions savings with SCR system installed (g/km)		6.03	2.30
Environmental benefit (€/tonne NO_X)		9,951	9,951
System lifetime (years)		4	6
Discount rate (%)		1.5	1.5
Present value	Costs	€27,965	€28,352
	Benefits	€13,185	€7,443
Proportion factor		2.1	3.8

Based on guidance set out in Section 8.1.3, a proportion factor greater than 1.33 – 2 is required for an investment in this type of project to be considered disproportionate (or greater than 10 to be considered grossly disproportionate). The estimated proportion factor for a Euro IV bus (2.1) suggests that the investment is close to being justifiable and a Euro V (3.8) is such that the investment costs may be considered disproportionate to the benefits gained.

There is, however, varying levels of uncertainty associated with the input values used to carry out the analysis. We have carried out a sensitivity analysis to examine the extent of the impact on the CBA of changing the input values (e.g. capital costs, discount rates, damage costs).

8.2.6 Sensitivity Analysis

For the sensitivity analysis, we apply upper and lower values for each of the parameters using the following assumptions.

- *Capital costs:* we discounted the cost of the SCR system (€26,720) by 10%, to account for economies of scale for purchasing multiple units (the lower cost is also spread evenly over the lifetime of the system instead of being incurred in the first year). Although we stated in Section 8.1.7 that shadow pricing was not applicable in determining the cost of the SCR system, we have applied the shadow pricing factor (1.3) to obtain an upper cost value to demonstrate its impact on the overall analysis.
- *Operating costs:* the minimum and maximum AdBlue consumption values measured for each bus during the period 21st March 2019 to 25th April 2019 were used.

- *NO_X emission savings:* a range of input values were assessed, including the DTTAS NO_X emission factor[60], EA's pre- and post-retrofit data, and data from the Eminox Telemetry Hub.
- *Environmental benefit*: the DTTAS CAF (lower) and EU CAFÉ study (upper) NO_X emission damage values, as shown in Table 38, were applied.
- *System lifetime*: we've assumed the SCR system will operate for between 1 and 12 years.
- *Discount rate*: a lower value of 0% and a higher value of 4% were used (refer to Section 8.1.4).

Table 38: Sensitivity Analysis for SCR system

Parameter	Euro IV		Euro V	
	Central value	Range	Central value	Range
Capital cost (€)	26,720	24,048 – 34,735	26,720	24,048 – 34,735
Operating cost (€/yr)	426	260 – 734	356	247 – 622
NO_X emissions savings with SCR system installed (g/km)	6.03	4.53 – 7.14	2.30	0.65 – 4.97
Environmental benefit (€/tonne NO_X)	9,951	5,688 – 11,707	9,951	5,688 – 11,707
System lifetime (yrs)	4	1 – 12	6	1 – 12
Discount rate (%)	1.5	0.0 – 4.0	1.5	0.0 – 4.0

Figure 22 (Euro IV) and Figure 23 (Euro V) show the impact on the proportion factor of varying each input parameter – the horizontal bars show the proportion factor range. For example, a system lifetime of 1 year equates to a proportion factor of 7.9 for a Euro IV bus, whereas a lifetime of 12 years equates to a proportion factor of 0.8. In this case, the more conservative estimate (12 years) yields a proportion factor that would be considered justifiable.

[60] DTTAS CAF: Table A.15 – NO_X emission factors (g/km), 2013

Figure 22: Sensitivity analysis for Euro IV bus

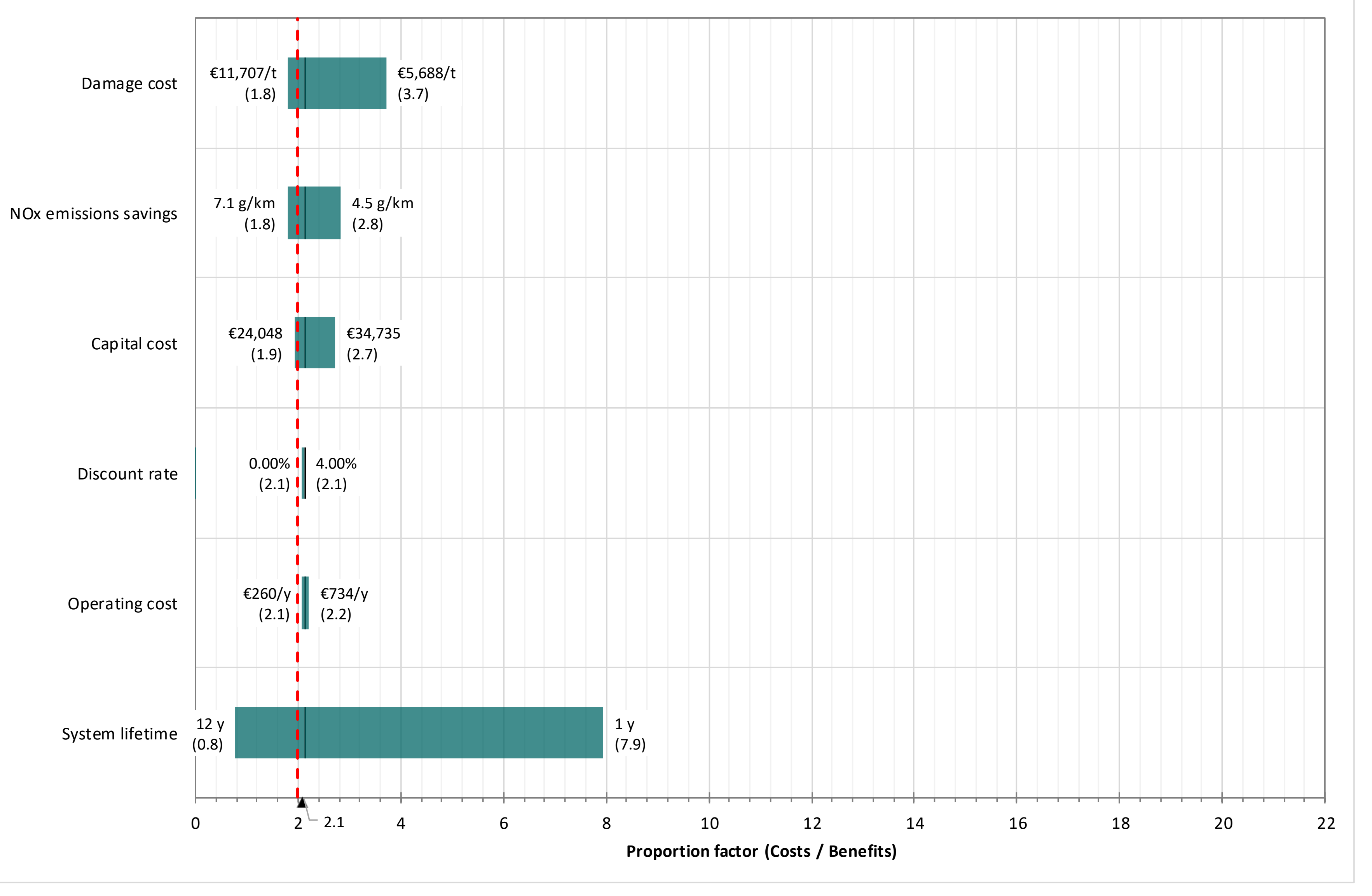


Figure 23: Sensitivity analysis for Euro V bus

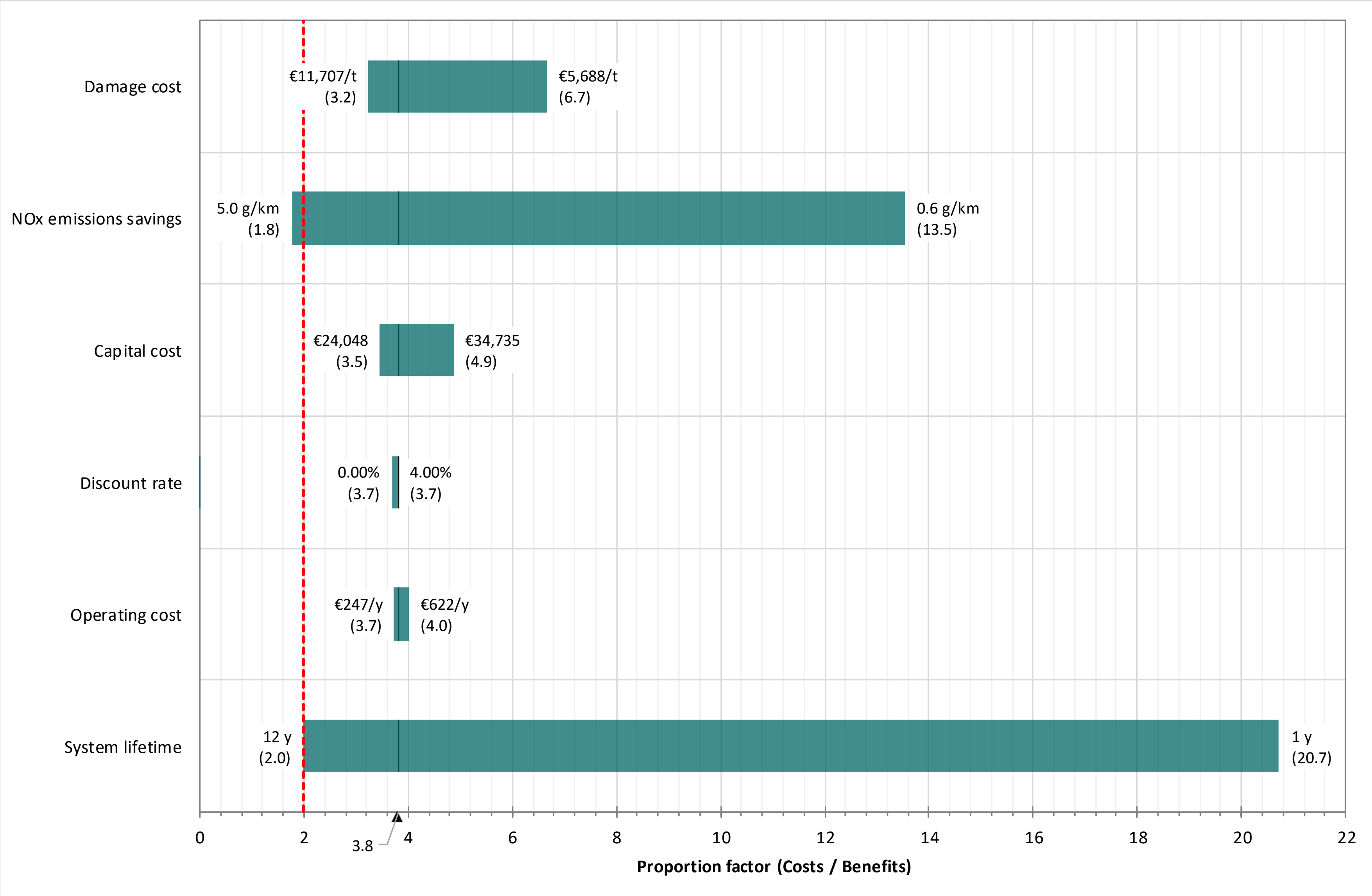


Figure 22 and Figure 23 show that the biggest influence on the proportion factor for the two buses is the SCR system lifetime. The NO_X damage costs and emission reductions achieved by the SCR system, particularly for a Euro V bus, are also important factors. The capital cost of the SCR system, its operating costs, and the discount rates have less of an impact.

Given that many Euro V buses have been in operation since 2012, and have an estimated operational life of 12 years, it would not be expected that Euro V buses would remain in service until 2031 (19 years in service). Notwithstanding this, there are 289 Euro III buses (22% of the Dublin Bus fleet) in operation, many of which are more than 12 years old. We also understand that some multi-axle Euro V buses may be more valuable than the standard two-axle buses and thus may have a longer expected life. In a scenario in which the NO_X emission savings could be increased to 6 g/km (similar to savings achieved by the retrofitted Diesel 1 Euro IV bus), operating an SCR system for greater than 4.2 years would give a proportion factor of 2 – operating it for longer would reduce the proportion factor further.

8.2.7 Additional Considerations

As discussed in Section 5.5.2.1, when the Diesel 2 Euro V bus was initially tested following the installation of the SCR system, EA data showed that NO_X emissions increased relative to the pre-retrofit tests. Eminox resolved the issue by adjusting the AdBlue dosing rate at lower exhaust temperatures. Subsequent testing demonstrated that a reduction in NO_X emissions was achieved by the system; however, this adjustment introduces a potential secondary issue: ammonia (NH_3) slippage.

The Eminox training manual states that urea deposits are created if too much AdBlue is injected under the wrong conditions and with poor mixing. This can result in uncontrolled releases of NH_3 at higher temperatures, i.e. ammonia slip. Eminox advises that complete hydrolysis of AdBlue is required to avoid deposits and its equipment employs several control measures to prevent deposits: accurate dosing strategy using system sensors and calibration, a mixing section to ensure even distribution across the catalyst face and an optimised injector design. However, NH_3 is not monitored by the SCR system so it is not possible to confirm if NH_3 slip is prevented by the SCR system.

8.3 Cost-Benefit Analysis: Alternative-Fuelled vs Diesel Buses

8.3.1 Overview

The Government has committed to transitioning to a low emission urban public bus fleet to tackle transport emissions. Diesel-only buses, as of July 2019, will no longer be purchased for the urban public bus fleet. The purpose of this assessment is to examine potential investment options by comparing the associated costs and benefits.

Unlike the cost-benefit analysis on the SCR system, in this case we are examining four different technologies. In addition, three of the technologies can run alternative fuels, which have different characteristics. For example, the CNG buses can operate on natural gas (a fossil fuel) or biomethane (a renewable fuel). Thus, the assessment is more complicated. We have selected fourteen different fleet investment options, as set out in Table 39, as a basis for comparing the technology and alternative fuel options available.

Table 39: Fleet investment options

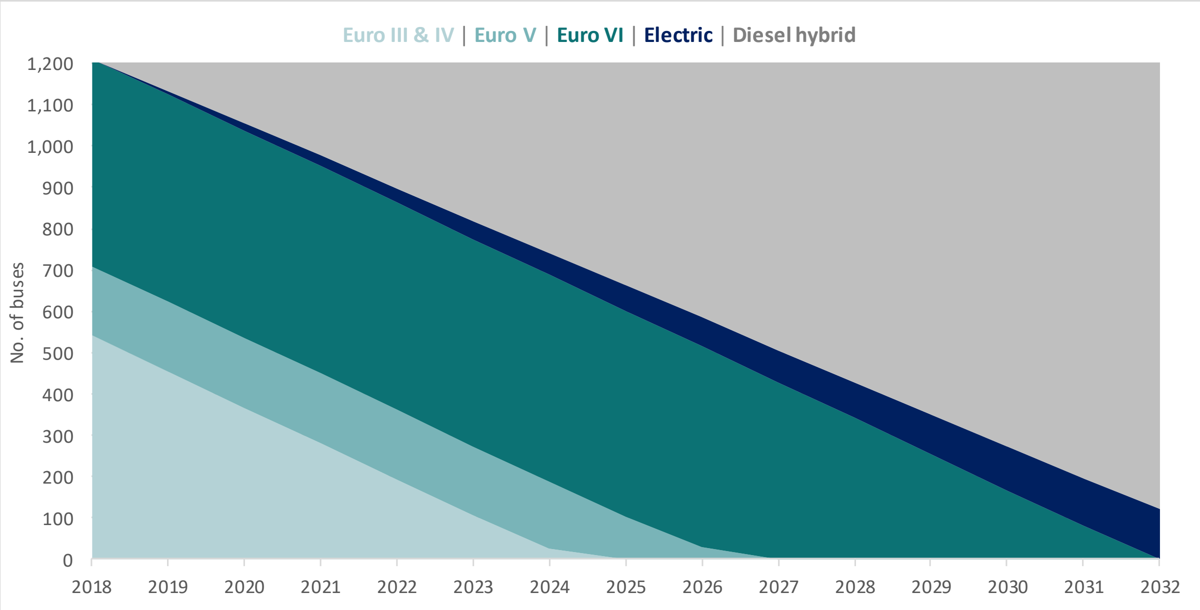
ID	Option
1	10% electric; 90% diesel hybrid
2	50% electric; 50% diesel hybrid
3	100% electric
4	10% CNG; 90% diesel hybrid
5	50% CNG; 50% diesel hybrid
6	100% CNG
7	10% bioCNG; 90% diesel hybrid
8	50% bioCNG; 50% diesel hybrid
9	100% bioCNG
10	10% diesel hybrid (HVO fuel); 90% diesel hybrid
11	40% diesel hybrid (HVO fuel); 60% diesel hybrid
12	100% diesel hybrid (HVO fuel)
13	100% diesel hybrid
14	65% CNG; 35% bioCNG

In general, the base case is often a ‘do nothing’ scenario, i.e. defer investment and continue with the existing operation; however, since the public fleet is upgraded on a yearly basis, we have assumed a base case where the current fleet is replaced over time until it is comprised entirely of Euro VI diesel buses (we assume this occurs in 2032[61]). For the purposes of this analysis, we have also assumed that the size of the fleet remains the same.

To model each scenario, we assume that the NTA continues to purchase new buses at approximately 90 buses per year and the buses purchased correspond to the investment options set out in Table 39. For example, for option 1, if 90 buses are purchased in year 1, 9 will be electric and the remainder (81) will be diesel hybrids. The changing make-up of the fleet for option 1 is presented in Figure 24.

[61] Dublin Bus vehicles typically travel 57,000 km each year. The original Clean Vehicles Directive (2009/33/EC) suggests a lifetime mileage of 800,000 km for buses; thus, we’ve assumed that the current fleet will be turned over every 14 years i.e. 1/14th of the fleet will be replaced with newer buses each year. This is in keeping with the data for the Dublin Bus fleet which has an average age of approximately 7 years.

Figure 24: Example of a changing urban public bus fleet for investment option 1, 2018 – 2032



8.3.2 Costs

8.3.2.1 Capital Costs

Buses

The estimated prices of double deck buses are set out in Table 40 (based on data provided by the NTA).

Table 40: Bus prices (approximate)

Technology	Price (ex VAT)
Diesel (Euro VI)	€270,000
Diesel hybrid (Euro VI)	€390,000
CNG	€310,000
Electric	€530,000

Technology improvements and increased demand for alternative-fuel bus technologies will result in reductions in the price gap between the different technologies over time. We assume a linear decrease to zero, for all technologies, by 2032, i.e. price parity will be achieved in 2032 between diesel, CNG, hybrid and electric buses. While this is a relatively broad and simplifying assumption, there is no doubt that if these technologies become more popular, economies of scale will reduce the prices. This, in turn, will reduce the influence price will have on the investment decisions. (According to a Bloomberg report on electric vehicles (44), electric cars will achieve price parity with ICE vehicles in the EU between 2025 and 2029.)

Fuelling infrastructure

There are no additional infrastructure requirements associated with purchasing diesel hybrid buses as the batteries are charged by the kinetic energy generated during braking and coasting[62].

For a small fleet of CNG buses (10 to 20 buses), it may be possible to meet ongoing fuel requirements via road tankers or by using existing CNG filling stations (e.g. Circle K Dublin Port or GNI's facility in Cork City). Neither option is likely to appeal to a bus operator. Unless the bus depot is adjacent to the filling station, it will add additional cost (both fuel and staff time). Thus, we consider on-site fuelling to be a requirement if there is an investment in CNG buses.

GNI estimates a total cost of installing a fuelling station for up to 100 buses, including design, project management and grid connection, of approximately €1.4m. A similar-sized station was opened in Bristol in mid-2019, which currently serves 22 buses (77 additional buses are planned by April 2020). The cost of this facility was £0.96m. Based on the GNI and Bristol data, we have assumed that a CNG filling station will cost approximately €1.25m.

Dublin Bus has seven bus depots (Donnybrook, Ringsend, Conyngham Road, Summerhill, Clontarf, Phibsboro and Harristown), which cater for over 1,000 buses (three of the depots – Donnybrook, Phibsboro and Harristown – each cater for approximately 200 buses). In addition, Bus Éireann has depots in Cork, Galway, Limerick and Waterford, which collectively store over 200 buses. If an investment in a full fleet of gas buses is made, we estimate that up to 14 CNG filling stations will be required to service these depots.

There are several methods of charging electric buses: charging stations; opportunity charging/charging lanes; and battery swapping. We only consider depot charging stations in this CBA. Opportunity charging and battery swapping are costly and complex solutions that would need to be considered as part of a national strategy for electric buses.

The current power requirement for electric bus charging stations is in the region of 50-80 kW per bus. Based on data from Iceland (see Section 6.6), an NTA low emission vehicle market consultation (45) and a recent *Journal of Cleaner Production* paper (46), we estimate the cost of electric bus charging infrastructure is approximately €18,250 per bus, albeit during normal operation it is unlikely that all buses will be charged at the same time. We have assumed a bus charger to electric bus ratio of 0.75 for this CBA, i.e. for every four electric buses purchased, three chargers are also purchased.

We have not considered electricity or gas grid connection charges, or potential network capacity upgrades, as part of this assessment.

8.3.2.2 Operating Costs

Maintenance

The maintenance costs associated with each technology are set out in Table 41. The data was sourced from an NTA market consultation report completed in 2017 (45).

[62] An alternative to a 'diesel hybrid' bus is a 'plug-in hybrid' bus, which comprises a larger battery pack, along with a small diesel tank, to power an electric motor. These buses can drive for longer periods on electrical power alone; however, an external energy source is required to fully recharge the batteries (the buses are also designed with re-generative braking systems to improve efficiency).

Table 41: Annual maintenance costs

Technology	Cost per bus (ex VAT)
Diesel (Euro VI)	€10,344
Diesel hybrid (Euro VI)	€14,196
CNG	€10,344
Electric	€17,714 [Note]
Note: Includes battery replacement costs.	

We assume that price parity will be achieved across all technologies by 2032 (as per the bus purchase costs). This is to account for cost efficiencies from scaled deployment of these technologies and more widely available maintenance expertise.

Fuel

Dublin Bus and Bus Éireann are state-owned companies and receive funding from the Irish Government for purchasing fuel. The funding covers the excise duty and VAT payments. As such, the cost to Ireland is simply the wholesale price[63] of the fuel. The unit cost for each fuel is set out in Table 42.

Table 42: Fuel prices

Item	Diesel	HVO[Note 1]	Natural gas (47) Note 2	BioCNG Note 3	Electricity – band ID (47) Note 4	Electricity – band IF & IG (47)
Wholesale price	0.511 (€/litre)	1.617 (€/litre)	0.021 (€/kWh)	0.071 (€/kWh)	0.108 (€/kWh)	0.092 (€/kWh)
Wholesale price (€/100 MJ)	1.418	4.492	0.593	1.982	2.986	2.542

Note 1: It is difficult to get the market prices paid for HVO. Anecdotal reports from industry suggest that the wholesale price of HVO could be up to twice that of biodiesel and the price fluctuates between seasons (cheaper in summer and more expensive in winter). We assessed HVO using a 75% mark-up on the biodiesel wholesale price, which was $1,050/tonne in August 2019 (48).

Note 2: We've assumed an equivalent unit price for band I4 & I5 since no price has been published for band I5.

Note 3: Average of GNI estimate (August 2019) and value from SEAI biomethane report (49).

Note 4: The band ID rate applies where annual electricity consumption does not exceed 20 GWh. When consumption exceeds this threshold, we've assumed the lower rate (band IF/IG) applies.

8.3.2.3 Shadow Price of Public Funds

A factor of 1.3 has been used as the shadow price of public funds, in line with recent DPER guidance (38).

[63] The wholesale price of a fuel is the price excluding all taxes (i.e. excise duty, carbon tax, levies and VAT)

8.3.3 Benefits

The potential environmental benefits, relative to the base case, are considered in the context of CO_{2eq} and NO_X emissions. CO_{2eq} and NO_X emission factors for each technology are set out in Sections 7.2.2 and 7.2.3. As the focus of the CBA is on emissions from a national perspective, we consider lifecycle CO_{2eq} emissions to be more appropriate for this analysis.

8.3.4 Appraisal Period

The CAF advises that road and rail infrastructure projects should be evaluated over a thirty-year period whereas shorter-lived projects should be appraised over the lifetime of the asset.

The assessment is considered over a 14-year period (2019 – 2032) for the reason outlined in Section 8.3.1.

8.3.5 Analysis

The findings from our analysis are set out in Table 43. (The inputs are summarised in Appendix 5).

It should be noted that as the purpose of the DTTAS bus trials is to examine alternative-fuel technologies that can assist with reducing emissions, investment options that do not offer environmental benefits relative to a diesel-only fleet are unlikely to be considered appropriate from a policy perspective. Therefore, proportion factors are not calculated for options that give rise to negative benefits.

Table 43: Cost Benefit Analysis for alternative-fuel buses (relative to base case investment)

ID	Option	Present value costs (with shadow pricing) (€m)	Present value benefits (€m)	Net present value (PV benefits minus PV costs)	Proportion factor
1	10% electric; 90% diesel hybrid	92.1	11.0	(81.1)	8.4
2	50% electric; 50% diesel hybrid	141.4	21.3	(120.0)	6.6
3	100% electric	202.8	34.3	(168.5)	5.9
4	10% CNG; 90% diesel hybrid	72.9	5.4	(67.5)	13.4
5	50% CNG; 50% diesel hybrid	51.3	(6.4)	(57.7)	Note
6	100% CNG	24.3	(21.2)	(45.5)	
7	10% bioCNG; 90% diesel hybrid	92.3	10.2	(82.1)	9.0
8	50% bioCNG; 50% diesel hybrid	148.3	17.5	(130.8)	8.5
9	100% bioCNG	218.2	26.5	(191.7)	8.2
10	10% diesel hybrid (HVO fuel); 90% diesel hybrid	97.2	11.6	(85.6)	8.4
11	40% diesel hybrid (HVO fuel); 60% diesel hybrid	153.8	21.4	(132.4)	7.2
12	100% diesel hybrid (HVO fuel)	266.9	40.8	(226.0)	6.5
13	100% diesel hybrid	78.3	8.4	(69.9)	9.3
14	65% CNG; 35% bioCNG	92.2	(4.5)	(96.7)	Note
Note: These options give rise to a negative benefit which means that the after investing in these technologies the investor is in position which is less rewarding than the base case.					

The key findings are:

- None of the options examined would give rise to a positive NPV, i.e. on purely an economic basis, none of the investments provide a better return than the base case.
- As it is national policy to stop purchasing diesel buses because of the negative impacts on the environment and human health, the options that give rise to negative benefits (i.e. the benefits derived have a negative impact on human health and the environment relative to the base case scenario) are not considered as eligible options.

- The analysis suggests that, in general, the following priority should be given to the technologies assessed:
    1. Electric
    2. HVO diesel hybrid
    3. BioCNG
    4. Diesel hybrid
    5. CNG
- All 14 options require greater investment than the base case option (replacing the current fleet with 100% Euro VI diesel buses).
- All but three options (50% CNG/diesel hybrid mix, 65% CNG/35% bioCNG mix and 100% CNG) provide environmental benefits.
- The three CNG options (no. 4, 5, 6) have the lowest NPVs, but either don't offer any environmental benefits (relative to the base case) or have a higher proportion factor than other investment options.
- Moving to a 100% HVO diesel hybrid fleet offers the greatest potential for environmental benefits but is also the most expensive option (primarily because of high fuel costs).
- While bioCNG performs well relative to the other options examined, biomethane is currently not available to the transport market in sufficient quantities to power Ireland's bus fleet.
- Five of the investment options (50% electric, 100% electric, 40% HVO hybrid, 100% HVO hybrid and 100% bioCNG) achieve the Climate Action Plan target (see Section 2.10) of a 45 to 50% reduction in GHG emissions by 2030, relative to the emissions for the baseline fleet in 2019 (105 kt CO_{2eq}).

As there are varying levels of uncertainty associated with the input parameters used, we have carried out a sensitivity analysis on the following three options to illustrate the sensitivity of each technology to changes in the input parameters: 100% electric, 100% HVO and 100% bioCNG. The inputs to the sensitivity analysis are provided in Appendix 6.

8.3.6 Sensitivity Analysis

The results from the sensitivity analysis are provided in Figure 25 (100% electric), Figure 26 (100% BioCNG) and Figure 27 (100% HVO). Each tornado diagram illustrates the impact on the proportion factor of varying each input parameter – the wider the horizontal bars, the greater the impact. In all cases, the proportion factor is calculated relative to the baseline fleet (100% Euro VI diesel).

Figure 25: Sensitivity analysis for 100% electric bus fleet

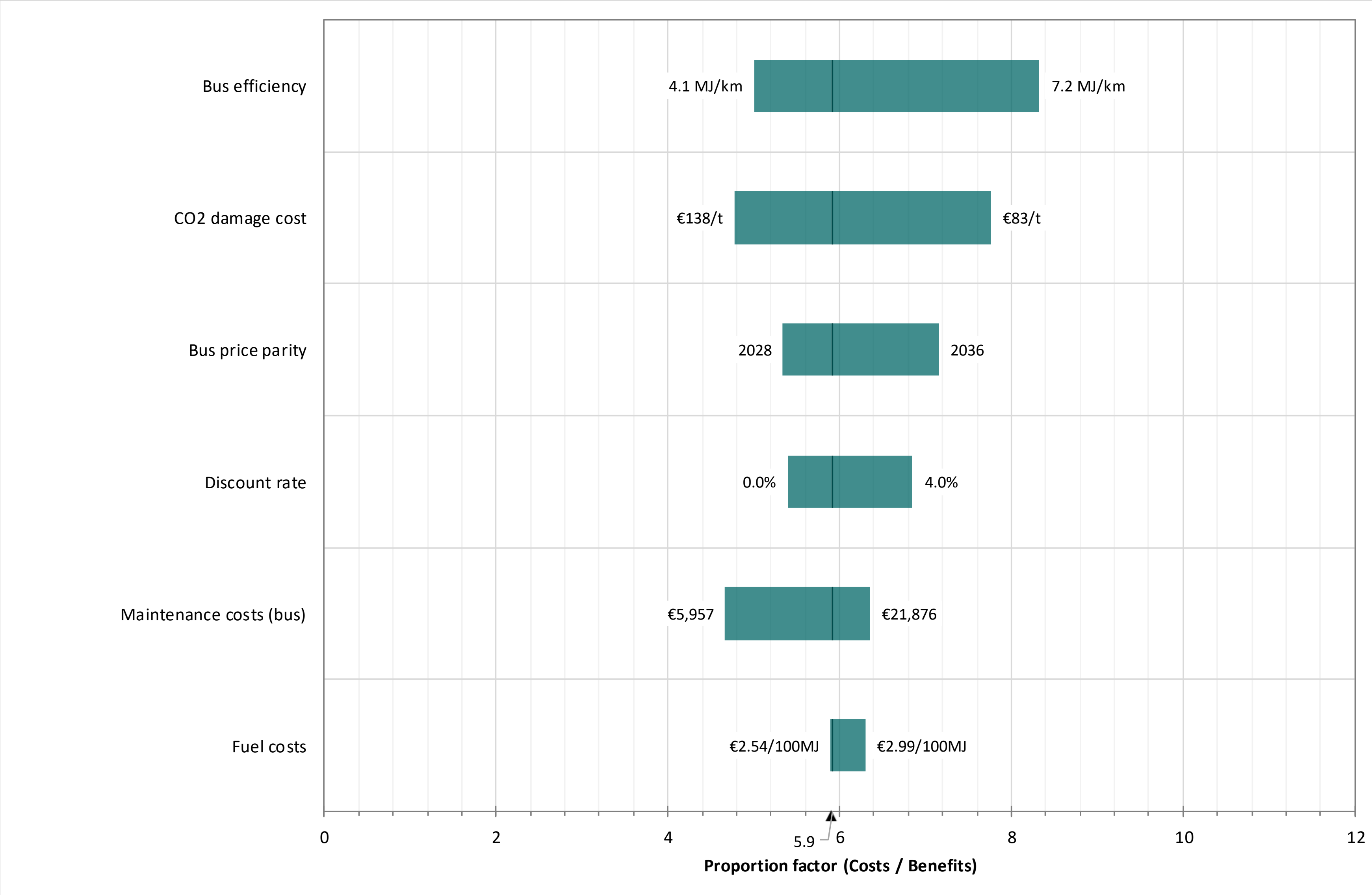


Figure 26: Sensitivity analysis for 100% BioCNG bus fleet

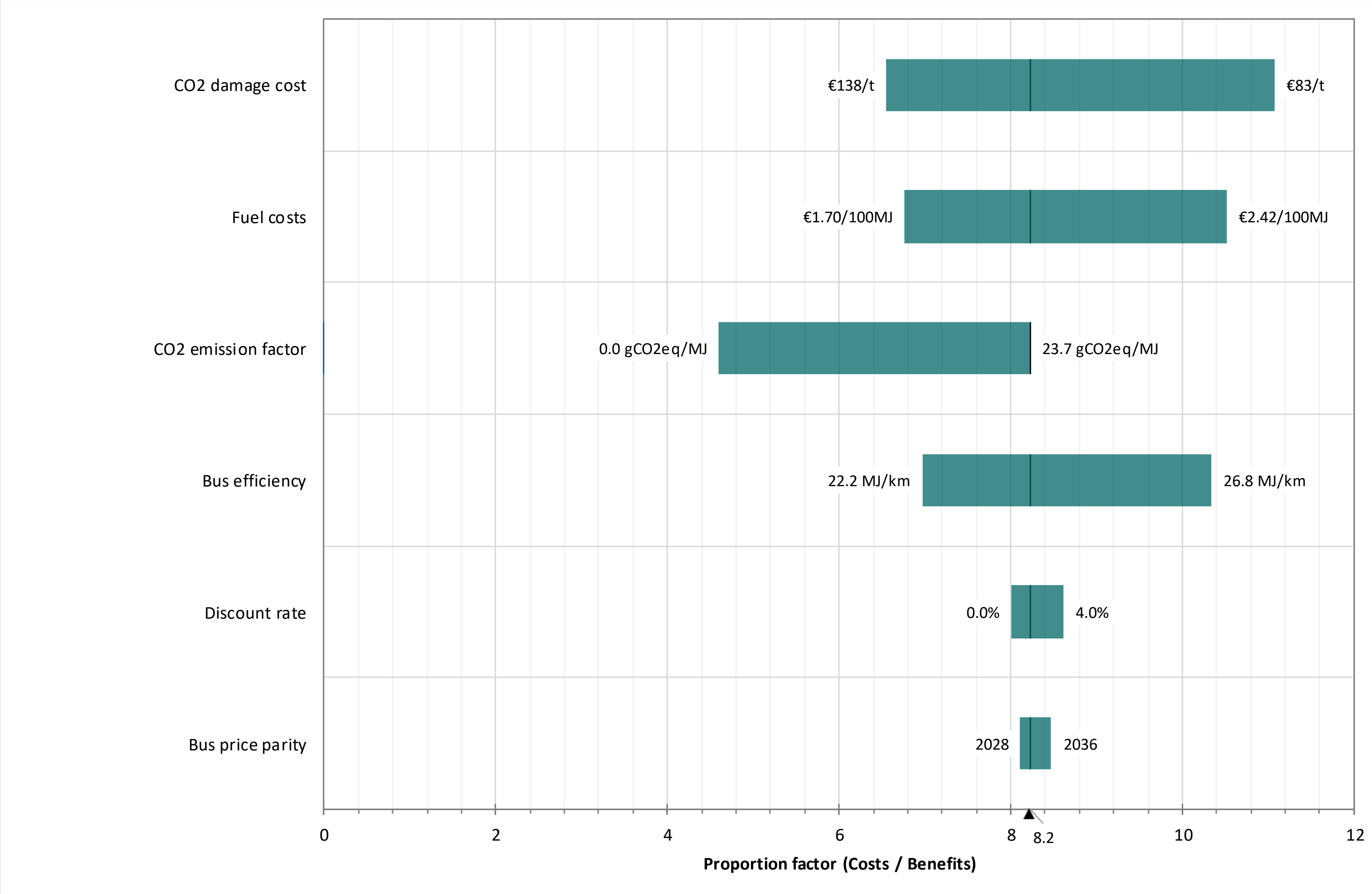


Figure 27: Sensitivity analysis for 100% HVO hybrid bus fleet

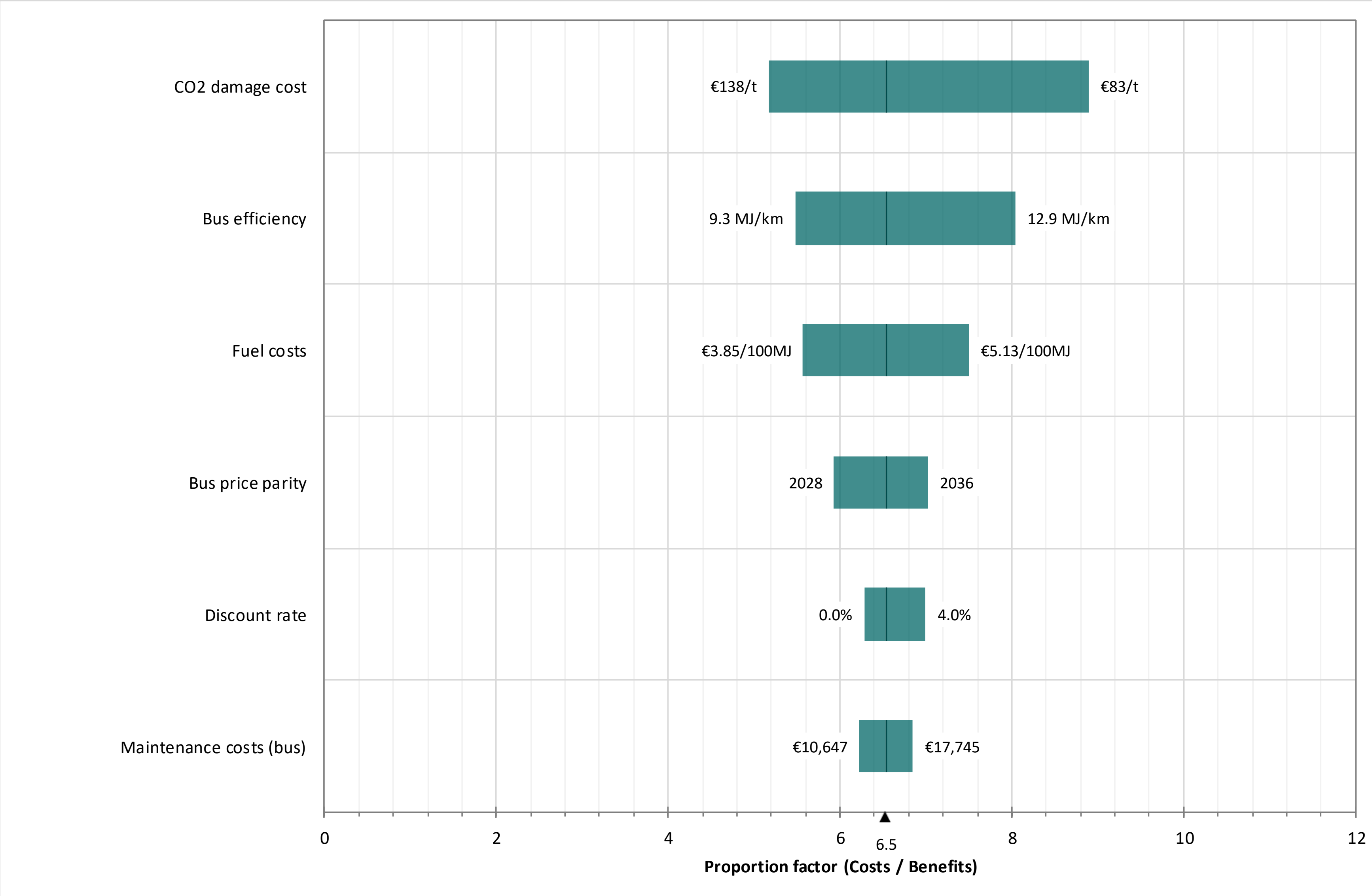


Figure 25, Figure 26 and Figure 27 show that the biggest influences on the proportion factor for bus fleets are the CO_2 damage costs, the efficiency of the vehicles and the fuel costs. The CO_{2eq} emission factor also has a significant influence on the bioCNG investment option. In our central scenario, we assume the biomethane is produced in an anaerobic digestion plant with closed digestion and with a 60:40 mix of wet manure and grass silage. By increasing the wet manure mix to 75%, the CO_{2eq} emission factor can be reduced to approximately 0 gCO_{2eq}/MJ (a wet manure mix in excess of 75% could result in a negative CO_{2eq} emission factor). Reducing the carbon intensity of bioCNG to 0 gCO_{2eq}/MJ reduces the proportion factor to 4.6 (the central scenario proportion is 8.2).

The discount rate, bus maintenance cost and bus purchase price are also important factors for each investment option. For electric buses, reduced maintenance costs could give a proportion factor of 4.6 (Appendix 6 sets out the rational for varying the input values). The NO_X damage cost and emission factor have less of an impact because much smaller quantities of NO_X are emitted relative to GHG emissions. Maintenance costs and GHG emission factors (for electric and HVO options), and the capital and operational costs associated with fuelling infrastructure also have less of an impact.

8.3.7 Additional Considerations

Promoting bioCNG and/or HVO buses as replacements for the diesel fleet offer opportunities for maximising the benefits to the environment, human health and Ireland's energy security[64]; however, there are several reasons why these two options would be difficult to introduce.

- The availability of the fuels – there is a limited supply of both in Ireland.

  While biogas is currently produced in very small quantities in Ireland and, in general, is used for heat and electricity generation, several steps are being taken to increase production and to make use of it in the transport sector. The Climate Action Plan sets out a variety of actions for promoting of biomethane, which includes setting a target for the quantity of biomethane to be injected to the grid by 2030, taking account of the domestic supplies of sustainable feedstock and the supports required, and developing a CNG fuelling network to support the uptake of CNG vehicles. However, supports for biogas and biomethane may not last for a long time. In 2016, the UK reduced subsidies by 5 to 10% for biomethane grid injection under its Renewable Heat Incentive (RHI) to reflect growing concern that certain feedstocks were competing with food crops for land. In 2014, Germany removed incentives for biogas production from energy crops and upgrading biogas to biomethane.

  In relation to HVO, it is not currently produced in Ireland. Anecdotal evidence from industry suggests that there are difficulties in sourcing the fuel due to its cost and limited production worldwide, albeit countries like Sweden are producing and consuming significant quantities in their public transport fleets (see Section 6.4.2). Whitegate refinery has produced HVO previously, so it is possible to manufacture in Ireland.

- As set out in Section 2.9, the recast Clean Vehicles Directive sets a zero-emission sub-target for buses. A varying percentage of buses purchased after 2021 must be 'clean', of which 50% must be zero-emission vehicles, i.e. buses without an ICE or with an ICE that emits less than 1 gCO_2/kWh. Neither HVO nor biomethane will meet this threshold (only electric and fuel cell technologies currently meet this minimum standard). It may be possible to use HVO or biomethane in 'clean' buses – in the case of HVO, it could not be blended with diesel.

[64] Ireland's energy import dependency in 2017 was 66%. The increased availability of bioCNG or HVO, produced from indigenous feedstocks, would assist with reducing this dependency.

9 CONCLUSIONS

9.1 DTTAS bus trials

The results from trials show that the electric buses are the most energy efficient and emit the least amount of NO_X (on a tailpipe basis). Notwithstanding this, electric buses are more carbon intensive than hybrid buses run on biodiesel or HVO. On a primary energy basis, the energy efficiency of electric buses is comparable with the diesel hybrids; however, with increasing renewable energy penetration on the electricity grid, it would be expected that the overall efficiency of electricity production will improve. This will in turn improve the primary energy efficiency of the electric buses and reduce lifecycle GHG emissions.

The CNG buses were the least energy efficient, and even though the carbon intensity of natural gas is less than that of diesel, CNG buses emit more CO_2 per kilometre travelled than the current bus fleet. The PEMS data also show that the carbon intensity of CNG is higher than the default values provided in the literature, which are typically based on methane. This is because the composition of natural gas varies (e.g. methane 90% – 98%, ethane 0.5% – 5%, CO_2 0% – 2%), which can give rise to higher CO_2 emissions.

The PEMS results also show that driver behaviour and traffic congestion can have a significant impact on energy efficiency and consequently CO_2 emissions – reducing the rate at which a driver accelerates/decelerates and/or reducing traffic congestion will improve both.

The CO_2 emissions from the hybrid buses were on average 20-25% lower than the Diesel 3 Euro VI bus (the baseline bus). However, somewhat surprisingly, NO_X and particulate emissions were typically higher for the hybrid buses relative to the Diesel 3 Euro VI bus. One reason for this could be that the Diesel 3 Euro VI bus has been procured and optimised for city-centre driving in Ireland, whereas several of the hybrid models were demonstration buses. Similar modifications to the hybrid buses, such as adjusting the dosing strategy for the existing hybrid bus configurations or employing a more sophisticated AdBlue dosing strategy (e.g. incorporating a second SCR or a lean NO_X trap), could yield reduced NO_X and particulate emissions It may also be possible to specify particular sections of a route along which the hybrid buses would operate in electric-only mode, to reduce emissions in areas where it is known that diesel engines have high emission levels.

Overall, particulate emissions were low, except for the Euro V pre-retrofit. It is likely that the DPF for this bus was not functioning correctly during these tests, which highlights the importance of regular DPF maintenance on diesel buses. The PEMS results show that the particulate emissions observed (excluding cold starts) were significantly below the particulate limit for passenger cars.

All hybrid and gas buses showed reduced CO emissions relative to the Diesel 3 Euro VI bus, except for some of the cold start tests on the CNG buses. The Diesel 3 Euro VI bus has significantly lower CO emissions than the older diesel buses.

In general, the findings from the PEMS testing and testing on the electric buses are in keeping with the findings from other similar trials and studies.

1. Electric buses are the most energy efficient (on a final energy basis), followed by hybrid and diesel buses – CNG buses are the least efficient.

2. Electric buses emit no tailpipe CO_2 emissions. Of the remaining technologies, diesel hybrid buses emit the lowest quantities of CO_2 per kilometre travelled. Even though the carbon intensity of natural gas is less than that of diesel, the energy efficiency of the CNG buses is such that the CO_2 emitted per kilometre is greater than the Euro VI diesel bus and the hybrid bus.

3. On a lifecycle CO_2 emission basis, electric buses perform the best, when compared with diesel hybrid buses and CNG buses run on fossil fuels (biofuels were not addressed in other trials or studies).

4. The performance of CNG buses and diesel buses vary with respect to NO_X emissions. In some cases, the data indicate that, relative to diesel buses, NO_X emissions can be marginally higher for CNG buses; in other cases, NO_X emissions from CNG buses are lower.

5. In general, the buses operated more efficiently in Dublin, and thus, had lower CO_2 emissions. CO emissions were similar in both cities. NO_X emissions were marginally higher in Dublin because the buses stopped more frequently, which reduced the exhaust temperature and the effectiveness of the SCR systems. The results show that the particulate emissions observed at both locations (excluding cold starts) were significantly below the particulate limit for passenger cars.

In relation to the buses fitted with SCR, the PEMS found that they still emitted significantly higher quantities of NO_X than the Diesel 3 Euro VI bus. The initial problems encountered with the SCR system (i.e. during the initial tests NO_X emissions from the Diesel 2 Euro V bus were higher with the SCR system installed than compared with the pre-retrofit tests) suggest that the standard settings on the Eminox SCR system are not suited to city-centre driving.

9.2 Contribution to renewable targets and emission reductions

RED II sets a 14% renewable energy target in transport for 2030. Given that public buses consume around 1% of national road transport energy, the potential contribution towards national renewable energy targets by increasing renewable energy in the public bus fleet is limited, as is reducing emissions. Notwithstanding this, increasing renewables in the public bus fleet will support achieving renewable energy and emissions reduction targets, as well as demonstrating leadership in the transport sector.

We examined several technology penetration scenarios (10% electric buses to 100% electric buses, 10% bioCNG to 100% bioCNG, and 10% HVO to 100% HVO in hybrid buses). The largest contribution to the 2030 renewable energy target would be delivered by gas buses run on 100% bioCNG: 1.4%. An entirely electric fleet would contribute, at most, 0.46%, and running a hybrid fleet entirely on HVO (or biodiesel) would contribute 0.75%. These results are, however, deceptive. Electric buses are the most energy efficient (on a final energy basis); thus, they consume less energy to perform the same work – gas buses are the least energy efficient. Therefore, gas buses, by virtue of consuming more renewable energy than the electric buses or the HVO hybrid buses, would contribute more to the 2030 renewable energy target.

While multiple counting of renewable energy supplied to electric buses and biofuels produced from wastes is allowed for in RED II, it gives a distorted view of the performance of the buses. In terms of reducing the GHG emissions from the transport fleet, biodiesel (produced from waste) currently achieves the largest reduction per kilometre travelled. Even though bioCNG has a very low carbon intensity, because gas buses require approximately 50% more energy to travel the same distance as diesel hybrid buses, the GHG emissions per kilometre are almost four-times those emitted by buses powered by biodiesel. Electric buses also emit more GHG emissions than biodiesel-powered buses. While the carbon intensity of electricity will reduce as the penetration of renewables on the grid increases, to achieve similar GHG emissions reductions as biodiesel, the grid emission factor would need to reduce by approximately 80%, which is very ambitious.

9.3 Air Quality

We estimate that the national bus fleet emits approximately 0.7% of Ireland's transport related NO_X. Under all the scenarios examined, there will be significant reductions in NO_X emissions by 2030 (greater than 80%). This is being driven to a large extent by transitioning the fleet away from older Euro IV and V engines to Euro VI hybrids. While moving to an electric fleet would eliminate tailpipe emissions of NO_X, the emissions associated with generating the electricity would remain.

In general, CO emissions for hybrid and gas buses were lower than the Euro VI bus (Diesel 3). The highest CO emissions were observed on the older diesel buses, particularly on cold start tests. Installing the SCR system on these buses reduced CO emissions to the Euro VI bus levels.

While particulate emissions from the pre-retrofit Diesel 2 Euro V bus were high, this was probably the result of a faulty DPF on the bus. Except for this result, the emissions observed (not including cold starts) were significantly below the PN limit for passenger cars.

9.4 Cost Benefit Analyses

Two costs benefit analyses have been carried out. In both, we adopted a benefit cost ratio (BCR) approach. In the first analysis, we examined the merits of an SCR system installed on two diesel buses. The estimated proportion factor for installing the SCR on the Euro IV bus was 2.1; this suggests the investment is close to being justifiable (a proportion factor of greater than 2 indicates the costs maybe disproportionate to the benefits). The proportion factor for the Euro V bus was 3.8, suggesting the costs may be disproportionate to the benefits gained.

The sensitivity analysis shows that the lifetime of the SCR has the greatest influence on the proportion factor. For the Euro IV, a lifetime of greater than 4 years will drop the proportion factor to below 2; for the Euro V, the lifetime of the SCR would need to increase to 12 years for the proportion factor to achieve a proportion factor of 2.

Apart from the length of time the SCR is installed, the magnitude of the NO_X damage costs and the efficiency of the SCR system also have significant impacts on the proportion factor. The capital cost, the operating cost and the discount rate have very little influence.

The second cost benefit analysis was carried out on the four different technologies (electric, CNG, diesel and hybrid) using different fuel inputs. In total, fourteen investment options were assessed relative to a baseline fleet comprised entirely of Euro VI diesel buses. All the options examined required greater investment than the base case. The analysis found that, in general, the following priority should be given to the technologies: electric, HVO diesel hybrid, bioCNG, diesel hybrid and CNG. CNG buses (fuelled by natural gas) perform poorly because, relative to the base case, lifecycle GHG emissions are high as a consequence of poor energy efficiency. Although bioCNG buses also suffer from poor energy efficiency, bioCNG has a much lower CO_{2eq} emission factor than CNG and consequently is a more attractive option.

A sensitivity analysis carried out on three investment options (100% electric, 100% BioCNG and 100% HVO) showed that the biggest influences on the proportion factor for these bus fleets are the CO_2 damage costs, the efficiency of the vehicles, the fuel costs and when bus price parity is achieved. HVO, and to a lesser extent bioCNG, are viable alternatives to a fully electric fleet, particularly if the price of carbon rises and the cost of these fuels reduce; however, fuel availability is a concern and while buses run on HVO and bioCNG could be classified as 'clean vehicles', they could not be considered to be 'zero-emission heavy duty vehicles', as defined in the Clean Vehicles Directive.

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APPENDIX 1: TEST VEHICLES

ID	Type	Year of Registration	Fuel Type	Regulatory Stage (Euro Class)
Diesel 1	Double	2008	Diesel	IV
Diesel 2	Double	2013	Diesel	V
Diesel 3	Double	2018	Diesel	VI
Diesel 4	Single	2018	Diesel	VI
Hybrid 1	Double	2018	Diesel hybrid	VI
Hybrid 2	Single	2017	Diesel micro-hybrid	VI
Hybrid 3	Double	2018	Diesel hybrid	VI
CNG 1	Single	2016	CNG	VI
CNG 2	Double	2018	CNG	VI
Electric 1	Single	2018	Electricity	-
Electric 2	Single	2017	Electricity	-
Electric 3	Single	2017	Electricity	-
Electric 4	Single	2017	Electricity	-

Bus Technology	LowCVP (27) Definition
Electric	Electric buses operate using an electric motor powered by a battery for propulsion rather than a diesel internal combustion engine. Electricity from the grid is used to recharge the battery, with various strategies in existence for recharging. Electric buses are designed with regenerative braking, enabling a proportion of the energy that would otherwise have been lost when the vehicle is decelerating to be recovered back to the batteries and stored to power the vehicle.
Gas	The power train for gas buses is a spark ignition engine. Gas is stored on board the bus in compressed cylinders. The fuel source for gas buses can be natural gas or biomethane.
Hybrid	A hybrid bus typically retains a diesel engine but uses additional equipment to drive the bus when needed. There are many types of hybrid system currently in operation. On a conventional bus, when the driver brakes, the kinetic energy of the moving bus is dissipated as heat in the brakes or retarder. The bus slows down, but the energy is lost. On a hybrid bus when the driver brakes, the hybrid system captures kinetic energy and stores for use later when it is required for propulsion. The next time the bus accelerates, the stored energy is fed back to the driving wheels, reducing the load on the engine thereby saving fuel and reducing CO_2 emissions. Provided there is sufficient energy storage, and a powerful enough motor, hybrid buses can provide a modest amount of zero emissions driving. Typically, this is limited to low speed driving when approaching or departing from bus stops.
Diesel fitted with electrified ancillaries ('micro-hybrid')	Conventional ancillaries such as the air compressors, electrical systems and the alternator on a bus are driven by the engine and consume power according to demand. 'Micro hybrid' is the terminology used to describe the intelligent control of engine ancillaries to harvest energy thereby giving rise to fuel savings.
Plug-in hybrid	Hybrid buses that can additionally charge their batteries from external sources are known as plug-in hybrid buses. The speed and electric range depend on electric power capabilities and battery capacity. Provided that sufficient energy and power are available, a plug-in hybrid can provide emissions-free operation over parts or all of a bus route. This can give the zero emission benefits of an electric bus in the city centre combined with the range and flexibility of a diesel hybrid bus for sections of the route that are less emissions-sensitive. Plug-in hybrid buses can offer improved energy efficiency over conventional hybrids. They are designed with regenerative braking, enabling energy lost during decelerating to be recovered back to the batteries and stored to power the vehicle.

Appendix 2: Photographs

Figure 28: EA PEMS equipment (gas measurement system, particulate number counter, heated line and battery pack)

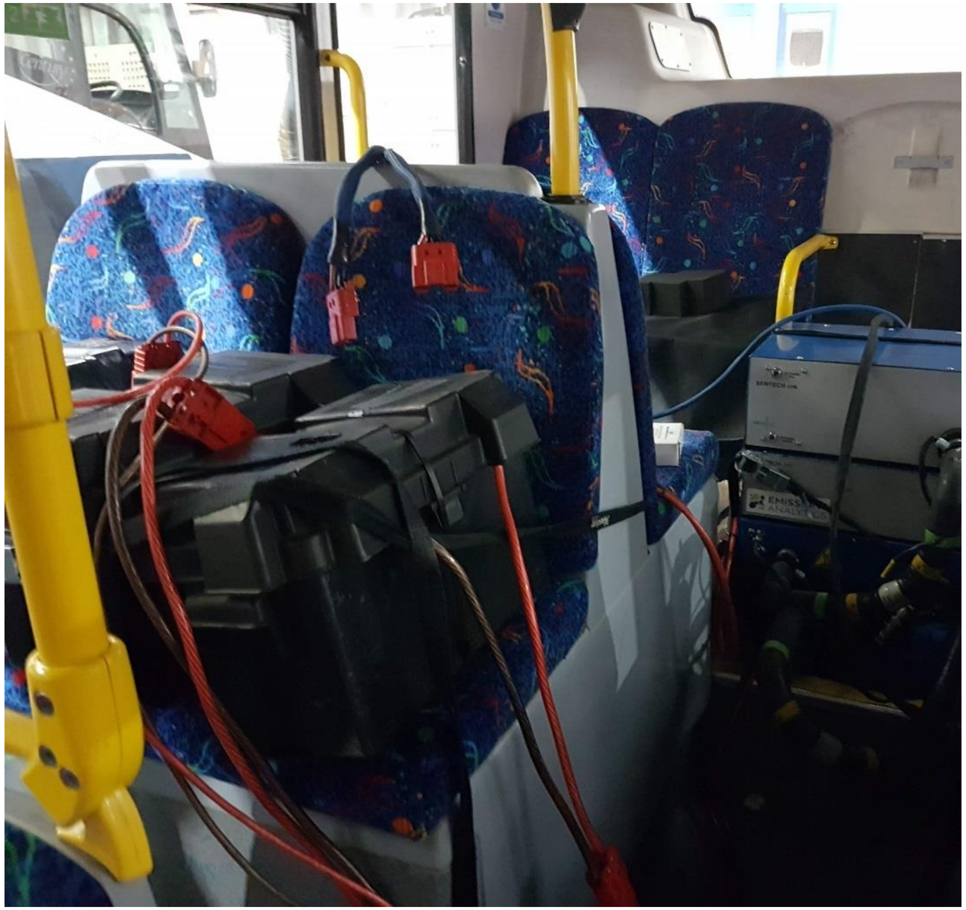


Figure 29: EA weather station

Figure 30. Bruno GX112 diesel generator

Figure 31. Data logger housing

Figure 32. Fluke 1734 data logger

Figure 33. 50 kW DC charger

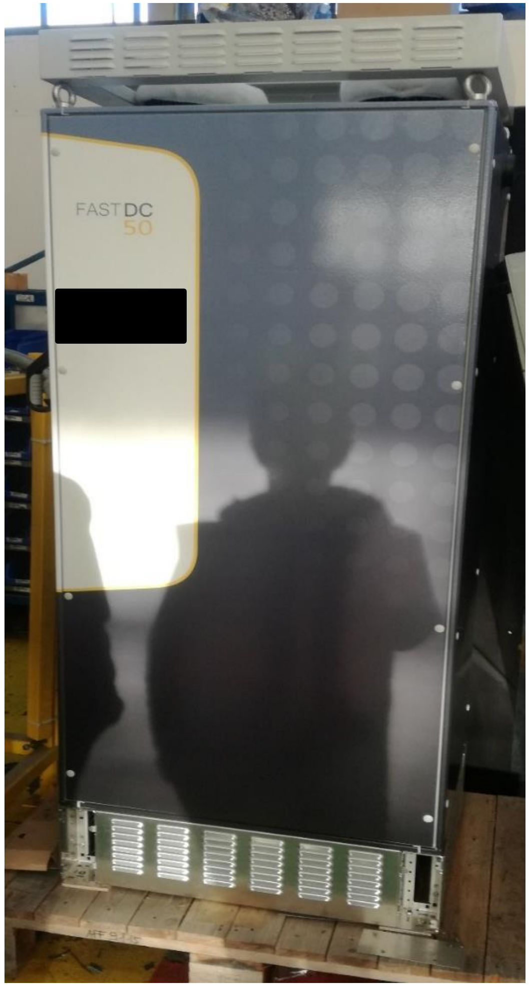


Figure 34. 80 kW DC charger

Figure 35. 60 kW DC charger

APPENDIX 3: ELECTRIC BUS CHARGER SPECIFICATIONS

The chargers were specific to each electric bus and were provided by the manufacturers. The specifications of the chargers are summarised in Table 44.

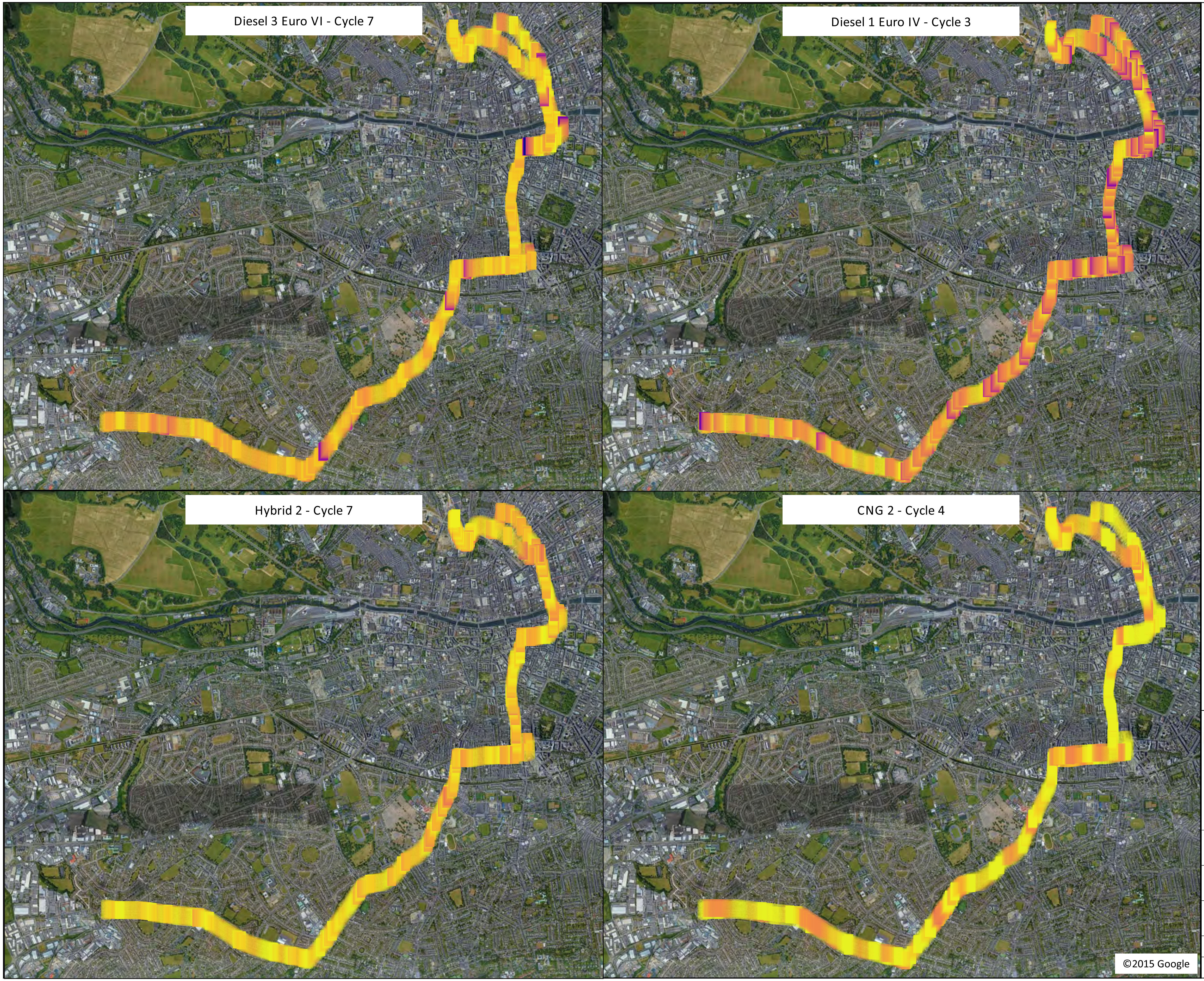
Table 44: Electric Bus Charger Specifications

Manufacturer	Maximum Power Output (kW)	Current Flow	Output Interface Standard	Charging cycle
Electric 1	21 Note 1	AC	IEC62196	Charging was carried out at a constant 21 kW until fully charged.
Electric 2	80	DC	CCS 2	Initially, a constant 80 kW was supplied. On reaching approximately 69% SOC, the power began to decrease linearly. On reaching approximately 94% SOC, the charger underwent an off/on cycle to bring the overall SOC to 100%.
Electric 3	50	DC	CCS 2	Initially, a constant 50 kW was supplied. On reaching approximately 90% SOC, the power began to decrease linearly. On reaching approximately 97% SOC, the charger underwent an off/on cycle to bring the overall SOC to 100%. Note 2
Electric 4	60	DC	CCS 2	For most of the charge, a constant 60 kW was supplied. The power increased marginally at around 97% SOC before briefly reducing until the bus was fully charged.

Note 1: This was a portable charger provided for trialling purposes. The standard charger has an output of 80kW.

Note 2: The DC charging process incorporates these stages of power ramp-down to control cell temperatures and maintain a consistent SOC across all battery packs. Consequently, an 80kW charger will take longer than one hour to supply 80kWh of charge because the power supplied is not 80kW for the entire charge.

APPENDIX 4: INSTANTANEOUS EMISSIONS MAPS



Legend

Instantaneous CO emissions (g/s)

- 0.000 - 0.001
- 0.001 - 0.010
- 0.010 - 0.100
- 0.100 - 0.250
- 0.250 - 0.500
- 0.500 - 0.750
- 0.750 - 1.000
- 1.000 - 1.250

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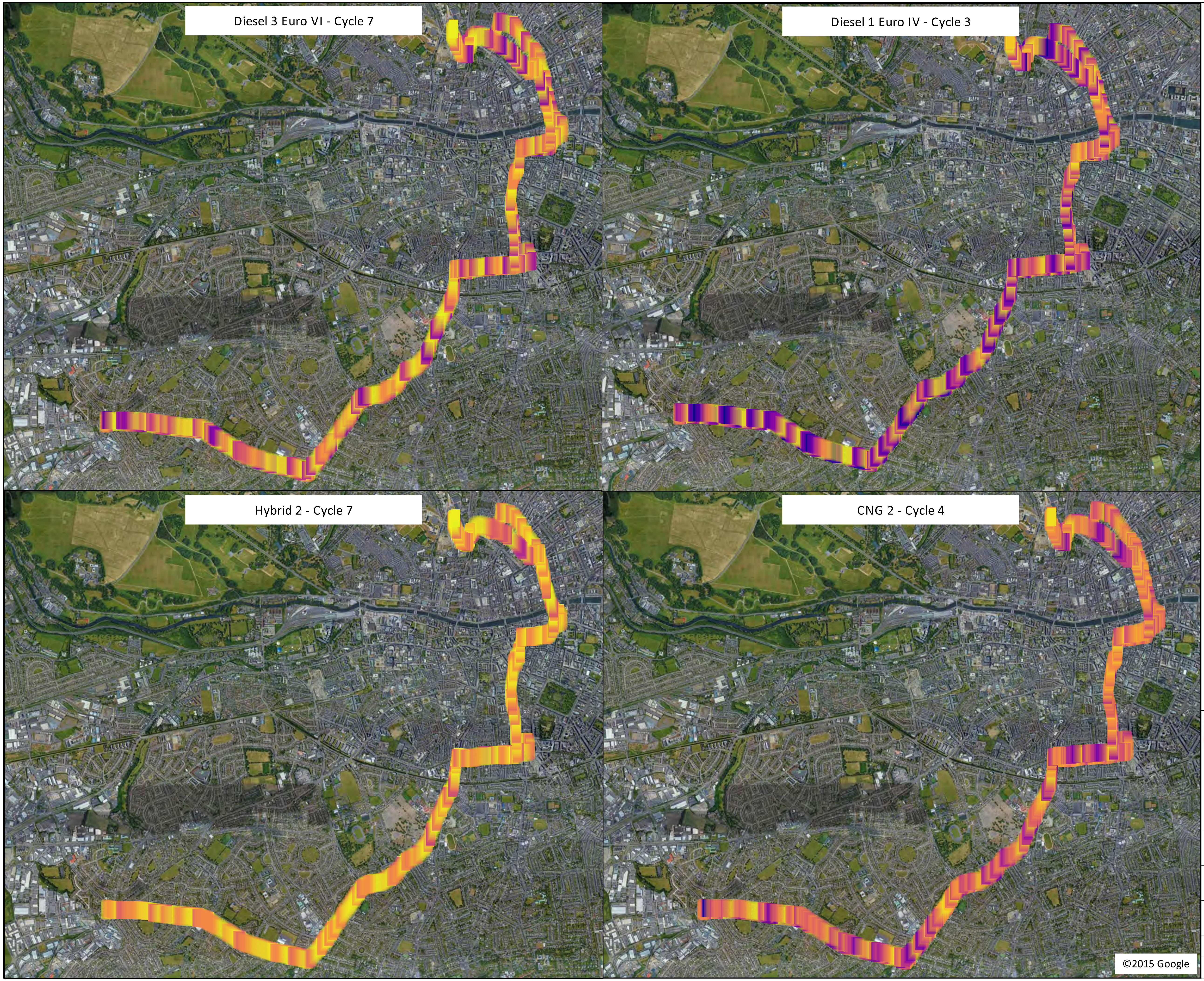
Client	**Department of Transport, Tourism & Sport**		
Project	**Alternative Fuel Bus Trials**		
Title	**Instantaneous CO emissions**		
Scale	1:65,000	**546-19X0091 Appendix 4**	R0
FBS	01.01.18		



Legend

Instantaneous CO2 emissions (g/s)

- 0.0 - 2.5
- 2.5 - 5.0
- 5.0 - 10.0
- 10.0 - 15.0
- 15.0 - 20.0
- 20.0 - 25.0
- 25.0 - 30.0
- 30.0 - 35.0

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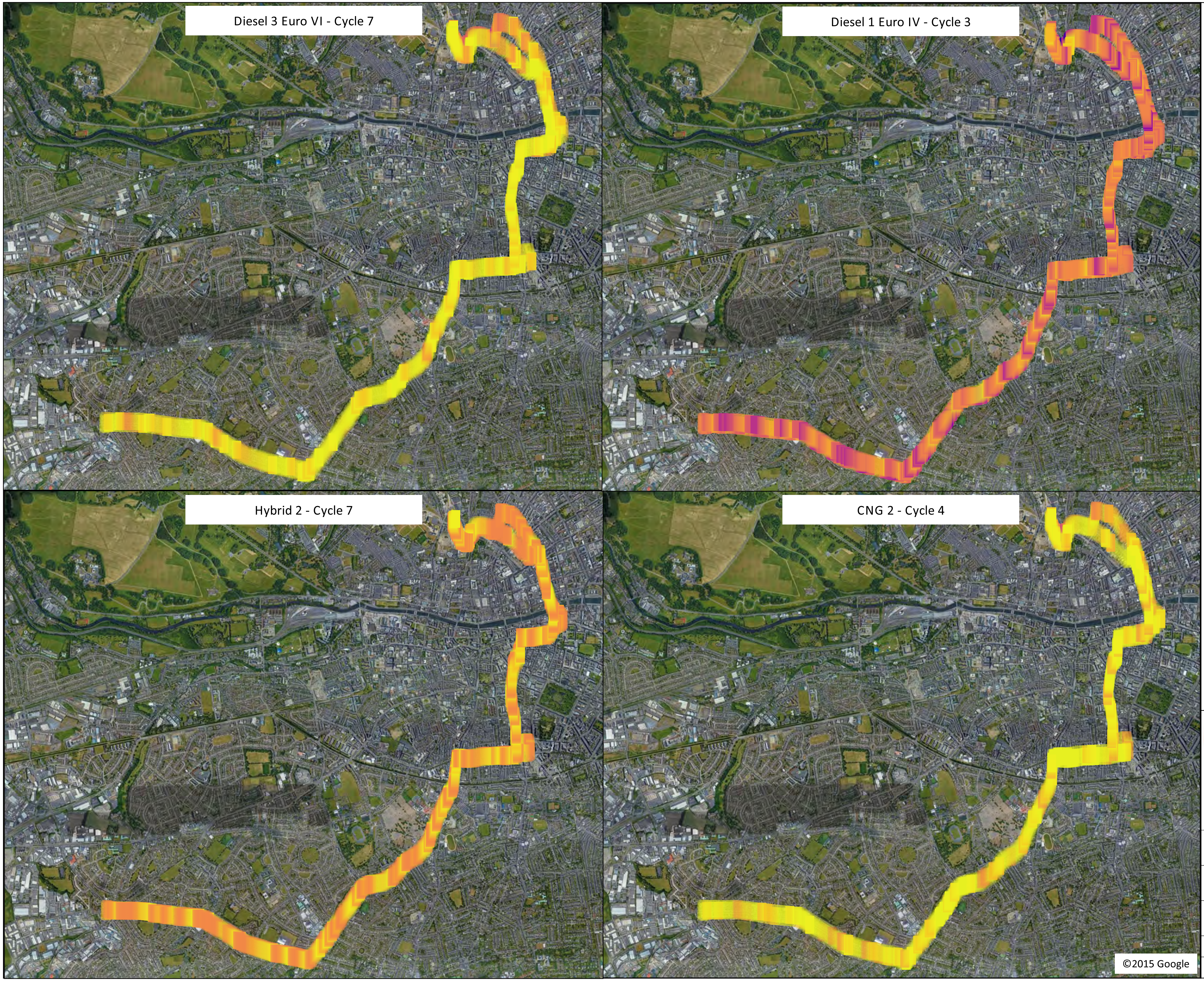
FBS	01.01.18		



Legend

Instantaneous NOx emissions (g/s)

- 0.000 - 0.001
- 0.001 - 0.010
- 0.010 - 0.100
- 0.100 - 0.200
- 0.200 - 0.300
- 0.300 - 0.400
- 0.400 - 0.450
- 0.450 - 0.500

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Client	Department of Transport, Tourism & Sport	
Project	Alternative Fuel Bus Trials	
Title	Instantaneous NOx emissions	
Scale	1:65,000	546-19X0091 Appendix 4	R0
FBS	01.01.18		

Appendix 5: Inputs for CBA on Alternatively-Fuelled Buses

Input Variable	Year	Diesel	Electric	CNG	BioCNG	Diesel Hybrid	Diesel Hybrid (HVO)
Capital cost: bus (€/bus)	2019	268,293	528,455	308,943		390,244	
	2032	268,293					
Capital cost: fuelling infrastructure (€/bus)	-	-	18,250			-	-
Capital cost: fuelling infrastructure (€m/station)	-	-	-	1.2	1.2	-	-
Operating cost: fuel (€/100MJ)	-	1.418	2.542 – 2.986	0.593	1.982	1.418	4.492
Operating cost: maintenance (€/bus/year)	2019	10,344	17,714	10,344		14,196	
	2032	10,344					
Operating cost: maintenance (€/station/year)	-	-	-	35,000	35,000	-	-
NO_x emissions (g/km)	-	4.6 (existing fleet) 0.4 (Euro VI)	0	0.5	0.5	1.0	1.0
Environmental benefit (€/tonne NO_x)	-	9,951					
Emission factor (gCO_{2eq}/MJ)	2019	95.1	115	77.8	23.7	95.1	12.6
	2032		71				
Environmental benefit (€/tonne CO_{2eq})	2019	20					
	2032	110					
Appraisal period (years)	-	14					
Annual bus replacements	-	15 (Bus Éireann), 72 (Dublin Bus)					
Annual distance travelled (‘000 km)	-	10,176 (Bus Éireann), 57,072 (Dublin Bus)					
Discount rate (%)	-	1.5					

Appendix 6: Sensitivity Analysis Inputs for CBA on Alternatively-Fuelled Buses

Parameter	100% EV		100% BioCNG		100% HVO	
	Central value	Range	Central value	Range	Central value	Range
Capital cost, bus (€/bus)	528,455 (price parity = 2032)	Price parity = 2028 – 2036	308,943 (price parity = 2032)	Price parity = 2028 – 2036	390,244 (price parity = 2032)	Price parity = 2028 – 2036
Capital cost, fuelling infrastructure (€/bus)	18,250		-	-	-	-
Capital cost, fuelling infrastructure (€m/station)	-	-	1.2	1.1 – 1.4	-	-
Operating cost, fuel (€/100MJ)	2.54 – 2.99	2.54 – 2.99	1.98	1.70 – 2.42	4.49	3.85 – 5.13
Operating cost, maintenance (€/bus/year)	17,714	5,957 – 21,876	10,344	10,344	10,344	10,344
Operating cost, maintenance (€/station/year)	-	-	35,000	30,000 – 40,000	-	-
NO_X emission factor (g/km)	0	0	0.5	0.4 – 0.5	0.9	0.7 – 0.9
NO_X damage cost (€/tonne NO_X)	9,951	11,707 – 5,688	9,951	11,707 – 5,688	9,951	11,707 – 5,688
CO_{2eq} emission factor (g/MJ)	67	63 – 73	0 – 23.7	0 – 23.7	12.6	12.6
CO_{2eq} damage cost (€/tonne CO_{2e})	20 – 110 (2019 to 2032)	25 – 138 (lower) 15 – 83 (upper)	20 – 110 (2019 to 2032)	25 – 138 (lower) 15 – 83 (upper)	20 – 110 (2019 to 2032)	25 – 138 (lower) 15 – 83 (upper)
Fleet efficiency (MJ/km)	5.1	4.1 – 7.2	24.1	22.2 – 26.8	10.8	9.3 – 12.9
Discount rate (%)	1.5	0.0 – 4.0	1.5	0.0 – 4.0	1.5	0.0 – 4.0

The following bullets set out how the ranges have been arrived at.

- For the fuelling infrastructure, we assume that the Bristol Community Transport (lower) and GNI (upper) costs were applied for CNG fuelling stations (see Section 8.3.2.1). The upper and lower costs for electric bus chargers, as shown in Section 8.3.2.1, were also applied.
- The fuel costs for the central scenarios are the wholesale prices set out in Table 42. For electricity in the central scenario, the level of consumption determines the price band. For the lower cost, we assume all the electricity is charged at the lower rate and for the higher cost we assume all the electricity is charged at the higher rate. For bioCNG, the lower cost was estimated by GNI and the upper cost is that set out in an SEAI report on the costs and benefits of biogas in Ireland (49). For HVO in the central scenario, we assume the price of HVO is 75% higher than that of biodiesel. For the lower cost we assume a 50% mark-up and for the higher cost we assume a 100% mark-up.
- The maintenance costs for the diesel and CNG buses were not varied. The hybrid bus maintenance costs were varied by ± 25%. For electric buses, we've used the average value (€21,876) that was applied in the KPMG report (45) as the maximum annual maintenance cost. The minimum cost (€5,957) assumes a 45% reduction in annual maintenance costs compared to ICE buses. This value was sourced from data contained in three recent publications by the International Energy Agency (50), Transport & Environment (51) and the European Copper Institute (52). These reports suggest that electric bus maintenance costs are approximately 40-50% lower than ICE buses; however, it's unclear from these publications if these maintenance costs include for battery maintenance and replacement.
- For the maintenance costs (fuelling infrastructure), the range specified in the KPMG report (45) was used for CNG filling stations.
- A range of bus efficiencies measured during the trials were assessed for each alternative-fuel bus technology. As the existing fleet, including Euro VI diesel buses, are optimised for Irish driving conditions, their efficiencies were not adjusted.
- The NO_X emission factor for alternative-fuel buses were reduced by 25%. No upward adjustments were made because the test conditions were conservative, i.e. low speed and low ambient temperature.
- The DPER (lower) and EU CAFÉ study (upper) NO_X emission damage values, as shown in Table 38, were applied. DPER shadow prices for CO_2 were adjusted by ± 25%.
- The CO_{2eq} emission factors were varied as follows:
  - The central CO_{2eq} emission factor (23.7 gCO_{2eq}/MJ) for bioCNG assumes a feedstock consisting of 60% wet manure and 40% grass, which could be representative of inputs to an anaerobic digestion facility in Ireland, and includes 'methane slip' (see Section 5.5.2.4 and 7.2.2). By increasing the proportion of wet manure to 75% of the feedstock mix (with 25% grass), and ignoring 'methane slip', the CO_{2eq} emission factor would reduce to around 0 gCO_{2eq}/MJ.
  - Electricity CO_{2eq} emission factors were forecast by linear interpolation (further detail is provided in Section 7.2.2) relative to a projected 2050 value. This value was adjusted by ± 100%.
- A lower discount rate of 0% and a higher value of 4% were used (refer to Section 8.1.4).

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