HYDROGEN DEMAND IN SCOTLAND: A MAPPING OF TRANSPORT APPLICATIONS

Report for: Scottish Enterprise

Ref. P23-0058

Ricardo ref. ED17380 Issue: 1 30/03/2023

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Customer:
Scottish Enterprise

Customer reference:
P23-0058

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ED17380

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1. INTRODUCTION

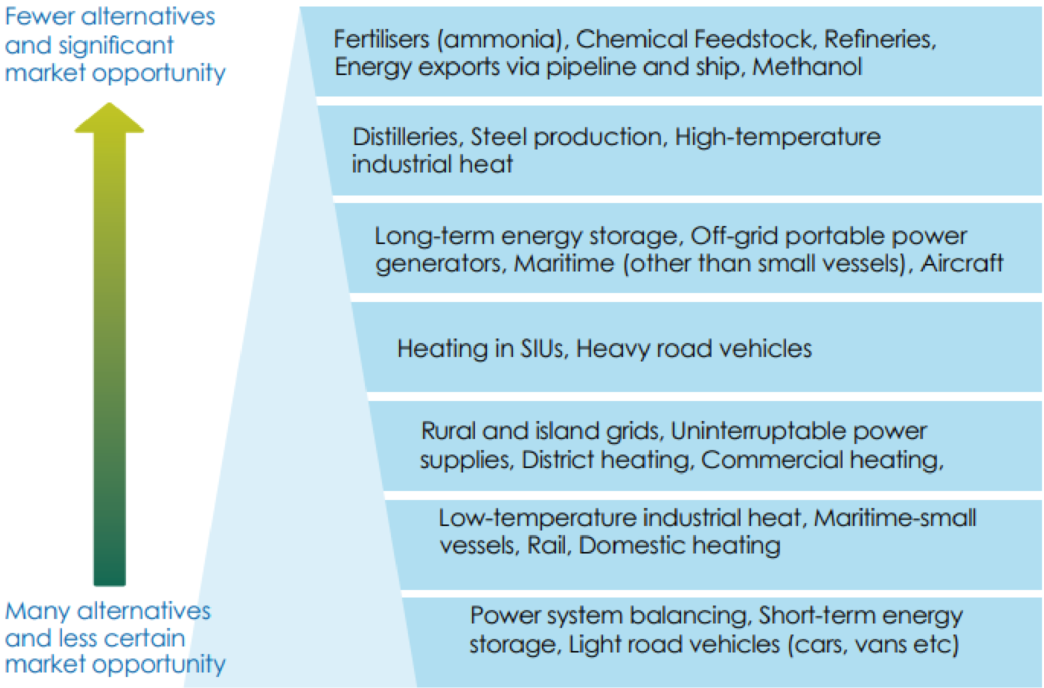
Scotland is committed to reaching net zero by 2045, five years ahead of the UK's national target. The government have also set an interim target of a 75% reduction by 2030. To achieve these goals the Scottish Government have outlined a range of policies that include increasing renewable energy, increasing energy efficiency and supporting low-carbon transport options.

In 2020, the Scottish government released a Hydrogen Policy Statement which acknowledged that the deployment of hydrogen could support Scotland in reaching its net zero targets and being an opportunity for economic growth. The document sets out a series of commitments including targeting 5GW of low carbon hydrogen production by 2030, supporting research and development, investing in supply chain infrastructure and collaboration with industry to advance its uses cases.

In 2022, the Scottish government followed the policy statement with a Hydrogen Action Plan which gave more detail to the policy statement by providing a list of actions that they planned to take to support the industry. They acknowledge that electrification will contribute the most to energy decarbonisation, but hydrogen has a place an alternative energy source.

The document also provides a hierarchy of use cases that highlights the best opportunities for hydrogen, shown in the image below. The ranking is based on a range of influencing factors such as economic, technical, and logistical issues.

Figure 1-1 Hydrogen use case hierarchy from the Scottish Government's Hydrogen Action Plan



1.1 SCOPE

Scottish Enterprise (SE) are supporting the government in their ambition to enable a domestic hydrogen economy. To support these efforts SE contracted Ricardo to study the location, nature and scale of demand of hydrogen for transport in Scotland. The transport sectors to be reviewed were: shipping; ferries; road; rail; aviation; off-road; and space.

The findings from the mapping exercise are published alongside this report. The mapping exercise provides locational signals of forecasted hydrogen demand that can support in hydrogen production siting and offtaker strategy. It will provide added value to inward investors less familiar with Scotland's transport sector.

1.2 OBJECTIVES

The key objectives of the study are as follows:

- Perform a literature review to:
  - describe the potential use cases for hydrogen in transport, split between sectors of interest;
  - discuss techno-economic barriers that each sector faces and how industry has addressed or is addressing them with a market assessment; and
  - discuss the infrastructure required to enable them.
- Quantify the potential demand of hydrogen for with low medium and high uptake scenarios for each sector of interest
- Present maps of Scotland showing locations for the end-use for hydrogen in each sector

In parallel, Scottish Enterprise contracted Element Energy to conduct a study into the potential hydrogen usage in industrial applications and commissioned a technical study into the use of hydrogen in Scottish distilleries.

2. REVIEW OF TRANSPORT SECTORS

The objective of this literature review is to provide an overview of the current status and progress in the development of hydrogen as a fuel for the transport sector. Each sector will discuss the operational needs for vehicles and how hydrogen could play a role in their decarbonisation. The discussion will also focus on the technological advancements and steps being taken to bring hydrogen-powered vehicles to the market. Lastly it will summarise the refuelling infrastructure required to make them a possibility.

Demand scenarios presented in this study are all derived from the Transport Scotland 'Zero Emission Energy for Transport Report: National Demand Forecasts for Electricity and Hydrogen' study (Transport Scotland, 2022) (hereby referred to as the Transport Scotland study). Where six scenarios had been developed in that study, three scenarios were chosen for this hydrogen-specific report: representing Low (L), Medium (M) and High (H) hydrogen uptake. The scenario acronyms describe the level of uptake of electrification first, followed by the hydrogen uptake (e.g. HL = High electrification and Low hydrogen; MM = Medium electrification and Medium hydrogen).

There are three exclusions to this where Ricardo have developed their own methodology. They are:

- All three off-road sectors - agriculture, construction and forestry
- Hydrogen for shipping
- E-kerosene for aviation

2.1 CROSS-SECTOR PROPULSION TECHNOLOGY

Before addressing each sector, it is worth addressing that there are currently two prominent hydrogen-powered technologies at Technology Readiness Level 9 (TRL) that can be used for transport propulsion - they are fuel cells and internal combustion engines (ICE). These two technologies are repeatedly referred to within the document so there is value in understanding the key benefits and drawbacks to each.

2.1.1 Fuel cells

Fuel cells are a developing technology that utilise a chemical reaction between hydrogen and oxygen to create electricity. The electricity is then used to power vehicle drive trains much like an electric vehicle, and are commonly referred to as Fuel Cell Electric Vehicles (FCEV). They have good efficiency, quiet operation and the only emission from the process is water vapour.

The key negatives are the high capital costs associated with a developing technology (although these are continuously reducing) and the lack of supply chain infrastructure. The fuel cells require very high purity of hydrogen (99.999%), without it they can become irreversibly damaged and require a costly replacement. There is also a requirement for rare materials for proton exchange membrane (PEM) fuel cells, which are the most in demand due to their favourable utilisation parameters.

2.1.2 Internal combustion technology

ICEs are a well understood, cost effective technology already utilised in fossil fuel transport across the world. Designs can be relatively easily adapted to take hydrogen and combust it with air to create mechanical energy to power vehicle drive trains. They can be flexible in their fuel sources having low regard to hydrogen purity for successful operation and can be engineered to take mixtures of hydrogen and traditional fuels. This potential for partial decarbonisation makes them well suited as transition technologies for some fleets.

Fuel cells are more efficient at converting hydrogen into propulsion energy than ICE. Although it depends on the loading and fuel type, fuel cells for road vehicles achieve efficiencies of approximately 50% compared to 35% for ICE. Furthermore, ICE have an unavoidable environmental impact when combusting any fuels with air. The nitrogen in the air reacts with oxygen when exposed to high temperatures creating Nitrogen Oxide (NOx) emissions that are hazardous to human health and an indirect greenhouse gas. Exhaust treatment technologies like Selective Catalytic Reduction (SCR) can reduce the amount of NOx emitted to very low levels.

2.2 ROAD TRANSPORT

The road transport sector comprised 58% of transport greenhouse gas (GHG) emissions in Scotland (Transport Scotland, 2020). Some progress has been achieved in making petrol and diesel vehicles more efficient and less polluting, but the largest improvements will be seen with switches away from fossil fuels. The transition to battery electric vehicles (BEV) is already on the rise in the UK. This is driven by taxation - both vehicle excise duty and benefit in kind, rising fossil fuel prices, the introduction of local emission zones, the 2030 ban on the sale petrol and diesel cars and the 2040 ban on diesel trucks. Hydrogen powered vehicles, in particular Fuel Cell Electric Vehicles (FCEV), are seen as an alternative option to bypass the range and payload limitations of BEV in certain vehicle types and applications.

2.2.1 How hydrogen can support the operational needs of road vehicles

BEVs typically have a range of 150-300 miles on a single charge, which is sufficient for most light duty passenger vehicle journeys in the UK. However, there will be some users who regularly exceed that range and therefore require a vehicle with a longer range. FCEVs may be a suitable alternative for these users, particularly if they are willing to pay more for the extra utility. This demand for FCEVs is more likely to come from businesses, who may weigh up the economic benefits of longer range and faster refuelling times against the higher purchase and running costs of FCEVs. The typical FCEV range (Table 2-1) is comfortably higher than the average daily distances of typical road transport vehicles.

Table 2-1 Average daily distances per vehicle type, and corresponding assumed FCEV range in miles (Ricardo, 2020)

Vehicle class	Vehicle type	Fuel type	Units	Assumed FCEV range	Average daily distance
LDV	Car	H2	Miles	311	45
LDV	Van	H2	Miles	311	40
HDV	Rigid Lorry	H2	Miles	311	118
HDV	Artic Lorry	H2	Miles	622	199
HDV	Bus	H2	Miles	249	112
HDV	Coach	H2	Miles	373	144

Range tends to be limited by the space for hydrogen tanks rather than weight and has a smaller impact on vehicle cost than batteries (though the cost of the tanks is currently a significant proportion of total vehicle cost), and passenger or load space can be impacted. Tanks are typically 700 bar for light duty vehicles (LDVs) such as cars and vans, and 350 bar for heavy duty vehicles (HDVs) such as trucks, buses, and coaches.

2.2.2 Market assessment of available vehicles/vessels/technologies

2.2.2.1 Passenger cars

The market for hydrogen vehicles has not yet developed to the extent of that for electric vehicles. There are currently two models of hydrogen powered car on the market which have a fuel range of around 400 miles. By comparison, some battery electric cars of a similar price can cover over 300 miles, and a few more expensive models claim to achieve 400. While fuel cell powertrains may become cheaper as they are manufactured in larger volumes, hydrogen vehicles will always cost more to run than battery electric vehicles due to higher fuel costs and lower efficiencies. Therefore, it seems likely that hydrogen powertrains will be limited to some larger vehicles requiring a longer range and longer continuous operating periods, but for most cars, battery electric powertrains will be more economic. FCEVs available on the market include:

- The Toyota Mirai is the most well-known commercialised FCEV. It has a fuel tank that holds 5kg of hydrogen and has a certified range of 400 miles.
- The Hyundai Nexo has a fuel tank that holds 6.3kg of hydrogen and has a range of 413 miles. The vehicle managed to achieve 551 miles in a world record attempt.
- BMW have been piloting an FCEV SUV called the “iX5 Hydrogen”. It has a fuel tank of 7.3kg and a range of 311 miles.

Some of the key limitations preventing uptake of hydrogen passenger cars include:

- Most drivers do not often need to cover long distances on a regular basis
- The EV charging point network in Scotland is well established, whereas there are currently only 2 hydrogen refuelling points, both in Aberdeen
- FCEV car models are expensive compared to ICE models; the Toyota Mirai starts from £50k purchase cost, plus the high cost of fuel (compared to BEV)
- For those with a driveway, home charging of BEV cars is a convenient option, given the current lack of hydrogen fuelling stations

2.2.2.2 Light Duty Vehicles

The situation for vans has been similar to that of passenger cars, with a few pilot vehicles available, specialist conversions, and a limited production of small vans so far. However, hydrogen vehicles are now being launched. A range of hydrogen FCEV mid-size vans is being launched by European OEMs (FuelCellsWorks, 2021) with a claimed range of around 250 miles, higher than the equivalent battery electric model. The van market is likely to need hydrogen models for some longer-range, larger vehicles despite battery electric offering lower running costs, so the technology choice will come down to the application, and the practical and financial considerations.

- Renault are launching a larger van with a range of 300 miles, around three times that of the battery electric version (CommercialFleet, 2021).
- Peugeot have launched the e-Expert that carries 4.4kg of hydrogen and can reach 250 miles before needing to refuel. Vauxhall’s Vivaro-e Hydrogen is based on the same platform with the same hydrogen capacity and range.

2.2.2.3 Heavy Duty Vehicles

There is a lot of interest in hydrogen fuel cells for HDVs, although so far there are limited numbers of vehicles on the roads. Several manufacturers including Toyota and Paccar (parent company of DAF), Scania, Fuso, Iveco, and specialist converters have produced hydrogen trucks for pilot deployments (Interreg, 2023). Others including Volvo, Mercedes, and Nikola are developing hydrogen truck models.

- Hyundai were first to put a full-size hydrogen truck into series production. The Xcient has a range of 250 miles with a storage capacity of 31kg of fuel (Hyundai, 2020). The initial production of 1,600 is destined for Switzerland (FuelCellTrucks, 2020) and will extend to other European countries, although it is not currently expected to be launched in the UK.
- US-based hydrogen specialist Hyzon have advertised an articulated tractor unit and a coach for Europe (Hyzon, 2023)

- UK start-up Tevva are planning a 7.5 tonne hybrid EV-hydrogen truck that has a 9kg hydrogen tank giving a range of 350 miles (Tevva, 2023).
- Scotland-based company Hydrogen Vehicle Systems (HVS) has received government grants to develop a self-driving heavy goods vehicle, which will be trialled alongside partner Asda. HVS also offer a Chassis Cab vehicle (GVW 4.25 to 7.5 tonne) and a HDV Artic Tractor (GVW up to 19 tonnes) (HVS, 2023).

Widespread availability of hydrogen trucks from major manufacturers such as Volvo and Mercedes is expected from 2025, but uptake will depend on refuelling infrastructure and running costs. The DfT are funding trials to demonstrate hydrogen fuel cell trucks and infrastructure for road freight operations which started in 2022 (Department for Transport, 2022).

2.2.2.4 Refuse Collection Vehicles (RCV)

RCVs regularly operate from an urban environment and have a back-to-base model that makes them ideal for adopting zero emission technologies. As with battery electric, hydrogen fuel cell powered RCVs have been piloted across Europe and the UK. Both Aberdeen (Aberdeen City Council, 2022) and St Helens council in Merseyside recently put RCVs into service (tppl, 2022), while Glasgow have plans for a fleet of 20 (SMMT, 2021). Some vehicle body builders/manufacturers include:

- Aberdeen City Council demonstrated the UK's first hydrogen refuse collection truck, a Geesinknorba pilot vehicle. The vehicle is based on a Mercedes-Benz chassis and has a 15kg tank. It is refuelled to a pressure of 350bar at the Kittybrewster hydrogen refuelling station
- Ballard Motive Solutions acquired Dundee based Arcola in late 2021 to acquire their hydrogen fuel cell powered RCV solution. The vehicle is based on a Dennis Eagle chassis and has 31kg of hydrogen storage providing up to 100 miles of operational range (Ballard, 2023).
- Geesinknorba have since showcased a commercial version of their hydrogen RCV, the Geesink GPM at TECMA 2022, a trade fair for professionals in the International urban planning and environment sector.
- Bluepower by FAUN Zoeller is a hydrogen powered RCV that can take up to 16kg of hydrogen at 700bar. This vehicle has entered commercial production in 2023. These are the vehicles purchased by St Helens council (Faun-Zoeller, 2023).

2.2.2.5 Buses

Bus operators have piloted the use of hydrogen fuel cells since their often urban operation incentivises the adoption of zero emission vehicles, while the back-to-base operation and local authority interest can facilitate the adoption of new technologies. Hydrogen buses can be considered proven, albeit so far only on small pilot fleet deployments. Availability is currently more limited than electric buses but is developing.

- Aberdeen introduced ten hydrogen buses in 2015 as part of a Clean Hydrogen Partnership and European Union project (HYTransit, 2018), and have added more since.
- Three hydrogen buses were introduced in London as early as 2002, and eight more in 2010 (LondonReconnections, 2021). As of March 2022, there were 22 operating in London.
- As of April 2022, the Zemo partnership reported 66 hydrogen buses in service across the UK and 230 more planned.
- Wrightbus have a double-deck hydrogen bus in series production that can store 27kg of hydrogen at 350bar to get a range of 280miles (WrightBus, 2023). Brighton & Hove Metrobus purchased 20 of the single decker version and planning to purchase 34 more.
- Alexander Dennis will shortly be launching a double-deck hydrogen bus (AlexanderDennis, 2023). The bus has 29.4kg of storage at 350bar. 20 of them have been ordered for Liverpool City.

Other hydrogen bus manufacturers include Caetano, Van Hool, Citaro, Solaris and Toyota-Hino.

2.2.3 Infrastructure needs

Refuelling a hydrogen road transport vehicle takes just a few minutes at a hydrogen refuelling station. In theory, a public commercial facility could be used, in the same way that diesel vehicles can refuel at a forecourt.

However, there are less than a dozen public hydrogen refuelling stations in the UK and not all are suitable for all types of vehicles (UKH2Mobility, 2023) (glpautogas, 2023). Private fleets (such as HGV, bus and RCV) as early adopters will need access to a reliable and convenient supply. The commercial case for additional hydrogen refuelling requires HDVs to become adopters – as these typically have a higher energy requirement and 20 to 30kg tanks whereas passenger vehicles have 5kg tanks and may not need to refill daily.

Hydrogen can be supplied to refuelling stations by road from a central production facility using tube trailers in pressurised gaseous form, or in cryogenic liquid form in insulated vacuum tanks. It can also be produced on-site with an electrolyser. There are various configurations of hydrogen refuelling station:

- An on-site electrolyser produces hydrogen by electrolysis. As well as the electrolyser, hydrogen purification, compression, and storage will be required, along with dispensers to refuel the vehicles. The capacity will depend on the size of the electrolyser but will be suitable for supplying larger quantities than a tube trailer, upwards of 400 kg/day serving fleets of 50 or more buses, depending on their daily energy needs. As with electric chargers, an upgraded electrical grid connection is likely to be required. The GHG intensity of the hydrogen produced will depend on the electricity used, and so a dedicated renewable energy supply agreement is essential for “green” low-carbon hydrogen.
- A permanent refuelling facility without an on-site electrolyser can receive hydrogen delivered by truck in pressurised tube trailers. The trailer is typically left parked at the facility to act as the storage unit. The facility will have compressors to pressurise the hydrogen into a high-pressure buffer tank ready for quickly dispensing into vehicles. UK tube trailers are able to carry between 500kg and 950kg of hydrogen which could serve between 60 and 120 buses. It is anticipated that tube trailers may be able to reach 1,300kg of hydrogen with materials improvements.
- Liquid hydrogen storage allows larger quantities of hydrogen to be stored and transported in fewer truckloads. Hydrogen is cooled below -253°C after production and stored in vacuum-insulated pressurised cryogenic tanks. A truck can transport 3 to 3.5 tonnes of liquid hydrogen while on-site storage can hold several tonnes. The liquid hydrogen is vaporised and dispensed in gaseous form to be utilised by FCEVs. Despite its advantages, liquid hydrogen will be more costly than gaseous hydrogen as the liquefaction process is energy- and capital-intensive. There are also important skills and safety requirements for staff handling cryogenic liquid.
- There are also mobile refuelling stations. Direct transfer from a mobile refueller a quick way to provide refuelling for a small number of vehicles, without the need to install any infrastructure. NanoSun are a leading company in the UK manufacturing these refuellers. Each delivery provides sufficient hydrogen for 10-15 refuels (Nanosun, 2023). This provides a means to supply a trial or a transitioning fleet of vehicles in low numbers or temporary or off-road users.

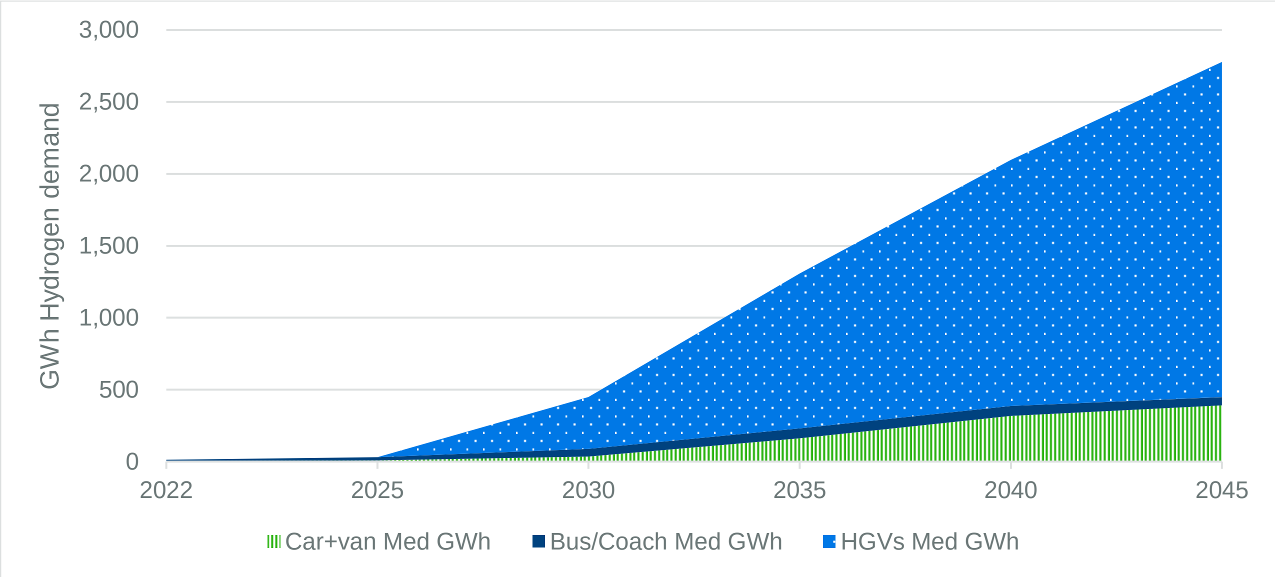
2.2.4 Demand Scenarios

The total road transport demand for hydrogen could reach over 2,700 GWh per year by 2045 for the medium uptake scenario.

For passenger cars and vans, there were three unique scenarios presented in the Transport Scotland study, and therefore these were carried forward to represent the low, medium and high uptake rates for hydrogen in this sector. For HGVs, the ‘low’ and ‘high’ scenarios were taken from the Transport Scotland report, and a subsequent ‘medium’ scenario was derived as being the average of the low and high scenarios.

For buses and coaches, six unique scenarios were modelled in the Transport Scotland study. In each scenario, competing technologies of battery electric or hydrogen fuel cell were assumed to uptake at different rates, and the scenarios each relate to a combination of high, medium or low uptake of either hydrogen or battery electric buses. The three scenarios selected represent a high, medium and low cost of hydrogen fuel cell technology (and associated fuel) to give a range in possible scenarios out to 2045.

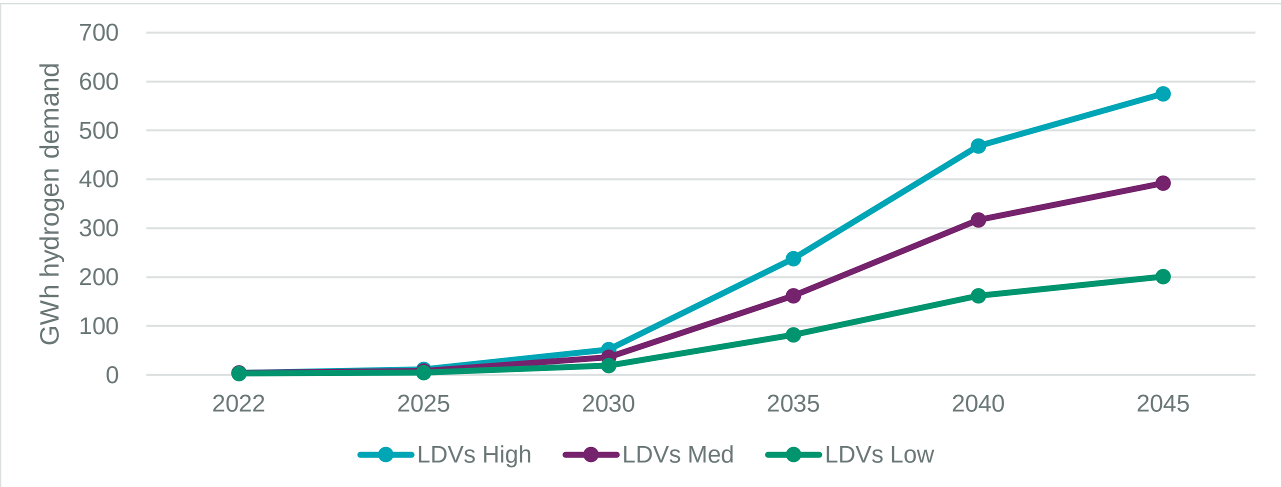
Figure 2-1 Total road transport sector hydrogen demand in Scotland to 2045 (medium uptake scenarios) as taken from the Transport Scotland study



2.2.4.1 *Light duty vehicles*

Demand from passenger cars and vans could reach between 200 and 600 GWh per year in 2045 under these 'scenarios. In recent years, battery electric passenger cars (and even battery electric vans) have come to the market and look likely to become the technology of choice for the majority of the LDV segment. Therefore, it seems likely that hydrogen powertrains will be limited to some larger vehicles requiring a longer range, but for most cars, battery electric powertrains will be more economic.

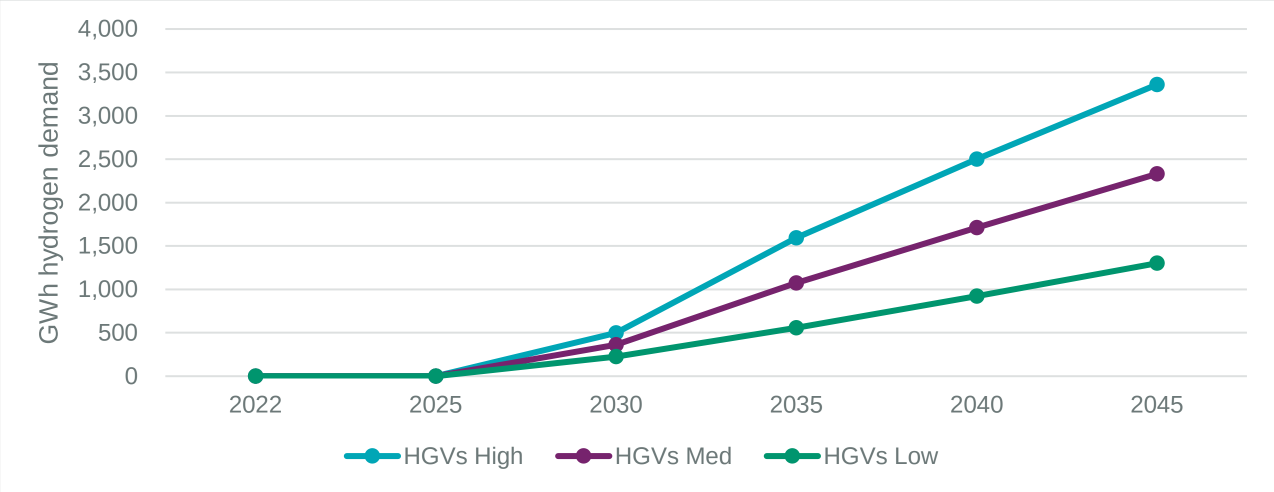
Figure 2-2 Total passenger car and van hydrogen demand in Scotland to 2045 per uptake scenario as taken from the Transport Scotland study



2.2.4.2 *Heavy duty vehicles*

HGVs have the highest potential in terms of overall hydrogen demand in Scotland to 2045 out of the different road transport sectors. Under the high scenario, this demand could reach between 1250 and 3,300 GWh per year. Similar to LDVs, battery electric HGVs could potentially be suitable for this sector (if battery prices reduce and battery energy density increases). However, the zero-emission future technology for HGVs is still unclear, and it is likely that BEVs and FCEVs will both be suitable for different HGV types and use cases. Therefore, there is a wide range in possible future hydrogen demand out to 2045, ranging from 1,300 GWh per year in the 'low' hydrogen scenario to possibly 3,300 GWH in the 'high' hydrogen scenario.

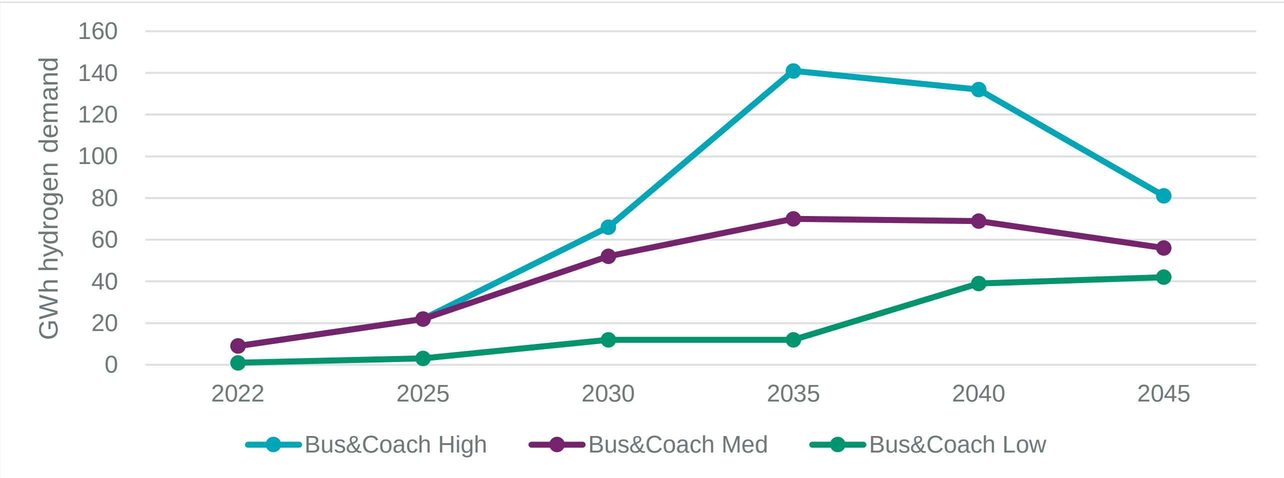
Figure 2-3 Total HGV hydrogen demand in Scotland to 2045 per uptake scenario as taken from the Transport Scotland study



2.2.4.3 *Bus and coach*

Bus and coach hydrogen demand in 2045 will likely be the smallest proportion of total hydrogen demand from road transport, with between 40 and 80 GWh required per year in Scotland in 2045. The hydrogen demand for buses and coaches peaks in 2035 (under the medium and high scenarios) and reduces after this year. This is a result of the demand scenarios assuming that the cost of battery electric buses decreases after 2035, and therefore battery electric buses become a more commercially viable option (when compared to fuel cell buses) for some particular duty cycles of buses and coaches.

Figure 2-4 Total bus and coach hydrogen demand in Scotland to 2045 per uptake scenario as taken from the Transport Scotland study



2.3 RAIL

Scotland's railway operators include Network Rail, ScotRail, and other train and freight operating companies. Rail accounts for 1.1% of total transport emissions, as per the Carbon Account for Transport 2020 (Transport Scotland, 2020).

The Scottish Government has set a goal for the decarbonisation of the passenger rail sector by 2035 (Transport Scotland, 2021). Further electrification will be a key solution in decarbonising the railways. Presently, Scotland's railway has around 76% of passenger rail and 45% of freight rail on electric traction. Electrification is already in the process of being implemented for the Fife Circle, East Kilbride & Barrhead, Borders and Levenmouth lines. In the case of the Borders and Fife Circle lines short sections of 25kV overhead wire will allow battery trains to replace diesel. Further electrification is planned for the Highland Mainline, and the line from Dundee to Aberdeen.

This leaves a number of very rural lines which have long distances and limited numbers of trains per day, such as the West Highland, Far North and Kyle lines. The Scottish Government's 2020 rail decarbonisation plan does not specify the traction solution but identifies battery and hydrogen-powered vehicles as the leading candidates. The Scottish Government's rail decarbonisation action plan is due for an update later in 2023 and it will provide a revised view on which routes will use each solution, as well as updated timings.

There is no specific interim target for decarbonisation of rail freight ahead of the 2045 Net Zero target overall for Scotland, but this is recognised as a priority, as freight can remove significant HGVs from roads. There is strong interest in biodiesel but also a recognition that supplies are limited and this will put a price premium on these fuels. Decisions on route electrification will be influenced by the need to create routes for freight, for example, to Inverness via Aberdeen. A number of new freight facilities have opened such as at Highland Spring Carluke and Kincardine. The mass of a freight train is a challenge for many of the zero carbon fuels hence the main freight routes are often targets for electrification.

In February 2023, Transport Scotland released their High-Level Output Specification (HLOS) document for 2024-2029 for the rail industry. It discusses their commitment to electric and battery trains but there is no reference to hydrogen. There is a requirement for Network Rail to prepare network infrastructure for the introduction of new trains and ensure a seamless transition. This could include hydrogen refuelling infrastructure.

2.3.1 How hydrogen can support the operational needs of trains

2.3.1.1 Passenger

Scotland's rail passenger fleet includes diesel and electric power rolling stock with plans to remove diesel passenger trains by 2035. A programme of successful electrification of routes is underway, and work has started on the planning and installation of the 25kV overhead wire systems to allow electric trains on additional routes.

On rural routes, the high initial cost of the 25kV overhead wire systems means that battery and hydrogen trains are more viable. The practical range of a battery train is around 50 miles, so this solution would need some sections of the line to have 25kV overhead wire systems to enable the battery to re-charge. Hydrogen trains are likely to have the range needed and do not require the expense of 25kV overhead wire systems. They could be particularly useful in lightly used routes such as rural areas where electrification is not economically feasible. However, hydrogen trains have a higher purchase cost (up to 20% higher than diesel equivalent) and higher fuel costs (RSSB, 2019).

2.3.1.2 Freight

Rail freight largely depends on diesel powered traction. Compared to passenger rail, rail freight has a higher variability in their operation as they are demand-sensitive and do not run as often on fixed routes. They also have a high energy demand due to the weight of their cargo which they need to haul uphill in some circumstances.

To decarbonise rail freight, bi-mode trains that can switch between electric and diesel would be an attractive interim option. Bi-mode electric and hydrogen fuel cell is an alternative decarbonisation option for freight rail in the longer term. A robust refuelling network is required across the rail network, to enable freight to completely switch away from fossil fuels.

2.3.1.3 General

A notable engineering challenge for hydrogen trains is the integration of hydrogen storage on the train. Solutions vary from having storage: on the roof of a train; in cylinders on-board the train; or in tenders repurposed from wagons which are connected to the locomotive. The solution will correspond with the range, and other operational needs of the trains, which will dictate the size of the fuel storage. Safety is a key consideration for the railways, therefore use of large quantities of hydrogen as a fuel will require careful study.

2.3.2 Market assessment of available vehicles/vessels/technologies

Europe has taken the lead in hydrogen fuel cell trains. Several hydrogen train pilot projects have been launched in Germany, Great Britain, Spain, France and Italy by various manufacturers and project partners. Some examples of adoption include:

- The state of Lower Saxony, in Germany, operates a fleet of 14 Alstom Coradia iLint fuel cell trains which can travel 621 miles on a single tank of hydrogen. They consume 0.3 kg hydrogen per km while moving at a maximum speed of 140 km/h. The same trains will be supplied to the Italian region of Lombardy.
- HydroFLEX is the UK's first passenger train which can operate under 'tri-mode', electric, battery and hydrogen power. It operates with hydrogen fuel cells and the high-pressure tanks carry up to 277kg of hydrogen which can provide 300 miles of operation.
- Bo'ness and Kinneil Railway has had a retrofitted hydrogen demonstrator train running along the railway. The Hydrogen Accelerator team and partners (including University of St Andrews, Transport Scotland, Scottish Enterprise, Ballard Motive Solutions, Abbott Risk Consulting, ARUP, Aegis and Angel Trains (University of St Andrews, 2022)) converted a retired Class 314 to a class 614 fuel cell electric powertrain.
- Testing of Spanish company Talgo's Vittal-One hydrogen train is scheduled for summer 2023. Its fuel cell consumes 0.25 kg of hydrogen per km and provides the train with a range of 800 km (500 miles).
- CAF's train Civia is under demonstration trials in Spain and Portugal. The fuel cells are supplied by Toyota for the project.

2.3.3 Infrastructure needs

Hydrogen refuelling stations for trains are likely to be located in the same depots that were previously used for diesel refuelling, as diesel refuelling would not take place any longer. Road trailers can carry hydrogen to refuelling stations as compressed gas or cryogenic liquid. Depots in electrified zones could also provide fuel from on-site electrolysis as they may have the enabling power infrastructure.

Linde has built a stationary hydrogen train filling station in Bremervörde, Germany, with a total capacity of 1,600 kg per day, equipped with high pressure tanks (up to 500 bar), compressors and fuel pumps. It takes less than 15 minutes for the refuelling process.

2.3.4 Demand Scenarios

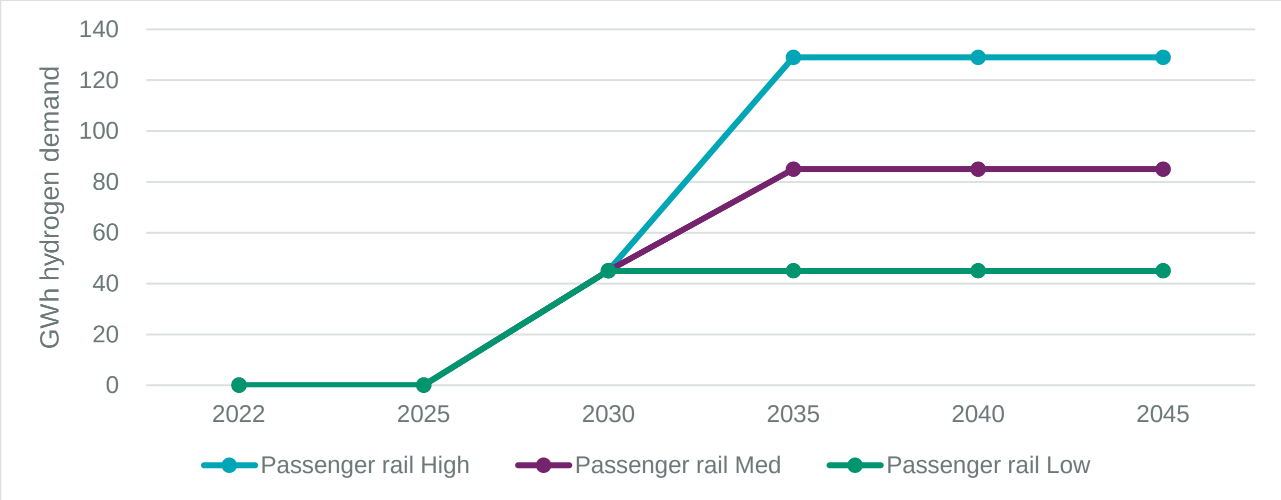
2.3.4.1 Passenger rail

The Zero Emissions Energy for Transport Report provides hydrogen demand forecast for ScotRail only, and specifies that Network Rail maintenance vehicles have very small energy demand in the Scottish railway network and are therefore excluded. The three unique scenarios for hydrogen uptake correspond to Medium-Low (ML), Medium-Medium (MM) and Low-High (LH) within the report. The first word relates to electricity uptake and the second relates to hydrogen uptake. These two uptake rates can compete with each other and affect one another's results. For low demand, hydrogen trains are introduced on the Far North and West Highland only. For medium demand, hydrogen trains are introduced to the Far North, West Highland, and Stranraer services. For high demand, hydrogen trains are introduced to the Far North, West Highland, Stranraer services and Inverness to Aberdeen.

Table 2-2 Hydrogen energy demand scenarios for ScotRail (in GWh)

GWh	2022	2025	2030	2035	2040	2045
1: LH (High)	0	0	45	129	129	129
6: MM (Medium)	0	0	45	85	85	85
2: ML (Low)	0	0	45	45	45	45

Figure 2-5 Hydrogen demand scenarios for passenger trains (ScotRail)



**Note: hydrogen demand for rail is unlikely before 2028, and so whilst there may be some take up of hydrogen for the Far north and West Highlands line before the 2030 point, the majority of demand is expected in 2030.*

2.3.4.2 Rail Freight

The Zero Emissions Energy for Transport Report does not anticipate any energy demand for battery electric or hydrogen fuelled trains for freight operating trains. Therefore, bespoke hydrogen demand scenarios for rail freight were developed. The scenarios were calculated using total freight activity (ORR, 2022) in Scotland, proportion of electrified network and hydrogen locomotive energy efficiency values.

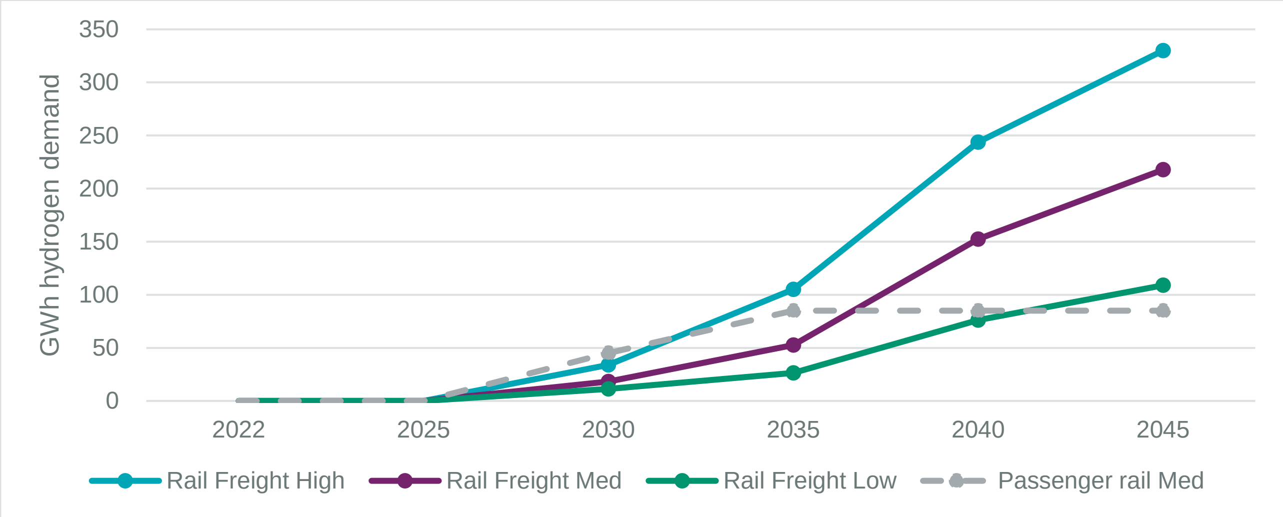
Given that 25% of the Scottish rail network is currently electrified, the assumed theoretical maximum hydrogen potential for Scottish rail freight is 75% of the total energy demand (assuming all locomotives run on hydrogen). This is the theoretical maximum demand only, and it is likely that some locomotives may be 'dual mode', with hydrogen complementing the overhead line electrification (OLE) in areas where the infrastructure is not available. Hydrogen for rail freight has the benefit of retaining the 'go anywhere' capability which is essential for rail freight operations, as it is not as reliant on infrastructure compared to overhead line electrification. In line with the passenger rail hydrogen uptake rates, it was assumed that hydrogen would not be technically feasible for rail freight before 2030, and only after this date hydrogen locomotives are introduced gradually into the fleet. Although hydrogen has a potential role to play in rail freight, there is still uncertainty around the optimal zero-emission technology for rail freight. Battery electric locomotives, low-carbon fuels, dual mode hydrogen and OLE, and expanding the overhead line electrification in Scotland's rail network could all offer routes to decarbonising the rail freight sector in Scotland. Therefore, three possible hydrogen uptake rates for rail freight in Scotland were derived related to the theoretical maximum scenario.

Table 2-3 Hydrogen rail freight uptake scenarios used in the modelling exercise

Scenario	2020	2025	2030	2035	2040	2045
Scenario 1: Maximum hydrogen	0%	0%	11%	30%	60%	75%
Scenario 2: Medium uptake	0%	0%	6%	15%	37%	49%
Scenario 3: Low uptake	0%	0%	4%	7%	19%	25%

Due to the high energy demand of rail freight trips combined with the forecasted rail freight traffic growth to 2045 the hydrogen demand from rail could reach between 110 and 330 GWh per year by 2045. This hydrogen demand is over twice as much as passenger rail in 2045, with passenger rail requiring 85 GWh per year in 2045. This is partly due to high passenger demand corridors (e.g. Glasgow to Edinburgh) being electrified via overhead line, and therefore it is unlikely hydrogen will be viable for these routes as utilising the overhead connection is more cost-effective (and energy efficient) for operators.

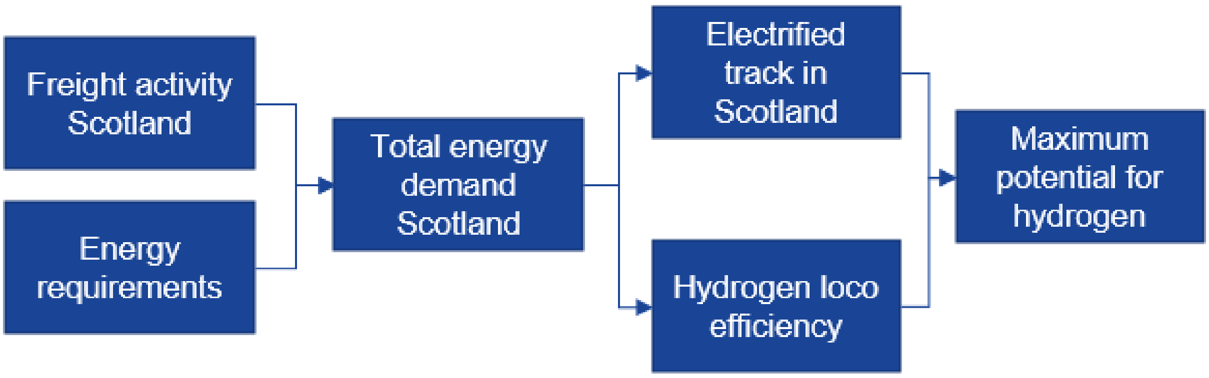
Figure 2-6 Hydrogen demand scenarios for freight trains in comparison to passenger rail



Rail freight demand methodology

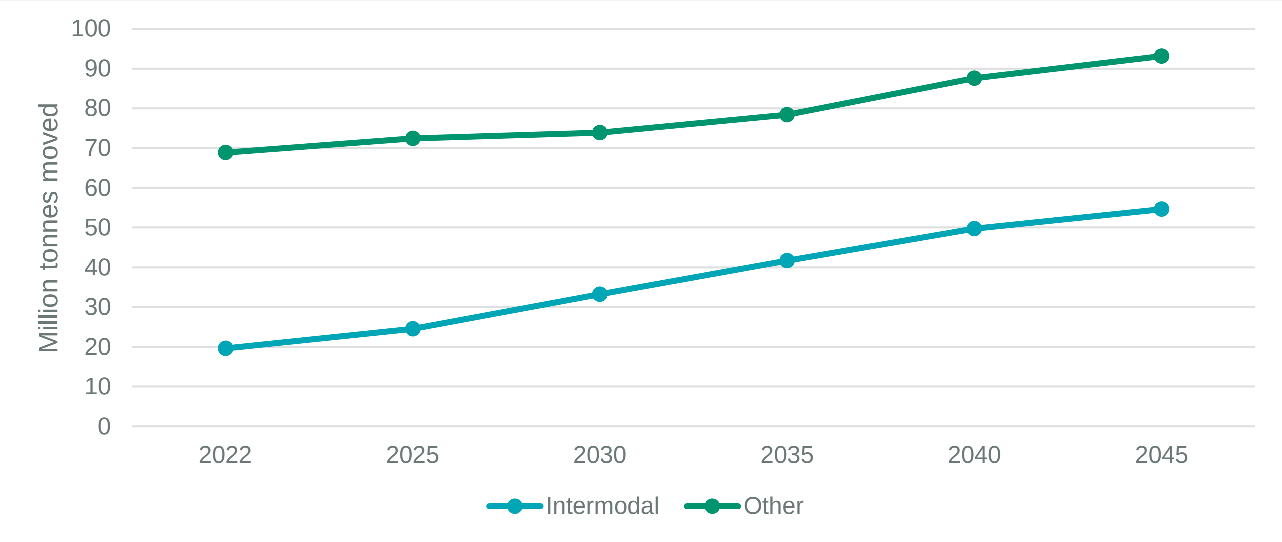
The total hydrogen demand for rail freight was based on total freight activity in Scotland and energy requirements per trip to calculate total energy demand for rail freight in Scotland (Ricardo, 2020) (ORR, 2022). This energy demand was reduced based on hydrogen locomotives being 30% more energy efficient compared to diesel counterparts; also accounting for the 25.3% of currently electrified track in Scotland (which is assumed to run overhead line electrification locomotives as the infrastructure is already in place) (Transport Scotland, n.d.). A high-level overview of this methodology is shown in the figure below.

Figure 2-7 High-level methodology for estimating maximum hydrogen demand for rail freight



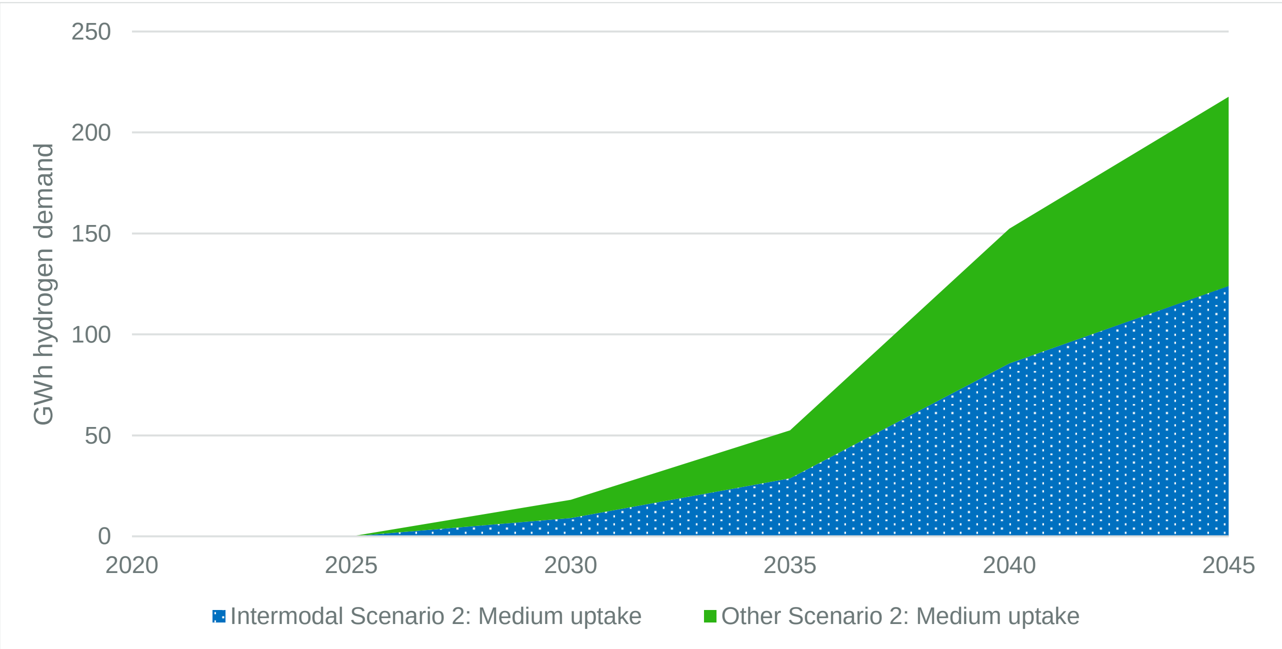
Rail freight can largely be split into two main segments, intermodal (container freight typically from ports and other freight terminals) and heavy bulk aggregates + others ('other'). Whilst both of these segments are expected to increase in activity out to 2045 intermodal traffic is expected to increase at a faster rate (255% increase by 2045 compared to 2019) than other freight traffic (55% increase by 2045 from 2019). Although intermodal trips typically have a light trailing load compared to other freight trips (249 tonnes average vs 377 tonnes average), the faster line speed of intermodal freight along with the typically longer journey lengths results in a higher energy consumption of intermodal freight compared to other freight trips. According to the T1160 rail freight decarbonisation report, an average intermodal freight trip consumes 12.2 MWh whilst other freight trips consume 8.2 MWh per trip.

Figure 2-8 Forecasted freight activity (in million tonnes moved) to 2045 (intermodal and others) for the UK as a whole (Ricardo, 2020)



The total energy required for each freight segment was calculated using the split of rail freight into intermodal and other movements and future activity across the UK as a whole and applying this to the share of freight activity in Scotland (vs total UK). As a result of the higher intermodal trip energy consumption and the forecasted increase in freight movements by 2030, the hydrogen energy demand for intermodal trips overtakes the demand required for other freight movements in Scotland.

Figure 2-9 Medium scenario hydrogen uptake for hydrogen rail freight in Scotland to 2045 (GWh hydrogen required)



2.4 SHIPPING

Shipping is a hard-to-decarbonise transport sector, accounting for 15% of Scotland's transport emissions (Transport Scotland, 2020). The International Maritime Organisation (IMO) has set targets to reach a 50% reduction in emissions by 2050 (relative to 2008 levels), though this target is expected to become more ambitious. It will be challenging for the shipping sector to achieve net zero emissions in line with the Scottish Government's 2045 target, considering ships have operating lives of up to 30 years and few low-carbon vessels are being manufactured today.

In order to achieve emissions reduction, various strategies can be employed such as employing energy efficiency measures, but the most significant approach is replacing fossil fuels with zero carbon alternatives. There are a variety of options for alternative fuels derived from hydrogen, however, delivering to the vessels requires additional costly extra infrastructure in addition to the cost of hydrogen production infrastructure. There is also no clear consensus on which fuel is the best option, which could lead to inefficient and disjointed progress in the shipping energy transition in the long term.

2.4.1 How hydrogen can support the operational needs of shipping vessels

Shipping vessels undertake long voyages to deliver freight domestically and internationally. The largest trans-continental vessels can be at sea for weeks, in some cases using over 100T of heavy fuel oil per day. They require large fuel quantities on-board with appropriately sized storage vessels. Currently, fuel storage has little impact on cargo capacity, as the fossil fuels used have a very high volumetric energy density.

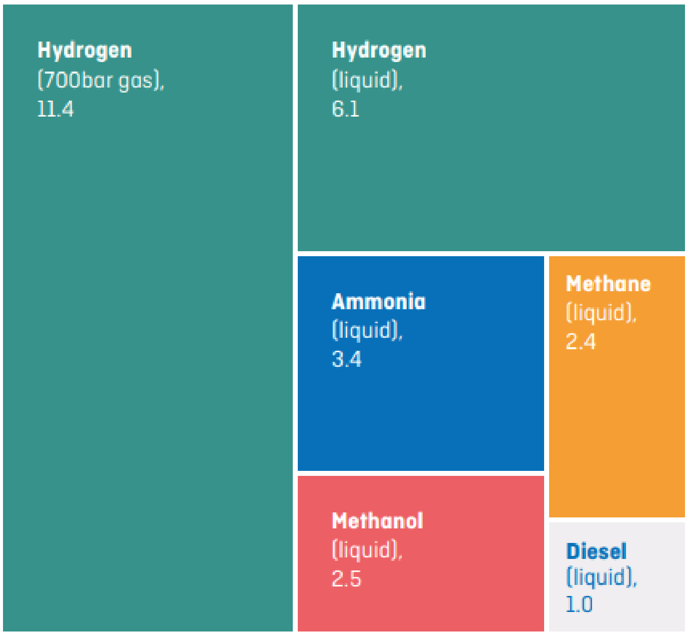
Vessels aiming to utilise hydrogen will require more volume for fuel storage onboard as compared to previously, given the low volumetric density of hydrogen gas compared to conventional fossil fuels, even when compressed at high pressures. Storing hydrogen as a liquid allows more energy to be stored, due to the higher volumetric energy density, but significant amounts of energy and infrastructure are required to cool the hydrogen to -253°C to convert it into the liquid phase. Another option is to store hydrogen in a metal hydride or liquid organic compound; however, these chemicals are difficult to return to hydrogen without the appropriate dehydrogenation infrastructure on-board the vessel and therefore this application in the maritime sector is not at a high technology readiness. It is generally accepted that hydrogen will not be a suitable energy vector for long-distance shipping due to the low volumetric energy density.

Hydrogen can also be stored in the form of ammonia given the compound's more favourable properties, in particular its higher volumetric density. Ammonia is a gas at ambient temperatures, but it is relatively easy to convert to a liquid with relatively high volumetric energy density as it requires cooling to only -34°C. Fuels which are liquid at room temperature and pressure are inherently easier to handle and store than gases. Methanol is another hydrogen derivative which is a candidate for shipping, given its even higher volumetric energy density and that it is found in liquid form at room temperature. The table and figure below offer a comparison of the major zero-emission fuel candidates with conventional fuel, when considering the decarbonisation of shipping based on volumetric energy density:

Table 2-4 Summary of volumetric densities and production costs of various fuels (Arup, 2016) (Advanced Motor Fuels, 2020) (Solakivi, et al., 2022)

Fuel	Energy density (MWh/m^3)	Approximate production cost (£$_{2030}$/toe)
Compressed Hydrogen Gas (300 bar)	0.75	1,206
Liquid Hydrogen (-253°C)	2.36	1,863
Marine Oil (IFO)	12.6	282
Ammonia (-33°C)	3.51	1,583
Methanol (STP)	4.34	2,027

Figure 2-10 Relative fuel storage volume for various shipping fuels (volume including tank relative to diesel) (Ricardo, EDF, 2021)



It can be noted from the above that based on the metrics of volumetric density and the difficulty to convert and handle the fuel in the liquid phase, gaseous hydrogen is not the most favourable fuel. The following will discuss the benefits and challenges related to utilising ammonia, methanol or liquid hydrogen in the maritime sector as opposed to gaseous hydrogen.

2.4.1.1 Ammonia

Since Ammonia (NH_3) is a globally traded commodity, there are existing regulations and industry understanding on the storage and handling of ammonia on ships. It has the benefit of having a relatively high volumetric energy density and can be handled in a liquid form. However, ammonia is significantly toxic both to humans and aquatic life and does pose a risk with regards to flammability and explosivity. Regulations for ammonia powered ships are in development at the class societies and over 100 ammonia-ready ships have been ordered. The first ammonia-ready vessel was delivered in February 2022. Exhaust emissions will require aftertreatment due to the risk of compounds of nitrogen. However, selective catalytic reduction will be easy, as the main compound of SCR systems is ammonia, which can be easily added to the exhaust.

2.4.1.2 Methanol

Methanol (CH_3OH) is traditionally mainly consumed in the processing industry as a feedstock but has recently been considered a worthy candidate in decarbonising shipping. This has been due to investments by industry leaders such as Maersk investing in the technology to enable methanol use as a transitional marine fuel. Not only has Maersk ordered 19 methanol powered ships, but it has invested in methanol production. Methanol is a liquid at room temperature and has a relatively good volumetric energy density when compared to diesel or LNG. However, methanol is toxic to humans, its vapour is heavier than air and so it can linger even in open spaces presenting a higher inhalation risk to crew.

The major consideration with methanol is that, even if produced by means of green hydrogen, it still contributes to GHG emissions if the CO_2 used in its production is not sustainably sourced.

Utilising CO_2 captured from industry can be a transitional solution, sharing the emissions burden between the industry and shipping. This fuel source is compatible with the IMO's ambition of 50% decarbonisation by 2050 but not with net zero ambitions. The EU's Renewable Energy Directive (REDII) legislation has a proposed delegated act that will alter standards for the classification for Renewable Fuels from Non-Biological Origin (RFNBO). It proposes that from 2041, CO_2 sourced from industry will no longer be acceptable for RFNBO classification. The most promising CO_2 sources that are considered indefinitely sustainable are from:

- Direct Air Capture (DAC) technology which sources CO_2 directly from the atmosphere thereby removing the GHG impact; however, this technology is currently inefficient, expensive, and yet to be proven at a large scale.
- Biomass Energy with Carbon Capture (BECC), where bioenergy is combusted, but the resulting CO_2 is captured and utilised. As the life of biomass is circular and CO_2 is drawn from the atmosphere this would be carbon negative if stored and carbon neutral if utilised.

2.4.1.3 Liquid hydrogen

As mentioned, liquid hydrogen is produced cryogenically and is liquid form at -253°C. Maintaining this temperature is challenging and warming leads to evaporation, also termed as boil off. The conversion to gas builds pressure in a container, eventually leading to a pressure release valve releasing hydrogen into the atmosphere.

The low temperature also poses a risk of cryogenic burns in the event of human exposure. Further risk around the flammability and explosivity of hydrogen need to be carefully considered for safe handling. It will require learning within the maritime industry to ensure that liquid hydrogen can be safely stored, handled, and reconverted on-board to power ships. Hydrogen is expected to be a viable energy source only for smaller vessels travelling smaller distances.

2.4.2 Market assessment of available vessels/technologies

Currently the maritime industry predominantly utilises fossil fuels for energy, with ships containing internal combustion engines (ICEs) designed for fossil fuel use. The manufacture of new ships is needed to enable the uptake of hydrogen or ammonia as a fuel within the sector. Retrofitting is very difficult due to the need for new storage vessel materials, additional size requirements and containment and safety requirements. Existing fuel tanks are often built into the hull of ships, embedded within the frame structure which is not easily accessible.

For smaller vessels, cruise ships and for hotel loads, hydrogen fuel cells are likely to find adoption. Methanol to hydrogen fuel cells are in trial use. However, fuel cells are not yet proven for the long operating hours and harsh conditions at sea, so it is expected that most larger vessels will continue to use ICEs.

The following offers examples of existing applications of alternative fuels within the shipping context:

- One of the world's largest shipping companies, Maersk, have chosen methanol (green methanol) as their solution and have ordered 19 dual-fuel engines to deploy within replacement vessels.
- The "Energy Observer" is a hydrogen fuel cell powered catamaran which conducted a world tour in 2019. The team behind it have since presented a design of a multi-purpose cargo ship fuelled by liquid hydrogen.
- The "Hurtigruten MS Roald Amudsen" and "Hurtigruten MS Fridotjof Nansen" are 140m long hybrid-electric cruise ships vessels powered by batteries and fuel cells
- Finnish manufacturer Wartsila will sell an ICE that is able to take an ammonia and marine gas oil blend. They are partnering with Norwegian shipping firm Eidesvik Offshore to retrofit a supply vessel with the engine.
- Both Wartsila and Eidesvik are also part of Norway's ShipFC project which will involve installing a 2MW SOFC onto a vessel called Viking Energy.
- In China, a shipyard has built an ammonia-ready vessel that is designed to operate as a fossil fuel vessel in the near term but can retrofit to operate on ammonia in the future.

2.4.3 Storage and refuelling infrastructure needs

2.4.3.1 Hydrogen

There are various available options for the storage and refuelling of gaseous hydrogen in ships. Due to the gas' low volumetric density, large amounts of storage would be required to meet vessels' fuel demand. Hydrogen can either be piped to the dockside or delivered by train/truck and refuelled directly alongside the vessel.

For fixed refuelling infrastructure, pressure balance refuelling[1] is unlikely to be feasible due to the space required by the buffer tanks being difficult to accommodate in ports. The variety of receiving vessels is also unlikely to be accommodated by one design. Direct compression from a lower pressure pipeline into vessel storage is a more likely scenario. The safety case for refuelling hydrogen vessels will need development.

2.4.3.2 Ammonia

To store ammonia as a liquid it must be stored at -34°C. Storage vessels typically have inbuilt refrigeration systems to maintain its liquid state and are covered with insulation materials to reduce heat transfer from outside. It is important to have spill monitoring and well-trained operators given the hazardous nature of handling ammonia. The fuel can either be pumped as a liquid through a hose from a storage unit or it can be delivered by truck, train, or barge to dockside. Safe refuelling of ammonia may be a challenge for smaller ports, as safety distances will need maintaining, in a similar manner to LNG today.

2.4.3.3 Methanol

Methanol, like other alcohols such as ethanol, is a liquid at room temperature making it relatively easy to store in storage tanks. Methanol is generally delivered by conventional chemical transportation methods. However, unlike traditional fossil fuels, extra care is required against spillages and methanol vapour leaks which can be a toxic inhalation risk for humans.

2.4.3.4 Liquid hydrogen

Liquid hydrogen has to be cryogenically stored at -253°C. Given this, storage vessels that are heavily insulated and have inbuilt cooling systems are required to ensure loss of gas through boil-off is prevented. Skilled operators are imperative given the hazards related to cryogenics handling. Cylindrical storage vessels are required for storing the fuel and currently it is mainly transported by tanker trucks. Given the conditions of the liquid, there would be significant challenges in establishing any kind of pipeline. As with ammonia, safe refuelling will be challenging.

2.4.4 Demand scenarios

2.4.4.1 Ammonia

The Transport Scotland study forecasted fuel demands for the Scottish maritime sector, including both domestic and international shipping. The report selects ammonia as the dominant zero-carbon fuel for international shipping and for domestic shipping where electrification is not viable, based on scenarios set out in the UK’s sixth Carbon Budget and based on the following considerations:

- The potential to retrofit ship engines at relatively low cost
- It has a higher energy density than hydrogen
- The lower cost of production compared to methanol

Fuels such as methanol are also part of the ongoing conversation as it allows for a good transitional fuel that reduces emissions and is easy to apply to existing systems, as shown by its adoption by Maersk and Stena. However, considering the immaturity of carbon capture technologies and the relatively expensive nature of methanol production, it is not further discussed in this section of the study.

When considering the base case scenarios, namely those from the *“Zero Emissions for Transports”* report, it is noted that there are effectively 4 unique scenarios and of these 3 have been chosen as seen below. These estimate an ammonia demand of between 2166 – 8715 GWh by 2045.

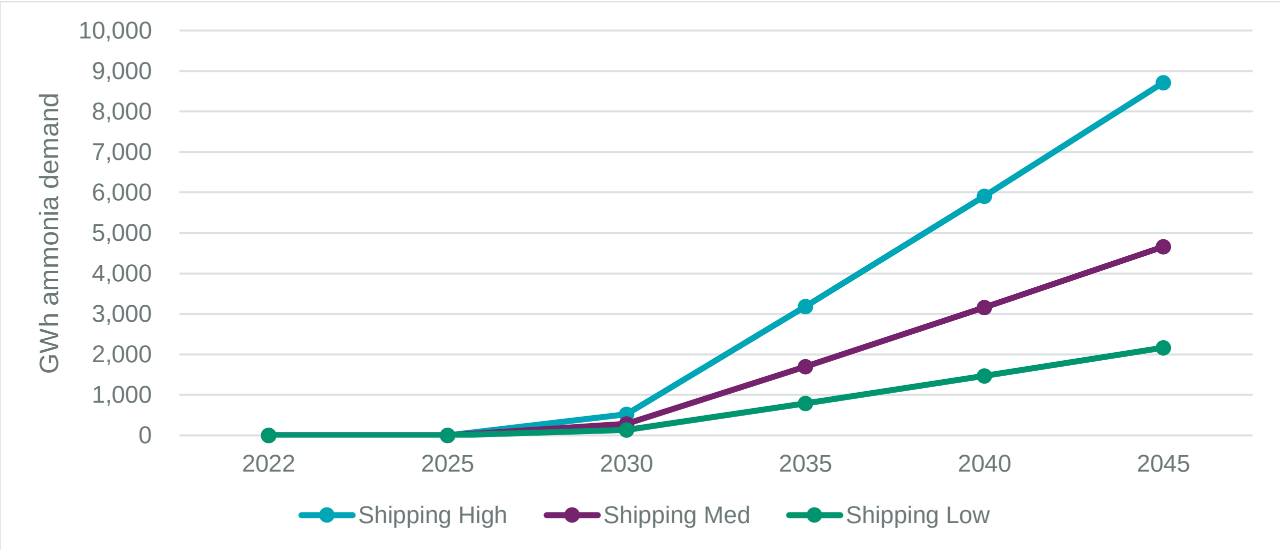
[1] Pressure balance refuelling is a method of transferring hydrogen from one container to another by pressurising a buffer vessel higher than that of the receiving vessel. When connected with a hose, a valve is opened and the principle of pressure equilibrium sees hydrogen flow into the receiving vessel. The process requires no energy during transfer but does require energy to pre-pressurise the buffer vessel in advance of refuelling.

Table 2-5 Ammonia energy demand scenarios for the Scottish maritime sector

GWh	2022	2025	2030	2035	2040	2045
1: LH (High)	0	0	525	3,182	5,906	8,715
6: MM (Medium)	0	0	282	1,702	3,159	4,660
2: ML (Low)	0	0	132	793	1,470	2,166

The moderate scenario is considered to be most likely considering the significant progress which is required to demonstrate ammonia in shipping. The following figure highlights the chosen ammonia scenarios.

Figure 2-11 Ammonia demand scenarios for the Scottish shipping sector



2.4.4.2 *Hydrogen*

For this study, there was an acknowledgement that hydrogen will still play a role in the fuel mix for the maritime sector, and as such Ricardo developed additional maritime hydrogen demand scenarios based on the projected uptake of ammonia.

Statistical data from the DfT relating to port traffic and freight tonnage was used to determine the hydrogen demand for the decarbonisation of the Scottish maritime sector. Scenarios were based on the assumption that domestic Ro-Ro vessels will be hydrogen powered, whilst liquid bulk, dry bulk & Lift On Lift Off (Lo-Lo) vessels were assumed to be powered by ammonia. The reasoning for this is as follows:

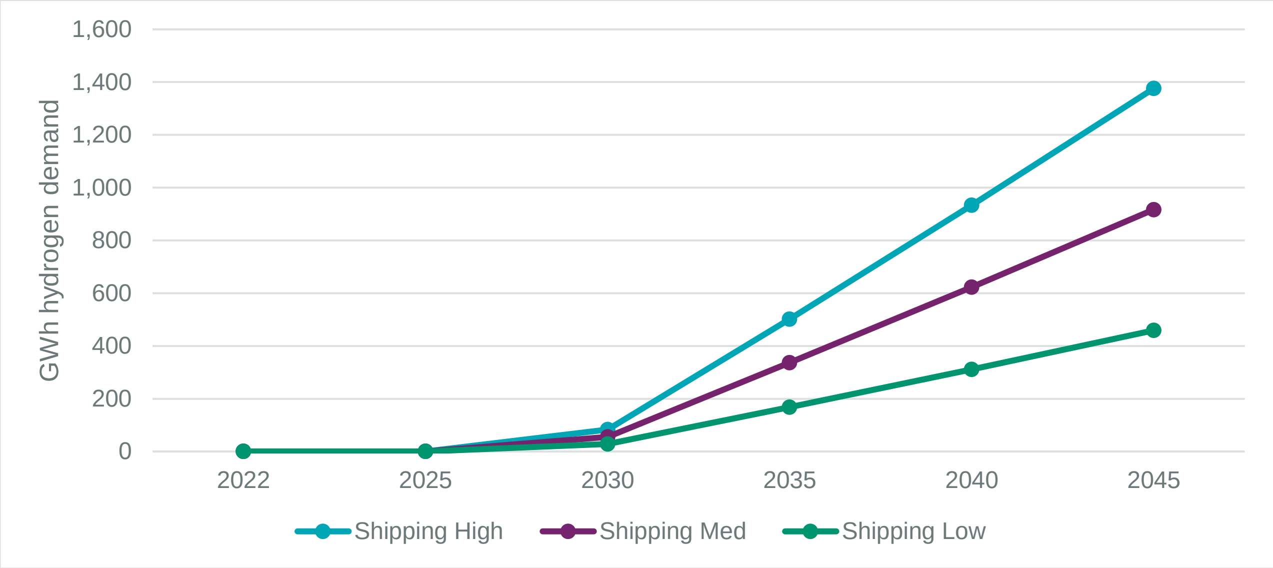
- Lo-Lo, bulk freight and liquid freight are densely packed with heavy loads thus will likely require a more energy-dense fuel such as ammonia.
- Domestic Ro-Ro vessels are less densely packed with trailer freight, contain lighter loads and would travel shorter distances. Given this, it is assumed that these will be hydrogen powered.

The following methodology was used to determine the scenarios:

- Determine high scenario based on % demand in shipping represented by domestic Ro-Ro (this is = 12%). This value is assumed for 2045
- Medium and low scenarios are assumed to be 8% and 4% respectively
- Thereafter, it is assumed that the hydrogen scenarios follow a similar curve to that of the ammonia scenarios

The resulting scenarios estimate hydrogen demand between 459 – 1376 GWh by 2045 as seen below:

Figure 2-12 Hydrogen demand scenarios for the Scottish shipping sector



2.5 FERRIES

Scottish ferry emissions are encapsulated in the maritime emissions discussed in section 2.4. Ferries provide vital lifeline services for the Scottish Islands carrying vital supplies and passenger traffic for commerce, as well as enabling the tourist trade that is a key part of island economic life. There are no specific national or international policies for ferries, but some ferries are owned by local government or procure service contracts for them. This gives opportunity for net zero commitments for local government operations and low-carbon service procurement being a lever for early adoption.

CMAL are leading the small vessel replacement programme - these are smaller vessels that serve shorter more frequent crossings, e.g. Largs-Cumbrae and Lochaline to Mull. An update in 2023 provides details of the battery propulsion that is planned for this fleet of 9 vessels. The plan outlines use of a 5MWh battery which would be charged overnight – as the short turnaround times do not allow recharging during operational hours. Ricardo understands that a number of other public sector operators (Highland Council, Argyll & Bute Council) will follow CalMac's design for small ferries.

2.5.1 How hydrogen can support the operational needs of ferries

The requirements of ferries vary significantly, with some routes being short and regular with a high passenger count, and some routes being long and irregular. Propulsion is currently facilitated by diesel ICE but alternative fuels will be required for decarbonisation.

As the Small Vessel Replacement Programme is showing, battery electric will likely be the leading solution for most short and regular routes where electrification assets can support their needs. Hydrogen and hydrogen derivative fuels will best suit longer, more exposed routes that require more energy in a single trip such as:

- CalMac: Ullapool to Stornoway and other routes
- Northlink: Aberdeen to Orkney and Shetland
- Stena: Cairnryan to Larne

While these vessels are larger, the amount of energy needed is likely to require use of liquid hydrogen or another hydrogen derivative that uses less volume such as methanol or ammonia (though there are questions as to whether ammonia will be suitable for passenger carrying vessels).

Hydrogen could also be a solution for regular routes where quick refuelling is required to enable a quick off-loading and on-loading. Ultimately, this will be determined on a case-by-case basis. Having the grid readily available or having to extend a line to facilitate electrification could be a key cost factor.

2.5.2 Market assessment of available ferries

The ferry market is an opportunity for hydrogen sea vessel demonstration. The fixed routes mean that a single refueller is enough to provide their needs and investment can be made with confidence. There are several demonstrations active in the UK and in Europe:

- The Stena Germanica Ro-Pax ferry operating between Gothenburg and Kiel was converted to run on both diesel and methanol in 2015. The ferry can carry 1300 passengers and 300 cars
- HySEAS III is a 40m long fuel cell powered Roll-On Roll-Off (Ro-Ro) ferry currently in the third stage of development by a consortium of Scottish partners including Caledonian Maritime Assets Ltd (CMAL), St. Andrew's University, Orkney Islands Council and several European organisations. It is proposed that this vessel will operate inter-island in Orkney and has a storage capacity of 350kg of compressed hydrogen at 250bar.
- Hydroville is a 14m long, 13-passenger ferry operating with a hydrogen ICE developed by UK firm CMBTech.
- MF Hydra is 82.4m long and was the world's first hydrogen-powered Ro-Ro ferry. It has been developed by Norled in Norway first as a battery powered ferry and then has subsequently had a fuel cell added to support operations in the winter months.
- Alserwasser is a 25m long, 100-passenger river ferry with a storage capacity of 50kg of hydrogen.

2.5.3 Infrastructure needs

Hydrogen refuelling infrastructure for ferries is expected to be the same as that for shipping as discussed in 2.4.3.1. One key difference is that not all ferries depart from busy ports. Some can be in rural locations, the perfect example being the inter-island ferries of the Shetland Islands. In those circumstances, there is more space to install refuelling infrastructure with pressure balance refuelling to quickly fill ferries that go regularly. For ferries that require refuelling less regularly, mobile refuellers are a preferred solution as it allows the refuelling asset to be shared amongst several locations and avoid an investment in an under-utilised refuelling point.

2.5.4 Demand scenarios

Three scenarios are provided in the Transport Scotland study for ferries. These scenarios are governed by the following assumptions:

- Ferry journeys less than 40km will rely on electrification
- Journeys equal to or more than 40km will be powered by hydrogen
- By 2045 all journeys greater than 40km will be hydrogen powered
- Lastly, large ferries between Cairnryan and Loch Ryan are assumed to be ammonia powered

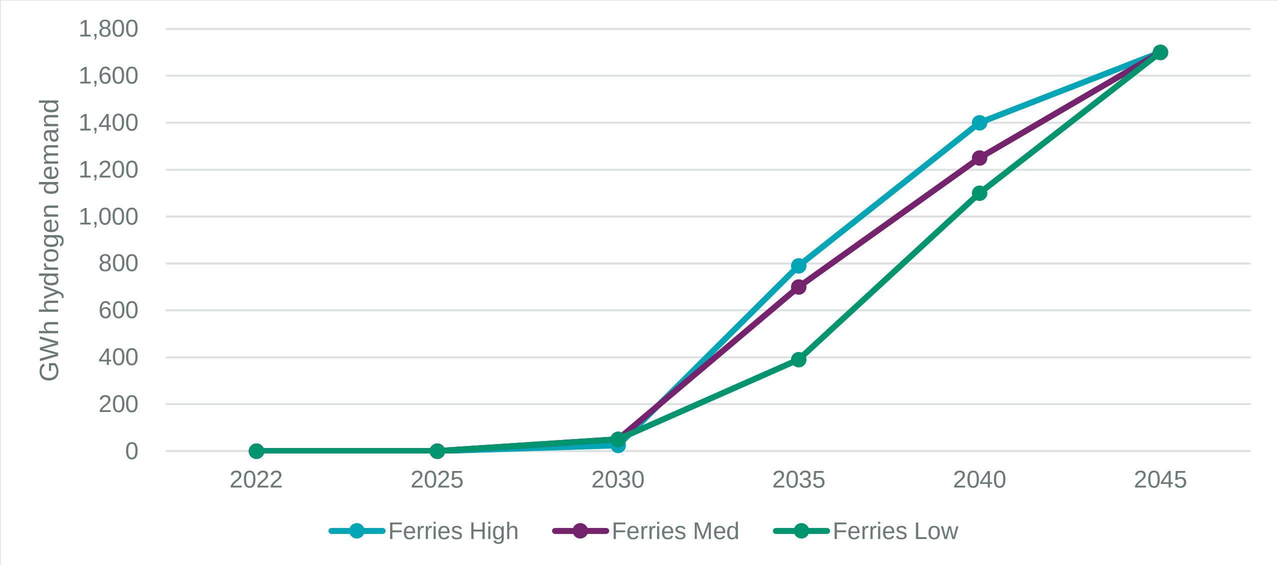
The table below outlines the three hydrogen demand scenarios for the ferries sector.

Table 2-6 Hydrogen energy demand scenarios for Scottish ferries

GWh	2022	2025	2030	2035	2040	2045
High	0	0	50	790	1,400	1,700
Moderate	0	0	50	700	1,250	1,700
Low	0	0	50	390	1,100	1,700

The low or moderate scenarios are considered to be most likely as progress must be made in commercialising hydrogen vessels. Electric ferries have thus far shown the greatest progress in commercialisation and application. The following chart outlines the three hydrogen scenarios as seen above, all leading up to the delivery of the Scottish Government's aforementioned objective for ferries by 2045.

Figure 2-13 Hydrogen demand scenarios for Scottish ferries



2.6 AVIATION

The Climate Change Committee (CCC) expects the aviation sector to be the second largest contributor to UK GHG emissions by 2050 as well as the fastest growing source of GHG emissions today. In Scotland, the aviation sector represents around 15% of transport emissions. The aviation industry has recently adopted the goal of reaching net-zero emissions by 2050 (WEF, 2022) highlighting the amount of attention the sector is placing on decarbonisation.

Recently, UK industry and government partners formed alliances and carried out research to make the case for these efforts in the respective Jet Zero and Fly Zero programmes. The global industry is demanding vastly increased production of Sustainable Aviation Fuel (SAF) to reduce emissions by 60-85% (depending on the type of SAF) between now and the 2070s on existing aircraft. Gaseous hydrogen is critical feedstock, alongside CO_2 from carbon capture, in the chemical manufacturing process for Synthetic Aviation Fuels (e-kerosene).

A report to be released by Optimat found that 93 stakeholders responding to their consultation showed particular support for electric and hydrogen powered aircraft, and also recognised the need for sustainable and synthetic aviation fuel, including domestic production, as part of the pathway towards zero emissions.

In the longer term, the aviation industry has expressed that it will invest significant resources to bring entirely new aircraft to market in the 2030s that would utilise liquid hydrogen (LH_2) as the fuel. This ambition requires access to sources of LH_2 in the coming years for the R&D and engineering required to design, certify and manufacture these aircraft ready for that date. Stakeholders that may be involved in these activities include the key industrial and academic players in aerospace within Scotland, such as at Glasgow and Prestwick and the SATE project in Orkney.

2.6.1 How hydrogen can support the operational needs of aircraft

The aviation sector pays a premium for kerosene as a high-grade fuel suitable for trans-continental travel. Its higher energy density, both volumetrically and by weight, is a critical factor for maximising efficiency, carrying more cargo and for longer range. Replacement fuels that meet the needs of aircraft and the sustainability criteria to reach net zero are expensive and difficult to obtain, making aviation a hard to decarbonise sector.

Like the maritime sector, outside of short-distance journeys and aircraft of 19 seats or less, direct electrification is not seen as a viable route to decarbonisation due to the energy density of current battery technologies and their inability to meet the high power-to-weight ratio demands of aircraft. Other fuels such as liquid hydrogen and SAF will be required to meet most of the energy demands for longer-distance flights in the transition to net-zero (Smil, 2021).

2.6.1.1 *Liquid hydrogen*

The International Council on Clean Transportation (ICCT) believe that liquid hydrogen-powered combustion aircraft can play an important role in the sector meeting its 2050 climate goals, with designs favouring smaller turboprop and narrow-body turbo fan suitable for short- and medium-haul flights (ICCT, 2022). It is a light fuel with a high energy density, and it produces considerably lower NOx emissions than standard jet fuel when combusted (European Commission, 2022). It also has the potential to be used as a fuel for fuel cells to extend the range of electric aircraft, avoiding direct emissions. However, they still emit some water vapour which produce contrails.

Although liquid hydrogen contains around 2.5 times more energy per kilogram than kerosene, it also has a lower volumetric density meaning that for longer journeys liquid hydrogen would occupy four times the space as that of kerosene. These constraints relating to volumetric density are why longer-haul flights are currently predicted to use SAF as an alternative. Further, the long-haul market generally changes at a slower pace and thus shorter routes and smaller plans will likely lead the way in hydrogen propulsion.

2.6.1.2 *Sustainable Aviation Fuels*

SAFs are highly appealing to the industry as they can be used as a drop-in replacement for conventional jet fuel without requiring any significant design changes to today's planes.

Scotland has access to chemical science skills, infrastructure and many of the eligible feedstocks, for waste-derived biofuel SAFs including bracken, category 1 & 2 farmed salmon oil and pot ale. However, the availability of such feedstocks is dependent on the waste resource potential and on market demand from competing uses.

The key alternative is to produce e-kerosene using green hydrogen, produced from offshore wind in Scotland for example, and CO_2 as the feedstock from BECCS or DAC. The production method has similar needs to that described in 2.4.1.2 for methanol.

2.6.1.3 *Ammonia*

Ammonia as an energy carrier has also been considered in the development of zero-emission aviation. With few modifications, an engine can be converted to run on ammonia. However, the fuel has a very low energy density making it over twice as heavy per unit of energy compared to conventional aviation fuels. It is also notable that ammonia is toxic and although fuel dumping occurs on the rarest of occasions for emergency reasons, the prospect of an aircraft having to jettison ammonia along with all the additional safety considerations to consider working with the public will likely make ammonia a less desirable option as a sustainable fuel within the aviation sector.

2.6.2 Market assessment of available aircraft

The aviation sector is very early on in its energy transition and the reality of using hydrogen as a fuel has only become accepted within the last few years. As discussed, liquid hydrogen is seen as an alternative fuel for newly designed aircraft. However, bringing new aircraft designed around this fuel to market is a complex process that takes time. Aircraft design is a highly technical field that requires significant effort into research, testing and prototyping to ensure the design is safe, reliable and efficient. It is also subject to strict certification and regulatory requirements that must be met for an aircraft to be approved for commercial use. As a result, there are currently no commercially available aircraft on the market. However, there are several projects currently underway aiming to demonstrate the viability of hydrogen-based fuels in aviation. The following highlights a few examples of such projects:

- In 2023, ZeroAvia conducted a 10-minute flight with a 19-seat Dornier 228 testbed aircraft with full size prototype hydrogen-electric powertrain, as part of the HyFlyer II project (Herald, 2023). The hydrogen fuel was supplied by partner European Marine Energy Centre in Orkney[2]
- In 2023, Universal flew a 40-passenger turboprop using fuel cell propulsion for 15-minutes. They converted an ATR 72 aircraft that is used for regional flights
- The RAF conducted project MARTIN, the world's first flight with 100% synthetic aviation fuel derived from green hydrogen (RAF, 2021). The aviation fuel was supplied by the Scottish company iGTL and their partner Zero Petroleum and the hydrogen feedstock from EMEC.

- The SATE project aims to develop the use of hydrogen fuel cells, batteries as well as SAF as low-carbon aircraft power sources within short routes between the islands. The project also aims to decarbonise airport infrastructure with the addition of hydrogen-powered combined heat and power (CHP) based on green hydrogen at Kirkwall Airport. The SATE partners include: HIAL, Arcadis Consulting Limited, Connected Places Catapult, EMEC, Flare Bright Ltd, HITRANS, UHI, Windracers Limited, Zeroavia, HIE and Orkney Islands Councils
- Airbus is seeking to flight test a direct combustion engine aircraft fuelled by hydrogen, and are developing a hydrogen fuel cell powered 100-passenger aircraft for regional flights (Patterson, 2022)
- Airbus also launched the “Hydrogen Hub at Airports” initiative in 2020 to help identify infrastructure requirements for future hydrogen aircraft as well as across the entire value chain (Airbus, 2022). In 2022, Airbus teamed up with the industrial gases and engineering company Linde to work on the development of hydrogen infrastructure at airports worldwide.

2.6.3 Infrastructure needs

2.6.3.1 Liquid hydrogen

Liquid hydrogen will require similar infrastructure as described in 2.4.3.4 for the shipping sector. One key difference is that refuelling will be from bowser refuellers much like the ones used for refuelling aircraft with conventional fuels.

2.6.3.2 Sustainable Aviation Fuels

SAF require the same infrastructure as kerosene and therefore have readily available access to it.

2.6.4 Demand scenarios

2.6.4.1 Hydrogen

There were six scenarios outlined in the Scottish Transport study, including domestic and international routes, only four of which were unique. The key assumptions behind the scenarios were:

- Small turboprops were assumed to only be electric powered
- hydrogen aircraft were assumed to go into service between 2030 and 2040, for small and large aircraft respectively
- All aircraft which were not hydrogen or electric are assumed to be either kerosene, SAF or another fuel

From these scenarios, three have been selected, as indicated below, which estimate a demand of between 736 and 1,969 GWh by 2045:

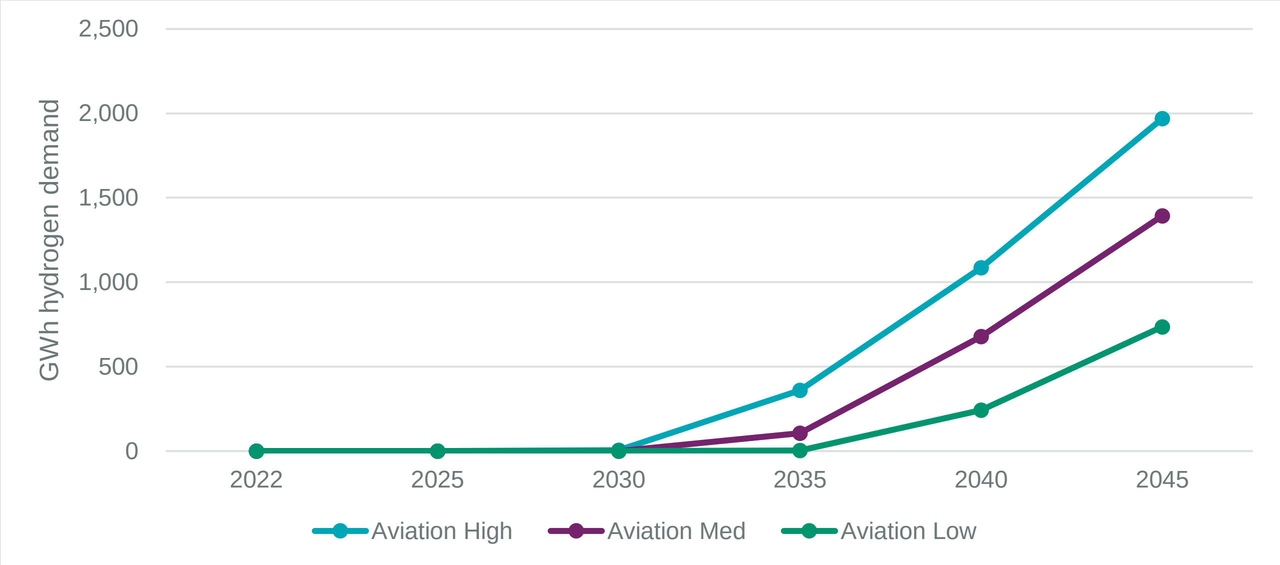
Table 2-7 Hydrogen energy demand scenarios for the Scottish aviation sector

GWh	2022	2025	2030	2035	2040	2045
1: LH (High)	0	0	6	359	1,085	1,969
6: MM (Medium)	0	0	0	105	678	1,393
2: ML (Low)	0	0	0	3	242	736

The low or moderate scenarios are considered to be most likely since significant progress is still required to demonstrate the related technology for hydrogen, whilst other fuels such as biofuel, SAF and e-kerosene have gained greater attention and would require less significant technological advancement for implementation.

However, as stated above, there are several demonstration projects ongoing for hydrogen aircraft and it is not impossible that some may achieve commercialisation before 2030.

Figure 2-14 Hydrogen demand scenarios for the Scottish aviation sector

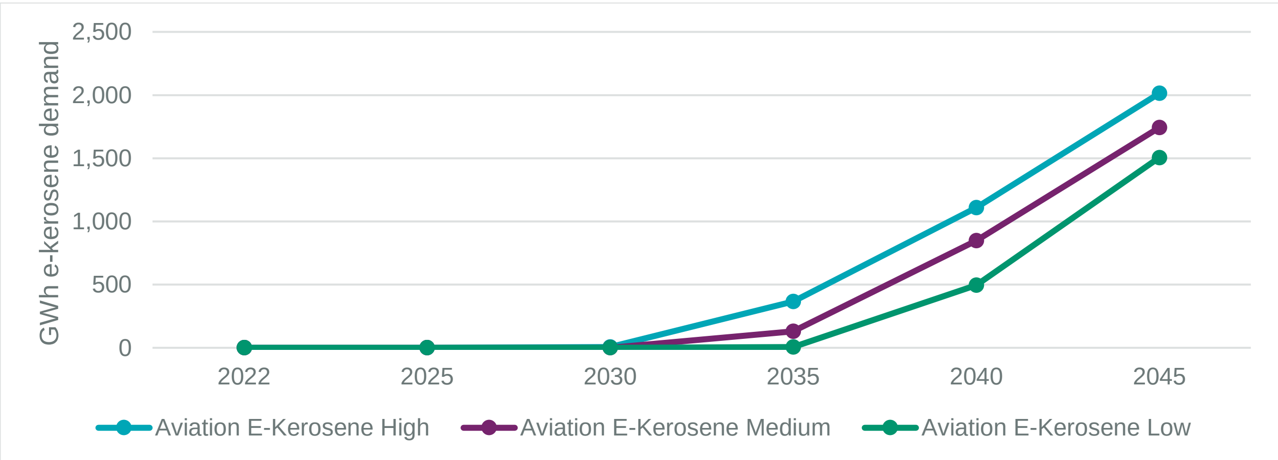


2.6.4.2 E-kerosene

For the purposes of this study, it is assumed that the remaining demand after considering hydrogen and electricity demands would be attributed to SAF consisting of biofuels and e-kerosene. E-kerosene is a hydrogen derivative fuel, and it was agreed that including it would be beneficial for the study.

EU legislation highlights that by 2050, 85% of all aviation fuels should be sustainable aviation fuels (of which 50% would be e-kerosene). This allows for a split of 5/8.5 and 3.5/8.5 for synthetic fuels and biofuels respectively. This split was applied to the calculated SAF demand, 1506 – 2013 GWh by 2045, to develop scenarios for e-kerosene adoption and applied to the same rate of uptake as the hydrogen projection. This is the case as carbon capture technology will need to mature alongside hydrogen production to ensure the sustainable production of e-kerosene.

Figure 2-15 E-kerosene demand scenarios for the Scottish aviation sector



2.7 OFF-ROAD VEHICLES

Off-road vehicles are not accounted for in transport emissions by the Scottish Transport Statistics. They are viewed as industrial equipment but are included under this study due to their mobile nature. There are no clear policies targeting any off-road vehicles but from 2022 the UK Government removed the entitlement to cheaper “red” diesel for certain off-road sectors, notably construction and waste management. The UK Government ran a £40m Red Diesel Replacement Competition in 2023 to fund the development and demonstration of hydrogen (and other low-carbon fuels) for the construction sector as part of the wider hydrogen strategy.

Off-road vehicles are a broad category of vehicle types, ranging from small agricultural vehicles to large construction equipment. For the purposes of this study, the off-road vehicle sector can largely be split into three main categories:

- Agriculture vehicles - these vehicles are typically used in farming and can range from small lawnmower vehicles to large tractors and combine harvesters. These vehicles are used for long periods at a time, and therefore have a high energy consumption requirement.
- Construction vehicles - these vehicles are used for a wide range of tasks on a building site, such as excavation, transportation, and grading of materials. There are many types of construction vehicles, each with its own unique capabilities and functions.
- Forestry vehicles - these are unique vehicles which are used in harsh environments. There are two main types of off-road forestry vehicles: harvesters and forwarders.

2.7.1 How hydrogen can support the operational needs of vehicles and equipment

Off-road vehicles are used for different applications in different environments, depending on the vehicle's type and the sector they are being used in. However, the majority of off-road vehicles are used intensively, have a high-power demand and high energy requirements.

2.7.1.1 Agriculture

Off-road vehicles in the agriculture sector are used for a wide range of applications, ranging from small lawn-mover style vehicles to large combine harvesters and therefore the operational needs are different depending on the use case. Off-road agriculture vehicles can range from under 35 horsepower to over 500 horsepower.

Typical applications of agriculture vehicles include cultivation, planting and fertiliser distribution, field crop or fruit spraying, and crop harvesting. For the smaller, less powerful agriculture off-road vehicles it is possible that battery-electric technology can fulfil the duty cycle and could be the preferred zero-emission powertrain.

For the larger agriculture vehicles, hydrogen could play a significant role in decarbonisation as the increased energy density (vs battery electric) can offer longer runtimes for these types of vehicles. However, powertrain cost, fuel cost, hydrogen storage requirements, fuel cell durability and cooling of the system have been identified as potential challenges to hydrogen powered agriculture vehicles.

2.7.1.2 Forestry

There are two main off-road vehicle segments for forestry vehicles: harvesters and forwarders. Harvesters are slow vehicles with a crane arm attached, with the role of stripping branches and trees. The role of forwarders is to pick up the logs, drive through the forest and stack the logs in the forest. Both vehicles operate in harsh conditions, and diesel is a very safe and reliable option for these vehicles.

Industry stakeholders identified that hydrogen could be a viable zero-emission technology for forestry off-road vehicles, although these stakeholders are open-minded on the future of decarbonising this sector. Given the higher energy density of hydrogen compared to battery electric vehicles, hydrogen may be the preferred alternative powertrain option to decarbonise the off-road forestry vehicles. These vehicles are also nomadic by nature, and therefore it is challenging to implement recharging infrastructure to serve battery electric vehicles. These vehicles also have a long runtime required in difficult terrain, again aligning to the strengths of hydrogen powered vehicles over battery electric.

2.7.1.3 Construction

As with agriculture vehicles, there are a wide range of applications and use cases required for construction off-road vehicles. Some vehicles are required to have almost 24 hours of daily usage, and at 200kWh per hour energy consumption this could require up to 4.8 MWh of energy per day.

Off-road construction vehicles with higher energy consumption and longer daily use are likely to be more suitable for hydrogen (compared to battery electric vehicles), as hydrogen can offer a longer use time. However, additional research and development is needed in the hydrogen powertrain for these larger vehicles, as Komatsu stated that current (2021) hydrogen fuel cell technology can operate a 20-tonne excavator for 8 hours, whereas a diesel ICE counterpart can operate for the full 24 hours required (Komatsu, 2021). Hydrogen could possibly be suitable for the smaller, less energy intensive construction vehicles, but it is likely that battery electric vehicles will have a cheaper total cost of ownership in these use cases. This trend has somewhat been observed in industry to date, with Komatsu having developed small-sized battery excavators, but stating that all zero-emission options will likely be needed to suit to wide range of construction vehicle applications.

2.7.2 Market assessment of available vehicles/vessels/technologies

The off-road hydrogen powered vehicle market is still in the early stages, with no commercially available hydrogen powered vehicles available, but there have been new developments:

- JCB are in the final prototype stages of their hydrogen internal combustion engine for construction equipment.
- JCB also developed a mobile hydrogen refueller to enable on-site refuelling of their vehicles.
- Hyundai Construction Equipment announced that they will be designing, manufacturing and evaluating the performance of hydrogen-powered excavators and forklifts
- Chinese company SANY presented hydrogen fuel cell powered dump and mixer trucks that can provide a driving distance of 310 miles.

2.7.3 Infrastructure needs

Whilst all the off-road vehicle sectors (agriculture, forestry, construction) have different applications, the vehicles are unlikely to have easy access to static hydrogen refuelling stations due to the nature of their operations. For any on-site production, storage or refuelling facilities of hydrogen, fuel safety and regulatory requirements for handling and storing hydrogen must be considered. This is particularly the case for off-road vehicles, which may require refuelling in harsh environments (such as construction sites or forest environments).

2.7.3.1 Agriculture

Agriculture vehicles will likely have two options for fuel supply and infrastructure to the farms they operate on:

- **Hydrogen delivery to the farm**: farms are typically in rural areas and therefore will not likely be nearby to a hydrogen refuelling station in future (as these will likely be placed in areas of high hydrogen demand). Therefore, hydrogen will need to be transported to the farm for on-site storage and refuelling.
- **Hydrogen production on the farm**: a different option could be for farms to produce their own hydrogen on-site. This will come at a very high capital cost, particularly for smaller farms. This would require connection to the electrical grid (which may not be sufficient in rural locations) or direct connection to a renewable energy asset.

Both options will come with their own challenges, however the on-site hydrogen production will likely only be feasible for very large farms which can afford the capital investment into the hydrogen production facilities and are willing to achieve the necessary planning and safety approvals. This leaves smaller farms relying on direct hydrogen deliveries. As farms are fixed locations, it may be possible for on-site hydrogen storage and refuelling to be viable.

2.7.3.2 Construction

As construction sites move around across Scotland, so will the non-road mobile machinery used for construction purposes. In a transition to hydrogen-powered off-road construction vehicles, mobile hydrogen refuelling will be key to supplying. Currently 97% of off-road construction vehicles have fuel delivered to the construction sites, therefore customers are already used to a transportable fuel. Hydrogen will likely need to be stored on site in these mobile refuelling stations, as construction sites are unlikely to be nearby to a static refuelling station. Construction sites may be non-flat, space constrained and have heavy vibrations, making on-site mobile hydrogen refuelling technically challenging. However, in October 2022 JCB unveiled a mobile hydrogen refueller for construction purposes. This mobile refueller allows for hydrogen to be taken from on-site tube trailers and distributed to construction machines working on the site. It is not clear how much hydrogen the mobile refueller can store, but with JCB investing £100m into hydrogen engines it is likely that this technology will improve in future.

2.7.3.3 Forestry

Off-road forestry vehicles are currently refuelled by a mobile diesel tanker, which is placed in a nearby location and the vehicles can refuel directly from it. This corresponds to the nature of forestry operations (i.e. moving to different locations regularly).

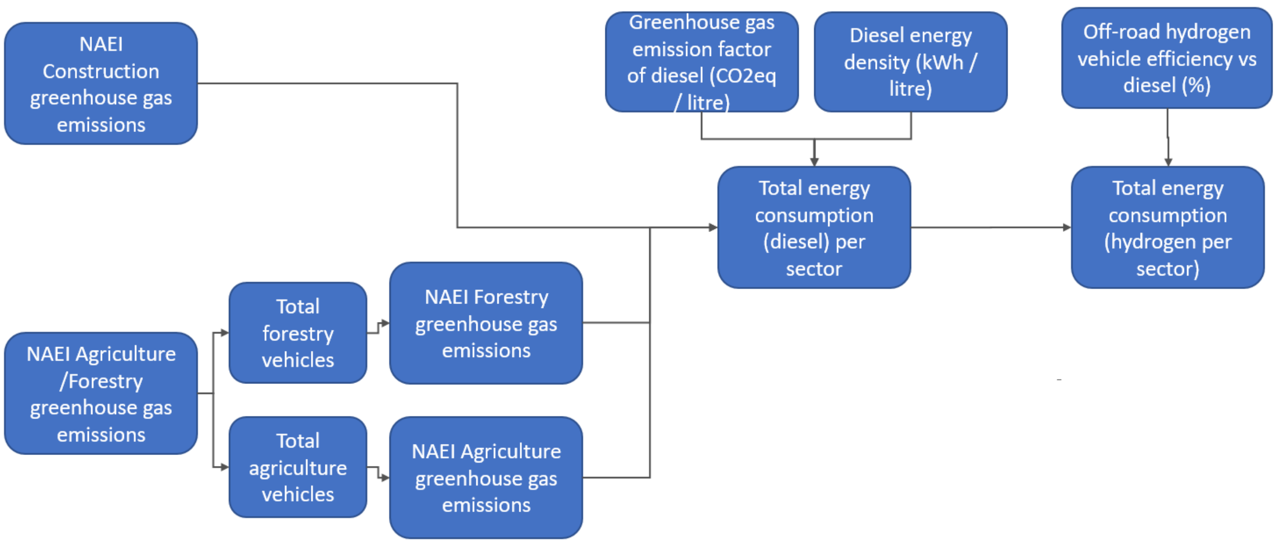
It is likely that the forestry sector will have similar infrastructure and refuelling challenges to the construction sector, and as construction is a much larger sector than forestry in Scotland (in terms of energy consumption and vehicle numbers) it is likely that forestry can utilise any technological advances in mobile hydrogen refuellers developed by the construction sector.

2.7.4 Demand scenarios

The hydrogen demand scenarios for off-road vehicles were developed using total greenhouse gas emissions from Agriculture/Forestry vehicles and non-road mobile machinery (NRMM) from the construction sector. This data was taken from the National Atmospheric Emission Inventory (NAEI) and represents emissions responsible for Global Warming Potential (GWP) including carbon dioxide (CO_2), methane (CH_4), and nitrous oxides (N_2O). The emission data per sector (in tonnes CO_{2eq}) was converted into litres of fossil fuel (largely diesel) using conversion factors (in CO_{2eq} per litre fuel burned), and then converted into total energy demand (GWh) using energy density of the fuel (kWh per litre fuel) (BEIS, 2022). Hydrogen-powered vehicles are on average around 30% more efficient than fossil fuel equivalents for off-road vehicles (Climate x Change, 2022), and therefore the total energy demand (from fossil fuel vehicles) was finally converted into hydrogen demand by accounting for the lower energy required for hydrogen-powered vehicles.

The NAEI data is available for agriculture/forestry and construction vehicles separately. The total energy demand for forestry and agriculture vehicles was separated using ratios of total vehicles in the fleet, with forestry vehicles only representing around 2.5% of the combined agriculture and forestry vehicle fleet (around 1,000 forestry vehicles compared to around 40,000 agriculture vehicles) (Climate Exchange, 2023). This baseline energy consumption (2019, based on the latest NAEI data) was used to form the total maximum hydrogen potential for the off-road vehicle sectors. A high-level overview of this methodology is shown in the figure below.

Figure 2-16 methodology used to estimate total potential hydrogen demand for off-road vehicles (based on NAEI emission data)

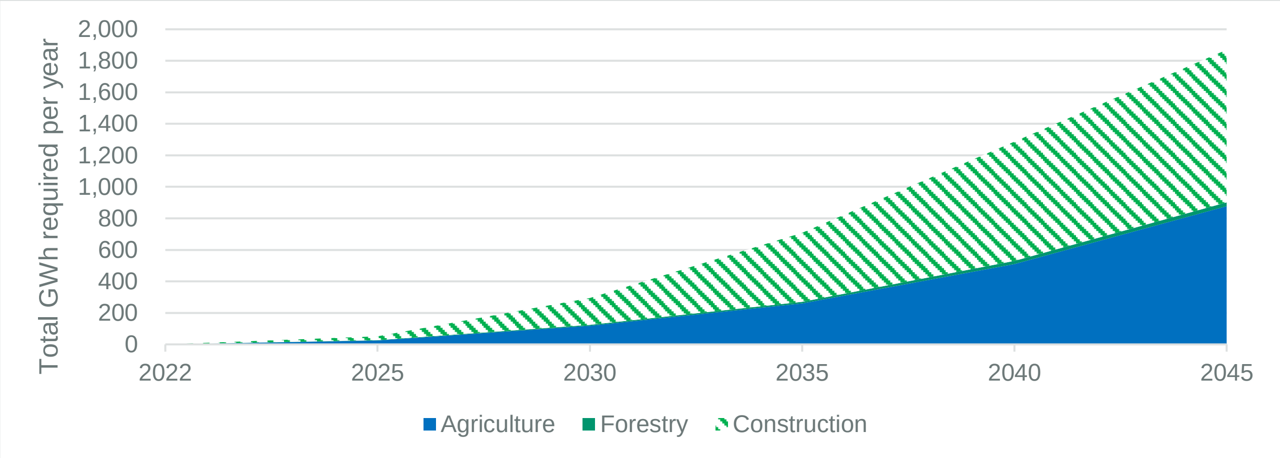


Energy calibration

A high-level sense check was performed against the total energy demand from the calculations outlined above against the total red diesel consumption in the UK. As a result of policy changes from 2022, the red diesel consumption in the UK is largely limited to use in off-road vehicles. Red diesel represents around 15% of the total diesel consumption in the UK (HM Treasury, 2018), and it is estimated that 23.3 million tonnes of diesel was used in the UK in 2019 (DfT, 2022). According to the NAEI data, Scotland's off-road vehicles represent 12% of all greenhouse gas emissions (and therefore red diesel consumption) in the UK. These values result in around 420,000 tonnes of red diesel consumed in Scotland per year (based on the 2019 data). The top-down approach as outlined in the section above results in around 400,000 tonnes of diesel consumed by off-road vehicles (2019). As both estimates are within 5% error, the top-down approach was deemed to give a reasonable estimate for off-road vehicle energy consumption in Scotland.

Based on the calculation methodology used, the total hydrogen demand for off-road vehicles could reach around 1,800 GWh per year in 2045 (under the medium uptake scenario). Construction and agriculture off-road vehicles result in a similar overall estimated hydrogen demand by 2045, whereas forestry vehicles only represent around 1.3% of the total hydrogen demand for off-road vehicles by 2045. This is a substantial overall demand for hydrogen in the off-road vehicle sector, which is comparable to the HGV demand of around 2,300 GWh in 2045 under the medium uptake scenario.

Figure 2-17 Hydrogen demand scenarios for off-road vehicles (medium uptake scenarios)



2.7.4.1 *Agriculture*

For each of the three off-road vehicle sectors, uptake rates for hydrogen-powered vehicles were derived, and these uptake rates were applied to the overall hydrogen demand potential.

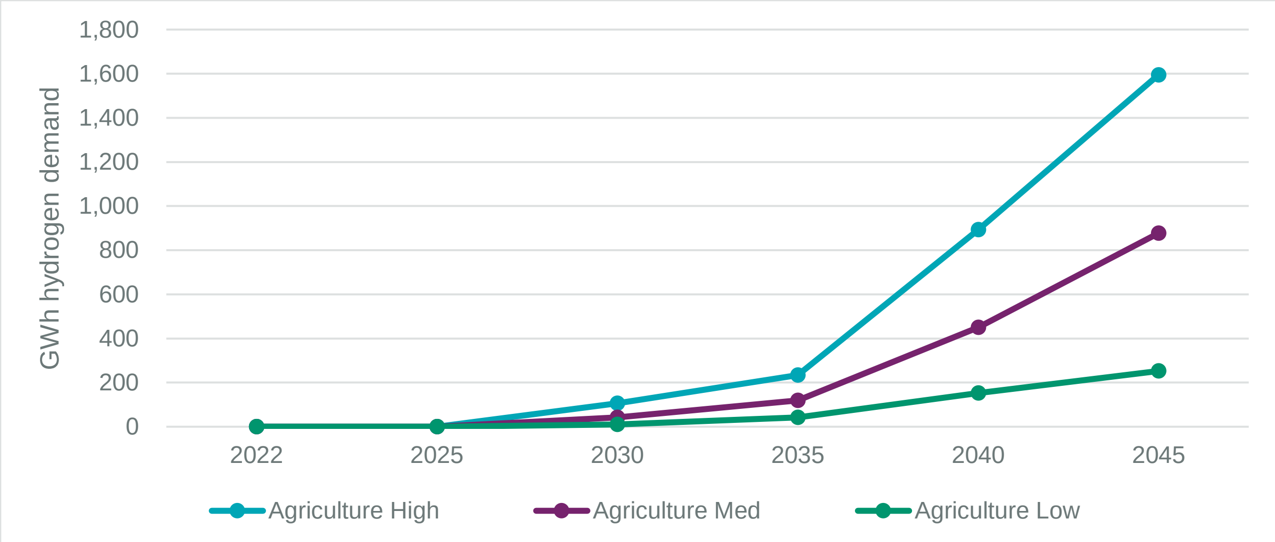
For the agriculture sector, the uptake of hydrogen-powered vehicles was taken from the recent report on agriculture decarbonisation (Climate Exchange, 2023), as shown in Table 2-8. The report estimated a high potential uptake of hydrogen in the agriculture sector by 2035. As agriculture is one of the remaining sectors to have the red diesel fuel incentive, it is likely that agriculture vehicles could be one of the last sectors to decarbonised. Therefore, the demand scenarios from Climate Exchange were shifted back for this analysis by 5 years between 2025 and 2035 (with the 2040 and 2045 values remaining the same). This results in 2040 marking a step change in hydrogen vehicles under the demand scenarios. The three uptake scenarios presented in the agriculture decarbonisation study represent a wide range of hydrogen across agriculture vehicles, from only 12% in the ‘low’ uptake scenario to 75% in the ‘high’ scenario by 2045.

Table 2-8 Hydrogen demand scenarios for agriculture

Sector	Scenario	2022	2025	2030	2035	2040	2045
Agriculture	High	0%	0%	3%	11%	48%	75%
Agriculture	Med	0%	0%	1%	6%	24%	41%
Agriculture	Low	0%	0%	0%	2%	8%	12%

The hydrogen uptake scenarios for agriculture, along with the estimated energy demand, results in between 200 and 1600 GWh hydrogen required per year in 2045 under the medium scenario for agriculture vehicles. As mentioned above, there is a wide range in possible zero-emission vehicle futures for the agriculture sector, with no zero-emission technology (battery electric, hydrogen fuel cell, or low-carbon fuels) a clearly preferred option at this stage. The hydrogen demand will depend on multiple factors, including the commercial feasibility of hydrogen powered vehicles but also technological advances in hydrogen powered vehicles and competing technologies (i.e. battery electric vehicles).

Figure 2-18 Hydrogen demand scenarios for agriculture vehicles



2.7.4.2 Construction

There is a lack of data on registered vehicles used for construction purposes (or non-road mobile machinery, NRMM) in Scotland. The best estimate split of vehicles used for construction purposes identifies that vehicles range from low-power forklifts and paving equipment to large rigid dump trucks which can have around 700kW of engine power (diesel) (DEFRA, 2004). Whilst the source from the Department for Environment, Food and Rural Affairs (DEFRA) is now outdated, it gives an indication of the types and shares of vehicles used in the construction sector.

NRMM with (diesel) engine power of 35 kW or less represents 62% of the construction vehicle fleet, in the UK (and can be used as a proxy for the share in Scotland) and is estimated to consumed 28% of the total energy consumed by construction vehicles (based on engine power and estimated annual operating hours). It is likely that the NRMM with a lower engine power rating (35 kW or less) and lower energy consumption will likely transition to battery electric, as this could be more cost effective than hydrogen. Therefore, the 'high' demand scenario for construction vehicles is limited to 72% of the total energy consumption from construction vehicles, as the remaining 28% is anticipated to transition to battery electric.

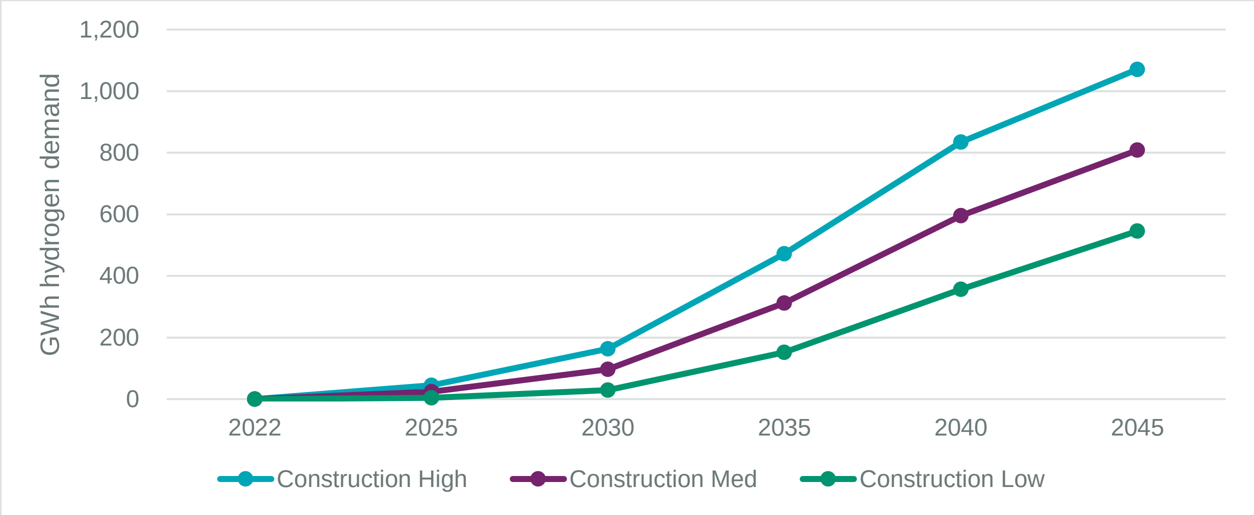
The 'low' uptake rate was determined from the recent Optimat study on 'Decarbonisation of Construction Site Heavy Duty Vehicle Plant and Equipment', and the response to the use of hydrogen currently or in future as answered by the industry participants to the study. In this survey, 37% of respondents indicated that they have not used hydrogen vehicles, but plan to in the future. The medium uptake scenario was calculated as the mid-point between the low and high uptake demand scenarios.

Table 2-9 Hydrogen demand scenario for construction

Sector	Scenario	2022	2025	2030	2035	2040	2045
Construction	High	0%	3%	11%	32%	56%	72%
Construction	Med	0%	2%	7%	21%	40%	54%
Construction	Low	0%	0%	2%	10%	24%	37%

Applying the uptake scenarios to the total energy demand from the construction sector results in between 550 and 1,400 GWh of hydrogen required under the medium uptake scenario by 2045. Whilst the overall energy demand for agriculture vehicles is currently higher in Scotland than the construction sector, the more ambitious uptake rates for hydrogen powered vehicles in construction result in a higher overall energy demand compared to agriculture by 2045.

Figure 2-19 Hydrogen demand scenarios for construction vehicles



2.7.4.3 *Forestry*

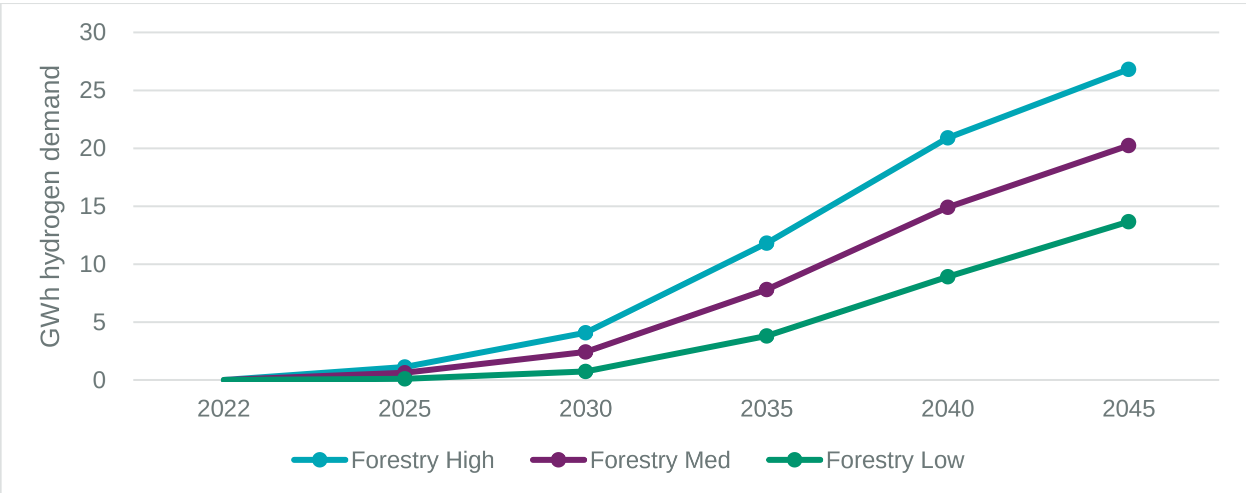
Whilst off-road forestry vehicles are used for very different applications compared to construction vehicles, the types of vehicles used (in terms of size and power demand) are somewhat similar. Therefore, the uptake rates for hydrogen in the forestry sector are assumed to be similar to the construction sector hydrogen uptake rates.

Table 2-10 Hydrogen demand scenarios for forestry

Sector	Scenario	2022	2025	2030	2035	2040	2045
Forestry	High	0%	3%	11%	32%	56%	72%
Forestry	Med	0%	2%	7%	21%	40%	54%
Forestry	Low	0%	0%	2%	10%	24%	37%

The forestry sector represents a small proportion of the overall energy demand for off-road vehicles (when compared to agriculture and construction sectors). Therefore, despite having ambitious hydrogen powered vehicle uptake scenarios the overall estimated hydrogen demand is relatively low.

Figure 2-20 Hydrogen demand scenarios for forestry vehicles



2.8 SPACE

The space sector in Scotland currently has no emissions related to spacecraft fuel. However, Scotland is taking steps to develop the domestic space industry and its first orbital launch is expected in 2023. There is strong experience in satellite manufacturing, rocket manufacturing, data and ground-breaking research. In 2021 Scotland launched the Scottish Space Strategy. Included in the strategic actions in the sector, is a section on Sustainable Space Focus. This section ensures that Scotland's space ambitions and the plans for their delivery are in line with Scotland's target to transition to a net zero society by 2045, raises the importance for this sector to investigate pathways of decarbonisation.

Scotland's geography makes it the best place in the UK to reach sought-after satellite orbits with vertically launched rockets. Companies need access to affordable launch services that spaceports in Scotland will be able to offer.

2.8.1 Operational needs of vehicle/vessels

Space sector fuels have specific needs from fuel properties which differ from regular applications. Fuels need to have a high gravimetric energy density to reduce the weight of the spacecraft and a high specific impulse to maximize the efficiency of the propulsion system. Spacecraft also need to be able to operate in harsh requirements that can subject fuels to extreme temperatures, pressures and radiation. Fuels for the space sector must therefore be highly reliable and able to withstand these conditions. At present, different propellants (can be in the form of a solid, liquid or gas) are used for different missions and differ among the stages of any given rocket.

- Solid - Ammonium perchlorate mixed with powdered aluminum that is held together in a rubberlike matrix is the most common solid propellant
- Liquid - liquid hydrogen and liquid oxygen have a very high specific impulse and are used for the upper or second stages of a rocket. Smaller rockets often use refined kerosene or LPG as these fuels are easier to handle
- Gas - gaseous fuels lack density but can offer some performance and long-term storage advantages for space travel.

2.8.2 Market assessment of available vehicles/vessels/technologies

Spacecraft and rockets have long been purpose-built, used only once and discarded after their missions were completed. Modern reusable rockets such as Space X's Falcon 9 (using rocket grade kerosene) and Blue Origin's New Shepard (liquid hydrogen) can be used multiple times and therefore represent a revolution in the industry. These are the closest rockets to being commercialised at fulfilling delivery contracts for NASA.

Scotland accounts with 5 spaceports: Shetland, Sutherland, Argyll, Prestwick, and the Outer Hebrides. Public information on the ports is summarised as follows:

- **Shetland - SaxaVord Spaceport** has been designed to host a wide variety of launch missions on rockets with payloads of up to 1.5 tonnes. Lockheed Martin are developing launch operations.
- **Sutherland – Space Hub.** In 2018 the UK Space Agency (UKSA) announced the development of a vertical launch site in Sutherland. The number of satellite launches is expected to grow to a maximum of 12 a year. Rocket company Orbex opened the facility in Forres for developing their Prime launch vehicle which will launch from Space Hub Sutherland. They use a renewable, bio-propane fuel that cuts carbon emissions by 90% compared to traditional fossil hydrocarbons.
- **Argyll - Spaceport Machrihanish** plan to offer horizontal, vertical and high-altitude platform services.
- **Outer Hebrides – Spaceport 1** is a consortium opening a vertical launch spaceport. They state that due to the high level of combustion efficiency required for launches, a number of propellant mixtures do not include fossil fuels. A small proportion of rocket fuels adopt hydrocarbon-based fuels as a propellant (e.g., kerosene). However, non-fossil fuels are more frequently adopted as an alternative (hydrogen peroxide, liquid O_2).
- **Prestwick Spaceport** will provide horizontal launch capabilities for small satellite delivery. In addition, the site also has the potential for hosting human spaceflight and commercial sub-orbital hypersonic flight services. Prestwick Spaceport secured Astraius, a UK-based horizontal launch company, as its launch partner. Each satellite is fitted into a rocket, which is secured under the plane's wing. After the

plane takes off, it reaches a specified location and drops the rocket. Once clear of the plane, this engages and transports the satellite into Low Earth Orbit. The satellites being launched from Prestwick Spaceport by Astraius will be used for earth observation purposes to combat climate change and will use solid fuel rather than liquid or gas, which removes the potential for leaks.

According to the literature review in the space sector, there is a strategy and increasing investment supporting the development of the space sector in Scotland, running in parallel with the objective to be aligned with zero emission objectives. In Scotland's spaceports there are different launch methods with different fuels used. However, there is currently no clear evidence of hydrogen being used in ports launches or data of launches' fuel demand. Based on this, the space sector is not included in this data and mapping exercise.

2.8.3 Infrastructure needs

2.8.3.1 Liquid hydrogen

Liquid hydrogen will require equivalent infrastructure to that discussed in 2.4.1.3.

2.8.3.2 Sustainable aviation fuels

SAF such as e-kerosene require the same infrastructure as kerosene and therefore are readily accessible.

2.8.4 Demand scenarios

Due to the low data availability and high level of uncertainty in this nascent sector it has been assumed for the purpose of quantifying demand that there is no hydrogen or hydrogen derivative fuels adopted in this sector. As the industry grows the needs and scale will become clearer.

3. SUMMARY OF DEMAND SCENARIOS

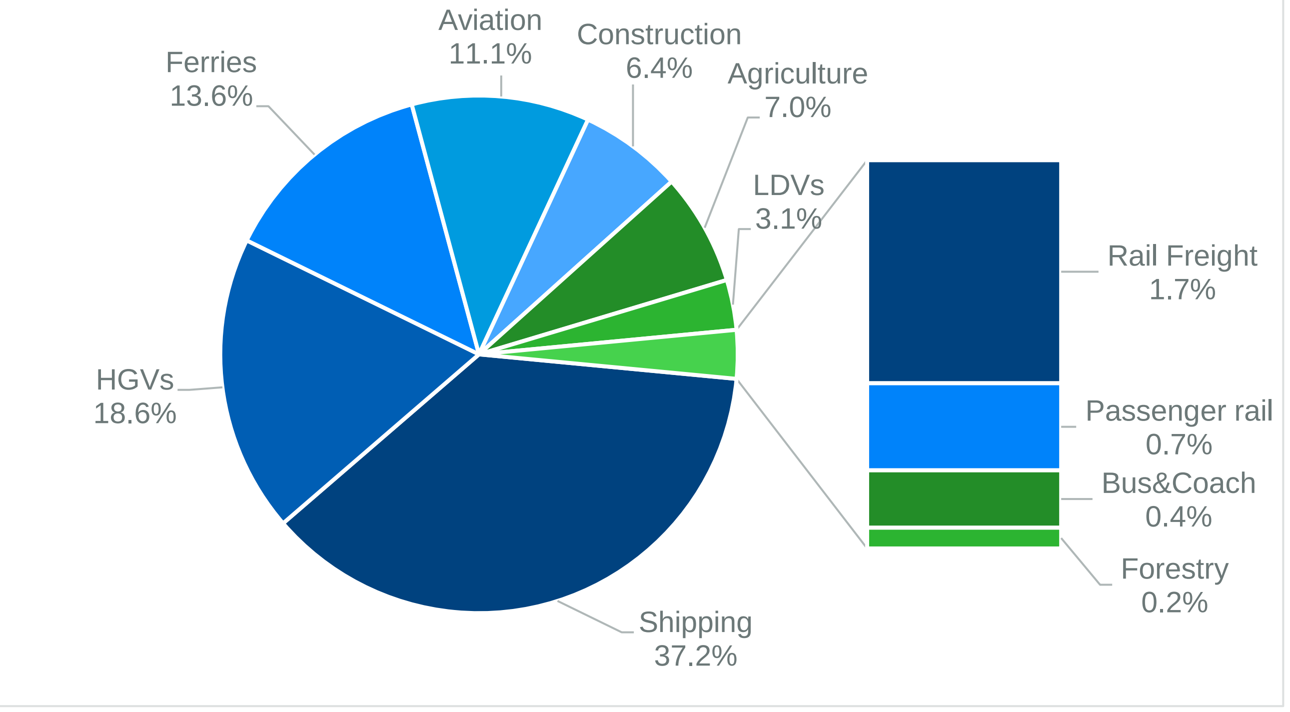
This section presents findings from literature on national hydrogen and hydrogen-based fuel uptake scenarios for each of the sectors. High, medium and low demand scenarios out to 2045 are shown for each. For the following sectors, scenarios were developed using available data:

- Hydrogen demand for shipping
- E-kerosene demand for aviation
- Hydrogen demand for agriculture, construction and forestry off-road subsectors

The scenarios form the foundational basis of the uptake values plotted in the mapping exercise.

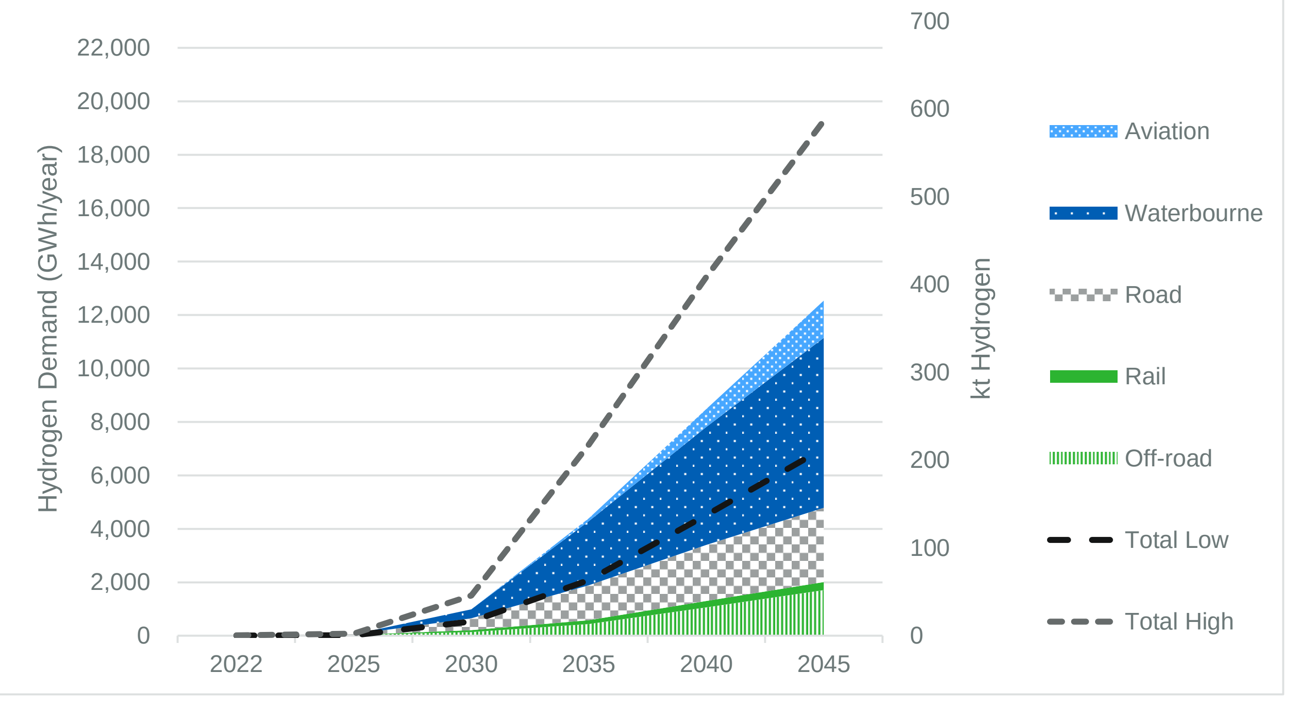
The chart below shows the split of energy requirements by sector. As a hard to decarbonise sector, shipping has a high energy requirement for hydrogen derived fuels. HDVs are the next largest sector due to them being a portion of an overall large emitting sector. Ferries follow, experiencing similar difficulties to the shipping sector. Aviation is also difficult to decarbonise but has its demand for hydrogen derived fuels reduced by the assumption of access to aviation grade biofuels. LDV, Bus, passenger rail and rail freight are all comparatively low demands.

Figure 3-1 Split of demand for hydrogen derived fuels (including ammonia, e-kerosene) in 2045



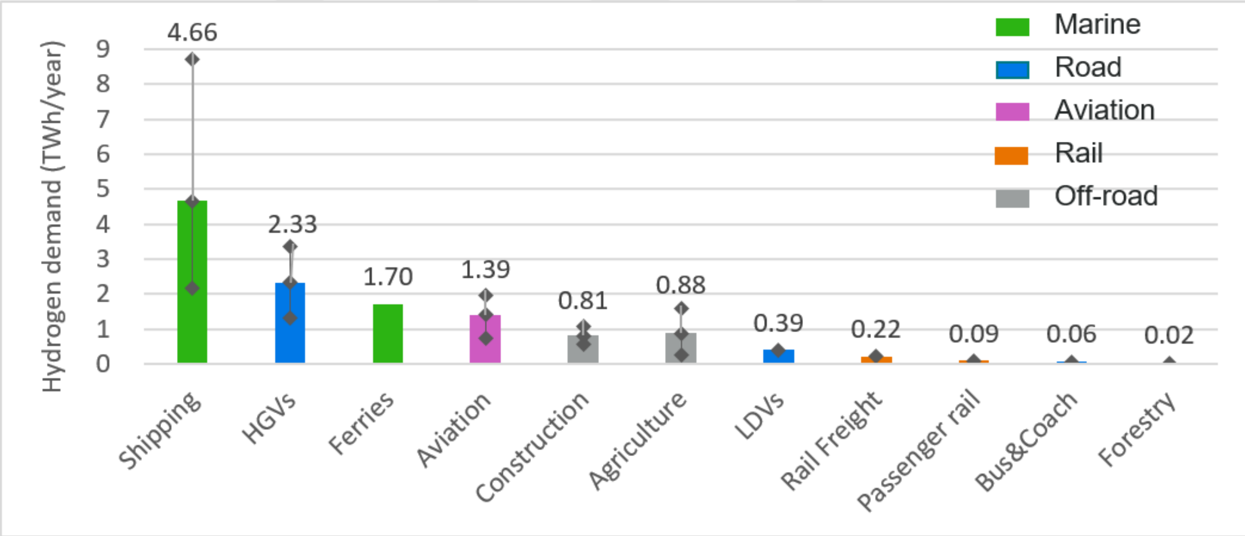
Until 2030, the demand for hydrogen is mainly from road transport, with a smaller demand from waterborne transport. After 2030, hydrogen demand increases, with the largest demand moving to the waterborne sector. Road continues to be a significant demand after this time. Off-road demand ramps up from 2035 but remains below road. Aviation demand begins from 2035, but remains below off-road, while rail remains the smallest sector (other than space, which currently shows minimal demand). The total median demand of around 12.5TWh by 2045 is equivalent to around 2.3GW of electrolyser capacity, assuming 70% efficiency at 90% load factor.

Figure 3-2 Aggregated sector hydrogen demand to 2045 in the **medium** scenario, along with total estimates for low and high demand scenarios in GWh demand and kilotonne of hydrogen*.



Note: a lower heating value for hydrogen was used (120 MJ/kg hydrogen) to calculate kt hydrogen

Figure 3-3 Individual sector hydrogen demand estimates for all uptake scenarios in 2045



In 2045, shipping is the most significant demand for hydrogen, being almost double that for HGVs. Note however that most of this demand will be for ammonia, with only around 900GWh being for pure hydrogen. HGVs are predicted to be the second greatest individual consumer, followed by ferries and aviation, which have similar demand values. Construction and agriculture have similar demands, though agriculture has a large uncertainty. Light duty vehicles are not expected to be a significant demand, while rail, bus & coach and forestry have negligible demands.

4. MAPPING

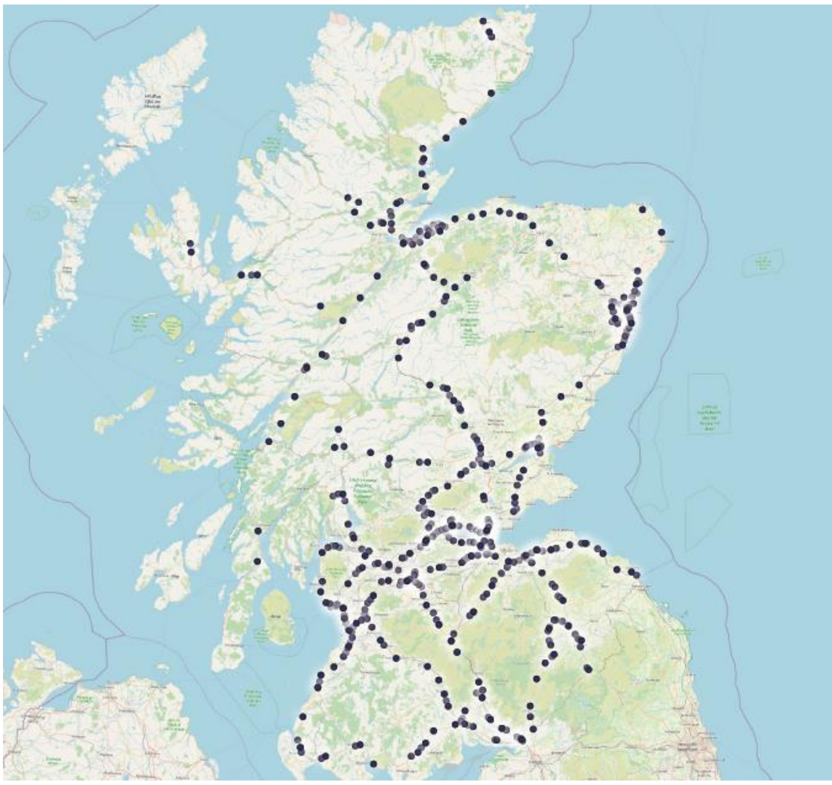
Hydrogen's difficult handling properties means that consuming hydrogen close to the point of production will always be the most efficient and often cost-competitive transport option. The future of hydrogen production will therefore be decentralised initially, and hydrogen trade will be regional until pipeline infrastructure and conversion to derivatives are developed to enable exports. Understanding where those needs are likely to be can help developers and public decision makers to know where the best domestic opportunities are. The mapping exercise aims to support this.

4.1 ROAD

4.1.1 Data apportionment methodology

For light-duty vehicles (cars and vans) the hydrogen demand data was geospatially disaggregated using population estimates as a proxy for vehicle registration locations (SpatialDataScotland, 2021). The mapping analysis is provided to Scotland's Intermediate Zone Boundaries (equivalent to middle layer super output areas, MSOAs, in England and Wales). There are 1,279 Intermediate Zones covering the whole of Scotland. It is anticipated that the majority of LDV refuelling would be undertaken in an area near to the registration location (i.e. users' private property) of the vehicle.

Figure 4-1 Traffic count data locations used for the bus, coach and HGVs hydrogen demand geospatial disaggregation (mainland Scotland)



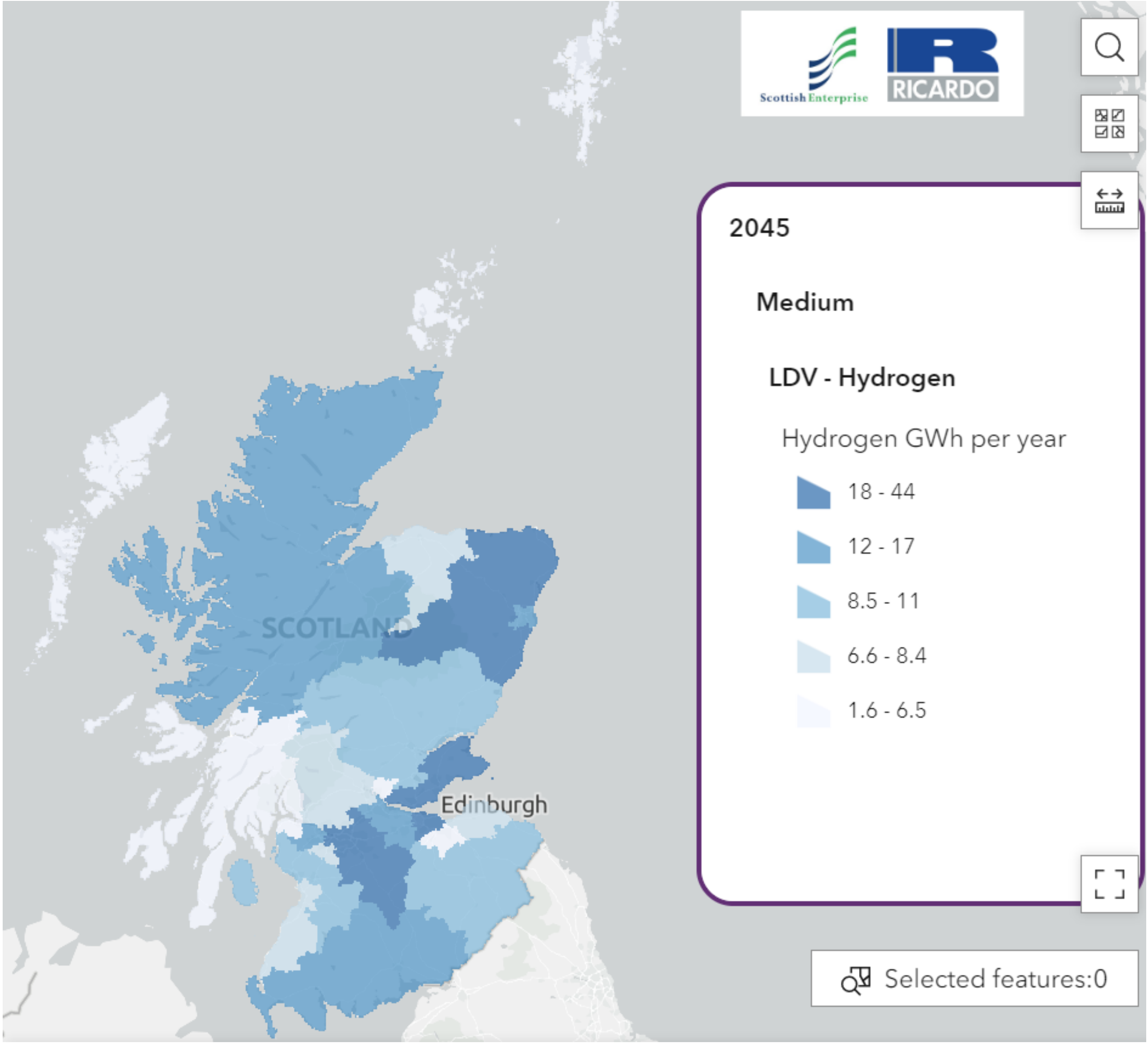
For buses and coaches, the hydrogen demand was apportioned geographically based on traffic count data received from Transport Scotland (Transport Scotland, 2023a). This traffic data provides an indication for the movements of buses and coaches within Scotland, and the hotspots of vehicle traffic. This gives an indication of likely demand for refuelling. Figure 4-1 shows the locations of the traffic count data used in the geospatial disaggregation of hydrogen demand.

A similar approach was used for HGVs accounting for the traffic count data as a proxy for where vehicles are likely to refuel in a future hydrogen scenario. However, previous research has indicated that the majority of HGV (hydrogen) refuelling will likely be undertaken at the vehicle's depot (70-90%), with the remaining (10-30%) being refuelling *en route* (National Grid, 2022). To complement the traffic count data in the mapping business registration locations were used as a proxy for depot locations of HGVs (ONS, nomis, 2021). Local unit registration locations for transport & storage, wholesale and motor trade companies were used at an Intermediate Zone boundary level as a proxy for potential depot locations. The total demand for HGV hydrogen refuelling was calculated using 20% of demand for *en route* refuelling from the traffic count data and the further 80% of demand was apportioned based on total local unit registrations of companies likely operating HGVs.

4.1.2 Hydrogen demand mapping results

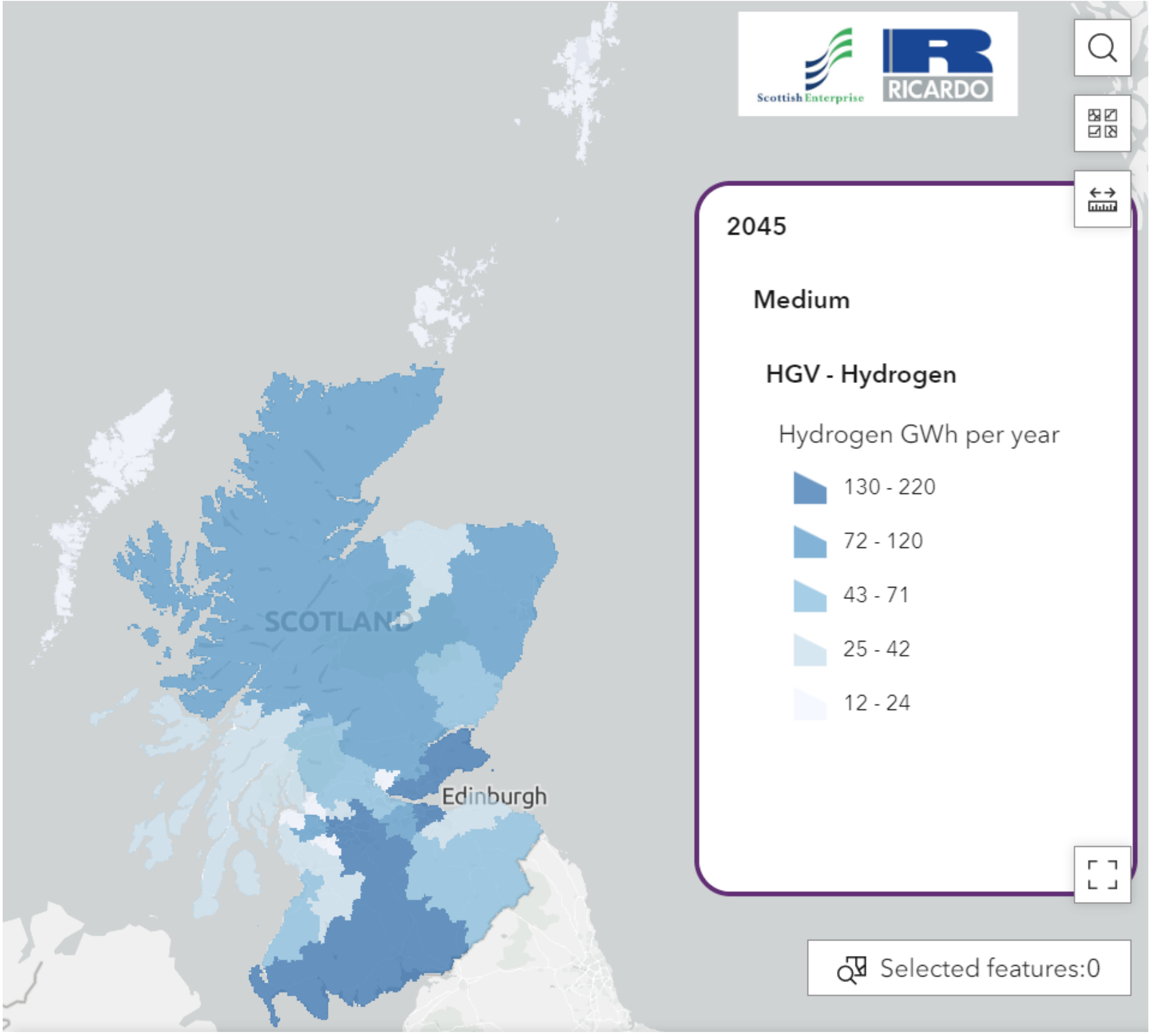
The largest potential hydrogen demand from LDVs in 2045 is located around the Central Belt (Edinburgh and Glasgow) in Scotland (Figure 4-2). This is to be expected, as these regions have higher populations, and therefore more likely to have vehicle ownership and usage compared to the other regions in Scotland.

Figure 4-2 Hydrogen demand (GWh/year) in 2045 for the LDV sector under the medium scenario



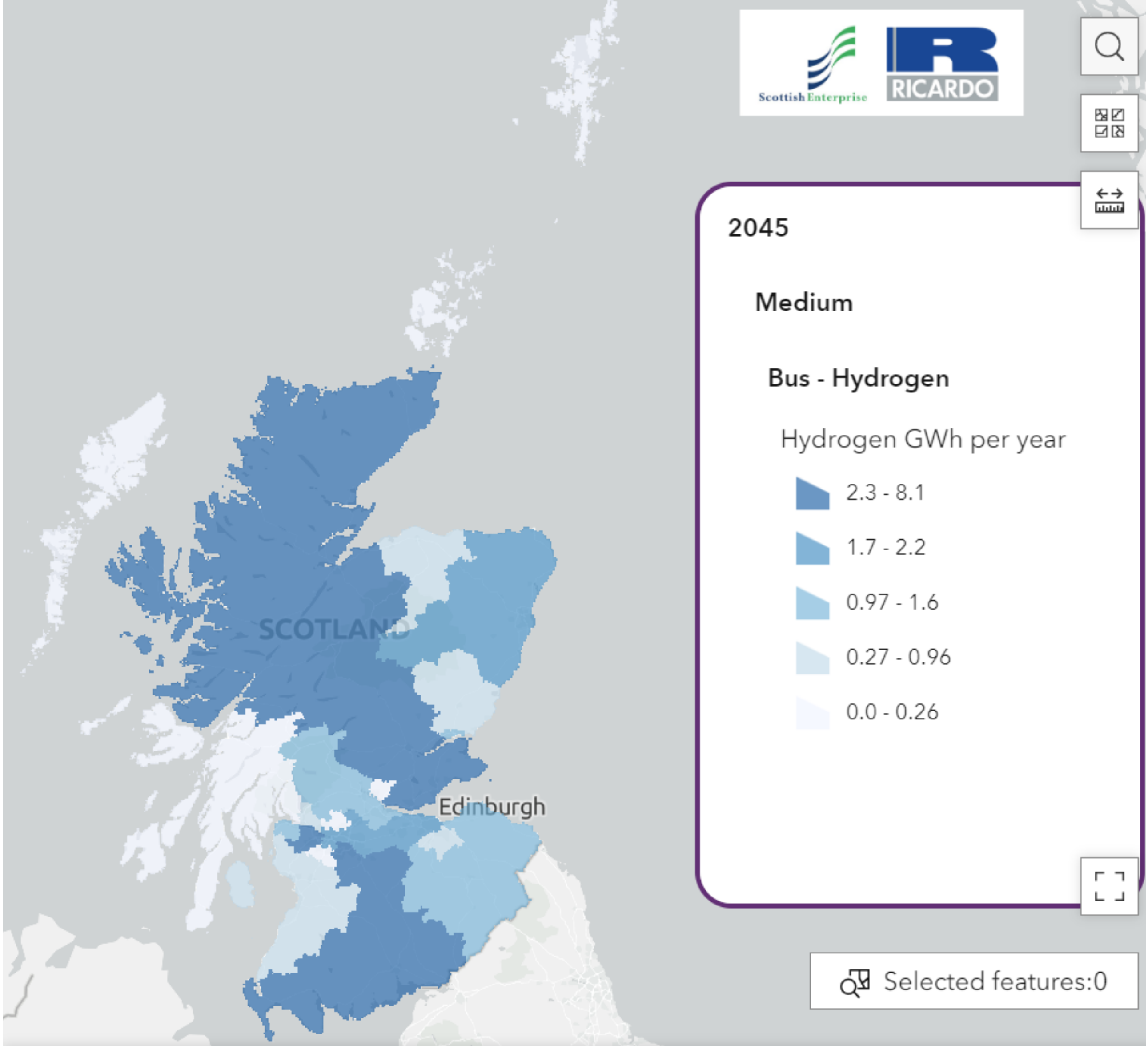
The geographical disaggregation of HGV hydrogen demand in Scotland is similar to the LDV disaggregation (Figure 4-3), with the highest demand regions being around the Central Belt of mainland Scotland. This is a result of potential HGV depots in these areas, along with some hydrogen refuelling expected along the major road network in Scotland.

Figure 4-3 Hydrogen demand (GWh/year) in 2045 for the HGV sector under the medium scenario



The hydrogen demand for buses shows a different geospatial disaggregation compared to LDVs and HGVs (Figure 4-4). This is based on the use of traffic count data to estimate hydrogen refuelling demand for buses as locations of bus depots or bus garages were not available. The greatest hydrogen demand (at a regional level) for buses and coaches is in the Dundee and St Andrews area, with high demand also showing in the south west of Scotland as a result of coach traffic along the A74(M). It should be noted that as the demand for buses and coaches is low (in comparison to other sectors), there is limited variation in hydrogen demand between the regions in absolute terms.

Figure 4-4 Hydrogen demand (GWh/year) in 2045 for the bus and coach sector under the medium scenario



4.2 RAIL

4.2.1 Data apportionment methodology

The key rail corridors between Glasgow and Edinburgh are mostly electrified (i.e. has overhead electrified line), and therefore will continue to utilise electric traction in future for passenger rail. As described under the passenger rail demand scenarios, only a few key corridors are potentially suitable for hydrogen traction in future. The key depot locations (Figure 4-5) were used as likely hydrogen refuelling locations for both passenger and freight demand. The passenger demand was allocated between the key passenger depots along the potential routes converted to hydrogen (Far North, West Highland, Stranraer services and Inverness to Aberdeen), assuming that there is an even distribution of hydrogen refuelling demand at the start and end of each corridor.

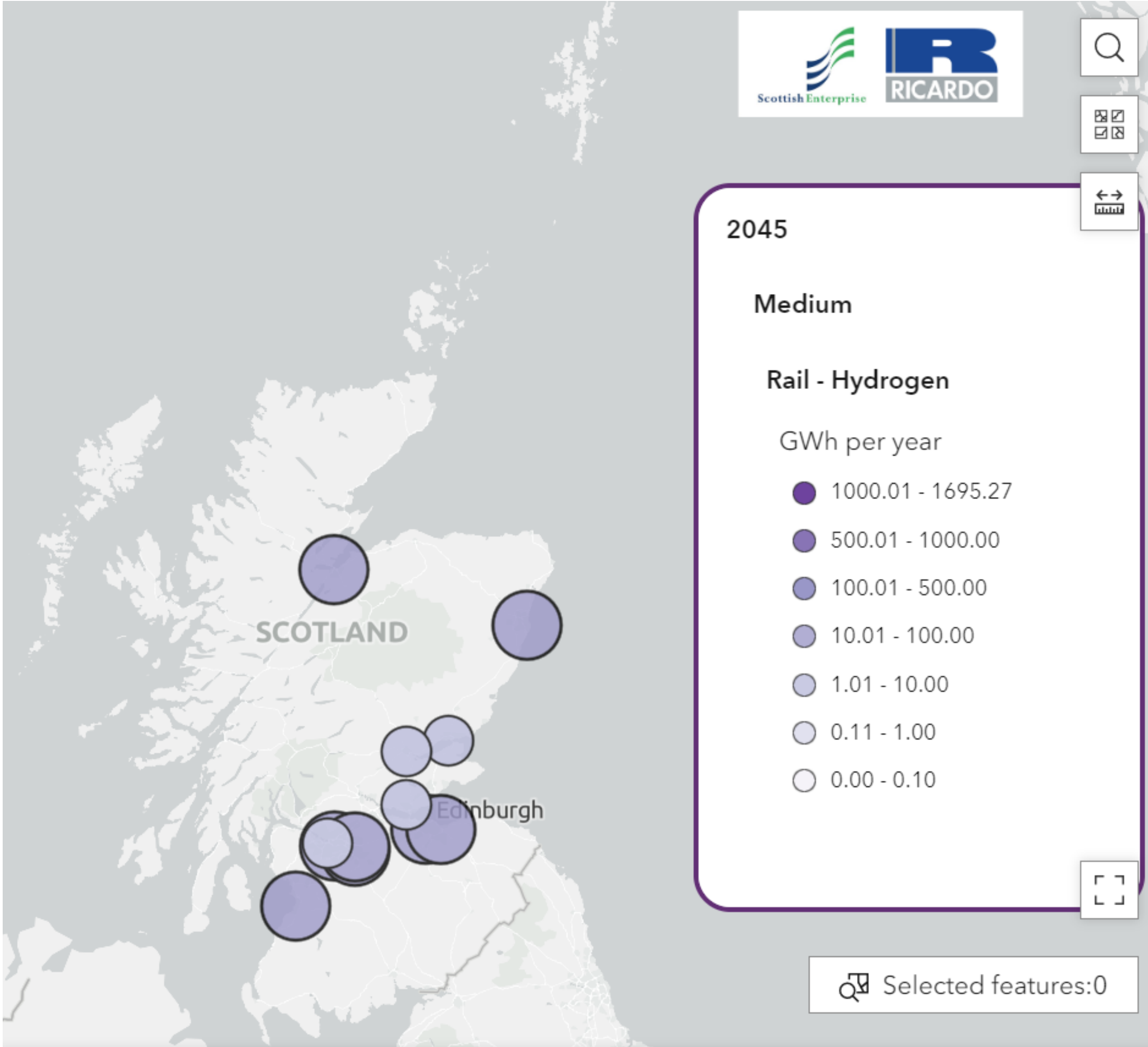
Rail freight locomotives are likely to move around the network, maintaining a ‘go anywhere’ capability and not restricted to a particular line. In the UK, the core rail freight network covers Edinburgh and Glasgow only (from routes in Scotland) and is responsible for 80% of the total rail freight demand (Ricardo, 2020). As the core network accounts for 80% of rail freight demand in the UK, 80% of total hydrogen refuelling demand from rail freight locomotives was assigned to the freight depots along the core freight network (i.e. near Glasgow and Edinburgh), with the remaining 20% evenly distributed to the remaining rail freight depots across Scotland.

Figure 4-5 Key rail depots (passenger and freight) used for rail hydrogen demand geospatial disaggregation

4.2.2 Hydrogen demand mapping results

The highest hydrogen demand for rail is located in Inverness (Figure 4-6). This is a result of both passenger and freight (hydrogen) demand being high in this area. There is also high hydrogen demand expected around Edinburgh and Glasgow as a result of these depots being along the core freight corridors. Passenger lines are mostly electrified around the Central Belt from Edinburgh and Glasgow, and therefore passenger demand for hydrogen rail is limited in these locations, and the demand is mostly a result of the freight demand.

Figure 4-6 Hydrogen demand (GWh/year) in 2045 for the rail sector under the medium scenario



4.3 SHIPPING

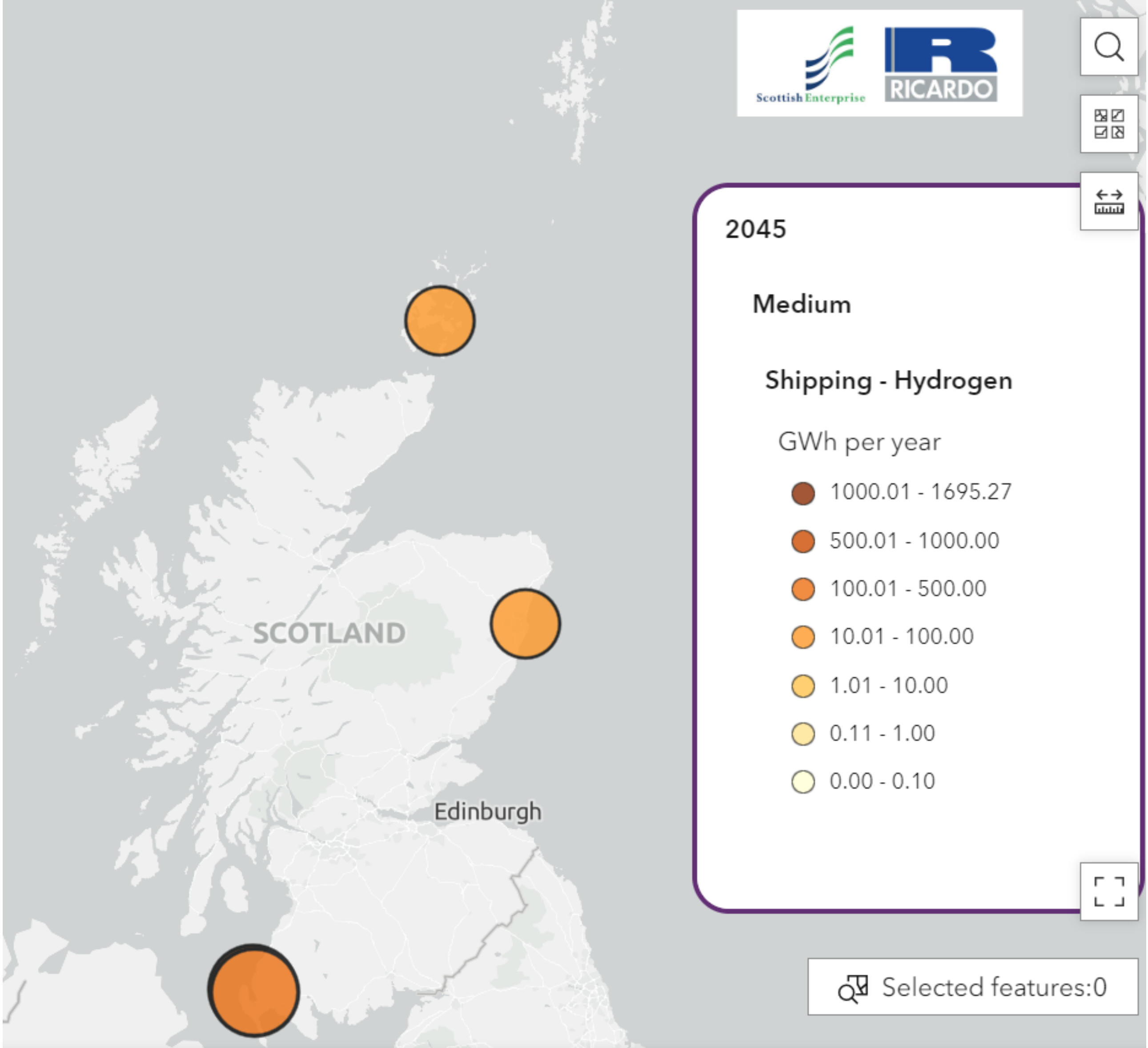
4.3.1 Data apportionment methodology

The shipping industry bunker at the same ports where they deliver or collect freight. The location of shipping ports have been identified and linked with port level statistics published by the Department for Transport (Department for Transport, 2023). Incoming and outgoing freight tonnage was selected as a proxy to apportion the national fuel requirements of the maritime sector. For hydrogen, this was limited to the freight tonnage being transported by domestic Roll-on Roll-off transport.

4.3.2 Hydrogen demand mapping results

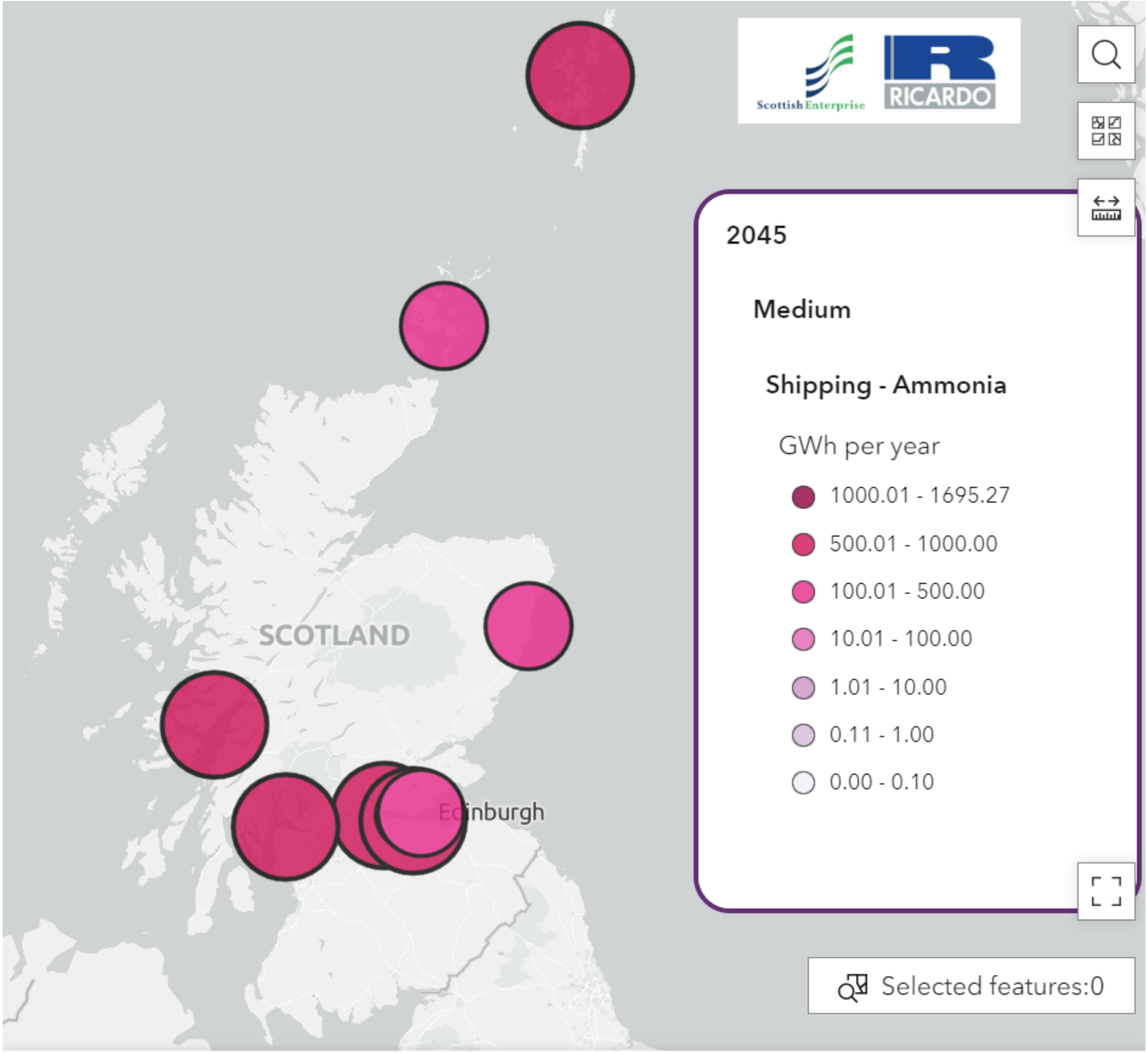
The largest hydrogen demand for the shipping sector by 2045 is located at Cairnryan port (Figure 4-7). This is a result of Cairnryan having a large freight tonnage transported by domestic Roll-on-Roll-off transport. For this hydrogen scenario, Aberdeen and Orkney also have a demand for hydrogen, whilst the other reports are limited in the potential hydrogen demand in 2045.

Figure 4-7 Hydrogen demand (GWh/year) in 2045 for the shipping sector under the medium scenario



Ammonia demand (Figure 4-8) is somewhat opposite to hydrogen, with Cairnryan port having a limited ammonia demand expected by 2045. The largest ammonia demand in 2045 is located at Grangemouth port, as this port has a substantial freight tonnage moved. Demand for ammonia in 2045 is also high at Clyde, Glensanda and Houndpoint on mainland Scotland. Sullom Voe port in the Shetland Islands can also be expected to have a high demand for ammonia in 2045.

Figure 4-8 Ammonia demand (GWh/year) in 2045 for the shipping sector under the medium scenario



4.4 FERRIES

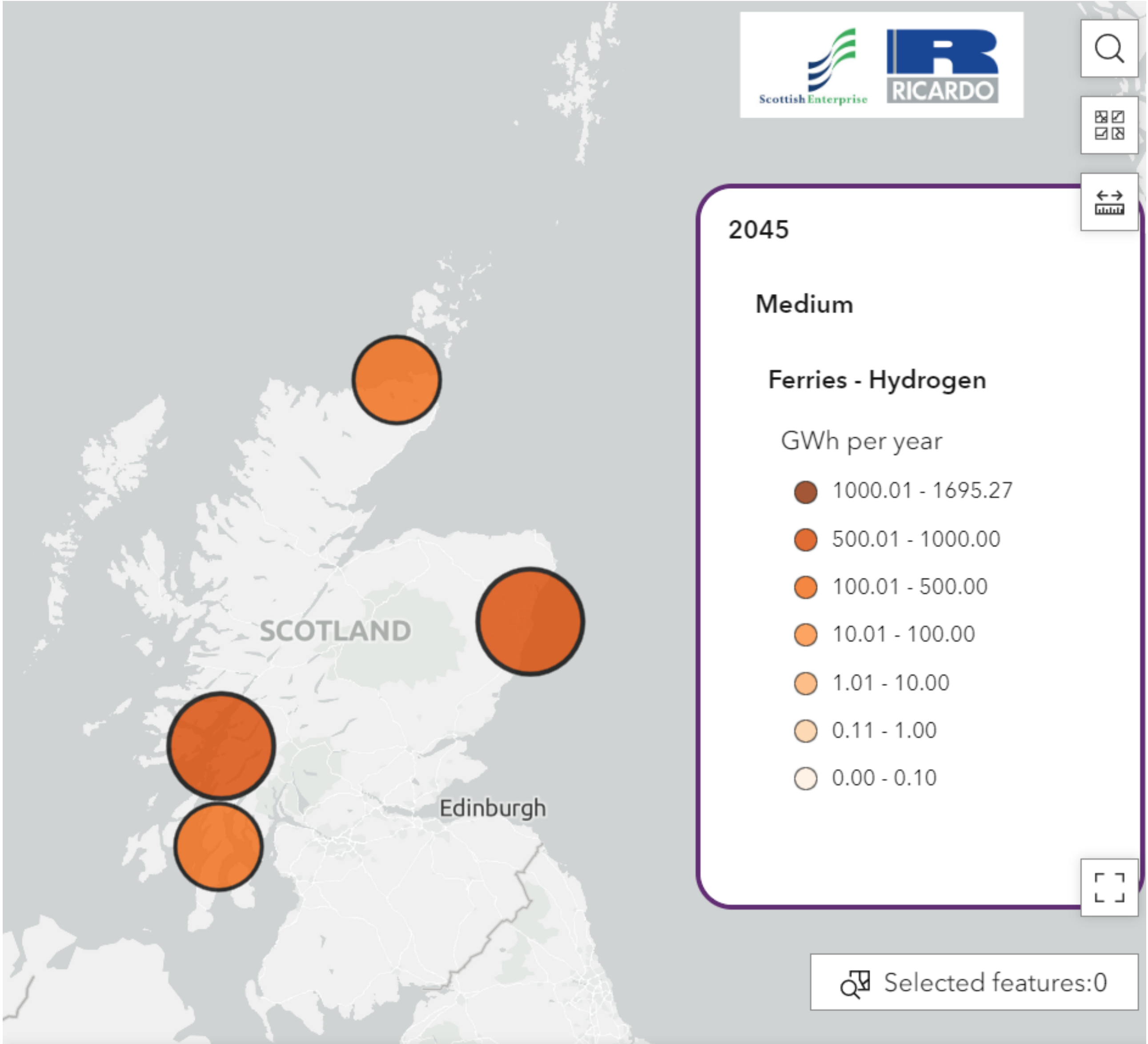
4.4.1 Data apportionment methodology

Ferries refuel at the largest port of the journey. The geographical location of ferry ports has been identified, along with the total length of journey, approximate number of crossings per year, and tonnage of vessel. The forecasted hydrogen demand for individual ports has been calculated using the individual ferry route data collected by Ricardo and statistics published by Transport Scotland (Transport Scotland, 2022). This methodology assumes that all crossings over 40km will use hydrogen fuel with the exception of large ferries between Cairnryan and Loch Ryan to Northern Ireland, that are assumed to use ammonia.

4.4.2 Hydrogen demand mapping results

The greatest hydrogen demand is shown for the port of Aberdeen as it connects Scotland to the Shetland Islands and Orkney Islands. The next largest demand is the port of Oban, which has a dedicated ferry terminal, and lastly the port of Scrabster.

Figure 4-9 Hydrogen demand (GWh/year) in 2045 for the ferries sector under the medium scenario



4.5 AVIATION

4.5.1 Data apportionment methodology

Commercial aviation will refuel at the airports they are contracted to operate to and from. The location of commercial airports of Scotland have been identified and linked to statistics derived by the Civil Aviation Authority and published on the Transport Scotland website (Transport Scotland, 2019). Domestic Air Traffic Movements (ATM) of each airport were used as a proxy for apportioning hydrogen demand between them. This is because hydrogen for aviation's best use case is for short-medium journeys typical of domestic and neighbouring European flights.

Longer flights will require SAFs like biofuels and e-kerosene. Therefore, the same methodology was followed but with International ATMs as its proxy.

4.5.2 Hydrogen demand mapping results

For both hydrogen (Figure 4-10) and e-kerosene (Figure 4-11) the demand is highest in Glasgow and Edinburgh airports. This is due to these airports having high activity compared to the other airports in Scotland.

Figure 4-10 Hydrogen demand (GWh/year) in 2045 for the aviation sector under the medium scenario

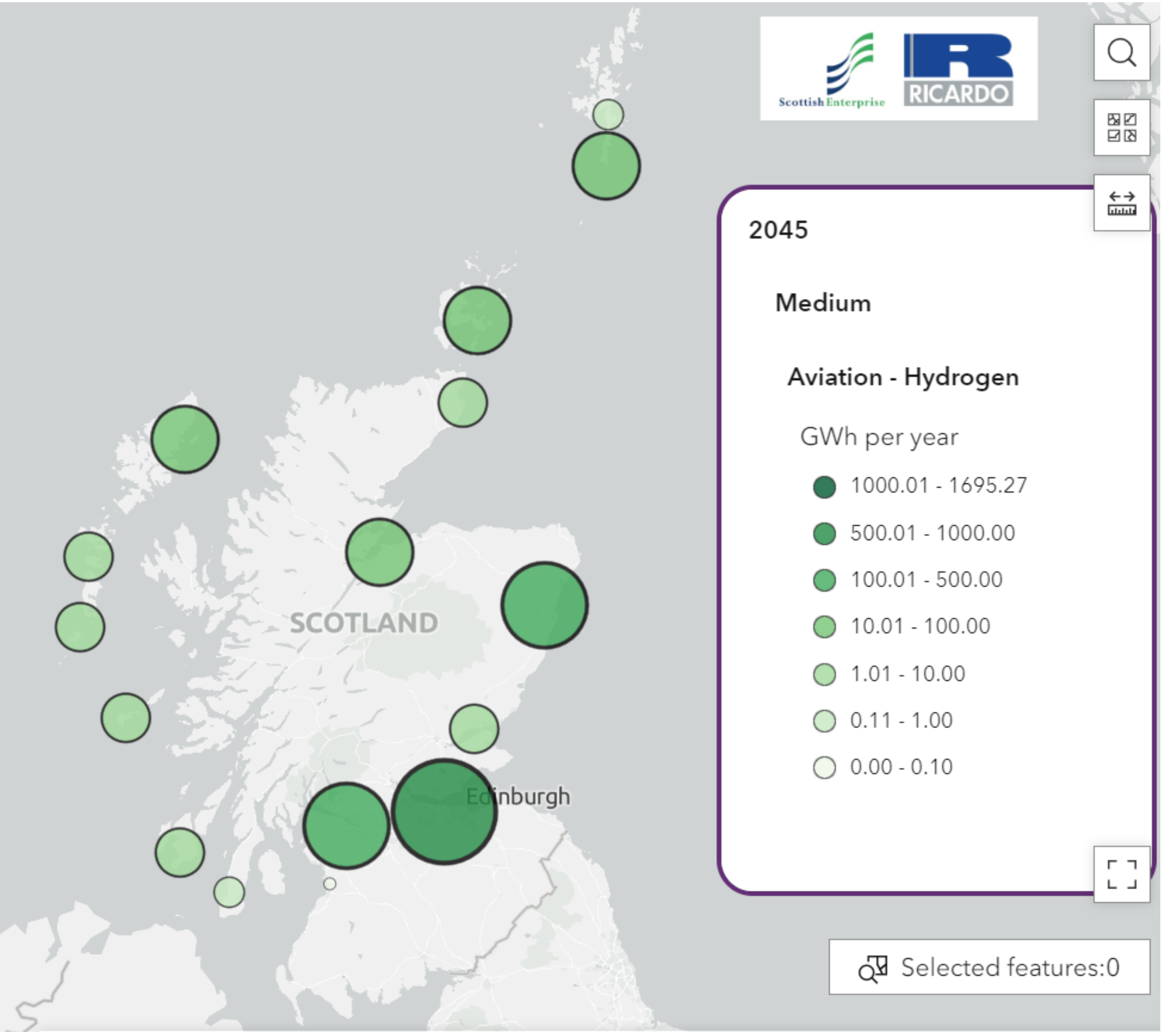
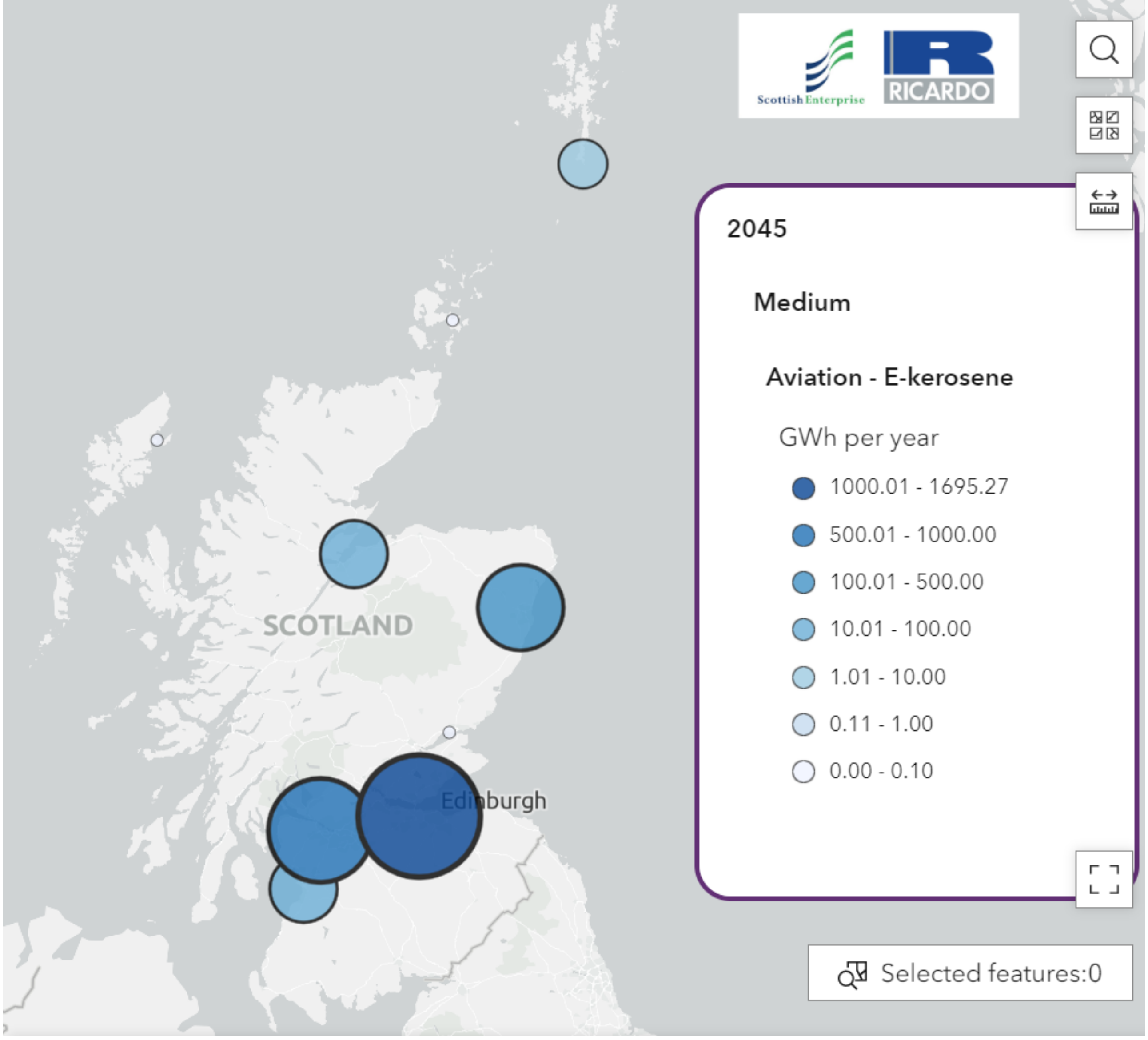


Figure 4-11 e-kerosene demand (GWh/year) in 2045 for the aviation sector under the medium scenario



5. CONCLUSIONS

Hydrogen has a role to play in decarbonising parts of the transport sector, particularly where electrification cannot serve operational requirements. Fuel cell technologies are mature and commercialised but have not yet experienced growth in adoption. The primary reason for this is due to vehicle cost and limited access to refuelling infrastructure. As the market scales up these barriers will shrink. However, the fuel costs of hydrogen are expected to keep the total cost of ownership of fuel cell vehicles higher than battery electric vehicles.

The potential demand of hydrogen in the transport sector for this report was informed by the Transport Scotland study entitled “Zero Emission for Transport Report: National Demand Forecasts for Electricity and Hydrogen”. For each sector, three scenarios were selected to reflect the high, medium and low scenarios of hydrogen uptake. New methodologies were developed to provide forecasts for specific shipping routes, synthetic kerosene for aviation and the off-road sector.

The total demand of the medium scenario was estimated at 12.5 TWh/year by 2045. This figure is equivalent to around 2.3GW of electrolyser capacity[3] , so while domestic transport it cannot be expected to fulfil demand for the 45GW of installed capacity envisioned the Scottish Government’s Hydrogen Action Plan (2023), transport will be a key enabler in the short-term and an important customer in the long term.

It must be stressed that these figures are not meant as predictions, but as prompts for market engagement and enablement. There is significant uncertainty around the decarbonisation paths that transport will follow.

Until 2030, the demand for hydrogen is mainly from road transport, with a smaller demand from waterborne transport. After 2030, hydrogen demand increases, with the largest demand moving to the waterborne sector. Road continues to be a significant demand after this time. Off-road demand and aviation demand ramps up from 2035 but both remain below road. Rail remains the smallest sector (other than space, which currently shows minimal demand).

Hydrogen will especially support hard-to-decarbonise sectors such as international shipping and aviation. Shipping requires energy dense, compact fuels that do not impede on freight load capacity. Aviation additionally requires light fuels to maximise in-flight efficiency. These can come in the form of hydrogen-derivative fuels such as ammonia, synthetic methanol and synthetic kerosene. Ferries that have a schedule and travel short, fixed routes are better suited for hydrogen, while the shortest routes can use electricity.

On land, hydrogen is expected to play a role where electricity cannot reach, whether that be due to insufficient electric vehicle range, short time availability for refuelling or the cost and availability of electricity infrastructure. Heavy duty vehicles, including road freight and refuse collection vehicles, may be suited to hydrogen as they need to travel long-distances or to rural locations, and some busses are expected to operate 24/7 without the opportunity to recharge.

Off-road sectors face similar challenges to on-road. The temporary nature of construction means that there is a limited investment proposition for implementing electric infrastructure. Agricultural practices occur in rural environments, often at the very extreme ends of the power grid, and forestry in no-grid environments. To solve these challenges, mobile hydrogen refuellers are being developed which can provide an all in-one transportable solution.

The main driver to adopt hydrogen vehicles is the national regulatory push to decarbonise. This is supported by further drivers such as the beginning of restrictions on the sale of new combustion engine vehicles from 2030, tax breaks and introduction of clean air zones by local government. There are also business lead activities such as net zero objectives and sustainable procurement practices.

In Scotland, the public sector could consider developing further policies and support schemes alongside the private sector that enable the most efficient decarbonisation options for transport. This could involve coordinated agreement on the key hydrogen refueling spots within Hydrogen Hubs, innovation to reduce technology costs, stimulating new skills to manufacture or maintain hydrogen vehicle components in Scotland, and the funding of large scale infrastructure improvements to ports, harbours and airports which reflect the industry’s desired low-carbon fuels of the future.

[3] Assuming 70% efficiency at 90% load factor.

6. REFERENCES

Aberdeen City Council, 2022. *Aberdeen City Council adds UK's first hydrogen fuel cell waste truck to the fleet.* [Online]
Available at: https://www.aberdeencity.gov.uk/news/aberdeen-city-council-adds-uks-first-hydrogen-fuel-cell-waste-truck-fleet
[Accessed Feb 2023].

Advanced Motor Fuels, 2020. *Ammonia Application in IC Engines,* Paris: International Energy Agency.

Airbus, 2022. [Online]
Available at: https://www.airbus.com/en/newsroom/press-releases/2022-11-airbus-teams-up-to-advance-green-hydrogen-availability-at-airports

AlexanderDennis, 2023. *Enviro400FCEV.* [Online]
Available at: https://www.alexander-dennis.com/products/double-deck-buses-2-axle/enviro400fcev/
[Accessed Feb 2023].

Anon., n.d. [Online]
Available at: https://www.heraldscotland.com/business_hq/23264716.scotland-boosts-worlds-largest-hydrogen-electric-aircraft/

Arup, 2016. *Five minute guide to Hydrogen,* London: Arup.

ATI, 2022. *Aerospace Technology Institute.* [Online]
Available at: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf

Ballard, 2023. *Full powertrain integration capability to accelerate the adoption of fuel cell mobility.* [Online]
Available at: https://www.ballardmotivesolutions.com/
[Accessed Feb 2023].

BEIS, 2022. *Greenhouse gas reporting: conversion factors 2022,* London: Department for Business, Energy & Industrial Strategy.

Blain, L., 2022. *New Atlas.* [Online]
Available at: https://newatlas.com/aircraft/aviation-h2-ammonia-fuel-jet-aircraft/

Climate Exchange, 2023. *Decarbonisation of mobile agricultural machinery in Scotland – an evidence review,* Edinburgh: Climate Exchange.

Climate x Change, 2022. *Decarbonisation of mobile agricultural machinery in Scotland – an evidence review,* s.l.: s.n.

CommercialFleet, 2021. *Hydrogen Renault Master Van H2-Tech unveiled by Hyvia.* [Online]
Available at: https://www.commercialfleet.org/news/van-news/2021/10/15/hydrogen-renault-master-van-h2-tech-unveiled-by-hyvia
[Accessed Feb 2023].

DEFRA, 2004. *Non-Road Mobile Machinery Usage, Life and Correction Factors,* s.l.: s.n.

Department for Transport, 2022. *£200 million boost to rollout of hundreds more zero-emission HGVs.* [Online]
Available at: https://www.gov.uk/government/news/200-million-boost-to-rollout-of-hundreds-more-zero-emission-hgvs
[Accessed Feb 2023].

Department for Transport, 2023. *Port and domestic waterborne freight statistics: data tables (PORT).* [Online]
Available at: https://www.gov.uk/government/statistical-data-sets/port-and-domestic-waterborne-freight-statistics-port
[Accessed 21 03 2023].

DfT, 2022. *Energy and environment: data tables,* London: Department for Transport.

DfT, 2022. *Port and domestic waterborne freight statistics: data tables (PORT),* London: Department for Transport.

DoE, 2020. *Sustainable Aviation Fuel: Review of Technical Pathways,* s.l.: Energy, U.S. Dept of.

DoT, 2022. *UK Gov.* [Online]
Available at:
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1100050/sustainable-aviation-fuels-mandate-summary-of-consultation-responses-and-government-response.pdf

European Commission, 2022. *ENABLing cryogEnic Hydrogen based CO2 free air transport (ENABLEH2).* [Online]
Available at: https://cordis.europa.eu/article/id/428900-lh2-powered-aircraft-are-coming-but-when
[Accessed 06 03 2023].

Faun-Zoeller, 2023. *Bluepower.* [Online]
Available at: https://faun-zoeller.co.uk/bluepower/
[Accessed Feb 2023].

Flexport, 2022. [Online]
Available at: https://www.flexport.com/blog/decommissioned-planes-salvage-value/#:~:text=On%20average%2C%20an%20aircraft%20is,before%20metal%20fatigue%20sets%20in.

FuelCellsWorks, 2021. *Citroen unveils the 400-km hydrogen fuel cell van.* [Online]
Available at: https://fuelcellsworks.com/news/citroen-unveils-the-400-km-hydrogen-fuel-cell-powered-jumpy-van/
[Accessed Feb 2023].

FuelCellTrucks, 2020. *HYUNDAI: 1.600 H2 Xcient trucks in Switzerland.* [Online]
Available at: https://fuelcelltrucks.eu/project/hyundai-1-600-h2-xcient-trucks-in-switzerland/
[Accessed Feb 2023].

glpautogas, 2023. *Hydrogen Stations in UK United Kingdom.* [Online]
Available at: https://www.glpautogas.info/en/hydrogen-stations-united-kingdom.html
[Accessed Feb 2023].

Gov UK, 2018. *Red diesel: call for evidence.* [Online]
Available at: https://www.gov.uk/government/consultations/red-diesel-call-for-evidence/red-diesel-call-for-evidence

Gov UK, 2022. *Energy and environment: data tables (ENV).* [Online]
Available at: https://www.gov.uk/government/statistical-data-sets/energy-and-environment-data-tables-env

Herald, T., 2023. [Online]
Available at: https://www.heraldscotland.com/business_hq/23264716.scotland-boosts-worlds-largest-hydrogen-electric-aircraft/

HM Treasury, 2018. *Consultation outcome - Red diesel: call for evidence.* [Online]
Available at: https://www.gov.uk/government/consultations/red-diesel-call-for-evidence/red-diesel-call-for-evidence
[Accessed 06 03 2023].

HVS, 2023. *ZERO EMISSION HYDROGEN-ELECTRIC COMMERCIAL VEHICLES.* [Online]
Available at: https://www.hvs.co.uk/
[Accessed March 2023].

HYTransit, 2018. *HYTRANSIT.* [Online]
Available at: https://www.fuelcellbuses.eu/projects/hytransit
[Accessed Feb 2023].

Hyundai, 2020. *Hyundai XCIENT Fuel Cell Heads to Europe for Commercial Use.* [Online]
Available at: https://www.hyundai.news/eu/articles/press-releases/hyundai-xcient-fuel-cell-heads-to-europe-for-commercial-use.html
[Accessed Feb 2023].

Hyzon, 2023. *HYDROGEN-POWERED Fuell Cell Electric Vehicles.* [Online]
Available at: https://www.hyzonmotors.com/vehicles
[Accessed Feb 2023].

ICCT, 2022. [Online]
Available at: https://theicct.org/publication/aviation-global-evo-hydrogen-aircraft-jan22/

Interreg, 2023. *The worldwide overview of heavy-duty trucks running on hydrogen..* [Online]
Available at: https://fuelcelltrucks.eu/
[Accessed Feb 2023].

Komatsu, 2021. *Decarbonization Approaches Construction Equipment.* [Online]
Available at: https://www.energy.gov/sites/default/files/2021-12/923-2-mission-innovation-komatsu.pdf
[Accessed 21 03 2023].

LondonReconnections, 2021. *The Second Coming of Hydrogen? London's hydrogen buses.* [Online]
Available at: https://www.londonreconnections.com/2021/the-second-coming-of-hydrogen-londons-hydrogen-buses/
[Accessed Feb 2023].

NAEI, 2022. *Devolved administration emission inventories.* [Online]
Available at: https://naei.beis.gov.uk/data/das?view=by-source

Nanosun, 2023. *Looking to fuel a hydrogen powered vehicle fleet?.* [Online]
Available at: https://www.nanosun.co.uk/pioneer/pioneer-hydrogen-refuelling-station
[Accessed Feb 2023].

National Grid, 2022. *New National Grid-led analysis shows expanding Government's electric vehicle Rapid Charging Fund (RCF) would accelerate the decarbonisation of all road transport.* [Online]
Available at: https://www.nationalgrid.com/new-national-grid-led-analysis-shows-expanding-governments-electric-vehicle-rapid-charging-fund-rcf
[Accessed Feb 2023].

ONS, nomis, 2021. *official census and labour market statistics.* [Online]
Available at: https://www.nomisweb.co.uk/
[Accessed Feb 2023].

ORR, 2022. *Table 1310 - Freight moved by commodity,* s.l.: Office of Rail and Road.

Patterson, T., 2022. [Online]
Available at: https://www.flyingmag.com/boeing-and-airbus-a-stark-contrast-on-hydrogen/

RAF, 2021. [Online]
Available at: https://www.raf.mod.uk/news/articles/a-net-zero-raf-by-2040/

Ricardo, EDF, 2021. *South Africa: fuelling the future for shipping,* Copenhagen: Global Maritime Forum.

Ricardo, 2020. *Decarbonisation and Air Quality Improvement: a Roadmap for the Rail Freight Industry (T1160 Report),* London: Rail Safety and Standards Board.

Ricardo, 2020. *Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA,* Brussels: European Commission.

Rolls-Royce, 2022. [Online]
Available at: https://www.rolls-royce.com/innovation/accel.aspx

RSSB, 2019. *T1145 - Options for Traction Energy Decarbonisation in Rail,* s.l.: s.n.

Smil, V., 2021. *IEEE.* [Online]
Available at: https://spectrum.ieee.org/electric-airplanes-wont-make-much-of-a-dent-in-air-travel-for-decades-to-come

Smith, J. a. J., 2020. *The joys of automatically referencing documents that you're allowed to reference.* [Online]
Available at: www.referencelocation.com

SMMT, 2021. *Glasgow City Council creates world's largest hydrogen RCV fleet.* [Online]
Available at: https://www.smmt.co.uk/2021/06/glasgow-city-council-creates-worlds-largest-hydrogen-rcv-

fleet/
[Accessed Feb 2023].

Solakivi, T., Paimander, A. & Ojala, L., 2022. Cost competitiveness of alternative maritime fuels in the new regulatory framework. *Transportation Research.*

SpatialDataScotland, 2021. *Intermediate Zone Boundaries 2011.* [Online]
Available at: https://www.spatialdata.gov.scot/geonetwork/srv/api/records/389787c0-697d-4824-9ca9-9ce8cb79d6f5
[Accessed Feb 2023].

Tevva, 2023. *Newsroom.* [Online]
Available at: https://www.tevva.com/en/news
[Accessed Feb 2023].

tppl, 2022. *St. Helens Council invests in OEM hydrogen fuel cell RCV via TPPL's Framework.* [Online]
Available at: https://www.tppl.co.uk/resources/latest-news/tppl-and-nepo-hgv-framework-supports-supply-of-hydrogen-fuel-cell-rcv/
[Accessed Feb 2023].

Transport Scotland, 2019. *Chapter 8: Air Transport.* [Online]
Available at: https://www.transport.gov.scot/publication/scottish-transport-statistics-no-39-2020-edition/chapter-8-air-transport/
[Accessed 21 03 2023].

Transport Scotland, 2020. *Carbon Account for Transport,* Glasgow: Scottish Government.

Transport Scotland, 2021. *Decarbonising the Scottish Transport Sector,* s.l.: s.n.

Transport Scotland, 2022. *Zero Emission Energy for Transport Report National Demand Forecasts for Electricity and Hydrogen,* Glasgow: Transport Scotland.

Transport Scotland, 2023a. *Statistics.* [Online]
Available at: https://www.transport.gov.scot/our-approach/statistics/
[Accessed 22 Feb 2023].

Transport Scotland, n.d. *Electrification programme.* [Online]
Available at: https://www.transport.gov.scot/projects/electrification-programme/electrification-programme/
[Accessed 06 03 2023].

UKH2Mobility, 2023. *Refuelling stations.* [Online]
Available at: https://www.ukh2mobility.co.uk/stations/
[Accessed Feb 2023].

University of St Andrews, 2022. *Scottish hydrogen train project on track to deliver climate targets.* [Online]
Available at: https://news.st-andrews.ac.uk/archive/scottish-hydrogen-train-project-on-track-to-deliver-climate-targets/
[Accessed March 2023].

WEF, 2022. [Online]
Available at: https://www.weforum.org/agenda/2022/12/aviation-net-zero-emissions/#:~:text=The%20aviation%20industry%20has%20adopted,on%20CO2%20emissions%20reduction%20measures.

WrightBus, 2023. *WELCOME TO THE WORLD OF NEXT-GEN TRANSPORT.* [Online]
Available at: https://wrightbus.com/en-gb/hydrogen-bus-streetdeck-hydrolinerFCEV
[Accessed Feb 2023].

ZeroAvia, 2020. [Online]
Available at: https://www.zeroavia.com/press-release-25-09-2020

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