

# Exploring Low Emissions Public Transport; Analysis of Ireland's 1<sup>st</sup> Hydrogen Bus Trial - 2020



James Carton  
Dublin City University  
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## Author Note

This report is prepared by Dr James Carton of Dublin City University, with partners Insight DCU & Smart DCU, with information & data supplied by Caetano Bus, CIE, BOC Ireland, Bus Éireann, Dublin Bus, ESB, Dublin Airport and Toyota Ireland.

DCU is one of Ireland's leading energy research institutions and Insight is a world leading SFI Research Centre for Data Analytics. DCU is a member of MaREI, the Science Foundation Ireland Centre for Energy, Climate and Marine Research. DCU has expertise in energy systems modelling, including hydrogen in mobility, power-to-X, fuel cell & electrolyser technology, energy storage and techno economics of hydrogen technologies and supply chains.

DCU is a partner in the EU funded project HySkills; Hydrogen Mobility Ireland, is lead of H2West and Lead of HyLIGHT and associate partner of GenComm, SEAFUEL and HUGE, EU Interreg projects.

## Executive Summary

Hydrogen is becoming increasingly popular as an alternative fuel source to decarbonise the transport and energy sectors. At present, hydrogen mobility has been adopted in many other countries as part of clean energy and emission reduction targets. In addition to contributing zero emissions, hydrogen fuel cell electric vehicles are highly efficient while improving air quality and noise pollution. This report analyses the data gathered from the first hydrogen-powered fuel cell electric bus, a Caetano H2.CityGold bus, operated on various routes throughout Dublin & Meath between November and December 2020. The trial was organised by Hydrogen Mobility Ireland (HMI) and DCU and supported by CIE, Bus Éireann, Dublin Bus, the Department of Transport, and other stakeholders.

The hydrogen fuel cell electric bus travelled 3086km on Irish roads during the 8 week trial period. The bus, which can be refuelled in less than 9 minutes and a range of 400km, received a high level of public passenger satisfaction when surveyed. It was found that the hydrogen bus has suitable design, range, efficiency, refuelling time and comfort for the various circuit and shuttle routes chosen in either urban or suburban and rural settings, in various winter weather conditions on Irish roads. The hydrogen bus performed with an average hydrogen consumption of 5.6kg/100km or 6.7MJ/km with zero tailpipe emissions (zero NO<sub>x</sub> or CO<sub>2</sub> or CO or CH<sub>4</sub> emissions). It is shown that hydrogen fuel cell vehicles using hydrogen produced directly from renewable sources can have lower life cycle carbon intensity and equivalent efficiency as grid connected battery electric vehicles.

This trial is important from the perspective of the Irish State, who are the key actor in developing a pathway for Ireland to deliver the levels of emissions reductions required between now and 2030. Seeing and trialling hydrogen bus technology is essential for Irish bus owners and operators, to gain experience and understanding of this zero emissions technology. It is important for those who provide public transport services in Ireland and their partners to gain knowledge in the operation of a Hydrogen fuel cell bus in actual service on a mix of urban, suburban and rural routes.

Two main recommendations are for government to development Ireland's Hydrogen Strategy and for government to support the development of a national hydrogen refuelling network for public transport and heavy duty vehicle applications in Ireland.

This trial is seen in the context of further deployments involving double decker buses in Dublin by the NTA in 2021 and the developments in Northern Ireland where Hydrogen Fuel Cell Buses will operate on the Belfast City Bus fleet using green hydrogen.

*Keywords:* Bus, Hydrogen, Ireland, Refuelling, Zero Emissions, Public Transport.

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## Abbreviations

AFHDV – Alternatively Fuelled Heavy Duty Vehicle

AVG - Average

BEB – Battery Electric Bus

BEV – Battery Electric Vehicle

CVD – Clean Vehicle Directive

CVRT – Commercial Vehicle Roadworthiness Test

DCU – Dublin City University

EU – European Union

FCEV – Fuel Cell electric Vehicle

HDV – Heavy Duty Vehicle

HHV – Higher Heating Value

ICE – Internal Combustion Engine

LDV – Light Duty Vehicle

MCP – Manifolded Cylinder Pallet

N/A – Not applicable

NM – Not Measured

Nox – Nitrous Oxides

PEMS – Portable Emissions Measuring System

PHEV – Plug-in Hybrid Electric Vehicle

RDE – Real Driving Emission

SOC – State of Charge

TTW- Tank-to-Wheel

VRT – Vehicle Registration Tax

WTT - Well-to-Tank

WTW - Well-to-Wheel

## Introduction

Globally transport systems, operators and local authorities are under increasing pressure to reduce their environmental and health impacts and to aggressively decrease carbon emissions to achieve city, national, EU and global goals agreed within the Paris Agreement, resulting EU green deal and EU climate policy [1]. In Ireland transport is the largest end-user of energy across all sectors, currently 97% reliant on imported fossil fuel oil. Mobility has shown the largest increase in carbon emissions of any other sector in Ireland; more than doubling since 1990 to over 12MtCO<sub>2</sub>eq in 2019; resulting in Ireland missing its 2020 EU transport target [2]. Although heavy duty vehicles (HDVs), including trucks and buses, only account for approximately 5% of vehicles on EU roads, they are responsible for around 25% of all road transport emissions including particulate matter and NO<sub>x</sub> emissions. Electric drivetrains offer a zero tailpipe emission solution to mobility.

Hydrogen fuel cell vehicles are electric vehicles and offer a zero emission fuel solution with fast fuel refill and with long range, not compromised by weight. Hydrogen fuel cell vehicles operate on the same principal as battery electric vehicles, however a fuel cell, in place of a large battery, is used to convert energy stored in the hydrogen directly to electricity to power an electric motor. The hydrogen fuel can be produced by the electrolysis of water by renewable electricity and can even assist the deployment of additional renewable energy on the electricity system (by mopping up excess produced electricity, reducing curtailment and relieving electricity grid constraint). The technology has been developed and deployed by car, bus and truck auto manufacturers, while vehicle mass manufacture has scaled up in recent years. Many hydrogen vehicles have been trialled to the public in cities to ensure wide coverage and political impact. Over 2,000 Hydrogen buses are in operation globally across the US, Europe and China; London, Aberdeen, Paris, Korea, Germany, New Zealand, Australia, California [3-9].

The hydrogen fuel cell bus trialled in 2020 was the first on the island of Ireland to go into service with passengers. The trial aimed to demonstrate the viability of hydrogen as a clean transport fuel for today and the future, supporting policymakers and transport operators who are aiming to take immediate action on air pollution and achieve Ireland's net zero emission targets. This document reports on the data collected from the hydrogen bus trial, exploring the use of hydrogen as a low emissions fuel in public bus transport in Ireland.

The objectives of this report are to:

- Assess and analyse the primary data gathered from the hydrogen fuel cell bus trial.
- Compare the hydrogen fuel cell bus with existing fossil fuel fleet as well as low or zero emission solutions including battery powered electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs).
- Present recommendations and next steps to assist government, bus operators and local authorities with procurement decisions involving future zero emission hydrogen fuel cell vehicles.
- Disseminate the hydrogen fuel cell bus trial to the stakeholders & connected organisations, transport operators, policymakers and the general public.

### **Hydrogen Transport Initiatives in Neighbouring Countries**

In 2020, **Northern Ireland's** Department of Infrastructure granted a large investment of £66 million toward the decarbonisation of the public transport sector. The funding enabled the public transport operator Translink to invest in 100 zero emissions buses including 20 hydrogen fuel cell electric buses. Translink and the Energia group are working together to ensure the hydrogen fuel is produced using renewable resources, wind power in this case. These efforts are

aligned with Northern Ireland's 2040 targets which set out to completely decarbonise public transport [10 & 11].

A recent report by NUIG & DCU funded by the **Northern Ireland** Department for the Economy mentioned the unique position of Ireland to become a leader in hydrogen deployment and on a high scenario Northern Ireland could have 600 buses, 1000 trucks & 18 trains operating on hydrogen by 2030 [12].

In **Scotland**, the Aberdeen hydrogen bus project included two initiatives: the HyTransit project and the High V.LO-City project. Both projects were supported with funding by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU). The HyTransit project ran between 2013 and 2018. A fleet of six hybrid fuel cell buses were introduced to public city routes operated by Stagecoach to demonstrate the ability for hydrogen to meet and exceed the performance of diesel buses. As part of the High V.LO-City project, an additional four single-decker fuel cell buses were deployed by FirstGroup in Aberdeen. To support the projects, the largest hydrogen production and refuelling station in the UK was set up in Kittybrewster, Aberdeen. The production facility manufactures the green hydrogen from renewable resources [13].

JIVE and JIVE 2 set out to introduce 291 hydrogen fuel cell buses to **22 European cities** between them. Both projects are co-funded through grants by the FCH JU under EU Horizon 2020 framework programme. The 6-year JIVE project began in 2017 and cooperated with local and national governments to introduce the fuel cell buses and associated infrastructure to cities in **5 countries**. Fifteen hydrogen fuel cell buses were put into service in Aberdeen **Scotland** under the large EU-funded JIVE. The world's first hydrogen-powered double decker buses began operation at the start of 2021, operated by the Scottish transport provider First [14]. Today, Aberdeen has twenty-five hydrogen fuel cell buses operating on its streets. Aberdeen is the leading city in the

UK in terms of hydrogen mobility with many others following suit in the JIVE 2 project. JIVE 2 is an expansion of the first JIVE project aiming to introduce further fuel cell electric buses to **14 European cities**. Both projects make up the largest hydrogen bus project in Europe [15 & 16]. The fuel cell projects and initiatives outlined above introduce hydrogen fuel cell buses on a small scale to cities. Through trials and early deployments and by demonstrating hydrogen supply, hydrogen refuelling and the hydrogen fuel cell electric vehicles the intention is to create momentum for low emission mobility, its ability to lower emissions, reduce noise levels and improve air quality as well as to show case the technology, to educate the public and encourage further uptake of hydrogen fuel cell technology by city bus operators, local authorities and governments.

## **Policy Drivers for Low Emissions in Transport**

### **Ireland's Climate Action Bill**

The Climate Action and Low Carbon Development (Amendment) Bill 2021 aims to deliver on the promises of the 2020 Programme for Government to put Ireland on track for a 51% reduction of Ireland's emissions by 2030 and proposes to increase the use of public transport, cycling and walking [17 & 18].

### **The Clean Vehicle Directive**

The Clean Vehicle Directive (CVD) sets binding minimum targets for the share of 'clean' vehicles, as defined in the Directive, in procurements undertaken by public sector bodies over the relevant service contract value thresholds [19]. This means that Ireland now has to legally ensure that a proportion (at least 50%) of public vehicle procurement is low or zero-emission, see table 1. Regardless of national green procurement policy ambition, which may be more ambitious, the

targets set out in the Directive are the minimum. The CVD has different definitions of clean vehicle for light-duty vehicles and heavy-duty vehicles. Light duty vehicle is shown in Table 1.

*Table 1 Definitions of clean vehicle for light-duty vehicles*

Vehicle Category	Until 31 December 2025		From 1 January 2026	
	<CO <sub>2</sub> g/km	RDE Air Pollutant Emissions as a % of emissions limits	CO <sub>2</sub> g/km	RDE Air Pollutant Emissions as a % of emissions limits
M1 & N1 (LDV)	50	80%	0	N.A.

A “clean heavy-duty vehicle” is defined as any truck or bus using one of the following alternative fuels: hydrogen; battery electric (including plug-in hybrids); natural gas (both CNG and LNG, including bio-methane); liquid biofuels; synthetic and paraffinic fuels; LPG. The Directive also sets a separate definition for "zero-emission heavy-duty vehicles (HDVs)", as a sub-category of clean heavy-duty vehicles. Zero-emission HDVs are trucks and buses without an internal combustion engine or with an internal combustion engine that emits less than 1g CO<sub>2</sub>/kWh as measured in accordance with Regulation (EC) No 595/2009, or that emits less than 1g CO<sub>2</sub>/km as measured in accordance with Regulation (EC) No 715/2007. The Directive applies to cars, vans, trucks and buses (excluding coaches) with values over relevant procurement thresholds, procured through:

- Purchase, lease, rent or hire-purchase contracts under obligations by EU public procurement rules (Dir. 2014/24/EU and 2014/25/EU)
- Public service contracts for the provision of passenger road transport services (Reg. 1370/2007)

- Services contracts for public road transport services, special-purpose road passenger-transport services, non-scheduled passenger transport, refuse collection services, mail and parcel transport and delivery.

*Table 2 The minimum clean vehicle targets over the two reference periods*

LDVs Targets to 2030	HDVs Targets to 2025		HDVs Targets 2025 - 2030	
	Trucks	Buses	Trucks	Buses
38.5%	10%	45%	15%	65%

The Directive is technology neutral and as such there is no requirement on public bodies to procure specific vehicles. The decision on which technology is most suitable is a decision solely for the procurer.

### **Renewable Energy Directive (RED)**

The Renewable Energy Directive (RED) has been an important renewable energy policy in Ireland's transport sector and now RED II is its successor. RED II was published in December 2018 and will need to be transposed into Irish law by 2021 [20].

The objectives of the RED are to give regulatory certainty to industry, to promote investment, enable cost-effective renewables to be incorporated into the electricity sector, decarbonise the transport sector, promote advanced biofuels, and incorporate more renewables into the heating and cooling sectors.

RED II foresees a bigger role for advanced fuels (including hydrogen) and sets the direction to move away from food-based biofuels. RED II sets a 14% renewable energy target in transport for 2030 with a binding target is for advanced fuels set at 7% (liquid or gaseous fuels made from electricity called e-fuels and hydrogen can be counted towards this 7%).

The GHG emissions saving from the use of renewable liquid and gaseous transport fuels of non-biological origin must be at least 70% from 1 January 2021. Furthermore, to ensure these

fuels contribute to GHG reduction, the directive currently indicates that the electricity used for the fuel production (e.g. electrolysis) should be of renewable origin i.e. it needs to be produced using additional renewable electricity not the electricity grid.

### **Hydrogen Fuel Cell Electric Vehicle Government Supports**

In January 2021 the National Transport Authority launched the “Electric small public service vehicle grant scheme”, allowing up to €25,000 capital funding for replacing fossil fuel vehicles with zero tailpipe emissions vehicles, including battery & hydrogen fuel cell electric vehicles [21].

In March 2021 the Department of Transport launched the Alternatively-Fuelled Heavy-Duty Vehicle (AFHDV), allowing up to 60% price differential of the capital funding for replacing fossil fuel vehicles with zero tailpipe emissions vehicles, including hydrogen fuel cell electric vehicles [22].

In 2020 the NTA board agreed to buy three hydrogen fuel cell electric double-decker buses from WrightBus in Ballymena, Co. Antrim, to be operated initially in Dublin as the first deployment of a fleet of hydrogen fuel cell electric buses in the Republic of Ireland [23].

In budget 2022 the Accelerated Capital Allowance scheme was extended to 2024 and the scheme was also extended to include hydrogen powered vehicles and refuelling equipment [45]. The Accelerated Capital Allowance Scheme for Gas Vehicles and Refuelling Equipment was introduced in Finance Act 2018. The scheme allows taxpayers to deduct the full cost of expenditure on eligible equipment from taxable profits in the year of purchase.

## The Hydrogen Bus Trial

### Stakeholders & Partners of the 1<sup>st</sup> Hydrogen Bus Trial in Ireland

The hydrogen bus trial was a collaborative project between many stakeholders. All partners were each focused on their own particular area of interest and expertise ensuring that the trial had the potential to deliver on all aspects of a very complex delivery project for Hydrogen as a green, sustainable, renewable, zero emissions transport solution. The stakeholders are:

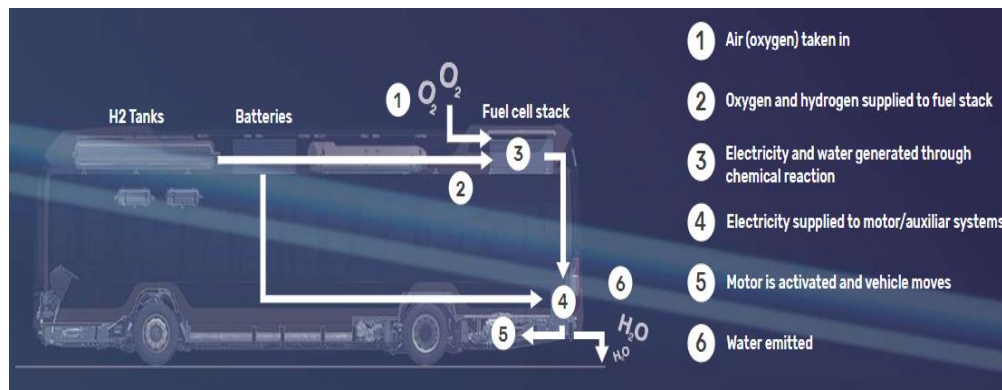
- *Caetano Bus*, the bus manufacturer, supplied the hydrogen bus for this trial. Caetano also trained the personnel to manage and drive the hydrogen bus.
- *CIE* lead the contract negotiations with *Caetano Bus* and supplied the necessary legal and financial support for the trial as well as lead the communication strategy
- *TFI & HMI & Toyota Ireland* assisted *CIE* with the hydrogen bus trial management.
- *Toyota* supplied the fuel cell to the bus manufacturer.
- *ESB* supplied the certified green electricity to the electrolyser that produces the hydrogen.
- *BOC Gases* supplied the hydrogen for the bus.
- *Toyota Ireland* sponsored the cost of the hydrogen used during the trial
- *Bus Éireann & Dublin Bus* are the bus operators and provided the trained drivers/operators.
- *Westward Garages, & Toyota Ireland* supported the movement & storage of the bus.
- *Insight DCU, Dublin City University, & Smart DCU* supplied data loggers and collected data from the trial and analysed and shared the results to partners and the public to ensure wide dissemination of the trial.
- Trial routes were selected for the *Department of Transport, Bus Éireann, Dublin Airport & Dublin City University*.
- *The Department of Transport* provided supporting information for the trial and report.



*Figure 1 Stakeholders involved with Ireland's 1st Hydrogen Bus Trial*

## The Hydrogen Bus

The hydrogen bus on trial is a prototype single deck, H2 City Gold 10.7m right hand drive manufactured by CaetanoBus Portugal (the design spec was proposed by UK London Bus) with a max capacity of 65 passengers, has a range of 400 km and can refuel in 9 minutes.



*Figure 2 Hydrogen Fuel Cell Bus Layout & Operation*

The bus's 180kW motor (Siemens) are powered by two roof mounted 29kWh batteries (Forsee Power) charged by a 60kW hydrogen fuel cell stack (Toyota) and five roof mounted hydrogen tanks with a total capacity of 37.5kg hydrogen (at 350bar max).



*Figure 3 Ireland's 1st Hydrogen Fuel Cell Bus used for the Trial in 2020*

## Training & Support Services

The H2 city gold bus is similar looking and drives similar to other single deck buses including battery electric buses. As with every new vehicle on trial training was necessary to safely operate the bus as well as the need to familiarise operators with the safety systems, shut down procedures and exits in case of an unexpected emergency.

Training was delivered by *Caetano Bus* for *GoAhead, Bus Éireann & Dublin Bus* drivers, *BOC Gases Ireland* refuelling technicians, *Westward Garages* support service staff, and *Dublin Fire Brigade* staff, who both provided important breakdown, maintenance and support services respectively during the trial period. Training included operation, safety checks and shutdown procedures as well as a review of redundancy systems, automatic shut offs and isolation systems on the hydrogen bus. Key components on the bus, easily accessed for maintenance were reviewed and studied; for example; colour-changing tape is used to assist visual checks for possible leaks of hydrogen, reducing maintenance time and allowing technicians to have confidence that their inspection is carried out safely. As with all vehicles in the Republic of Ireland the following were required and actioned before the trial period; vehicle registration tax, (VRT), the addition of registration plates, road tax and a commercial vehicle roadworthiness test (CVRT).



*Figure 4 Training for operators*

## Hydrogen Production

BOC Gases Ireland, part of the Linde group, have been operating a commercial electrolytic hydrogen production facility in west Dublin for over 40 years. The hydrogen is produced for industry customers all across the island of Ireland. BOC offers a range of high-purity hydrogen in a variety of container sizes, MCPs and tube trailers (used to transport large volumes of hydrogen). The alkaline electrolysis system (at efficiencies exceeding 65%) has a maximum production rate of just over 200kg/day using grid electricity. *Electric Ireland* (the electricity supplier of *ESB*) supplies electricity to BOC. For the purpose of the trial and to understand the process of energy certification, the electricity used to produce hydrogen has been certified green by *ESB & Electric Ireland* (the certified source is Ardnacrusha hydro-electric power station on the Shannon Estuary, county Clare).



Figure 5 BOC Gases Ireland hydrogen production facility in Dublin

## Hydrogen Refuelling

*BOC Gases Ireland* organised refuelling for the hydrogen bus trial by decant method (explained in the methodology section) from a stationary tuber trailer. A typical trailer can be filled to 228 bar and can carry up to 300 kg of hydrogen. A hydrogen refuelling hose with suitable nozzle for hydrogen vehicles was used to deliver the hydrogen. Hydrogen use is calculated by pressure difference from the known volumes of the large tube trailer and small bus hydrogen tanks (with temperature measured and constantly monitored). Trained, consistent operators refuelled the bus between 1pm & 3pm each day and recorded values of pressure (the accuracy of measurement of pressure was to 1 bar and precision was kept tight as possible for the duration of the trial). Each refill, using the decant method, took about 30minutes, whereas normal hydrogen refuelling time is a maximum of 9minutes from a standard refuelling station (as per SAE J2601-2 & SAE J2799 (IR)).



*Figure 6 BOC Gases Ireland refuelling the hydrogen bus during the trial*

## Hydrogen Bus Trial Schedule & Routes

With arrangement from Caetano Bus a trial period of 8 weeks was agreed to commence in late October 2020 to be completed prior to Christmas 2020. With consensus between partners it was agreed to operate the hydrogen bus 5 days a week Monday to Friday on the morning (c.06:00) to mid-afternoon (c.15:00) routes to accommodate maximum daylight hours in mid-winter Ireland, the refuelling schedule and to be within an 8 hour shift of one bus driver. This schedule incorporated morning rush hour as well as normal traffic conditions. The following schedule was completed every day; the bus driver arrived in Toyota Ireland collected the bus and drove to the starting/end point of their route on that particular day. After completing between 4 & 6 hours on the route or between 3 & 18 circuits of the route (depending on route), the driver would depart the end point/start point of the route, arriving in Broadstone Bus Garage near Phibsborough, Dublin, where the bus washed and cleaned, before driving to BOC Gases Ireland, where the bus was refuelled with hydrogen. The driver then drove the bus to Toyota Ireland’s premises where the bus was parked overnight & over the weekends. The schedule was repeated during the trial period.

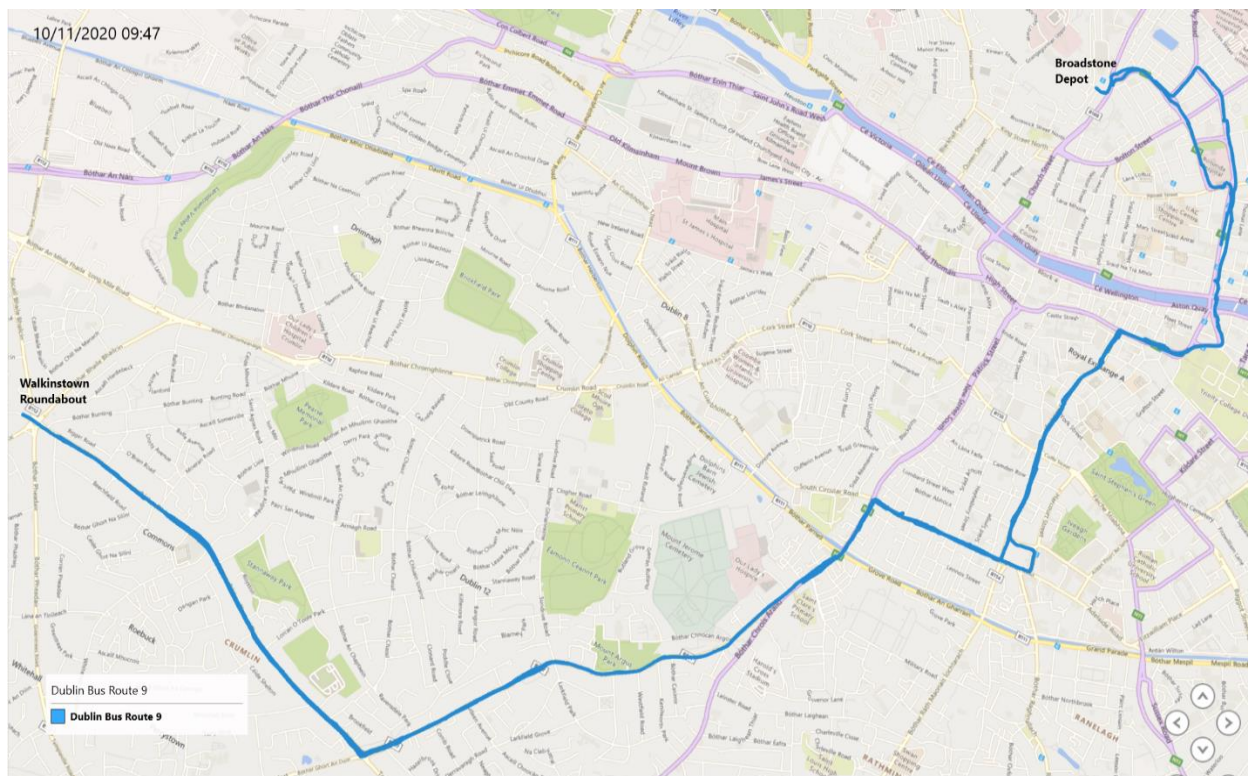
*Table 3 Hydrogen Bus Trial Routes*

<b>Route</b>	<b>Start and end stop</b>	<b>Approximate route length [km]</b>
Dublin Bus Route 9 (modified)	Broadstone Depot, Phibsborough, Dublin 7	19.8
Bus Eireann 109A (modified)	Dublin Airport- Atrium Road Zone 11	51.4
DCU via Ballymun Road	The Helix, DCU Glasnevin Campus	8.9
Dublin Airport (Green, Red & Holiday Blue Car Parks)	Terminal 1	6

## Department of Transport – Low Emissions Vehicle Route

The Department of Transport Low Emissions Vehicle Trial was carried out over the typical operating cycle of a bus, i.e. during rush hour and off-peak, on the route 9 [24] over 2 days operated by GoAhead drivers in November 2020. This trial simulated the operating conditions of a bus loaded with 30 passengers; so 2,000 kg of ballast was added to the bus for this part of the trial, supplied by Dublin Bus. The buses had scheduled stops for 20 seconds at each designated bus stop along the route (unscheduled stops, e.g. due to traffic or traffic lights were also recorded). The hydrogen bus completed six test loops over two days (12 loops in total).

A separate report presenting the results from the Department of Transport – Low Emissions Vehicle Route 9 Hydrogen Bus will be published by Byrne O’Cleirigh Consultants for addition to the Department of Transport for their Alternative-Fuel Bus Trial Report [25]. Due to methodology approaches, see below, both reports & results should correspond well.



*Figure 7 Department of Transport Route 9 Trial*

## Bus Éireann – Route

The Bus Éireann trial covered 13 days on the 109A route [26] over the typical operating cycle of a bus, i.e. during rush hour and off-peak, with city and rural road driving and terrain. The 109A bus (Direction: Dublin Airport – Ashbourne) had 16 stops departing from Dublin Airport stop and ending in Ashbourne (opposite Ashbourne business park).

Bus Éireann, part of Córas Iompair Éireann, is Ireland's largest national bus company, delivering public transport services in Cork, Limerick, Galway, Waterford and many regional towns including Sligo, Drogheda, Athlone and Dundalk with a fleet of over 250 urban buses. The company also operates commuter services in the Greater Dublin Area, regional public transport routes and commercial intercity Expressway services with a fleet of over 500 coaches. Bus Éireann also operates a fleet of over 300 schools buses on behalf of the Department of Education.

Bus Éireann's sustainability strategy aims to achieve a 50% reduction in greenhouse gas emissions by 2030, where half of our vehicles will be zero emissions with the remainder being at low and ultra-low emission levels.

While battery electric buses (BEB) currently provide a viable solution for core urban public transport services, Bus Éireann also recognises the potential of Hydrogen fuel and fuel cell electric vehicles (FCEV) as a viable zero emissions solution for:

- Longer urban bus routes where BEB range is restricted by battery technology
- Future 24 hour urban bus services optimised by fast refuelling
- Longer range commuter routes from satellite towns into the major urban centres
- Regional routes connection rural towns and villages
- Long distance inter-city routes operated by coaches

While most FCEV technology products are currently being developed for urban transport services, Bus Éireann believes Hydrogen fuel cell technology also has significant potential to deliver Zero Emissions in the longer range coach product segment.

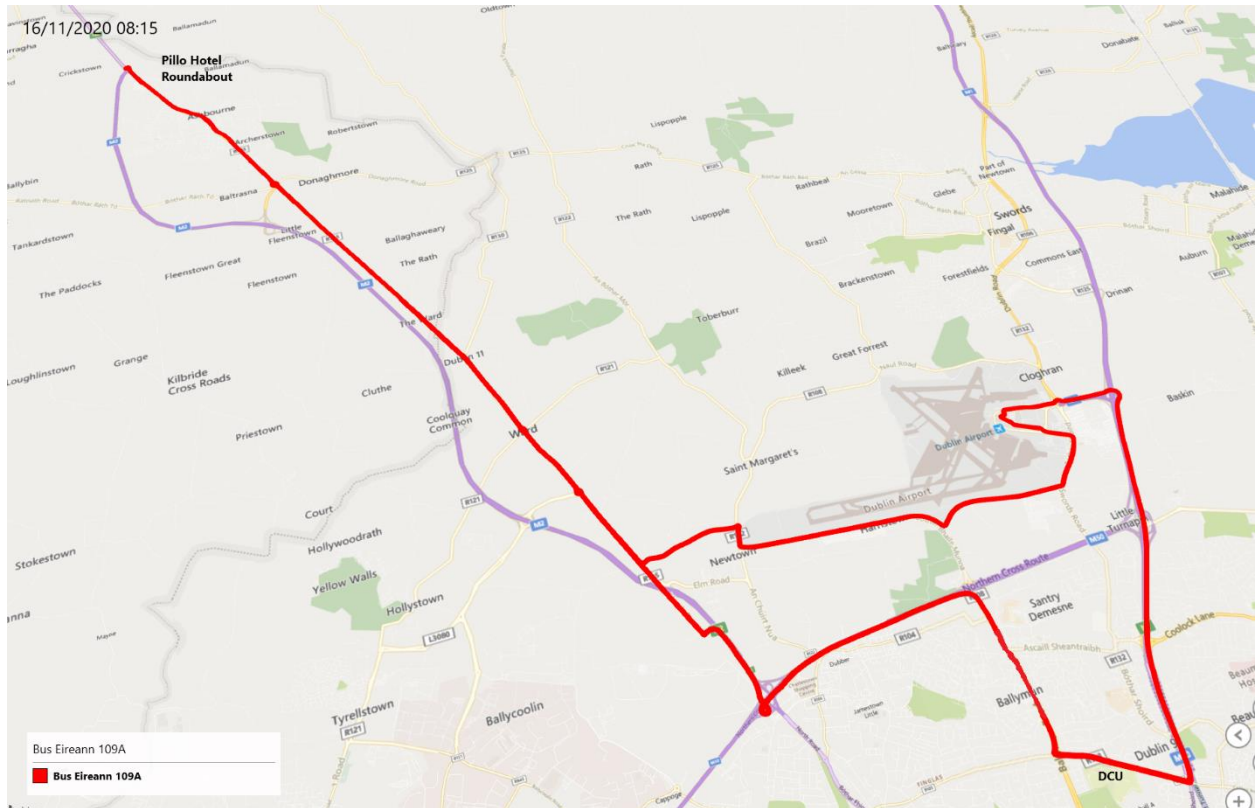


Figure 8 Bus Éireann 109a Trial route

## Dublin Bus – Routes

Dublin Bus, part of Córas Iompair Éireann, operates an extensive network of 110 radial, cross-city and peripheral routes and night routes in the city of Dublin and the Greater Dublin Area, carrying 138 million passengers in 2019.

Dublin Bus plans to move to a zero emission fleet in the city and has introduced 10 hybrid diesel buses to its fleet on routes 4, 122, 123 and 140 in 2021. While battery electric buses (BEB) currently provide a viable solution for core urban public transport services, Dublin Bus also recognise the potential of Hydrogen fuel and fuel cell electric vehicles (FCEV) as a viable zero emissions solution for

- Longer urban bus routes where BEB range is restricted by battery technology
- Medium distance continuous routes optimised by fast refuelling
- Future 24 hour urban bus services optimised by fast refuelling

Dublin Bus explored continuous short circular shuttle routes with Dublin City University's campus route over three days & Dublin Airport's three separate Car Parks routes over 2 days.

## Dublin City University

Located in North Dublin, Dublin City University (DCU) provides education to over 17,000 students with over 1,600 and staff after its expansion to incorporate St Patricks Education College, Mater Day College & Alpha Business Campus, is now a multi campus university; the second largest commuting hub in the north Dublin region after Dublin Airport. 20% of DCU’s CO<sub>2</sub>e emissions (c.12 ktCO<sub>2</sub>e) originate from its staff & student commuting [27]. DCU’s location and population is important to future public transport developments, including walking & cycling pathways, Bus Connects and proposed Metrolink.

“Placing sustainability at the core of the university & advance our reputation for world-class research” are two of Dublin City University’s specific activities to achieve its Strategic Plan [28]. Improving inter-campus connectedness, both physical and perceived, will ensure the most efficient use of resources and the best student and staff experience. In accordance with the strategic objectives of the university it is essential that any solution is an exemplar of sustainable mobility, and hydrogen bus trial is essential on DCU’s road to sustainability.



Figure 9 Dublin City University campus trial route

## Dublin Airport

Dublin Airport is located approximately 10km north of Dublin City Centre. In 2019 Dublin Airport managed 229,143 flights with over 32.65million passengers and London routes were the most popular for passengers that year. Dublin Airport is accessible by over 1,000 buses and coaches daily, reaching many areas in and around Dublin and towns and cities across Ireland. In 2021 Dublin Airport is the first airport in Ireland to achieve carbon neutral status and has done so following an extensive programme of activities to reduce and offset its carbon emissions [29]. Dublin Airport has 4 short term and two long-term car parks as well as staff car parks and hotel connections with over 23,000 spaces serving both Terminals 1 and 2 via shuttle buses. Zero emissions vehicles, including hydrogen fuel cell electric vehicles will aid in the physical reduction of emissions at Dublin Airport.

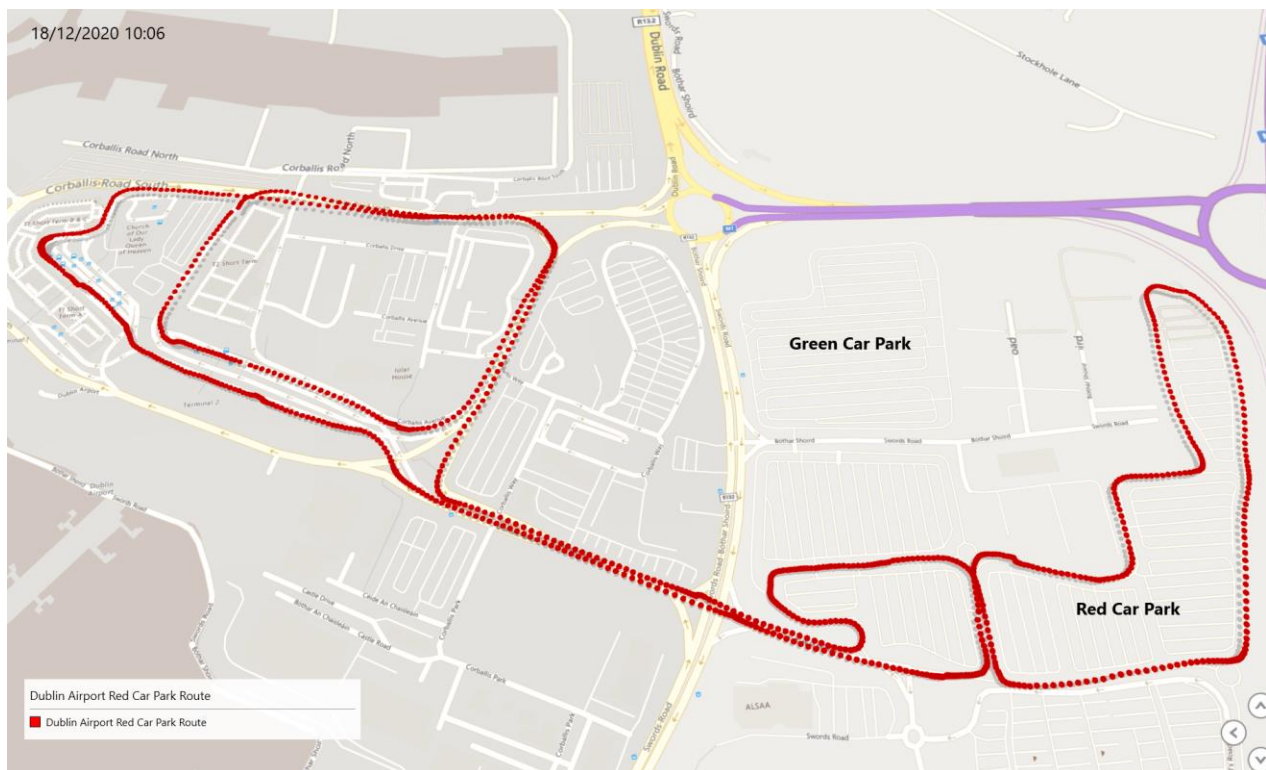


Figure 10 Dublin Airport's Express Red Carpark Trial route



## Data Gathering & Methodology

The main objectives of the hydrogen bus trial were:

- To assess the performance of the hydrogen fuel cell bus in real time and under varying operating conditions, including different routes; urban & rural and short & long.
- To share experiences of hydrogen production, hydrogen supply, hydrogen refuelling with industry shareholders.
- To share experiences of hydrogen bus maintenance and safety.
- To inform on the potential for hydrogen to be used as an alternative zero-emissions fuel source in the transportation sector.
- To inform public bodies & the general public on hydrogen transport technology and its capability to reduce transport emissions.
- To engage decision-makers on hydrogen transport technology and its capability to reduce transport emissions.

During the trial period the global Covid-19 pandemic was ongoing. This meant that all activities related to bus training, planning, operation and communication were curtailed with all government guidelines implemented including mandatory facemasks, social distancing, etc.

### Caetano Bus Data

Caetano bus automatically collects data from many of its systems and saves it to a virtual cloud based fleet management system Viriciti [30]. This system gives a real-time overview of the status of a number of selected parameters such as; state of charge (SOC), range and location of the bus as indicated in Table 4. In addition diagnostic alerts can detect malfunctions while the vehicle is on or off the road. DCU have been given access to raw data sets from the hydrogen bus trial period. These files were converted to CSV files and post processed in Microsoft Excel.

*Table 4 Data supplied from the Hydrogen bus by Caetano*

GPS coordinates with elevation (including driving to route, route, returning to wash, driving to refill and parking) for each day
GPS Speed
Distance travelled along each day (average speed & average road speed)
Hydrogen usage along each day
Pressure rise and fall along each day
Temperature of all hydrogen tanks along each day
Temperature of bus (internal & external) along each day
State of charge of battery along each day

### **Refuelling & Refuelling Data**

BOC Ireland organised refuelling for the hydrogen bus trial by decant method from a stationary hydrogen tube trailer. Decant method or decanting or trans-filling is the process of slowly transferring a gas between two or more cylinders, where one cylinder is larger and at a higher pressure than the other. The process involves decreasing the pressure of the larger cylinder by allowing the gas to flow into the smaller cylinder, eventually both cylinders will equalise in pressure at a lower value than that of the initial pressure of the bigger cylinder. Due to ideal gas law, for a closed system with constant volume, the fluid temperature is proportional to the fluid pressure. Therefore, both the temperature and pressure will drop in the bigger cylinder during this process. In the reversed process, the increasing pressure in the filling process will cause the fluid temperature to increase in the smaller tank (the bus storage cylinders). Hydrogen use is calculated by pressure difference from the known volumes of the large tube trailer and small bus hydrogen tanks (with temperature change recorded). Trained consistent operators refuelled the bus between 1pm & 3pm each day and recorded values of pressure in bar (the accuracy of measurement of pressure was to 1 bar and precision was kept tight as possible for the duration of the trial). Data was shared with DCU in Microsoft Excel format and post processed.

## State of Charge

State of Charge (SOC) relates to the capacity of energy in the battery of the hydrogen bus. Regenerative braking, a capability of electric vehicles, ensures they are highly efficient in comparison to traditional ICE vehicles. The kinetic energy generated when the vehicle decelerates can be recovered and stored in the battery on board, increasing the SOC. This energy can be used once the vehicle begins to accelerate again or for auxiliary power demand. During vehicle acceleration, power flows from the battery to the wheels depending on the power demand. The opposite occurs during regenerative braking when the mechanical work output at the wheels is converted back into electricity. In conventional vehicles, the energy generated from braking dissipates which is inefficient if a vehicle is required to stop and start frequently such as in public transport operations. How often a vehicle stops and starts can significantly impact a vehicle's fuel consumption. Buses and other heavy-duty vehicles require more braking energy to bring the vehicle to a halt making the recovery of braking energy favourable because it can reduce fuel consumption and extend driving range. The bus's capacity to regenerate braking power is dependent on several factors including wheel power demand i.e. power required to drive the bus, auxiliary power demand and internal power losses. The total power demand is:

$$P_{tot}(t) = P_w + P_{aux} + P_{losses}$$

Power consumption is negative when the bus is decelerating and utilising the brakes because the energy is travelling in the opposite direction. The total power output from braking is the available recoverable energy.

$$\sum P_w(t) < 0 = E_{available}$$

SOC was collected via Viriciti and these files were converted to CSV files and post processed.

## Additional Sensor Platforms Data

Smart DCU and Insight DCU supplied five devices from partner companies to operate and gather data for the hydrogen bus trial as shown in Table below.

*Table 5 Data supplied from Additional Sensor Platforms*

Company	Ref	GPS	Humidity	CO <sub>2</sub>	tVOC	Temp	Pressure	Power	Data
AmbiSense	[31]	-	Y	PPM	PPB	Y	Y	Battery	LoRa/SD
Safecility	[32]	-	Y	-	Y	Y	-	Battery	NB-IoT
VTag	[33]	Y	-	-	-	Y	-	Battery	Sigfox
XLR8Solutions	[34]	Y	-	-	-	Y	-	USB/Battery	LoRa/WiFi/SD
Vodafone	[35]	-	-	-	-	-	-	USB/Battery	WiFi HotSpot

Environmental sensors from AmbiSense and Safecility are self-contained devices, configured to detect CO<sub>2</sub> in the PPM level, tVOC (volatile organic compounds) at the PPB level, humidity, temperature and barometric pressure. Comparison data was retrieved against Dublin Airport weather data [36].

VTag is a low cost IoT sensor that is used to track and monitor any kind of asset. It has a 10+ year battery life and can be easily installed within seconds. It includes a number of technologies including GPS, Accelerometer, Wifi sniffing, BLE sniffing, BLE advertising and Sigfox 0G communications. In conjunction with the VT Octopus platform, users can make assets work harder with control tower visibility and cutting edge data analytics.

XLR8Solutions provided a sensor system that measures a number of parameters including GPS, acceleration, gyro-scopic and temperature. The system has an on-board AI that looks for exceptional events in the data and sends an alert over the LoRa and WiFi network to detect out of schedule route or movement.

Vodafone supplied a Wi-Fi dongle so the sensors could communicate to cloud storage as well as for bus passenger use (Hotspot name is “HydrogenBus” with password “SmartDCU”).

Data was shared with DCU in Microsoft Excel format and post processed.

## **Passenger Survey Data**

CIE behavioural analysis team have experience in surveying public transport passengers and collecting data, therefore DCU developed a passenger survey in conjunction with the team in CIE. The main sections of the survey included passenger info, frequency of using public transport, knowledge of hydrogen use in transport and satisfaction of the journey on the hydrogen bus. Due to Covid-19 restrictions the amount of passengers travelling on public transport, in November & December 2020, were greatly reduced affecting the number of participants. Secondly, one of the most efficient ways to gather data from the public is by face-to-face interviews (involving the researcher approaching respondents personally, on the bus or at designated stops), but unfortunately this also was deemed a risk during the pandemic so a poster was created with a QR code and link for passengers to scan and complete the survey. In addition, one page survey sheets were distributed on the bus for passengers to complete. The survey questions and poster used are shown in Appendix.

## **Driver & Driver Sentiment Information**

Six bus drivers were trained to operate the H2.City Gold bus although 2 drivers operated the bus for the majority of the trial. The drivers, in so far as possible, drove in a consistent manner to reduce the influence of driver style and behaviour on the results. These bus drivers were interviewed and surveyed on their experience of driving and operating the hydrogen bus on their routes.

## Data Cleaning & Pre-Processing

Before the data could be analysed, it was pre-processed and organised. The data was collected in a number of Excel spreadsheets in its raw form. Each spreadsheet consisted of the parameter(s) measured and the date and time stamp of measurement. Each sensor had a different sample. Different software was used to manage the vast amount of data points for post processing. A combination of Microsoft Excel, ArcGIS and other online conversion and extraction tools were utilised. Three sample journeys were chosen for each route to be analysed in detail. Journeys on different days with different weather and temperature patterns were used where possible for each route. At least one rush hour test was incorporated where possible. There were some GPS gaps that may have been due to the tracking system's refresh rate or loss of signal, the routes with the least GPS gaps were picked to be the representative routes.

## Analysing Energy Usage

### Fuel Efficiency

Several parameters can be used to quantify the efficiency of a vehicle and the fuel used to propel it. In practice, the fuel consumption is influenced by many operational conditions which can vary between urban, suburban or rural routes in the trial. Such parameters are considered:

- Drive cycle
- Duration of drive cycle
- Acceleration and deceleration periods.
- Number of stops. (when speed=0, neglecting small fluctuations between idling)
- Average speed
- External ambient temperature / Weather conditions
- Time of day considering varying traffic levels
- Mass of vehicle

For the purposes of this study well-to-wheel and tank-to-wheel efficiency were analysed. Tank-to-wheel efficiency is the ratio between the energy output from the wheels and the energy content of the fuel in the tank, while well-to-wheel efficiency is used to comprehensively account for the energy used starting with the production or sourcing of the fuel to the power-energy conversion in the vehicle.

The rate of fuel consumption by the hydrogen bus is calculated by the total fuel used, over a full drive cycle, divided by the distance for that drive cycle, producing an average fuel consumption rate in kilogram per hundred kilometre (kg/100km).

$$FC = \frac{\text{Distance driven}}{H_2 \text{ used}} \times 100 = \frac{kg}{100km}$$

Cold start data is measured to capture variations in fuel consumption prior to the bus reaching its optimum operating temperature. Cold start data is recorded from the start of the bus from its overnight location at Toyota Ireland's premises to where the route begins (the data collected shows that cold start did not affect the bus fuel efficiency).

## Potential Power Available for Recharge

Depending on the road slope/elevation more power can be drawn from the regenerative braking which increases the SOC of the battery indicating a correlation between the route topography and the effectiveness of regenerative braking (other parameters may affect SOC). Therefore road slope cannot be neglected for heavy-duty vehicles subject to load variation. The elevation is used to determine the resistance forces including the slope force and rolling friction at the bus wheels.

$$F_{res} = F_R + F_S + F_D$$

$$P_w(t) = (ma + F_{res}) \times V$$

Buses are classed as heavy duty vehicles and the weight and dynamic loading can affect how the vehicle performs in terms of power output and fuel usage. Public transport buses operate differently to other heavy vehicles because while operating, the passenger number is constantly changing. The rolling force and slope force are dynamic resistance forces that act on the vehicle during movement. Both forces are dependent on the weight. The two forces along with the aerodynamic drag force affect the power demand needed to drive the wheels of the bus at a desired speed. Power consumption is positive throughout majority of the drive cycle when the vehicle is generating traction force. Power flows from the electric motor to the wheels during this time.

Negative values for acceleration are assumed to be from the bus braking and slowing down. Deceleration leads to negative power-to-wheel values which are exhibited in the graph as points below zero (in the results section), energy that potentially could be recovered and fed back to the battery during regenerative braking. The power values below zero is the potential regenerative power. This data is analysed and presented to see how the route affects efficiency.

## Well-to-wheel efficiency of hydrogen

The well-to-wheel efficiency of hydrogen produced from electrolysis using grid electricity and also hydrogen produced from electrolysis fully powered by non-biological renewable energy are calculated and compared. The assumptions are presented below:

- 2017 electricity grid emissions factor used to compare data with the LEV Trial data [25].
- 2017 energy supply mix is used (70% thermal vs 30% renewable) [39]
- Power station thermal efficiency range between 38-50% [20].
- The electricity transmission grid is 95% efficient [41].
- The electricity distribution grid is 85% efficient [42].
- The total electricity transformation losses accounted for 42%, meaning that 58% of all the energy used to generate electricity ends up as electricity [44].
- The renewable electricity is produced by a non-biological renewable energy source, e.g. wind, connected directly to an electrolyser plant.
- The hydrogen electrolyser is 65-70% efficient (depending on technology & balance of plant).
- Balance of Plant at the electrolysers could reduce the efficiency by up to an additional 10%.
- Hydrogen is typically produced at relatively low pressures (20–30 bar) and compressed to 350Bar for transport and fuel station requirements.
- Hydrogen compression, transport and fuel station requirements, consume 3-6kWh/kg hydrogen compressed [43].
- Hydrogen energy density is 33kWh/kg or 120MJ/kg.
- Battery electric vehicle charging stations can be 92% efficient.

## Results & Outputs

### Hydrogen Trial Department of Transport LEV Route 9:

On average the Route 9 was 19.8kms round trip, on average this route consumed 1.18kg of hydrogen or 5.93kg/100km hydrogen per km or 7.15MJ/km. The average maximum road speed for the bus being 47km/hr. The weather was mainly light rain and cloudy and between 10 to 14°C for the routes analysed. The bus stopped an average of 62 times per trip, ranging between 28 and 83 times (a mix between planned and unplanned stops) depending on rush hour traffic.

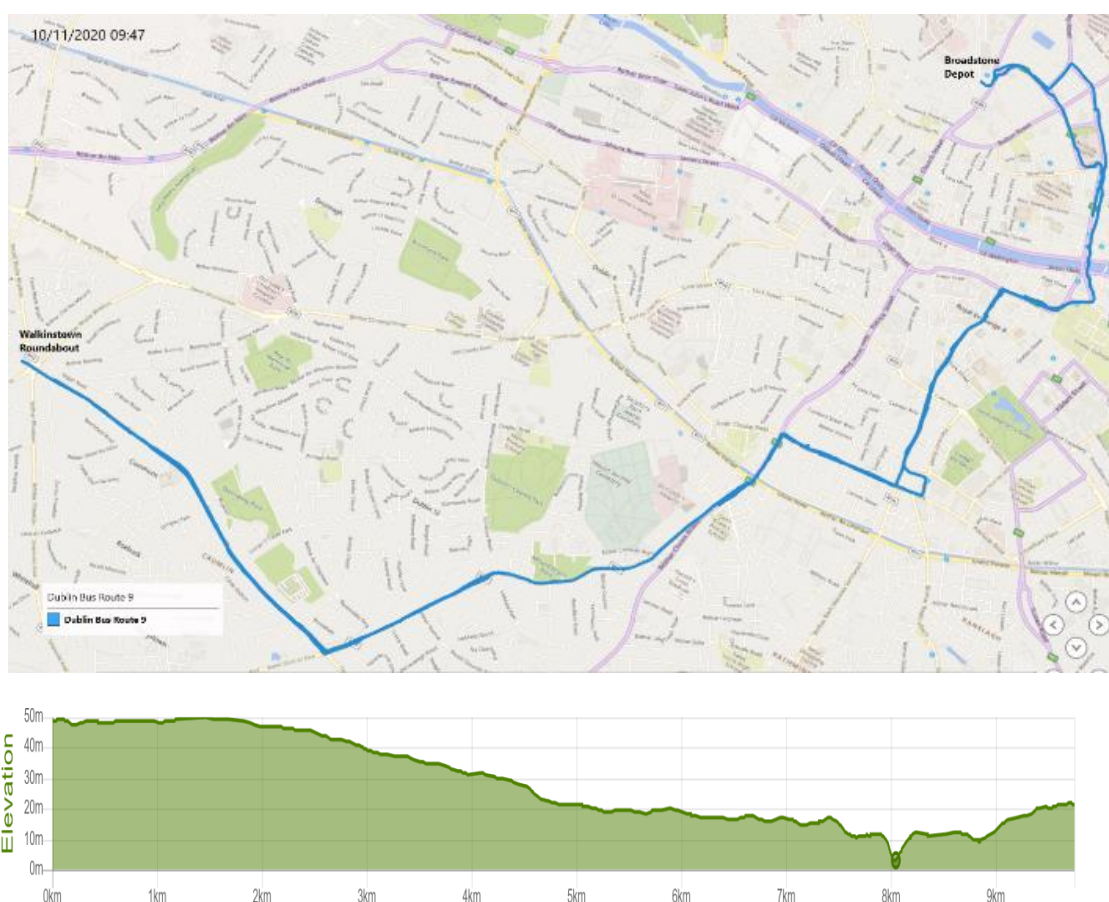


Figure 13 Department of Transport LEV Route 9 Trial; Route Map & Elevation

Figure 14 indicates the SOC of the battery which, as expected, generally follows an inverse correlation with the terrain elevation.

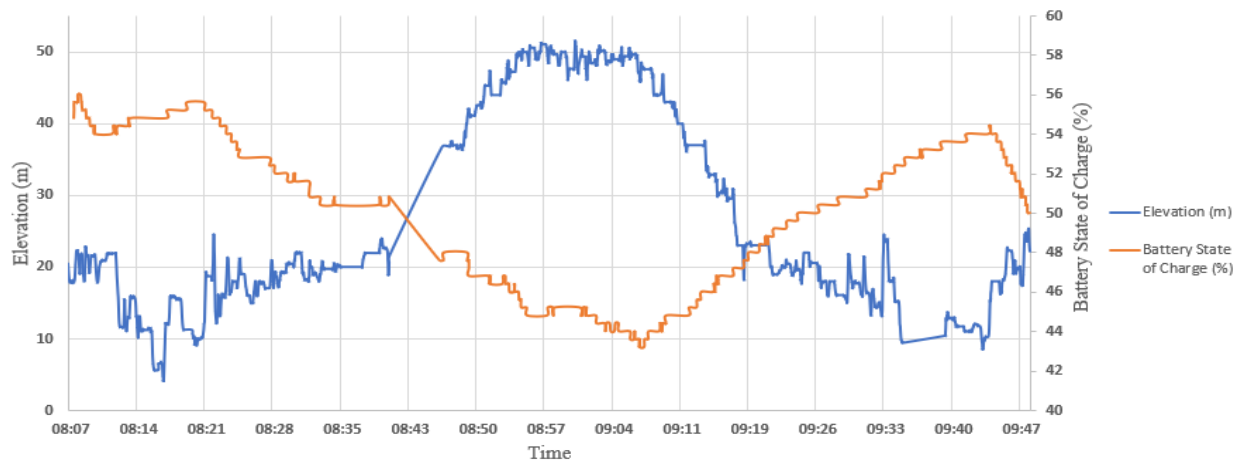


Figure 14 Department of Transport LEV Route 9 Trial Topography & Battery State of Charge

Figure 15 reflects the potential energy recovered by the regenerative braking system, based off the trial information (the real value is dependent on the braking system efficiency and the battery state of charge at the time of deceleration). However the graph indicates that over 146kW (the sum of the red) of power was available from deceleration on this route.

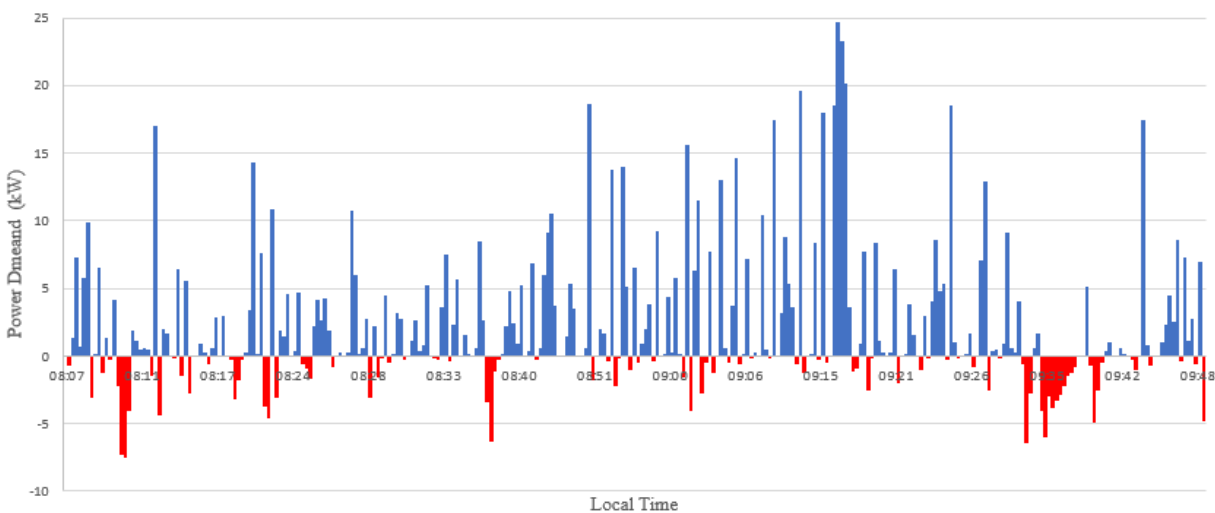


Figure 15 Department of Transport LEV Route 9 Trial - Power available

## Hydrogen Trial Route Bus Éireann 109a:

On average the Route 109a was 54.4kms round trip, on average this route consumed 2.7kg of hydrogen or 5.53kg/100km hydrogen or 6.64MJ/km. The average road speed for the bus being 65km/hr. The weather was mainly light rain, drizzle and cloudy and between -1 to 14°C for the routes analysed. The bus stopped an average of 15 times per trip, ranging between 13 and 25 times depending on rush hour traffic.

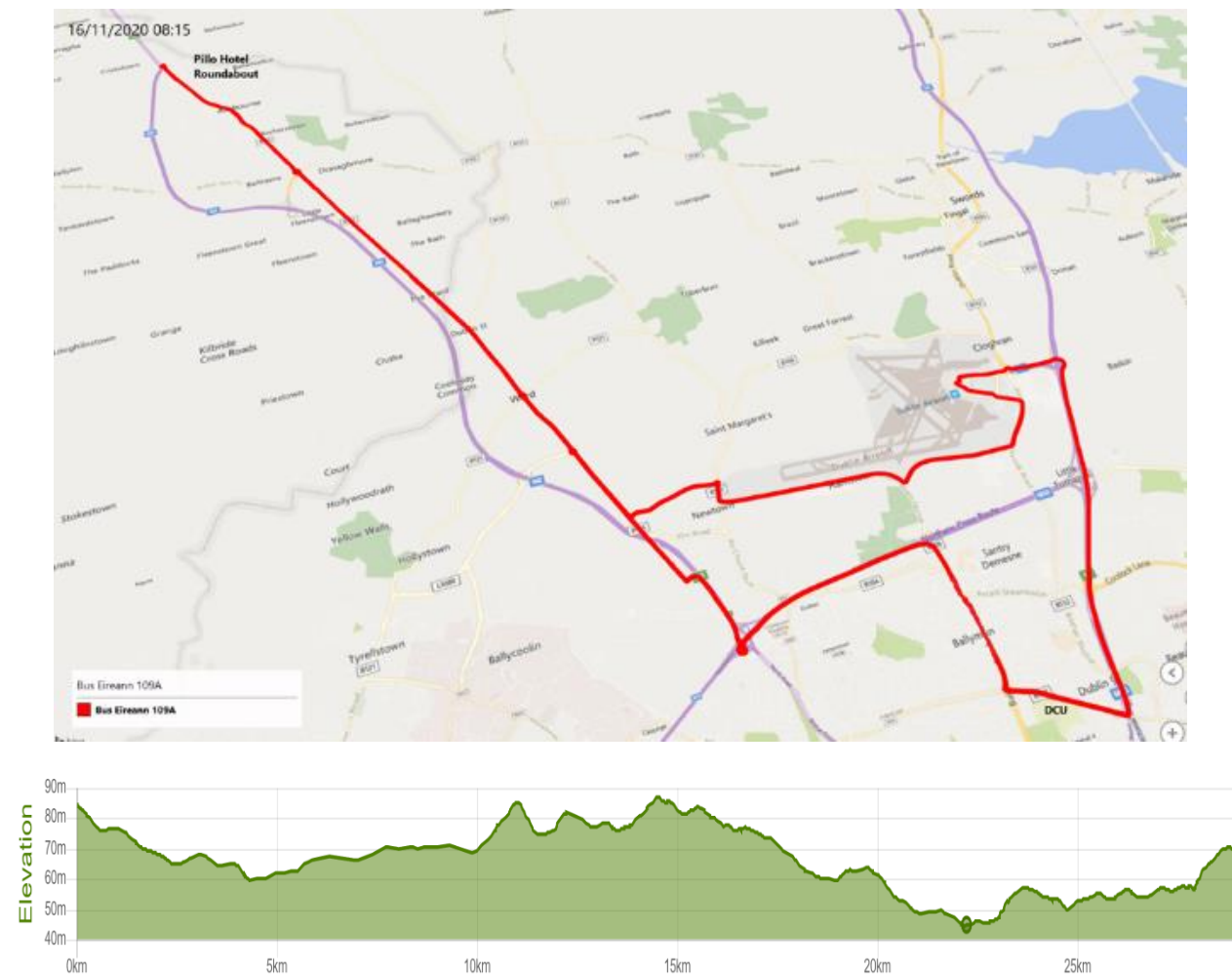


Figure 16 Bus Éireann Route 109a Trial; Route Map & Elevation

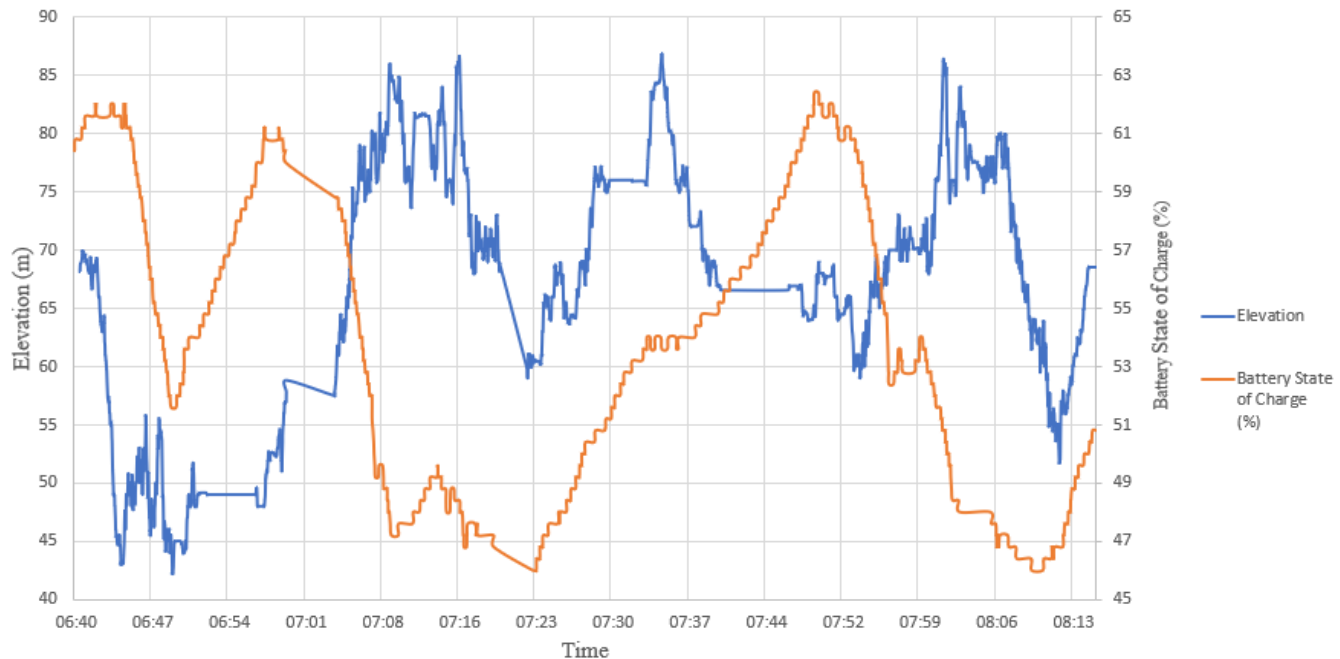


Figure 17 Bus Éireann 109a Trial route Topography & Battery State of Charge

Figure 18 indicates that approximately 81kW of power was available from deceleration on this route. Less power available even though over twice than route 9 due to it was suburban, route and less stops

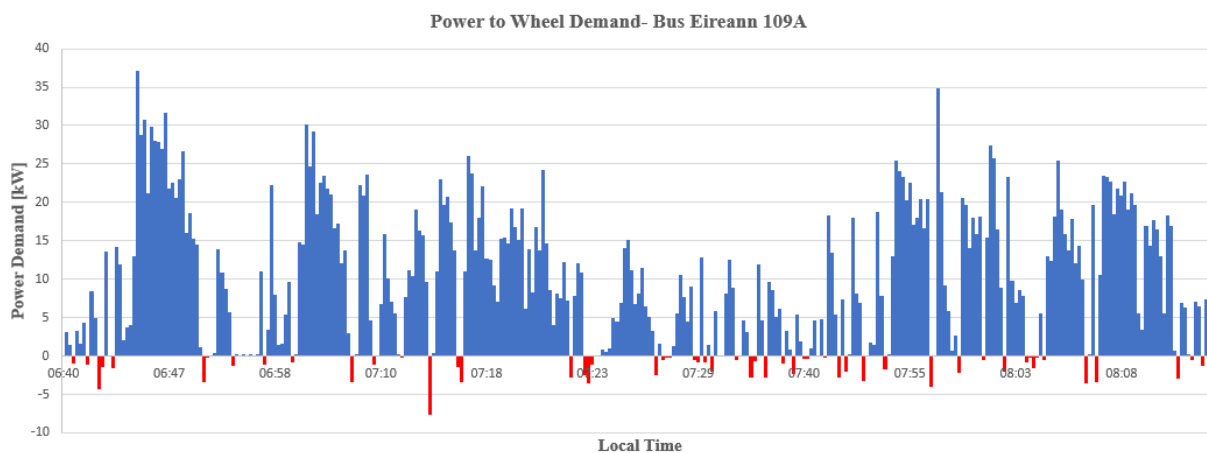


Figure 18 Bus Éireann Route 109a Trial - Power available

## Hydrogen Trial Route DCU

On average the DCU Campus Route was 8.9kms round trip, on average this route consumed 0.34kg of hydrogen or 3.7kg/100km hydrogen or 4.5MJ/km. The average road speed for the bus being 65km/hr. The weather was mainly light rain and cloudy and between 7 to 10°C for the routes analysed. The bus stopped an average of 14 times per trip, ranging between 12 and 15 times depending on rush hour traffic.

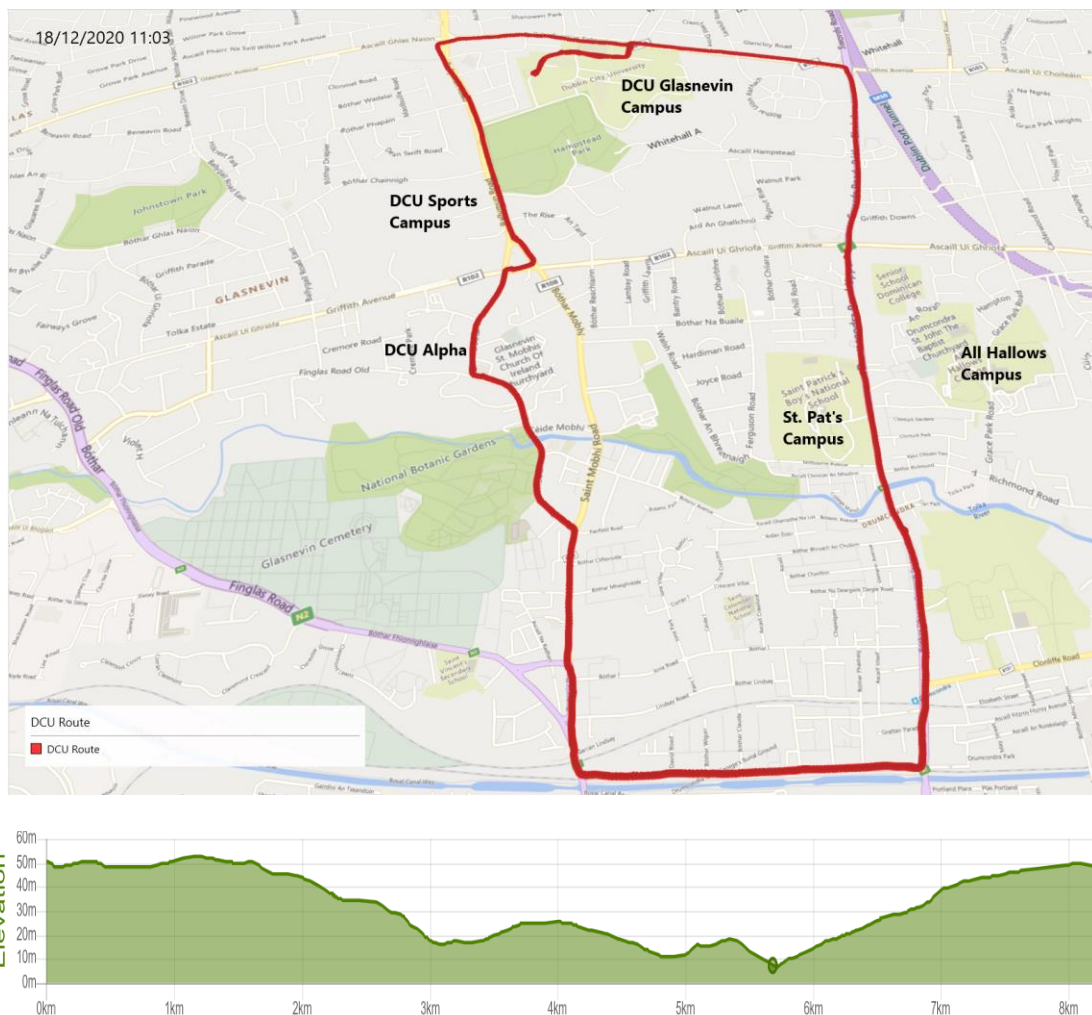


Figure 19 Dublin City University Trial; Route Map & Elevation

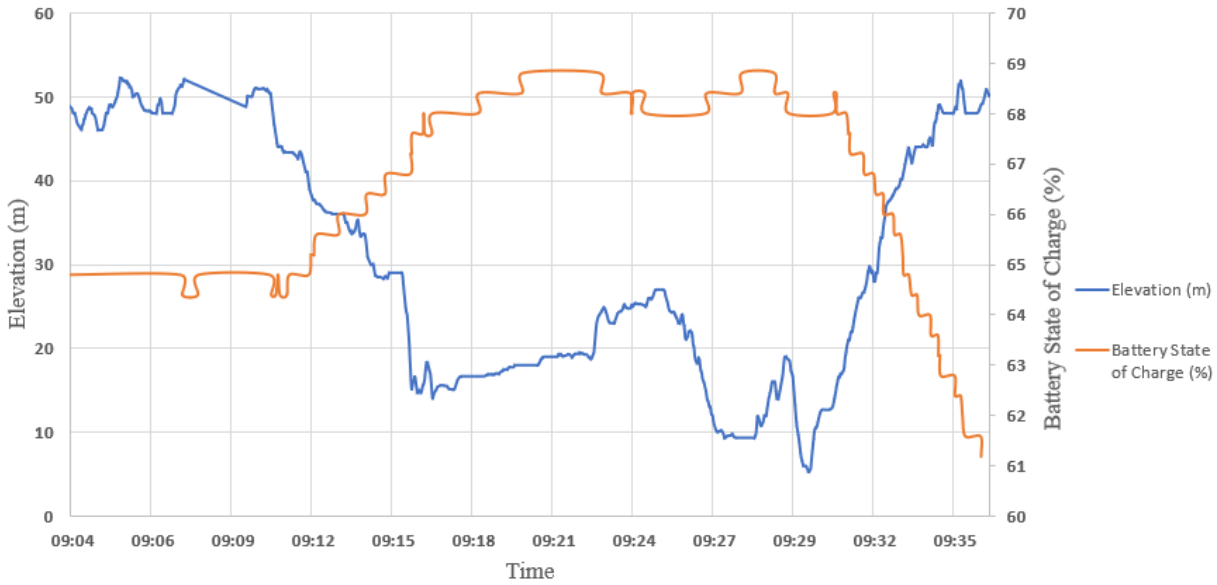


Figure 20 Dublin City University Trial Topography & Battery State of Charge

Figure 21 indicates that approximately 35kW of power was available from deceleration on this route.

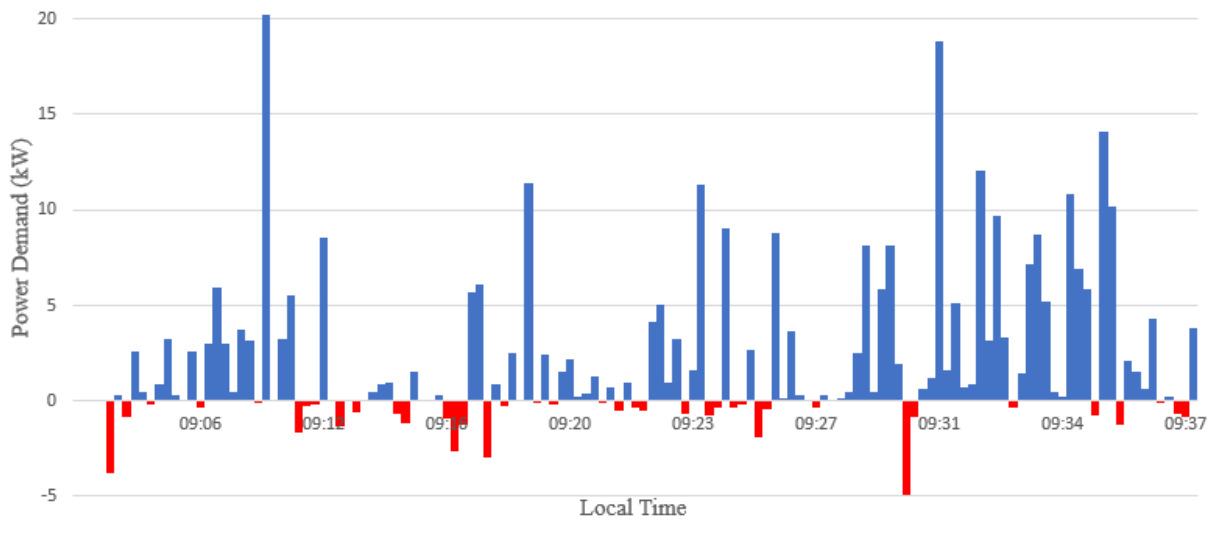


Figure 21 Dublin City University Trial - Power available

## Hydrogen Trial Route Dublin Bus Dublin Airport

On average the Dublin airport routes were very short but numerous. The Red carpark route was 6.74kms round trip, on average this route consumed 0.29kg of hydrogen or 4.25kg/100km hydrogen or 5.11MJ/km. The average road speed for the bus being 40km/hr. The weather was mainly cloudy and between 6 to 9°C for the routes analysed. The bus stopped an average of 10 times per trip.

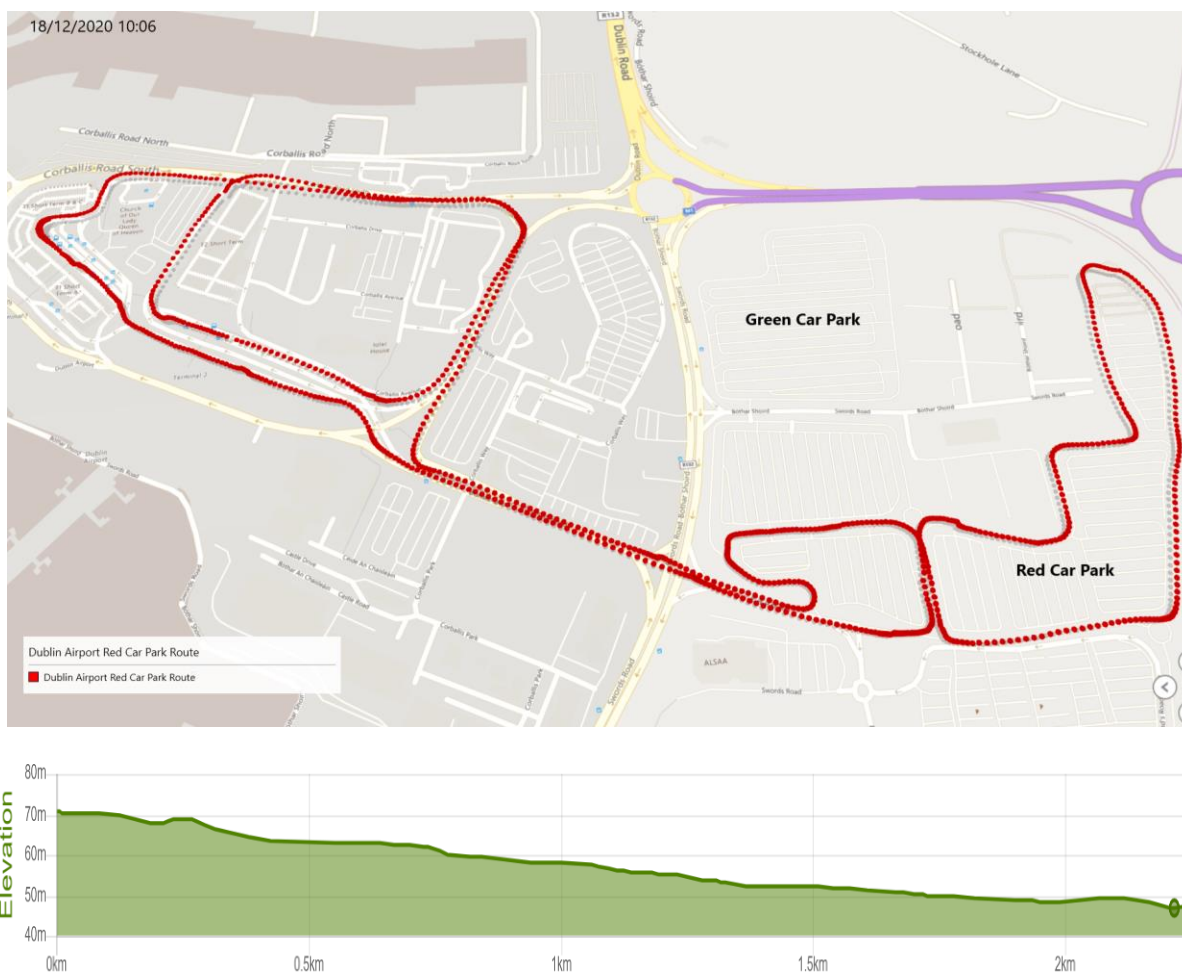


Figure 22 Dublin Airport's Express Red Carpark Trial; Route Map & Elevation

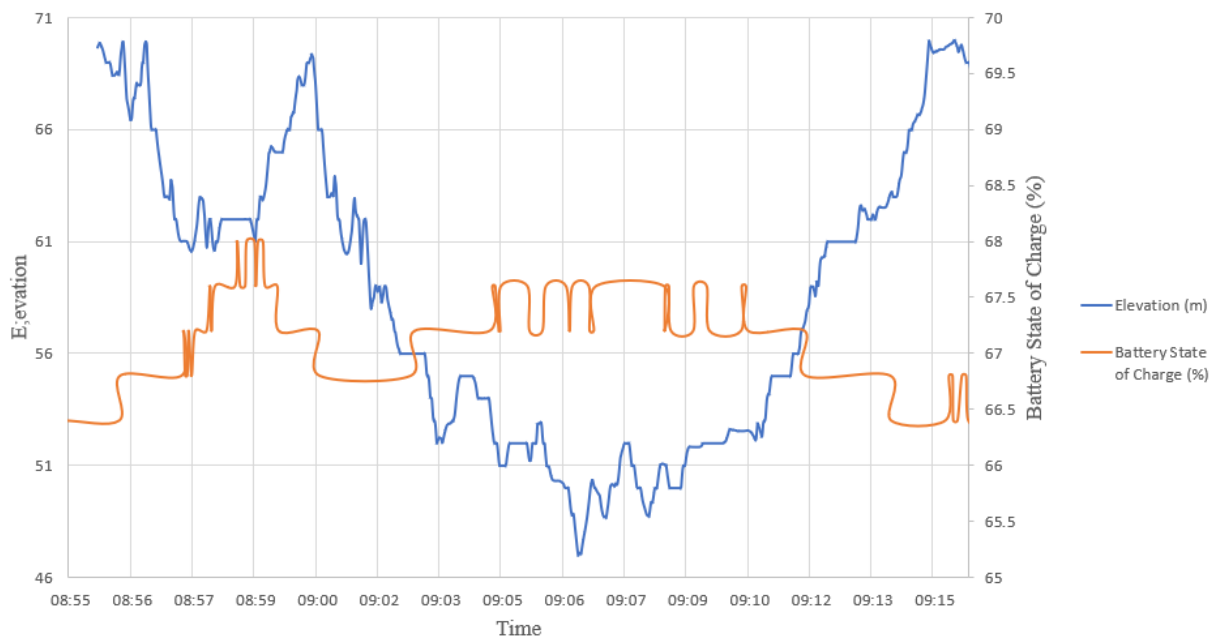


Figure 23 Dublin Airport’s Express Red Carpark Trial; Trial Topography & Battery State of Charge

Table 6 presents the summary data from the Dublin Airport routes.

Table 6 Dublin Bus Dublin Airport’s Example Route Data

Route	FUEL ECONOMY [kg/100km]	FUEL ECONOMY [MJ/km]	MAX SPEED [km/h]	NO. OF STOPS	WEATHER	TEMPERATURE [C]
Red CP Route 1	4.40	5.29	40.60	9.00	Cloudy	6 to 9
Red CP Route 2	4.20	5.06	40.70	12.00	Cloudy	6 to 9
Red CP Route 3	4.15	4.99	41.60	10.00	Cloudy	6 to 9
Avg	4.25	5.11	40.97	10.33	-	-
Green CP Route 1	4.30	5.13	44.80	7.00	Cloudy	6 to 9
Green CP Route 2	5.90	7.08	61.40	12.00	Sunny	9 to 12
Avg	5.10	6.11	53.10	9.50	-	-
Blue CP Route 1	3.80	4.59	63.90	8.00	Cloudy	6 to 9
Blue CP Route 2	3.30	3.97	59.30	10.00	Cloudy	9 to 14
Blue CP Route 3	2.90	3.46	54.80	8.00	Cloudy	9 to 14
Avg	3.33	4.01	59.33	8.67	-	-



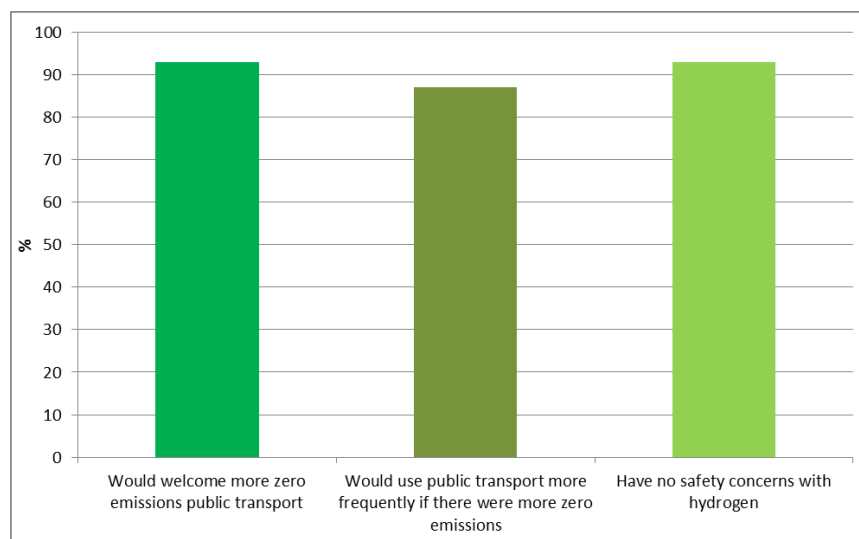
## Passenger Survey

A total of 30 completed surveys were collected, 2 digitally and 28 returned by hard copy. The age demographic composed of almost 45% in the 25 to 44 age bracket, just over 40% above 44 years old and less than 14% below 25 years old. The gender split is almost even between male and female.

37% of respondents use public transport either daily or two to six times per week, with 44% using public transport at least once per week or a number of times a month, the remaining 20% using public transport at least once per month.

The following results were found:

- 87% of participants were aware they were travelling on a hydrogen bus.
- 77% of participants were familiar with hydrogen being used as a fuel source in transport.
- 87% of participants would use public transport more frequently if there were more zero emissions buses.
- 93% of participants had no safety concerns with hydrogen in transport.
- 93% of participants would welcome more zero emissions public transport.



*Figure 26 Satisfaction level of the hydrogen bus journey*

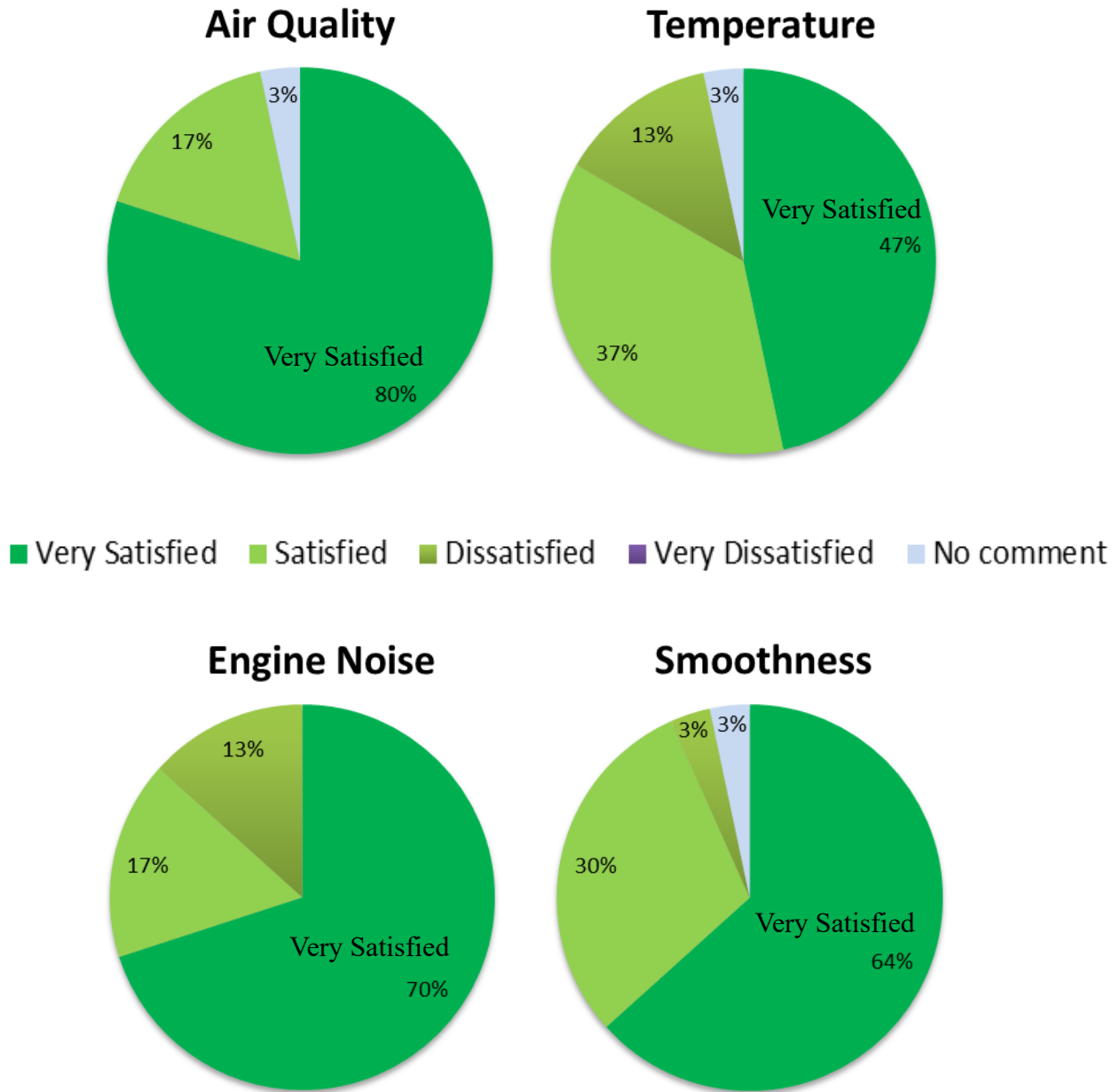


Figure 27 Satisfaction level of different aspects of the hydrogen bus journey

Feedback from the surveyed passengers included statements such as “no vibrations”, “very quiet”, “better than diesel”, “smoothness”, “high quality interior, a big positive and very quiet”, “No smell of diesel or petrol” “Comfort, vibration, silent”, “Less noisy”, “Stop and start is smooth”, “Smell (none), Noise (low)”. Further detailed comments are in the Appendix.

## **Dissemination, Communication & Public Engagement of Trial**

DCU has become the world's first designated autism-friendly university. Several autistic students were invited onto the hydrogen fuel cell bus for the DCU campus route. The students were receptive to the vehicle and also commented on the vehicles comfort and smoothness. This was a very sample size but the feedback is valuable for future planning of an autism friendly operational environment.

There were press releases, radio interviews, TV interviews and TV documentaries on the Ireland's 1<sup>st</sup> Hydrogen Fuel cell Bus Trial 2020 reaching a large portion of the public via national broadcasters, local radio stations web and social media as well as print media to communicate to the wider society on low emissions transportation solutions for public transport (see examples in appendix).

## **Bus Operator / Driver Sentiment**

Six bus drivers were trained to operate the H2.City Gold hydrogen bus, although 2 drivers operated the bus for the majority of the trial. The bus drivers were in contact with the DCU team daily to report on the performance of that days trial and to indicate any updates on data loggers and sensors, as well as survey respondents. The drivers were invaluable to encourage passengers to complete the survey which has helped disseminate the trial. The drivers also kept logs of the weather, number of passengers, speed, temperature, traffic conditions, etc which was correlated later with the data sensors to ensure accurate data collection and assisted in easier post processing of the large volumes of data collected.

The drivers themselves were interviewed on their experience of operating the hydrogen bus and their feedback included statements such as “a user-friendly vehicle”, “similarities to conventional vehicles”, “easy of adaptation”, “low noise”. Other points of note was the drivers perceptions from an operational and training point of view. All drivers indicated that the training provided by Caetano was very useful and straight forward while the operation of the hydrogen bus was very similar to existing buses.

## Comparison to the Department of Transport’s Low-Emission Bus Trial

For this section only the Department of Transport’s LEV Route 9 bus data is used, as this was the same route that was completed for the Department of Transport’s Low-Emission Bus Trials. As can be seen from Table 7 the hydrogen bus trial collected an extensive amount of data and the data collected correlated well with the Department of Transport’s Low-Emission Bus Trials [25].

*Table 7 Data Collected on low emission Bus Trials*

<b>Data Collected</b>	<b>Low-Emission Bus Trials [25]</b>	<b>Hydrogen Fuel cell Bus Trial 2020</b>
Start & End time of Each run	Y	Y
Odometer readings	Y	Y
SOC of Battery	Y	Y
Speed of Bus	Y	Y
Inside CO <sub>2</sub>	-	Y
Inside VOC	-	Y
Inside Cabin temperature	Y	Y
Inside Cabin Humidity	-	Y
Inside Pressure	-	Y
Outside temperature	Y	Y
Outside Humidity	-	Y
Outside Pressure	-	Y
Weather Conditions	Y	Y
Traffic Conditions	Y	Y
Hydrogen Tank temperature	N/A	Y
Hydrogen Tank Pressure	N/A	Y
Hydrogen filled	N/A	Y
Hydrogen used	N/A	Y

## Emissions

Portable emissions measuring system (PEMS) testing was not carried out on the hydrogen bus trial because there are no tailpipe emissions; only a small constant drip of water from the fuel cell (the battery-electric bus trials were managed in a similar way for the Department of Transport's Low-Emission Bus Trials [25]).

*Table 8 Tailpipe Emissions on the Dublin Route 9 Comparison to Department of Transport Trial [25]*

Single Decker Bus Type	Dublin Route 9 Bus	Tailpipe PN #x10 <sup>11</sup> /km	Tailpipe gCH <sub>4</sub> /km	Tailpipe gCO <sub>2</sub> /km	Tailpipe gNO <sub>x</sub> /km	Tailpipe gCO/km
Hydrogen Fuel Cell	Hydrogen Fuel Cell	0	0	0	0	0
Battery Electric	Electric 1*	NM	NM	NM	NM	NM
Battery Electric	Electric 2,3,4	0	0	0	0	0
CNG Euro VI Engine	CNG 1	-	0.2-2.3	1654-2428	1.2-2	1.5-6.9
Diesel Hybrid EuroVI Engine	Hybrid 2	0.1	0	941-1123	2.1-7	1-2.3
Diesel Euro VI Engine	Diesel 4	0.3-2.4	0	1183-1704	4.5-15.6	0.5-1.3

\*Electric Bus 1 had a diesel-powered climate control system but the emissions were not measured (NM)

Table 9 Lifecycle emissions vs tailpipe emissions of various fuels.

Fuel	Tailpipe GHG per directives* (gCO <sub>2</sub> eq/MJ)	Tailpipe GHG measured [25] (gCO <sub>2</sub> eq/MJ)	Well to Tank Life cycle GHG (gCO <sub>2</sub> eq/MJ)	Well to wheel^ Life cycle GHG (gCO <sub>2</sub> eq/MJ)
Hydrogen from Electrolysis fully powered by non-biological renewable energy (HHV)	0	0	9.1 [37]	3.6
Hydrogen from natural gas using steam reforming (HHV)	0	0	104.3 [37]	41.7
Hydrogen from Coal (HHV)	0	0	234.4 [37]	93.8
Hydrogen from Grid Electricity (HHV)	0	0	205.7 <sup>~</sup>	82.3
Battery Grid Electricity	0	0	121 <sup>~</sup>	48.4
Diesel	73.3	73.3	95.1 [37]	95.1
BioDiesel	0	73.3	12 [25] (13.8-80.7 [38,40])	12
CNG	56.9	62.1	77.8 [25] 69.3 [37]	77.8
BioCNG	0	62.1	15.1 [25] (12.3-36 [38,40])	15.1

\*Directive EU 2015/652 [37] & Directive (EU) 2018/2001 [20]

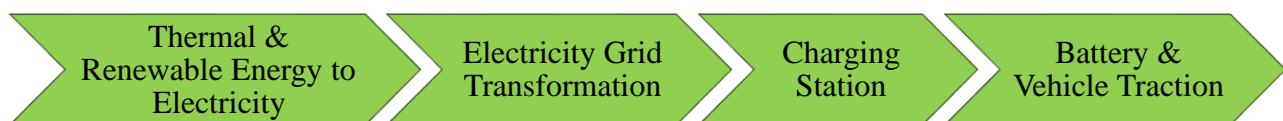
<sup>~</sup> 2017 electricity grid emissions factor used to compare data with the LEV Trial data [25]. Standard hydrogen electrolyzers are 60-70% efficient & energy is used to compress & store the hydrogen. With increasing renewable energy penetration on the electricity grid, it would be expected that the overall carbon intensity of electricity production will improve and thus the carbon intensity of hydrogen produced from grid electricity will also improve (in 2018 the value improved to 107gCO<sub>2</sub>eq/MJ while in 2019 it had improved to 90gCO<sub>2</sub>eq/MJ [39])

<sup>^</sup>Including powertrain efficiencies [37]

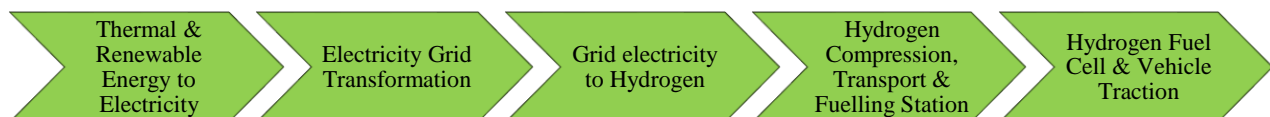
## Efficiency

The hydrogen bus efficiency is presented in Figure 28 - 32. The Dublin route 9 hydrogen bus can be compared against the Department of Transport’s Low-Emission Bus Trials also measured on the same route 9. The tank-to-wheel efficiency of the hydrogen bus is shown to exceed all the Diesel, Diesel Hybrid and CNG alternatives by a large degree. The efficiency of the Hydrogen bus also exceeds the Battery Electric alternative with an average energy consumption of 7.15 MJ/km compared with the battery electric buses with an average energy consumption of 7.65 MJ/km over the three selected routes during the LEV trials, noting that the efficiency ranges from 5.2 to 10.6 MJ/km for the electric buses on the same route 9.

The well-to-wheel efficiency is also measured and compared against battery electric vehicles (Figure 28), assuming grid electricity to produce hydrogen (Figure 29) and taking into account grid and electrolysis losses the consumption increases to 20-24 MJ/km. However using renewable energy and taking account of electrolysis losses and delivering the hydrogen to a refuelling station (Figure 30) the consumption can be as low as 12-15 MJ/km, equivalent to grid connected battery electric vehicle average on a life cycle bases (Figure 31 & 32) .



*Figure 28 Energy Input/Loss for Battery EV using grid electricity source*



*Figure 29 Energy Input/Loss for Hydrogen EV using electricity from grid electricity source*

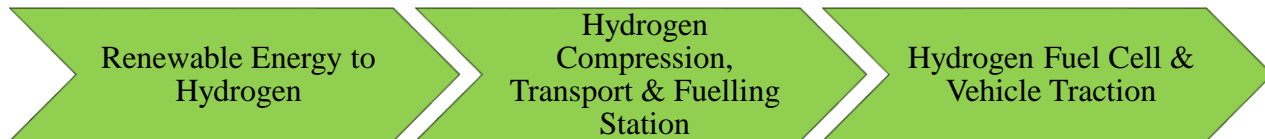


Figure 30 Energy Input/Loss for Hydrogen EV using electricity from renewable source

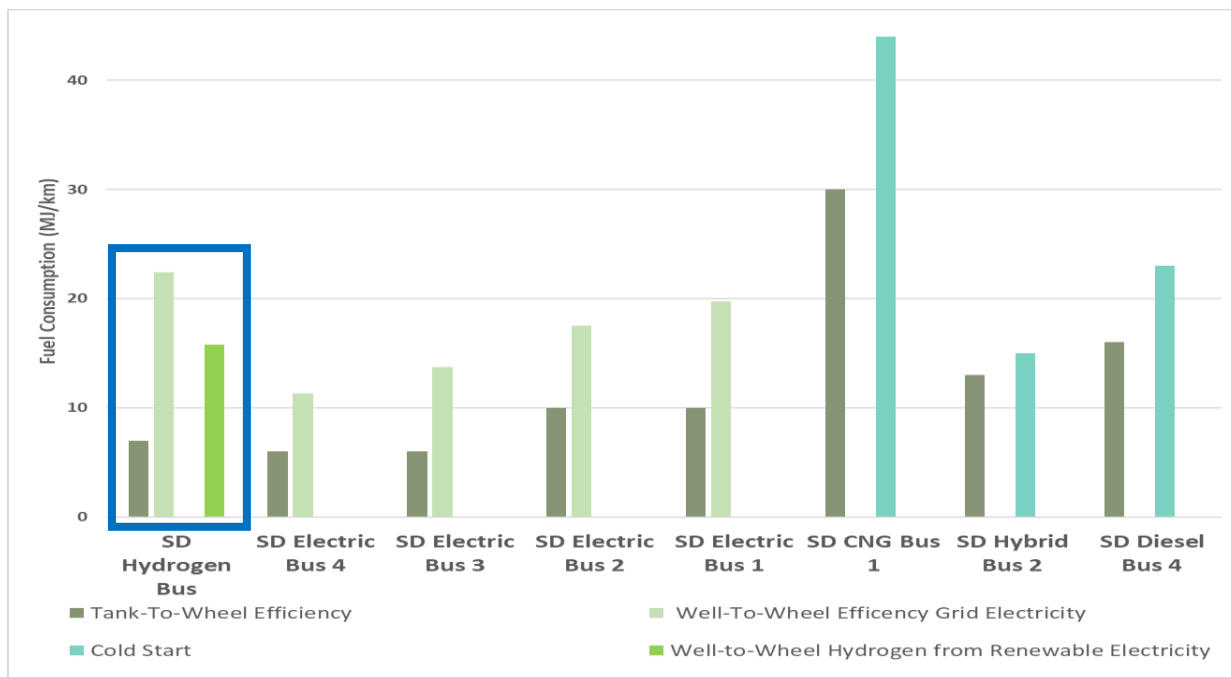


Figure 31 Energy Efficiency of Single Decker Route 9 Trial Buses (hydrogen from renewable electricity)

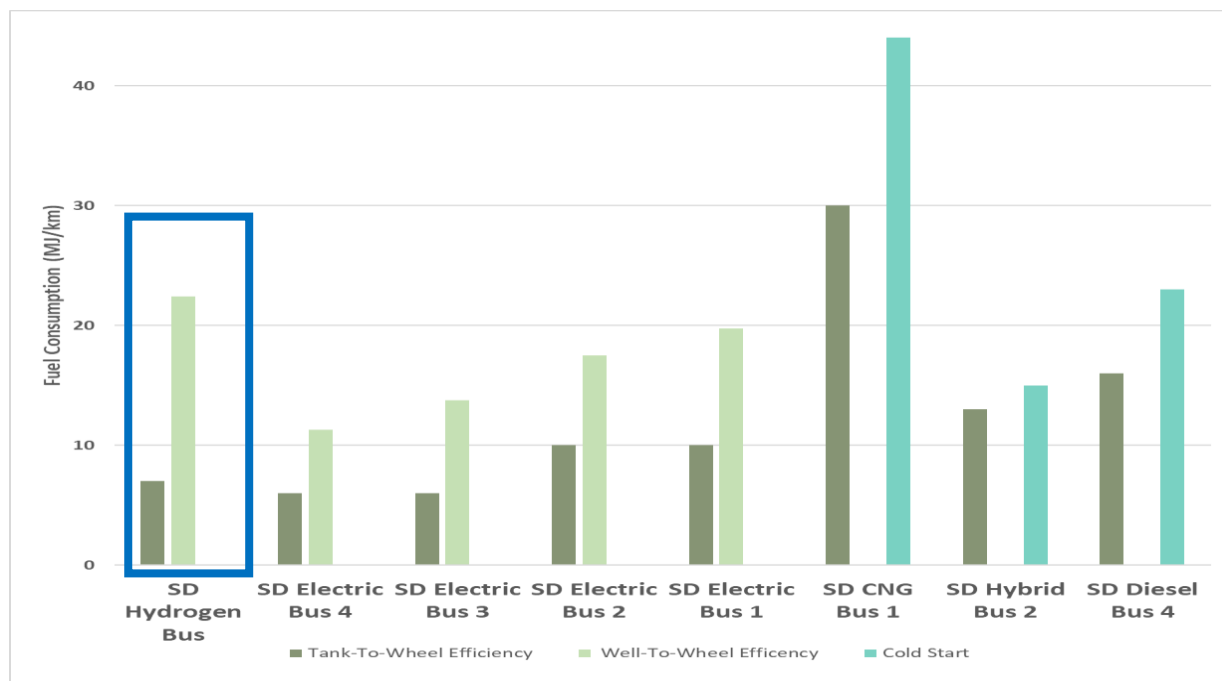


Figure 32 Energy Efficiency of Single Decker Route 9 Trial Buses

## Contribution to Renewable Energy and Emissions Reductions

Over 68,000 tonnes of CO<sub>2</sub>eq per annum could be eliminated on a life cycle basis compared to the most efficient diesel bus, assuming 30% of the bus fleet (almost 750 vehicles) in Ireland are hydrogen fuel cell buses and the hydrogen is supplied from renewable electricity sources. To fuel this amount of hydrogen fuel cell buses would require almost 3,000 tonnes of hydrogen, produced from just over 22 MW of installed electrolyzers at a single or multiple renewable energy sites on the island of Ireland. To put this in context over 12% of Ireland's renewable energy was switched off in 2020, equating to over 500 MW of renewable electricity that was wasted, that could otherwise have been available to convert to energy carriers such as hydrogen. Hydrogen production can be an efficient way to deploy renewable infrastructure and can be effective when used to decarbonise difficult to decarbonise sectors such as heavy duty vehicles; public transport buses. Converting 30% of the bus fleet to a fleet of hydrogen fuel cell buses could contribute to almost 1% per annum of the 51% decarbonisation target by 2030.



*Figure 33 Renewable Wind Energy in Ireland*

## Summary Results

- The hydrogen fuel cell bus travelled 3086km on Irish roads in total during the trial period with an average hydrogen consumption of 5.6kg/100km with zero tailpipe emissions (zero NO<sub>x</sub> or CO<sub>2</sub> or CO or CH<sub>4</sub> emissions).
- Similar to battery electric buses, hydrogen fuel cell electric buses reduce local environmental air pollution & noise pollution and have reduced vehicle particle emissions.
- The trial demonstrated the bus can be refuelled in less than 30minutes (in less than 9minutes once suitable hydrogen refuelling infrastructure is deployed).
- The bus range was tested to beyond 250km during the trial and is capable of in excess of 400km range (once suitable hydrogen refuelling infrastructure is deployed).
- The data indicates that the hydrogen fuel cell bus trialled has suitable design, range, efficiency, fast refuelling and comfort for the various circuit and shuttle routes chosen in either urban, suburban or rural settings, in various winter weather conditions on Irish roads.
- The potential energy recovered by the regenerative braking system was found to be 146kW for the route 9 urban route larger than the other routes.

*Table 10 Total CO<sub>2</sub> emissions saved during the trial*

kgCO <sub>2</sub> eq	Alternative Transport Options
0	Hydrogen Bus Trialled
26,587	Each passenger driving a car*
6,138	A similar CNG Euro VI Engine Bus
4,176	A similar Euro VI Engine Diesel Bus
3,185	A Hybrid Euro VI Diesel Bus

\*Average car emits 132.8g CO<sub>2</sub>/km and buses are at capacity [39]

- The passenger survey indicates a high level of satisfaction with the hydrogen bus and the hydrogen fuel cell technology.

- The hydrogen fuel cell bus tank to wheel efficiency was similar to the average efficiency of similar battery electric vehicles measured and up to 4 times more efficient than some combustion engine vehicles measured.
- Hydrogen produced from grid electricity has high carbon intensity compared to hydrogen produced directly from a renewable source, as indicated in Table 11.
- With increasing renewable energy penetration on the electricity grid, it would be expected that the overall lifecycle carbon intensity of electricity production will improve and thus the carbon intensity of hydrogen produced from grid electricity will also improve.
- Hydrogen fuel cell vehicles using hydrogen produced directly from renewable sources can have better life cycle carbon intensity as grid connected hydrogen or battery electric vehicles, as indicated in Table 11.
- Hydrogen fuel cell vehicles using hydrogen produced directly from renewable sources can have equivalent well-to-wheel efficiency as grid connected battery electric vehicles.

*Table 11 Emissions & Efficiency comparison of various fuels on single decker buses on Route 9*

Fuel	Tailpipe GHG measured (gCO <sub>2</sub> eq/MJ)	Well to Tank Life cycle GHG (gCO <sub>2</sub> eq/MJ)	WTW Life cycle GHG (gCO <sub>2</sub> eq/MJ)	Average Life cycle WTW Efficiency (MJ/km)	Average Vehicle TTW Efficiency (MJ/km)
Hydrogen from Electrolysis fully powered by non-biological renewable energy	0	9.1	3.6	12-15	7.15
Hydrogen from natural gas using steam reforming	0	104.3	41.7	-	7.15
Hydrogen from Grid Electricity	0	205.7	82.3	20-24	7.15
Battery Grid Electricity	0	121	48.4	14.33	7.65
Diesel	73.3	95.1	95.1	-	16
BioDiesel	73.3	12	12	-	16
CNG	62.1	77.8	77.8	-	30
BioCNG	62.1	15.1	15.1	-	30

## **Recommendations**

### **1. Hydrogen Fuel Cell Electric Buses have reached commercialisation**

This trial has demonstrated that hydrogen fuel cell electric buses have reached the commercialisation stage in that they have significant performance, suitable production vehicle levels of reliability and OEM support and maintenance and can therefore be adopted into full time service. It is recommended that hydrogen fuel cell electric buses be considered in earnest for public transport applications and other heavy duty vehicle applications in Ireland.

### **2. Hydrogen Fuel Cell Electric Vehicles Suitable for Irish Conditions**

The data from this trial indicates that the hydrogen fuel cell electric bus trialled has suitable design, range, refuelling time, efficiency, and comfort for the various circuit and shuttle routes chosen in either urban or suburban or rural settings, in various winter weather conditions on Irish roads. It is recommended that hydrogen be seriously considered for public transport and heavy duty vehicle applications where range and refuelling logistics are of importance for the fleet operator.

### **3. Implementing the Clean Vehicle Directive**

Ireland is obligated to meet the requirements set within the Clean Vehicles Directive and to provide leadership in the switch to zero-emission technologies. Hydrogen fuel cell vehicles offer advantages in range & refill logistics to fleet operators where battery electric vehicles may struggle. It is recommended that hydrogen be seriously considered to help achieve and exceed the Clean Vehicle Directive targets.

### **4. Hydrogen Refuelling**

The development of a supply chain for hydrogen, including production, distribution and refuelling infrastructure in Ireland is necessary to introduce zero emissions hydrogen fuel to appropriate vehicles to help reduce carbon emissions from the public transport sector as well as other heavy

duty vehicle applications. One of the limiting factors for deploying hydrogen fuel cell vehicles for public transport or heavy duty vehicle applications is the development of suitable refuelling infrastructure. It is recommended to support the development of a national hydrogen refuelling network for public transport and heavy duty vehicle applications in Ireland

## **5. Hydrogen Production & Decarbonisation Strategy**

The interpretation of RED II and the implementing of electrolyzers, hydrogen and e-fuels correctly in RED II and proceeding policy and regulations will impact the growth of hydrogen production, its availability and its cost to the customer. It is recommended that Ireland develop and publish its hydrogen Strategy and that the hydrogen used for zero emissions transport in Ireland should be the most sustainable, lowest carbon hydrogen available as well as support renewable energy integration, helping to support decarbonisation on the island of Ireland.

## **6. Hydrogen can enable the energy transition**

Given that hydrogen can be an enabler of the energy transition in terms of the introduction of much more renewable electricity, decarbonising of heavy industry and also provide energy security and storage - the introduction of a significant fleet of hydrogen fuel cell electric buses and heavy duty vehicles can help stimulate the development of a complete hydrogen eco-system for Ireland. It is recommended that the challenges, including cost of introducing hydrogen infrastructure and hydrogen buses and heavy duty vehicles should be looked at in the wider context of decarbonising the energy system and society; and the common good that this confers.

## **7. Wider Hydrogen Economy**

The potential of hydrogen to meet decarbonisation objectives has been recognised in the EU's Hydrogen Strategy. Hydrogen is a sustainable zero carbon energy carrier for renewable electricity generation (wind, onshore or offshore, solar hydro, waste, etc); a raw material and fuel for industry;

and an important zero emission fuel for the transport sector. It is recommended that it is time for Ireland to embrace domestically produced hydrogen; supporting the infrastructure and reaping the benefits of economic growth, energy security, jobs and new industries while reducing carbon emissions across the entire energy sector.

## **8. Hydrogen needs supports**

Substantial supports are necessary to introduce zero emissions hydrogen fuel to appropriate vehicles and facilitate market growth in the sector; reducing carbon emissions and environmental air pollution from the public transport (e.g. buses and other heavy duty vehicles). These could include: Capital funding for initial hydrogen deployment projects and refuelling infrastructure in Ireland; An incentive program for hydrogen-fuelled vehicles; An incentive scheme which rewards the production of green hydrogen; And once cost competitive, hydrogen could be taxed.

## **9. Data sharing from NTA & Northern Ireland Hydrogen Bus Trials**

The 1<sup>st</sup> Hydrogen fuel cell bus trial on the island of Ireland should be viewed as the first of many hydrogen bus, truck, fleet trials and deployments that are planned over the next few years. In July 2021 three double decker hydrogen fuel cell buses have been deployed in Dublin by the NTA while earlier this year the Belfast City Bus fleet is commencing its role out of Hydrogen Fuel Cell Buses in Northern Ireland. It is recommended that learnings and data should be shared between trials and early deployments to benefit and progress hydrogen in transport and the reduction of carbon emissions from the transport sector on the island of Ireland.

## **10. Bring the public on the journey**

To ensure Ireland achieves a fast, full energy decarbonisation the transition must be fair and just and the public must be informed and educated and able to become part of the solution. It is recommended that this would form the core of Ireland's Hydrogen Strategy.

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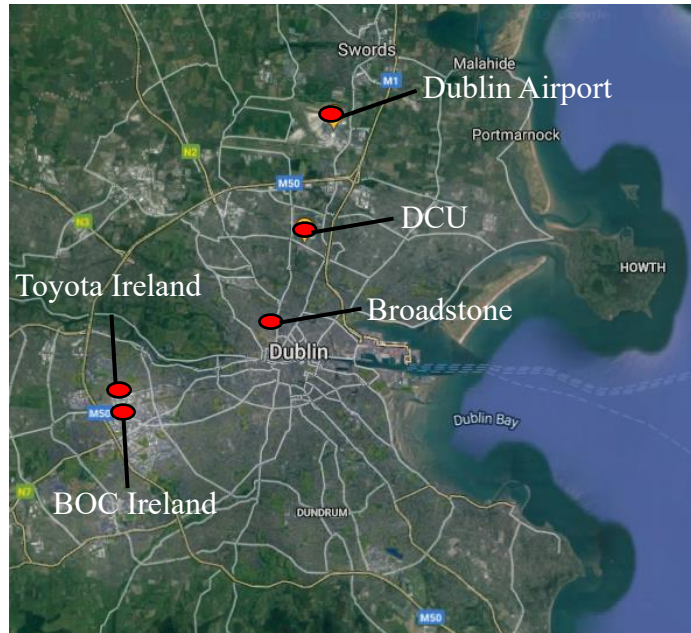
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Finally a special thank you to the public who travelled on the first hydrogen bus on the island of Ireland, we want to thank you for engaging with us and very much appreciate your input and feedback.

## Appendix



*Figure 34 Main Dublin locations during the trial*



*Figure 35 Insight DCU Sensor Array*



#### Appendix: Other More Detailed Survey Comments:

- “The way forward. It would be fantastic if Ireland took a leading role in having hydrogen power our public transport. This project could help seed the establishment of a hydrogen supply network. In time, this could encourage other vehicles like semi-trucks etc to adopt hydrogen as a fuel.”
- “Driving more smooth. Stops and drives more smoothly. No smell of diesel or petrol. The stop and start is smooth. The engine noise is predictable - stays the same and no sudden loud bursts.”
- “The sooner the better, important that hydrogen comes from a sustainable source. Thanks for the opportunity to take a spin. Really enjoyable and well done to all the partners on the project.”
- “Changes like this may be uncomfortable for some but is needed for all for a better future.”
- “Beeping when door opens is a little intrusive.”
- “Not much difference.”
- “Vehicle collision, flammability.” (see section on hydrogen safety below)
- “Need signage for exit. Lights too bright. Different noises - have to get used to the vibrations and the drill like noises. White light is sharp.”
- “I hope to see more of these buses on the network.”

## Hydrogen Safety

Hydrogen is the simplest and most abundant element and its simple chemical structure make hydrogen gas flammable and relatively easy to ignite as well as giving it its non-toxic, odourless, tasteless and light properties. When handled responsibly, hydrogen's properties can make it as safe to handle as conventional fuels, such as gasoline, propane, methane or diesel. When hydrogen is converted to electricity in a fuel cell it produces only water and the conversion of hydrogen to electricity occurs at less than 80°C, well below ignition temperatures. Sensors are a requirement for hydrogen fuelling stations, equipment, and facilities so that even the smallest leak is detected before it can manifest into a potential risk. Hydrogen storage tanks in fuel cell vehicles are made to resist impacts and high temperatures and pressures and if they fail they are designed to fail safe, using the properties of hydrogen to dissipate hydrogen safely. If hydrogen does leak or spill into the environment it will not contaminate the environment or threaten the health of humans or wildlife, as it will typically rise and disperse rapidly.

Hydrogen has well known safety hazards gained from industry experience pressurising and transporting hydrogen in pipes and trucks and bottles for decades and using hydrogen for over a century in oil refineries, fertilizer manufacture, metal cutting, semiconductor manufacture, butter and chocolate manufacture, etc. The technology, risks, regulation, standards and safety measures developed by industry are now proving to be valid and vital to ensure safe use of hydrogen as an energy carrier and as a clean fuel in transport; sectors that will continue to prioritise hydrogen safety measures in all applications. Hydrogen properties must be respected, used and implemented safely. Centres like HySAFER [46], (Hydrogen Safety Engineering & Research Centre) based in Ulster University, carry out research in safety of hydrogen as an energy carrier, essential to educate first responders and engineers on the risks and mitigation methods of using and handling hydrogen.

## Supplementary Data from Trial

Table 12 Department, Bus Eireann & Dublin Bus Example Route Data

Route	FUEL ECONOMY [kg/100km]	FUEL ECONOMY [MJ/km]	MAX SPEED [km/h]	NO. OF STOPS	WEATHER	TEMPERATURE [C]
Route 9 -1	5.70	6.83	48.30	28.00	Light rain	12 to 14
Route 9 -2	5.90	7.15	47.40	75.00	Cloudy	10 to 12
Route 9 -3	6.20	7.46	46.90	83.00	Light rain	12 to 14
Avg	5.93	7.15	47.53	62.00	-	-
Bus Eireann 109A -1	5.40	6.51	74.30	17.00	Cloudy	7 to 9
Bus Eireann 109A -2	5.40	6.46	75.60	25.00	Light rain	9 to 14
Bus Eireann 109A -3	6.30	7.58	71.20	8.00	Cloudy	-1 to 6
Bus Eireann 109A -4	5.00	5.99	72.20	13.00	Drizzle	8 to 10
Avg	5.53	6.64	73.33	15.75	-	-
Dublin Bus DCU - 1	2.80	3.35	49.50	14.00	Cloudy	7 to 9
Dublin Bus DCU -2	3.90	4.68	42.60	12.00	Rain	9 to 10
Dublin Bus DCU -3	4.50	5.43	53.10	15.00	Light rain	7 to 9
Avg	3.73	4.49	48.40	13.67	-	-

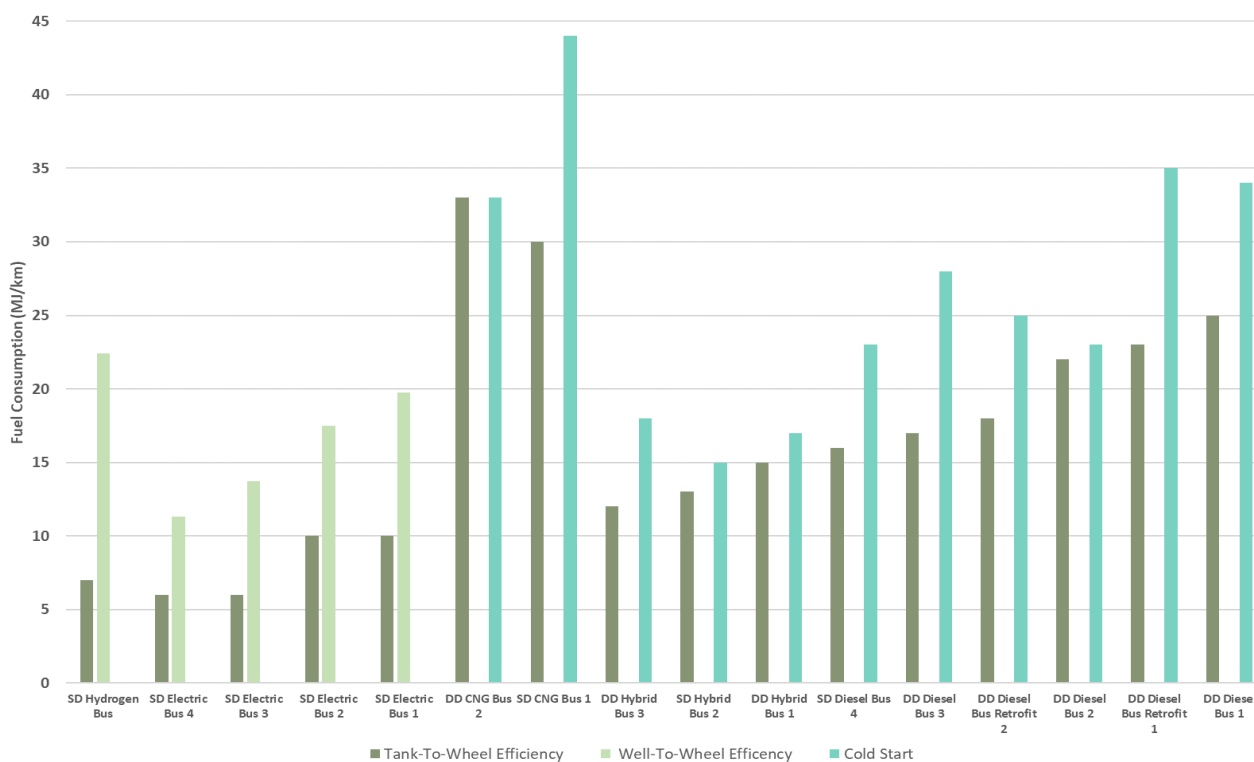


Figure 37 Energy Efficiency of Single & Double Decker Trial Buses

## Raw Data from Trial:

### Kilometres Travelled

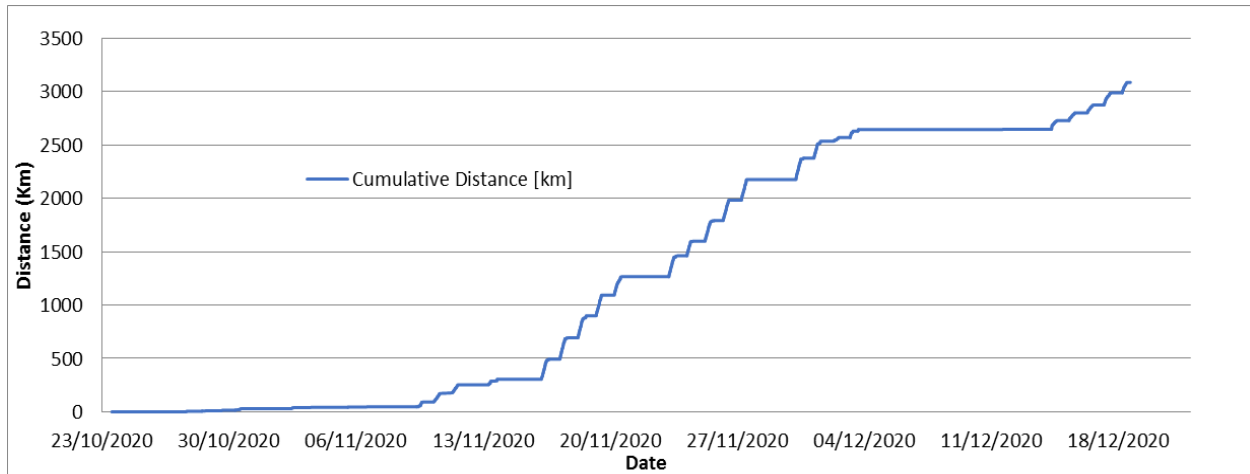


Figure 38 Cumulative Km travelled by the hydrogen bus during the trial (Bus was not in full service from 23<sup>rd</sup> October - 9<sup>th</sup> November & the 4<sup>th</sup> - 14<sup>th</sup> December)

### Hydrogen Consumed

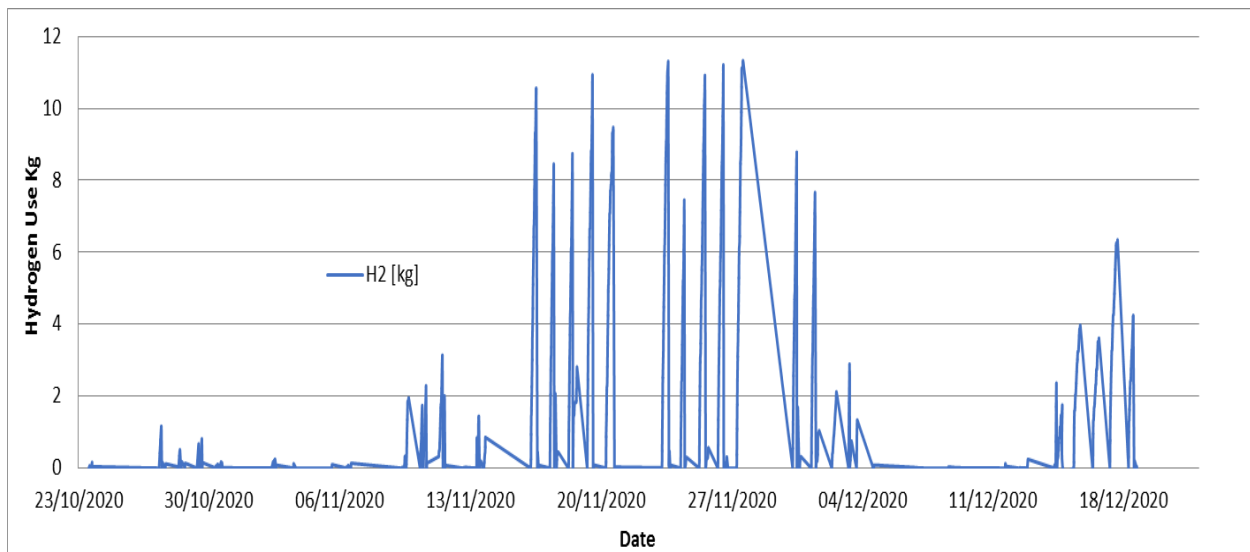


Figure 39 Hydrogen consumed by the bus along each day

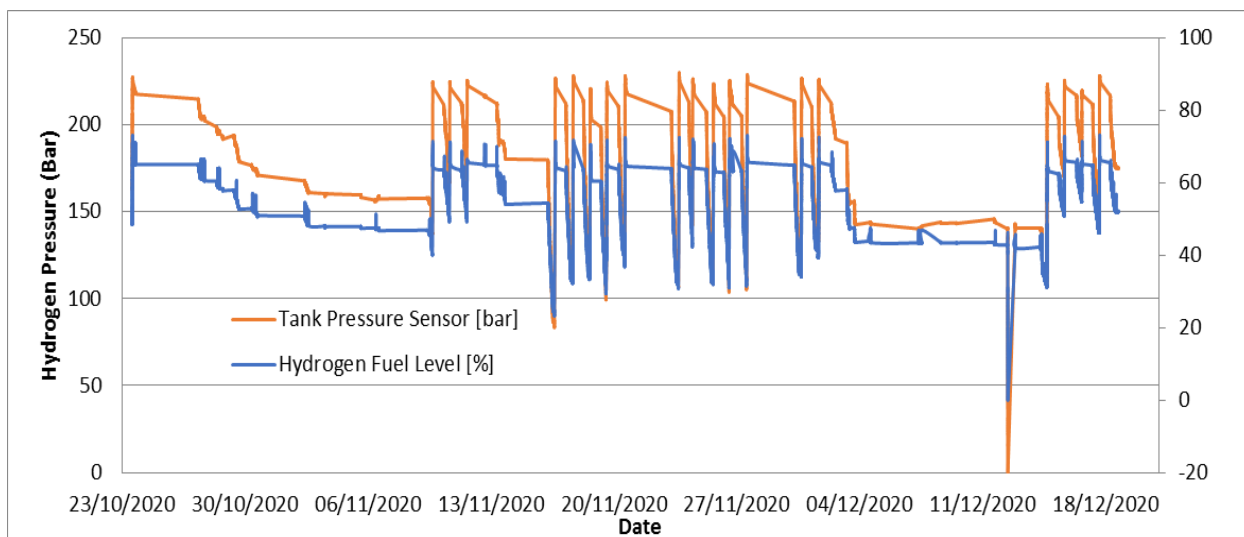


Figure 40 Hydrogen Pressure & % in tanks along each day

The decant systems process is as was expected.

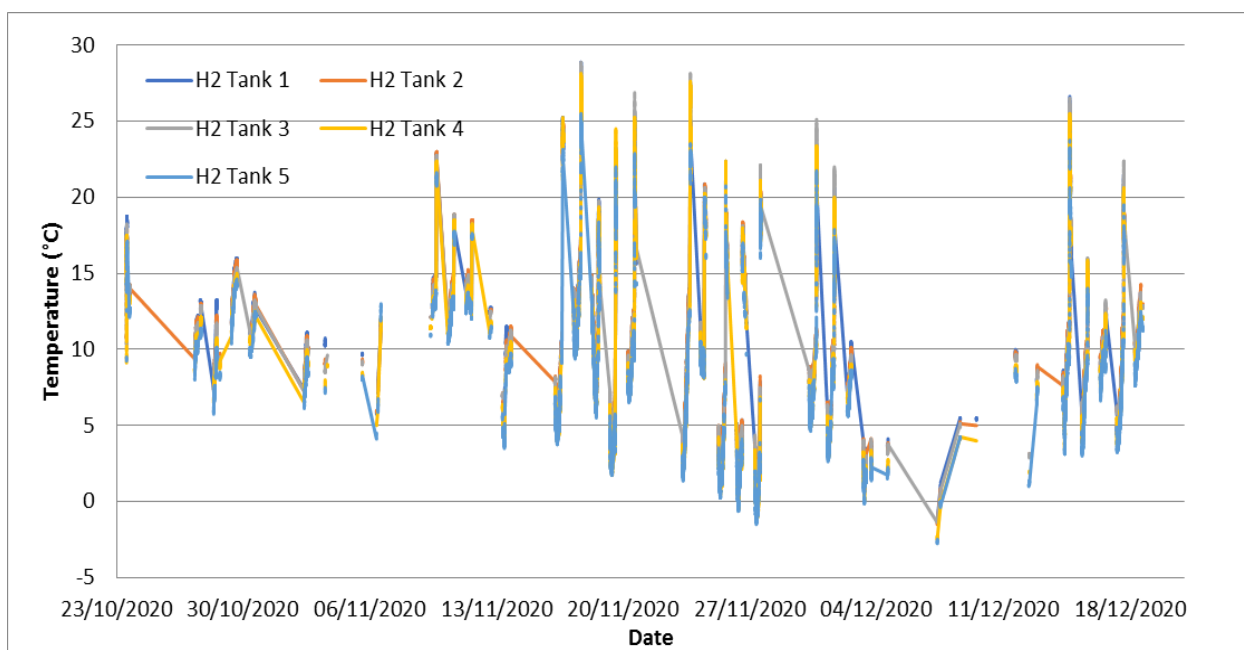
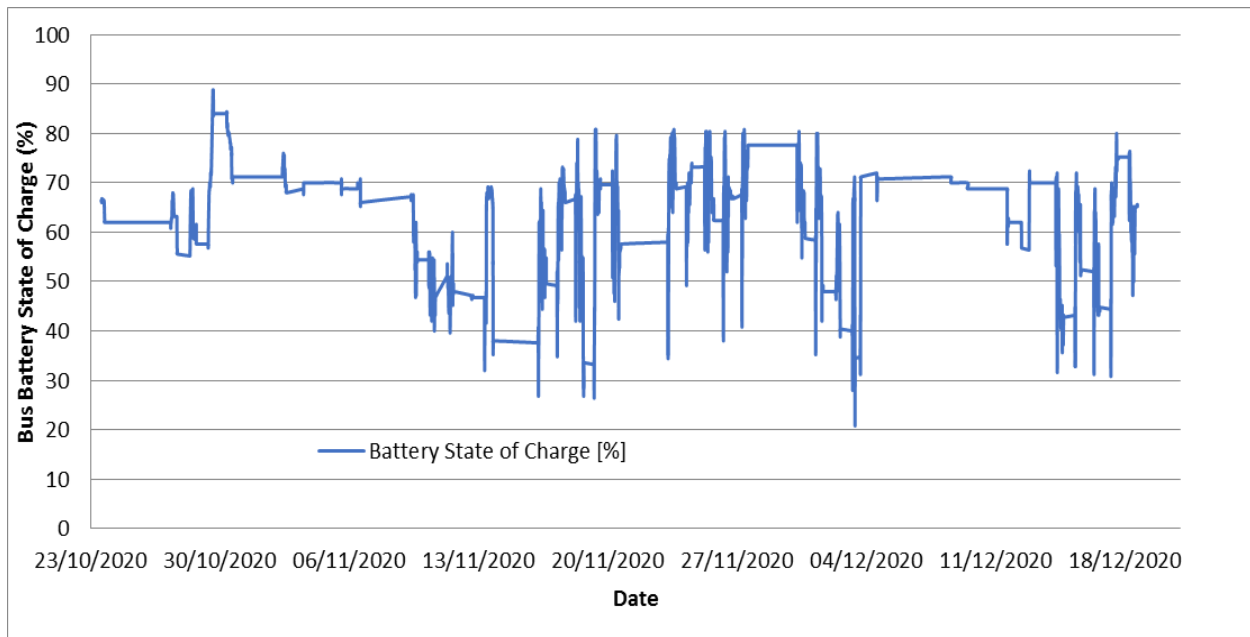


Figure 41 Hydrogen Tank Temperature along each day

## Battery Charge

State of charge is consistent with topography.



*Figure 42 Battery State of Charge along each day*

## Ambient Air Temperature

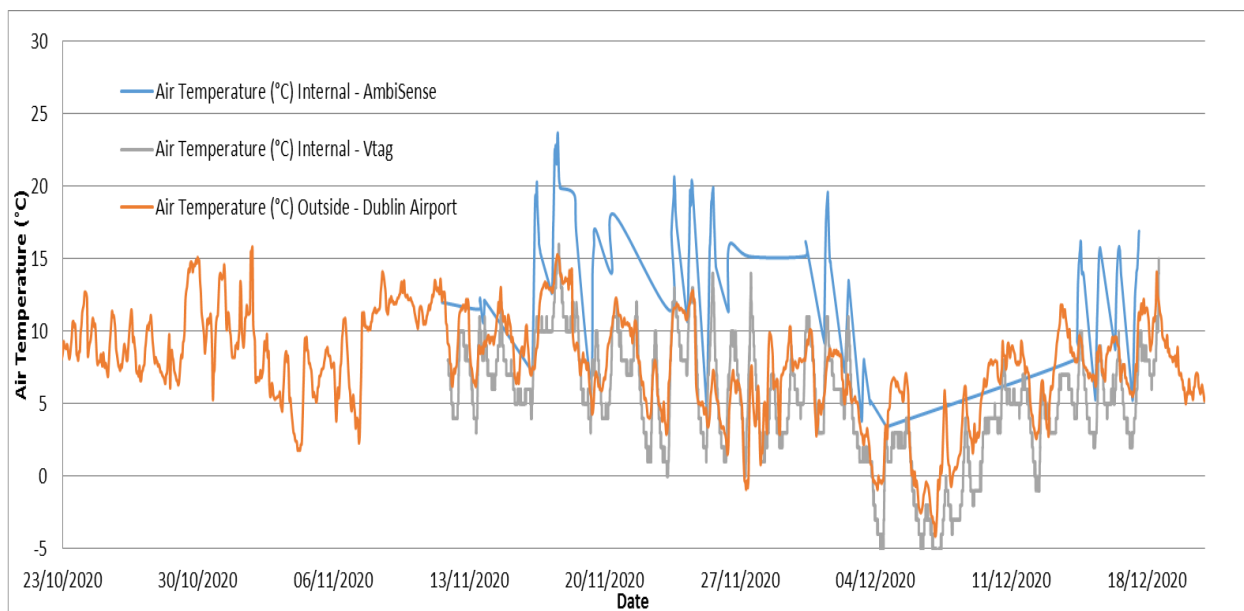


Figure 43 Ambient Air Temperature of bus (internal & outside) along each day

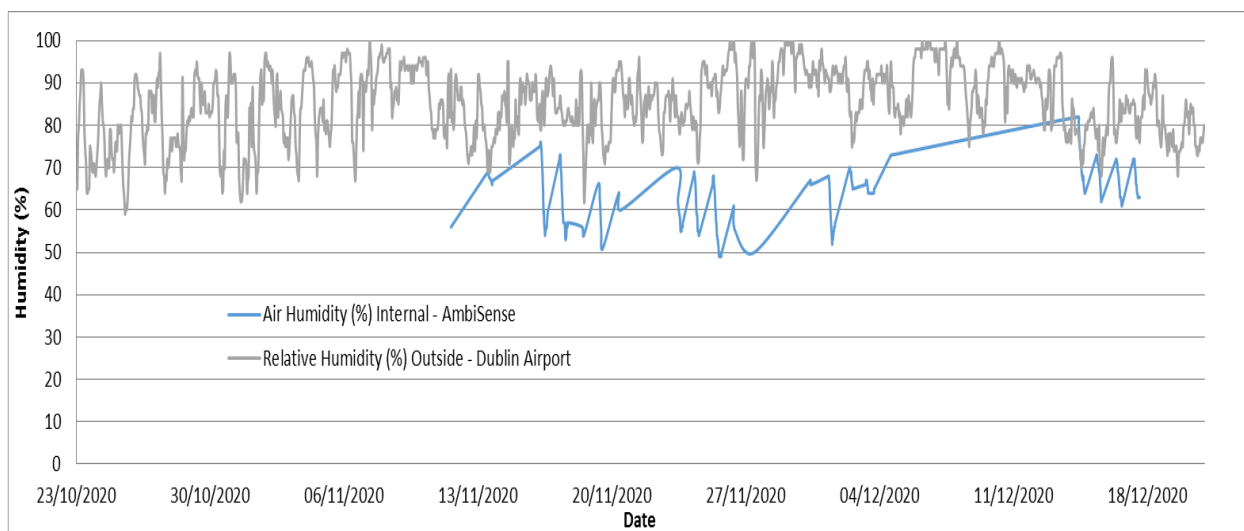


Figure 44 Air Humidity of bus (internal & outside) along each day

## Internal Bus Air Quality

No volatile organic compounds (VOCs) were detected on the bus during the trial period.

CO<sub>2</sub> emissions on the bus correlated with passenger numbers on the bus.

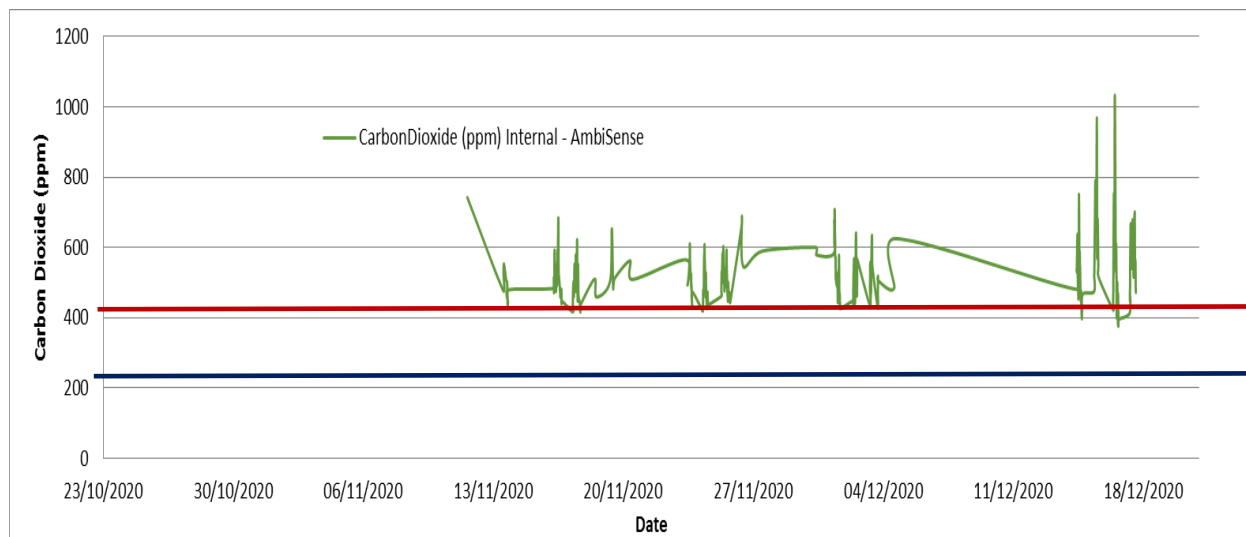


Figure 45 Carbon dioxide levels inside the bus along each day are shown in the **Green Line**. (The **Red line** denoting average CO<sub>2</sub> level in 2020; the **Blue Line** indicates preindustrial CO<sub>2</sub> level)

Measured pressure readings correlated well with atmospheric pressure reading from literature.

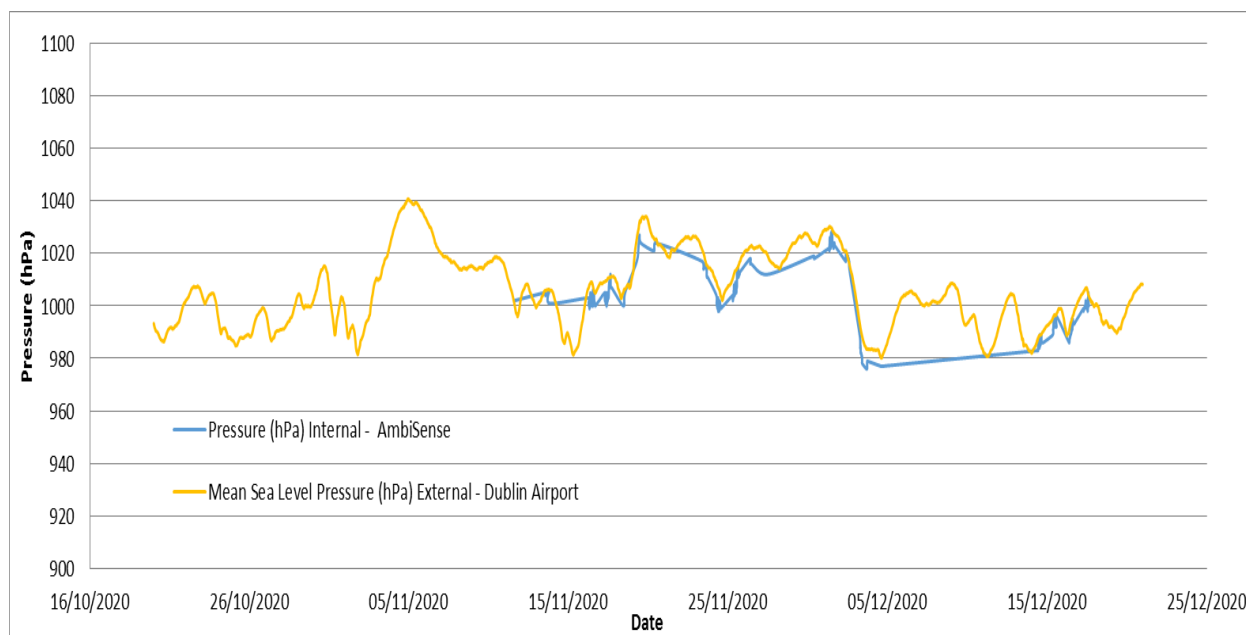


Figure 46 Ambient Air Pressure (hPa) along each day

## Other Information



*Figure 47 The Hydrogen Bus outside, DCU Glasnevin, DCU Alpha & DCU St Patrick's Campuses.*



*Figure 48 Hydrogen Bus Trial at the Helix DCU Glasnevin Campus*



*Figure 49 Hydrogen Bus at Toyota Ireland premises for media shoot*



*Figure 50 Bus Eireann driver and training supervisor Simon Byrne puts the finishing touches to the first hydrogen-powered bus to enter public service in Ireland (Irish Times image of the week)*

*Photograph: Naoise Culhane*

*(<https://www.irishtimes.com/news/ireland/irish-news/images-of-the-weekend-1.4409962>)*

## Selected Media Releases

# Hydrogen buses to hit the streets of Dublin with new trial

by Colm Gorey

2 DAYS AGO 1.23K VIEWS



From left: Steve Torney, Toyota Ireland and Minister for Climate Action, Communication Networks and Transport Eamon Ryan, TD. Image: Paul Sharp

gov.ie Departments Consultations Publications

Press release

## Minister Ryan welcomes Ireland's first Hydrogen Bus Trial as part of move towards cleaner, greener public transport

From Department of Transport  
Published at 10 November 2020  
Last updated 11 November 2020

Minister for Climate Action, Communication Networks and Transport Eamon Ryan TD, has welcomed the commencement of a multi-week trial of a hydrogen fuel cell electric bus in the transport fleet.

This will be the first ever hydrogen bus put into public service operation in Ireland and forms part of the Department of Transport's Low Emission Bus Trials. The vehicle will be trialled on a number of routes across Dublin by Bus Éireann, Dublin Bus, Dublin City University (DCU) and Dublin Airport from November to mid-December. The results will form part of the decision making process to help further transition our public transport fleet to lower emitting fuels and technologies.

**Commenting on the trial, Minister for Climate Action, Communication Networks and Transport Eamon Ryan TD said:**

"Moving our urban bus fleet to cleaner and greener technologies is essential if we are to further reduce the carbon footprint of our public transport system and limit air pollutant emissions in our cities. Under the National Development Plan, Ireland committed to stop buying diesel-only urban buses and to transition to lower-emission alternatives."

**A bus powered by a hydrogen fuel cell will start**

## Hydrogen-powered bus takes to streets of Dublin

Vehicle being trialled over coming weeks ahead of extensive rollout of such buses in 2021

Mon, Nov 9, 2020, 10:29

Kevin O'Sullivan Environment & Science Editor



CE chief sustainability officer Caoimhe Dornally and CE group chief executive Larcán O'Connor with the hydrogen-powered bus which is going on trial over coming weeks.

The first hydrogen-powered bus to be used in public transport in Ireland is taking to the streets of Dublin.

The bus, which will be undergoing trials over coming weeks before more extensive rollout of hydrogen buses next year, is part of the Hydrogen Mobility Ireland (HMI) initiative involving industry; academic researchers, public transport providers, energy utilities and the public sector on the island of Ireland.





## Ireland's First Hydrogen Fuel Cell Bus Trial

Welcome to the future - Ireland's First Hydrogen Fuel [...]

10 Things to Know About @10Things\_ToKnow

The fleet of the future?! @jonathan\_mccrea and James Carton (@EAASolutions) take a ride on the first #hydrogen fuel cell electric vehicle (FCEV) to go into public service in Ireland in an upcoming episode of @10Things\_ToKnow About! @SEAI\_ie @EPAIreland



10:42 AM · Nov 10, 2020 · Twitter Web App

Figure 51 Media coverage during the Hydrogen bus trial period.

## Selected Media Links

- <http://dcuinvent.ie/news/dcu-part-of-hydrogen-mobility-ireland-trial-of-a-fuel-cell-electric-bus-in>
- <https://www.h2-view.com/story/dublin-to-trial-hydrogen-powered-bus/>
- <https://www.irishtimes.com/news/environment/hydrogen-powered-bus-takes-to-streets-of-dublin-1.4404748>
- <https://www.gov.ie/en/press-release/74094-minister-ryan-welcomes-irelands-first-hydrogen-bus-trial-as-part-of-move-towards-cleaner-greener-public-transport/>
- <https://www.focustransport.org/2020/11/dublin-hydrogen-bus-trial.html>
- <https://www.siliconrepublic.com/machines/hydrogen-bus-dublin-trial-hmi>
- <https://www.irishtimes.com/news/ireland/irish-news/images-of-the-weekend-1.4409962#.X7I06uOwzdw.twitter>
- <https://www.toyota.ie/world-of-toyota/articles-news-events/2020/hydrogen-fuel-cell-powered-bus.json>
- <https://www.dcu.ie/commsteam/news/2020/dec/dcu-part-drive-behind-irelands-first-ever-zero-emissions-hydrogen-bus-trial>
- <https://fuelcellbuses.eu/public-transport-hydrogen/ireland-embarks-first-trial-hydrogen-fuel-cell-bus>
- <https://www.dcu.ie/commsteam/news/2020/nov/dcu-part-hydrogen-mobility-ireland-trial-fuel-cell-electric-bus-dublin-area>
- <https://hydrogenireland.org/news/3/>
- <https://irishtechnews.ie/irelands-first-hydrogen-fuel-cell-bus-trial/>
- <https://h2mi.ie/irelands-first-hydrogen-fuel-cell-bus-trial/>
- <https://www.world-energy.org/article/15458.html>
- <https://www.insight-centre.org/environmental-insights-insight-part-of-the-drive-behind-irelands-first-ever-zero-emissions-hydrogen-bus-trial/>
- <https://fleet.ie/bus-eireann-trialling-hydrogen-bus/>