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Turasóireachta agus Spóirt
Department of Transport,
Tourism and Sport

Sustainable Mobility Policy Review

Background Paper 5
Greener Buses – Alternative fuel options for the urban bus fleet

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Context and questions for consideration

This background paper is one of a number of papers that have been prepared by the Department of Transport, Tourism and Sport to inform a public consultation on Ireland's sustainable mobility policy. The review work arises from a commitment in the *Programme for a Partnership Government*[1] to review public transport policy "to ensure services are sustainable into the future and are meeting the needs of a modern economy". The public consultation is designed to give stakeholders, interested parties and the general public the opportunity to reflect on the information and analysis in the papers, to share their views, and to contribute to the development of a Sustainable Mobility Policy Statement.

Sustainable Mobility can be described as linking people and places in a sustainable way by supporting:

- comfortable and affordable journeys to and from work, home, school, college, shops and leisure;
- travelling by cleaner and greener; and
- a shift away from the private car to greater use of active travel (walking and cycling) and public transport (e.g. bus, rail, tram).

All elements of sustainable mobility (public transport, cycling, walking) are being considered in the policy review. Each background paper includes a number of questions to generate ideas about the extent to which the present approach to sustainable mobility is working well, the areas which are not, and future priorities.

This paper consists of a qualitative and quantitative appraisal of a range of alternative fuel options available for Ireland's Public Service Obligation (PSO) urban bus fleet. The questions below are included as a guide. Participants in the public consultation are not confined to answering the suggested questions and are invited to offer any other contribution they wish to make. It is recommended that submissions are confined to circa 2,500 words or less.

5.1 What challenges and issues need to be considered in relation to transitioning the PSO urban bus fleet to alternative fuels and technologies?

5.2 Based on the additional investment costs associated with alternatively fuelled vehicles and their associated infrastructure, should bus fare structures be modified?

5.3 Are there international best practice examples around the use of alternative fuels in urban bus fleets that could be applied in an Irish context?

1 Overview

1.1 Structure of the paper

Section 2: **Introduction** provides a background of Ireland's requirements to meet European targets for greenhouse gas emissions. These targets represent a significant challenge for the transport sector. The Section describes the public transport emissions profile in Ireland. It also looks at the European and National policies which aim to encourage the transition towards a lower emitting transport sector.

Section 3: **Profile of the urban bus fleet** describes the Dublin Bus, Bus Éireann and Go-Ahead bus fleets that are currently in operation in Dublin, Cork, Galway, Limerick and Waterford. It describes the fleet size, Euro Class profile and renewal rates of the buses in operation. The Section also gives information on the passenger numbers and passenger flow of the services.

Section 4: **Assessment of alternative fuels and technologies** includes an evaluation of low-emitting fuels and technologies across a number of criteria including carbon dioxide (CO_2) emissions, air quality emissions, infrastructural requirements, fuel supply limitations, costs and their ability to contribute to targets. The alternative fuels/technologies that are evaluated are: full electrification, diesel-electric hybrid, compressed natural gas, biogas/biomethane, biodiesel, bioethanol, hydrotreated vegetable oil and hydrogen.

Section 5: **Economic evaluation** describes the analysis that was conducted to assess the costs and benefits associated with the introduction of alternative fuels/technologies into the bus network. The analysis comprises two components, a qualitative comparison of the different fuel types under a number of criteria and a modeled quantitative examination of these fuels to compare their phased introduction into an existing fleet. The quantitative analysis includes a calculation of Well-to-Wheel vs. tailpipe emissions analysis as well as the EU standard vehicle emissions calculator COPERT (Calculation of Air Pollutant Emissions from Road Transport).

Section 6: **Most appropriate fuelling options for different locations** considers the suitability of the alternative fuels/technologies for both present and future passengers as well as the capacity to maintain a degree of flexibility for route alterations or expansions. The Section also looks at the effect of congestion and the effect of driving style on alternative fuels and technologies. Although this paper is focused on transitioning the urban bus fleet, a short discussion is provided on location specific considerations for transitioning town service fleets.

1.2 Purpose of background paper

The Public Service Obligation (PSO) bus fleet forms the backbone of Irish public transport provision with over 178 million passenger journeys in 2018 on bus services alone. Continued investment in public and sustainable transport networks has supported an increase of over 58 million journeys on subsidised public transport compared to 2013. This expansion of public transport has helped mitigate against transport emissions in Ireland.

Under the *National Development Plan 2018-2027*[2] (NDP) and the all-of-Government *Climate Action Plan*[3] (2019), Ireland has committed to transition to low emission buses, including electric buses, for the urban public bus fleet and to cease purchasing diesel-only buses from July 2019. This commitment, which has now come into effect, will help reduce CO_2 emissions from the transport sector, as well as potentially contributing towards renewable energy ambitions and improving air quality (AQ). Furthermore, a transition towards alternative fuels and technologies, in this way by the State sector demonstrates a strong leadership role and normalises the use of non-conventional fuels to broader society.

The purpose of this paper is to set out a qualitative and quantitative evaluation of a range of alternative fuel and technology options for replacing diesel-only buses in the national fleet. This information will help inform purchasing decisions and fleet renewal strategies in the medium term to meet the *NDP* commitment. The following alternative fuels/technologies are considered:

- full electrification;
- diesel-electric hybrid;
- compressed natural gas;
- biomethane;
- biodiesel;
- bioethanol;
- hydrotreated vegetable oil; and
- hydrogen.

The alternatives are compared across a number of criteria, namely: CO_2 emissions, AQ emissions (particularly Nitrogen Oxide [NO_x] and particulate matter), infrastructural requirements, fuel supply limitations, vehicle and infrastructure costs, and contribution towards renewable energy and clean procurement targets. An initial review of the appropriateness of different alternatives in different locations, as well as the impact of congestion, is also undertaken. The analysis presented in this paper solely addresses Tank-to-Wheel (TTW) or tailpipe emissions which are emissions generated during fuel or power consumption.

1.3 Data sources

The European Union (EU) standard vehicle emissions calculator COPERT is employed to assess CO_2 and AQ emissions; due to an acknowledged error in the software, modelled emissions from Compressed Natural Gas (CNG) buses are not included in this paper. Comprehensive comparative analysis is therefore constrained; nevertheless, use of additional complementary data sources yields indicative results. In addition, the Department of Transport, Tourism and Sport (DTTAS) oversaw a low emission bus trial, monitoring real world driving emissions and fuel economies from a number of alternative fuels/technologies. This data will act as a meaningful comparator to the modelled results and also will help inform future purchasing decisions.

1.4 Scope of paper

A variety of PSO bus and coach services operate throughout Ireland, namely:

- Bus Services: Urban bus services in the Greater Dublin Area (GDA) and the cities of Cork, Limerick, Galway and Waterford, as well as several regional towns;
- Coach Services: Commuter carriage services from the GDA and the regional cities; and
- Coach Services: Stage carriage services linking communities in primarily rural areas.

This paper focuses on PSO fleets associated with the provision of urban bus services in Dublin, Cork, Galway, Limerick and Waterford. This is consistent with the urban focus outlined in National Strategic Outcome 4 (Sustainable Mobility) of the *NDP*. It also reflects the scope of the *BusConnects* Programme,

The current provision and potential future expansion of regional town bus services (serving the towns of Drogheda, Dundalk, Navan, Balbriggan, Athlone and Sligo, with new services envisioned for Carlow, Kilkenny and Mullingar) is considered in the *NDP*, subject to operational funding support, under National Strategic Outcome 3 (Strengthened Rural Economies and Communities). While the findings of this paper will help further inform future purchase choices for town services, full analysis of fleet profiles and most appropriate fuelling options for these services is beyond the scope of this paper. Equally, commuter and stage carriage services are excluded from this paper due to the marked differences in technology availability and variety in journey routes undertaken between coaches and buses. Alternative modes of public transport not currently in operation in Ireland, such as trolley buses and bus rapid transit (BRT) systems, are likewise excluded.

Acknowledging that transitioning the heavy rail system towards lower-emission alternatives will also contribute carbon savings from the transport sector, it was determined that rail transport would not be examined in this paper. A significantly larger share of passenger numbers and a greater proportion of public transport's carbon emission profile are associated with urban bus services and the focus was limited to the PSO bus fleet accordingly. This does not preclude or undermine the importance of transitioning towards decarbonisation in all public transport modes.

2 Introduction

2.1 Decarbonising public transport

The Paris Agreement[4] sets out a global action plan to address climate change by limiting global warming to below 2°C. Ireland, as a Member State of the EU, is a signatory to this agreement. The EU has set Member States binding greenhouse gas (GHG) emission reduction targets to limit the global warming potential across Europe. Ireland is required to deliver a 20% reduction (relative to 2005 levels) in greenhouse gas emissions in the non-Emissions Trading Scheme (ETS)[i] by 2020. Post 2020, Ireland will have legally binding non-ETS emissions reduction targets for each year until 2030 by when national non-ETS emissions should be 30% below their level in 2005. The 30% reduction target is higher than the EU average reduction target of 23%.

These targets are national rather than sectoral in nature; however, as the second-largest contributor of non-ETS emissions after agriculture[5], the transport sector has a critical role to play in reducing national emission levels.

Moving to a low carbon society represents a significant challenge for the transport sector where the use of fossil fuels and individual travel patterns are firmly established. Decoupling growing transport demand, and subsequent emissions, from economic growth is difficult; in fact, the most recent projections indicate that without additional policy intervention transport sector emissions are likely to increase by 11% over the period 2018-2030[6].

A successful measure which has mitigated against growing transport emissions has been Ireland's continued investment in public and sustainable transport networks, leading to an increase of over 58 million journeys on subsidised public transport compared to 2013[7]. In 2018 alone, public transport, walking and cycling accounted for approximately 70% of all journeys into Dublin at peak morning times, a significant increase from 59% of journeys in 2010 (based on Canal Cordon[8] findings). Bus services carry the majority of public transport passengers and continue to demonstrate annual increases in passenger numbers. In 2018, the three largest PSO bus operators Dublin Bus, Bus Éireann and Go-Ahead Ireland carried 140 million, 35 million and 1.4 million passengers respectively. Therefore, transitioning to greener, more-efficient buses has the potential to reduce transport emissions from a growing cohort of public transport passengers.

Encouraging people away from single occupancy private cars towards all forms of public transport, including light and heavy rail, also contributes to decarbonising the transport sector. The *NDP* sets out a commitment to deliver priority public transport programmes including BusConnects, Luas Green Line Capacity Enhancement, DART Expansion Programme and MetroLink. These investments will progressively reduce the emission profile of public transport systems over the longer-term; in the short term, on-going bus fleet renewal represents an immediate and cost-effective mechanism to secure emission savings in the public fleet.

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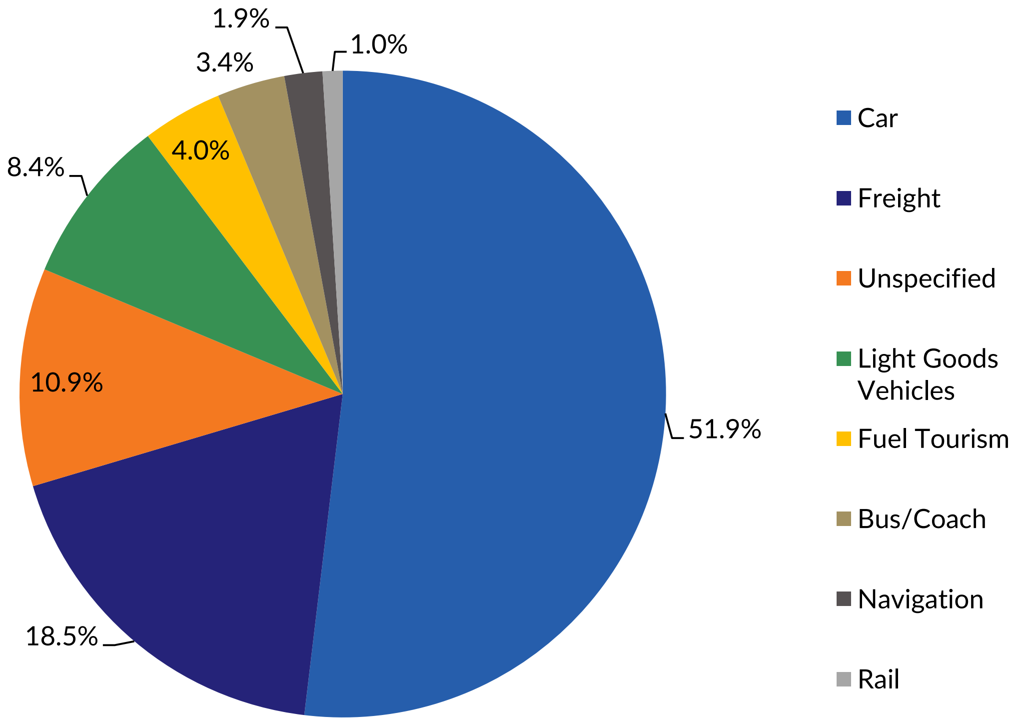
[i] Non-ETS emissions arise from sectors outside the Emissions Trading Scheme and include agriculture, transport, residential, commercial, waste and non-energy intensive industries.

2.2 Public transport emissions profile

2.2.1 CO_2 emissions

Carbon dioxide (CO_2) is a greenhouse gas that can have a damaging effect on the climate. From the most recent (2017) emission inventory by the Sustainable Energy Authority of Ireland (SEAI), it is estimated that just 3.4% of all transport-derived CO_2 comes from bus and coach fleets (Figure 2.1). This category also includes other public passenger services such as small service public sector vehicles (SPSVs – taxi/hackney/limousines). Therefore, converting these fleets to low-carbon alternatives can only have a limited mitigation impact on national CO_2 emissions, however it will undoubtedly begin to promote and normalise the use of non-conventional fuels and technologies.

Figure 2.1: Ireland's transport CO_2 emissions per mode in 2017



Source: SEAI

2.2.2 Air pollutant emissions

Certain transport emissions can also have an adverse impact on local air quality. Air quality is an issue of increasing social concern with a number of pollutants being linked to a range of medical conditions including strokes, cancer, lung and cardiovascular diseases. In 2014, it is estimated that across Europe more than 400,000 premature deaths can be attributed to exposure to particulate matter (PM) with a further 70,000 deaths due to nitrogen dioxide (NO_2); in Ireland approximately 1,600 premature deaths have been attributed to fine PM and other air pollutant exposure[9]. Furthermore, it is estimated that in Ireland, air pollution is responsible for health-related costs of over €2 billion per year including the loss of 382,000 workdays per year[10].

Ireland generally has better overall air quality than most countries in Europe[11]. Nevertheless, in larger towns and cities, where prevailing winds are disrupted and harmful pollutants cannot disperse due to high density developments, the negative implications for local ambient air quality and for public health and wellbeing are exacerbated.

Road transport is a major source of air pollution emissions, particularly NO_x and $PM_{2.5}$, from both exhaust releases and tyre-and-brake-wear. Ireland's expected economic growth and subsequent increased travel demand are likely to negatively impact AQ. Exhaust emissions can contain high levels of carbon monoxide (CO), NO_x, sulphur oxides (SO_x), PM_{10} and $PM_{2.5}$, black carbon and volatile organic compounds (VOCs)[12]. Given the limited CO_2 mitigation potential of converting the bus fleet to alternative fuels/technologies, the influence of pollutants on air quality is arguably as relevant.

Newer vehicles, adhering to more stringent technical specifications, have shown marked decreases in several AQ emissions (Table 2.1).

Table 2.1: Estimated emissions from different Euro Class double deck diesel buses

From Older to Newer Euro Class Bus Models				
Euro-Class / Emissions	Euro III Diesel (2000)	Euro IV Diesel (2005)	Euro V Diesel (2008)	Euro VI Diesel (2012)
CO_2 g/km	1,349	1,208	1,188	1,212
NO_x g/km	14.22	8.21	9.71	0.57
PM g/km	0.37	0.16	0.17	0.10

Source: Modelled through COPERT (V5)

Road transport is the principal source of NO_x emissions in Ireland accounting for approximately 41% of the total NO_x emissions in 2016[13]. Between 2008 and 2016, national NO_x levels reduced by over 18% due to the economic recession and improvements in vehicle technologies; however, between 2015 and 2016, a 7.5% increase was recorded and has been attributed to increased vehicle numbers and kilometres driven.

PM emissions are a major concern for many EU countries; 19% and 7% of the EU-28 urban population were exposed to above the daily limit values of PM_{10} and $PM_{2.5}$ respectively in 2015. Fortunately, in Ireland, even under the more stringent World Health Organisation (WHO) annual mean limits, compliance for PM_{10} and $PM_{2.5}$ emissions is generally recorded. Road transport PM has been decreasing since 2005, with nearly a 46% reduction between 1990 and 2016, largely attributed to technological advances and the age profile of the national fleet. In 2016, for the first time since 2005, an increase in transport derived PM emission (1.5 %) was noted[12].

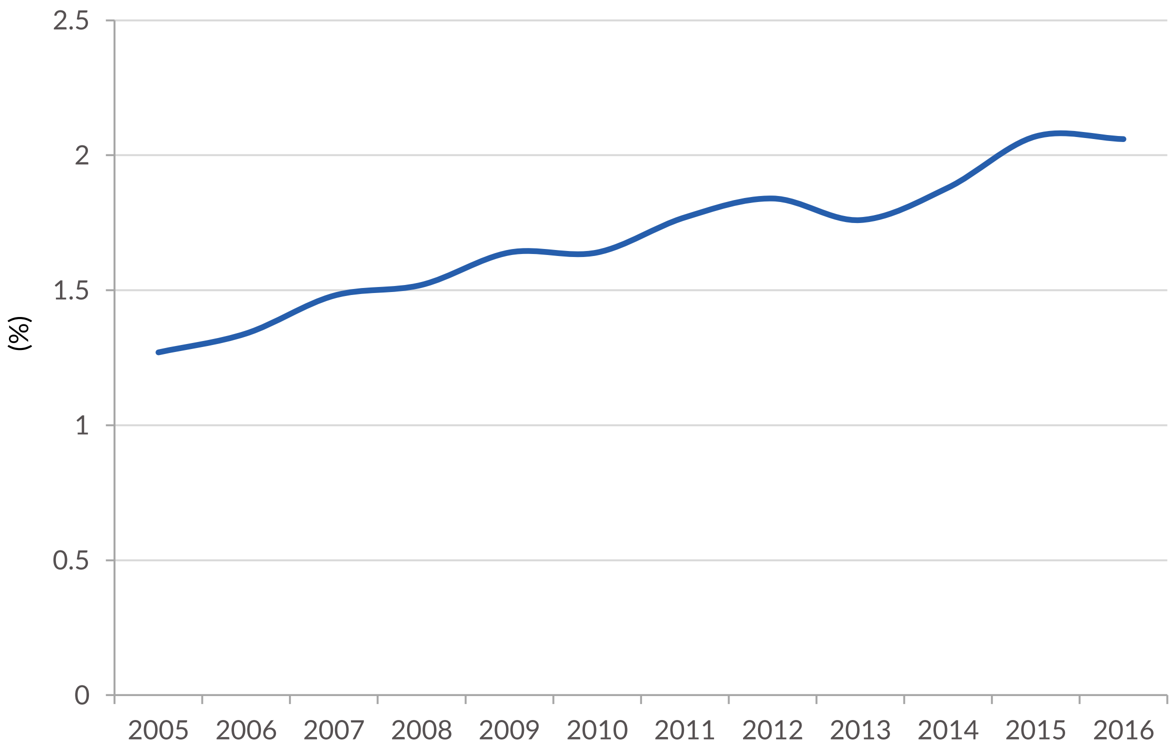
2.3 Public transport policy context

2.3.1 European policies

There are a number of European initiatives underway to support a cohesive transition towards a lower-emitting transport sector. The European Commission's *Low-Carbon Economy Roadmap 2050*[14] is a cornerstone strategy that proposes Member States reduce CO_2 emissions from transport by 60% below 1990 levels by 2050. This target is expected to be achieved in part by upgrading public transport systems[15]. Meanwhile, the *Clean Power for Transport package*[16] aims to facilitate the creation of a single market for alternative fuels for transport in Europe and the *Deployment of Alternative Fuels Infrastructure Directive* (2014/94/EU)[17] establishes EU standards for recharging and refuelling infrastructure to ensure interoperability.

Despite strong policy guidance, the uptake of alternative fuels in bus fleets across Europe is limited, just about 2% in 2016, although it is beginning to gain momentum. Gas fuelled buses have steadily increased in numbers over the years, but still accounted for only *c.* 1.3 % of the total bus fleet in 2016; France, Sweden, Italy, Germany and Spain are the only countries with notable numbers (i.e. above 600) of natural gas buses[18]. The numbers of liquid petroleum gas (LPG) and electric (mainly trolley) buses are lower; electric buses are starting to show low growth rates (Figure 2.2 and Table 2.2).

Figure 2.2: Percentage of alternatively fuelled buses as a proportion of the overall (EU) fleet



Source: EEA[17]

Table 2.2: Number of alternatively fuelled buses in operation during 2016 from a selection of major cities

No. of alternatively fuelled buses	Barcelona	Brussels	Dublin	Istanbul	Lisbon	London	Paris
Diesel (up to and including B10*)	595	675	989	1,810	560	9,537	4,471
Electric	4	-	-	-	-	71	30
Hydrogen	-	-	-	-	-	8	-
CNG	385	-	-	331	40	-	140
Diesel Electric Hybrid	180	-	-	-	-	2,529	510
CNG Electric Hybrid	13	-	-	-	-	-	-

Source: International Bus Benchmarking Group

*B10 refers to a blend of conventional diesel with up to 10% biodiesel. See Section 4.7 for further information.

2.3.2 Irish policy framework

Transitioning Ireland's urban bus fleets towards cleaner alternative fuels and technologies is consistent with the objectives of a number of national policies; notably the *National Mitigation Plan (NMP)*[19], the *Climate Action and Low-Carbon Development Act*[20], the *Climate Action Plan to Tackle Climate Breakdown* and the forthcoming *National Clean Air Strategy*[21]. These policies collectively establish a clear and ambitious vision for the transport sector over the long term to improve air quality and lower CO_2 emissions through, amongst other mitigation measures, securing as early a transition as is feasible away from fossil fuels towards cleaner, lower carbon fuels and technologies.

Project Ireland 2040

Project Ireland 2040 is the overarching national policy initiative which sets out, through the *National Planning Framework (NPF)*[22] and the *National Development Plan 2018-2027*, a cogent and integrated vision towards the development of a sustainable public transport system in Ireland. Implementation of the *NPF* should ensure better integration of land-use and transport planning policy taking into account the projected rise in public transport demand. The *NPF* establishes sustainable mobility as a key strategic outcome and the *NDP* commits Ireland to accelerating investment in public transport particularly across the five main cities (Cork, Dublin, Galway, Limerick and Waterford). It is intended that the expansion of attractive and sustainable public transport will provide meaningful alternatives to private car transport and so help reduce both congestion and emissions. The *NDP* commits Ireland to transition to low emission buses, including electric buses, with no diesel-only buses purchased from July 2019, in line with the *BusConnects* Programme.

The transition to low-emission alternatives will be a phased process and it is expected that by 2023, half of the bus fleet operating in the GDA (approximately 500 buses) will be converted, with plans for full conversion by 2030[23]. The Programme will also be expanded to include urban bus fleets in the four other main cities.

Climate Action Plan to Tackle Climate Breakdown

The *National Mitigation Plan (NMP)* initiated the process of developing medium to long term mitigation choices for the years to come. The *Climate Action Plan to Tackle Climate Breakdown*, published in June 2019, is the follow-on plan to the *NMP*; it maps out a whole-of-Government approach to climate action and a potential pathway to meet Ireland's 2030 emissions commitments. The *Plan* clearly recognises that Ireland must significantly step up its commitments to tackle climate disruption and sets out strong governance arrangements to ensure that climate action is a key consideration in all State projects. The *Plan* reaffirms the *NDP* commitment to transition the urban PSO public bus fleet to low-emission vehicles and sets out clear timeframes for the implementation of a short-term low-emission procurement approach and the adoption of a medium-term fleet technology pathway for the public bus fleet.

National Policy Framework on Alternative Fuels Infrastructure in Ireland

The *National Policy Framework for Alternative Fuels Infrastructure for Transport in Ireland: 2017-2030*[24] represents Ireland's first step in communicating a national vision for decarbonising the transport sector. The cornerstone of the *Framework* is a national ambition that by 2030 all new cars and vans sold in Ireland will be zero-emissions capable, while setting out the expectation that this trajectory towards low-emission vehicles will continue concurrently in the bus sector towards 2050.

Green Public Transport Fund

The Department of Transport, Tourism and Sport (DTTAS) established a *Green Public Transport Fund* in 2017 to support the uptake of energy-efficient technologies for PSO operators within the bus and SPSV sector. In 2018, under the *Fund*, a grant scheme was launched to encourage taxis, hackneys and limousines to transition to electric vehicles (EVs). In 2019, the *Fund* has supported the *Low Emission Bus Trial* (see Section 5.4) and the purchase of nine pilot buses for the Dublin PSO fleet.

2.4 Synergies with broader transport policy

There are a number of European developments underway, addressing wider transport and climate concerns, which may impact upon and influence the selection of a low-emitting alternative for the Irish urban bus fleet.

2.4.1 Renewable energy

In addition to the national target for CO_2 emission reduction, Ireland has a separate binding target under the provisions of the Renewable Energy Directive (2009/28/EC)[25] (RED) to reach a 10% share of renewable energy in transport by 2020. This is commonly known as Renewable Energy in Transport (RES-T). To move towards this target Ireland introduced a Biofuels Obligation Scheme[26] (BOS) to ensure that a proportion of the transport fuel used in the State consists of environmentally sustainable biofuels. The BOS rate has incrementally increased from a share of

4.166% (by volume) in 2010 to 11.111% in 2019. The obligation rate is likely to be increased further[27] to displace more fossil fuels with renewable alternatives. The revised RED (2018/2001/EU) (known as RED II) will increase Ireland's renewable energy obligations to 2030; therefore, the bus fleet transition to lower emissions must also be assessed with regard to its potential capacity to contribute towards achieving more stringent targets on using energy from renewable sources.

2.4.2 Clean vehicle procurement

The European Commission recognises that public procurement can assist in the deployment of low-emission vehicles; the recast *Clean Vehicles Directive* (CVD) (2009/33/EC)[28] legislates at EU-level for the purchase of vehicles by public authorities. The scope of the recast *Directive* has been broadened to include contracts for lease, rental and hire purchase and will introduce binding national targets and associated reporting obligations for public procurements of light and heavy-duty vehicles in Member States, including for the purchase of public urban buses and buses contracted under school transport schemes. The recast *Directive* requires that 45% of buses procured from mid-2021 to the end of 2025 will be 'clean' (low-emission)[ii], with a 25% share to be zero-emission. Under the *Directive*, zero-emission heavy-duty vehicles (HDV) (trucks, buses and coaches) are defined as those without internal combustion engines (ICEs) or with an ICE that emits less than 1g CO2/kWh or 1g CO2/km. From 2026 to 2030, 65% of buses procured will be 'clean' (low-emission), with 50% of this share to be zero-emission. It should be noted that coaches are excluded from the *Directive* as low-emission technologies have not yet sufficiently matured to allow for procurement in this sector. These changes will result in a wider deployment of low-emission and zero-emission vehicles in the public fleets and should be considered in medium-to-long-term PSO fleet purchasing decisions.

2.4.3 Heavy-duty vehicle emission monitoring standards

CO_2 emissions from heavy-duty vehicles (HDVs) represent approximately one quarter of road transport CO_2 emissions across Europe; equivalent to approximately 6% of total CO_2 emissions from the EU[29]. New EU legislation will oblige manufacturers of HDVs to monitor and report the CO_2 emissions and fuel efficiency of new vehicles produced for the European market using a *Vehicle Energy Consumption Calculation Tool* (VECTO)[30]. To date, monitoring and reporting systems for CO_2 emissions have not been implemented in Europe despite similar systems being firmly established in the US, China, Japan and Canada[31]. In the context of bus fleet transition, the

[ii] 'Clean' heavy-duty vehicles (including buses) are defined in the recast Directive 2009/33/EC as those fuelled or powered by, inter alia: electricity; hydrogen; biofuels; synthetic and paraffinic fuels; natural gas, including biomethane, in gaseous form (compressed natural gas or CNG) and liquefied form (liquefied natural gas or LNG); and liquefied petroleum gas (LPG), in line with Article 2 (1) of Directive 2014/94/EU. Conventional hybrid technologies i.e. vehicles which cannot be recharged externally, are not considered 'clean' under the Directive.

Biofuels and synthetic or paraffinic fuels must be deployed in concentrations of 100% i.e. unblended with conventional fossil fuels; and must be solely sourced from sustainable feedstocks listed within Annex IX (A) of the recast *Renewable Energy Directive* 2018/2001/EU. Notably, biodiesels produced from palm oil will not be considered 'clean'.

introduction of monitoring standards is likely to usher in a wide-scale market transition towards the production of less polluting and more fuel efficient heavy duty vehicles. Greater market availability of low and zero-emission vehicles, in conjunction with increased global political impetus for climate action, should improve the economic viability of such vehicles in the longer term.

3 Profile of Ireland's urban bus fleet

3.1 Public Service Obligation (PSO) bus services

Each year taxpayer funding is provided for the provision of public transport services in Ireland that are considered to be financially unviable yet socially necessary. In urban areas, subvented bus services are currently operated primarily by Dublin Bus (serving the GDA) and Bus Éireann (serving the regional cities: Cork, Galway, Limerick and Waterford). Recently, under a Bus Market Opening initiative 10% of bus routes were opened to competitive tendering[32]; Go-Ahead[iii] a new entrant to the Irish PSO bus market- won the tenders for a number of routes in the Outer Dublin Metropolitan Area[33] and along the Kildare Commuter Corridor[34] while Bus Éireann secured the tender for the Waterford City bus services[35].

3.2 Profile of the urban PSO fleet

3.2.1 Fleet size

Dublin Bus

Dublin Bus is currently the largest PSO urban bus fleet operator in Ireland with 987 buses in operation at the end of 2018 serving the GDA. This figure comprises of 985 double-deck vehicles and 2 midibuses.

Bus Éireann

Bus Éireann is currently the second largest PSO urban bus fleet operator in Ireland with 210 buses in the Regional City fleet. Bus Éireann operate a mixture of single deck, double deck and midi-bus type vehicles; at the end of 2018 the Bus Éireann Regional City fleet served Cork with 120 buses, Galway with 36 buses, Limerick with 30 buses and Waterford with 24 buses.

Go-Ahead Ireland

Go-Ahead Ireland operates 125 buses on Dublin Metropolitan Area PSO routes; 40 single-deck buses and the remaining 85 double-deck.

3.2.2 Fleet euro class profile

Euro Class standards are the main way of classifying vehicles into emission categories across the EU, with the Euro VI standard currently representing the most efficient and lowest-emitting engine for HDVs. All PSO buses in Ireland are purchased to the highest Euro class standard at the time of procurement, such that:

- new buses registered in the period 2003-2006 were obliged to be compliant with the Euro III Class standard;
- new buses registered in the period 2007-2009 were obliged to be compliant with the Euro IV standard;
- new buses registered between 2012-2013 were obliged to be compliant with the Euro V standards; and

[iii] Data on Go-Ahead reflects the fact that the company has only recently commenced to operate as a PSO service provider.

- new buses registered since 2014 are compliant with only Euro VI standards.

Therefore, the Euro class profile of the bus fleet reflects the fleet's vehicle age profile.

Dublin Bus fleet

Euro VI Class standard buses represent 47% of the current Dublin Bus fleet (Table 3.1), with the majority of vehicles in operation adhering to earlier Euro standards.

Table 3.1: Number of Dublin Bus buses per Euro class standard

Euro Class Standard III	Euro Class Standard IV	Euro Class Standard V	Euro Class Standard VI	Total
201 (20%)	174 (18%)	148 (15%)	464 (47%)	987

Source: NTA, Dublin Bus

Bus Éireann fleet

54% of Bus Éireann Regional City buses at end-August 2018 are Euro VI vehicles (Table 3.2) with the remainder of the fleet (just over 46%) consisting of older vehicles falling within the Euro III-V classes.

Table 3.2: Number of Bus Éireann buses per Euro class standard

Location	Euro Class Standard				Total
	III	IV	V	VI	
Cork	6 (5%)	42 (35%)	10 (8%)	62 (52%)	120
Galway	0	14 (39%)	4 (11%)	18 (50%)	36
Limerick	0	8 (27%)	7 (23%)	15 (50%)	30
Waterford	0	5 (21%)	0	19 (79%)	24
Total	**6**	**69**	**21**	**114**	**210**

Source: NTA, Bus Éireann

Go-Ahead Ireland fleet

The Go-Ahead Ireland fleet mainly consists of Euro VI-class vehicles (90%), with the remainder meeting Euro V standards (Table 3.3).

Table 3.3: Number of Go-Ahead buses per Euro class standard

Euro Class Standard V Single-Deck	Euro Class Standard V Double-Deck	Euro Class Standard VI Single-Deck	Euro Class Standard VI Double-Deck	Total
0	12 (10%)	40 (32%)	73 (58%)	125

Source: NTA

3.2.3 Fleet renewal rates

During the economic downturn, investment in public transport was curtailed leading to low vehicle renewal rates and a consequent aged fleet. Therefore, there are fewer Euro V standard vehicles and a high number of older vehicles (Euro III and IV classes) in the current operating fleet than would be expected if there had been continuous steady fleet replacement rates. In 2016, the average age of the Dublin Bus fleet was 7.5 years (a rise from an average of 6.8 years old in 2010); the Bus Éireann Regional City fleets were on average 6.3 years old for the same period (from a 2010 average of 4.8 years old). It is worth noting that this trend has closely mirrored the broader European context. A survey conducted by the European Environmental Agency (EEA) found that the average age of road vehicles in Europe increased since 2000; with an average age for buses across the EU-28 of 9.4 years in 2014[36]. The annual replacement rate for double deck buses in Dublin Bus is approximately 100 buses per annum; as economic activity and consequent demand for public transport services increases, fleet expansion must also be considered.

3.2.4 Depot locations

Well-located depots are essential to the effective and sustainable deployment of the bus fleet and required to provide high-quality bus services; additional bus depot capacity may be required as the bus network expands. Depots are currently mainly located in inner city urban sites and a significant part of any expansion requirement will be to support greater provision of bus services in suburban areas. This will require the NTA working with bus operators, local authorities and others to safeguard existing capacity as well as recognising the potential need for future depot changes and reviewing suitable locations.

Dublin Bus

Dublin Bus currently operates from 7 depots serving all GDA routes (Figure 3.1 overleaf). The depots located at Donnybrook (235 buses), Harristown (209 buses) and Phibsborough (177 buses) house the largest number of vehicles (24%; 21%; and 18% of the overall Dublin Bus fleet respectively); with lower storage capacity at Ringsend (110 buses: 11%), Conyngham Road (97 buses: 10%), Clontarf (81 buses: 8%) and Summerhill (80 buses: 8%).

Bus Éireann

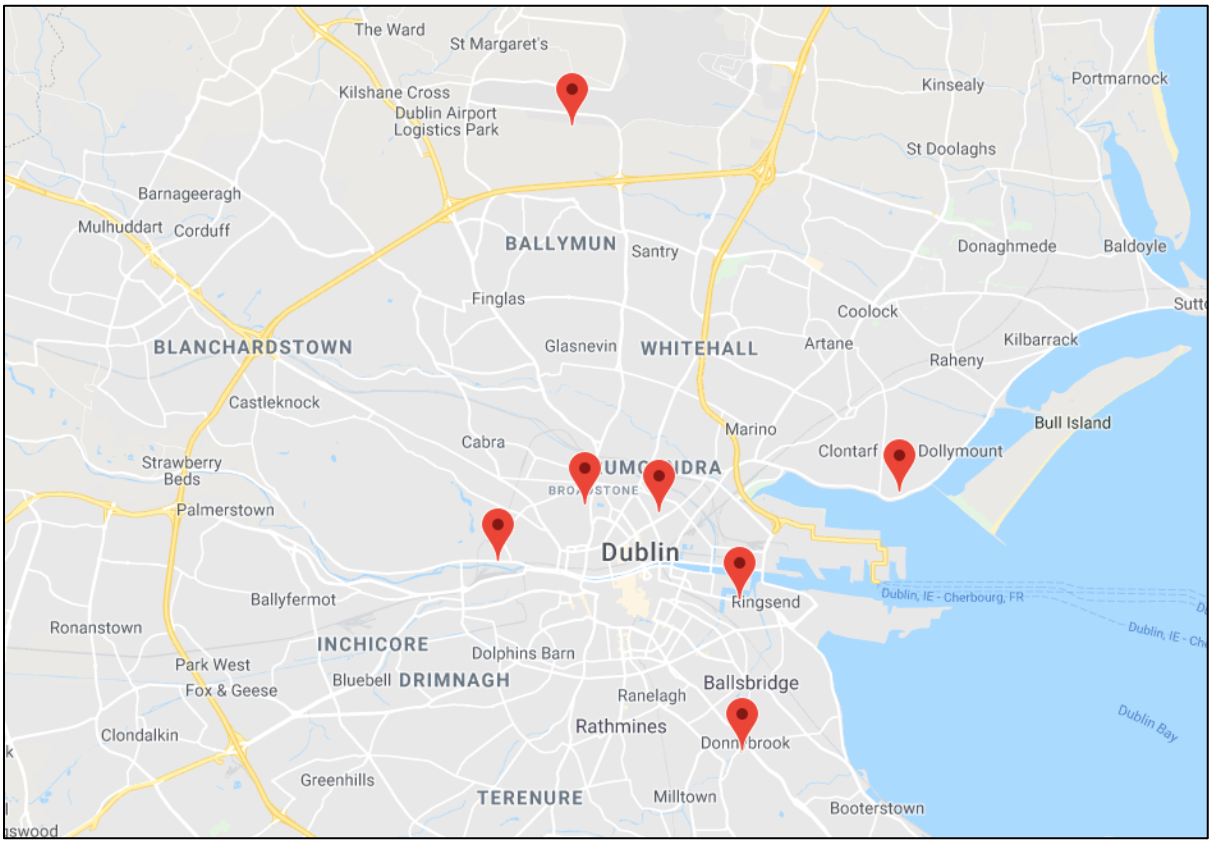
There is currently one Bus Éireann depot located in each of the regional cities of Cork (Capwell), Galway (New Docks Road), Limerick (Roxboro) and Waterford (Ferrybank) (Table 3.4).

Table 3.4: Number of buses at each Bus Éireann regional city depot

City	Depot	Number of Buses
Cork	Capwell	120
Galway	New Docks Road	36
Limerick	Roxboro	30
Waterford	Ferrybank	24

Source: NTA

Figure 3.1: Dublin Bus depot locations



<u>Go-Ahead Ireland</u>

The Go-Ahead depot (125 buses), serving GDA routes, is located near Walkinstown.

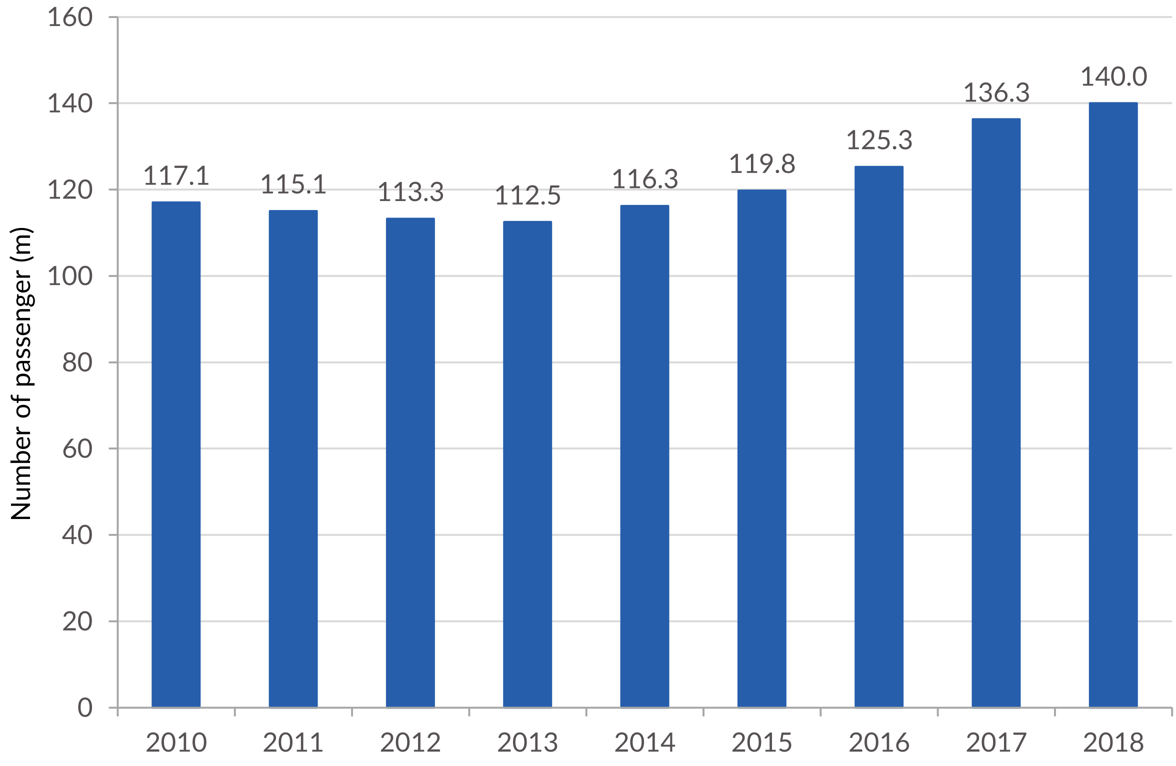
3.2.5 PSO passenger numbers

Transport is a derived demand and annual public transport passenger numbers closely reflect Ireland's economic activity and labour market movements in particular. Patronage on public transport declined after 2007, associated with the economic downturn, and was followed by renewed annual growth since 2012 in line with subsequent economic recovery.

<u>Dublin Bus</u>

Dublin Bus passenger numbers have increased year-on-year from a low of just over 112 million in 2013. Over 140 million passenger journeys were provided in 2018 representing an increase of over 2.8% compared with 2017 (Figure 3.2).

Figure 3.2: Dublin Bus Passengers 2010-2018



Source: NTA

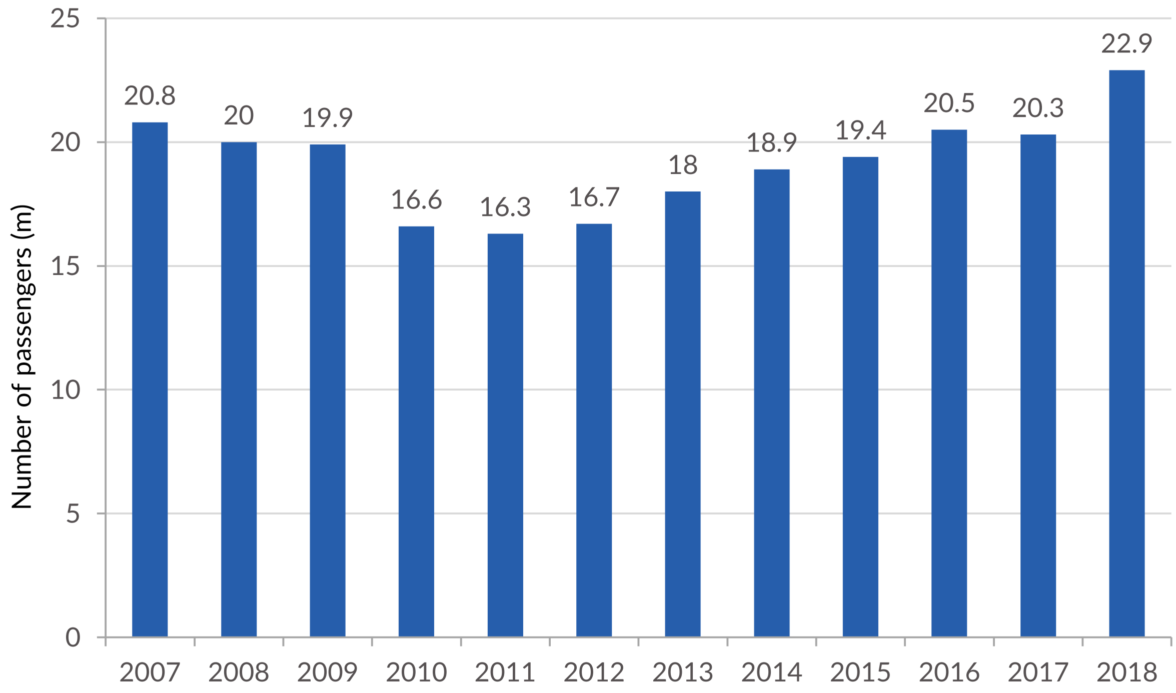
<u>Bus Éireann</u>

Bus Éireann regional cities passenger numbers similarly show a strong correlation to economic activity; with a steep decline in usage following a 2007 peak and an increase from 2013-2018 (Figure 3.3). Bus Éireann passenger numbers on regional city services decreased in 2017 from 2016 figures[iv] with return to a peak figure of *c.* 22.9 million in 2018.

Due to substantial differences in population and areas of operation, each Bus Éireann Regional City fleet carries considerable fewer passengers than Dublin Bus per annum. Just under 23 million passengers journeys were made between the four regional fleets in 2018, with Cork City carrying the highest number of users (just under 13.9 million), followed by Galway (*c.* 4.7 million), Limerick (*c.* 3.5 million) and Waterford (*c.* 830,000) (Figure 3.4).

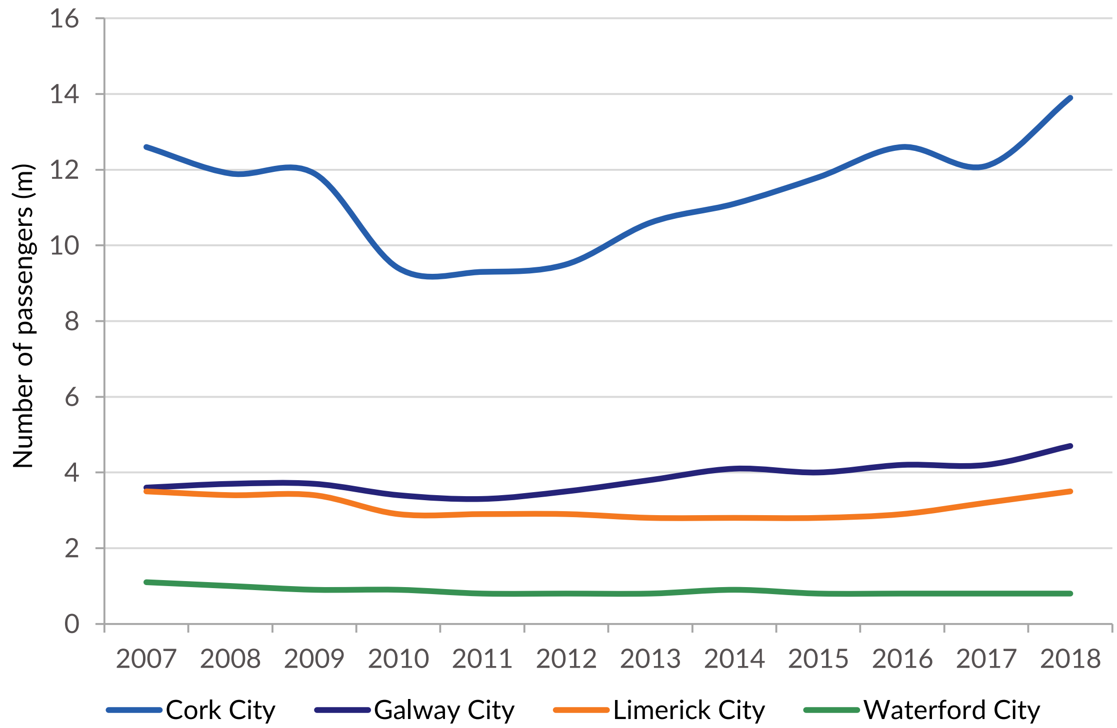
[iv] Analysis suggests that the decrease in 2017 figures can largely be attributed to a 21 day suspension of service as a result of industrial action. On a like-for-like basis, the underlying trend in the annual number of passenger journeys was a 6.8% increase in 2017 compared to 2016.

Figure 3.3: Bus Éireann Regional City fleet passenger numbers, 2007-2018



Source: NTA, Bus Éireann and CSO

Figure 3.4: Bus Éireann Regional City passenger numbers, 2007-2018



Source: NTA, Bus Éireann, CSO

3.2.6 Passenger flow

Dublin Bus

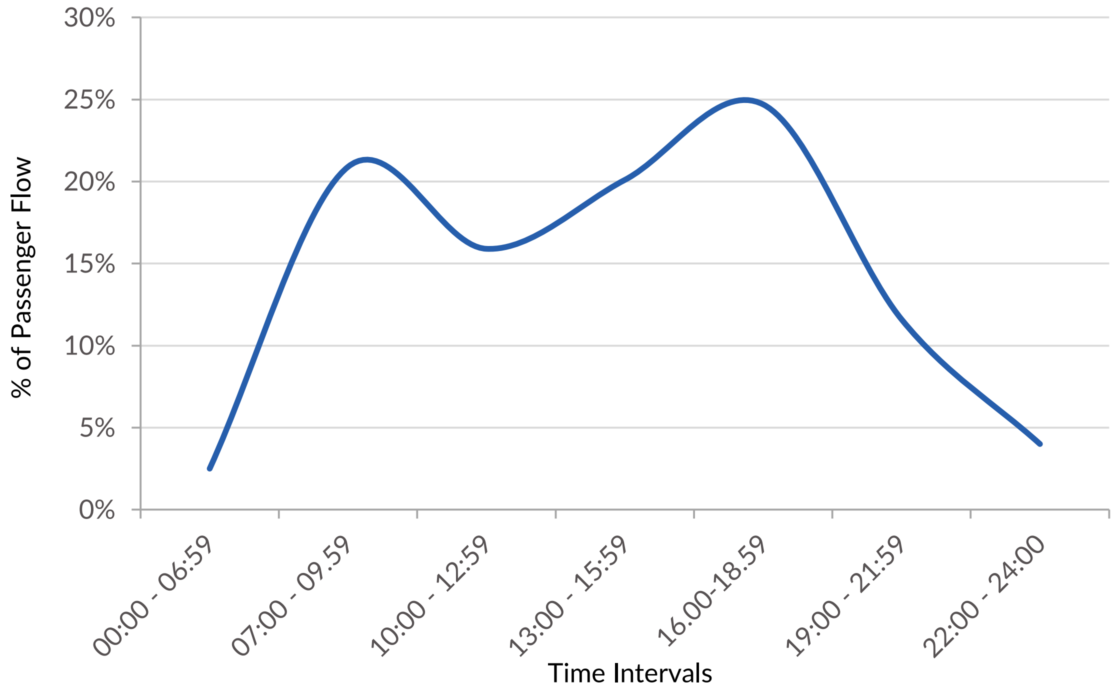
In 2017, passenger flow on Dublin Bus averaged between *c.* 400,000 to 450,000 weekday journeys (Table 3.5). Heaviest bus use was recorded on Thursdays with an average of over 454,000 passengers; fewest passengers travelled on weekends with a significant drop-off on Sundays (200,378). Consequently, Saturday services typically utilised only *c.* 55% of the fleet with Sunday services requiring only approximately 40% of the fleet. On weekdays at peak hours, *c.* 87% of the total fleet is in service; off-peak this falls to just under 65%. The busiest time on the bus is between 7am and 9am; and later in the day between 4pm and 6pm, corresponding to core commuter travel. Unsurprisingly, Midnight to 7am (NightBus services) is the period of lowest service use (Figure 3.5).

Table 3.5: Average daily flow of Dublin Bus passengers, 2017

Day of the Week	Dublin Bus Passenger Numbers
Monday	395,241
Tuesday	435,395
Wednesday	447,695
Thursday	454,196
Friday	447,024
Saturday	296,485
Sunday	200,378
Total	**2,676,404**

Source: CSO

Figure 3.5: Passenger use on Dublin Bus, 2017 (average percentage of passengers per time interval)



Source: CSO

Bus Éireann

Weekly passenger number data for Bus Éireann Regional City services show a similar daily pattern to that of Dublin Bus (Table 3.6) and is relatively consistent across the four cities. All cities show a marked decrease in passenger numbers on weekends; notably Waterford City where Sunday service operations were extremely limited until end-2018, with full Sunday services commencing operation in December of that year.

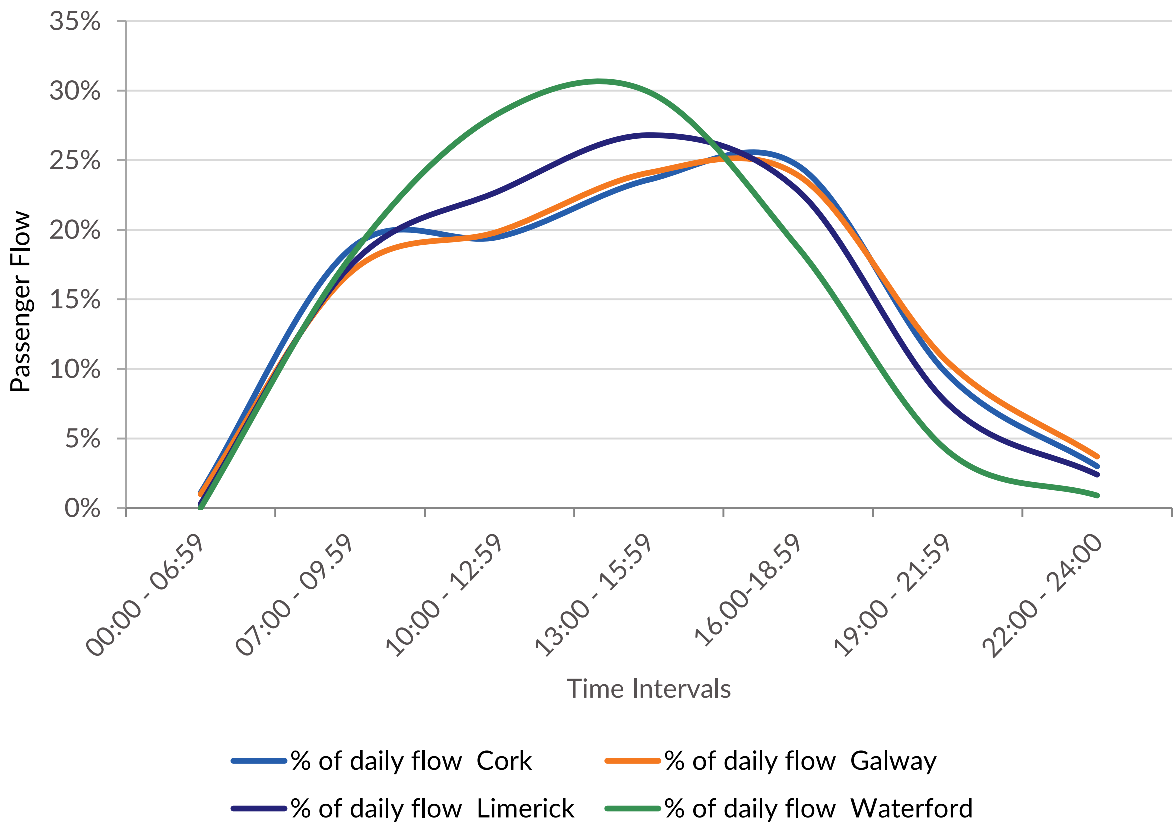
Table 3.6: Average weekly flow of Bus Éireann passengers by city services and day of week

Bus Éireann Regional City Passenger Numbers				
	Cork City	**Galway City**	**Limerick City**	**Waterford City**
Monday	33,172	11,639	8,749	2,154
Tuesday	38,258	13,165	10,015	2,537
Wednesday	39,440	13,445	10,369	2,641
Thursday	39,839	13,739	10,761	2,805
Friday	39,621	13,220	10,538	2,709
Saturday	26,517	9,611	7,377	1,533
Sunday	15,053	5,484	3,364	3
Total	**231,900**	**80,303**	**61,173**	**14,382**

Source: CSO

The daily passenger flow data for Cork City services mirror those experienced in Dublin Bus with most passengers carried during the morning and evening commute times (Figure 3.6). Limerick and Galway display similar passenger flow patterns with nearly 20% of passengers using the service in the morning commute period, followed by a slow but steady increase in passenger trips up until a peak at about 7pm. Waterford demonstrated a constant increase in passenger numbers from the beginning of service to later afternoon (4pm) followed by a steady decline.

Figure 3.6: Passenger flow pattern of Bus Éireann Regional City Services in 2017 (average percentage of passengers per time interval)



Source: CSO

4 Assessment of alternative fuels and technologies

4.1 Assessment approach

From July 2019 Ireland has committed to no longer buying diesel-only buses for the urban public bus fleet[2]. To supplement purchasing decisions a qualitative and quantitative (Sections 4 and 5) evaluation of a range of alternative fuels and technologies was conducted to indicate the potential suitability of different systems; an initial review of the appropriateness in different locations was also undertaken (Section 6). The following alternative fuels/technologies were considered: full electrification, diesel-electric hybrid, compressed natural gas, biogas/biomethane, biodiesel, bioethanol, hydrotreated vegetable oil (HVO) and hydrogen. The alternatives were compared across a number of criteria, namely: CO_2 emissions, AQ emissions (particularly NO_x and PM), infrastructural requirements, fuel supply limitations, vehicle and infrastructure costs, and their ability to contribute towards RES-T and clean public procurement targets. Details of the qualitative evaluation can be found in Appendix 1. A summary of the findings is presented below.

4.2 Diesel

In light of the policy position that no diesel-only buses will be purchased for the urban public bus fleet from July 2019, diesel is presented here solely to provide a comparator against which the other fuels/technologies can be measured. Currently, 100% of all public urban buses are diesel powered. On average, diesel vehicles tend to emit fewer CO_2 emissions than petrol equivalents due to higher engine efficiency[37].

AQ emissions in diesel heavy-duty vehicles have improved markedly through the implementation of more rigid Euro standards. The widespread implementation of Euro VI standards has greatly decreased levels of pollutants emitted from buses. The transition from Euro V to Euro VI diesel buses has seen a reduction in NO_x emissions of *c*.75%, primarily due to the use of "exhaust after-treatment" systems, and *c*.66% reduction in PM emissions through the use of diesel oxidation catalysts and particle traps. Modern diesel vehicles are fitted with particulate filters to reduce PM emissions but they require specific driving conditions and regular maintenance to perform optimally. Operating the filter technology is associated with increased maintenance and service costs.

The contribution of diesel to RES-T targets is wholly dependent on the proportion of biodiesel employed in the fuel mix. Incremental increases in the biofuel blend rates have progressively incorporated more sustainable fuel into the national mix, positively contributing towards renewable energy objectives; however, 'blend walls' (the maximum proportion of biofuel that can be added to conventional fuel before manufacturer's warranties are affected) may be breached with significant increases in biofuel concentrations, possibly limiting diesel's RES-T potential.

Table 4.1: Assessment summary of Euro VI diesel bus performance in the existing PSO bus fleets, using the traffic light system. For greater details refer to Appendix 1

(Green: considerable improvement; Amber: moderate improvement; Red: dis-improvement; Shaded cells represent disagreement in the literature.)

(Technology readiness colour code system: Green: readily available on the market; Amber: limited/emerging market; Red: very restricted market availability.)

(CVD colour code system: Green: Considered zero-emission under the Directive; Amber: Considered 'clean' [low-emission] under the Directive; Red: Not considered 'clean';
Amber shaded cells represent that fuels will be considered 'clean' if they are sourced from sustainable feedstocks under RED II; Red shaded cells indicate that only some variants of the technology i.e. plug-in hybrids will be considered 'clean' technologies).

Diesel Buses	Summary
CO_2 Emissions	Baseline CO_2 emission levels to which all other fuel/technology types will be compared.
Air Quality (AQ)	Euro VI standards have decreased levels of AQ pollutants compared to earlier Euro standards.
Infrastructure	No additional infrastructure required in depots to refuel diesel buses.
Fuel Supply Availability	Continued complete reliance on imported fuel.
Costs	Relative to other alternatively fuelled vehicles, diesel buses are the cheapest option; however, maintenance costs associated with newer filter technologies (Euro VI engines) have increased in recent years.
RES-T	Contribution towards RES-T is dependent on the proportion of biodiesel in the fuel mix and is potentially limited by the 'blend wall'; although blends with 'drop in' sustainable diesel options could present an alternative solution.
Technology Readiness	Technology is readily available; existing fleet renewal practices replace oldest diesel buses in the fleet with Euro VI models as standard.
CVD	Diesel buses may not be counted towards minimum low-emission or zero-emission procurement targets under the *Clean Vehicles Directive*.

4.3 Full electric

Full electric buses do not have combustion engines and instead rely entirely on batteries for power. Batteries are charged by connection to an external power source; EV buses also have regenerative braking enabling energy recapture during deceleration[38]. A range of recharging systems can be employed (pantographic, inductive, and overnight) but may necessitate upgrading the local electricity network to accommodate increased power demands. The operating range and route flexibility of electric buses is greatly influenced by battery capacities and recharging strategies. The driving range of EV buses is also heavily dependent on gradients, on-board ancillary systems (heating and cooling systems) and driving styles. Traditionally, electric buses were single-deck vehicles as heavier vehicles could not easily be supported by the batteries; however, improving battery efficiencies has meant that electric double-deck buses are currently being trialled in cities such as Paris, Leeds, York and London[39]. Depending on vehicle design, the size and location of battery packs can negatively impact passenger carrying capacity. At present, electric buses have significantly higher acquisition costs than conventional diesel buses (*c.* 100% price premium); however it can be expected that prices will decrease as the technology develops. Battery replacement and associated recharging infrastructure costs can be expensive. Conversely, fuel-cost savings are considerable.

Electric buses do not produce tailpipe emissions. Under the established European CO_2 emission accounting mechanism, EVs can be considered as zero emissions within the non-ETS sector. Emissions from electricity generation are captured under the ETS scheme. The role of renewable sources of electricity generation in reducing national CO_2 emissions will become increasingly important as EV numbers increase. Renewable inputs into the national grid are expected to continue growing with an aim of 40% renewables by 2020[40]; achieving and surpassing this level of renewable electricity would enable electric buses to positively contribute towards RES-T targets. Electric buses have no direct tailpipe AQ emissions (depending on demand of auxiliary systems); however, non-exhaust emissions still persist, from brake and tyre wear, and may be exacerbated by the increased mass of the vehicle. It should be noted that all vehicles, regardless of fuel or technology, will emit non-exhaust emissions.

Table 4.2: Assessment summary of electric urban buses compared to a Euro VI diesel equivalent, using the traffic light system. For greater details refer to Appendix 1

Electric Buses	Summary (compared to diesel Euro VI buses)
CO_2 Emissions	Electric vehicles emit zero direct tailpipe CO_2 emissions.
Air Quality	Large reductions in NO_x and SO_X emissions – dependent on fuel consumptions of some auxiliary systems; reductions in PMs.
Infrastructure	Recharging infrastructure will be required on route or at depots/termini; infrastructure may limit route planning flexibility; grid may require upgrading to meet additional demand for electricity.
Fuel Supply Availability	Renewable electricity generation is increasing; however, sufficient renewable electricity to power an entire bus fleet may not be available without additional measures.
Costs	Significantly higher acquisition costs (100% price premium). Infrastructural costs are likely to be substantial. Battery replacements are also likely. Fuel costs, operating and maintenance costs will be lower than diesel.
RES-T	Potential to positively contribute towards RES-T as the proportion of renewable electricity on the national grid increases although overall impact (due to fleet size) will be limited.
Technology Readiness	Single-deck electric low-floor buses are readily available; double-deck electric bus technology is in market infancy.
CVD	Electric buses may be counted towards minimum zero-emission procurement targets under the *Clean Vehicles Directive*.

4.4 Electric/Diesel hybrid

A conventional hybrid vehicle is one which uses two different energy sources, in the automotive industry, the term ‘hybrid’ is typically used to refer to hybrid electric vehicles (HEVs), which combine an internal combustion engine with one or more electric traction motors and an on-board electrical energy storage system (OESS). Diesel is the most common fuel used to power bus hybrids, but ethanol-CNG hybrids have also been developed. There is a wide range of hybrid technologies in operation with the most common engines classified as either ’series’ or ’parallel’, differentiated on the batteries ability to supplement or replace the mechanical drive. In both series and parallel hybrids the OESS is charged by energy recovered during braking, reducing the load on the engine thereby saving fuel and reducing CO_2 emissions. On-board control systems determine the most efficient source for the energy (i.e. OESS and/or engine) at any given time, with the state of charge of the OESS being a key determinant. Plug-in hybrid electric vehicles (PHEVs), on the other hand, contain OESSs that can be charged both from an on-board engine, brake regeneration and from an external power source.

All hybrid technologies have the potential to provide emissions-free operation, the duration is influenced by the extent to which the electric motor is in use, and is strongly affected by topography, travel speed and driving styles. Newer models tend to be fitted with OESSs with greater electrical energy storage capacity permitting the vehicle to cover significant parts of a bus route in full electric mode. CO_2 emissions and AQ pollutants are still released when the bus operates on diesel[41]. Reductions in emissions are directly linked to reduced diesel consumption; similarly, their ability to contribute towards the RES-T target varies depending on the degree of operation in full electric mode. Conventional hybrid buses, where electricity is produced only through regenerative braking, are limited to biodiesel’s contribution towards renewable targets.

Hybrid-electric buses have higher upfront acquisition costs (*c.* 30% price premium) in comparison with conventional diesel equivalents, in addition to higher maintenance costs associated with employing dual fuel technologies and the potential need for battery replacements. No additional infrastructure is required for conventional hybrids. PHEVs tend to employ external charging, although this is likely to be a less substantial requirement than that associated with full electric buses and could be limited to overnight charging if required. Fuel savings in the range of 30%-40% per annum have been reported[42].

Table 4.3: Assessment summary of diesel hybrid urban buses compared to a Euro VI diesel equivalent, using the traffic light system. For greater details refer to Appendix 1

*(CVD colour code system: Red shaded cells indicate that only some variants of the technology i.e. plug-in hybrids will be considered 'clean' technologies).

Electric/Diesel Hybrid Buses	Summary (compared to diesel Euro VI buses)
CO_2 Emissions	Zero emissions in electric mode; limited benefit to CO_2 emissions when operating on diesel. CO_2 emissions may even be higher in diesel mode due to the extra weight of the vehicle.
Air Quality	Reductions in pollutants can be up to 30% (in line with reduced use of diesel).
Infrastructure	No additional refuelling or recharging infrastructure is required for conventional hybrid vehicles; PHEVS tend to require access to external recharging.
Fuel Supply Availability	Hybrid vehicles operate in diesel and electric modes; therefore slight reduction on dependence on fuel imports due to lower consumption rates.
Costs	30% price premium. Operational and maintenance costs likely to be higher due to potential replacement of the electric battery and additional maintenance associated with operating dual fuel systems. Annual fuel savings of approximately 30% are possible.
RES-T	Contribution through the use of biodiesel when operating in engine mode. PHEVs have the potential to positively contribute towards RES-T as the proportion of renewable electricity on the national grid increases although overall impact (due to fleet size) will be limited.
Technological Readiness	Hybrid bus technology is readily available.
*CVD**	Plug-in hybrid buses may be counted towards minimum low-emission procurement targets under the *Clean Vehicles Directive*; conventional hybrid buses will not be considered 'clean' and may not be counted.

4.5 Compressed Natural Gas (CNG)

CNG is an established source of transport fuel with over half a million natural gas-fuelled vehicles in use across Europe, of which 6.8% are buses. It shares similar operating and refuelling characteristics to the current diesel fleet[43]. A varying range of CO_2 and AQ emission values has been reported in numerous studies but it is well established that emission reduction potential can be substantially increased if CNG is blended with biogas (Section 4.6). Reported NO_x emissions savings from manufacturers and trials undertaken in European cities range from 30% to 90% in comparison with diesel engines[44,45,v] with significantly lower SO_X emissions. Since natural gas is a fossil fuel, the deployment of 100% CNG in the bus fleet would not contribute towards meeting

[v] Data derived from KPMG market consultation undertaken on behalf of the NTA.

RES-T targets. There is potential for CNG/biogas blends to positively contribute if the biogas is produced in a sustainable and certified manner.

CNG vehicle acquisition costs are *c.*20% more expensive than conventional diesel buses, but potential fuel savings in the medium term can be significant due to the continuing Government commitment (since 2015) to maintain the excise rate for natural gas and biogas at the EU minimum rate for 8 years. Operational and maintenance costs are broadly similar to those of Euro VI diesel buses. Infrastructural costs are potentially considerable, with installation of a refuelling point estimated over €500,000 and maintenance of the refuelling point over €30,000 per annum[46]. Connection to the grid at depots and need for gas extraction equipment must also be considered. The developing network of publicly-accessible CNG refuelling stations could act as an auxiliary refuelling network to depot installations. There is currently indigenous natural gas extraction[47] but in the medium term a reversion to imported gas would be required.

Table 4.4: Assessment summary of CNG urban buses compared to a Euro VI diesel equivalent, using the traffic light system. For greater details refer to Appendix 1. *Shaded text indicates uncertainty within the literature

CNG Buses	Summary (compared to diesel Euro VI buses)
CO_2 Emissions	Limited CO_2 emission savings potential*
Air Quality	Potential substantial reductions in NO_X and SO_X; varyingly linked to high emissions of CO, hydro-carbons (particularly methane) and VOCs.
Infrastructure	Refuelling infrastructure required. Access to gas grid in all cities and direct connection at depots may be possible; publicly accessible refuelling network on the Trans-European Transport Network (TEN-T) Corridor will be available through GNI's Causeway Project.
Fuel Supply Availability	Indigenous production is possible in short term; potential to incorporate biogas as longer term solution.
Costs	Vehicle acquisition costs 20% higher than diesel. Significant potential fuel cost savings against diesel due to application of minimum excise rate until *c.* 2022. Similar operational and maintenance costs over bus lifecycle. No requirement for diesel exhaust fluids such as Ad Blue or maintenance of diesel particle filters. Costs for installing infrastructure at depot are estimated to be high.
RES-T	Deployment of 100% CNG does not contribute towards RES-T targets.
Technological readiness	Gas is a mature technology in the bus sector; readily available (suppliers mainly in left-hand drive market).
CVD	CNG buses may be counted towards minimum low-emission procurement targets under the *Clean Vehicles Directive*.

4.6 Biogas/Biomethane

Household or agricultural organic waste, sewage sludge, grass silage, and manure can all be used to make biogas through a process termed anaerobic digestion (AD). AD is a naturally occurring process where bacteria act upon moist organic material and decompose it into biogas as well as the nutrient rich digestate[48]. Biogas can be upgraded to biomethane (vehicle fuel quality) by changing the CO_2 content; the upgraded biomethane can then be purified to match defined natural gas specifications, allowing it to be injected directly into the national gas grid. Energy generated from biogas is considered to be CO_2 neutral, as the CO_2 released by combusting biogas fuel was previously removed from the atmosphere during the development of the biomass through photosynthesis. Real CO_2 emission savings from biomethane are dependent on the feedstocks utilised in production, with manure, energy crops, sewage and municipal organic waste representing the greatest emission savings[49]. The choice of feedstocks (namely animal manure and sewage sludge) can also positively contribute to Ireland's renewable energy targets by promoting advanced biofuel use.

Biomethane use can reduce pollutant emissions compared to diesel powered engines below the emission levels expected from the use of biodiesel and bioethanol[50] (see Section 4.7). Notably, biomethane as a vehicle fuel emits up to 95% less PM, with some studies also showing decreases in NO_x compared to Euro VI diesel emissions standards[51]. In addition, as a non-sulphurous fuel biomethane produces virtually no SO_x emissions. Data in relation to emissions from CNG/biomethane blends is not readily available; however, it can be reasonably assumed that improved savings occur in line with the proportion of blended biomethane into the fuel mix.

There are approximately 14,000 AD digesters operating throughout Europe[52]; large-scale biogas/biomethane production does not currently exist in Ireland and it is unlikely that levels of commercially available indigenously-produced gas would be sufficient to fuel the entire public transport in the short-term. The SEAI estimate that 28% of all gas supplies by 2050 can be replaced by biogas if further investment is made in AD.

It is assumed that vehicle acquisition costs for biogas buses are identical to CNG-fuelled buses (*c.* 20% premium). Infrastructural, operational and maintenance costs accrued over the lifecycle of the vehicles would likewise be similar to CNG-fuelled buses. Similar depot infrastructure to Section 4.5 would be required. In relation to potential fuel cost savings, Gas Networks Ireland (GNI) estimates that a blend of CNG and biogas/biomethane in the ratio of 80:20 represents a cost-efficient solution (54% fuel spend savings) for fuel consumers and provide 34% CO_2 savings (based on 100 buses operating over a period of one year). As biomethane can be directly 'dropped in' for CNG, there is potential for higher blends, up to 100%, which would offer significantly higher savings in CO_2 but markedly reduce fuel spend savings.

Table 4.5: Assessment summary of biomethane fuelled urban buses compared to a Euro VI diesel equivalent, using the traffic light system. For greater details refer to Appendix 1

*(CVD colour code system: Amber shaded cells represent that fuels will be considered 'clean' if they are sourced from sustainable feedstocks under RED II)

Biomethane Buses	Summary (compared to diesel Euro VI buses)
CO_2 Emissions	Considered CO_2 neutral; represents 100% reduction in carbon emissions.
Air Quality	Potential pollutant reduction compared to diesel, notably in SO_X and PM.
Infrastructure	Refuelling infrastructure and AD plants required. Access to gas grid in all cities and direct connection at depots may be possible; publicly accessible refuelling network on TEN-T Corridor will be available through GNI's Causeway Project.
Fuel Supply Availability	Limited production in Ireland at present but strong indigenous production capacity from grass and waste sources; mature technology in Europe - importation possible.
Costs	Vehicle acquisition costs 20% higher than diesel. Cost of fuel blends with biomethane higher than CNG alone. GNI estimate 100% biomethane represents only *c.* 5% cost savings against diesel fuel. Lifecycle costs for operation and maintenance would be similar to CNG fuelled vehicles.
RES-T	When produced from feedstocks included in Appendix 4 of the recast RED, biomethane can be considered an advanced biofuel and make a significant contribution towards RES-T.
Technological readiness	Gas is a mature technology in the bus sector; readily available (suppliers mainly in left-hand drive market).
*CVD**	Biomethane buses may be counted towards minimum low-emission procurement targets under the *Clean Vehicles Directive* only where it is produced from sustainable feedstocks under Annex IX (a) of the *Renewable Energy Directive* 2018/2001/EU.

4.7 Biofuels

Biofuels are renewable transport fuels produced from biomass material[53]. They are manufactured from a wide range of materials including sugarcane, wheat and corn, and also from waste materials such as used cooking oils (UCOs) and tallow. Key biofuels for the Irish transport sector include:

- biodiesel – typically deployed blended with mineral diesel and used in diesel-powered vehicles;
- bioethanol – typically blended with gasoline and used in petrol vehicles;
- hydrotreated vegetable oil (HVO) – can be used as a direct replacement or 'drop-in' for diesel; and
- biomethane – can be deployed for use in natural gas vehicles (Section 4.6).

In general, the processing methods and the choice of feedstocks utilised in biofuel production measurably impacts upon the CO_2 reduction potential. In 2018, biodiesel sold in Ireland was produced from Category 1 Tallow, UCOs, spent bleached earth and palm oil mill effluent (POME)[54], which are lower CO_2 emitting feedstocks (although it is to be noted that palm oil of which POME is a by-product is a higher emitting feedstock). Bioethanol is often considered a “first-generation” or “crop-based” biofuel because the feedstocks used in its production, such as corn, wheat, sugar cane and sugar beet, can result in high ‘well-to-wheel’ emissions once emissions associated with indirect land-use change are considered[55]. While in HVOs the high-energy content, purity levels and lack of contaminants tend to yield significant CO_2, SO_x, NO_x and PM emission reductions. CO_2 tailpipe savings of up to 75% have been reported. Consumption of biofuels in low blends in the national fuel mix is likely to have little impact on air quality.

For the 2018 obligation period, the majority of the feedstocks used to produce biofuel for the Irish market were sourced from China (21.5%), followed by Spain (15.1%); *c.* 11.3% was sourced indigenously[53]. Biofuels are deemed as a limited resource[56] with the main limiting factor in biofuel feedstock production being a threat to food supply. Corn and soybean crops, for example, which occupy significant land areas and require considerable water resources, do not produce enough energy per acre to meet current fuel needs without compromising the food chain and causing negative indirect land-use change (ILUC). The extraction of some feedstocks, such as POME, will effectively increase lifecycle carbon emissions as a result. It is worth noting however that almost 62% of all the biofuel placed on the market in Ireland for the 2018 obligation period was produced from UCOs, which is considered a waste product.

It is possible to directly use lower blend rates of some biodiesel in unmodified diesel engines; however, higher blends can only be used where a specific warranty has been provided by the vehicle manufacturer. Bioethanol (95% ED95) is a non-substitutable fuel which cannot be used as a blend with any other fuel and would require parallel refuelling infrastructure or flexi-fuel pumps to be installed at bus depots. HVO (at any blend rate up to 100% substitution) does not require any changes to vehicle engines or associated refuelling infrastructure (minor modifications may be required e.g. heating/insulation).

There is a price premium for biofuels in comparison with diesel[54]. Biodiesel and HVO have the potential to strongly contribute towards meeting RES-T targets when derived from waste-based feedstocks; however, bioethanol is typically produced from first generation feedstocks with high ILUC emissions like sugar cane, maize and wheat, which do not meet the sustainability criteria in the recast RED. As a result, a bioethanol fleet, unless produced solely from approved feedstocks such as straw, can make a very limited contribution to RES-T targets to 2030.

Table 4.6: Assessment summary of biofuelled urban buses compared to a Euro VI diesel equivalent, using the traffic light system. For greater details refer to Appendix 1

*(CVD colour code system: Amber shaded cells represent that fuels will be considered 'clean' if they are sourced from sustainable feedstocks under RED II)

Summary (compared to diesel Euro VI buses)	Biodiesel	Bioethanol	HVO
CO_2 Emissions	CO_2 emissions dependent on feedstocks. Tailpipe emissions lower than conventional diesel fuels.	CO_2 emissions dependent on feedstocks. Tailpipe emissions can be lower than conventional petrol fuels.	HVO can reduce tailpipe CO_2 emissions by up to 75%.
Air Quality	Reduction in PMs and CO; however PM can increase in 'cold-start-operations (i.e. in winter months).	Some reduction in CO, PMs and hydrocarbons; limited impact on NO_X.	Significant reductions in NO_x, PM and CO, dependent on blend ratios. 100% reduction in SO_x.
Infrastructure	At current blend rates no additional infrastructure would be required. Can be blended only during summer months.	Parallel refuelling infrastructure or flexi-form pumps would be required.	HVO is a 'drop-in' fuel and requires no additional refuelling infrastructure. Can be used year round.
Fuel Supply Availability	The majority of biodiesel in use in Ireland is currently imported. This is likely to continue, although Irish refineries could potentially produce biodiesel.	Limited ED95 fuel production in Europe.	There is some limited HVO refinement in Ireland at present; in use in a number of European fleets so import is possible.
Costs	Price premium associated with biodiesel. Lifecycle costs analogous with Euro VI diesel buses. At higher blend rates more frequent changes of filter are required.	Limited market availability of vehicle suppliers would negatively impact on acquisition costs. Price premium on fuel costs. No data available on operational and	HVO fuel is more expensive than conventional diesel; no additional associated infrastructure, operational or maintenance costs.

Summary (compared to diesel Euro VI buses)	Biodiesel	Bioethanol	HVO
		maintenance costs over the vehicle lifecycle.	
RES-T	'Blend wall' limits potential contribution towards RES-T targets. Dependent on feedstocks outlined in RED Appendix IX; not wholly Appendix IX compliant at present.	Contribution towards RES-T targets dependent on feedstocks outlined in RED Appendix IX; not wholly Appendix IX compliant at present.	HVO can be produced entirely from feedstocks contained within RED Appendix IX and can therefore be classed as an advanced biofuel and make a significant contribution towards RES-T targets.
Technological Readiness	Some diesel engines cannot operate biodiesel beyond blend wall within warranty; limited availability of biodiesel-suitable engine technology; limited availability.	One EU-based vehicle supplier (left-hand drive market); limited availability.	HVO is suitable for Euro VI diesel bus technology; readily available.
CVD*	Biodiesel buses may be counted towards minimum low-emission procurement targets under the *Clean Vehicles Directive* only where it is unblended with fossil fuels and produced from sustainable feedstocks under Annex IX (a) of the *Renewable Energy Directive* 2018/2001/EU.	Bioethanol buses may be counted towards minimum low-emission procurement targets under the *Clean Vehicles Directive* only where it is unblended with fossil fuels and produced from sustainable feedstocks under Annex IX (a) of the *Renewable Energy Directive* 2018/2001/EU.	HVO buses may be counted towards minimum low-emission procurement targets under the *Clean Vehicles Directive* only where it is unblended with fossil fuels and produced from sustainable feedstocks under Annex IX (a) of the *Renewable Energy Directive* 2018/2001/EU.

4.8 Hydrogen

Hydrogen is often envisaged as a major element of the future transport fuel mix due to its very high specific energy content and significant potential to provide clean, efficient power. It is proposed that hydrogen use could limit oil dependency, enhance energy security, and reduce greenhouse gas emissions and air pollution. When hydrogen is generated from solar or wind electrolysis to power fuel cell electric vehicle (FCEVs) there are zero total life-cycle CO_2 emissions and the process is fully independent of fossil fuels. Hydrogen fuel-cell vehicles contain no carbon, produce virtually no exhaust emissions when combusted or used in a fuel cell (excepting water vapour) and therefore can make a positive contribution to urban air quality. Hydrogen can be produced from a range of different energy sources such as natural gas, petroleum products, coal, solar and wind electrolysis, and biomass. Therefore, a positive contribution to targets for the share of renewable energy in transport can potentially be achieved when the hydrogen is produced from approved feedstocks or from renewable electricity. If hydrogen is produced from fossil fuels sources, it cannot be counted towards RES-T targets and may negatively impact on the overall proportion of renewable energy used within the transport sector.

As hydrogen is still an immature technology, transport fuel, vehicles, infrastructure and on-going operation and maintenance costs have not been thoroughly investigated to date. Hydrogen buses have a very high acquisition price premium; although, it is estimated that the proposed more stringent CO_2 vehicle standards will increase the market share of hydrogen vehicles in the coming years. Conservative estimates position infrastructure costs (on a per gigajoule GJ basis) at potentially 5 times higher for hydrogen relative to electricity, with this figure decreasing to double by 2030 (under the assumption that utilisation rates substantially increase as the technology develops). A single refuelling station capable of refuelling *c.* 2-3 buses per hour costs approximately €800,000[57] (excluding fuel production facilities). There is no hydrogen refuelling infrastructure in operation in Ireland with few commercial organisations capable of constructing or bearing the cost of a stand-alone hydrogen project. Initiatives that could speed up the introduction of hydrogen production, refuelling infrastructure and certain types of vehicles in Ireland in a concerted way could potentially allow hydrogen to be brought under consideration earlier.

Table 4.7: Assessment summary of hydrogen-fuelled urban buses compared to a Euro VI diesel equivalent, using the traffic light system. For greater detail refer to Appendix 1

Hydrogen	Summary (compared to diesel Euro VI buses)
CO_2 Emissions	Zero CO_2 tailpipe emissions; 100% reduction in comparison with diesel buses.
Air Quality	Virtually zero tailpipe emissions.
Infrastructure	No existing hydrogen refuelling infrastructure in Ireland; few commercial organisations capable of constructing or bearing the cost of a stand-alone hydrogen project.
Fuel Supply Availability	Hydrogen not currently available as a transport fuel in Ireland. Hydrogen production across Europe extremely limited.
Costs	Vehicle acquisition and initial fuel and infrastructure costs likely to show significant price premiums over diesel fleets. Data on on-going maintenance and operation costs is not available.
RES-T	If hydrogen is produced from solar, wind, or from biomass produced from feedstocks in RED Appendix IX it could potentially contribute to RES-T targets.
Technological readiness	Hydrogen transport fuel production, infrastructure and technology are in market infancy.
CVD	Hydrogen buses may be counted towards minimum zero-emissions procurement targets under the Clean Vehicles Directive

5 Economic evaluation

5.1 Introduction

An economic evaluation has been undertaken to assess the estimated costs and benefits associated with the introduction of various potential alternative fuels/technologies into the bus network. This analysis comprises two components, a qualitative comparison of the different fuel types under a number of criteria for both single-deck and double-deck buses, and a modelled quantitative examination of these alternative fuels to compare their phased introduction into an existing fleet. Under these analyses the pre-*NDP* "Business As Usual" case was included as a baseline for comparative reference. Hydrogen was excluded from the analysis owing to both the limited maturity of the technology and the lack of real world vehicle and refuelling data for the bus sector.

5.2 Qualitative evaluation

An overall qualitative assessment of the different fuel types available for buses provides a general overview of their respective strengths and weaknesses. Information used is based on both real-world instances of these vehicles in use and from information provided by the vehicles' manufacturers. Given the relatively short time for which some of the bus technologies have been in use, this type of assessment only gives an indicative summary of what benefits and costs could be involved, and what potential policy and infrastructural challenges are posed by each of the available fuel-types. The criteria in this analysis included costs (acquisition, maintenance and fuel), range, infrastructure requirements and availability. Results are presented in Table 5.1.

The principal conclusion from this qualitative analysis is that the fuel types that cost most to introduce and maintain have the lowest fuel use. This presents policy decision-makers with a trade-off between costs incurred and emission savings made; this interchange will also be influenced by infrastructure, capacity, and technological considerations. For example, a 100% biogas bus service may have similar acquisition, maintenance and fuel costs with significant reductions in carbon emissions relative to diesel but this scenario may be hindered by a lack of capacity in biogas production or the extensive costs involved in updating infrastructure for fuelling the new buses.

Table 5.1: Qualitative assessment of alternative fuels for buses relative to diesel

	Diesel	Diesel/Electric Hybrid	Compressed Natural Gas	CNG/Biogas blends	Biogas	Electricity
Acquisition Costs (per bus)	Assuming *c*.€330k for Double-Deck Bus	125% cost of Diesel Bus (*c*.€413k)	120% cost of Diesel Bus (*c*.€396k)	120% cost of Diesel Bus (*c*.€396k)	120% cost of Diesel Bus (*c*.€396k)	200% cost of Diesel Bus (*c*.€660k)
Annual Operating Costs (per bus), incl. vehicle maintenance	Assuming *c*.€21k	133% cost of Diesel (*c*.€28k)	Similar costs as Diesel (*c*.€21k)	Similar costs as Diesel (*c*.€21k)	Similar costs as Diesel (*c*.€21k)	200% cost of Diesel (*c*.€42k)***
Annual Fuel Costs (per bus)	Assuming *c*.€31k	30% reduction (*c*.€22k)	42% reduction (*c*.€18k)	80/20 = 35% reduction (*c*.€20k) 50/50 = 22% reduction (*c*.€24k)	Similar costs to Diesel (*c*.€31k)	70% reduction (*c*.€10k)
Range*	Assuming 500km	300km – 800km	200km – 500km	200km – 500km	200km – 500km	150km – 300km (enhanced with on-street charging opportunities)
Infrastructure Requirements	On-site fuelling at bus depots.	No major changes in infrastructure requirements.	Fuel equipment: *c*.€1.2m per 100 buses; Maintenance per unit is *c*.€35k p.a.	Similar infrastructure requirements as CNG. Biogas production capacity will need to be expanded to ensure that it could meet growing demand from the bus fleet.	Similar infrastructure requirements as CNG/Biogas blend options.	Infrastructure required incl. purchase of chargers & upgrade of network connection to depots. On-street charging could supplement charging at depot but cost, tech & logistical considerations.
Availability: No. of Manufacturers making buses**	Multiple Manufacturers	Double Deck: 5 Single Deck: 3	Double Deck: 2 Single Deck: 4	Double Deck: 2 Single Deck: 4	Double Deck: 1 Single Deck: 4	Double Deck: 2 Single Deck: 10

* Range estimates assume full fuel tank or full battery charge.

** The availability criteria related to the number of manufacturers or distributors that had confirmed in an NTA-commissioned survey that they could supply buses for each of the fuel/technology types.

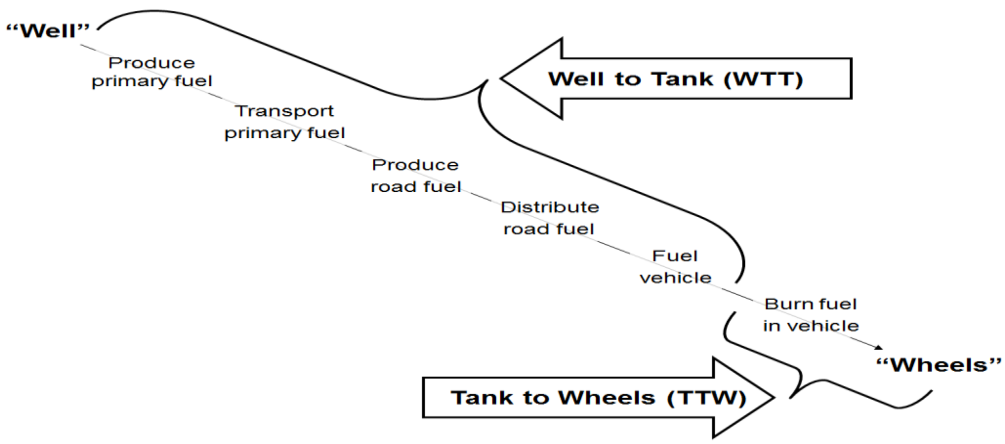
*** Includes replacement battery cost

5.3 Quantitative evaluation

5.3.1 Calculation of Well-to-Wheel vs. Tailpipe emissions analysis

Well-to-Wheel (WTW) analysis is a lifecycle analysis of the efficiency of a transport fuel pathway from source to final fuel or power consumption; it spans resource extraction, fuel production, delivery of the fuel to vehicle, and end use of fuel in vehicle operations. WTW analysis is typically understood as two distinct stages: analysis of those emissions generated during the fuel or power production process, known as Well-to-Tank (WTT); and analysis of those emissions generated during fuel or power consumption, known as Tank-to-Wheel (TTW) or 'tailpipe' emissions. For hydrocarbon fossil fuels such as diesel, gas and biofuels, tailpipe emissions typically represent the greater share[58], although lifecycle emissions are still significant. Lifecycle analysis is more important for electric and hydrogen modes as these vehicles have zero tailpipe emissions, the majority of the associated GHG emissions occur in the well-to-tank phase during the production and distribution of the energy sources[59].

Figure 5.1: Graphic representation of Well-to-Wheel analysis[60]



The analysis presented in this paper solely addresses TTW (tailpipe) emissions; this does not dispute the importance of undertaking a comprehensive WTW analysis of each technological pathway considered in this paper. Any such WTW analysis would outline the impacts of each technology on the global climate challenge and would consider the sustainability of total energy chains, including, in the case for biofuels, indirect land-use change emissions associated with cropland expansion. WTW examination would require national rather than sectoral level participation; therefore, within the limited scope of this paper, consideration of tailpipe emissions represents a more tangible method to identify lower emitting alternatives for buses in an Irish context. In the interim, WTW analyses of various alternative fuels and powertrains have already been undertaken at a European level and will provide a valuable complementary perspective to the analysis outlined in this paper[61].

5.3.2 COPERT analysis

This Section presents the methodology employed to calculate the emission levels from the current public transport bus fleet as well as potential changes in the emission profile through the use of alternative fuel options and technology using the Environmental Protection Agency (EPA)-approved COPERT (Calculation of Air Pollutant Emissions from Road Transport) software tool. COPERT is a peer-reviewed EU-standard vehicle emissions calculator, developed for official road transport inventory preparation for European Environment Agency (EEA) member countries at national-or-state-level, which assumes that emissions from a given vehicle are essentially a function of its average speed. This software tool was identified as the most suitable vehicle emission model for the work undertaken for this paper for a number of reasons, including but not limited to the following:

- Emissions of significant pollutants from road transport are calculated;
- Major vehicle classes, including buses (M3) are included;
- It is applicable to Ireland as an EU and EEA Member State; and
- It can be used to calculate transport emissions from 1970-2030[62].

COPERT requires detailed input data such as fuel consumption, trip information (trip length, trip duration), activity (speed, mileage and mileage share), fleet configuration (number of buses of each fuel type and technology class) and environmental information (monthly average relative humidity and monthly average minimum and maximum temperature) to calculate emissions and energy consumption for specific countries or regions. For this work, the emission levels of CO_2, NO_x, total suspended PM and $PM_{2.5}$ were calculated in tonnes using COPERT 5.2.1[63], the current iteration of the software at the time.

The effect on emissions of transitioning the urban bus fleet was assessed under five scenarios in comparison with a baseline case representing the pre-*NDP* policy position of replacing older diesel buses with Euro VI diesel buses. The input figures were based on average Dublin Bus journey and load data from 2017 and the results presented are based solely on Dublin Bus fleet metrics using the current composition and complement (1,157 buses), average journey speeds and travel times. Dublin Bus data is employed in this analysis as this operator carries out the majority of Ireland's urban bus travel in the PSO sector, accounting for 84.4% of the PSO national urban bus fleet in 2017 and 87% of all bus passenger journeys. Analysis of Bus Éireann data is presented in Section 6 of this paper where the influences of regional city journey characteristics are considered separately in order to establish a consistent baseline against which to compare scenarios. Meteorological data from the weather station at Dublin Airport were also employed (monthly averages from 1985–2015).

The analysis was carried out for two distinct timeframes (2023 and 2030) that align with the *BusConnects* ambition that 50% and 100% of the bus fleet within the GDA will be alternatively fuelled by these respective dates. It was assumed that the older diesel buses (Euro III and IV) were the first to be replaced with the newer alternatives.

The Dublin Bus 2017 fleet comprised of:

- 408 x Euro III;
- 20 x Euro III tri-axle;
- 150 x Euro IV;
- 50 x Euro IV tri-axle;
- 160 x Euro V; and
- 369 x Euro VI.

Under the 2023 scenarios, where 50% of the older fleet is replaced with an alternatively fuelled alternate, the fleet composition was assumed to be:

- 578 x alternatively-fuelled buses;
- 30 x diesel Euro IV;
- 70 x diesel Euro IV tri-axle;
- 110 x diesel Euro V; and
- 369 x diesel Euro VI.

In 2030, it was assumed that the entire fleet is alternatively fuelled.

COPERT can calculate emissions from diesel, biodiesel and CNG buses for different Euro technology classes; unfortunately, COPERT does not estimate emissions from hybrids and biogas blends and so these were calculated separately. In addition, COPERT 5.2.1 does not model Euro VI CNG buses but instead models EURO enhance environment-friendly vehicle (EEV) CNG buses which are akin to Euro VI; a study conducted by Trinity College Dublin, in an earlier version of COPERT, reported no comparable difference when modelling both bus types. It is important to note that under TTW emission methodologies EVs are considered to be zero emission vehicles, although there is on-going research to attempt to determine non-exhaust emissions[64]. For this reason EV buses were excluded from the following analysis.

The scenarios considered for this quantitative analysis were:

- **Base Case (S1):** The business-as-usual situation before the policy decision to cease buying diesel-only buses post July 2019 is presented as a **comparative baseline**. In this baseline scenario older buses in the fleet are incrementally replaced by Euro VI models with the assumption that in 2030 the fleet would entirely consist of Euro VI diesel engine buses. Emissions were calculated using COPERT.

- **Scenario 2 (S2):** This scenario represents the introduction of **CNG** into the fleet, systematically replacing diesel models. Emissions were calculated using COPERT.

- **Scenario 3 (S3):** This scenario represents the introduction of **100% biodiesel** buses into the fleet, gradually replacing the diesel buses. Emissions were calculated using COPERT.

- **Scenario 4 (S4):** This scenario represents the introduction of CNG/biomethane fuelled buses into the fleet. The blend rate chosen was **80:20 CNG:biomethane**. The CO_2 emissions were assumed to be zero at tail pipe for the biomethane element of the fuel mix; the emissions from the CNG proportion of the fuel were based on S3 estimates.

- **Scenario 5 (S5):** This scenario represents the introduction of **CNG/biomethane** fuelled buses into the fleet with a blend rate of **50:50**. Again, zero-tailpipe CO_2 emissions were assumed for the biomethane element of the fuel mix and emissions from the CNG proportion of the fuel were based on S3 estimates.

- **Scenario 6 (S6):** This scenario represents the introduction of **hybrid buses** into the fleet, replacing diesel models. COPERT does not have the capacity to model for hybrid buses; instead average emission levels from the three most popular double deck hybrid buses currently on the market, based on the UK Low Carbon Vehicle Partnership (CVP) methodology[65] were used. The limitations of this methodology, in relation to comparisons with COPERT estimates, is acknowledged; despite the Low CVP test cycle replicating rural and inner/outer London routes, laboratory tests do not necessarily represent real world driving emissions (as previously seen with misrepresentative car emissions values from the New European Driving cycle).

Table 5.2: Summary of scenarios examined, including comparative baseline case designated 'S1'

Timeframes:	*2023*			*2030*		
Scenario	No. of buses	Fuel Type	Technology Class	No. of buses	Fuel Type	Technology Class
S1 (Baseline)	30	Diesel	Euro IV	1157	Diesel	Euro VI
	110	Diesel	Euro V			
	947	Diesel	Euro VI			
	70	Diesel	Euro IV*			
S2	578	CNG	Euro VI	1157	CNG	Euro VI
	30	Diesel	Euro IV			
	110	Diesel	Euro V			
	369	Diesel	Euro VI			
	70	Diesel	Euro IV*			
S3	578	100% Biodiesel	Euro VI	1157	100% Biodiesel	Euro VI
	30	Diesel	Euro IV			
	110	Diesel	Euro V			
	369	Diesel	Euro VI			
	70	Diesel	Euro IV*			
S4	578	CNG/Biomethane 80:20 blend buses	Euro VI	1157	CNG/Biomethane 80:20 blend buses	Euro VI

Timeframes:	2023			2030		
	30	Diesel	Euro IV			
	110	Diesel	Euro V			
	369	Diesel	Euro VI			
	70	Diesel	Euro IV*			
S5	578	CNG/Biomethane 50:50 blend buses	Euro VI	1157	CNG/Biomethane 50:50 blend buses	Euro VI
	30	Diesel	Euro IV			
	110	Diesel	Euro V			
	369	Diesel	Euro VI			
	70	Diesel	Euro IV*			
S6	578	Hybrid	Euro VI	1157	Hybrid	Euro VI
	30	Diesel	Euro IV			
	110	Diesel	Euro V			
	369	Diesel	Euro VI			
	70	Diesel	Euro IV*			

*A tri-axle vehicle has three axles and as such is typically a larger vehicle with increased weight-carrying (increased passenger) capacity.

5.3.3 Emission results

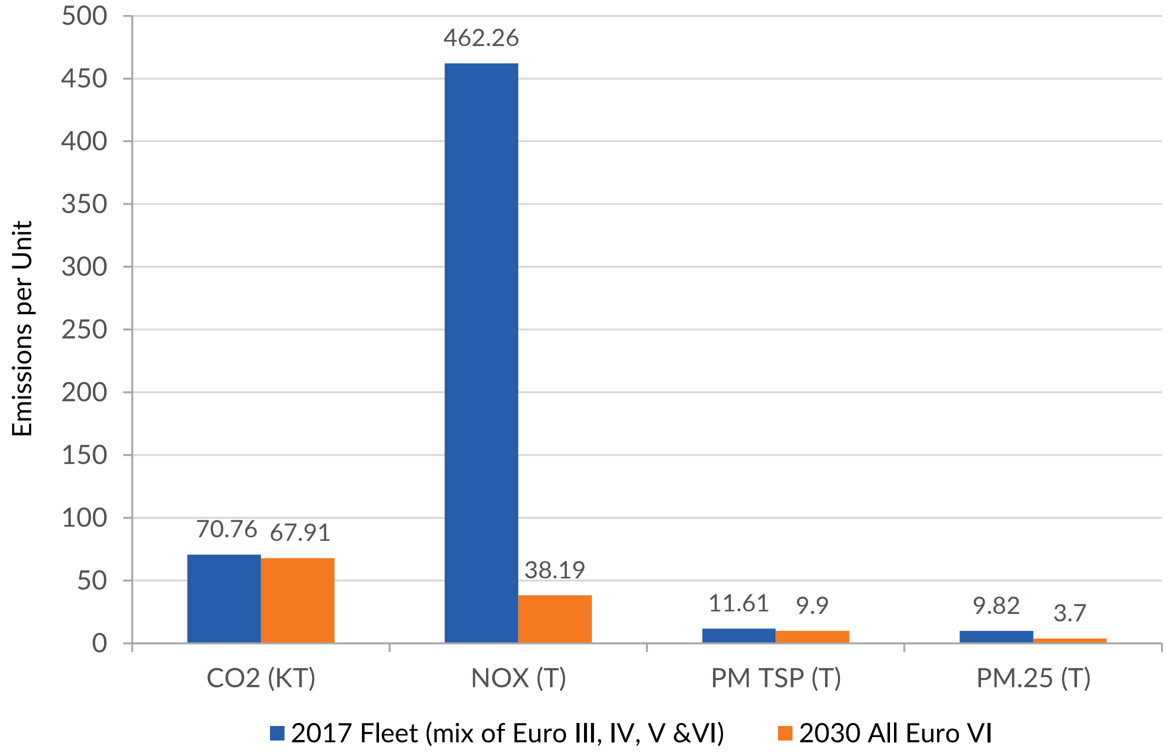
COPERT modelling software was used to estimate tailpipe emissions from the current diesel fleet, with the existing mix of Euro classes: 408 x Euro III; 20 x Euro III tri-axle; 150 x Euro IV; 50 x Euro IV tri-axle; 160 x Euro V; and 369 x Euro VI. It was estimated that the current fleet, under average journey speeds and times emitted over 70kT of CO_2, *c.*462T of NO_x and 11.6T of PM. These results are consistent with the known fuel usage by Dublin Bus, whereby approximately 27.6m litres of diesel are used to power the fleet which equates to 74.09 kT of CO_2 (using the SEAI conversion figure of 2.7 $kgCO_2$/litre).

The existing fleet data was used to establish a baseline (S1) where the fleet consisted of only Euro VI vehicles by 2030 (Figure 5.2). Comparing the Euro VI only and existing fleets showed a marked decrease in all pollutants;

- a 3.37% reduction in CO_2 emissions;
- a 38.5% reduction in PM emissions;
- a 62% decrease in PM;$_{2.5}$ and
- a significant decrease of almost 92% in NO_x levels.

These results suggest that the continued introduction of more stringent Euro classes has a significant impact on reducing fleet emissions, especially AQ pollutant emissions.

Figure 5.2: Modelled emissions for the current Dublin Bus fleet compared to a diesel Euro VI only equivalent fleet



Under the pre-*NDP* business-as-usual policy older buses were systematically replaced by newer Euro VI models (S1). Table 5.3 represents the potential emission savings from changing to alternative fuels/technologies compared to this baseline S1 scenario. This essentially allows for a *like-for-like* comparison as S1 is not static and better replicates the emission savings that would be expected to accrue in the fleet through replacing older buses with more efficient models. Moreover, it should be noted that EURO V diesel engines perform, on average, marginally better than Euro VI diesel engines in terms of CO_2 emissions; the main emissions reductions for Euro VI are observed in NOx and PM levels. This can be observed in the difference between CO_2 emissions in 2023 and 2030 for Scenario 1 in Table 5.3.

Table 5.3: Percentage difference in emission levels of a range of scenarios compared to the baseline case. Traffic light colouring system Green: improvement of over 5%; Amber: improvement up to 5%; Red: disimprovement.

Time Frame	Pollutants	Emissions (t)	% Difference compared to the baseline case (S1)				
		S1 Baseline (Diesel)	S2	S3	S4	S5	S6*
2023‡	CO_2	67,686.03	6.9%	-5.4%	-4.3%	-21.2%	-17.74
	NO_x	134.45		33.5%			-29.00
	PM	10.69		2.4%			-45.58
	$PM_{2.5}$	4.40		6.1%			
2030°	CO_2	67,908.62 *(+0.3% relative to 2023)*	12.5%	-12.1%	-10.0%	-43.8%	-38.02
	NO_x	38.19 *(-71.6% relative to 2023)*		1.1%			-86.94
	PM	9.9 *(-7.4% relative to 2023)*		-0.6%			-99.59
	PM2.5	3.7 *(-15.9% relative to 2023)*		-0.7%			

* Based on averaged UK Low CVP emissions from three double deck bus models (not modelled in COPERT)

‡ In 2023 scenarios 2,3,4,5 & 6 assume a 50/50 split in the fleet between Diesel buses and alternatively fuelled buses.

° In 2030 it is assumed that all scenarios the bus fleets are 100% the selected fuel type (i.e. Scenario 2 assumes a fleet comprising 100% CNG buses).

Note to Table 5.3: In light of an acknowledged error in the European Environment Agency's COPERT software relating to modelled AQ emissions from CNG buses - and in order to avoid undermining the integrity of the dataset - the AQ results for all gas scenarios (S2, S4 and S5) have been omitted from this paper. When the COPERT software is updated (and corrected in due course), the emission analysis could then be recalculated in a further study as required. In the meantime, to enable some relevant comparison, data on the emissions and energy consumption of a double deck ADL Scania E400 biomethane bus undergoing the Low Emission Bus Scheme Certification process at Millbrook, UK, is provided in Appendix 2 to this paper. Further relevant comparative data will also be available from the results of an alternatively fuelled bus trial undertaken within the past year to monitor real world driving emissions from a number of alternative fuels/technologies, including gas buses (see Section 5.4). Data from this trial will provide insight into gas related AQ emissions as well as acting as a meaningful comparator to the COPERT results.

Noting the limited outputs due to concerns with modelled emissions from gas buses in COPERT, based on available data this analysis suggests that the best performing scenario is S6 (Hybrids) where improvements are made for all emissions categories for which data is available in both time periods. Inclusion of the missing AQ components may impact upon this result. In the interim, the 50:50 CNG:biomethane scenario (S5) offers significant improvement in CO_2 emissions for both 2023 and 2030. The results also suggest that moderate CO_2 savings would also be achieved through a reduced CNG:biomethane blend (S4). In S3, (biodiesel comprising 50% of fleet) improvements in CO_2 emissions were noted in both time periods compared to 100% Diesel but were accompanied by an increase in NO_x emissions. PM levels in S3 improved in 2030. From this rudimentary analysis we can observe that phasing in hybrid buses may offer the best option for improving emissions, but CNG:biomethane may represent a feasible alternative if emission reductions in NO_x and PM levels are established.

It is important to highlight that this form of assessment has some limitations; notably, that it does not incorporate any expected improvements in emissions performance for any of the technologies and instead holds emission levels static to current technology levels. Lower-emitting alternatives for transport represent a rapidly developing industry and it is likely that advancements, particularly for technologies that are currently in their infancy, will further improve emission savings. In like manner, for analysis purposes, this assessment assumes that the size of the PSO bus fleet remains static over the time periods examined, however, fleet expansion is planned as part of the strategy to accommodate increasing passenger demand for public transport to 2030. Furthermore, the results of this assessment would additionally benefit from sensitivity analysis which explores alternative emissions factors compared to those pre-populated within the COPERT model.

5.4 Low-emission bus trial

In December 2018, DTTAS, in collaboration with Bus Éireann, Dublin Bus and the NTA, launched a low-emission bus trial, testing a range of full electric, hybrid-electric, hydrogen and compressed natural gas/biogas buses alongside retrofitted diesel buses under real-driving conditions. The trial was supported by the *Green Public Transport Fund* and intended to provide analysis of the fuels and technologies currently available independently of the findings of any in-service trials conducted in previous years[vi]. Using portable emissions measurements systems (PEMS) technology, the trials considered CO_2 emissions, the impacts to ambient air quality, and the potential contribution towards the sector's renewable energy targets, with each of the fuels and technologies undergoing testing compared against the most up-to-date diesel Euro VI models as a baseline. In addition, other criteria such as costs and fuel economy, market availability and the infrastructural requirements for each technology were also examined, with drivers providing

[vi] Dublin Bus conducted in-service feasibility trials of a gas-fuelled (LPG) single-deck bus in the later 1990s; a first-generation hybrid-electric bus from 2008-2012; and a current generation hybrid-electric bus in 2014. Bus Éireann trialled a CNG-fuelled bus in 2012. Rapid technological advancement in the intervening period has effectively rendered obsolete the findings of these small-scale trials; the main reason for the recent low-emission bus trial was to provide an up to date analysis on a comparative basis of the various lower-emitting alternatives that are currently available.

qualitative data on the operational experience of each drivetrain. The buses were evaluated on the Number 9 route in Dublin City and on the Number 207a route in Cork City. Both cities present different driving conditions, in relation to topography, average driving speeds and typical stopping distances which present unique challenges to the different fuels and technologies under assessment. Results for the trial, expected in late-2019, will supplement the findings of this paper and further inform future purchasing decisions for urban buses.

6 Most appropriate fuelling options for different locations

6.1 Introduction

A comprehensive review of the feasibility of alternative fuel or technology options for the bus fleet would be incomplete without considering the potential impact of location specific factors. The appropriate siting of alternative systems must ensure that both present and future passenger needs are provided for, as well as maintaining a degree of flexibility for route alterations or expansions. Some of the key considerations are:

- Typical route lengths (present and future estimates with respect to the *BusConnects* Programme);
- *BusConnects* and other schemes may lead to the re-routing of urban bus services along certain streets/roads, with associated fuelling option restrictions;
- Journey duration (current congestion levels and future projections);
- Typical daily vehicle usage patterns and return-to-depot rates (as well as likely future changes);
- Typical passenger capacity requirements (suitability of double-or-single-deck buses) and ability to cater for future travel demands;
- Capacity for refuelling/recharging facilities at depot;
- Possible implementation of demand management measures such as establishment of low and ultra-low emission zones and/or clean air zones in urban areas;
- Access to external refuelling/recharging networks along route; and
- Training and Health & Safety requirements.

6.2 Flexibility and future-proofing services

Any alternative technology transition must have the capacity to cater for increasing passenger numbers, future fleet expansion and altering bus routes. Consequently, it is imperative that purchase choices avoid inflexible 'lock-ins' that would inhibit or delay growth of the public transport network. Major operational and infrastructural changes are costly and take time; therefore, an initial transition must not preclude any subsequent transitions between technologies as this will create undesirable and expensive delays in public transport expansion. It is worthy of note that the zero-emission procurement sub-targets set out in the *Clean Vehicles Directive* to 2025 and to 2030 will necessitate significant disruption in terms of refuelling at depots regardless of the technology choice.

Medium- and longer-term procurement decisions should also consider the possibility of future traffic restrictions in certain locations and environments. To date, travel demand management measures such as low emission zones (LEZ) or ultra-low emission zones (ULEZ) have not been deployed in urban centres in Ireland. The *Climate Action Plan*[3] commits to the commission of a demand management study in order to consider the potential role of these measures to address economic congestion, air quality concerns and to reduce climate-harmful emissions in cities. This study is expected to consider key demand management drivers in an Irish context (e.g. congestion, air quality, climate considerations); review international best practices on measures such as urban congestion charging, low emission zones and parking pricing policies; and make recommendations for the most appropriate responses for Dublin, Cork, Galway, and Limerick, taking into account overall transport strategies in each case.

6.3 Quantitative evaluation

As part of the quantitative assessment of this paper, COPERT modelling using bus fleet data from the regional cities was also undertaken in an attempt to ascertain whether regional city specific driving conditions impacted on the various fuel-types' emissions performances. However, this modelling was severely restricted on two fronts: firstly, COPERT analysis is based on average journey times and speeds, as such location specific characteristics tended to be smoothed out during the averaging process; and secondly, COPERT does not hold real world emission values for single-deck CNG and biodiesel buses, which is problematic as a substantial proportion of the regional cities' fleets is currently single deck (although it should be noted that the NTA has in recent years been transitioning the urban public bus fleet in the bigger regional cities (i.e. Cork, Galway and Limerick) away from single-deck buses to double-deck buses). The limited results of the analysis are presented in Appendix 3.

6.4 Location specific considerations for transitioning urban bus fleets

6.4.1 Full electric

Depending upon journey lengths, durations and travel patterns full electric buses have the capacity to service certain urban bus routes. This form of technology may currently be better suited to shorter trips with defined routes to enable predetermined or on-route charging. Ranges of full electric buses are improving but careful timetabling and route planning would still be required to ensure continued bus services while facilitating recharging requirements. Furthermore, range uncertainty is still a concern during unpredicted events such as prolonged traffic jams or adverse weather where battery drawdown continues beyond the anticipated normal operating conditions.

Currently, the majority of buses in the urban fleet are in operation throughout the day with limited returns to the depot; this severely restricts recharging opportunities without imposing heavy operational limitations on services. Some bus routes, particularly during off-peak hours, may have greater flexibility and the capacity for more frequent charging without impacting on service provision. It is likely that additional vehicles would be required to both accommodate charging downtime requirements as well as compensating for reduced passenger capacity.

Alternative recharging solutions can mitigate the need for vehicles to return to the depot, such as the installation of opportunity charging along routes or at route termini. These solutions present other location-specific challenges, including space requirements, availability to grid connection points, and capacity of the local power supply. The installation of on-route charging infrastructure, either inductive or pantographic systems, is expensive, disruptive and inelastic. Such investments would 'lock-in' buses to agreed routes, limiting them to long-term strategic traffic arteries, such as those identified under the *BusConnects* Programme. It may not also be possible to install such infrastructure on certain routes due to space or traffic limitations (e.g. single lane roads with no layby areas).

6.4.2 Hybrid-electric

The dual fuel capacity of hybrid-electric buses lessens their reliance upon refuelling infrastructure and affords a greater degree of flexibility in route planning. The engine efficiency of hybrid-electric buses is broadly similar to that experienced with Euro VI diesel equivalents, and coupled with the capability to operate in electric mode, is unlikely to impose any significant constraints to route ranges. Hybrid-electric vehicles are particularly suitable for urban journeys where stop-start traffic conditions persist as the buses can utilise electric mode for limited periods to conserve fuel and reduce return-to depot rates. However, lower fuel efficiencies may negatively impact fuel costs and necessitate more frequent refuelling on less congested, lengthier routes where the vehicle is travelling predominately in diesel mode.

Minimal changes to existing diesel refuelling infrastructure at depots would be required in transitioning a fleet toward hybrid-electric; however, where plug-in hybrid buses are deployed, parallel refuelling and recharging systems would be required. This recharging could be provided at depot or along routes and is subject to similar operational restrictions associated with full electric buses.

6.4.3 Compressed natural gas / Biomethane

Double-deck gas buses provide similar passenger capacity and offer comparable or slightly reduced ranges to diesel-fuelled vehicles; therefore, minimal changes would be required to existing route configurations. Significant investment would be required for the initial installation of gas refuelling and compression infrastructure, with installation of a refuelling point estimated over €500,000 and maintenance of the refuelling point over €30,000 per annum[vii]. It is possible that direct connection at depot sites can be achieved, given that the GDA and regional cities are served by the existing gas grid. Evaluation of the local grid capacity would be required. In the coming years access to public gas refuelling points along the TEN-T core network could represent feasible auxiliary refuelling solutions for fleets serving GDA, Cork and Limerick.

Deployment of natural gas and biomethane confers additional benefits for depots housing multiple vehicle types, e.g. regional city depots where coaches for longer commuter journeys serving hinterlands and adjoining rural areas terminate, as these are fuels potentially suitable for deployment within the coach sector and could make use of the same refuelling infrastructure. Similarly, commercial vehicles could potentially make use of refuelling facilities if appropriate.

6.4.4 Biofuels

In terms of operational flexibility, HVO represents a strong solution as it can provide for similar ranges to conventional diesel and has no additional refuelling infrastructure requirements. As a 'drop-in' fuel, existing fleets would simply continue to undergo the present rate of replacement and expansion allowing for passenger capacity to be maintained without the need for ancillary vehicles. Single-and-double-deck vehicles can continue to be purchased as needed. Similarly for

[vii] Data derived from KPMG market consultation undertaken on behalf of the NTA.

biodiesel there are no specific infrastructural requirements that would limit its use in any particular location, although storage requirements do vary depending on the blend rate; Biodiesel (B100) would require modified and perhaps larger tanks. ED95 requires distinct refuelling infrastructure. For both biodiesel and bioethanol it is likely that current refuelling infrastructure at existing depots could be converted. There are volume implications however, as biofuels tend to be less energy efficient than conventional fuels and so more is required to travel the same distance. This consideration would likely impact on bus operation, as more frequent fuel drops or installation of additional fuel storage tanks at depot may be necessitated.

6.4.5 Hydrogen

Hydrogen fuel cell buses could potentially represent a strong option to meet urban fleet operational requirements as range is not a limiting factor thus facilitating existing route configurations. Hydrogen bus technology is still in demonstration phase and evidence is not yet widely available in relation to the market availability of single-deck and double-deck vehicles. The lack of double-deck vehicles is an issue in the context of fleet expansion, as passenger capacity will be restricted necessitating purchase of a greater number of buses. Single-deck fleets may be a feasible option for certain regional city fleets in the short term but it is likely will become inadequate in the longer term based on anticipated growth in passenger numbers. Hydrogen infrastructure is as yet not established in Ireland and refuel points at depot would be necessary in the absence of any external refuelling network. As a longer term option, transition of the natural gas grid towards hydrogen could be explored.

6.5 Effect of congestion on alternative fuels and technologies

Traffic in Ireland is on the rise leading to slower speeds and longer journeys across all of the major routes. Data from car navigation units has demonstrated that average traffic speeds on Dublin main roads during the 8am to 9am peak hour fell by almost 13.8% between 2015 and 2016[66]. The *BusConnects* programme is one of the measures being employed to help address congestion issues; it plans to develop a network of segregated 'next generation' bus corridors to ensure that journeys are faster and more reliable by public transport on the busiest routes. The NTA estimate that journey times on these routes could decrease by 40-50%.

The proportion of time a bus spends in slow-moving traffic has implications for fuel and battery use as well as idling emissions. Most technologies have incorporated start-stop systems that reduce fuel use and emissions when stationary; however, in some technologies engine efficiencies are lowest in slow moving traffic. Vehicles with an electric mode tend to perform well in these circumstances; whereas, conventional liquid and gas fuels are generally high emitting when pulling away, particularly in heavy buses.

Energy modelling reported in the *Road to Zero*, which compared a range of alternatively fuelled buses, demonstrates that emissions from buses are heavily dependent on the average driving speed. The data is based on both the LowCVP Urban Bus test cycle and Millbrook London Transport Bus Cycle. The LowCVP Urban Bus test cycle has an average speed of 22.4 km/h and reflects a mixed urban and extra-urban duty cycle (Figure 6.1); the Millbrook London Transport

Bus Cycle has a lower average speed of 14.9 km/h (Figure 6.2). The figures illustrate WTW GHG emissions (emissions from fuel production and combustion) and tailpipe emissions of nitrogen oxides (NO_x) for a range of powertrain/fuel combinations for a representative double deck bus in 2017 and 2050.

Hydrogen and full electric buses are shown to perform strongly at both the lower and higher average speeds and are expected to further improve as the technologies develop out to 2050. Euro VI diesel buses marginally outperform hybrid-electric in terms of tailpipe NO_x emissions at lower speeds, but this finding is reversed at higher speeds. Moreover, GHG emissions on a WTW basis of the hybrid bus are substantially improved relative to diesel due to the use of electricity in the powertrain. Parallel hybrid buses are not examined in this piece, but it is reasonable to expect that results would be broadly similar to those of the series hybrid. The results also indicate that CNG bus energy consumption is very sensitive to the duty cycle, at lower speeds the energy penalty relative to diesel increases and at higher speeds it reduces.

It is to be noted that the *BusConnects* programme anticipates a reduction to journey times and higher speeds as a result of the establishment of core bus corridors. Further research may be required when average urban bus journey speeds increase under *BusConnects*. The potential for the long-term introduction of bus operation systems not previously deployed in Ireland such as urban trolleybus and Bus Rapid Transit systems, which may offer additional routes towards decarbonisation, could also be examined as part of this research.

Figure 6.1: Estimated WTW GHG and tailpipe NOx emissions for a double deck bus on the LowCVP Urban Bus test cycle (average speed 22.4 km/h, indicating more free flowing traffic and extra-urban drive cycles) [1] Future projections (vehicle energy consumption held at 2017 levels) Source *Road to Zero*[63]

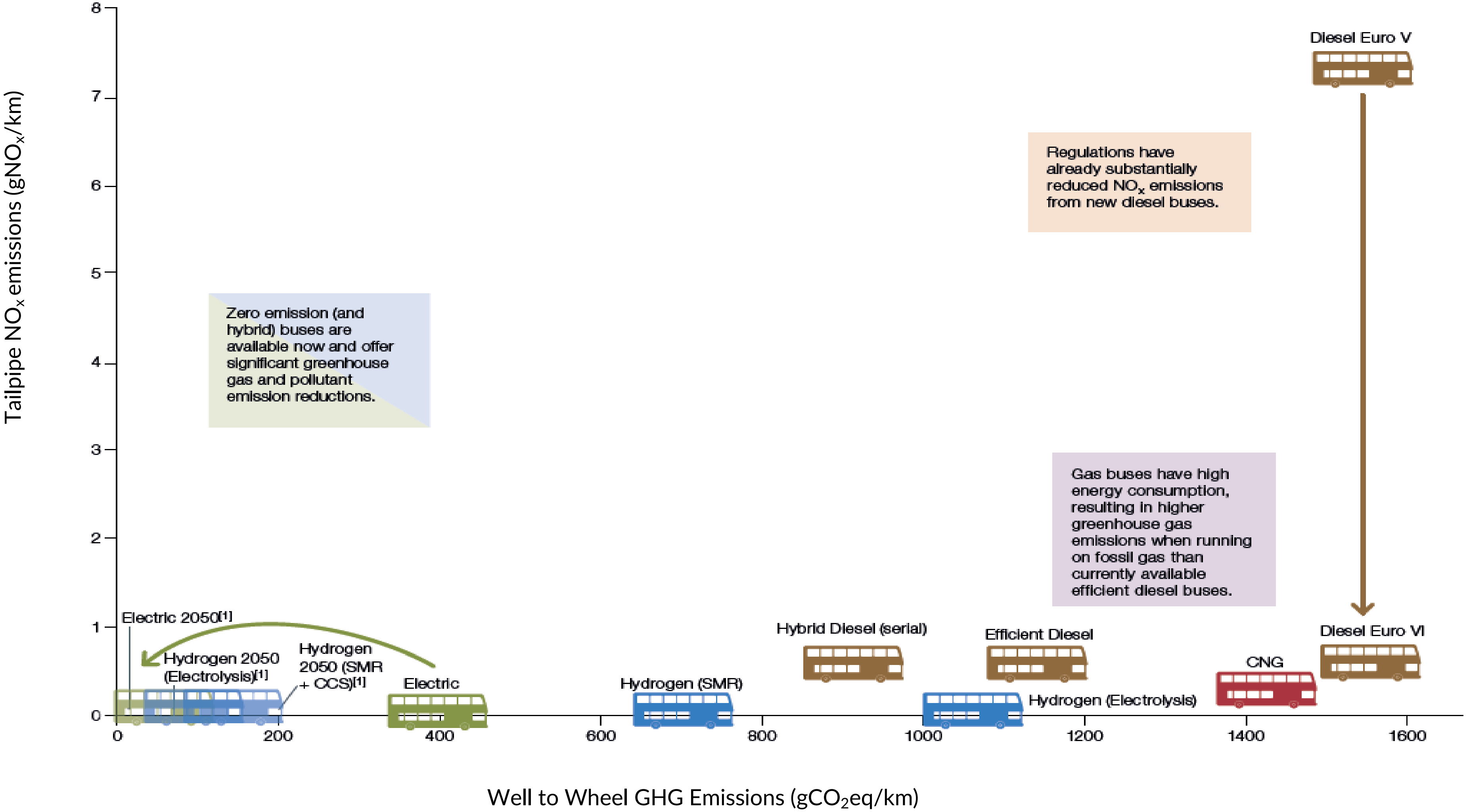
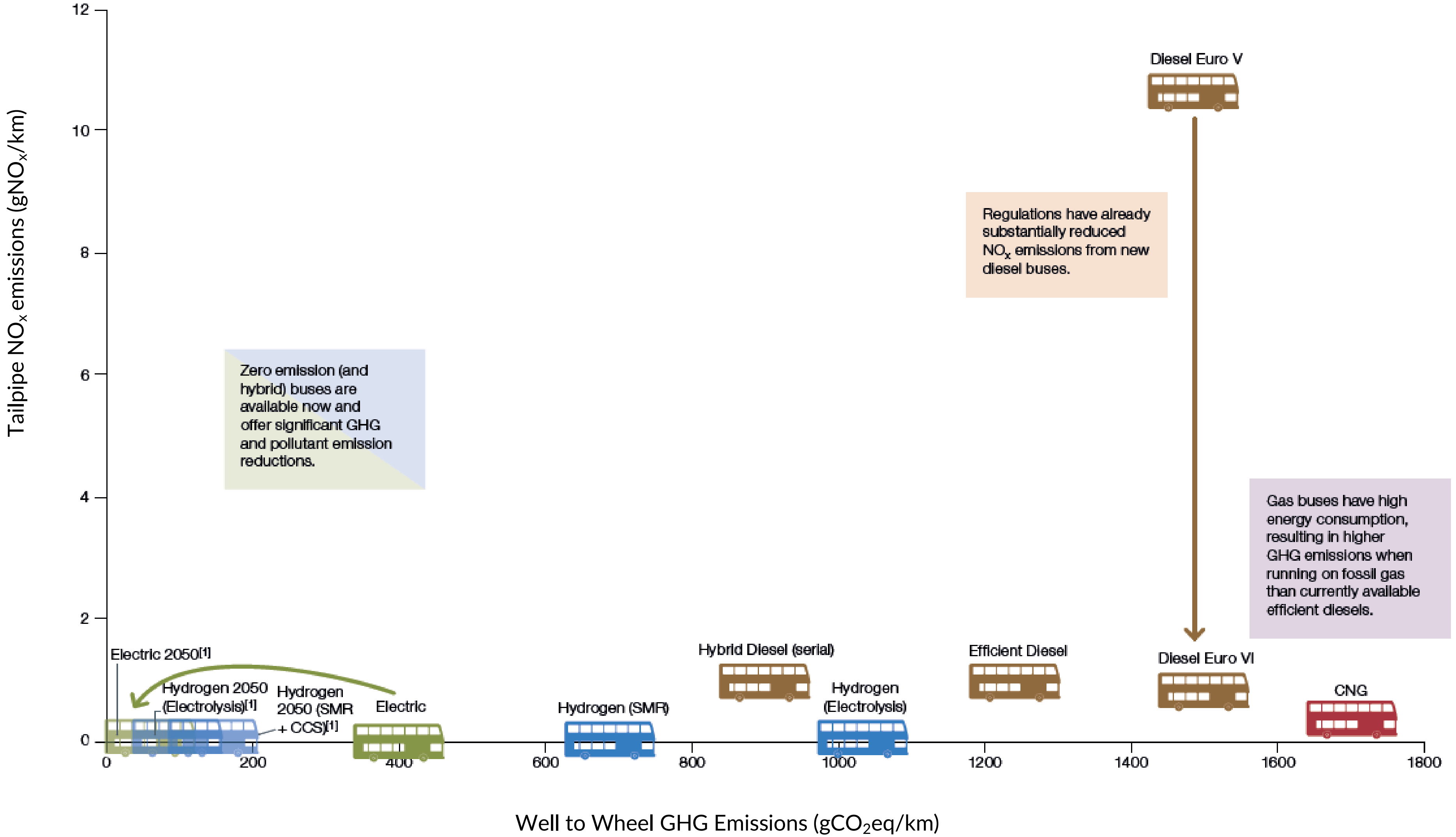


Figure 6.2 Estimated WTW GHG and tailpipe NOx emissions for a double deck bus on the Millbrook London Transport Bus test cycle (average speed 14.9 km/h, indicating slow moving traffic and heavy congestion representative of inner-city driving [1] Future projections (vehicle energy consumption held at 2017 levels) Source *Road to Zero*[63]



6.5.1 COPERT congestion modelling

COPERT modelling of CO_2 emissions was carried out for the various fuel types to evaluate their performances under different congestion levels in the Irish context. The impact of congestion levels was measured on the six scenarios detailed in Section 5.3.2 under the 2023 timeframe which aligns with the *BusConnects* ambition of 50% of the bus fleet being alternatively fuelled. Three congestion levels were modelled: (1) Base level: reflecting current average journey speeds and times in the GDA; (2) High Congestion: which assumes a continued increase in congestion with journey times and average travel speeds 30% slower than 'Base' level; (3) Low Congestion: which reflects the travel and journey time improvements expected through *BusConnects* (15% quicker journey times compared to 'Base' level). The effect of congestion on each of the respective scenarios is presented in Table 6.1 and Figure 6.3.

Unsurprisingly, CO_2 emission levels increased under the high congestion conditions and fell under the lower congestion levels for all the modelled fuels/technologies, except for S6 (Hybrids) where under lower congestion conditions CO_2 modelled emissions are expected to actually rise by *c*.2.5%. As noted previously, the emissions for S6 are derived from average UK Low CVP test cycle results so comparing the different methodologies (COPERT and Low CVP values) may account for this variance. Under higher congestion CNG demonstrated the greatest percentage change increase in CO_2 emissions, while hybrids showed the lowest percentage increase. In low congestion levels CNG had the most significant decrease in CO_2 emissions, showing that the CO_2 emission performance of the fuel to be the most sensitive to changes in traffic conditions.

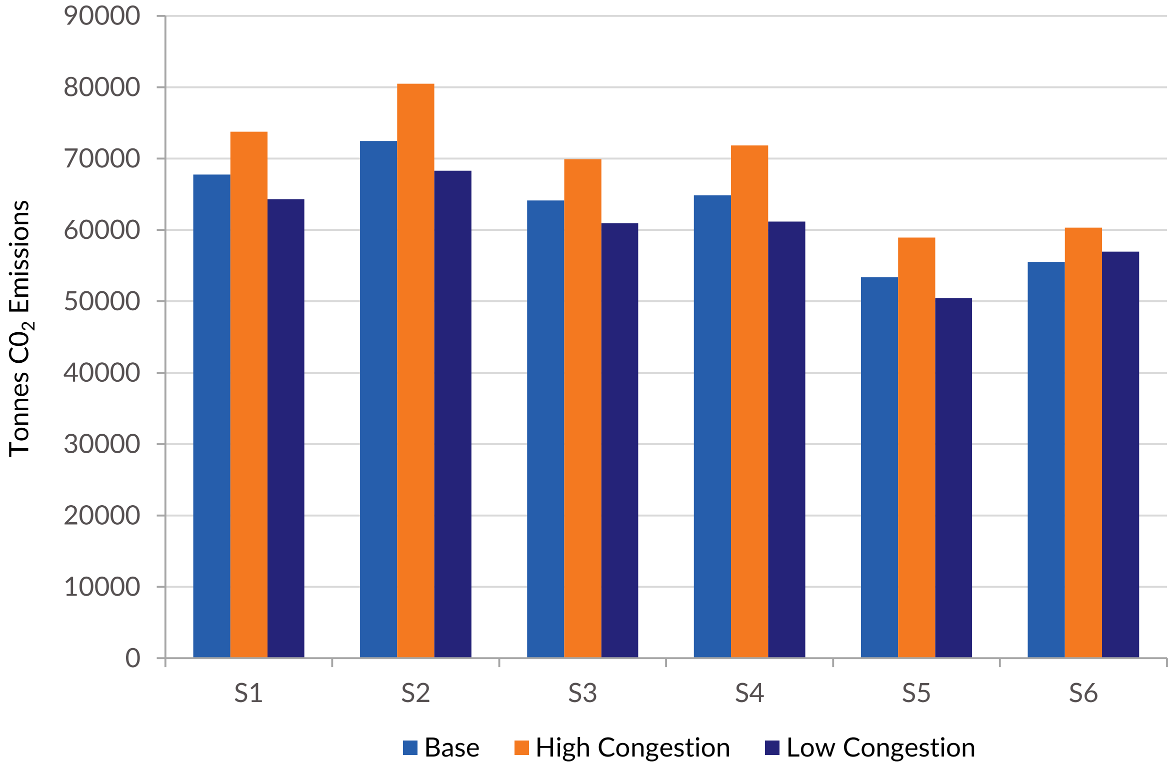
When considering absolute CO_2 emissions under both high and low congestion levels S5 (CNG:biomethane 50:50) emitted the least followed very closely by S6 (hybrids); while S2 (CNG) performed least well, emitting approximately 6,700 more tonnes of CO_2 under heavy congestion than the S1 diesel equivalent. This analysis illustrates how responsive the different fuel types are to congestion conditions as well as highlighting the importance of alleviating congestion as soon as possible.

Table 6.1: Percentage difference in COPERT modelled CO2 emissions under three different congestion levels for the 6 alternatively fuelled 2023 bus fleet composition scenarios. Traffic light colouring system: Green: improvement of over 5%; Amber: improvement up to 5%; Red: disimprovement

Scenario / Congestion	*S1 Diesel*	*S2 CNG*	*S3* 100% biodiesel	*S4* 80:20 CNG:Biomethane	*S5 50:50 CNG:Biomethane*	*S6* Hybrid*
Base	67.8 (Kt)	72.5 (Kt)	64.1 (Kt)	64.8 (Kt)	53.4 (Kt)	55.6 (Kt)
High congestion	8.9%	11.1%	9.0%	10.8%	10.3%	8.64%
Low congestion	-5.1%	-5.7%	-4.9%	-5.7%	-5.5%	2.52%

*S6 based on averaged UK Low CVP emissions from three double deck bus models (not modelled in COPERT).

Figure 6.3: COPERT modelled CO2 emissions under three different congestion levels for the 6 alternatively fuelled 2023 bus fleet composition scenarios



6.6 Effect of driving style on alternative fuels and technologies

Driver behaviour and driving style is an important factor to consider in assessing the energy usage of any bus, regardless of the fuel or technology deployed, as fuel economy directly influences the CO_2 emissions in vehicles. Reducing the overall fuel consumption of vehicles will directly improve tailpipe CO_2 emissions. Findings suggest that educational eco-driving campaigns have the potential to significantly reduce emissions (*c.* 5-10%) over sustained periods of time. By driving more smoothly, choosing appropriate speeds and minimising hard acceleration and braking, vehicle fuel consumption can be significantly reduced. A study carried out by the University of California[67] estimated that a typical freight truck uses excess fuel due to speeding (33%), hard acceleration (25%), idling (20%), hard turning (16%) and hard braking (6%); these findings may be indicative for other HDVs such as buses. Currently, all State public transport operators carry out eco-driving programmes as part of their driver training programmes.

Significant fuel savings can be achieved through employing efficient driving styles and simple vehicle maintenance, such as:

- *Reducing Driving Speeds*: As energy use increases at higher speeds a reduction in speed limits could potentially avoid emissions.
- *Avoiding 'Aggressive' Driving:* Fuel consumption increases with acceleration; maintaining steady speeds is the optimal driving style for limiting tailpipe emissions. Aggressive starts

and hard braking should be replaced with slow and smooth acceleration and deceleration. Selection of the correct gear is also important to avoid unnecessary fuel use.

- *Avoiding Idling:* Studies show that vehicles idling in traffic (stopped at traffic lights or in traffic jams) produce high levels of emissions and can account for up to 10% of total fuel consumption. Reviewing and modifying traffic management systems to improve traffic flow could potentially yield fuel and emission savings.

- *Maintaining Vehicles:* Properly serviced vehicles perform and use fuel more efficiently. As carrying unnecessary weight impacts fuel use, excess weight should be limited. Properly inflated tyres reduce rolling resistance; fuel consumption can be reduced by up to 5% by increasing the tyre inflation pressures from 2 to 3 bar[68]. Furthermore, use of air conditioning can increase fuel consumption as much as 10% in city driving in some vehicle models.

6.7 Location Specific Considerations for Transitioning Town Services Fleets

Town service fleets, serving Drogheda, Dundalk, Navan, Balbriggan, Athlone, Sligo and the anticipated services in Carlow, Kilkenny and Mullingar, are typically characterised by:

- Shorter journey duration than those associated with city services due to less traffic congestion;
- Lower passenger demand; and
- Greater deployment of single-deck vehicles.

6.7.1 Full Electric

Given that town services typically experience lower passenger numbers full electric single-deck vehicles may be sufficient to cater for passenger demand. Additionally, full electric bus ranges will likely be sufficient for scheduled town services due to shorter distances travelled and a greater reliance on return-to-depot routes. Short journey distances would negate the need for en-route charging, instead depot or termini charging facilities would likely be sufficient. The capacity to install recharging infrastructure at certain depots may be limited due to space constraints as town depots tend to be smaller than city counterparts.

6.7.2 Hybrid-Electric

Hybrid-electric vehicles are suitable for town services in terms of range and anticipated passenger demand; however, as environmental and economic advantages of this technology accrue predominately in electric mode, the extent to which buses operate in diesel mode (i.e. when travelling at higher speeds or over longer distances) could somewhat negate these benefits. Hybrids would not require additional infrastructure but plug-in vehicles may be subject to similar infrastructural constraints as full electric buses if the operator chose to deploy grid power.

6.7.3 Compressed Natural Gas / Biomethane

Commercially available CNG/biomethane buses have sufficient range and passenger capacity to cater for town services. Additionally, the required gas infrastructure could facilitate a later transition to larger buses (even double-deck buses) or coaches as future demand dictates.

However, access to the national gas grid or to publicly accessible refuelling points may be a concern and would require site-specific evaluations.

6.7.4 Biofuels

Biofuel use may be a viable option in town depots where sites are too small to accommodate a change to existing fuelling infrastructure.

7 Conclusions

7.1 Fleet transition objectives

Based on current and expected fleet numbers, a transition to low carbon alternatives will have limited impact on reducing national emissions. In addition, analysis contained within *the Climate Action Plan*[3] notes that low emission buses have greater upfront costs; however, their deployment may be justified by the benefits they offer, including better air quality, and because the Government has an obligation to provide strong leadership in the area of climate change and sustainability. The early adoption of low emission buses would demonstrate public sector leadership.

Significant measures are being taken across Government to promote the use of low emitting technology and this effort must be similarly reflected in the public transport system. The bus fleet is highly visible and as such can be used as an efficient mechanism to promote alternative fuels and technologies, stimulate their uptake in the commercial and private passenger car fleets, and importantly provide the opportunity for members of the public to experience their benefits. Notwithstanding the need to provide greener public transport, it is imperative that the State continues to provide efficient and cost-effective services in order to encourage modal shift towards more sustainable modes of travel.

7.2 Implications for future fleet procurement decisions

From the outset it is important to note that Ireland is not a market influencer in the bus manufacturing sector. Other EU markets, such as the UK, France and Germany, with greater buying powers can have significant impacts on market development and can drive down vehicle acquisition costs. As such, the recent calls for tender from London and Paris may accelerate production capacities and alter the current whole-life costs in the successful technologies. It should be noted that Ireland occupies a niche position in the international bus market, as a right-hand drive purchaser with bespoke procurement requirements, not least a heavy reliance on high-capacity double-deck vehicles which are little used outside this jurisdiction. This may limit the number of potential suppliers to the Irish market, as well as delaying benefit from advancements made in bus technology for larger market shares, such as the more common left-hand drive, single-deck models.

There is a range of factors that should to be taken into account when choosing to purchase any particular type of lower-emitting bus technology, including significant changes to the standard fleet procurement processes. The NTA has responsibility for vehicle procurement for the urban PSO bus fleet. To date, the purchase of PSO vehicles has been financed through State capital investment while services are subsidised through PSO payments. In the context of transitioning towards alternative fuels, where greater acquisition capital costs but lower operating costs are likely, it is increasingly more appropriate to use the total cost of vehicle ownership model. Factors such as annual mileage; fuel or electricity consumption; ownership period; capital cost of the bus, including the cost of replacing expensive components after warranty; capital and installation cost of infrastructure (whether through outright purchase or by lease); maintenance; and any resulting requirement for additional fleet capacity ('spare' buses) to cover bus downtime should all be considered.

The existing State financing mechanisms concerning fleet procurement may have to undergo review to adapt to potentially higher capital and lower current investment requirements. Furthermore, many alternative fuel/technology providers, especially electric bus providers, offer full service contracts that spread the cost of investment over the lifetime of a vehicle as well as including battery replacements and infrastructure installation costs. This new form of procurement will need to be assessed.

7.3 Suitability of alternatives

7.3.1 Full Electric

Significant CO_2 emission savings are possible with transition towards electricity as well as significant improvements to local air quality when compared against the existing diesel fleet. The substantial benefits associated with the deployment of electric buses are somewhat negated by the costly infrastructural requirements, as well as significant price premiums for vehicle acquisition and inflexibilities in route configurations. The limited market availability of double-deck electric buses coupled with range and recharging concerns may make a transition to this form of technology in urban areas challenging.

7.3.2 Hybrid-Electric

Hybrid-electric vehicles are a strong option for urban bus fleets as no additional investment in infrastructure or reconfiguration of the network would be required. However, carbon emission reductions, air quality improvements and fuel cost savings are linked directly to the extent to which the bus operates in electric mode; therefore, along certain routes where buses operate predominately in diesel mode it is possible that hybrid technologies would not produce substantial benefits in terms of CO_2 and air quality pollutant levels and as such a transition to this vehicle type would be limited in its effectiveness.

7.3.3 CNG

CNG does not provide benefits to transport's carbon emissions profile in the short term but does provide a pathway towards incorporating biomethane into the fuel mix. Refuelling infrastructure costs are high; however, lower fuel prices may mitigate this over time. CNG provides a high level of flexibility to transition to other lower-emitting fuels such as biomethane, or potentially hydrogen, in the future. However, heavily investing in this technology may impede future movement towards electro-mobility options that are expected to emerge in the coming years.

7.3.4 Biomethane

Biomethane can reduce CO_2, improve air quality and substantially contribute towards the sector's RES-T targets to 2030. Given Ireland's strong indigenous capacity for biomethane production through waste-based anaerobic digestion there is an opportunity for Ireland to improve national fuel security; in tandem, the AD industry can positively contribute towards the creation of a circular economy between the transport and agriculture sectors. At present, AD in Ireland is limited and biogas purchased from the EU may be required to bridge the gap until the Irish market reaches maturity. Furthermore, incorporating biomethane in a gas fuel mix in high blends will substantially increase fuel costs and may not be as desirable to operators as a low-biogas blend from a value-for-money perspective.

7.3.5 Biofuels

With the exception of hydrotreated vegetable oils, biofuels performed poorly in this evaluation with constrained benefits to air quality and limited contributions towards meeting RES-T targets to 2030. A 100% HVO blend would most closely meet the requirements of the fleet but increased fuel prices and the limited availability of HVO, both within Ireland and across Europe, could present significant operational challenges.

7.3.6 Hydrogen

Large-scale transition towards hydrogen is not yet feasible. As the technology matures a market for hydrogen buses could develop in the future. At that point hydrogen will increasingly represent an effective solution to reduce carbon emissions from the public transport fleet.

7.4 Evaluation summary

Analysis of the suitability of different fuelling options for urban bus fleets is complicated and requires consideration of a range of diverse factors. From the evaluation undertaken in the compilation of this paper, it is evident that no single fuel or technology exists which fully satisfies the sector's ambitions for carbon emissions reduction, improvements in air quality and renewable energy targets while remaining affordable, sustainable and practicable to implement across multiple locations and types of service.

Unfortunately, at this juncture it was not possible with the currently available resources and data to present a comprehensive modelled emission profile for all the technologies under review. This has curtailed the process of identifying the most suitable alternative options for the future PSO bus fleet; however, from the data available several alternative fuel solutions have emerged which most closely meet the functional and environmental requirements of the urban bus fleet, specifically hybrid and biomethane fuelled buses. An illustrative summary of the findings of this paper is presented in Table 7.1 and Figure 7.1 while an overview of the operational experiences of other jurisdictions with alternatively fuelled buses is presented in Appendix 4.

No 'silver bullet' solution for public transport transition currently exists; therefore, an optimal alignment with as many parameters as possible must be chosen at this point in time. The analysis presented can reasonably inform short-term decisions but market developments and changes to whole lifecycle costs for buses will impact on these findings and as such this analysis should be kept under review. In particular, the rapid pace of technological advancements in this sector will undoubtedly alter the assessment of zero-emission technologies presented. The sector should seek to ensure that it is well-positioned to benefit from newer and cleaner transport options becoming available, avoiding technology 'lock in' to cost-intensive options suitable in the short term, noting that some zero-emission transition is required under the *Clean Vehicles Directive* regardless of technology choice. This issue will potentially be addressed by the establishment of shorter-term State procurement frameworks for the time period following July 2019 in line with the *NDP* commitment, with continued consideration of transition options for medium- to longer-term procurement. This would ensure that longer-term transport policy is not unduly constrained by the sector's need to take action in the current market delivery context.

The evaluation set forth in this paper should be taken into consideration in tandem with the findings of the low-emission bus trial, amongst other resources, in order to better inform the decision towards decarbonising our public transport fleets.

Table 7.1: Suitability evaluation of various alternative fuels/technologies for the PSO urban bus fleet relative to a Euro VI diesel equivalent, using the traffic light system

General: Green: considerable improvement; Amber: moderate improvement; Red: dis-improvement; Shaded cells represent disagreement in the literature

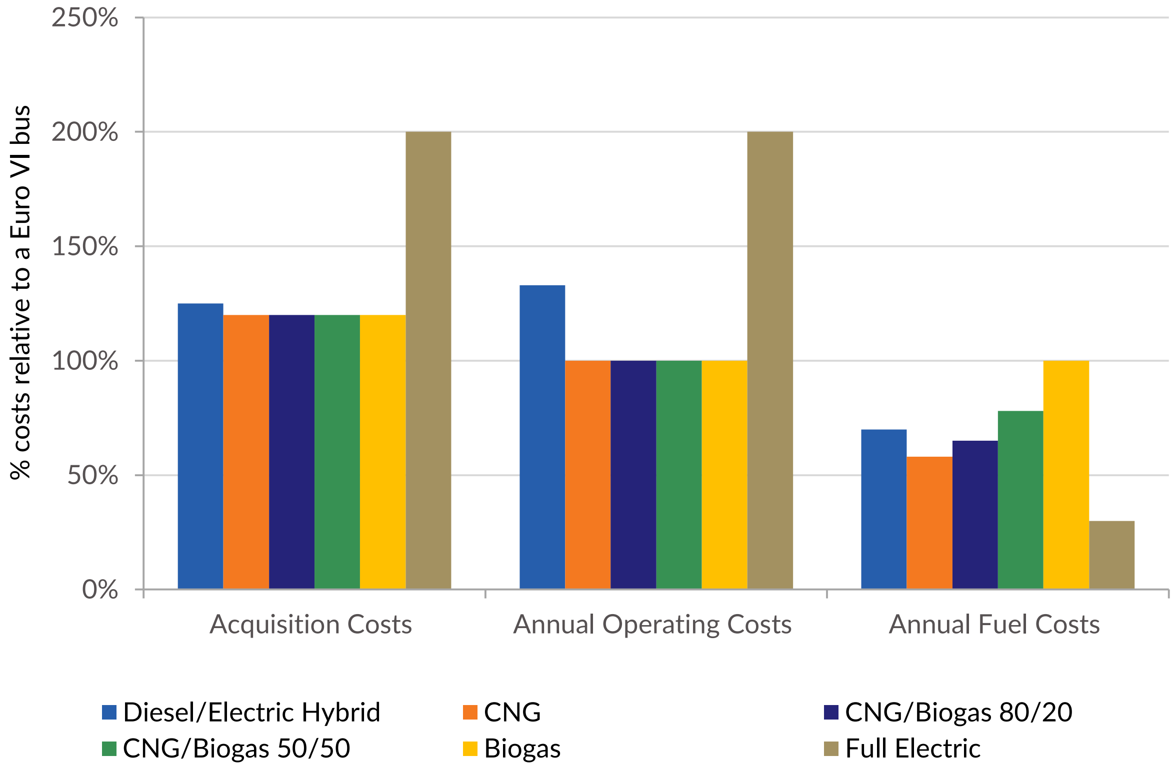
Technology readiness colour code system: Green: readily available on the market; Amber: limited/emerging market; Red: very restricted market availability.

CVD colour code system: Green: Considered zero-emission under the Directive; Amber: Considered 'clean' (low-emission) under the Directive; Red: Not considered 'clean'; Amber shaded cells represent that fuels will be considered 'clean' if they are sourced from sustainable feedstocks under RED II; Red shaded cells indicate that only some variants of the technology i.e. plug-in hybrids will be considered 'clean' technologies).

Fuel Type	CO_2 Emissions	Air Quality	Infrastructure	Fuel Supply	Costs	RES-T	Technology Readiness	CVD
Electric								
Hybrid								
CNG								
Biomethane								
Biodiesel								
Bioethanol								
HVO								
Hydrogen								

Figure 7.1: Acquisition, operation and fuel costs per bus for each of the alternative fuel-types relative to the baseline of a Euro VI double deck diesel bus

Note: Full electric costs relate to a single deck bus and operating costs include the cost of a battery replacement



Finally, a number of avenues for further analysis arise as a result of this work. It is possible that the most suitable method in the longer-term may be a mix of fuelling options, depending on service and location requirements. Consideration of other bus operation systems not previously deployed in Ireland, such as urban trolleybus and BRT systems which are potentially feasible under the core bus corridors anticipated by *BusConnects*, may also merit further assessment. In addition, the carbon reduction potential offered by modal shift away from road-vehicle travel, such as expansion of heavy or light rail networks, could undergo evaluation as part of a longer-term approach to public transport provision where passenger volumes would be sufficiently large to justify the considerable capital costs of providing such infrastructure.

Appendix 1: Qualitative assessment of alternative fuels/technologies

A1.1. Diesel

A1.1.1 Introduction

The *NDP* has committed Ireland to buying no diesel-only buses for the urban public bus fleet from July 2019. In light of this policy position, diesel is presented in this paper solely to provide a contextual background of the business-as-usual baseline**.**

At the end of 2017, diesel fuelled 62% of the national fleet and 97.2% of all Irish registered goods vehicles and buses. Diesel engines use compression ignition in contrast to petrol engines which use spark plugs to ignite an air-fuel mixture. Diesel engines also operate under higher compression compared to petrol engines, meaning their components must withstand greater stresses and so tend to be more robust and heavier than petrol alternatives. Due to the weight and strength of the diesel engine system they were traditionally used to power large vehicles such as buses and trucks.

A1.1.2 CO_2 emissions

Despite diesel on average containing more carbon than petrol, overall CO_2 emissions from diesel vehicles tend to be lower than petrol equivalents due to higher engine efficiency (approximately 27% efficient in converting fuel into mechanical energy, in comparison with 22% for petrol). However, on a 'well-to-wheel' basis, GHG emissions for diesel are 89.1g CO_2eq/MJ, against 87.5g CO_2eq/MJ for petrol, a difference of 1.8 %[69].

A1.1.3 Air quality improvements

The high temperatures at which diesel engines operate lead to relatively high levels of NO_x emissions; while incomplete combustion of fuel results in the generation of PM emissions. Modern diesel vehicles are fitted with particulate filters to reduce PM emissions but they require specific driving conditions and regular maintenance to perform optimally. The widespread implementation of Euro VI standards (requiring NO_x emissions to be reduced by a minimum of 77% relative to EURO V standards) has greatly decreased levels of pollutants emitted from heavy-duty vehicles including buses. Since 2014, only Euro VI diesel buses have been purchased for the urban public bus fleet. The Norwegian Centre for Transport Research and Institute of Transport Economics found that in comparison with real-driving emissions from a typical city bus with Euro V engines, emissions of PM and NO_x from the Euro VI bus engine were reduced by approximately 90-98%.

From an air quality perspective, future advancements in engine-efficiency could position diesel as a viable fuel option. New EU legislation on the monitoring and reporting of CO_2 emissions for heavy duty vehicles (including buses[31]) alongside further revisions of the Euro Class standards could potentially lead to marked reductions in NO_x, SO_x and PM emissions and thus improved air quality. As part of the type-approval process, manufacturers must demonstrate that heavy-duty engines comply with the emission limit values over an extended operating lifespan (to 700,000km/7 years for the heaviest HDVs and buses)[70]. In practice, this process comprises vehicle recall to undergo in-service conformity testing but real-world data on the depreciation of the technology is not readily available. Therefore a review of the amount of operational maintenance required, the mechanical limitations of engine improvements, and the long-term examination of air pollutant reduction efficiency is still needed.

A1.1.4 Infrastructure

The current PSO bus fleet is diesel-fuelled. Both Dublin Bus and Bus Éireann fuel their buses at their depots with B0 fuel purchased by the Córas Iompair Éireann (CIÉ) group (biofuel certificates are purchased in order to ensure BOS compliance). No infrastructural changes to bus depots would be required to facilitate the replacement of existing buses with newer Euro VI diesel vehicles.

A1.1.5 Fuel supply limitations

Ireland has no indigenous oil production and had the fifth highest oil dependency rate in the EU in 2016, at 50% of all energy use[viii]. Diesel is wholly imported, the majority coming from the UK (over 41% in 2016 figures); as such Ireland is vulnerable should market conditions change.

A1.1.6 Costs

Bus purchase prices are dependent on a variety of factors including size, model, technical specifications, manufacturer and number of vehicles purchased. The base vehicle cost for a double-decker Euro VI diesel bus typically ranges from just under €300,000 to just over €400,000[ix]. The NTA procures buses for *c*. €350k per model for a Euro VI double-deck city bus; representing a competitive price point related to economies of scale. Due to advancements in filter technology to limit tailpipe emissions, ongoing maintenance and operational costs for diesel buses have marginally increased in recent years, where increases for the price of oil are excluded.

A1.1.7 RES-T

Diesel is a fossil fuel and its contribution to RES-T targets is dependent on the proportion of biodiesel within the fuel blend. Incremental increases in the biofuel obligation rate to date have helped to incorporate increasingly more sustainable fuel into the conventional fuel mix, positively contributing towards sectoral targets for the share of renewable energy to 2020. However, the 'blend wall' for biodiesel of approximately 7% (the maximum proportion of biodiesel to conventional diesel before manufacturer's warranties are affected) effectively limits the potential contribution of biodiesel towards meeting RES-T targets.

Furthermore, the amended sustainability criteria for feedstocks in Appendix IX of the recast RED may limit the use of biodiesel from being counted towards RES-T targets to 2030 if it is not produced from approved feedstocks. Blending with sustainable diesels, such as HVO which can be produced from approved feedstocks, potentially represents a significant contribution towards RES-T targets.

[viii] Eurostat data provided by the SEAI.
[ix] Data sourced directly from the NTA.

A1.2. Full electric

A1.2.1 Introduction

Full EVs that are powered solely by a rechargeable battery are known as either full electric or battery electric vehicles (BEVs); electric buses do not need an internal combustion engine as they rely entirely on batteries – typically lithium ion - to run one or more electric traction motors. Electric buses tend to be designed with regenerative braking, enabling a proportion of the energy that would otherwise be lost when the vehicle is decelerating to be recovered and stored to power the vehicle. Electric buses tend to be quiet and smooth in operation, significantly decreasing noise pollution in city centres and potentially increasing passenger comfort.

The operating range and route flexibility of an electric bus is influenced by both battery capacities and charging strategies. Battery capacities currently vary from 76-340 kWh. The range of electric buses varies from 30-300km; however, this is heavily dependent on a range of factors including route characteristics, in particular inclines and hills, on-board ancillary systems such as heating and cooling systems, vehicle model (single or double deck) and driving styles. Electric buses are typically single-deck as the increased passenger capacity (weight) associated with double deck buses cannot easily be supported by current battery technologies; however, technological advancements are progressing apace and electric double deck buses are currently being trialled in cities such as Paris, Leeds, York and London. To date, this vehicle type has been less widely deployed than single-deck electric vehicles and is not yet considered a mature technology[71]. Depending on vehicle design, the size and location of battery packs can negatively impact passenger carrying capacity.

A1.2.2 CO_2 emissions

Electric powertrain vehicles emit no tailpipe CO_2 emission. Assuming a zero-emission grid, transition to full-electric vehicles could potentially reduce emissions from the bus fleet by up to 100%. However, Ireland's renewable electricity generation - consisting of wind, hydro, landfill gas, biomass and biogas - as a percentage of gross electricity consumption was just over 18% in 2017, with the remainder derived from fossil fuels[72]. The input of energy from renewable sources to the national grid is anticipated to increase in the coming years with an aim of 40% renewables by 2020. In addition, some EV buses power auxiliary systems, such as heating or cooling, through diesel to reduce the demand on the battery. This leads to some CO_2 emissions, which can be reduced through biodiesel or HVO use instead.

It should also be noted that the Norwegian University of Science and Technology[73] reported that larger EVs can have higher lifecycle GHG emissions than smaller conventional vehicles due to higher production impacts. However, a recent EEA report indicates that, considered over the lifecycle of the vehicle, greenhouse gas emissions of electric vehicles are about 17-30% lower than the emissions of those powered by petrol and diesel[74], with findings from a United States study noting that lifecycle emissions from electric buses were generally lower than equivalents irrespective of the power mix[75].

A1.2.3 Air quality improvements

Electrification of the bus fleet offers significant potential benefits for urban air quality as buses operating on electric motors emit no direct tailpipe emissions. Modelling conducted prior to the roll-out of electric bus fleets in Madrid and Barcelona projected that an ambitious scheme of electrification (approximately 40% of the urban bus fleet) could offer NO_x emissions reductions of 11-17%. However, fleet electrification does not significantly reduce PM emissions (<5%) due to the persistence of vehicular non-exhaust emissions[76]; on average, EVs are 24% heavier than equivalent internal combustion engine (ICE)-powered vehicles and as a result total PM_{10} emissions from EVs from the wear of tyres or brakes are similar to those of modern ICEs, with total $PM_{2.5}$ emissions only 1–3% lower than emissions from equivalent ICE-powered vehicles[77]. It should however be noted that all vehicles, regardless of fuel or technology, will emit non-exhaust emissions from tyre and brake wear.

A1.2.4 Infrastructure

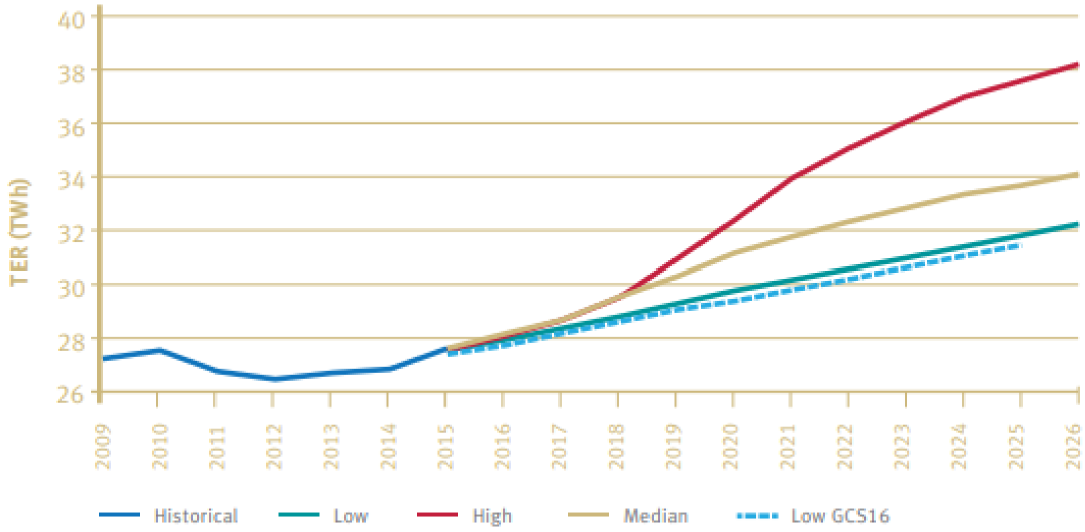
EV charging is an evolving field with numerous tried and emerging technologies. Buses can be charged en route (known as opportunity charging) either at charge points throughout the bus circuit or at first and final stops. Some buses might only require charging overnight, alternatively a combination of charging regimes is possible whereby the bus is charged overnight and topped up as needed during operating hours. Opportunity charging generally takes two forms: inductive or pantographic charging. Inductive charging is where electric coils installed under the road surface transfer energy to corresponding coils fitted beneath the floor of the bus via a magnetic field. Typical power capabilities, of up to 200 kW, can 'top-up' a battery in less than ten minutes. Pantographic charging uses conductive roof-mounted equipment to form an electrical connection between the bus and overhead power supply equipment. Inductive charging, with power capabilities of 150-300kW, takes approximately ten minutes to recharge a single-decker bus while pantograph systems are capable of very high power transfer with 'top up' charging reportedly taking between three and six minutes. The installation of inductive or pantographic infrastructure along specific routes will potentially impact timetable flexibility and 'locks-in' certain buses to particular routes. Overnight charging is generally performed using a slow (15kw) charging unit (usually integrated on board the bus) with an average charge time of up to 10 hours. Fast (22kw) and rapid (50kw) charging units are typically off-board. These connect to a three-phase power supply and facilitate quicker charge times from 1.5 to 4 hours. Plug-in buses must periodically perform a balance charge overnight at the depot to ensure battery stability and durability.

Recharging power requirements are higher for electric buses than for electric cars due to the larger battery capacity and charging-power levels (*c.* 40-100kW per bus). Electrification of a bus fleet would require installation of a number of high-power electric charge points at depots and potentially along routes. This may necessitate upgrading the local electricity network and the installation of new electricity substations at appropriate locations to accommodate power demands.

A1.2.5 Fuel supply limitations

Ireland's strong return to economic growth is now anticipated to continue and result in future increased energy demands[78]. The SEAI has forecast that total electricity demand over the next ten years could grow by up to 15% (under a low demand scenario), or by as much as 36% (under a high demand scenario). Eirgrid analysis in 2017 indicated that based on nationally generated electricity Ireland will have a surplus in the short term, with supply meeting demand by 2021 in a median demand scenario; in a high demand scenario, however, the network would be in deficit to almost 500 MW and additional capacity would be required[79] (Figure A1.1). The capacity of the national grid to support an electrified bus fleet – taking into account the projected growth of the fleet – should therefore be considered. Charging a high number of vehicles simultaneously may also cause difficulties as peak power requirement may exceed the power capacity of the local network; however, this effect can be mitigated through careful charging management.

Figure A1.1: Eirgrid's total electricity requirement forecast for Ireland



Source: EirGrid Group

In addition to considering increased energy demand, the share of renewable electricity in the energy mix will be important when evaluating the lifecycle or WTW emissions associated with electric buses. Projections of Ireland's renewable energy use to 2035 indicate that under current trends in energy-efficiency, renewable energy technology deployment will need to accelerate in order to counter projected growth in demand. Renewable electricity generation will be required to grow annually by over 11% to meet RES-E (renewable energy sources in electricity) targets (40%) by 2020, with a net increase in energy derived from wind, biomass and solar sources. Post-2020 projections of the share of renewables in Ireland's energy mix are less certain; however, under the ambitious *NEEAP/NREAP* scenario (the NEEAP and NREAP scenario assumes meeting all obligations captured in the *National Energy Efficiency Action Plan*[80] and in the *National Renewable Energy Action Plan*[81] by 2020), which proposes additional measures to promote renewable energy production, renewable energy capacity would be sufficient to fuel an electrified public transport fleet.

A1.2.6 Costs

Bus purchase prices are dependent on a variety of factors including size, model, technical specifications, manufacturer and number of vehicles purchased. In general, 100% electric buses have significantly higher acquisition costs than conventional diesel buses and other alternative fuels. Specific body and technology types as well as the type of electric charging infrastructure vary significantly in price. Market consultation has indicated that there would be a 100% price premium on EV buses when compared to an equivalent single-deck Euro VI conventional diesel bus; however it can be expected that prices will decrease as the technology develops. In addition, it has been suggested that in order to run the same services with full electric buses as with the existing fleet, approximately 15-20% more vehicles will be required due to smaller capacities (with each priced nearly double that of a conventional diesel bus). As the technology (and subsequently, vehicle design configurations) develops, passenger capacity may improve. EV technology that permits full day operation following overnight charging would permit one-to-one replacement with diesel Euro-VI models, should the technology permit.

The additional investment required for the installation of recharging infrastructure alongside potential battery replacement costs is likely to be prohibitive. The life-time of batteries for electric buses is uncertain and will be dependent on the frequency at which the battery is charged and discharged. It can be expected that batteries would require replacement at least once over its lifecycle. Maintenance costs may be less due to fewer moving parts. Brake pads require changing less frequently and there is no need for engine oil filter changes or Ad Blue requirements.

In relation to costs associated with the provision of electricity for recharging; 51% of Ireland's electricity was generated from natural gas in 2017 (down from a peak of 61% in 2010)[82], therefore the variability in the price of natural gas significantly impacts on the domestic price of electricity. Other factors that affect electricity prices include the level of competition in electricity generation, labour costs, taxation policy and the level of investment in infrastructure that is required (i.e. improving the electrical transmission and distribution networks). It is therefore difficult to accurately estimate the future cost of electrical charging; however, it may still represent a significant cost saving when compared with current diesel fuels.

A1.2.7 RES-T

Under the RED, a renewable electricity generation target of 40% by 2020 has been set for Ireland. Assuming that 40% is achieved and retained/increased under the recast RED, electrification of the bus fleet would positively contribute towards the sector's RES-T targets to 2030.

A1.3. Electric/Diesel Hybrid

A1.3.1 Introduction

A hybrid vehicle is one which uses any two different energy sources, but, in the automotive industry, the term 'hybrid' is typically used to refer to hybrid electric vehicles (HEVs), which combine an internal combustion engine with one or more electric traction motors and an on-board electrical energy storage system (OESS). Batteries remain the most common form of OESS found in HEVs, but OESSs consisting solely of capacitors or a combination of batteries and capacitors are becoming increasingly common. Diesel is the most common fuel used to power the internal combustion engines, but ethanol and CNG have also been employed. The batteries used by the electric motor are continually recharged by the engine or from energy generated during braking.

There is a wide range of hybrid technologies in operation with the most common powertrains classified as either ’series’ or ’parallel’. In a series hybrid, there is no direct mechanical/hydraulic linkage between the engine and the driven axle(s), the vehicle being exclusively propelled by the electric traction motor(s). The engine is employed solely to generate electrical energy that is used to charge the OESS and/or to power the electric traction motor(s). In a parallel hybrid, a direct mechanical/hydraulic linkage between the engine and the driven axle(s) is retained, with the OESS and the electric traction motor(s) supplementing rather than replacing this direct linkage. Parallel hybrids can be propelled by the torque produced by the engine, by the torque produced by the electric traction motor(s), or by a combination of the two. The control system determines the most efficient source for the energy (i.e. OESS and/or engine) at any given time, the state of charge of the OESS is a key determinant.

Plug-in hybrid electric vehicles (PHEVs) differ from HEVs by incorporating an OESS which can also be charged using an external (off-vehicle) power source (this is not essential as the OESS will still be charged by the engine and during braking events). Commonly, PHEVs are fitted with a larger battery to allow the vehicle to travel further in electric only mode. HEVs and PHEVs are now being fitted with an OESS with a greater electrical energy storage capacity than heretofore. An OESS such as this can permit the vehicle to cover significant stretches of a bus route with an inactive engine, the extent of emissions-free operation being determined by the capacity of the OESS, the length and topography of the route concerned, the number of stops and starts en route, and, in the case of a PHEV, whether any external charging infrastructure is provided within the depot or along the route.

A1.3.2 CO_2 emissions

CO_2 emissions savings from diesel-electric buses vary according to what extent the electric motor is used. This is strongly dependent on the duty cycle, and affected by aspects such as the topography, congestion and driving styles. Higher savings can be achieved in urban environments due to frequent speed changes; with typical reported fuel consumption of 13% for 18m buses, 20% for 20m buses and 22% for double-deck vehicles. Plug-in hybrid buses can have very high fuel economy and fuel consumption savings (75% - 80%). Emissions can be further reduced (up to 90%) by the replacement of conventional diesel with biodiesel.

A1.3.3 Air quality improvements

Euro VI hybrid vehicles can produce zero direct emissions when in full electric mode but can produce evaporative emissions from the fuel system as well as tailpipe emissions (NO_x, SO_x and PM) when operating on conventional diesel. Reductions in harmful pollutants are directly linked to reduced diesel consumption and can be up to 30%. PHEVs can provide significant NO_x emission reductions as they can be highly fuel-efficient if the engine achieves Euro VI-class standards and is run in electric-only mode in built up urban areas.

Diesel hybrid-electric vehicles are typically newer engines which may deploy selective catalytic reduction (SCR) exhaust treatment system to achieve reduced levels of NO_x from the diesel component of the engine. SCR technology requires the use of a diesel exhaust fluid (frequently trademarked as AdBlue™). SCR treats exhaust gas downstream of the engine. Metered amounts of diesel exhaust fluid are injected into the exhaust from the engine, where it vaporises and decomposes to form ammonia and carbon dioxide. The ammonia (NH_3) together with the SCR catalyst, converts the NO_x to nitrogen (N2) and water (H_2O) which are emitted through the exhaust, substantially reducing emissions[83].

A1.3.4 Infrastructure

Refuelling infrastructure for diesel-hybrid vehicles reflect the requirements outlined for both diesel-only and electric buses. Diesel refuelling facilities are installed at existing depots and no additional infrastructural investment will be required in the short-term, although this will require re-evaluation in the context of necessary fleet expansion to 2030. No additional infrastructure is required for conventional hybrids with an on-board generator or regenerative braking capacity. PHEVs do not require external recharging as the engine remains the primary source of power, along with energy recovered during braking. However, plug-in hybrid buses would require access to an electric recharging network to accrue the benefits from grid power, with associated cost implications and potential route limitations.

A1.3.5 Fuel supply limitations

There is similar fuel supply limitations associated with hybrid-electric buses as with diesel and full electric buses.

A1.3.6 Costs

Hybrid-electric vehicles have higher upfront acquisition costs in comparison with conventional diesel vehicles, in addition to higher maintenance costs for potential battery replacement and employing dual fuel technologies. Maintenance of the electric system alongside the standard diesel system must be undertaken including the resource heavy AdBlue and particle filter cleaning requirements. Market consultation indicates an average of a 30% price premium on hybrid electric vehicles when compared to an equivalent single deck Euro VI conventional diesel bus. However, no additional infrastructural costs are associated with conventional hybrid electric vehicles (additional infrastructure would be required for PHEVs) and a considerable saving in energy consumption (of approximately 30%-40% per annum) is possible. Fuel savings are strongly influenced by route selection and driver behaviour.

A1.3.7 RES-T

Employing conventional hybrid-electric buses (where electricity is produced only through regenerative braking) to contribute to the RES-T target effectively reflects the RES-T potential of biodiesel in the fuel mix and is therefore extremely limited. PHEVs, when operating in electric mode, can benefit from the increasing levels of renewable electricity within the national grid and so offer a greater RES-T prospective.

A1.4. Compressed Natural Gas (CNG)

A1.4.1 Introduction

CNG is natural gas compressed to less than 1% of the volume it occupies at standard atmospheric pressure. To produce CNG, natural gas is compressed through a series of tanks until the optimal pressure is achieved and it is then stored in pressurised tanks. CNG is an established source of transport fuel across Europe with over half a million natural gas-fuelled vehicles in use in the EU-27, of which 6.8% are buses. It is particularly suited to larger vehicles such as heavy duty vehicles travelling short-to-medium distances. CNG is a less energy-intensive fuel than conventional diesel, with a higher calorific value; however, CNG is less dense and more fuel is required on a volumetric basis compared to diesel. It shares similar operating and refuelling characteristics. However, the fuel is bulkier in gaseous form so liquid natural gas (LNG) is a more suitable alternative for longer-distance journeys, for instance, intercity bus services or HGVs undertaking transcontinental freight journeys[x].

A1.4.2 CO_2 emissions

There is a range of published values on the subject of CO_2 emissions from CNG vehicles; some industry bodies report that CNG-fuelled vehicles can reduce CO_2 emissions by 25%[84] while others claim likely increases in emissions of up to 8% over diesel equivalents[85]. Over a mixed urban-suburban drive cycle, it is reported that greenhouse gas emissions from CNG-fuelled buses can reduced by 8% in comparison with standard diesel buses. When compared with newer 'efficient diesel' models, however, gas bus emissions tended to be significantly (24%) higher in line with higher energy consumption. Energy consumption in gas buses is sensitive to the average speed of the vehicle and is typically higher at low to average driving speeds. CO_2 savings from gas buses may therefore be more effective on higher speed inter-urban routes than the stop-start conditions associated with more highly congested urban drive cycles. Emission savings can be substantially increased if CNG is blended with biogas or biomethane.

A1.4.3 Air quality improvements

The air quality benefits of CNG reported in the literature are mixed. In relation to NO_x emissions ranges from 30% to 90% reduction have been reported in a number of vehicle trials conducted in European cities on equivalent diesel and CNG enhanced environment-friendly vehicles (EEVs). Significantly lower SO_2/SO_x emissions are achievable in comparison with conventional diesel as SO_2 emissions are directly proportional to the sulphur content of the fuel. Equally, compared to diesel-only fuelled counterparts, CNG-fuelled vehicles emit very little PM *c.* 5 mg/km[86]. However, CNG deployment has been varyingly linked to high emissions of CO, hydro-carbons (particularly methane) and VOCs across a range of studies[87] and pollutant emissions reductions are largely matched by newer (Euro VI) standard diesel vehicles[88].

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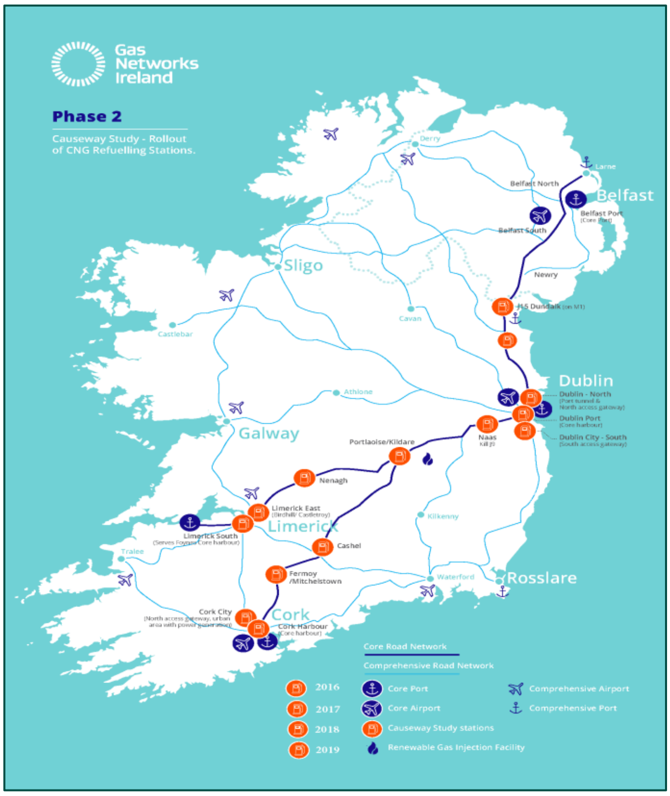
[x] LNG is predominantly methane which has been condensed by cooling to a temperature of approximately −162 °C. LNG is not currently used in Irish land transport or ports and the cost to develop LNG infrastructure, including cryogenic storage facilities and insulated tanker trucks for transportation, would be significant. The cost of a single LNG refuelling point (supporting up to 50 vehicles) is estimated at approximately €300,000.

An important factor to consider when evaluating the pollutant emissions associated with CNG is the possibility of methane slip. Unburnt methane, known as methane slip, from the exhausts of dual-fuel diesel/gas vehicles has the potential to eliminate any benefits. Testing undertaken for the UK Department of Transport showed that methane emitted from dual fuel trucks resulted in those vehicles having greater CO_2 equivalent emissions when compared to a standard diesel truck. This issue is not a concern with dedicated gas trucks, the design of which allows a more complete methane burn[89]. A separate study by Ricardo-AEA estimated that for a dual fuel vehicle operating at typical substitution rates, if 2% of the methane fuel passes through the engine, unburnt, with 98% combusted (i.e. if the level of methane slip was 2%) then this could completely negate the greenhouse gas savings offered by using methane as a vehicle fuel in place of diesel[90]. The Low CVP study found that none of the dedicated gas vehicles tested were found to emit significant quantities of methane during the trial. It should additionally be noted that findings should be considered as indicative as gas trucks are not entirely analogous to gas buses due to substantial differences in drivetrain design and typical drive cycles.

A1.4.4 Infrastructure

Gas Networks Ireland (GNI) has commenced the roll-out of publically accessible CNG refuelling infrastructure, including renewable gas injection infrastructure, under the "Causeway Project"[91], with funding support from EU and CRU (Commission for Regulation of Utilities) (Figure A1.2). The first refuelling station opened in Dublin Port in December 2018, to be followed in 2019 by Little Island in Cork. Both stations will be capable of refuelling up to 75 trucks and 38 vans per day. Phase 2 of this study is set to expand the network with a further 12 fast-fill stations along the TEN-T road network. There are also private stations in operation.

Figure A1.2: Proposed location of CNG refuelling stations under the Causeway Project



It is likely that bus operators would need to install refuelling infrastructure at depot locations but could be supported by access to the public recharging network. Ireland's natural gas grid connects the cities of Dublin, Cork, Galway, Limerick and Waterford but analysis must be undertaken at specific sites to determine if direct connection is possible, pressure capacity was adequate, and assess cost implications. The need for gas extraction equipment at depots should also be considered. Grid connections would see a marked reduction in fuel deliveries to depots and bunkering requirements.

A1.4.5 Fuel supply limitations

Until 2016, Ireland imported just under 96% of natural gas used from the UK via a system of two sub-sea pipelines to the Republic and one to Northern Ireland, connecting to a single pipeline at Moffat in Scotland. Ireland has some indigenous natural gas extraction from Inch near Kinsale, County Cork (until 2020/2021) and since 2016 from the Corrib Gas Field off the coast of Mayo (until 2024/2025). Once these gas fields have been depleted, Ireland will revert to importing gas from the EU; however given that 66% of the EU's natural gas is imported (primarily from Norway, Russia, Algeria and Qatar) the purchase price of CNG will be subject to external market pressures[92].

A1.4.6 Costs

CNG vehicle acquisition costs are typically *c.* 20% more expensive than conventional diesel buses, with significant potential fuel savings depending on the blend rate with biomethane (as much as 57% fuel cost savings over diesel buses)[93]. Feedback from market consultation indicates that expected operational and maintenance costs over the lifecycle of the vehicle are broadly similar to those of Euro VI diesel buses without the need for exhaust fluid or particle filter maintenance. The 2015 Budget confirmed that the excise rate for natural gas and biogas as a propellant will be set at the current EU minimum rate (€2.60 per GJ) and that this rate will be held for 8 years. This equates to a rate of approximately €0.11 per diesel-litre equivalent. However, infrastructural costs for widespread CNG adoption could potentially be high, with installation of a refuelling point estimated over €500,000 and standard maintenance of each refuelling point over €30,000 per annum[xi].

A1.4.7 RES-T

Since natural gas is a fossil fuel, the deployment of 100% CNG in the bus fleet would not contribute towards meeting RES-T targets to 2030. However, there is potential for CNG/biomethane blends to positively contribute in line with the blend ratio and the choice of feedstocks used.

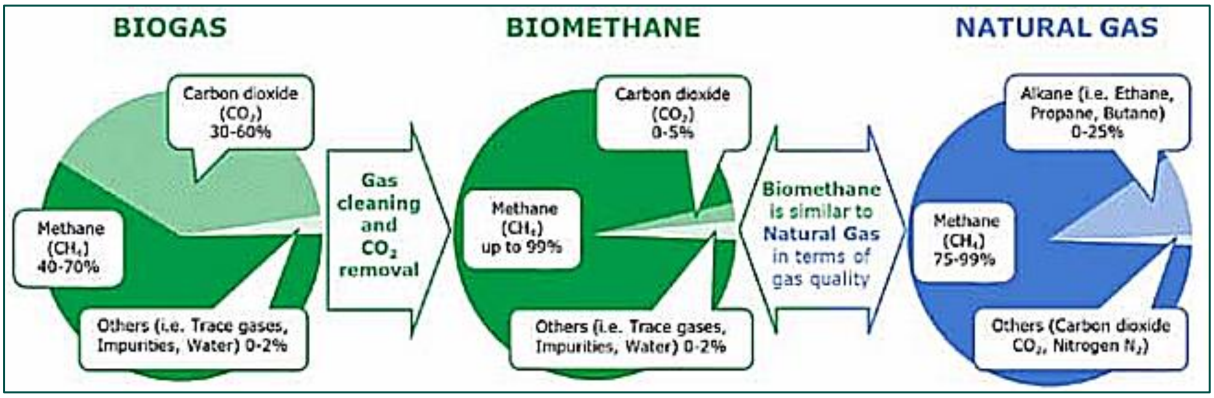
[xi] Data derived from KPMG market consultation undertaken on behalf of the NTA.

A1.5. Biogas/Biomethane

A1.5.1 Introduction

Biogas is a mixture of methane (CH_4) and CO_2; it can be sourced from almost all kinds of organic matter. Wet organic matter with low lignocellulose content, such as: household or agricultural organic waste, sewage sludge, grass silage, manure, can be utilised for biogas production through a process termed anaerobic digestion (AD). AD is a naturally occurring process where bacteria act upon moist organic material and decompose it into biogas as well as the nutrient rich digestate. Biogas can be upgraded to biomethane (vehicle fuel quality) by removing the CO_2 content (Figure A1.3). Propane may also be added (usually 3%) to increase the calorific value of the fuel[94]. Upgraded biomethane can then be purified to match defined natural gas specifications, allowing it to be injected directly into the national gas grid. The digestate by-product can be used as a fertiliser, reducing ammonia emissions and nitrate pollution in aquatic ecosystems.

Figure A1.3: Chemical compounds and approximate share of biogas, biomethane and natural gas[95]



A1.5.2 CO_2 emissions

Energy generated from biogas is considered to be CO_2 neutral, since the CO_2 released by combusting biogas fuel was previously removed from the atmosphere during the development of the biomass through photosynthesis. Furthermore, the production of biomethane can benefit the national emission reduction efforts as it entails capturing methane and CO_2 that would otherwise be released into the atmosphere during natural decomposition. Real CO_2 emission savings from biomethane are dependent on the feedstocks utilised in production, with manure, energy crops, sewage and municipal organic waste representing the greatest real emission savings. Farm slurry is associated with higher GHG emission savings than crop residues.

In addition to sectoral renewable energy targets, under the recast RED, Ireland will be required to meet a subtarget for the use of advanced biofuels by 2030. Biomethane can be considered an "advanced" or "second-generation" biofuel depending on the feedstocks used in its production. Presently, animal manure and sewage sludge feedstocks are permitted for the production of advanced biofuels whereas grass silage has not been included due to the potential indirect land-use change emissions arising from its use. The choice of feedstocks for future biomethane production could therefore positively contribute to Ireland's capacity to meet the proposed advanced biofuel subtarget and will need to be considered in the context of public transport fleet transition.

It is worth noting that during the biogas production and biomethane upgrade processes it is possible for methane slip to occur, escaping into the atmosphere which has very negative environmental consequences due to the high warming potential of methane. It has been suggested that a methane slip of more than 2% is sufficient to reverse the positive environmental savings of biomethane when compared to other fossil fuels[96].

A1.5.3 Air quality improvements

Biomethane use can reduce pollutant emissions compared to diesel powered engines below the emission levels expected from the use of other biofuels such as biodiesel and bioethanol. Notably, biomethane as a vehicle fuel emits up to 95% less PM, with some studies also showing decreases in NOx compared to Euro VI diesel emission standards. Reductions in NOx achievable with the use of biomethane are similar to those achieved through using modern Euro VI engines. According to expert feedback from IIASA, biogas emission factors are quite similar to those of natural gas, except for SO_2 emissions, which can be higher. However, other research notes that as a non-sulphurous fuel biomethane produces virtually no SO_x emissions. Data in relation to pollutant emissions from CNG/biomethane blends is not readily available; however, it can be reasonably assumed that blending biomethane with natural gas would potentially improve reduction of pollutants in line with the proportion at which it is blended in the fuel mix.

A1.5.4 Infrastructure

Upgrading biogas to biomethane for vehicle fuel or direct use in the gas grid is considered a mature technology. Injected biomethane can be used at any ratio with natural gas as a vehicle fuel without needing to upgrade existing vehicle or infrastructure systems. Similar depot infrastructure to Section A1.4 would be required.

A1.5.5 Fuel supply limitations

There are approximately 14,000 AD digesters operating throughout Europe; however, large-scale biomethane production does not currently exist in Ireland and it is unlikely that levels of commercially available indigenously-produced biomethane would be sufficient to fuel the entire public transport in the short-term. There are currently 11 AD plants in operation in Ireland ranging from small agricultural operations to industrial sized plants. The digester at Nurney, Co. Kildare is estimated to have production capacity of 90Gw/hr per annum which would be sufficient to fuel just over 250 buses annually. This would satisfy the fleet's initial transition fuelling needs and could fuel considerably more vehicles when blended with CNG.

SEAI estimates that 28% of all gas supply by 2050 can be replaced by biogas if further investment is made in AD. Ireland has a domestic supply of waste feedstocks (food wastes, cattle and pig manures or slurries) which could produce up to 126 ktoe (5.3 PJ) per year – equivalent to just over 3% of total natural gas supply in 2015. Grass silage also represents a significant potential resource for AD and SEAI estimate that 86% of the renewable gas production potential in Ireland lies in better available feedstocks of perennial ryegrass. However, this pathway would incur higher production costs than would be associated with waste feedstocks[xii]. Taking these available feedstocks into account, Ireland has substantial growth potential for industry expansion – approximately 15 times current production[97]. An increase in indigenous biomethane production would reduce dependency on fuel imports and provide a greater degree of fuel security for Ireland.

A1.5.6 Costs

Biomethane can be blended or directly substituted for CNG; therefore it is assumed that vehicle acquisition costs are identical to CNG-fuelled buses, that is, approximately 20% more expensive than conventional diesel-fuelled vehicles. Infrastructural, operational and maintenance costs accrued over the lifecycle of the vehicles would likewise be similar to CNG-fuelled buses. In relation to potential fuel cost savings, Gas Networks Ireland estimates that a blend of CNG and biogas/biomethane in the ratio of 80:20 represents a cost-efficient solution (54% fuel spend savings) for fuel consumers and provide 34% CO_2 savings (based on 100 buses operating over a period of one year). As biomethane can be directly 'dropped in' for CNG, there is potential for higher blends, up to 100%, which would offer significantly higher savings in CO_2 but markedly reduce fuel spend savings to 5%.

A1.5.7 RES-T

AD plants can utilise a wide variety of feedstocks ranging from food wastes, to animal slurries to specifically grown energy crops such as grass silage. Production from waste-based sources, such as manures and slurries would meet the sustainability criteria outlined in Appendix IX of the RED, allowing biomethane to be considered an 'advanced' biofuel and potentially eligible for double counting under the recast RED. Deployment of biomethane in the bus fleet would therefore allow the public transport sector to make a significant contribution towards RES-T to 2030.

A1.6. Biofuels

A1.6.1 Introduction

Biofuels are renewable transport fuels produced from biomass material. They are manufactured from a wide range of materials including sugarcane, wheat and corn, and also from waste materials such as used cooking oils (UCOs) and tallow. Key biofuels for the Irish transport sector include:

- biodiesel - typically deployed blended with mineral diesel and used in diesel-powered vehicles;
- bioethanol - typically blended with gasoline and used in petrol vehicles;

[xii] Recent analysis using explicit spatial data supports the SEAI's projections and indicates significant additional resource potential for biomethane associated with grass silage and cattle slurry (a theoretical resource of 128.4 PJ/a (35.67 TW h/a) and 9.6 PJ/a (2.67 TW h/a) respectively – equivalent to 77% of energy use in transport in 2013), which could potentially contribute over 26% of the projected 2020 energy consumption for the entire transport sector

- hydrotreated vegetable oils - can be used as a direct replacement or 'drop-in' for diesel; and
- biomethane - can be deployed for use in natural gas vehicles (Section A.1.5).

Biodiesel

The biodiesel used in Ireland is a FAME (Fatty Acid Methyl Esters) type fuel derived from natural vegetable oils including oilseed rape, sunflowers, soybeans and palm oil. FAME can also use waste oil as a feedstock and 62% of biofuel placed on the Irish market was produced from UCOs. Biodiesel in Ireland is typically blended into the fuel mix at concentrations up to 7% and is known as B7. Biodiesel has a lower energy density than standard diesel and so more fuel is required to travel the same distance.

Bioethanol

Bioethanol-adapted diesel engines for heavy-duty vehicles such as buses can run on ED95 (a fuel consisting of 95% hydrous bioethanol and 5% ignition improver). ED95 is a liquid fuel produced by the fermentation of starch, sugar and cellulose plants (such as corn, sugar beet, cassava or wheat, or cellulosic materials). This is slightly different to the bioethanol used for light-duty vehicles such as passenger cars or vans (typically bioethanol concentrations of 5% (E5) and 10% (E10)) and is not addressed under the Biofuel Obligation Scheme. ED95 has approximately 70% lower energy content compared to diesel, meaning that 70% more fuel is needed to drive a bioethanol bus the same distance as a diesel bus. It is not possible to retrofit diesel engines to enable bioethanol propulsion without an ignition improver as well as an increased compression ratio in the engine, as neat bioethanol has a low cetane number (causing ignition delay, reduced acceleration and slower speeds in comparison with diesel buses).

Hydrotreated Vegetable Oil (HVO)

Hydrotreated Vegetable Oil (HVO) is a synthetic paraffinic fuel which can be blended in high concentrations with conventional diesel or substituted as a complete replacement 'drop-in' fuel. A wide range of feedstocks can be used to refine HVO, including UCOs, tallow, tall oil pitch, algae oil and waste animal fats; the final fuel properties of HVO are strongly independent of the original feedstocks. In the production process, impurities are removed from the raw materials which are then hydrotreated (hydrogen added to remove oxygen content from the molecule) at a high temperature. The outcome is a colourless and odourless fuel of even quality that has an identical chemical composition with fossil diesel and a superior energy density than of biofuels. It is considered an "advanced" or "second-generation" biofuel depending on the feedstock employed. HVO may be a particularly suitable alternative for increasing the biofuel obligation as the amount of FAME that can be added to conventional diesel fuel is limited to maintain acceptable fuel quality and compatibility with the vehicles in the market.

A1.6.2 CO_2 emissions

Biodiesel

CO_2 emissions from biodiesel are determined by the origin of the feed stock material and the processing methods; as a result tailpipe CO_2 emission savings are difficult to ascertain, but are broadly considered to be lower than emissions associated with conventional diesel. Waste vegetable or animal oil cause the lowest emissions of FAME-based fuels, with sunflower oil biodiesel emitting three times as much per MJ energy compared to four times the amount for rape seed and five times as much from soybeans. Depending on the processing methods used, emissions from palm oil biodiesel emissions can be higher again. In 2018, biodiesel sold in Ireland was produced from category 1 tallow, UCOs, spent bleached earth and palm oil mill effluent (POMEs), which are lower CO_2 emitting feedstocks (although it is to be noted that palm oil of which POME is a by-product is a higher emitting feedstock).

Bioethanol

The choice of feedstocks utilised in bioethanol production measurably impacts upon the CO_2 reduction potential of the fuel as net lifecycle emissions vary significantly. Bioethanol is often considered a "first-generation" or "crop-based" biofuel because the feedstocks used in its production, such as sugar cane, can result in high 'well-to-wheel' emissions once emissions associated with indirect land-use change are considered.

HVO

In general, due to the high-energy content, high level of purity and lack of contaminants, synthetic fuels significantly reduce CO_2, SO_x, NO_x and PM emissions. CO_2 tailpipe savings of up to 75% have also been reported.

A1.6.3 Air quality improvements

Biodiesel

Consumption of biofuels in low blends in the national fuel mix is likely to have little impact on air quality. However, greater penetration of biodiesel may have positive benefits for air quality and human health. Burning biodiesel – in comparison with conventional diesel – reduces emissions of PM and CO (carbon monoxide) in tailpipe exhausts. The reduction in PM (especially PM_{10} up to 60%) is typically associated with biodiesel's higher oxygen content and lack of aromatic hydrocarbons and sulphur[98]. However, the benefits of biodiesel are dependent on a range of factors, including blend rate, engine efficiency, weather conditions and feedstocks[99]. The use of significantly higher blends (over 15%) or oxidized biodiesel blends can result in higher PM emissions particularly in relation to $PM_{2.5}$. Studies have also shown that cold-start operation, typically experienced in the winter months, can also leads to increased PM in exhaust emissions[100]. While biodiesel produced from saturated animal fats has been cited as demonstrating better emission performance than counterparts derived from vegetable and plant oils.

Bioethanol

At low concentrations, bioethanol leads to no change in NO_x emissions but slight reductions in CO, hydrocarbons and PM in comparison with conventional fossil fuels. ED95 is a higher blend and is likely to display greater reductions in harmful pollutants. However, other potentially toxic pollutants may be produced at high blend ratios, including acetaldehyde or formaldehyde concentrations.

HVO

Road trials of paraffinic fuels in several European capitals and elsewhere demonstrate that paraffinic fuels provide significant local air quality improvement in urban areas. As a synthetic paraffinic fuel, HVO is free of aromatics, oxygen and sulphur. In a three year trial (2007-2010) conducted by Neste Oil, in conjunction with Helsinki University of Technology, local emission reductions were examined over a range of speed and load configurations. Results suggest that 100% HVO use, yielded average reductions in PM (up to 46%), CO (up to 30%) and NO_x (over 16%). Other studies similarly report substantial reductions in NO_x, PM, CO, and HC emissions with the use of HVOs on heavy-duty engines[101,102,103], although NOx levels have consistently shown the smallest decreases and in some instances have been reported at similar levels to Euro VI diesel.

A1.6.4 Infrastructure

Biodiesel

Fatty acid methyl esters (FAME) biodiesel can be used in almost all unmodified diesel-engines; however, higher blends can only be used in vehicles where a specific warranty has been provided by the vehicle manufacturer. In the Irish fuel mix, B7 (a fuel blend with up to 7% biodiesel content) is typically used. No specific infrastructural investment will be required to facilitate the use of B7. Blending is usually performed only during the summer months (June, July and August) as in colder temperatures the fuel is susceptible to gelling - where wax crystals form in the oil due to low temperatures preventing the fuel from flowing - and can cause blockages in the fuel system. Storage requirements of biodiesel vary depending on the blend rate; B20 and B30 can be stored in existing bunded diesel tanks and utilise existing pump dispensers. Due to the higher risk of solidifying at cold temperatures, B100 must be stored in a modified tank with additives and potential facilities for stirring or heating; B100 infrastructure is more costly than the existing diesel system. Furthermore, the higher the biodiesel blend the greater the requirement for frequent fuel filter changes.

Bioethanol

ED95 is a non-substitutable fuel which cannot be used as a blend with any other fuel and requires parallel refuelling infrastructure or flexi-fuel pumps to be installed on forecourts or in bus depots. The fuel pumps for ED95 are the same as diesel fuel pumps and are similarly priced; however, the materials in the tank and dispenser must be bioethanol resistant. Diesel refuelling infrastructure can be converted but there are a number of safety concerns existing due to the lower flash point of ED95 compared to diesel.

HVO

HVO does not require changes to ICE engines or to refuelling infrastructure to be deployed either in fuel blends or as a ‘drop-in’ fuel (100% substitution). The hydrotreatment process removes oxygen from the molecule and allows the fuel to meet cold flow requirements i.e. winter fuel standards[104] which would allow blending throughout the year.

A1.6.5 Fuel supply limitations

For the 2018 obligation period, the majority of the feedstocks used to produce biofuel for the Irish market were sourced from China (21.5%) and Spain (15.1%); *c.* 11.3% was sourced indigenously. Biofuels are deemed as a limited resource with the main limiting factor in biofuel feedstock production being a threat to food supply. Corn and soybean crops, for example, which occupy significant land areas and require considerable water resources, do not produce enough energy per acre to meet current fuel needs without compromising the food chain and causing negative indirect land-use change (ILUC). The extraction of some feedstocks will effectuate increased lifecycle carbon emissions as a result. It is worth noting however that almost 62% of all the biofuel placed on the market in Ireland in 2018 was produced from UCO which is considered a waste product.

<u>Biodiesel</u>

In 2018, approximately 216 million litres of biofuel was placed on the Irish market of which over 70% was biodiesel. The majority of biodiesel in Ireland originated from UCO feedstocks.

<u>Bioethanol</u>

ED95 is not produced in Ireland. The fuel is produced predominately by Swedish company SEKAB and a new market entrant, Agroetanol[105]. The city of Stockholm has recently expanded a fleet of bioethanol buses (SCANIA) which run on ED95, indicating that a supply of the fuel may be available for import to the Irish market. However, production is comparatively limited. It is important to note that many of the feedstocks commonly used in the production of ethanol - for instance sugar cane and maize – are considered first-generation biofuels and as such a degree of market uncertainty exists regarding the endurance of production and whether production shifts towards approved alternate ethanol feedstocks such as wood chips or bagasse emerge.

<u>HVO</u>

The current production of HVO represents approximately 9% of the biodiesel market. This is anticipated to double within the next three to five years, reaching an estimated 16 – 23%. Neste Oil is the largest producer worldwide (69% HVO market share) with four plants (two in Finland and one in Holland and Singapore) and a production capacity of 2.4 million MT. Production facilities in Louisiana, US and Porto Marghera, Italy represent a further 14% of the HVO market share. Anticipated European HVO investments by ENI (Sicily), Total (France) and Petrobras (Portugal) are expected to add production capacity of 1,770,000 MT (representing a market growth of 88.5% within the next three years). Several other companies have also developed technologies for HVO production, among them ConocoPhillips, BP, Haldor Topsoe and Nippon Oil. HVO production is either mainly used for so called 'co-processing' purposes or not produced on a large scale suitable for transport fuel needs[106]. HVO has been produced at Whitegate Refinery, Co. Cork, with a small quantity placed on the market in 2015[25]. However, large-scale production of HVO has not to date taken place in Ireland.

It should be noted that, while a promising indication of future HVO availability, this increased production capacity will place additional pressure on limited feedstocks in Europe, with the needs of producers growing by at least 1 million MT by 2018. This is likely to be exacerbated by the movement away from high-ILUC feedstocks such as imported palm oil towards more sustainable waste-based low ILUC alternatives[107].

A1.6.6 Costs

Biodiesel

It is assumed that there will always be a price premium for biofuels in comparison with diesel. Biodiesel is currently blended into the national diesel mix at a rate of 7% (B7). No specific infrastructural investment will be required to facilitate the use of B7 and operational and maintenance costs can be assumed to be analogous with current Euro VI bus costs.

Bioethanol

At present, there is only one supplier of bioethanol buses (Scania) and one established commercial supplier of ED95 (SEKAB), effectively creating a market monopoly with little flexibility. No bioethanol–fuelled buses are currently available for the Irish right-hand drive market but data from other fleets suggests that the purchase price of a bioethanol bus is approximately 10% higher than that of an equivalent diesel bus.

In terms of fuel costs, due to the limited penetration of bioethanol in the European heavy-duty vehicle market, there is little competition and price comparison with lower-percentage ethanol blends and FAME-based biodiesel is not readily available. It is however unlikely that ED95 could achieve price parity with other biofuels and could represent a significant expense for bus operators. From an operational perspective, the lower energy content of bioethanol means that average fuel consumption will be higher, with 70% more fuel per volume required compared to a diesel vehicle.

The potential high cost associated with refuelling infrastructure and the concerns regarding the longevity of bioethanol as a fuel solution require close consideration. Transition towards ED95 would require the installation of either a fuel-specific parallel refuelling system or flexi-form pumps, representing a significant and long-term infrastructural investment for fleet operators. Given the scarcity of bioethanol bus fleets across Europe, no data is available in relation to ongoing operational and maintenance costs associated with this technology over the typical lifecycle of the vehicle.

HVO

HVO refinement can be expensive due to the capital costs of operating the hydrotreating process and therefore generally large-scale production facilities are only established. As a result HVO, particularly in high blends or as a direct substitute, is likely to incur higher purchase price than FAME-based biodiesel but this will be dependent on market conditions and on any regulatory incentives which are in place. There are no related infrastructure costs associated with the use of HVO as is it a “drop in” fuel and is therefore interoperable with existing refuelling infrastructure. In addition, there are no vehicle warranty issues with using HVO. Operational and maintenance costs will be analogous with those associated with diesel-fuelled Euro VI buses.

A1.6.7 RES-T

Biodiesel

Biodiesel has to date played a strong role towards meeting sectoral targets for the share of renewable energy in transport to 2020.

Bioethanol

The type of bioethanol suitable for buses (ED95) will not be subject to 'blend rate' limitations as the vehicle's engine is specifically designed to run on bioethanol. However, bioethanol is typically produced from first generation feedstocks with high ILUC emissions like sugar cane, maize and wheat, which do not meet the advanced sustainability criteria in the recast RED. As a result, a bioethanol fleet, unless produced solely from approved feedstocks such as straw, can make a very limited contribution to RES-T targets to 2030.

HVO

HVO can be produced from a wide range of feedstocks, including a number of waste-based feedstocks meeting the sustainability criteria outlined in Appendix IX of the RED. This would allow HVO to be considered an 'advanced' biofuel, which may be eligible for double counting. Deployment of HVO in the bus fleet would therefore allow the public transport sector to make a significant contribution towards meeting RES-T targets.

A1.7. Hydrogen

A1.7.1 Introduction

Hydrogen is often envisaged as a major element of the future transport fuel mix due to its very high specific energy content and significant potential to provide clean, efficient power. It is proposed that hydrogen use could limit oil dependency, enhance energy security, and reduce greenhouse gas emissions and air pollution. The *European Strategic Energy Technology Plan*[108] identified the development of hydrogen and hydrogen fuel cells as critical to achieving the required 60-80% reduction in greenhouse gases by 2050.

Hydrogen is an energy carrier and can be generated from many different energy sources including natural gas, petroleum products, coal, solar and wind electrolysis, and biomass. Hydrogen can either be directly combusted in an ICE analogously to CNG, or chemically converted to electricity in a fuel cell (FCEV: fuel cell electric vehicle), which is then used to power a vehicle analogously to a BEV. Hydrogen internal combustion engines tend to have a comparable design and comprise of similar components to those used in conventional diesel engines, as such their cost is considerably lower than those for FCEVs. FCEVs, on the other hand, convert compressed hydrogen from the fuel tank into electricity to power the engine of the vehicle. Unlike traditional combustion technologies that burn fuel, fuel cells undergo a chemical process to convert hydrogen-rich fuel into electricity. Fuel cells do not need to be recharged like conventional batteries; they continue to produce electricity as long as a fuel source is provided. As fuel cells do not have any moving parts they are quiet and highly reliable. Fuel cells can also be stacked together to form larger battery systems, although storage of energy recovered from regenerative braking is not possible.

The service life of fuel cells may necessitate replacement of elements of the cell over the c. 12 year life span of a typical urban bus. In general, hydrogen vehicles have similar range, performance, and refuelling times to ICE vehicles while FCEVs are up to three times more efficient than conventional vehicles. FCEVs have a range of *c.* 250-400km; this is influenced by the number of hydrogen storage tanks on the bus (usually located on the roof). Where tanks cannot be placed on the vehicle roof (due to external height restrictions etc.) the design configurations of hydrogen-fuelled buses and the upper limits regarding vehicle mass may somewhat limit passenger capacity.

A1.7.2 CO_2 emissions

When hydrogen is generated from solar or wind electrolysis to power FCEVs there are zero total life-cycle CO_2 emissions and the process is fully independent of fossil fuels. In fact, the H2 Mobility Roadmap[109] in the UK estimates that FCEVs can achieve 75% lower emissions compared to diesel vehicles by 2030 and continue on a path to zero emissions by 2050. FCEVs combine the emissions-free driving experience of an electric vehicle with the range and convenience of a traditional internal combustion engine. Therefore, hydrogen and specially FCEVs offer great potential for a practical mass-market solution to help meet Ireland's decarbonisation objective.

A1.7.3 Air quality improvements

Hydrogen fuel-cell vehicles contain no carbon, produce virtually no exhaust emissions when combusted or used in a fuel cell (excepting water vapour) and therefore can make a positive contribution to urban air quality. Studies have shown that hydrogen use can offer more long-term benefits by substantially decreasing atmospheric levels of ozone and $PM_{2.5}$ over time[110].

A1.7.4 Infrastructure

It has been estimated that the proposed more stringent CO_2 vehicle standards will increase the market share of hydrogen vehicles, by 2025 it is estimated that between 0.3-0.4% of the total vehicle stock will be hydrogen powered. To accommodate the refuelling needs of 0.9-1.1 million vehicles across the European Union 820-842 hydrogen refuelling stations are planned[111]. According to the H2REF project[59] a single refuelling station costs approximately €800,000 (excluding fuel production facilities) and is only capable of refuelling approximately 10 passenger vehicles per hour *c.* 2-3 buses). There is no hydrogen refuelling infrastructure in operation in Ireland with few commercial organisations capable of constructing or bearing the cost of a stand-alone hydrogen project. Coupled with the lack of right-hand drive hydrogen vehicles currently available for use on the Irish market, the rate of infrastructure development is expected to remain low in the medium term.

A1.7.5 Fuel supply limitations

Hydrogen is not currently in use in Ireland as a transport fuel, although it is produced for the industrial chemical market. Approximately 40 tonnes of hydrogen is produced in Ireland per year in a plant operated by BOC (Ireland) via a P2G/Electrolysis production process (using grid electricity). Hydrogen is a cleaner and more promising fuel in the long term, but hydrogen systems will require a significant period to develop (in terms of safety, distribution, cost and availability)[112]. As the technologies mature, the associated costs will likely decrease. On-going scientific research being conducted is examining the potential of new materials which enhance the splitting of water at a very low energy cost using earth abundant raw materials. This is significant because the energy efficient production of pure hydrogen is now possible using renewable energy sources which will potentially accelerate adoption of hydrogen as a fuel in energy efficient transportation[113]. However, this research is at an early stage – and coupled with the immaturity of the hydrogen transport fuel market at present and the lack of an established hydrogen fuel network – further gives weight to the suggestion that transition towards a hydrogen-fuelled fleet may be somewhat premature.

A1.7.6 Costs

Hydrogen buses have a high acquisition price premium in comparison with diesel vehicles. As hydrogen is still an immature technology, transport fuel, infrastructure and on-going operation and maintenance costs have not been thoroughly investigated to date. Data derived from the KPMG market consultation would indicate that infrastructure costs would be strongly influenced by scalability. Due to the lack of hydrogen vehicles in Ireland, any current refuelling facility would have an extremely low utilisation rate, thereby resulting in a particularly high per GJ cost. Conservative estimates position infrastructure costs (on a per GJ basis) would be 5 times higher for hydrogen relative to electricity, with this figure decreasing to double by 2030 (under the assumption that utilisation rates substantially increase as the technology develops). These cost projections must, of course, be kept under review as hydrogen production and the market for hydrogen fuelled vehicles develops in response to technological advances and market initiatives.

A1.7.7 RES-T

Hydrogen can be produced from a range of different energy sources such as natural gas, petroleum products, coal, solar and wind electrolysis, and biomass. Therefore, a positive contribution to targets for the share of renewable energy in transport can potentially be achieved if the hydrogen is produced from biomass included as an approved feedstock in Annex IX of the RED or from renewable electricity. If hydrogen is produced from fossil fuels sources, it cannot be counted towards RES-T targets and may negatively impact on the overall proportion of renewable energy used within the transport sector.

Appendix 2: Certified emissions from a biomethane fuelled bus

The following certificate shows the emission and energy consumption results for a double deck ADL Scania E400 biomethane fuelled bus that underwent the Low Emissions Bus Scheme at Milbrook

LowCVP — Low Carbon Vehicle Partnership | Approved Test facility — Millbrook

Low Emission Bus Scheme Certificate

Customer:	Alexander Dennis				
Customer Address:	Cameron House, East Pimbo, Lancashire, WN8 9QB				
Test Purpose:	LEB Testing			DYNAMOMETER SETTINGS	
Vehicle Manufacturer:	ADL Scania E400 CNG	*Unladen weight (kg)*	12107.0	Test Weight	14730 kg
Vehicle Type & Number:	DD16 GAS	*Gross Weight (kg)*	19500.0	F°	79.18 N
Engine:	Scania	*Seated Capacity*	74	F¹	21.7700 N/kmh
Transmission:	Auto	*Max Passenger Capacity*	82	F²	-0.32737 N/kmh ²
Euro VI certificate Y/N	Manufacturer Certified	GVW CHECK	OK	F³	0.0 N/kmh ³

Declared fuel, properties and source plus carbon conversion factors

Net Heating Value:	*Biomethane*	47.89	MJ / Litre	*Fuel Provider*	Gas Bus Alliance
Well-to-Tank Factor:	*Biomethane*	10.00	g CO2e / MJ	*WTT evidence*	UK GHG reporting factors 2016
Tank-to-Wheel Factor:	*Biomethane*	5.49	g CO2e / kg	*Fuel Type*	Biomethane

Emissions and Energy consumption results from approved test facility - Average 3 tests

Test Phase	HC (g/km)	CO (g/km)	NOx (g/km)	PM (g/km)	CO_2 (g/km)	CH_4 (g/km)*	N_2O (g/km)*	Fuel Consumption (kg)	Fuel Consumption (kg/100 km)
Rural	0.010	1.42	0.22	N/A	890.35	0.000	0.000	2.41	32.54
Outer London	0.01	2.61	0.25	N/A	1237.94	0.000	0.000	2.94	45.27
Inner London	0.03	6.34	0.18	N/A	1840.60	0.007	0.000	1.69	67.45
MLTB Average	0.02	3.65	0.23	N/A	1406.51	*0.002*	*0.000*	4.63	51.51
LUB Average	**0.01**	**2.64**	**0.23**	**0.0202**	**1173.23**	**0.001**	**0.000**	**7.04**	**42.91**

Zero Emissions (Z.E.) Range: Energy consumption and charging efficiency

Total measured energy consumed on vehicle (kWh)	N/A	Distance in Z.E. mode (km)	N/A	Usable Battery Capacity (kWh)	N/A
Measured grid energy during charging (kWh)	N/A	Charging efficiency (%)	N/A	Max Theoretical Z.E. Range (km)	N/A

Total Tank-to-Wheel GHG CO_2 equivalent

Test Phase	CO_2 (g/km)	CH_4 (g/km x 25)*	N_2O (g/km x 298)*	Fuel TTW** GHG (CO2 Equivalent g/km)
Rural	1.79	0.000	0.00	1.79
Outer London	2.49	0.000	0.00	2.49
Inner London	3.70	0.000	0.00	3.70
MLTB	*2.83*	*0.000*	*0.00*	*2.83*
LUB Total Average	*2.36*	*0.000*	*0.00*	*2.36*

Calculated total Well-to-Wheel GHG CO_2 equivalent emissions over test

Test Phase	Fuel Energy (MJ /km)	Fuel WTT* GHG Emissions (g CO_2e / km)	Electrical Energy (MJ / km)	Electricity WTT* GHG Emissions (g CO_2e / km)	Measured Fuel TTW** GHG Emissions (g CO_2e / km)	Total WTW*** GHG Emissions (g CO_2e / km)
Rural	15.582	155.82	N/A	N/A	1.79	157.60
Outer London	21.681	216.81	N/A	N/A	2.49	219.30
Inner London	32.303	323.03	N/A	N/A	3.70	326.74
MLTB	24.668	246.68	N/A	N/A	2.83	249.51
LUB Total Average	20.551	205.51	N/A	N/A	2.36	207.87

Data Generated by (On behalf of Test facility):	*29 Sept 2016*	*Data Approved by:*	*Insert Date*

Low Emission Bus Certificate Summary

GHG Well-to-Wheel	*207.9*	g CO2e / km
Euro V Average Diesel Equivalent	*1252.4*	g CO2e / km
WTW GHG saving (compared with Euro V diesel equvialent)	*1044.6*	g CO2e / km
% WTW GHG saving (compared with Euro V diesel equvialent)	*83%*	g CO2e / km
Zero Emission operating range (km)	*N/A*	km
WTW CO2 per passenger km (@ Max Pass Capacity)	2.5	g CO2e/pass km
Approved as Low Emission Bus? (15% saving or more)	***YES***	

** WTT : Well-to-Tank* *** TTW : Tank-to-Wheel* **** WTW : Well-to Wheel*

COMMENTS: Emission results marked in red are below detection levels. Tank-to-Wheel GHG CO2 equivalent emissions are calculated by multiplying the Tank-to-Wheel factor by the mass of biomethane consumed over each cycle - they are not taken from the original (tailpipe) emissions results. Note Vehicle is available with specifications from 79Pax (70seat+Whchair+8 stand) to 82pax. All variants are covered by this certificate - (Reissued 14/7/17)

Test Numbers: ML02015866 (9/27/2016), ML02015867 (9/27/2016), ML02015868 (9/27/2016). WTT Factors Published: 6th June 2016

Certificate approved by: *On behalf of Bus manufacturer*	*Certificate Approved by:* *On behalf of LowCVP/DfT*

Source: Low CVP[xiii]

[xiii] https://www.lowcvp.org.uk/Hubs/leb/LEBCertificates.htm

Appendix 3: Regional cities' analysis

As part of the COPERT 5.2 modelling analysis undertaken for this paper, trip and fleet data from the urban bus services in Cork, Waterford, Limerick and Galway were assessed to see if there were any significant differences in emission performance for alternative fuel types relative to those based on the Dublin Bus fleet. It was found that, generally, the emissions performance levels for alternative fuel types followed the same trends relative to the GDA modelled data.

However, it must be acknowledged that the limitations within COPERT software made it difficult to do precise like-for-like comparisons as the modelling software does not include options for single-deck CNG and biodiesel buses. Therefore, the modelling scenario assumed that in 2023 the bus fleet would comprise 50% double-deck alternative fuel buses and 50% diesel buses including a proportion of single-deck to as closely mirror the assumed composition of the full diesel fleet (S1). The 2030 comparison assumed that all the regional cities would be using double-deck buses only.

A summary of the results for the emissions in Cork city is provided below. This assumed 110 buses in the fleet, with a 50/50 split between diesel and the specific alternative fuel by 2023. The diesel buses comprise 30 single-deck buses and 25 double-deck buses. The 2030 emissions assume 100% diesel or alternatively fuelled buses, all double deck. Urban driving was assumed to be 80% on peak and 20% off peak (as with Dublin). An average speed of 17.01kmph was used with average distances assumed to be 12.49km taking on average 44mins. Diesel energy content was assumed to be 43.308MJ/kg and the weather data inputs were monthly averages of 1985–2015 taken from Cork Airport.

Table A3.1: Percentage difference in estimated emission levels of a range of scenarios compared to the baseline scenario based on fleet data for Cork City

Time frame	Pollutants	Emissions (t)	% Difference compared to baseline scenario (S1)				
		S1	S2	S3	S4	S5	S6
2023	CO_2	5,981	15.8%	2%	2.6%	-17.1%	-22.22
	NO_x	12.99		-35%			-46.06
	PM	1.13		-3%			-49.63
	$PM_{2.5}$	0.46		-9%			Not calculated
2030	CO_2	6,970	12.9%	-11%	-9.7%	-43.6%	-38.02
	NO_x	3.94		0%			-86.94
	PM	1.07		0%			-99.59
	$PM_{2.5}$	0.40		0%			Not calculated

The results of this modelling generally mirror the results observed in the analysis undertaken in Section 5 of this paper. Nevertheless, it is worth noting that the starker results for CNG and biodiesel in 2023 could be, in part, due to the comparative analysis being undertaken partially between single-deck diesel and double-deck CNG or biodiesel buses.

Appendix 4: Experiences with alternative fuels in some selected cities

A.4 Operational performance and reliability issues

Research has been conducted into the operational experience of various national and international operators with the following lower-emitting fuels and technologies:

- Electric;
- Hybrid-Electric;
- Compressed Natural Gas (CNG); and
- Biogas/Biomethane.

The findings of this research are presented in table format under the headings of the various fuels and technologies which underwent trial and demonstration, or were selected for widespread fleet transition following trial, across of number of urban locations. Qualitative data, in terms of the perceived performance; costs; and impacts to service of the various potential fuel and technology options is considered in this Section. The results of this research have been aggregated as some details can be considered commercially sensitive[114].

A4.1. Electric

Electric	
Trial/Fleet Transition Locations	London; York, Nottingham; Vienna; Indianapolis.
Vehicle Type	Typically single-deck electric buses (due to route constraints and general availability) and electric midibuses; one operator trialling 5 double-deck electric buses, further double-deck trial of 1 bus on *Park and Ride* services by a second operator.
Driver Experience	Driver buy-in and training found to be essential to optimise electric bus range and improve fleet efficiency. On-board telemetry support systems have been important in aiding transition and monitoring.
Passenger Experience	Delays and cancellations caused by inadequate battery range and need for recharging created some negative passenger experiences; however, operators reported public buy-in to fleet transition as electric vehicles were considered 'greener'.
Typical Service	Selected urban service routes, set orbital routes and *Park and Ride* style services.
Perceived Reliability	Operation of electric buses broadly considered cost-effective. Improvements in reliability were found as technology matured, in comparison with earlier vehicle trials.
Maintenance Requirements	Lithium ion batteries contain multiple battery cells. Periodic replacement of individual cells is required.

Electric	
Infrastructure Requirements	Mix of fast and slow (overnight) AC charging. Fast charge in 4 hours (once daily). Dedicated recharging points installed at depots or at strategic locations along selected routes. Some operators found that route planning and scheduling was essential to accommodate charging needs. Additional electric buses to accommodate charging downtime were required by one operator. One operator found that expensive and lengthy upgrading work to build capacity in the local electricity grid was required prior to rollout of electric services to cope with increased power demand.
Impacts to Service	One operator found that the electric battery size has inhibited passenger cabin space on double-deck vehicles – max. capacity 54 (seated) to 81 (standing and seated). Typical battery range on double-deck electric vehicles was also highlighted as a concern.
Cost Implications	Some operators found that day-to-day running costs were significantly lower than those associated with diesel buses, potentially up to approximately 50%. Some significant additional acquisition costs associated with buses to accommodate downtime.
Procurement Experience	No significant issues experienced with procurement of single- or double-deck buses. One operator noted that Singapore and Hong Kong operate right-hand drive double-deck electric buses, which indicates some market availability.

A.4.2 Hybrid-Electric

Hybrid-Electric	
Trial/Fleet Transition Locations	London; Bristol; Reading; Edinburgh; Newcastle; Sunderland; Dresden; Gothenburg; Hong Kong; Florida.
Vehicle Type	Double-deck series hybrids and double-deck parallel hybrids (conventional hybrid vehicles); one operator additionally trialled plug-in hybrids (3 buses).
Driver Experience	One operator found issues at introduction in relation to regenerative braking. Some instances were noted where the braking deceleration was so markedly different to a diesel bus that drivers became confused, leading to accidents. This was successfully addressed through driver retraining and through calibrating the braking system to capture braking energy but not reducing speeds too swiftly.
Passenger Experience	One operator found that the 'series' type hybrid was a smoother and more comfortable journey than the 'parallel' type hybrid with fewer shudders/jolts during transition between electric and diesel. Some operators found that delays or cancellations due to recharging requirements for plug-in hybrid buses lead to negative passenger experiences. Survey results from another case study indicated major reduction for the exterior noise; however the position of interior noise changed and this lead to some initial acceptance problems with drivers and passengers alike.
Perceived Reliability	One operator found that hybrids were very reliable. Other operators were dissatisfied with the overall energy-efficiency of the vehicles and cited limited fuel savings as motivation to consider other fuels and technologies for fleet transition. Some operators also reported extensive driving in diesel rather than in electric mode, limiting potential CO_2 savings and air quality improvements. One operator experienced frequent breakdowns attributed to design concerns, perceived poor quality of engine and battery components and frequent need to fully recharge vehicles. One study noted a lower reduction in fuel consumption than expected.
Maintenance Requirements	Extra training for maintenance staff required as some vehicles operate under high voltage (up to 600V) which can be dangerous.

Hybrid-Electric	
	Two operators found that the hybrid buses required frequent maintenance and those replacement parts, when required, were very expensive. This may be linked to the maturity of the technology at the time of trial. Lifetime of newer batteries was anticipated to be approximately 5 years; although one operator noted that battery replacement was required in the warranty period when using older technology. One operator noted that hybrid buses used in original trials were still operational five years later, although some may require battery replacement at the next standard refurbishment.
Infrastructure Requirements	Costly infrastructure requirements for plug-in hybrids. The buses were charged using inductive charging plates along the route (opportunity charging) which were considered difficult to install (due to large area required for installation and conflict with underground power, water, waste tubing and cabling etc.)
Impacts to Service	Plug-in hybrids were limited to routes upon which opportunity charging infrastructure was available and required 10-15 minutes 'downtime' to be built into schedule to accommodate recharging. One operator estimated that plug-in hybrids using overnight charging could complete approximately four runs on one route before depleting, necessitating a return to depot to recharge.
Cost Implications	Price premium associated which was not always met by reductions in fuel savings, encouraging a movement towards lower voltage (light) hybrids which have lower upfront acquisition costs (but less CO_2 emission reduction potential). One operator found that fuel savings can be increased if hybrids are run on profit-making routes. Another operator estimated 25% + fuel savings over conventional diesel double-deck buses. Some further additional costs associated with bus maintenance were reported. One operator factored this additional cost into the maintenance contract /tender processes to cover maintaining both the conventional and electric systems. Maintenance costs were considered lower than had been anticipated by the operator. A case study demonstrated significant cost reductions due to a reduction in brake abrasion of brakes.
Procurement Experience	No issues were reported with availability of right-hand drive vehicles.

A.4.3 Compressed Natural Gas

Compressed Natural Gas	
Trial/Fleet Transition Locations	Bristol; Sunderland; Reading; London; Barcelona; Madrid; Colorado; Texas; Arizona; California.
Vehicle Type	One operator deployed only single-deck buses (double-deck not required for services). A trial of one double-deck bus was successfully conducted to raise public awareness and acceptance. Double-deck vehicles were trialled by another operator and will be rolled out for full fleet transition (110 double-deck buses). In some cities CNG is the primary fuel type for bus service provision.
Driver Experience	No additional driver training required for gas bus operation. The greatest difference in terms of driver retraining was in the refuelling process, which was considered to be relatively straightforward and intuitive.
Passenger Experience	Passenger feedback very positive. Responses to one operator survey found that passengers considered gas buses smoother and more comfortable than diesel. Buses were found to be quieter with significantly less engine noise, smell, rattling and vibrations.
Perceived Reliability	Considered very reliable with no significant technical issues with operation. Some infrastructural issues were encountered in winter months by two operators. One found that excess moisture in the gas froze in cold temperatures and flooded the compressor filters. Buses were out of service for 30 hours. This is due to the susceptibility of the UK gas grid to moisture build-up, causing burn-off of glycols in the fuel. On-site dryers can be installed to condition the gas and avoid contamination.* One operator considered that a potential CO_2 savings and air quality improvement from CNG buses was not commensurate with additional investment over Euro VI conventional diesel buses.
Maintenance Requirements	Very few vehicles required additional work beyond ordinary wear and tear. Some additional maintenance/replacement requirements for the vehicles itself, largely associated with high frequency of spark plug replacement. Two operators favoured gas buses over hybrids (previously trialled) due to expense associated with replacement of battery components.

Compressed Natural Gas	
Infrastructure Requirements	The design and costs of fuelling infrastructure varied widely across the different case studies. The total timeframe for station development ranges from four months to two years. Natural gas distribution system interconnection timeframes are a key variable. Extensive infrastructure requirements associated with gas buses, including refuelling points and compressors to 250 bar, storage facilities for cooling tanks and equipment at depots. One operator was unable to install refuelling points at depot due to the distance of the location from the grid and instead refuelled at a public refuelling point. LNG tinkered at depot was proposed as an alternative option but was found to be challenging (the fuel required regular 'stirring' to maintain quality and had a somewhat limited 'shelf-life'). One operator discounted CNG as a potential fuel due to infrastructural constraints at depots. Diesel fuel tanks are located underground, with no space available to extend for additional infrastructure. Another operator reported a reduction in compressor electricity costs by approximately 30% through compressor programming and use timing.
Impacts to Service	Bus range found to be very similar to that of diesel buses with few changes to route planning or scheduling required. Vehicle speeds were found to be consistent with those associated with conventional diesel buses. Some issues were experienced by one operator in relation to passenger capacity on double-deck gas/biogas buses (approximately 70 persons) due to size of the on-board storage tank, which is lower than capacity for diesel double-deck vehicles, which necessitated additional buses on the route. One case study reported difficulties with fuelling tanks in cold temperatures using fast-fill pumps. All reports note expected changes in maintenance procedures.
Cost Implications	Cost differential between diesel and gas buses considered non-exorbitant; however, very high upfront costs associated with installation of infrastructure. One operator noted that the refuelling infrastructure can be

Compressed Natural Gas	
	accessed by third party freight and other public transport vehicles (such as taxis) to provide a level of return on investment for the operators. One procurement contract noted that CNG buses were slightly more expensive and hybrid CNG buses were a further 20% more expensive than a conventional CNG model. The hybrid models did yield *c.* 30% reduction in fuel use. Another report noted 50% vehicle fuel cost reduction compared to diesel vehicles.
Procurement Experience	Procurement of single-deck gas buses very straightforward. More limited supply of double-deck gas buses but still possible to procure for right-hand drive. Several reports noted that the variety of OEMs producing the vehicles was limited and this could act as a barrier to fleet expansion.

A.4.4 Biogas/Biomethane

Biogas/Biomethane	
Trial/Fleet Transition Locations	Bristol, Nottingham; Reading.
Vehicle Type	Following trial and demonstration, one operator plans to undertake full fleet transition (53 biogas double-deck buses) on all standard routes. A second operator currently deploying CNG buses has undertaken a demonstration project of a 100% biogas bus to raise public awareness. Some buses in the fleet have been successfully trialled using CNG-biogas blends at various ratios.
Driver Experience	Strong driver buy-in and acceptance from both operators. Drivers found no discernible operational difference between CNG and biogas buses.
Passenger Experience	Public perception was very positive, biogas buses considered cleaner, quieter and smoother running than diesel counterparts. Demonstration of biogas buses was very successful, with positive public response. Passengers could easily visualise food waste reused as fuel; although one operator noted that food wastes were considered preferable as a fuel source to human wastes due to the psychological assumption that exhaust odour was worse with the latter fuel supply.

Biogas/Biomethane	
Perceived Reliability	No specific technical or operational issues were experienced with biomethane at any blend ratio.
Maintenance Requirements	No technical problems on introduction; minimal engineering training was necessary for drivers or depot staff as buses have a conventional driveline.
Infrastructure Requirements	No issues experienced with refuelling infrastructure beyond those associated with CNG. One operator planned to further extend the refuelling station at depot to increase gas storage capacity.
Impacts to Service	Range, speed etc. found to offer equivalent performance as that of CNG-fuelled buses. Few changes to route planning or scheduling were required to accommodate transition.
Cost Implications	Fuel consumption met expectations, with one operator reporting 30% savings in fuel costs. Biogas was considered very commercially sustainable in comparison with conventional diesel fuels (although at greater cost than 100% CNG buses).
Procurement Experience	Procurement of vehicles as with CNG-fuelled buses.

**Ireland has plastic polypropylene piping which can support 'dry' gas and reduces need for dryers on-site.*

Acronyms

AD	Anaerobic Digestion
AQ	Air Quality
B7	Diesel with blended biodiesel up to 7%
B100	Biodiesel
BEV	Battery Electric Vehicle
BOS	Biofuels Obligation Scheme
BRT	Bus Rapid Transit
CH_4	Methane
CIÉ	Córas Iompair Éireann
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COPERT	Calculation of Air Pollutant Emissions from Road Transport
CRU	Commission for Regulation of Utilities
CSO	Central Statistics Office
CVD	Clean Vehicles Directive
CVP	Carbon Vehicle Partnership
DTTAS	Department of Transport, Tourism and Sport
E5	Petrol with bioethanol blended up to 5%
E10	Petrol with bioethanol blended up to 10%
ED95	Ethanol based fuel with 95% pure ethanol
EEA	European Environment Agency
EEV	Enhanced environment-friendly vehicle
EPA	Environmental Protection Agency
ETS	Emissions Trading Scheme
EU	European Union
EV	Electric Vehicle
FAME	Fatty Acid Methyl Esters
FCEV	Fuel Cell Electric Vehicle
GDA	Greater Dublin Area
GHG	Greenhouse Gas
GNI	Gas Networks Ireland
H_2O	Water
HDV	Heavy Duty Vehicle
HEV	Hybrid Electric Vehicle
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
IIASA	International Institute for Applied Systems Analysis
ILUC	Indirect Land Use Change
LEZ	Low Emission Zone

LNG	Liquid Natural Gas
LPG	Liquid Petroleum Gas
N	Nitrogen
NDP	National Development Plan 2018-2027
NH_3	Ammonia
NMP	National Mitigation Plan
NO_x	Nitrogen Oxide
NO_2	Nitrogen Dioxide
NPF	National Planning Framework
NTA	National Transport Authority
OESS	On-Board Electrical Energy Storage System
PEMS	Portable Emission Measurement Systems
PHEV	Plug-in Hybrid Electric Vehicle
POME	Palm Oil Mill Effluent
PM	Particulate Matter
PSO	Public Service Obligation
RED	Renewable Energy Directive
RES-E	Renewable Energy Sources in Electricity
RES-T	Renewable Energy in Transport
SCR	Selective Catalytic Reduction
SEAI	Sustainable Energy Authority of Ireland
SO_x	Sulphur Oxides
SPSV	Small Public Service Vehicle
TEN-T	Trans-European Transport Network
TTW	Tank-to-Wheel
UCO	Used Cooking Oil
ULEZ	Ultra-Low Emission Zone
VECTO	Vehicle Energy Consumption Calculation Tool
VOCs	Volatile Organic Compounds
WHO	World Health Organisation
WTT	Well to Tank
WTW	Well to Wheel

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- Reading Buses
- Stagecoach North East
- Transport for London (TfL)

Data sourced from operators has been supplemented by information from Clean Fleets EU (http://www.clean-fleets.eu/case-studies/); the American Public Transportation Association; civitas.eu; and individual published case studies. Additional information regarding average route topographies, vehicle ranges, and typical speeds is available from http://zeeus.eu/uploads/publications/documents/zeeus-ebus-report-2.pdf

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