TRANSPORT
SCOTLAND
CÒMHDHAIL ALBA

transport.gov.scot

Zero Emission Energy for Transport Report

National Demand Forecasts for Electricity and Hydrogen

Contents

Glossary

Air Traffic Movement – Landing or take-off of an aircraft operating a scheduled or non-scheduled service.

Ammonia – A compound of nitrogen and hydrogen (NH_3) which is typically used in fertilisers. However, there are future potential applications as a fuel source and a method for transporting and storing hydrogen.

Ammonia Engines – A combustion engine designed for use with Ammonia to provide propulsion.

Battery Electric Vehicles – Fully electric vehicles which use a rechargeable battery to store electricity and then power an electric motor. They are zero emission vehicles which do not generate any tailpipe emissions.

Blue Hydrogen – Hydrogen produced through reforming natural gas to produce hydrogen but with carbon capture and storage incorporated to capture CO_2 emissions.

Coaches – For the purpose of this analysis all privately owned or private hire vehicles are assumed to be coaches or minibuses. Coaches have been included in this section of the analysis. Minibuses are excluded as the energy trajectory for these is expected follow a trajectory similar to that of vans rather than that of buses and coaches.

Diesel Multiple Units – A multiple-unit train that is powered through diesel engines.

Eff – Efficiency.

Electric Aircraft – An aircraft that uses rechargeable batteries to store electrical energy and provide power to motors for propulsion. Different propulsion methods are still being researched and developed.

Electric-Battery Vessels – Ships powered by electric motors that are solely powered by stored electricity in rechargeable batteries.

Electric Ferries – Ferries that are powered by rechargeable batteries to provide the energy source for electric motors.

Electric Multiple Units – Trains consisting of multiple self-propelled carriages which utilise electrical energy as the power source.

Electric Train (Overhead) – Electric trains which use electrical energy supplied by overhead lines as the power source for electric motors.

Electric Train (Battery) – Trains powered by electric motors that rely solely on stored electrical energy in rechargeable batteries as the energy source.

Energy Density – Amount of energy stored in a given system or region of space per unit volume.

Freight Operating Companies (FOCs) – Freight trains operating on Anglo-Scottish routes and those operating within Scotland.

Green Hydrogen – Hydrogen produced through the electrolysis of water using renewable energy sources.

Higher Heating Value (HHV) - The higher heating value (also known as gross calorific value or gross energy) of a fuel is defined as the amount of heat released by a specified quantity (initially at 25°C) once it is combusted and the products have returned to a temperature of 25°C, which considers the latent heat of vaporization of water in the combustion products.

Hydrogen Aircraft – An aircraft that uses stored hydrogen to provide propulsion through either combustion or an electrochemical reaction within a fuel cell to power a motor. To achieve the energy density required it may be stored as liquid hydrogen.

Hydrogen Electric vehicle – Fully electric vehicle which uses stored hydrogen, typically within a fuel cell, to provide motive power. They may also include a smaller battery for electrical load balancing.

Hydrogen Ferries – Ferries that are powered by stored hydrogen. Typically, this will be used to create electrical energy within a fuel cell but could also incorporate the combustion of hydrogen to generate power.

Hydrogen Fuel Cell – A hydrogen fuel cell converts hydrogen as a fuel into electrical energy through an electrochemical reaction. Aside from the electricity produced, the only output from the cell is water.

Hydrogen Train – Trains using hydrogen as a stored fuel as the power source. The technology is currently focussed on the use of hydrogen within fuel cells to generate electrical energy.

Internal Combustion Engine – Heat engine in which the ignition and combustion of the fuel occurs within the engine itself.

Low Carbon Hydrogen – Hydrogen produced by methods which generate low quantities of greenhouse gas emissions below a certain threshold. Common forms are electrolytic ‘green’ and ‘blue’ hydrogen from natural gas with carbon capture and storage.

Lower Heating Value (LHV) - The lower heating value (also known as net calorific value) of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C, which assumes the latent heat of vaporization of water in the reaction products is not recovered.

Narrow Body Aircraft – An aircraft with a single passenger aisle that can contain up to 6 seats across the width.

Network Rail – The owner and manager of most of the UK rail infrastructure. For the purpose of this report this refers to a small fleet of inspection and maintenance trains operating in Scotland.

OAG – Global travel data provider for airports, airlines and travel tech companies. For this report this refers to data on and air traffic movements from Scottish airports.

Other Train Operating Companies (TOCs) – Cross border services including those by Avanti West Coast, TransPennine Express, LNER and Serco Caledonian Sleepers.

Policy Scenario 3 - Rapid introduction of low and zero-emission technologies. Passenger, freight, and vehicle kilometres travelled are reduced through modal shift from cars and planes to public and active travel modes, and reduced travel demand through trip shortening (facilitated through measures such as 20-minute neighbourhoods) and trip avoidance (facilitated through measures such as teleconferencing).

Plug-in Hybrid Electric Vehicle – A vehicle with both an internal combustion engine and electric motor to provide power. They contain a rechargeable battery which can be plugged into the grid to be recharged.

Regional Aircraft – A smaller aircraft used for short-haul flights. They often travel from smaller regional airports for internal flights.

Scheduled Buses – Scheduled buses are those which run on a fixed route, to a fixed timetable and the service is available to the general public. For the purpose of this analysis, it is assumed that they are served by single or double decker buses and not by minibuses.

Shore Power – The provision of electric power when a ship is at shore whilst the main and auxiliary engines are shut down thus reducing emissions.

ScotRail – The brand name for all rail and commuter services in Scotland.

Sustainable Aviation Fuels – Biofuel used to power aircraft that has similar properties to conventional jet fuel but with a smaller carbon footprint.

Turboprop – An aircraft with a turbine engine that drives a propellor to provide propulsion. Typically, these aircraft are smaller in size and travel at lower speeds.

Ultra-Low Emission Vehicles – Vehicles that produce tailpipe CO_2 emissions below a certain threshold. Typically, this is less than 75 grams of CO_2 per kilometre travelled.

Wide Body Aircraft – A larger aircraft which is wide enough to contain two passenger aisles in the fuselage with seven or more seats across.

Zero Emission Vehicles – Vehicles that produce zero tailpipe CO_2 emissions or other pollutants.

Abbreviations

ATMs – Air Traffic Movements

BEIS – Department for Business, Energy and Industrial Strategy (UK)

BEMU – Battery Electric Multiple Unit

BEV – Battery Electric Vehicle

Calmac – Caledonian MacBrayne Ferries

DfT - Department for Transport (UK)

DMUs – Diesel Multiple Units

Dom – Domestic

DRS – Direct Rail Services

ECML - East Coast Mainline from Berwick-upon-Tweed

EEDI – Energy Efficiency Design Index

EMUs – Electric Multiple Units

ESTAs - Network Rail's Electricity Supply Tariff Areas

EV – Electric Vehicle

FOCs - Freight Operating Companies (Rail)

GHG – Greenhouse Gas Emissions

GW/h – Gigawatt / Hour

HEV – Hydrogen Electric Vehicle

HGV – Heavy Goods Vehicles

HHV – Higher Heating Value (of Hydrogen)

IATA - International Air Transport Association

ICAO - International Civil Aviation Organization

ICCT - International Council on Clean Transportation

ICE – Internal Combustion Engines

IMO – International Maritime Organisation

Intl – International

Km – Kilometres

kW/h – Kilowatt / Hour

LM – Average linear metres

LGV – Light Goods Vehicles

LHV - Lower Heating Value (of Hydrogen)

LNER – London and North Eastern Railway

MW/h – Megawatt / Hour

PHEV – Plug-in Hybrid Electric Vehicle

PS3 – Policy Scenario 3 as per the *Decarbonising the Scottish Transport Sector Final Report*

SAFs – Sustainable Aviation Fuels

STPR2 – Second Strategic Transport Projects Review

TAG – Transport Analysis Guidance (Data Book)

TOCs - Other Train Operating Companies

TW/h – Terawatt / Hour

TMfS:18 - Transport Model for Scotland 2018

Tool – Microsoft Excel Results Tool for ZEEfT National Forecasts

VRPD – Vessel Replacement Deployment Plan

WCML - West Coast Mainline from Carlisle

WTT - Network Rail’s Working Timetable

ZEEfT - Zero Emission Energy for Transport programme

Chapter 1: Overview

1.0 Introduction

Transport Scotland is committed to removing greenhouse gas emissions from the transport system*.* *The Climate Change (Emissions Reduction Targets) (Scotland) Act 2019* requires Scotland to reduce greenhouse gas emissions to net-zero by 2045, with an interim reduction target of 75% against 1990 levels by 2030.

According to the most recent editions of the *Scottish Greenhouse Gas Emissions Statistics*, the transport sector (including international aviation and shipping) accounts for approximately 29% of total emissions in Scotland, making decarbonising this sector critical to achieving these emission reduction targets. Scotland’s transport and energy systems are interdependent and dynamic which means decarbonisation requires a combination of public sector strategic planning at national and local levels, with flexibility for market forces to operate.

Transport Scotland commissioned Jacobs to develop national demand forecasts for potential scenarios for the future of electricity and hydrogen as part of its commitment to decarbonise the transport sector.

The details of this study are outlined in the following report and estimate annual total electricity and hydrogen demand for domestic or intra-Scotland transport including road, rail, maritime and aviation annually between 2022 and 2030, and for 2035, 2040 and 2045.

Six transport technology transition scenarios were modelled according to a combination of high, medium, and low electric and hydrogen uptake for each transport mode and within each transport mode where relevant. This approach was adopted for simplicity and flexibility to compare different scenarios easily.

Importantly, this work builds on other transport and energy demand forecasts already being undertaken or developed on behalf of Scottish Government. These include Scottish Whole System Energy Modelling due for completion in early 2022 and the most recent update of the Transport Model for Scotland (TMfS:18) in October 2021, amongst others.

The three-part approach was adopted for forecasting hydrogen and electricity demand for transport in Scotland:

1. **Transport Demand Baseline and Forecasting**
2. **Technology Transition Scenario Development and Modelling**
3. **Energy Demand Calculations and Analysis**

While the overarching process was consistent across all transport modes (1-3 above), the individual methods for forecasting transport demand varied according to data availability. For example:

- Transport demand - was calculated for road and rail using bottom-up approaches to determine annual distance travelled, while for maritime and aviation top-down approaches were more feasible based on fuel use - given time and data constraints of the project.
- Technology transition - the underlying electric and hydrogen uptake assumptions differed according to the type of vehicle, rolling stock, vessel, or aircraft relevant to the mode.
- Energy demand - although general parameters such as conversions from hydrogen to electricity, electrolyser efficiency and renewable utilisation are consistent across modes; different assumptions are used for energy consumption, density, and efficiency according to power train or fuel type as relevant.

The study’s results are a series of energy demand forecasts categorised by total electricity and hydrogen demand required for transport in each forecast year for six scenarios. These results are then broken down into further categories; by transport mode (road, rail, maritime and aviation) and individual types of vehicles, rolling stock, vessels, and aircraft bodies (as relevant).

This report is accompanied by a Microsoft Excel Results Tool (Tool) detailing the results which enables the exploration and comparison between scenarios in greater detail beyond what is included within this report. Additionally, it places the results in context, by comparing them to the expected renewable electricity and hydrogen generation capacity for each forecast year – according to current Scottish Government ambitions and policy commitments.

Overall, the study has been designed with the intention to inform the market of the range of possible demand scenarios for electricity and hydrogen demand for transport purposes in Scotland as part of a broader commitment to decarbonise the transport sector.

It is important to note that while supply side considerations such as capacity of the existing infrastructure to produce and distribute electricity and hydrogen are critical, they have not constrained the modelling process. A key objective of the study is to indicate potential maximum demand scenarios for transport and thereby stimulate investment infrastructure for supply.

1.1 Policy Context

The overarching policies to deliver the greenhouse gas emission reduction targets until 2032 are set out in the *Scottish Government's Climate Change Plan 2018 to 2032 Update (CCPU)*. It updates the *2018 Climate Change Plan* with new greenhouse gas emissions targets outlined in Section 1.0 and sets out coordinated sector-by-sector policies and actions to achieving Scotland's climate change ambitions.

Prior to developing the national demand forecasts, a comprehensive, background, literature review was undertaken of the CCPU, supporting policies, strategies and work being undertaken across the Scottish Government Directorates, or UK policy commitments where applicable (maritime and aviation). This review formed the key assumptions held constant across the transport modes and is consistent within each of the technology transition scenarios for each mode, including:

- **Road**
    - 20% reduction in distance travelled by car by 2030
    - Phase out of new petrol and diesel cars and vans by 2030 and heavy vehicles by 2035
    - Majority of public service buses zero emission by 2023 (in Scenarios 4 and 5)
- **Rail**
    - Passenger rail decarbonisation by 2035
    - Net zero emission rail network by 2050
- **Maritime**
    - Low emission solutions in operations of Scottish Ports by 2032
    - Proportion of low emission Scottish Ferries 30% by 2032
    - Annual emissions from UK international shipping reduced by 50% by 2050
    - Net zero with zero emission ships commonplace globally
- **Aviation**
    - Decarbonisation of intra-Scotland scheduled flights by 2040
    - UK aviation sector to reach net zero by 2050

Additionally, two other major pieces of work were released during the period of forecast development. First, the *Decarbonising the Scottish Transport Sector Final Report* released in September 2021 aimed to understand the range of policy outcomes in terms of the introduction of zero-emission vehicles and changes in transport behaviour required to meet Scotland's emissions targets in the transport sector – of which only Policy Scenario 3 (PS3) met this ambition.

As such, the assumptions of forecasting for electricity and hydrogen included within this Report aim to be consistent with PS3, despite not all these policies necessarily being adopted by the Scottish Government at the present time.

Second, the *Scottish Government's Draft Hydrogen Action Plan* released in November 2021 confirmed a clear ambition of 5GW of installed hydrogen production capacity by 2030 and 25GW by 2045. The presentation of hydrogen forecast results within this Report and the accompanying Tool take these ambitions into consideration and seek to place the forecasts in this context, rather than forecast hydrogen production itself.

Similarly, electricity demand forecast results have been placed in the context of the generation ambitions cited in the *Scottish Government's Onshore Wind – Policy Statement Refresh 2021: Consultative Draft* and the *Offshore Wind Policy Statement*.

Finally, as mentioned in Section 1.0 the energy demand modelling has not been constrained by infrastructure, hydrogen, or electricity production requirements - as this is outside the scope of this study.

1.2 Scope of Work

The purpose of this study is to develop national demand forecasts for potential scenarios for the future of electricity and hydrogen as part of Scottish Government's commitment to decarbonise the transport sector. This required estimating annual total electricity and hydrogen demand for domestic or intra-Scotland transport including road, rail, maritime and aviation annually between 2022 and 2030, and for 2035, 2040 and 2045.

As part of this work six technology transition scenarios were modelled according to a combination of high, medium, and low electric and hydrogen uptake for each transport mode and within each transport mode where relevant, as detailed in Section 1.3 overpage.

1.3 Scenario Framework

As highlighted in previous sections, to provide an overview of how the technology transition to ZEEfT may occur, a series of six scenarios were developed to represent different pathways to decarbonisation as described in Table 1 below:

Table 1. Technology Transition Scenarios

Scenario	Notation	Scenario
1.	**LH**	Low transition to electric, high transition to hydrogen
2.	**ML**	Medium transition to electric, low transition to hydrogen
3.	**MH**	Medium transition to electric and high transition to hydrogen
4.	**HL**	High transition to electric and low transition to hydrogen
5.	**HH**	High transition to electric and high transition to hydrogen
6.	**MM**	Medium transition to electric and medium transition to hydrogen

Although the scenarios themselves were consistent across the modes, the individual construct of these scenarios for each mode varied in terms of their assumptions for technology uptake for different vehicles, rolling stock, vessels, and aircraft. These assumptions are detailed in the following Chapters for each mode of transport, as well as a comprehensive summary provided in Chapter 7 - Appendices and the accompanying Tool.

This mode-by-mode approach was taken due to the varying readiness of electric and hydrogen power train technology, adding too much complexity to standardise the scenario assumptions between modes. For example, hydrogen fuel cell technology in Scenario 5 (HH) for cars still represents a relatively low proportion of the total stock due to the expectation that battery electric vehicles (BEVs) are likely to be more dominant. This is due to their suitability for this application and higher state of current availability, amongst other reasons.

Conversely, in maritime and aviation industries, ammonia and hydrogen are likely to represent a much larger proportion of the overall transport energy demand in the future, as these fuels are expected to be suitable to serve all aircraft and vessel types. Conversely, due to the lower energy density of the batteries, electric technology is expected to only serve a niche segment of these markets.

1.4 Report Structure

The structure of this Report has been designed to present the results of the study in a mode-by-mode format as follows:

Chapter 1: Overview – Introduces the purpose and requirements of the study and explains the high-level policy context. It then sets out the scope of work, scenario parameters and explains the reasoning for the way in which findings are presented, and the report structured.

Chapter 2: National Demand Forecasts – Provides an overarching summary of the national demand forecasts for electricity and hydrogen for transport, as well as the combined results (accounting for electricity generation requirements for hydrogen production) and discusses them in the context of the energy system.

Chapter 3: Road; Chapter 4: Rail; Chapter 5: Maritime; Chapter 6: Aviation – Each of these mode-based chapters describes the following:

- **Transport Demand Forecasts**: the underlying total demand forecasts upon which the scenarios are based. These recognise that over the coming years changes in requirements and preference for different modes of transport will change, resulting in the total demand for each mode varying.
- **Technology Transition Scenarios**: how the six different scenarios will occur within each mode of transport and an explanation of the underlying assumptions and data supporting the models. At a basic level these represent varying proportions of the uptake of electric and hydrogen technologies within the total demand.
- **Energy Demand Analysis:** the energy modelling assumptions are detailed, based on analysis of the different technology options available within that mode. These are then subsequently applied to the overall demand and individual scenarios to generate total electricity and hydrogen requirements for that sector of transport at the point of use.

Chapter 7: Appendices – Provides a comprehensive summary of the overarching parameters and assumptions for transport demand, technology transition scenarios and energy demand analysis calculations used in the forecast modelling for electricity and hydrogen demand for transport.

Chapter 2: National Energy Demand Forecasts for Transport

2.0 Overview

Although Scotland’s current renewable energy capacity of around 12 Gigawatts (GW) meets the majority of Scotland’s current electrical energy requirements, as detailed by the *Scottish Energy Statistics* publications, future expansion of generation capacity will be required as the transition from fossil fuels continues. A significant increase in renewable electricity supply, coupled with low carbon hydrogen, will be necessary to meet the future forecast demand for transport along with expected demand growth from other domestic and commercial sectors.

This increase in requirements for low carbon hydrogen is highlighted by Scotland’s own ambition to have 5 GW of capacity by 2030 according to the *Draft Hydrogen Action Plan*. Although this generation is likely to come from blue hydrogen in the short-term, which requires a lower input of electricity during production, a significant and increasing proportion is expected to be provided through green hydrogen through to 2045.

This production of green hydrogen would be undertaken through electrolysis, which in turn, would place additional demand on the requirement to produce renewable electricity, particularly as Scotland moves towards the target of 25 GW of low carbon hydrogen production capacity by 2045.

To achieve the right energy system for the future, a greater understanding of the possible scenarios for electricity and hydrogen demand for transport is required to inform the market. As such, the subsequent sections provide a detailed overview, for each sector of transport, of the forecast future demand in total for electricity and hydrogen, by mode and combined.

The figures presented throughout the rest of this Chapter are also included in the accompanying Tool. The intention of the remainder of this Chapter is to provide an overview of the top-line results of the study, followed by a brief commentary of their potential implications.

2.1 National Electricity Demand Forecasts for Transport

The results of the national demand forecasts for electricity for transport are shown both in terms of the change in total electricity requirements over time in Figure 1 and Table 2 and how they vary between different modes of transport in Figure 2.

Total annual demand for electricity in 2022 for all transport modes combined varies between scenarios from around 0.6 Terawatt hours (TWh) in 2022, increasing to between 2.8 and 4.4 TWh in 2030, before reaching a peak of between 11.2 and 14.2 TWh in 2045.

Across the forecast years, road transport formed the majority of demand in every scenario as shown in Figure 1, while rail and maritime maintained relatively small proportions. The exception is aviation, which only becomes material in the high electric scenarios (HL and HH) in 2045 - as regional, small turbo and large turbo aircraft are not expected to transition to electric until beyond 2040.

Although these results show variation between the scenarios, they all follow relatively similar growth projections. A main observation is electricity demand gradually builds in the 2020s and then accelerates post 2030. This is primarily due to the restrictions placed on fossil fuel internal combustion engines (ICE) that commence around this period.

Importantly, these ranges are equivalent to the forecast amount of electricity required as an input to the modes of transport, and although important, do not consider the availability of supply and inefficiencies in the transmission, distribution, or storage of electricity. That is, they are based on fuel consumption, rather than generation – which remain important factors in calculating future demand requirements for transport at a more regional level.

Figure 2, which illustrates the breakdown of how the forecast for electricity requirements are likely to change across different modes of transport due to differing rates of adoption of new energy technologies. Two key observations are as follows:

1. The road sector dominates the projected demand requirements. This is due to the opportunities for electrification within this mode and that it accounts for around 65-70% of the total estimated transport emissions of 14.5 $MtCO_2$ in 2018 according to a report on *Decarbonising the Scottish transport sector*
2. Shipping and aviation are considerably more difficult to transition to electrification, whilst rail accounts for a considerably smaller portion of energy demand.

These observations are explored in further detail in Chapter 3, in terms of how electricity demand varies across cars, vans, heavy goods vehicles (HGVs), buses and coaches, along with an overview of the assumptions used in modelling the technology uptake.

In interpreting the forecast results consideration should also be given to the likelihood that most of the electricity supply for transport to 2045 will come from renewable sources. Therefore, while the results provide a strong guide to potential electricity demand for transport in the future, it will not necessarily be as simple as matching the demand requirements to the supply capacity – as contingency will also be required.

This is because the timing of when the demand is required and when supply is available will vary given the intermittent nature of renewable generation. Consequently, additional capacity and energy storage will need to be considered - which are outside the bounds of this study.

Figure 1. Electricity Demand for Each Scenario Across All Years

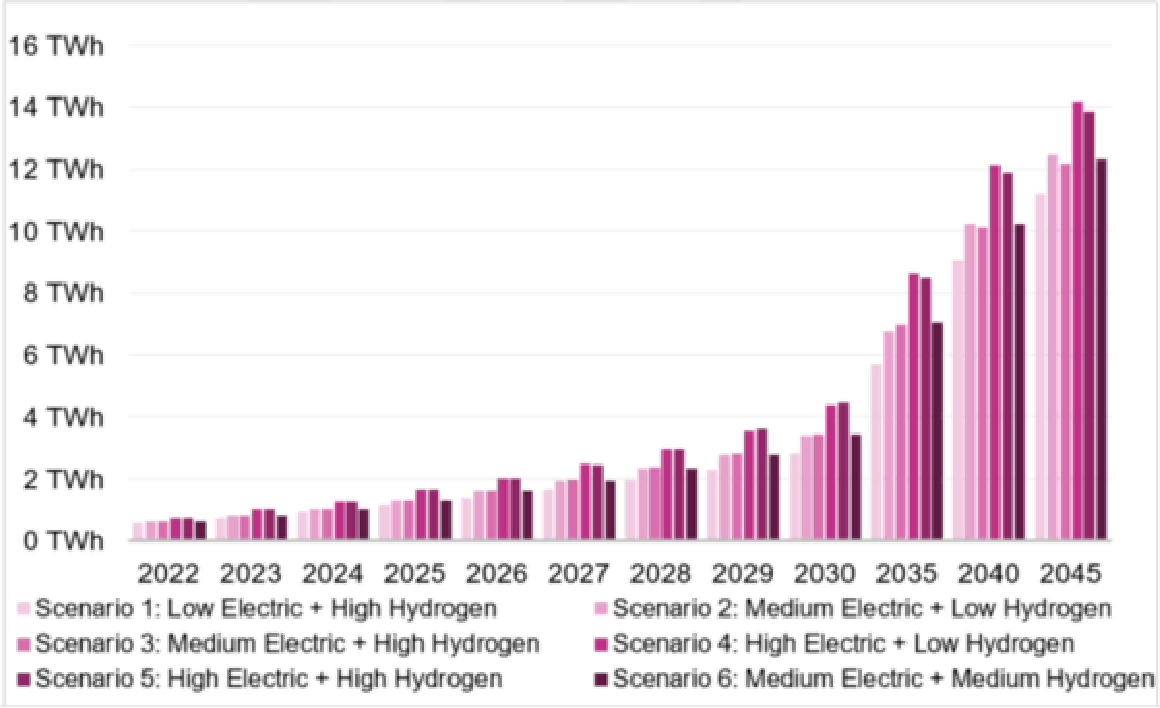
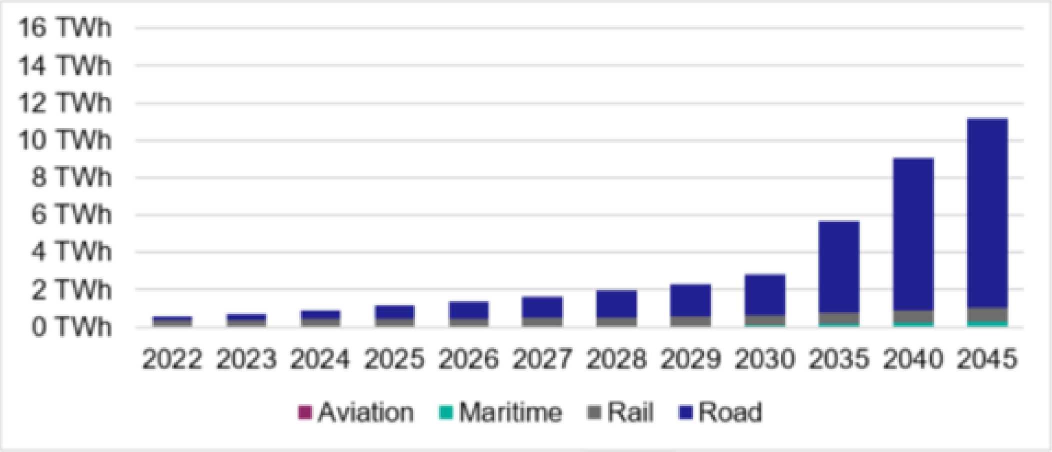


Table 2. Data for Electricity Demand (TWh) for Each Scenario

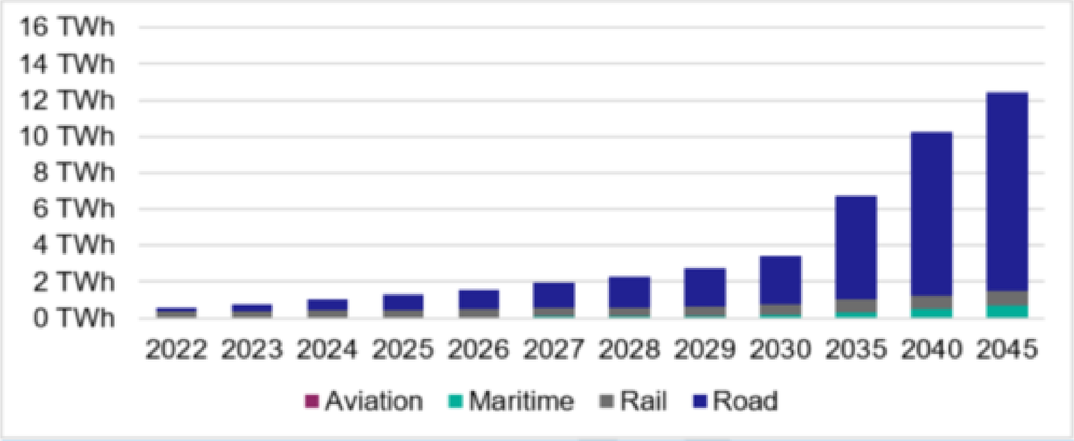
Year	Scenario 1: LH	Scenario 2: ML	Scenario 3: MH	Scenario 4: HL	Scenario 5: HH	Scenario 6: MM
2022	0.6	0.6	0.6	0.7	0.7	0.6
2023	0.7	0.8	0.8	1.0	1.0	0.8
2024	0.9	1.0	1.0	1.3	1.3	1.0
2025	1.2	1.3	1.3	1.6	1.6	1.3
2026	1.4	1.6	1.6	2.0	2.0	1.6
2027	1.7	1.9	2.0	2.5	2.5	1.9
2028	2.0	2.3	2.3	3.0	2.9	2.3
2029	2.3	2.8	2.8	3.6	3.6	2.8
2030	2.8	3.4	3.4	4.4	4.4	3.4
2035	5.7	6.7	7.0	8.6	8.5	7.0
2040	9.0	10.2	10.1	12.1	11.9	10.2
2045	11.2	12.5	12.2	14.2	13.8	12.3

Figure 2. Electricity Demand by Mode for Each Scenario Across All Years

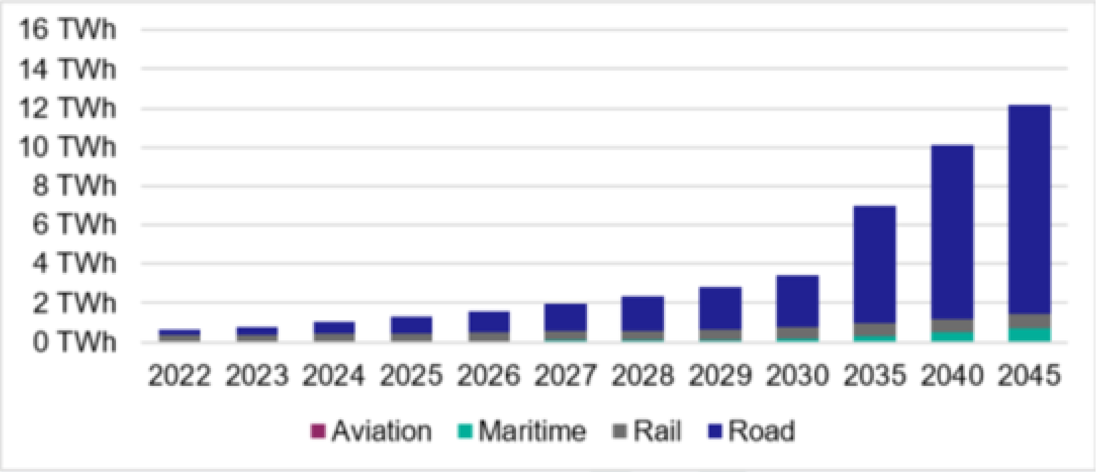
Scenario 1: LH



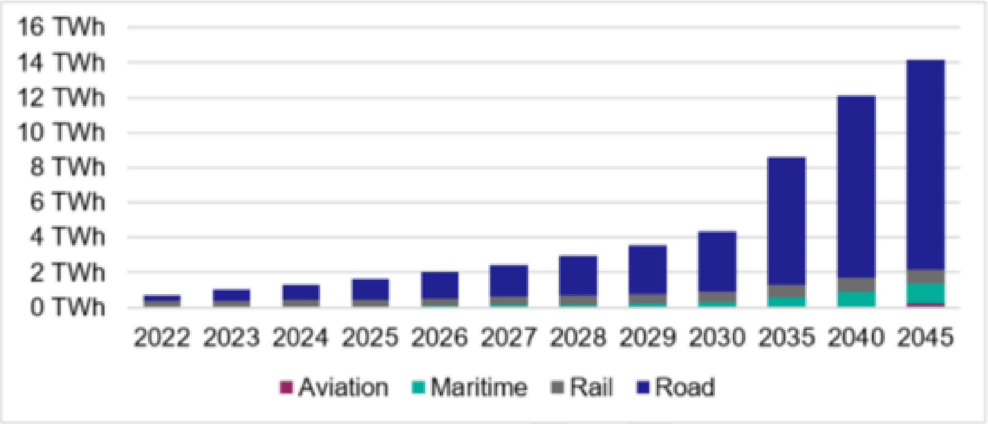
Scenario 2: ML



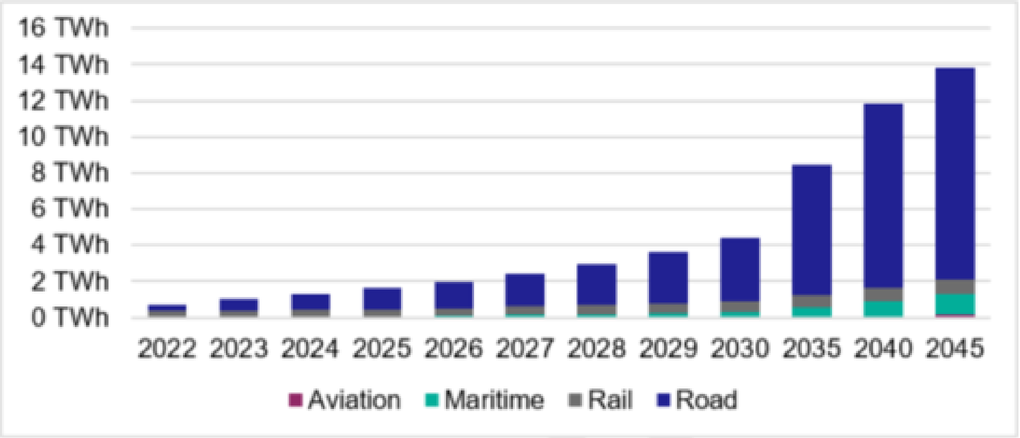
Scenario 3: MH



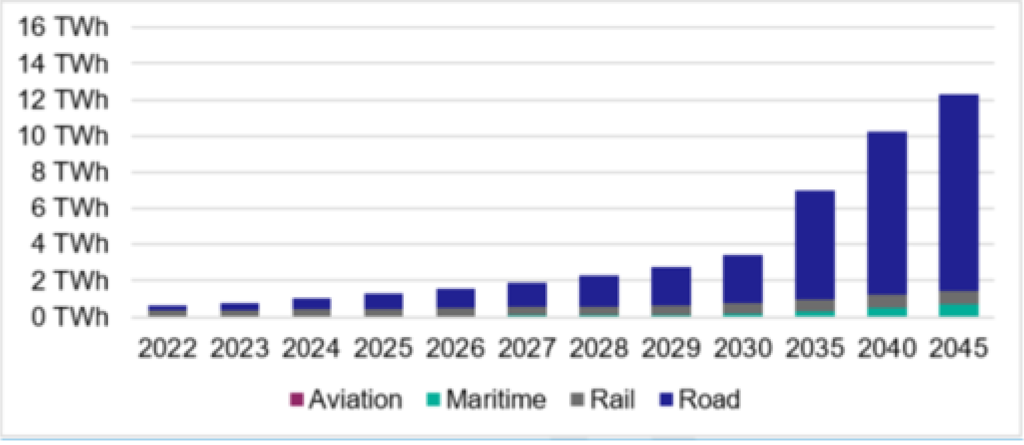
Scenario 4: HL



Scenario 5: HH



Scenario 6: MM



2.2 National Demand Forecasts for Hydrogen

The results of the national demand forecasts for hydrogen for transport are shown both in terms of the change in total electricity requirements over time in Figure 3 and Table 3 and how they vary between different modes of transport in Figure 4.

Total demand for hydrogen in 2023 for all transport modes combined is approximately 0.02 TWh for four of the six scenarios, increasing to a range between 0.43 and 1.19 TWh in 2030, before reaching between 4.45 and 14.83 TWh in 2045. From the comprehensive list of results in Table 3, several further observations can be made from these:

1. The circa 10 TWh in hydrogen demand in 2045 for the medium hydrogen scenario (MM) is in the same order of magnitude as for electricity (12-14 TWh). However, the variation across other scenarios is considerably larger with a range of 10.4 TWh compared to 3.0 TWh for electricity.
2. Hydrogen uptake is very low until 2025, before expected increases in the adoption of hydrogen. Demand then increases steadily to 2030, before then accelerating.
   Up until 2030, the hydrogen demand is driven by road and maritime transport, although in relatively small proportions. The transition to hydrogen for the aviation and rail sectors is forecast to take longer than road or maritime, and is expected to accelerate from 2030 onwards.
3. In terms of the potential energy requirements from each mode, once hydrogen demand becomes of a significant volume – the maritime and road sectors will account for the majority of its use.

Importantly, all results for modes shown in Figure 3 are hydrogen based, however for the maritime sector it is assumed most of the hydrogen demand will take the form of hydrogen-based fuels, such as ammonia. Further detail on the calculations and implications are provided in Chapter 5.

As with Section 2.1, the results are presented based on the quantity of hydrogen at the point of supply. However, for ease of comparison of figures with electricity, a conversion was used to transfer hydrogen demand in mass across to an equivalent energy content value.

Importantly, the Lower Heating Value (LHV) of hydrogen was used (33.46 kWh/kg) as the conversion rate as per the energy available for a fuel cell, rather than the Higher Heating Value (HHV) that can be used for conversions. However, while neither reflect the actual electrical energy required for hydrogen production through electrolysis (outlined in Section 2.3), LHV is a meaningful method of comparing the scale of electricity and hydrogen demand.

That is, the total input energy for hydrogen would ignore inefficiencies in providing and storing renewable energy as part of the wider energy system, for example generating hydrogen at times of wind curtailment. Additionally, we recognise that a significant proportion of the hydrogen may come from other sources aside from green hydrogen which have varying energy requirements for production.

Figure 3. Hydrogen Demand for Each Scenario Across All Years

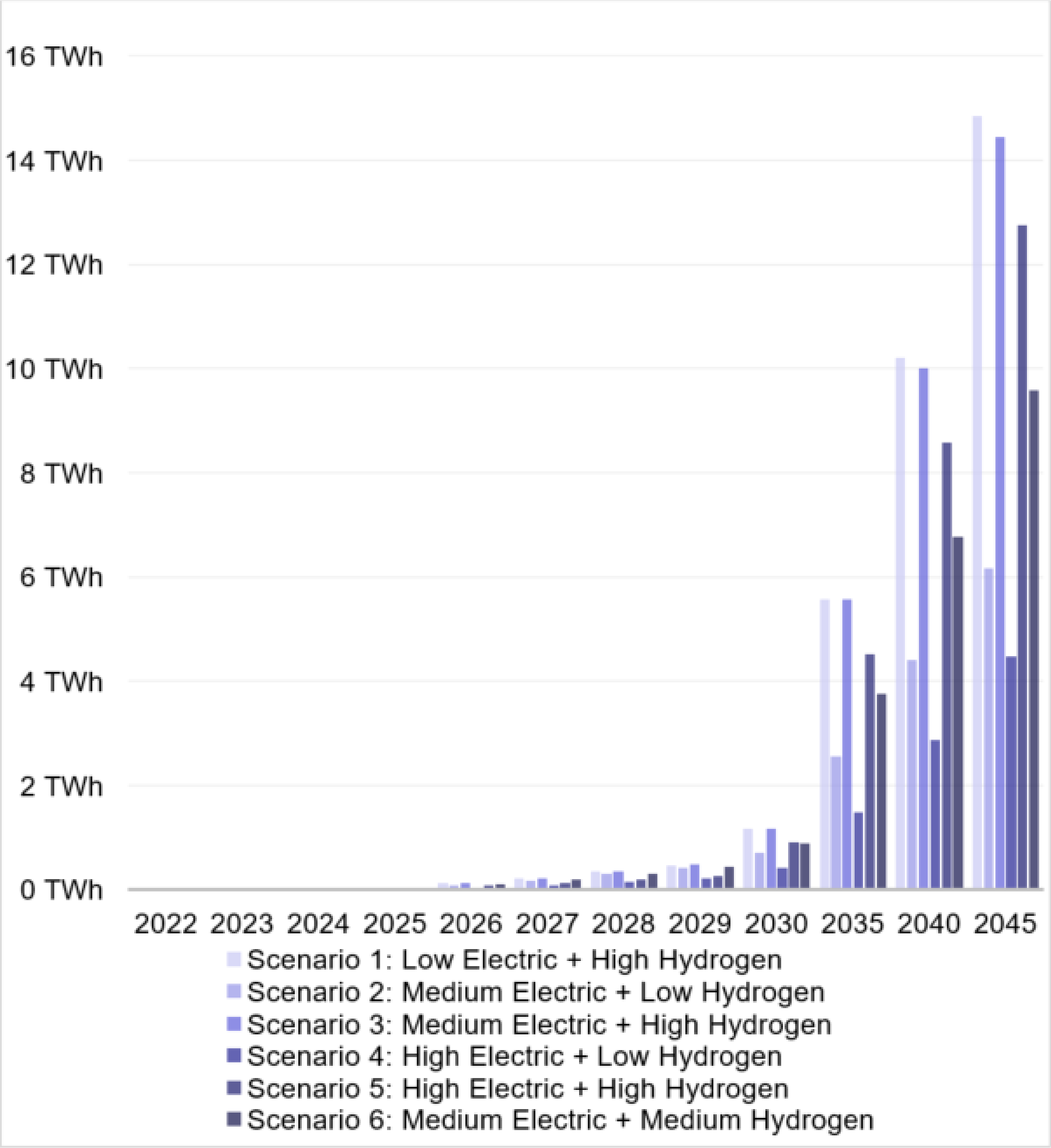
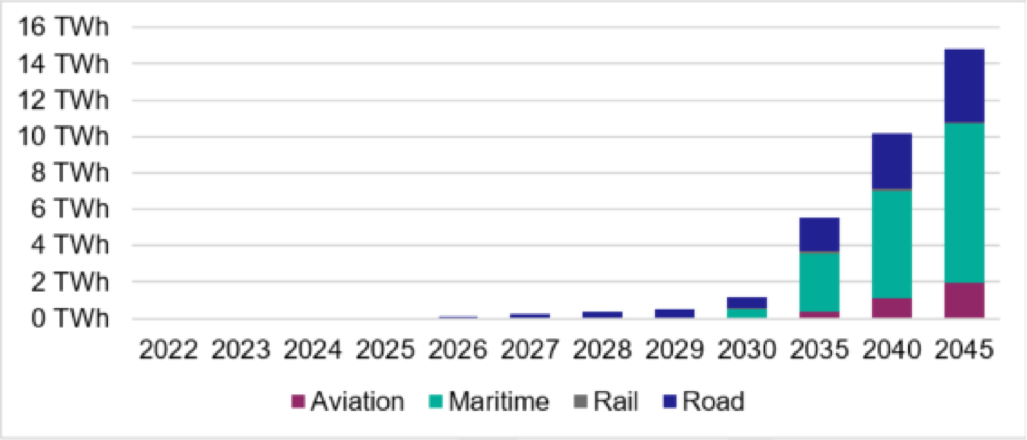


Table 3. Data for Hydrogen Demand (TWh) for Each Scenario

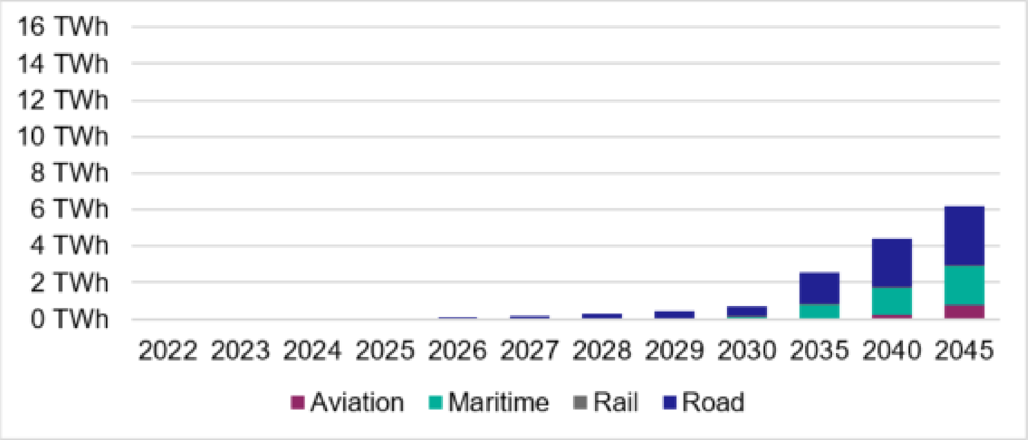
Year	Scenario 1: LH	Scenario 2: ML	Scenario 3: MH	Scenario 4: HL	Scenario 5: HH	Scenario 6: MM
2022	0.0	0.0	0.0	0.0	0.0	0.0
2023	0.0	0.0	0.0	0.0	0.0	0.0
2024	0.0	0.0	0.0	0.0	0.0	0.0
2025	0.0	0.0	0.0	0.0	0.0	0.0
2026	0.2	0.1	0.1	0.1	0.1	0.1
2027	0.4	0.2	0.2	0.1	0.1	0.2
2028	0.7	0.3	0.4	0.2	0.2	0.3
2029	0.9	0.4	0.5	0.3	0.3	0.4
2030	1.2	0.7	1.2	0.4	0.9	0.9
2035	5.6	2.6	5.6	1.5	4.5	3.8
2040	10.2	4.4	10.2	2.9	8.6	6.8
2045	14.9	6.2	14.4	4.5	12.8	9.6

Figure 4. Hydrogen Demand by Mode for Each Scenario

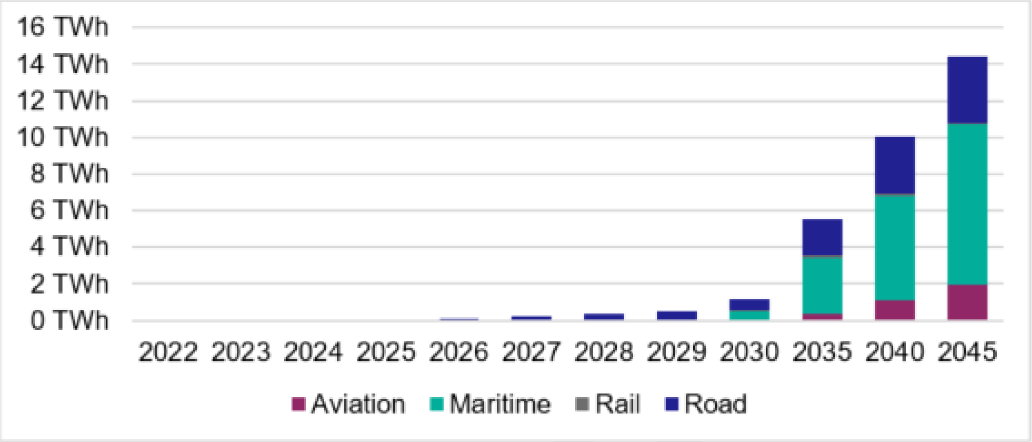
Scenario 1: LH



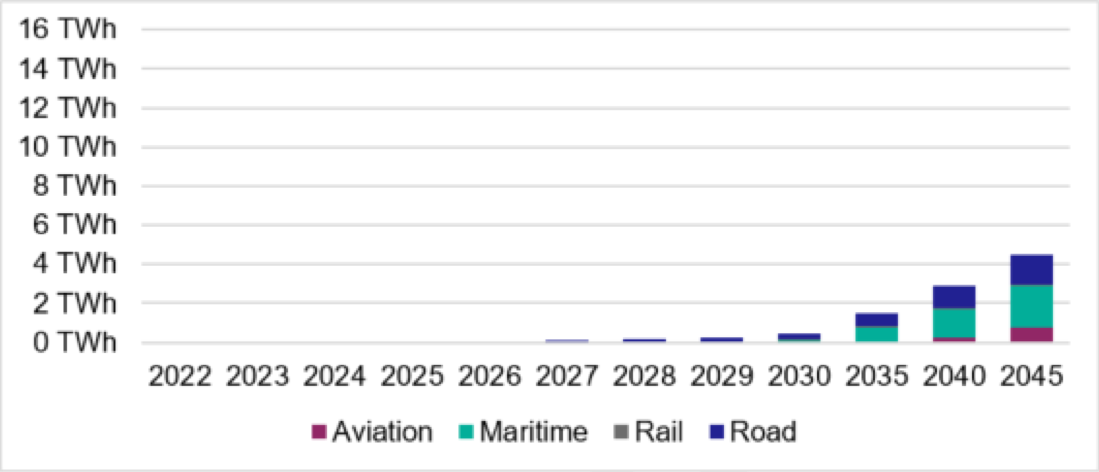
Scenario 2: ML



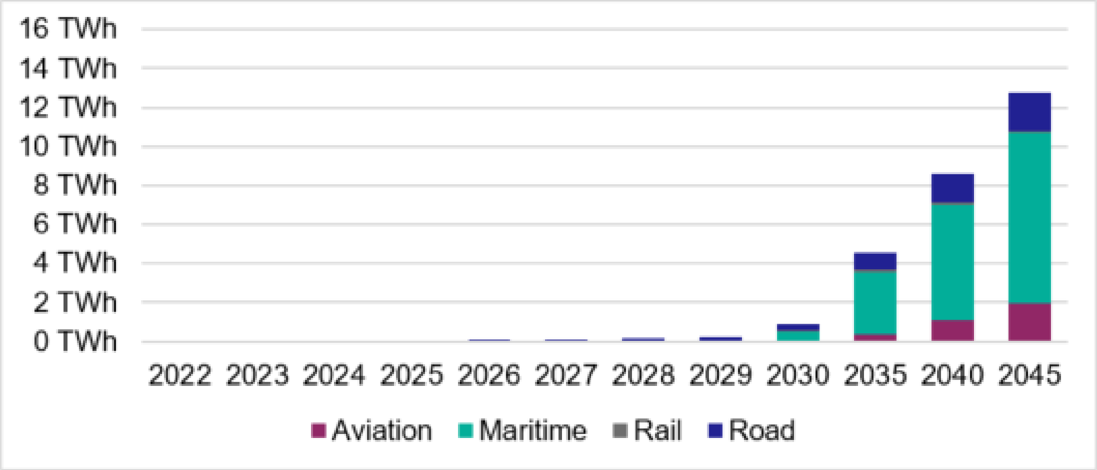
Scenario 3: MH



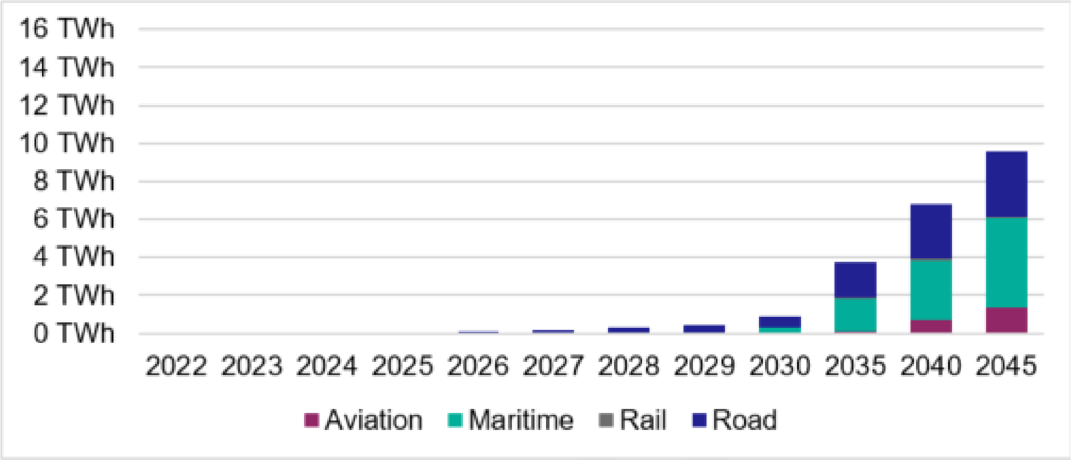
Scenario 4: HL



Scenario 5: HH



Scenario 6: MM



2.3 Combined Transport Energy Demand Forecasts

It is expected that a significant proportion of hydrogen production in the future will likely be generated from electrolysis according to the *Scottish Government's Draft Hydrogen Action Plan 2021*, thus requiring adequate supply of renewable electricity. As such, Figure 5 and Table 4 provide a summary of the estimated total electricity capacity required, taking into consideration hydrogen generation on the following basis:

- Electricity demand associated with hydrogen production is assumed to be for green hydrogen only, as this will demonstrate the maximum electricity requirement for transport. That is, if there is a significant proportion of blue hydrogen in the future, this electricity requirement would be lower due to the use of natural gas a feedstock.
- An efficiency of 65.4% is assumed for electrolysis from the LHV of hydrogen, equating to 51.2 kWh/kg. This was based on the *UK Government Hydrogen Production Costs Analysis* and verified against reference data for electrolyser suppliers and other sources such as the *Scottish Hydrogen Assessment*.
- The hydrogen production is assumed to run 24 hours per day.
- Inefficiencies in both the transmission of the electricity and requirements for transporting the hydrogen are excluded due to the national rather than regional nature of this study.
- Efficiency losses in storing electricity associated with renewable generation variability are not considered.
- Renewable generation utilisation in Scotland is assumed to be 30.5%, based on current generation capacity factors – broadly in line with the combined figure for onshore and offshore wind of 31.6% from the Department for Business, Energy and Industrial Strategy (BEIS). As the majority of new capacity is likely to be a combination of onshore and offshore wind (as described in the following Section 2.4), this renewable generation is likely to be a conservative estimate, as new offshore wind is expected to have higher load factors of around 55-60%.

Finally, the analysis underpinning the results presented in Figure 5 and Table 4 did not consider the timing of when electricity production will be required, which is outside the scope of this study. Consideration should therefore be given to the intermittent nature of renewables in the interpretation of these results, as it's likely that excess capacity or energy storage in addition to the results provided will be required to balance supply and demand.

Figure 5. Total Electricity Generation Capacity Required

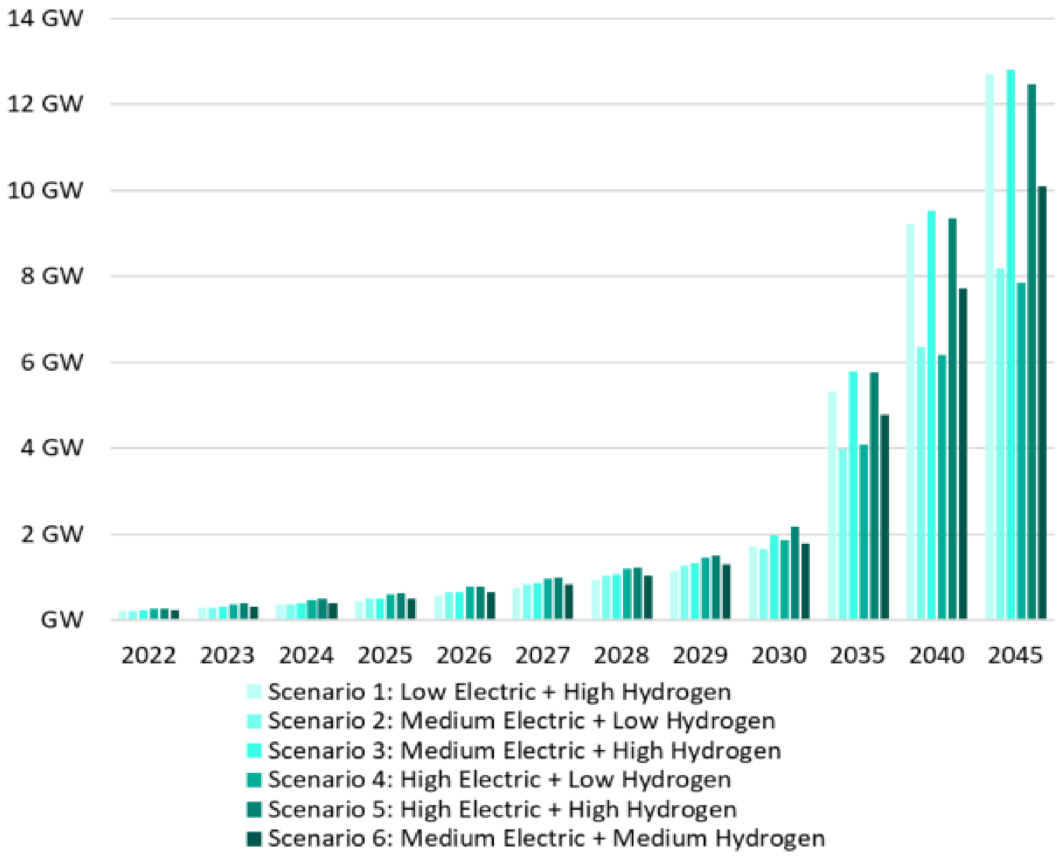


Table 4. Data for Total Electricity Capacity Required

Year	Scenario 1: LH	Scenario 2: ML	Scenario 3: MH	Scenario 4: HL	Scenario 5: HH	Scenario 6: MM
2022	0.2	0.2	0.2	0.3	0.3	0.2
2023	0.3	0.3	0.3	0.4	0.4	0.3
2024	0.4	0.4	0.4	0.5	0.5	0.4
2025	0.5	0.5	0.5	0.6	0.6	0.5
2026	0.6	0.6	0.7	0.8	0.8	0.7
2027	0.7	0.8	0.9	1.0	1.0	0.8
2028	0.9	1.0	1.1	1.2	1.2	1.0
2029	1.1	1.3	1.3	1.4	1.5	1.3
2030	1.7	1.7	2.0	1.9	2.2	1.8
2035	5.3	4.0	5.9	4.1	5.8	4.8
2040	9.2	6.3	9.6	6.2	9.3	7.7
2045	12.7	8.2	12.8	7.8	12.5	10.1

2.4 Implications for the Energy System

This section provides a guide of how the forecast demand for electricity, hydrogen, and their combined effect outlined in **Sections 2.1-3** as it relates to Scotland's renewable electricity and hydrogen supply ambitions.

Figures 6 and 7 show the forecast demand for electricity and hydrogen respectively (according to the conversion rate) for each scenario, against the proportion of their estimated generation. As shown, the proportion of electricity requirement increases over time even with the assumption of growth in capacity used. This is from a value of around 1.5% of total capacity in the short term to around 6-8% in 2030 and 24-37% by 2045 as there is significant increase in the adoption of electric and hydrogen technologies.

However, it is important to note that although the proportion and amount of electricity required is growing over this period, the estimated available volume of generation is still increasing in absolute terms from around 40 TWh initially to around 70 TWh in 2030. It then reaches around 90 TWh in 2045 which is due to the lower rate of increase in capacity over this period. The actual capacity increase may be larger than this, but there is a lack of targets for 2030 to 2045 at this point.

For hydrogen, the proportion grows to a range of 1.5 to 4.5% in 2030 across different scenarios and then to around 4 to 14% in 2045. Whilst these scenarios show a significant amount of variability, they represent a relatively low proportion of total forecast hydrogen production capacity. This indicates that there will be a significant amount of hydrogen available for other applications such as heating and industrial uses if these production capacities are achieved.

For context, in 2019 Scotland's transport sector accounted for 38 TWh of energy demand out of a total Scotland-wide demand of 157 TWh. Much of this energy demand was fulfilled by fossil fuels according to *Scottish Energy Statistics*. As the transition to a net-zero economy takes place, increased electric and hydrogen applications will develop in parallel with increased energy provision from renewable energy.

Scotland is currently working to expand its renewable energy generation capacity, both to serve domestic needs and to provide export opportunities. Scotland's current production of renewable energy accounts for around 30% of the UK total. In 2020, the vast majority of this is produced from onshore wind energy, accounting for just over 70% of the total capacity, with hydro providing the next largest contribution.

In 2019, 30.1 TWh of electricity was generated from renewable sources in Scotland out of a total generation of 49.6 TWh - accounting for 88.4% of gross electricity consumption in Scotland and net exports of 15.9 TWh. In 2020 this increased to 95.9% of total consumption. As the energy demand for transport transitions to renewable sources then increased supply of renewable energy is needed.

As discussed in Section 2.3, some hydrogen may be produced from fossil fuels as low-carbon blue hydrogen. However, the aim is for a significant proportion of this to be green hydrogen, so the analysis conducted assumed that the total electricity demand was based on the use of green hydrogen and the presentation of results in **Figures 6 and 7** are shown on that basis.

To meet this demand, Scotland has targets in place to have a total of 8-11 GW of offshore wind by 2030, of which 5.6 GW already has consent. Furthermore, there is also the aim to add 8-12 GW of further onshore capacity by 2032, with 4.6 GW awaiting construction and 4.7 GW in planning.

Other studies have forecast that Scotland requires around 17 GW of installed renewable capacity by 2030 to meet demand requirements. This is alongside the ambition, in the *Scottish Energy Strategy*, of the equivalent of 50% of Scotland’s consumption of energy in transport, heat and electricity to be from renewable sources and a 30% increase in the productivity of energy use.

In conducting this analysis, the following assumptions were made for electricity generation:

- It was assumed that the majority of the increase in capacity would come from increases in onshore and offshore wind. Other sources, although likely to grow, are not expected to be a major contributor to the overall increase at this point.
- In 2030 the lower estimate for onshore and offshore increase in capacity of 8 GW for both would be used, with no planned retirements, to give a total capacity of 27.0 GW. Other sources were assumed to have only minimal increases.
- In 2045 it is assumed that as a minimum the upper estimates of 12 GW for onshore wind and 11 GW for offshore wind will be achieved to give a total capacity of 34.0 GW.

It is hoped that these estimates will be the minimum increase in renewable capacity that is achieved. Therefore, the intention is that the presentation of the results and generation data shown should reflect a worst-case scenario of the proportion of future capacity that will be required.

However, as outlined in Section 2.3, in interpreting the data contained within Figure 6, consideration must be given to the intermittent nature of generation and timing of the transport energy demand. Energy storage will be crucial in balancing supply and demand.

In terms of hydrogen, while it is important to consider that hydrogen production only coupled to renewables will suffer the same effects of intermittent supply. The effect of this is that excess electrolysis capacity would be required to achieve the necessary volume of hydrogen if there is under-utilisation of the production assets.

To provide the total capacity for hydrogen, the analysis was again based on the estimations in the *Scottish Government's Draft Hydrogen Action Plan 2021*. This provided estimated production figures for 2030 and 2045, as previously discussed, and values for the intervening years were estimated from this.

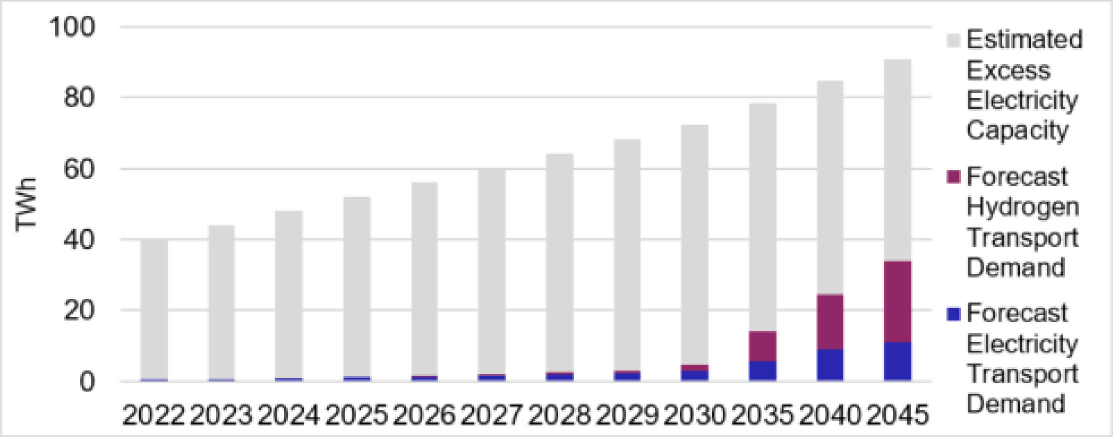
It is important to recognise that there is still considerable uncertainty surrounding the future capacity for low-carbon hydrogen production, due to the significant increase in both demand and capacity that will have to occur. As such, the *Scottish Hydrogen: Assessment Report* outlines three scenarios for expected hydrogen production output in 2045. These are given as a Low scenario of 21 TWh, Medium scenario of 85 TWh and a High scenario of 127 TWh with varying proportions of green and blue hydrogen. However, these depend significantly on how the market evolves over time. For this analysis, the following assumptions were made for hydrogen generation:

- That the expected production of hydrogen will be 27.5 TWh in 2030 from the capacity of 5 GW which is composed of an equal split of Blue and Green.
- The capacity of 25 GW in 2045 will provide 107.5 TWh of hydrogen based on a split of 5 GW of Blue hydrogen and 20 GW of Green hydrogen.
- Although it is recognised different sources will provide variation in hydrogen quality, the suitability for different transport modes was not considered.
- Similarly, the impact of where the hydrogen is produced, which is likely to influence which sources are used for which applications was not analysed.

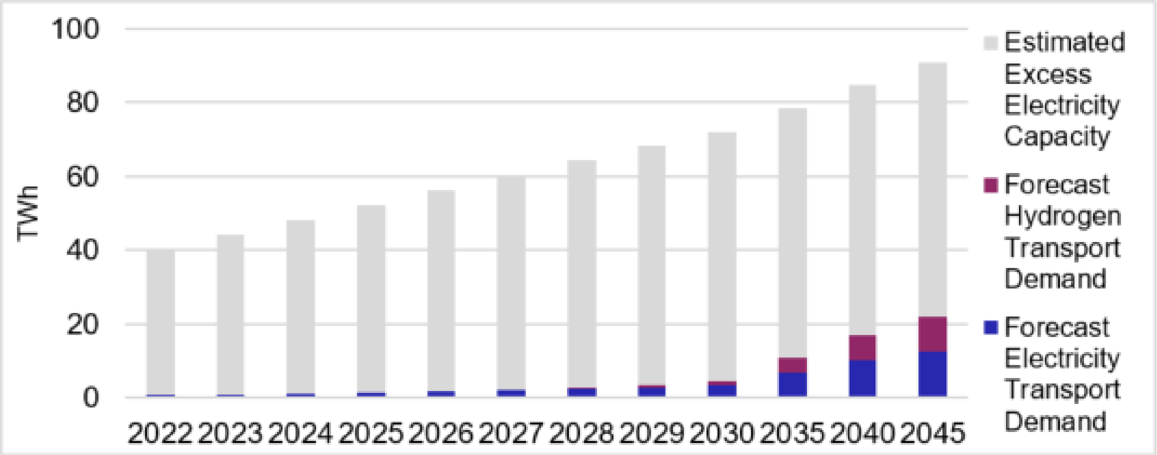
In interpreting the data contained within **Figure 7**, consideration must be given to the fact that there is considerable uncertainty in the expected production output for hydrogen and how that hydrogen can be used for different transport modes due to the quality, location and input requirements (e.g. ammonia) for different applications.

Figure 6. Forecast Electricity Demand versus Estimate Production

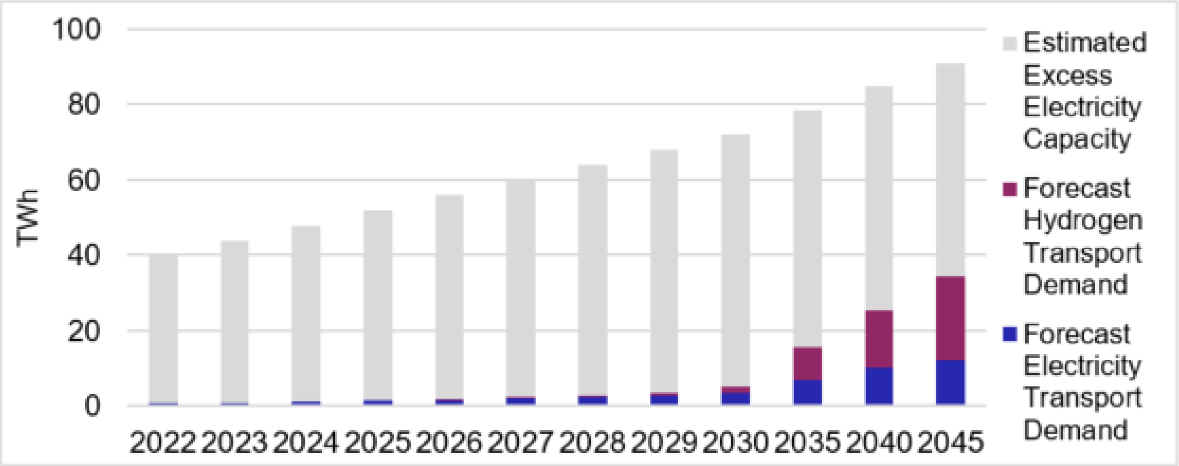
Scenario 1: LH



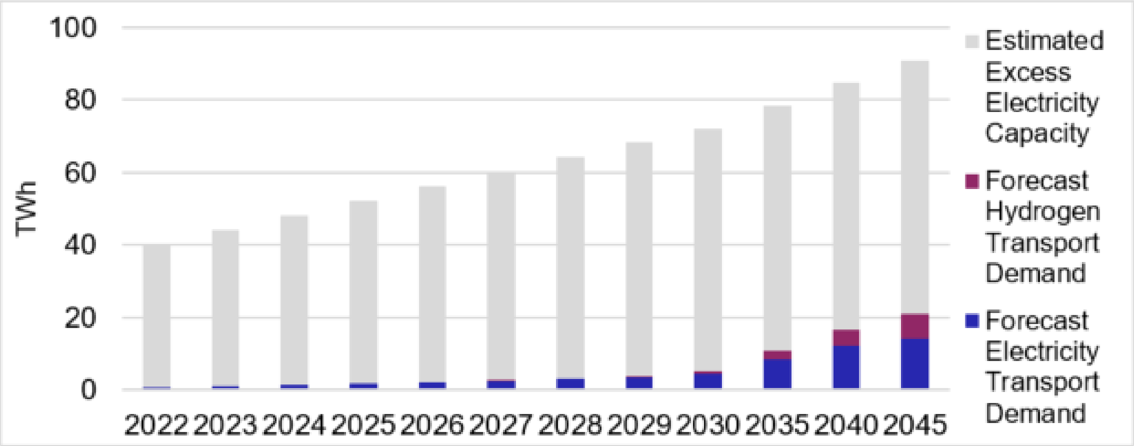
Scenario 2: ML



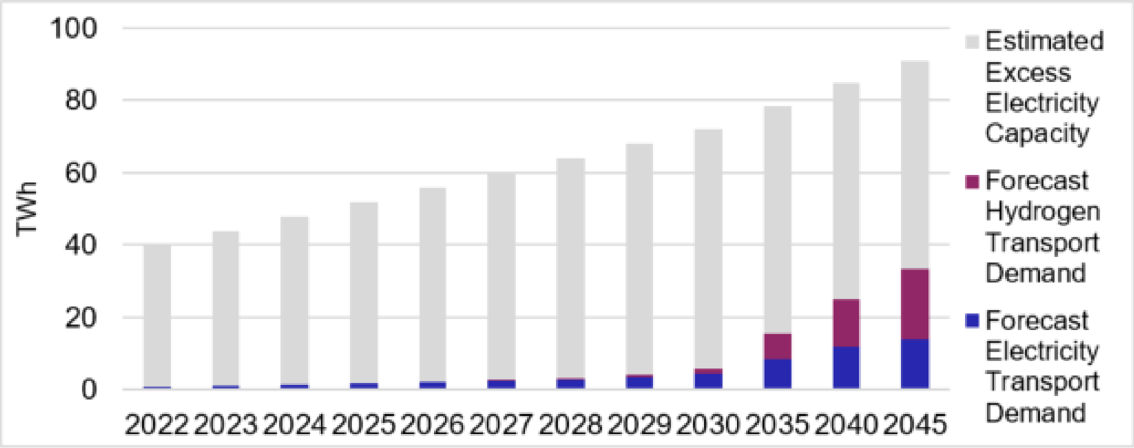
Scenario 3: MH



Scenario 4: HL



Scenario 5: HH



Scenario 6: MM

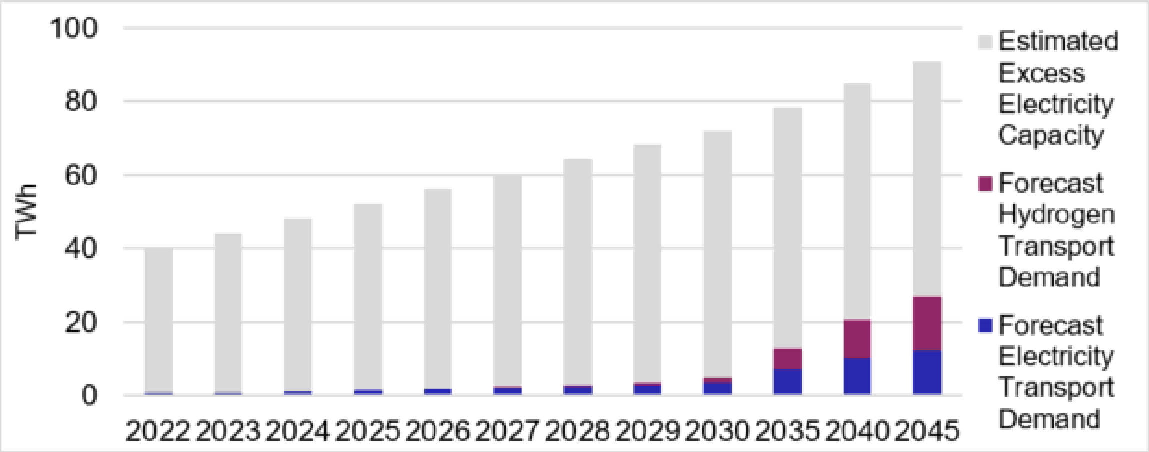
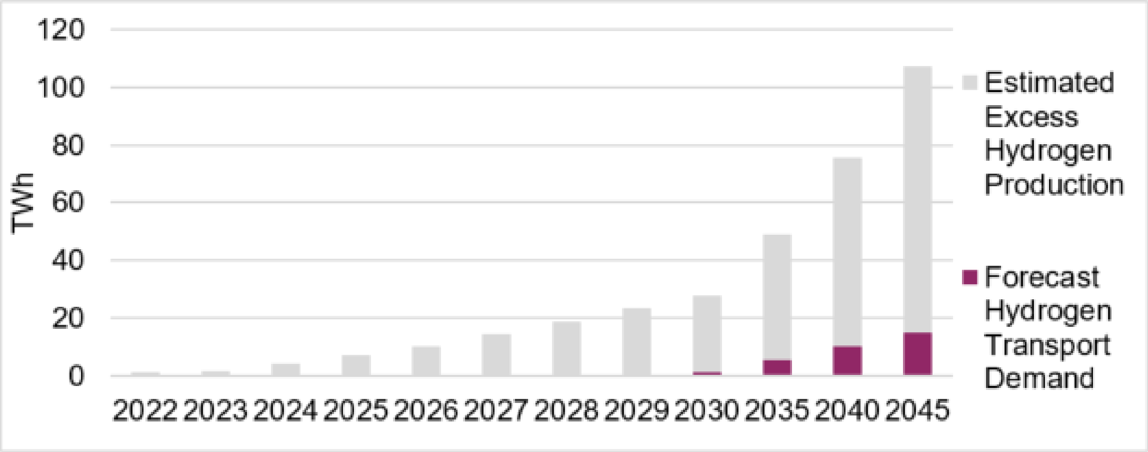
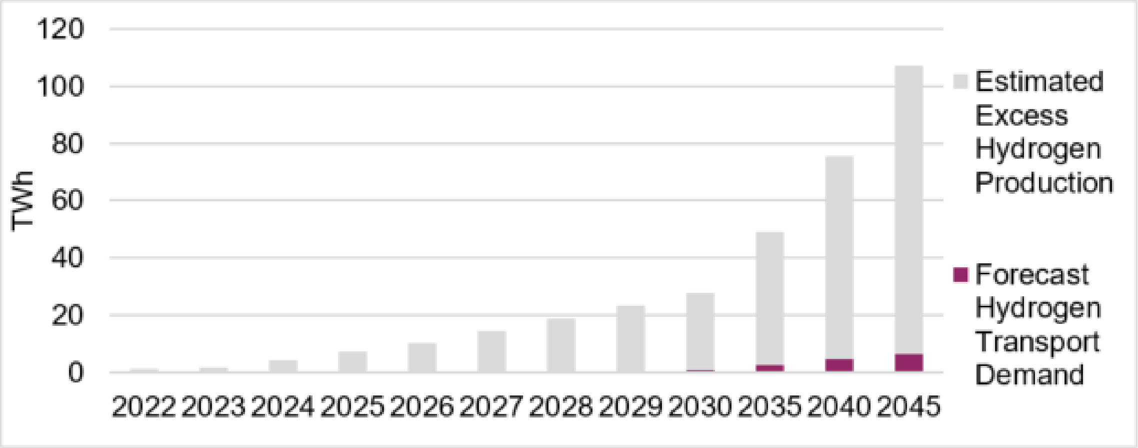


Figure 7. Forecast Hydrogen Demand versus Estimate Production

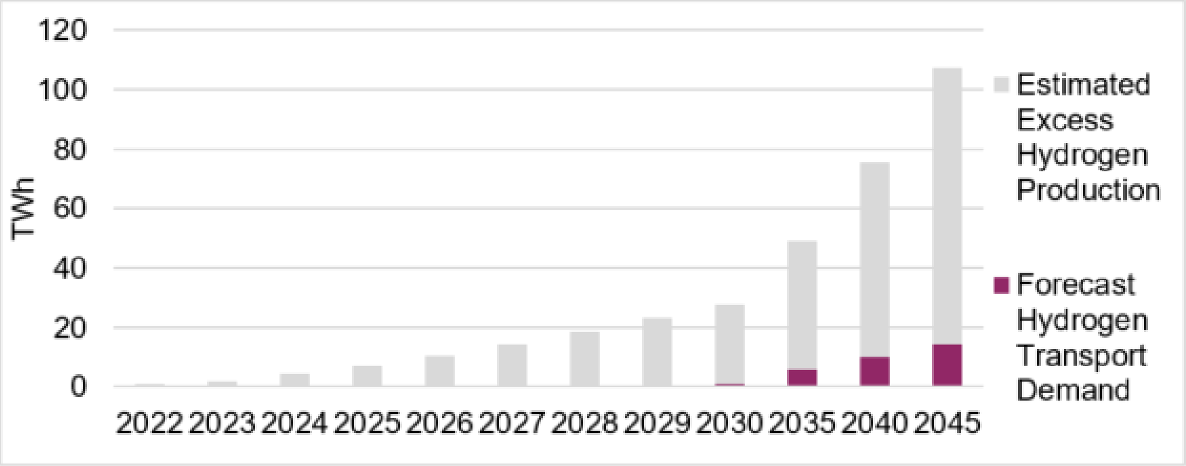
Scenario 1: LH



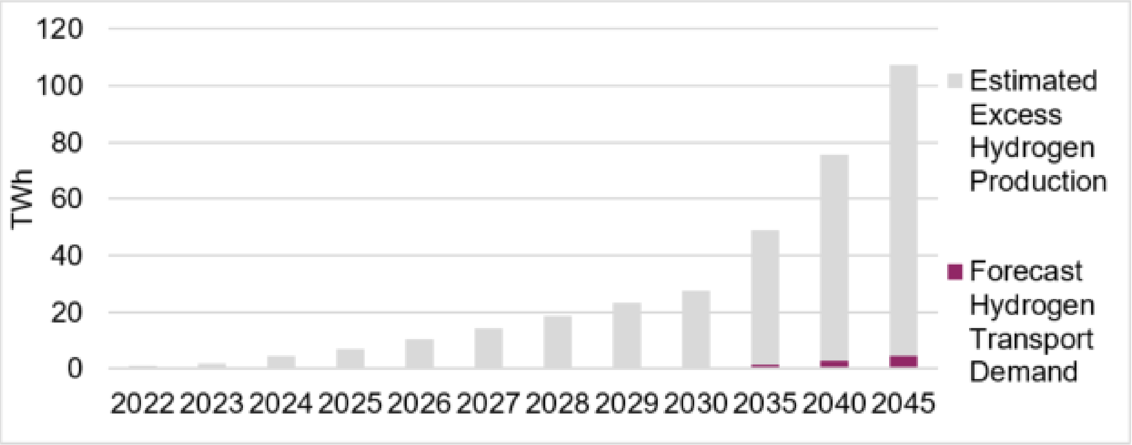
Scenario 2: ML



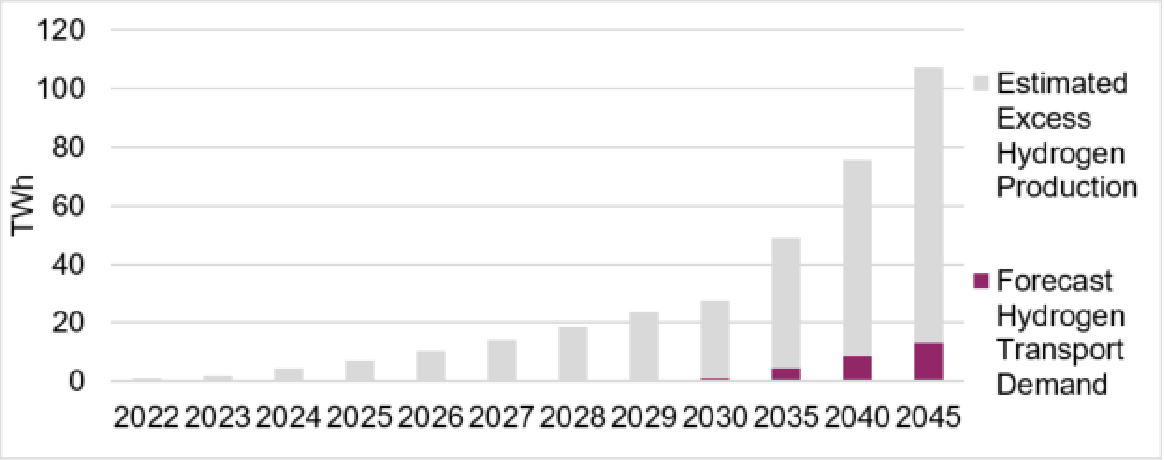
Scenario 3: MH



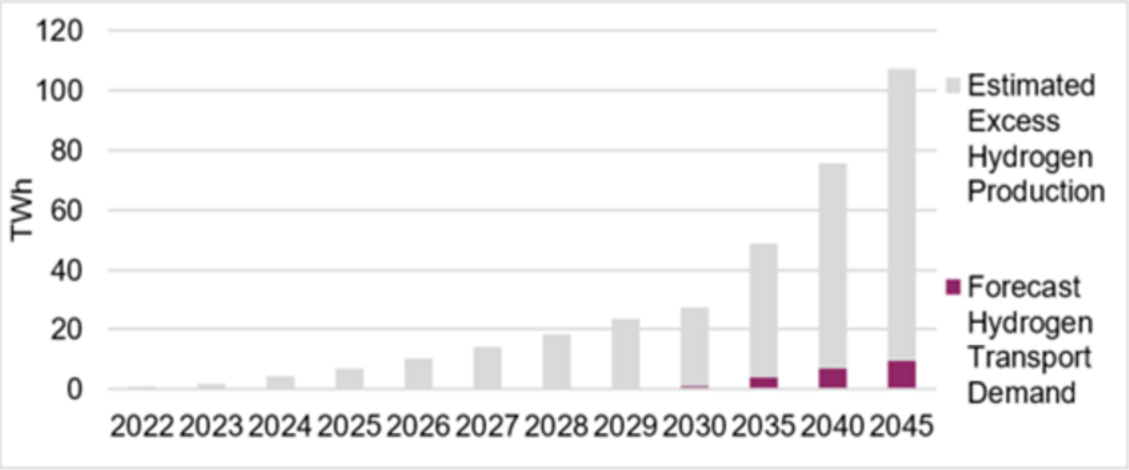
Scenario 4: HL



Scenario 5: HH



Scenario 6: MM



Chapter 3: Road

3.0 Introduction

Road transport comprised approximately 64% of transport greenhouse gas emissions according to the *Scottish Transport Statistics No. 39 2020 Edition*. Technological improvements have led to a reduced carbon emissions for every kilometre travelled, however the overall demand for transport has continued, leading to a consistent increase in road transport emissions over time.

Whilst road transport is a large source of current emissions, it is also the transport mode with one of the greatest immediate potential to decarbonise. The technology transition is already available with electric vehicle (EV) technology uptake on the rise for new cars across the UK.

This increase is leading the way for other light goods vehicles such as vans, which are expected to follow passenger car trajectory in the years to come. In terms of the technology for larger vehicles to transition to zero emission energy, particularly HGVs for long-distance road freight, it is in a more developmental stage.

3.1 Methodology

The electricity and hydrogen demand for cars, vans and HGVs has been constructed using a bottom-up approach, described in the following sections. This involved first considering transport demand projections (Section 3.1.1), before calculating fleet numbers (Section 3.1.2) and then estimating current and future vehicle fleet efficiency (Section 3.1.3).

From there, technology transition scenarios were constructed (Section 3.1.4) based on available information on uptake of electricity and hydrogen technology for road-based vehicles. An energy demand analysis was then undertaken (Section 3.1.5) to provide results mode-by-mode. Finally, the limitations of this approach are discussed in Section 3.1.6.

3.1.1 Transport Demand Forecasts

The TMfS:18 is Transport Scotland’s national transport model and has been used as the basis for road transport demand for this study. It is a multimodal, strategic transport model, which provides a broad representation of transport supply and estimates of transport demand, which has a base year of data from 2018.

The transport network covered by TMfS:18 includes all significant road and rail links on the Scottish mainland and the connections to significant islands. However, it represents few local roads and residential streets. Instead, TMfS:18 includes motorways, trunk, and principal roads (A class) and provides forecasts for these roads for 2019, 2025, 2030, 2035, 2040 and 2045, for cars, Light Goods Vehicles (LGVs), HGVs, buses and coaches.

There are two transport demand scenarios represented within TMfS:18, developed as part of the ongoing Strategic Transport Projects Review (STPR2) – High and Low (demand). For the purposes of this study, the Low scenario has been selected and forecast vehicle kilometres were extracted for each vehicle type for each year.

The Low scenario was selected due to its consistency with the current net-zero policy ambitions of the Scottish Government and include a sustained 20% reduction in the distance travelled by car by 2030 to meet Scotland’s emissions target by 2045. Under this scenario, the cost of travel by car must increase.

To supplement TMfS:18 forecasts, the UK Department for Transport’s (DfT) road traffic statistics have also been used where applicable. These provide estimates of the vehicle distance travelled each year in Scotland by vehicle type, road category and local authority area. This data is comparative with the TMfS:18 model overall (if the minor roads category is omitted), and hence the following steps have been undertaken as part of the methodology:

- For cars, LGVs, and buses, the TMfS:18 vehicle kilometre figures for 2019 are lower than the DfT licensing statistics estimates for the same year. This is because it is mainly cars, LGVs, and buses that operate on the minor roads and residential streets of Scotland that are not represented in TMfS:18.
- The difference between the DfT licensing statistics estimates and TMfS:18 data for each local authority area was used to estimate local road demand, disaggregated between Car, LGVs, and buses and was then added to the TMfS:18 data.
- The car element of this local road demand was assumed to reduce by 20% in line with the car vehicle kilometre figures from TMfS:18, while the distance travelled by LGVs, buses and coaches on non-modelled local roads was assumed to be constant through to 2045.
- For vans, the projections for hydrogen van production were adjusted as the original estimates were based on significant uncertainty surrounding the split between hydrogen and electric vans.
- For scheduled buses, and coaches, comparison between the TMfS:18 data and DfT licensing statistics indicated a shortfall. For example, the DfT dataset VEH004 indicates 12,500 buses, coaches and minibuses were licensed in Scotland at the end of 2020. TMfS:18 which only accounts for scheduled

buses and coaches estimated approximately only a third of that amount. Given a lack of Scottish data, this study assumes that the proportion of minibuses in Scotland is consistent with the UK and that buses and coaches make up 44% of these– a total of 5,500 vehicles.

- The buses and coaches in TMfS:18 are public service vehicles that follow a fixed route and run to a fixed timetable. For simplicity it has been assumed that these services are all provided by buses (not coaches). Private hire vehicle estimates have been added within the total of 5,500. In practice some scheduled services would be operated by coaches and private hires by buses, but these were deemed to be such a small proportion this simplification would not significantly alter the results.
- This study used unaltered TMfS:18 data for HGV demand as the TMfS:18 data for HGV in 2019 is slightly higher than the DfT estimates for 2019, which implies that TMfS:18 fully represents the road network used by HGV.

It should be noted that although TMfS:18 is a multimodal transport model, the public transport forecasts are for passenger demand that is likely to use a specified service provision. TMfS:18 does not forecast the number of buses or coaches that may be required to accommodate a significant increase in public transport demand and simply assumes higher occupancy of existing buses and coaches services.

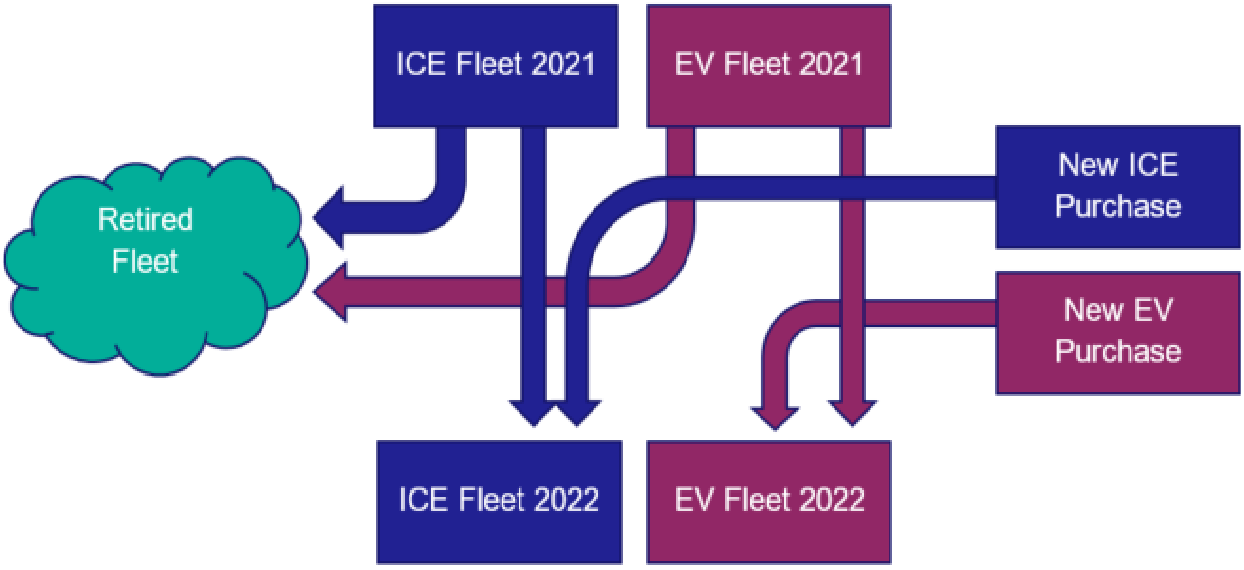
Furthermore, TMfS:18 includes only scheduled bus and coach services available to the general public and does not include privately owned and private hire vehicles – hence the adjustments made in the aforementioned methodology. Finally, TMfS:18 does not include rail freight and therefore HGV demand does not take account of aspirations to shift freight from road to other modes - like rail or coastal shipping.

3.1.2 Vehicle Fleet Numbers

Using TMfS:18 as the basis for transport demand, the vehicle fleet profile for any given year has been developed by calculating the uptake of zero emission technology across the different road vehicles as a function of the transition into the existing fleet, combined with the probability that those new vehicles will be zero emission.

Figure 8 is a schematic diagram showing how the road vehicle fleet alters year-on-year from 2021 to 2022 as an example. It shows how the composition of the vehicle fleet changes with the purchase of new vehicles and the removal of vehicles through the typical retirement (scrapping) process. Over time, the continuation of this process means the relative size of the vehicle fleet in terms of ICE and EV numbers will shift towards EVs - as a greater percentage of new vehicle purchases become electric.

Figure 8. Annual flow of vehicles within the vehicle fleet 2021-22

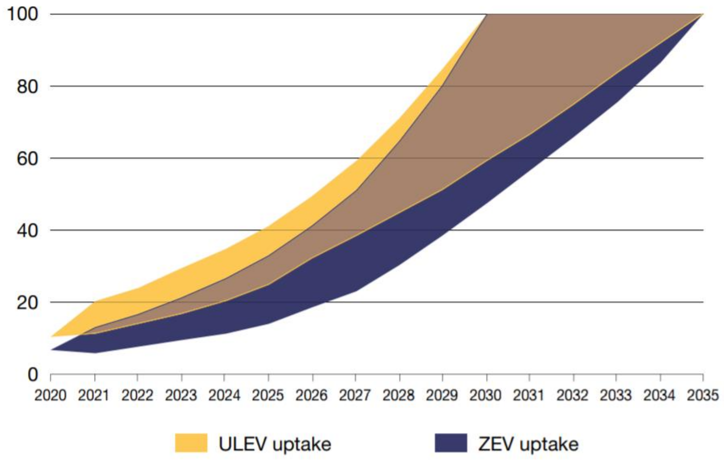


To model future fleet composition, requires establishing the current state (i.e. the fleet for 2021), the number of vehicles which will be scrapped from the vehicle fleet in any given year, the number of new vehicles which will be purchased in any given year and the percentage of those vehicles that will be zero emission. As such, the process undertaken to establish vehicle fleet numbers was as follows:

- To maintain a consistency with the outputs from TMfS:18, the total number of zero-emission vehicles has been scaled to meet the total number of vehicles per year in line with the model's forecast. This is to prevent the model diverging from the known values presented within the TMfS:18 and a necessary step as bottom-up derived models tends to be constructed as an ongoing process from a known initial output - in this case the TMfS:18 vehicle fleet at 2021.
- To simplify the underlying model, it was assumed that for the years previous to 2021, the vehicle fleet existed in a "steady state", meaning that the number of vehicles leaving the fleet was the same as those entering the fleet. Therefore, the vehicle fleet would be comprised of a cohort of vehicles with an age evenly distributed between 0 years, and the typical year of scrappage. For 2021 this was enhanced with the addition of Battery Electric Vehicle (BEV), Plug-in Hybrid Electric Vehicle (PHEV) and Hydrogen Electric Vehicle (HEV) with an amount for each year determined by TMfS:18.
- The type of vehicle purchased in each year, was derived from the UK's *Transitioning to zero emission cars and vans: 2035 delivery plan* for cars and vans, and the Climate Change Committee's (CCC) *Analysis to provide costs, efficiencies and roll-out trajectories for zero emission HGVs, buses and coaches* for HGVs. Both documents provide a breakdown on the percentage

of new vehicles which will be zero-emission under a range of different potential scenarios, an example is shown in **Figure 9.**

Figure 9. Percentage of new car sales accounted for by ULEV and ZEVs, from *DfT Transitioning to zero emission cars and vans: 2035 delivery plan*, page 5



Aside from the process itself, the inclusion of hydrogen vehicles within the car and van fleets are one of the greatest areas of technological uncertainty for the forecast results, further discussed in Section 3.1.4 below. However, for the purposes of the study, the trajectory of hydrogen vehicle uptake is assumed to follow TMfS:18 demand figures and vans to track closely to car uptake. This means the total number of hydrogen vehicles is predicted to peak in approximately 2035, with improvements in battery technology leading to a greater percentage of BEV by 2045.

In terms of HGVs, there is a much greater level of analysis available for the potential transition to hydrogen, combined with a greater confidence in this transition occurring for this vehicle type. As such, the hydrogen numbers for HGVs were taken directly from the CCC's *Analysis to provide costs, efficiencies and roll-out trajectories for zero emission HGVs, buses and coaches*.

3.1.3 Vehicle Fleet Efficiency

In addition to the vehicle numbers within the fleet, it is also critical to understand vehicle efficiency rates in each year forecast - as this will also affect the total energy demand for transport. While there are varying sources for efficiency values, this study relied on the following to guide energy demand for transport forecasting:

- The Transport Analysis Guidance (TAG) Data Book values for vehicle efficiency were used for the expected efficiency for BEVs for the car and van fleets up to 2045.

- For PHEVs, the International Council on Clean Transportation's (ICCT) white paper: *Real-world usage of plug-in hybrid electric vehicles: Fuel consumption, electric driving, and CO2 emissions* was used to derive a value for energy usage – approximately one third of the energy of a BEV.
- As HEV (non-plug-in hybrids) do not use electricity at source, they are not included as a separate vehicle class in this study.
- HGV estimates for BEVs was derived from multiple different sources to provide a composite estimate for the kWh/km for a typical HGV.
- For hydrogen vehicles, the only commercially available vehicle, the latest Toyota Mirai, was used to provide efficiency estimates for hydrogen consumption per km for vans and HGVs, through direct scaling against the BEV efficiencies.

Although this final technique is an approximation, with the potential to underestimate the efficiency of the larger vehicles due to the greater impact of battery weight, it does provide a value from which to improve future forecasts.

3.1.4 Technology Transition Scenarios

As introduced in Section 1.3, six technology transition scenarios have been developed for the purposes of forecasting future electric and hydrogen energy demand for transport. The following describes the key assumptions for each vehicle type within road transport for each technology scenario:

Road Scenario 1 (LH)

- **Cars and Vans:** Follow the slowest uptake rate for zero-emission vehicles as per DfT's forecast range in **Figure 9**, leading to a greater volume of PHEV within the car/van vehicle fleet. This uptake rate represents the minimum to meet the requirement that all new fleets will become fully zero-emission by 2035. Fleet numbers of hydrogen powered cars and vans are equal to those proportions specified by the *Decarbonising the Scottish Transport Sector Final Report* as applied to TMfS:18.
- **HGVs:** Assumed to follow the high uptake rates for hydrogen and the low uptake rates for electric, as specified within the report for the Climate Change Committee: *Analysis to provide costs, efficiencies, and roll-out trajectories for zero emission HGVs, buses and coaches*.
- **Coaches and Scheduled Buses:** It is assumed that they are typically retired (scrapped) every 15 years. Initially, the entire fleet is diesel-powered and the number to be scrapped each year is determined based on the age of the fleet. In this scenario the last new diesel buses are introduced in 2033 and coaches in 2039, with these retiring from service to give a net zero bus fleet in

2041 and coach fleet in 2044. These dates are chosen to give some useful life for the diesel vehicles before they are withdrawn and to meet the target for all road vehicles to be zero emission by 2045. However, this policy does not meet current Scottish Government ambitions, rather is included for comparison only.

- The replacement rate mix of diesel, electric and hydrogen is taken from the *Analysis to provide costs, efficiencies, and roll-out trajectories for zero emission HGVs, buses and coaches*, adjusted in accordance with the sensitivity analysis in that report for a case with high battery costs and low fuel cell costs. After the last diesel vehicles are introduced, the proportion of electric and hydrogen vehicles is increased to take up the share that would otherwise be forecast as diesel.
- Replacement rates are different for buses and coaches. This is the only distinction made between buses and coaches; the same average annual mileage is used for both.

Road Scenario 2 (ML)

- **Cars and Vans:** Are assumed to follow the average of the slowest and highest uptake rates for zero-emission vehicles as per DfT’s forecast range, resulting in a moderate volume of PHEV within the car/van vehicle fleet. The new fleets become fully zero-emission by 2032-2033. hydrogen powered cars/vans will be at 1/3 of the aggregate levels specified by the *Decarbonising the Scottish Transport Sector Final Report* as applied to TMfS:18.
- **HGVs:** Assumed to follow the same trajectory as the high transition to electric and low transition to hydrogen, due to the restrictions imposed by the uptake scenarios.
- **Coaches and Scheduled Buses:**
- It is assumed that they are typically retired (scrapped) every 15 years. Initially, the entire fleet is diesel-powered and the number to be scrapped each year is determined based on the age of the fleet. In this scenario the last new diesel buses are introduced in 2029 and coaches in 2039, with these retiring from service to give a net zero bus fleet in 2044 and coach fleet in 2045. These dates are chosen to give some useful life for the diesel vehicles before they are withdrawn and to meet the target for all road vehicles to be zero emission by 2045. However, this policy does not meet current Scottish Government ambitions, rather is included for comparison only.
- The replacement rate mix of diesel, electric and hydrogen is taken from the *Analysis to provide costs, efficiencies, and roll-out trajectories for zero emission HGVs, buses and coaches*, adjusted in accordance with the sensitivity analysis in that report for a case with high fuel cell costs. After the last diesel vehicles are introduced, the proportion of electric and hydrogen

vehicles is increased to take up the share that would otherwise be forecast as diesel.

- Replacement rates are different for buses and coaches. This is the only distinction made between buses and coaches; the same average annual mileage is used for both.

Road Scenario 3 (MH)

- **Cars and Vans:** Are assumed to follow the average of the slowest and the highest uptake rates for zero-emission vehicles as per DfT's forecast range, resulting in a moderate volume of PHEV within the car/van vehicle fleet. For both cars and vans, the new fleet will become fully zero-emission by 2032-2033. hydrogen powered cars/vans will be at the same level as specified in the *Decarbonising the Scottish Transport Sector Final Report* and applied to TMfS:18.
- **HGVs:** Assumed to follow the same trajectory as the high transition to hydrogen and low transition to electric, due to the restrictions imposed by the uptake scenarios.
- **Coaches and Scheduled Buses:**
- It is assumed that they are typically retired (scrapped) every 15 years. Initially, the entire fleet is diesel-powered and the number to be scrapped each year is determined based on the age of the fleet. In this scenario the last new diesel buses are introduced in 2032 and coaches in 2035, with these retiring from service to give a net zero bus fleet in 2033 and coach fleet in 2035. These dates are chosen to give some useful life for the diesel vehicles before they are withdrawn and to meet the target for all road vehicles to be zero emission by 2045. However, this policy does not meet current Scottish Government ambitions, rather is included for comparison only.
- The replacement rate mix of diesel, electric and hydrogen is taken from the *Analysis to provide costs, efficiencies, and roll-out trajectories for zero emission HGVs, buses and coaches*, adjusted in accordance with the sensitivity analysis in that report for a case with low fuel cell costs. After the last diesel vehicles are introduced, the proportion of electric and hydrogen vehicles is increased to take up the share that would otherwise be forecast as diesel.
- Replacement rates are different for buses and coaches. This is the only distinction made between buses and coaches; the same average annual mileage is used for both.

Road Scenario 4 (HL)

- **Cars and Vans:** Assumed to follow the highest uptake for zero-emission vehicles as per DfT's forecast range, resulting in a low volume of PHEV within the fleet. The new fleet will become fully zero-emission by 2030. hydrogen powered cars and vans will be at 1/3 the level as specified in the *Decarbonising the Scottish Transport Sector Final Report* and applied to TMfS:18.
- **HGVs:** Will follow the low uptake rates for hydrogen and the high uptake rates for electric, as specified within *Analysis to provide costs, efficiencies, and roll-out trajectories for zero emission HGVs, buses and coaches*.
- **Coaches and Scheduled Buses:**
- It is assumed that they are typically retired (scrapped) every 15 years. Initially, the entire fleet is diesel-powered and the number to be scrapped each year is determined based on the age of the fleet. This scenario meets the government pledge to remove the majority of fossil fuel buses in public transport by 2023, after which date no new diesel buses are introduced. The last new diesel coaches are introduced in 2033. The last diesel vehicles retire from service to give a net zero bus fleet in 2033 and coach fleet in 2036. This scenario therefore meets current Scottish Government ambitions.
- The replacement rate mix of diesel, electric and hydrogen is taken from the *Analysis to provide costs, efficiencies, and roll-out trajectories for zero emission HGVs, buses and coaches*, adjusted in accordance with the sensitivity analysis in that report for a case with low battery costs and high fuel cell costs. After the last diesel vehicles are introduced, the proportion of electric and hydrogen vehicles is increased to take up the share that would otherwise be forecast as diesel.
- Replacement rates are different for buses and coaches. This is the only distinction made between buses and coaches; the same average annual mileage is used for both.

Road Scenario 5 (HH)

- **Cars and Vans:** Are assumed to follow the highest uptake for zero-emission vehicles, resulting in a low volume of PHEV within both fleets – becoming fully zero-emission by 2030. hydrogen powered cars and vans will be at the same level as specified in the *Decarbonising the Scottish Transport Sector Final Report* as applied to TMfS:18.
- **HGVs:** Assumed to follow the same trajectory as the mixed transition to electric and hydrogen, due to the restrictions imposed by the uptake scenarios.
- **Coaches and Scheduled Buses:**

- It is assumed that they are typically retired (scrapped) every 15 years. Initially, the entire fleet is diesel-powered and the number to be scrapped each year is determined based on the age of the fleet. This scenario meets the government pledge to reduce the number of diesel powered buses by half by the end of 2023 and then the last new diesel buses are introduced in 2023 and coaches in 2031. The last diesel buses retire from service to give a net zero bus fleet in 2030, meeting an additional Climate Group target. The coach fleet becomes net zero in 2033. This scenario therefore meets current Scottish Government ambitions.
- The replacement rate mix of diesel, electric and hydrogen is taken from the *Analysis to provide costs, efficiencies, and roll-out trajectories for zero emission HGVs, buses and coaches*, adjusted in accordance with the sensitivity analysis in that report for a case with both low battery costs and low fuel cell costs. After the last diesel vehicles are introduced, the proportion of electric and hydrogen vehicles is increased to take up the share that would otherwise be forecast as diesel.
- Replacement rates are different for buses and coaches. This is the only distinction made between buses and coaches; the same average annual mileage is used for both.

Road Scenario 6 (MM)

- **Cars and Vans:** Are assumed to follow the average of the slowest and highest uptake rates for zero-emission vehicles, with the result that there will be a moderate volume of PHEV within the car/van vehicle fleet. The new fleets will become fully zero-emission by 2032-2033. hydrogen powered cars/vans will be at 2/3 of the level specified by the *Decarbonising the Scottish Transport Sector Final Report* applied to TMfS:18.
- **HGVs:** are assumed to follow the medium uptake rates for hydrogen and electric, as specified within: *Analysis to provide costs, efficiencies, and roll-out trajectories for zero emission HGVs, buses and coaches.*
- **Coaches and Scheduled Buses:**
- It is assumed that they are typically retired (scrapped) every 15 years. Initially, the entire fleet is diesel-powered and the number to be scrapped each year is determined based on the age of the fleet. In this scenario the last new diesel buses are introduced in 2033 and coaches in 2035, with these retiring from service to give a net zero bus fleet in 2035 and coach fleet in 2038. These dates are chosen to give some useful life for the diesel vehicles before they are withdrawn and to meet the target for all road vehicles to be zero emission by 2045. However, this policy does not meet current Scottish Government ambitions, rather is included for comparison only.

- The replacement rate mix of diesel, electric and hydrogen is taken from the baseline case in *Analysis to provide costs, efficiencies, and roll-out trajectories for zero emission HGVs, buses and coaches*. After the last diesel vehicles are introduced, the proportion of electric and hydrogen vehicles is increased to take up the share that would otherwise be forecast as diesel.
- Replacement rates are different for buses and coaches. This is the only distinction made between buses and coaches; the same average annual mileage is used for both.

3.1.5 Limitations

Overall, the mix of electric vehicles and hydrogen-powered vehicles continues to be in proportion to the *Analysis to provide costs, efficiencies, and roll-out trajectories for zero emission HGVs, buses and coaches*, although that model assumes that use of diesel continues – this assumption has not been adopted. Other modal limitations as follows:

- **Overall:** It is assumed that each vehicle has a fixed annual mileage each year.
- **Cars and Vans:** the scale of future EV uptake is relatively unknown. Whilst the scenarios presented represent reasonable approximations of possible future scenarios, it is plausible that uptake may be faster, or supply issues slow production of vehicles.
- **HGVs**: Unlike cars and vans, there is no developed technological pathway and as such there is uncertainty of the potential of any technology to become mature enough in the time required to enact the needed transition.
- **Coaches and Scheduled Buses**: In the absence of specific data on coach journeys all buses and coaches are assumed to cover the same daily mileage - whereas in practice coaches are likely to make longer journeys. Since the predicted number of vehicles powered by hydrogen is made up of more coaches than buses, this will to some extent underestimate the hydrogen demand in each scenario.
- Coaches have been assumed to use the same amount of energy per kilometre as a single decker bus.
- The energy demand for hydrogen buses and coaches of each type is calculated from the electricity demand. The energy needed for the hydrogen bus is factored up by 67% to allow for losses in a fuel cell with an assumed efficiency of 0.6. This results in the same amount of energy entering the traction battery in the hydrogen vehicle as in the electric vehicle. This value for fuel cell efficiency is taken from testing data on hydrogen fuel cells .

3.2 Energy Demand Forecasts

Having defined the approach taken to establishing transport demand forecasts, vehicle fleet numbers, age, efficiency, as well as technology transition scenarios in **Section 3.1**, electric and hydrogen energy demand forecasts were then developed for road transport, according to the following equation:

$$Energy_{year} = \sum_{year,mode,fuel} eff_{year,mode,fuel} \times Veh\#_{year,mode,fuel} \times mileage_{mode,fuel}$$

The results of these energy demand calculations for each vehicle type within road transport are outlined in the following **Sections 3.2.1 – 3.2.4**, and a discussion of their implications is contained within **Section 3.3**.

3.2.1 Cars

In terms of road transport, cars have the greatest certainty in terms of future pathways to zero-emission energy, and the largest impact of all transport modes in terms of emissions reduction. The technology transition is already well under way, however the speed in which it will be completed, is still uncertain.

As shown in **Tables 5 to 9**, the majority of zero emission cars will be electric – with only a small demand for hydrogen. This is shown across the scenario's results. Hydrogen demand ranges from 3-4 GWh in 2022, to between 176-503 GWh in 2045. Conversely, demand for electricity ranges from between 121-146 GWh in 2022, to between 6,044-6,470 GWh in 2045.

As such, the results demonstrate that while the proportion of the fleet that is electric versus hydrogen is relatively constant, the rate of transition varies considerably.

Table 5. Forecast electric and Hydrogen energy demand for cars under scenario 1: LH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	4	10	43	202	410	503
Electric	121	414	1,241	2,962	4,859	6,044

Table 6. Forecast electric and Hydrogen energy demand for cars under scenario 2: ML (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	3	5	16	70	142	176
Electric	134	505	1,576	3,665	5,569	6,470

Table 7. Forecast electric and Hydrogen energy demand for cars under scenario 3: MH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	4	10	43	202	410	503
Electric	134	503	1,564	3,595	5,417	6,273

Table 8. Forecast electric and Hydrogen energy demand for cars under scenario 4: HL (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	3	5	16	70	142	176
Electric	147	594	1,902	4,050	5,861	6,470

Table 9. Forecast electric and Hydrogen energy demand for cars under scenario 5: HH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	4	10	43	202	410	503
Electric	146	592	1,887	3,973	5,700	6,273

Table 10. Forecast electric and Hydrogen energy demand for cars under scenario 6: MM (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	4	7	30	137	278	343
Electric	134	504	1,570	3,630	5,492	6,370

3.2.2 Vans (LGVs)

Although the transition to electric vans is currently slower than cars, the technology has now been proven under almost all use cases and it is expected that the transition to zero emission will be able to proceed at pace, under the assumptions outlined in *UK Transitioning to zero emission cars and vans: 2035 delivery plan*

However, it is expected technology uptake will be similar to projections for the car fleet – as there are currently no commercial hydrogen LGVs for sale in Scotland and so even these reduced figures may be optimistic.

As shown in **Tables 11 to 16**, the majority of zero emission vans and LGVs will be electric – with only a small demand for hydrogen. This is shown across all the scenario's results. hydrogen demand ranges from 0-1 GWh in 2025, to between 25-73 GWh in 2045. Conversely, demand for electricity ranges from between 14-18 GWh in 2022, to between 1,344-1,456 GWh in 2045.

Table 11. Forecast electric and Hydrogen energy demand for vans and LGVs under scenario 1: LH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	1	9	36	58	72
Electric	14	63	251	634	1,028	1,344

Table 12. Forecast electric and Hydrogen energy demand for vans and LGVs under scenario 2: ML (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	3	12	20	25
Electric	16	81	343	829	1,195	1,443

Table 13. Forecast electric and Hydrogen energy demand for vans and LGVs under scenario 3: MH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	1	9	37	59	72
Electric	16	80	340	817	1,174	1,415

Table 14. Forecast electric and Hydrogen energy demand for vans and LGVs under scenario 4: HL (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	3	12	20	25
Electric	18	98	433	952	1,286	1,456

Table 15. Forecast electric and Hydrogen energy demand for vans and LGVs under scenario 5: HH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	1	9	37	59	73
Electric	18	98	430	938	1,263	1,427

Table 16. Forecast electric and Hydrogen energy demand for vans and LGVs under scenario 6: MM (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	1	6	25	39	49
Electric	16	80	341	823	1,184	1,429

3.2.3 Coaches and Scheduled Buses

Electric buses are already an established technology with significant fleets in place; there are 1,000 vehicles in service already in the UK and more planned. By contrast, although Scotland began the process of trialling the use of hydrogen buses in Aberdeen back in 2011, the first hydrogen fuel cell fleet of 20 buses in England was introduced only recently.

Importantly, Scenarios 4 and 5 are in keeping with recent announcements by the Scottish Government of an intent to remove the majority of fossil fuel buses in public transport by 2023; due to technology availability, this is likely to lead to a dominance of electric buses in the near term.

As hydrogen is not yet widely adopted, all forecast scenarios show a significant transition to electric buses with only a small role for hydrogen in the near term. **Tables 17 to 22** show hydrogen demand ranges from 3-22 GWh in 2025, to between 25-111 GWh in 2045. Conversely, demand for electricity ranges from between 20-230GWh in 2025, to between 511-563 GWh in 2045.

Table 17. Forecast electric and Hydrogen energy demand for buses and coaches under scenario 1: LH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	5	19	48	71	117	111
Electric	6	20	72	157	451	511

Table 18. Forecast electric and Hydrogen energy demand for buses and coaches under scenario 2: ML (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	1	3	12	12	39	42
Electric	12	39	113	113	418	552

Table 19. Forecast electric and Hydrogen energy demand for buses and coaches under scenario 3: MH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	9	22	66	141	132	81
Electric	21	46	167	473	499	552

Table 20. Forecast electric and Hydrogen energy demand for buses and coaches under scenario 4: HL (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	2	4	9	21	29	25
Electric	114	230	350	549	561	563

Table 21. Forecast electric and Hydrogen energy demand for buses and coaches under scenario 5: HH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	9	22	52	70	69	56
Electric	114	230	449	536	536	544

Table 22. Forecast electric and Hydrogen energy demand for buses and coaches under scenario 6: MM (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	5	13	36	85	89	73
Electric	21	46	139	457	524	534

3.2.4 HGVs

For HGVs the forecasting results across the scenarios show a much more even split between energy demand for hydrogen and electric solutions. This is due to the current technological limitation in both electric and hydrogen for the longer journeys that HGVs are required to make as freight deliveries.

As such, the differences between the results for each of the scenarios is driven by the relative split between hydrogen and electric uptake in the early years. **Tables 23 to 28** show hydrogen demand as 0 GWh until 2025 after which it starts to increase. By 2045, hydrogen demand ranges between 1,301-3,359 GWh – a considerable disparity. Conversely, demand for electricity ranges is steady at 54 GWh in 2022, before increased to between 2,505-3,515 GWh in 2045.

Table 23. Forecast electric and Hydrogen energy demand for HGVs under scenario 1: LH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	498	1,594	2,500	3,359
Electric	54	239	600	1,140	1,801	2,279

Table 24. Forecast electric and Hydrogen energy demand for HGVs under scenario 2: ML (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	492	1,628	2,455	2,983
Electric	54	239	603	1,119	1,828	2,505

Table 25. Forecast electric and Hydrogen energy demand for HGVs under scenario 3: MH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	492	1,628	2,455	2,983
Electric	54	239	603	1,119	1,828	2,505

Table 26. Forecast electric and Hydrogen energy demand for HGVs under scenario 4: HL (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	225	556	922	1,301
Electric	54	239	763	1,764	2,749	3,515

Table 27. Forecast electric and Hydrogen energy demand for HGVs under scenario 5: HH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	225	556	922	1,301
Electric	54	239	763	1,764	2,749	3,515

Table 28. Forecast electric and Hydrogen energy demand for HGVs under scenario 6: MM (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	492	1,628	2,455	2,983
Electric	54	239	603	1,119	1,828	2,505

3.3 Implications

The major implications from the results from the electric and hydrogen energy demand modelling for road transport are as follows:

- **Cars and Vans:** under all scenarios there will need to be a substantial investment in the ability to provide electric power for road transport. The transition to zero-emission vehicles will be dominated by electric technology in this vehicle type. This requires grid reinforcement both in terms of localised supply, and in overall generation.
- **Coaches and Scheduled Buses:** It seems highly likely the pathway to removing the majority of the fossil fuel (diesel) bus fleet by the end of 2023 will be through the rapid uptake of electric buses. Even in the lower electricity and higher hydrogen scenarios, hydrogen usage never exceeds 25% of the total energy demand for buses and coaches by 2045.
- **HGVs:** across the scenarios the energy sources, either electric or hydrogen are far more mixed dependent on the scenario, with the potential for substantial hydrogen capacity to be made available to the HGV fleet.

Chapter 4: Rail

4.0 Introduction

According to Scottish Transport Statistics 2020, there were 97 million passenger journeys originating in Scotland and 4.3 million tonnes of freight lifted by rail in 2019-20 - yet rail accounts for less than 5% of carbon emissions.

Nevertheless, rail is an important mode to decarbonise. The *Decarbonising the Scottish Transport Sector Final Report* released in September 2021 states under policy scenario three - the only scenario forecast to meet Scotland’s net-zero by 2045 ambitions – it also suggests to meet this ambition 23% of freight goods moved by road must be shifted to rail and ships by 2030.

4.1 Methodology

The electricity and hydrogen demand for rail, has been constructed using a bottom-up methodological approach as described in the following sections. These forecasts are split by energy type (electric and hydrogen) and have been produced for six different technology transition scenarios as outlined in Section 1.3.

This involved first considering transport demand projections (Section 4.1.1), before constructing, technology transition scenarios (Section 4.1.2) based on available information on uptake of electricity and hydrogen technology for rolling stock and railway lines.

An energy demand analysis was then undertaken (Section 4.1.3) to provide overall results, as well as split by Network Rail, ScotRail, Other Train Operating Companies (TOCs), and Freight Operating Companies (FOCs). Finally, the limitations of this approach are discussed in Section 4.1.4.

4.1.1 Transport Demand Forecasts

Unlike in the case of road transport, although TMfS:18 is a multimodal transport model, which includes a detailed representation of the Scottish rail network, it does not forecast the number of passenger trains required on the network - while freight trains are not represented.

Consequently, it was necessary to rely on data from Network Rail, ScotRail, the other TOCs, and FOCs to prepare transport demand forecasts for rail. This means rail demand forecasts have been derived from current demand with various assumptions being made with regards the future.

The information available for this study on current travel or electricity demand varies by train service provider, and is detailed, along with the accompanying assumptions for transport demand forecasting below:

- Network Rail's Electricity Supply Tariff Areas (ESTAs) to charge train operators for Electric Current for Traction provides outturn data in kWh for the four Scottish ESTAs for the year 2019/20, disaggregated by TOC and FOC.
- ScotRail provided via Network Rail, data detailing the number of vehicle miles travelled by each vehicle type on each service route for 2019/2020.
- It was assumed that Avanti West Coast, TransPennine Express and Serco Caledonian Sleepers, which all operate cross border trains, will continue to operate the same rolling stock with the same service frequency through to 2045 and that the electricity consumption for these operators in 2019/20 will be typical of all future years. This means that the assumed electricity usage for these TOCs is the same in all scenarios and scenario years. There may be growth in the number of passengers, but the number of trains is assumed to remain the same.
- For Cross Country trains, which currently operate an all-diesel fleet, it was assumed that the existing diesel-powered trains will continue to operate through to the end of 2035, at the same frequency as the 2021 timetable, at which point all services will switch to 5-car Class 800 bi-mode multiple units or some similar type of unit.
- London and North Eastern Railway (LNER) currently operate a fleet of 9-car Class 800 bi-mode trains, which draw power from the 25 kV overhead wire between Berwick-upon-Tweed and Edinburgh Waverley, Haymarket, Dunblane and Glasgow Central. Existing levels of electricity usage for the services to Edinburgh and Glasgow are included in the ESTA data supplied by Network Rail for 2019/20.
- To the north of Haymarket and Dunblane, the Aberdeen and Inverness services are currently diesel powered and it is assumed that in all future years through to 2045 these trains will continue to operate at the same frequency as the 2021 timetable but will switch from diesel power to overhead electric power as electrification of the mainlines north of the Central Belt are completed.

The information available for this study on current travel or electricity demand also varies by freight service provider, and is detailed, along with the accompanying assumptions below:

- It is assumed Anglo-Scottish freight trains could be considered to operate to and from the Scottish Central Belt via the West Coast Mainline (WCML) from Carlisle, or via the East Coast Mainline (ECML) from Berwick-upon-Tweed.

- Within Scotland, the principal services are assumed to operate from the Central Belt to Aberdeen and Inverness.
- Reference was made to the Scottish freight section of Network Rail's Working Timetable (WTT) for May - December 2021 to ascertain the existing level of demand based on reserved train paths immediately north of Carlisle and Berwick-upon-Tweed and immediately south of Aberdeen and Inverness.
- For each path in the WTT, a train was assumed to run on the days stated, except for the paths marked as 'runs as required'. For these paths, it was assumed that the booked train typically runs 50% of the time.
- All paths that are timed for electric locomotive haulage were ignored, as the energy draw from those services is included within the ESTA data, which is assumed to be constant over time in relation to existing electric hauled services.
- For the diesel hauled trains, it was assumed that the number of trains per annum is constant through to 2029, but these trains may be longer and heavier in the future, once they switch to electric traction. *Network Rail's Traction Decarbonisation Network Strategy Interim Programme Business Case* highlights that from a traction perspective, up to 87% greater tonnage could be hauled by an electric locomotive whilst still maintaining diesel timings.
- The WTT includes six diesel hauled freight paths between the Central Belt and Inverness and eight diesel hauled freight paths between the Central Belt and Aberdeen. The usage of these paths varies between a 'runs as required' service on only one day each week and paths that are used five, six or seven days per week. This equates to approximately 20 diesel hauled freight trains per week, or 1,040 diesel hauled freight trains per annum on the route to Inverness and 17.5 diesel hauled freight trains per week or 910 diesel hauled freight trains per annum on the route to Aberdeen.
- The maximum trailing weight of existing services to Inverness varies between 695 tonnes and 1,499 tonnes, while the maximum trailing weight of existing services to Aberdeen varies between 499 tonnes and 1699 tonnes. On each route, the heaviest service that currently operates is the Colas Rail service for Lafarge from Oxwellmains. On these routes rail freight services have an aggregate trailing load of up to around 950,000 tonnes per annum to Inverness and 1.1 million tonnes per annum to Aberdeen. Allowing for all electric hauled services to convey a trailing load of 1,800 tonnes would equate to a near doubling of freight moved to Inverness and a 50% increase in tonnes moved to Aberdeen, without increasing the number of freight paths.
- The WTT includes 33 diesel hauled freight paths on the ECML north of Berwick-upon-Tweed and 49 diesel hauled freight paths on the WCML north of Carlisle, which includes services routed via the Glasgow and Southwestern Route through Dumfries. The usage of these paths varies between a 'runs as required' service on only one day per week and paths that are used five or six

days per week. This equates to approximately 93 diesel hauled freight trains per week, or 4,836 diesel hauled freight trains per annum on the ECML and 130 diesel hauled freight trains per week, or 6,760 diesel hauled freight trains per annum on the WCML.

- The maximum trailing weight of existing services on the ECML varies between 499 tonnes and 2,299 tonnes, while the existing trailing weight of existing services on the WCML varies between 499 tonnes and 1,899 tonnes. On these routes rail freight services have an aggregate trailing load of up to 5.7 million tonnes per annum on the ECML and up to 6.8 million tonnes per annum on the WCML. Allowing for all electric hauled services to convey a trailing load of 1,800 tonnes would equate to a 50% increase in freight moved on the ECML and a 75% increase in freight moved on the WCML, without increasing the number of freight paths.
- The Rail Services Decarbonisation Action Plan highlights that there is demand for an additional four trains a day (in each direction) to both Aberdeenshire and Inverness-shire. For the purposes of this assessment, this has been interpreted as an additional 20 freight trains per week, or 1,040 freight trains per annum on each of the four core routes from the Scottish Central Belt to Aberdeen, Inverness, Berwick-upon-Tweed, and Carlisle by 2045, with one additional electric hauled freight train being added in 2030, a second in 2035, a third in 2040 and the final additional service in 2045. This equates to an additional 1.8 million tonnes of freight moved in each corridor by 2045 over and above the additional tonnage that could be conveyed through running longer and heavier trains.

Using the information detailed above, estimates of current transport demand on the rail network were generated. Building on this base demand, several assumptions have been applied to estimate future rail demand. Assumptions based on technology transition scenarios are detailed in **Section 4.1.2**.

- The planned May 2022 timetable will result in ScotRail operating 2,123 trains per day, which will provide 593,508 seats: approximately 92% of the number of seats provided by ScotRail in 2019.
- Although ScotRail anticipate running a similar number of services for the foreseeable future, it has been assumed that seat capacity and vehicle kilometres will recover to 2019/20 levels in 2030.
- The rate of recovery between 2022 and 2030 is assumed to be linear, with a 1% increase in seat capacity each year, from 92% in 2022, to 100% in 2030.
- It is assumed this level of demand will be constant, at pre-pandemic levels, between 2030 and 2045. These travel demand assumptions are consistent across all six scenarios.

Using these percentage values (percentage of future mileage relative to base mileage) and having data on the historic annual mileage of ScotRail services by unit type and route for 2019/20, a forecast for the total annual mileage of ScotRail services for each of the modelled years was created.

As indicated, for all other train services, it was assumed:

- The frequency and length of service provision is constant between the base year and 2045, with the only changes being the traction type.
- The number of annual trips for Cross Country, LNER, and freight services which currently operated by diesel traction is the same in all modelled years, with a switch in traction type assumed at the years defined in Section 4.1.2 below.
- The TOC and FOC services which are already electrified, and for which Network Rail supplied information on the total electricity usage, annual electricity consumption is constant across all modelled years and in all six scenarios.

4.1.2 Technology Transition Scenarios

As introduced in Section 1.3, six technology transition scenarios have been developed for the purposes of forecasting future electric and hydrogen energy demand for transport. The following describes the key assumptions for passenger and freight trains within rail transport for each technology scenario:

All scenarios

Passenger services:

- It has been assumed that expansion of overhead electrification will continue, but battery electric and hydrogen traction solutions will be required on peripheral sections of the network where service frequencies are lower.
- It is considered that overhead electrification of the Far North and West Highland lines is unlikely to be economic and battery electric traction is unlikely to have the range to operate services on this part of the network.
- Therefore, these lines are assumed to transition to passenger rolling stock powered by hydrogen fuel cells under all scenarios.
- Hydrogen fuel cell powered rolling stock may also be adopted for passenger services serving Stranraer and the Aberdeen to Inverness route and therefore these lines have been assumed to transition to hydrogen under the Medium and High transition scenarios.

Freight services:

- Transition to 25 kV overhead electric traction has been considered for all scenarios. Although some hydrogen powered locomotives are in development, it is not certain that these will be able to meet the demands of the freight market.
- Furthermore, a significant proportion of diesel-powered freight services currently run under a 25 kV overhead for a variety of reasons including: the lack of electrification at terminals; power constraints, particularly on the ECML, which means that there is already insufficient power for all current services to run on electric traction; and electrification gaps in England. If these network gaps are addressed, then using electric locomotives would be the most efficient solution.

Rail Scenario 1 (LH)

- No battery electric trains: all non-hydrogen lines are electrified with a 25 kV overhead.
- Hydrogen trains introduced on the Far North (2028 to Wick, 2029 to Kyle of Lochalsh), West Highland (2030), Stranraer services and Inverness to Aberdeen (2035).

Rail Scenario 2 (ML)

- Passenger trains serving Stranraer and operating on the Aberdeen to Inverness route will be Battery Electric Multiple Units (BEMUs) (2035).
- The Edinburgh to Tweedbank (2026) and Fife Circle services on the Levenmouth Branch Reopening will also use BEMUs (50% of all Fife Circle services in 2027).
- Hydrogen trains introduced on the Far North (2028 to Wick, 2029 to Kyle of Lochalsh) and West Highland (2030) only.
- The remainder of the network is assumed to be electrified with a 25 kV overhead.

Rail Scenario 3 (MH)

- Battery electric trains introduced to Edinburgh to Tweedbank (2026) and Fife Circle (50% in 2027 to reflect the reopening of the Levenmouth Branch Reopening).

- Hydrogen trains introduced on the Far North (2028 to Wick, 2029 to Kyle of Lochalsh), West Highland (2030), Stranraer services and Inverness to Aberdeen (2035).
- The remainder of the network is assumed to be electrified with a 25 kV overhead.

Rail Scenario 4 (HL)

- Battery electric trains introduced to Edinburgh to Tweedbank (2026), Fife Circle, Glasgow Central to Kilmarnock (2027), Glasgow Queen Street / Edinburgh Waverley to Perth, Dundee and Arbroath (50% in 2027, 100% in 2029), Glasgow Queen Street to Anniesland (2029), Aberdeen to Montrose, Glasgow Queen Street / Edinburgh Waverley to Aberdeen (2030), Glasgow Queen Street / Edinburgh Waverley to Inverness, Inverness to Aberdeen and Stranraer services (2035).
- Hydrogen trains introduced on the Far North (2028 to Wick, 2029 to Kyle of Lochalsh) and West Highland (2030) only.
- All remaining lines are assumed to be 25 kV overhead electric.

Rail Scenario 5 (HH)

- Battery electric trains introduced to Edinburgh to Tweedbank (2026), Fife Circle, Glasgow Central to Kilmarnock (2027), Glasgow Queen Street / Edinburgh Waverley to Perth, Dundee and Arbroath (50% in 2027, 100% in 2029), Glasgow Queen Street to Anniesland (2029), Aberdeen to Montrose & Glasgow Queen Street / Edinburgh Waverley to Aberdeen (2030) and Glasgow Queen Street / Edinburgh Waverley to Inverness (2035).
- Hydrogen trains introduced on the Far North (2028 to Wick, 2029 to Kyle of Lochalsh), West Highland (2030), Stranraer services and Inverness to Aberdeen (2035)
- All remaining lines are assumed to be 25 kV overhead electric.

Rail Scenario 6 (MM)

- Battery electric trains introduced to Edinburgh to Tweedbank (2026), Fife Circle (50% in 2027 to reflect the reopening of the Levenmouth Branch Reopening) and Inverness to Aberdeen (2035).
- Hydrogen trains introduced to the Far North (2028 to Wick, 2029 to Kyle of Lochalsh), West Highland (2030) and Stranraer services (2035).
- All remaining lines are assumed to be 25 kV overhead electric.

Using the methodology discussed in Section 4.1 of this report, two schedules for ScotRail services were produced. The first forecasts the total vehicle mileage for each route for each modelled year. The second contains the proportion of trips undertaken by each traction type along each route for each year and for each scenario.

For example, in scenario 1, 50% of trips from Glasgow Central to Barrhead or Kilmarnock in 2024 are assumed to be undertaken using overhead electric services. This is because the line is assumed to be electrified as far as Barrhead by that time, which means that the more frequent but shorter services between Glasgow Central and Barrhead can be operated by existing Electric Multiple Units (EMUs), whilst the longer and less frequent services to Kilmarnock will continue to be operated by Class 156 Diesel Multiple Units (DMUs).

Combining these two schedules a third schedule, which contains the total mileage undertaken by each traction type for each route, in each year and for each of the six scenarios was produced.

4.1.3 Energy Demand Analysis

The Energy Demand Analysis utilises the transport demand forecasts discussed in **Section 4.1.1**, the technology transition scenarios discussed in **Section 4.1.2**, and a series of additional modelling assumptions relating to energy usage to forecast future energy demand.

Electric Trains (Battery):

The core assumptions are the assumed rates of energy consumption for each traction type as follows:

- Vivarail, a British rolling stock manufacturer, has spent six years investigating, trialling, developing and testing battery technology for rail and has the UK’s only battery trains fully approved for passenger service.
- Vivarail supplied modelling data for a proposed Class 365 BEMU service between Windermere and Barrow-in-Furness, which indicated average electricity consumption at a rate of 5.6 kWh/mile.
- This rate has been used for all proposed BEMU services.

Hydrogen Trains:

Similarly, based on information from the *Zero Emission Train, Route to Market 2021* report published by ARUP, it has been assumed:

- All hydrogen vehicles consume fuel at a rate of 0.386 kg/mile. This was derived from an average of the modelling undertaken, which indicated:
    - 0.251 kg/km based on a Class 158 on the Far North line
    - 0.258 kg/km based on a Class 170 on the Far North line
    - 0.21 kg/km based on a Class 156 on the West Highland line.
- These figures are in line with data on the *Alstom Coradia iLint*, which various reports quote as using between 0.20 and 0.24 kg/km.

Electric Trains (Overhead):

Conversely, two differing rates of energy consumption have been used for ScotRail overhead electric services:

- For services that are already electrified, it has been assumed that energy is consumed per vehicle at a rate of 3.23 kWh/mile. This was derived by dividing ScotRail's Electric Current for Traction for 2019/20, as supplied by Network Rail, by the vehicle kilometre data provided by ScotRail for 2019/20 via Network Rail.
- For services that are yet to be electrified, but are anticipated to be electrified prior to 2045, a higher figure of 4.47 kWh/mile has been utilised. This was based on past modelling work undertaken by Network Rail to determine energy requirements for different types of rolling stock.
- It is not certain what rolling stock will be used in the future, so data for three modern EMUs was averaged. These were a 4-car Class 710 EMU running at 75 mph and stopping every 10 km; a 4-car Class 331 EMU running at 100 mph and stopping every 10 km; and a 4-car Class 360 EMU running at 100 mph and stopping every 10 km.
- The energy consumption figure used for each assumed that regenerative braking was turned off, which provided a marginally higher figure and therefore a more conservative estimate of potential energy demand.

Like the hydrogen and battery electric consumption figures assumed above, the inability to consider differing rates of electricity consumption for each route is a limitation of the model.

Network Rail also supplied data to create an estimate the future rate of electric consumption for Cross Country services, LNER services where they are currently diesel powered, and freight services which are currently operated by diesel traction, assumptions as follows:

- The same number of trains operating each year as is currently operated by these operators.

- Cross Country fleet will be replaced with 5-car Class 800 bi-mode units immediately after 2035.
- Current LNER 9-car Class 800 bi-mode units will switch to electric traction as 25 kV overhead is erected to the north of the Scottish Central Belt.
- Future Cross Country train services are assumed to consume 18.04 kWh/mile - based on a 5-car Class 800 Bi-mode unit running at 125 mph, stopping every 10 km with regenerative braking turned off.
- LNER services are assumed to consume 31.99 kWh/mile, based on a 9-car Class 800 Bi-mode unit running at 125 mph, stopping every 10 km with regenerative braking turned off.
- Freight services are anticipated to consume 79.52 kWh/mile, based on a Class 92 electric locomotive with a trailing load of 1,800 tonnes operating at 75 mph.

It should be noted that from the review of the train paths in the WTT, most freight trains currently operate with a trailing load of less than 1,800 tonnes, so although the energy forecasts make no explicit allowance for growth in the number of freight trains prior to 2030, the methodology adopted does assume that train lengths and weights increase following a switch to electric traction.

To calculate total energy demand for each route-scenario-year combination, the values in the third schedule, as indicated in Section 4.1.2 (mileage by traction type), were multiplied by the rates of energy consumption assumed for each traction type.

This generates a fourth schedule, which contains information on the energy consumption for each route-scenario-year combination, based on the traction type(s) operating that service. The summation of this schedule provides estimates of ScotRail electricity and hydrogen consumption/demand for each year between 2022 and 2030 and for 2035, 2040 and 2045.

The methodology used to forecast energy demand for all other train service providers is very similar. For Cross Country, LNER and freight services which are currently diesel, energy consumption has been forecast by multiplying the annual number of trips by the route length and by the energy consumption rate for that trip, dependent on the traction type expected to be used in each year. For the TOC and FOC services that are already electric, electricity consumption is assumed to be constant for all modelled years.

Finally, the actual rate of battery electric and hydrogen consumption will differ for each service route, dependent on route characteristics such as topography or gradient. The assumption that the rate of energy consumption will be consistent for all service routes operated by battery electric or hydrogen power is a limitation of the model.

4.1.4 Limitations

The *Decarbonising the Scottish Transport Sector Final Report* released in September 2021 states under PS3 - the only scenario forecast to meet Scotland's net-zero by 2045 ambitions - 23% of freight goods moved by road must be shifted to rail and ships by 2030. However, this policy does not identify the proportions of road freight that may shift to rail and the proportion that may switch to coastal shipping. As highlighted previously in 3.1.1 the road freight forecasts, based on output from TMfS:18, do not specifically consider the commitment for freight mode transfer.

These rail freight forecasts to 2030 include an assumption that electrification will result in longer and heavier freight trains, which will go some way to meeting the target for reducing the need for the road freight demand considered as part of this study. Additional rail freight paths are assumed once electrification of the Highland Mainline to Inverness and the East Coast Mainline to Aberdeen are complete.

The methodology for all energy demand assessments for this study are based on average consumption per mile for simplicity. The actual characteristics of individual lines in terms of gradients, speed restrictions and service stopping patterns may differ from this study's methodology to derive the average values presented.

4.2 Energy Demand Forecasts

Having defined the approach taken to establishing transport demand forecasts and technology transition scenarios in **Section 4.1.1-2**, electric and hydrogen energy demand forecasts were then developed for rail transport.

The results of these energy demand calculations for Network Rail, ScotRail, other Train Operating Companies and Freight Operating Companies are outlined in the following **Sections 4.2.1 – 4.2.4**, and a discussion of their implications is contained within **Section 4.3**.

4.2.1 Network Rail

Network Rail operate a small fleet of inspection and maintenance trains, which in 2019/20 consumed 3.7 GWh of electricity, which makes up a negligible proportion of electricity usage on the rail network. This is not anticipated to change in the future, as is shown in Tables 29 to 34. However, it should be noted that Network Rail's non-traction usage of electricity in 2019/20 was 1.6 GWh, which is not included in the figures presented in these forecasts as they do not relate directly to transport.

Table 29. Forecast electric and Hydrogen energy demand for Network Rail under scenario 1: LH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	0	0	0	0	0	0

Table 30. Forecast electric and Hydrogen energy demand for Network rail under scenario 2: ML (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	0	0	0	0	0	0

Table 31. Forecast electric and Hydrogen energy demand for Network Rail under scenario 3: MH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	0	0	0	0	0	0

Table 32. Forecast electric and Hydrogen energy demand for Network Rail under scenario 4: HL (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	0	0	0	0	0	0

Table 33. Forecast electric and Hydrogen energy demand for Network Rail under scenario 5: HH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	0	0	0	0	0	0

Table 34. Forecast electric and Hydrogen energy demand for Network Rail under scenario 6: MM (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	0	0	0	0	0	0

4.2.2 ScotRail

ScotRail services that are currently electrified consumed 255 GWh of electricity in 2019/20 and this is forecast to fall slightly in line with the reduced number of services anticipated to be running in 2022. Thereafter, electricity demand from 25 kV overhead lines is forecast to increase due to a combination of a gradual return of service numbers to pre-pandemic levels and the completion of several electrification schemes in various stages of development. By 2035, electricity demand from 25kV overhead traction could range from 274 kWh to 424 kWh depending on the uptake of BEMUs and hydrogen powered trains.

There are currently no battery electric trains in the ScotRail fleet, with the forecast energy draw from BEMUs ranging from zero under the low electric scenario to 206 GWh under the high electric scenario. The range is dependent on progress with overhead electrification and the extent of uptake of hydrogen trains on some routes.

There is currently no hydrogen powered trains in the ScotRail fleet. With the introduction of the first hydrogen powered trains anticipated from 2028 with energy from hydrogen usage anticipated to increase to between 45 GWh and 129 GWh depending on which routes are anticipated to switch to hydrogen powered traction.

As Transport Scotland are committed to decarbonising the ScotRail fleet by 2035 and transport demand has been assumed to be constant post 2030 the energy requirements for the ScotRail fleet in 2040 and 2045 is assumed to be the same as in 2035, which is reflected in Tables 35 to 40.

Table 35. Forecast Electric and Hydrogen Energy Demand for ScotRail under scenario 1: LH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	45	129	129	129
Battery Electric	0	0	0	0	0	0
Overhead Electric	243	259	381	409	409	409

Table 36. Forecast Electric and Hydrogen Energy Demand for ScotRail under scenario 2: ML (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	45	45	45	45
Battery Electric	0	0	0	37	37	37
Overhead Electric	243	259	381	409	409	409

Table 37. Forecast electric and Hydrogen energy demand for ScotRail under scenario 3: MH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	45	85	85	85
Battery Electric	0	0	0	0	0	0
Overhead Electric	243	259	381	424	424	424

Table 38. Forecast electric and Hydrogen energy demand for ScotRail under scenario 4: HL (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	45	45	45	45
Battery Electric	0	0	135	206	206	206
Overhead Electric	243	259	274	274	274	274

Table 39. Forecast electric and Hydrogen energy demand for ScotRail under scenario 5: HH

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	45	129	129	129
Battery Electric	0	0	135	169	169	169
Overhead Electric	243	259	274	274	274	274

Table 40. Forecast electric and hydrogen energy demand under scenario 6: MM

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	45	85	85	85
Battery Electric	0	0	0	19	19	19
Overhead Electric	243	259	381	409	409	409

4.2.3 Other Train Operating Companies

Other Train Operating Companies that operate cross-border services into Scotland include Avanti West Coast, Cross Country Trains, London and North Eastern Railway (LNER), Serco Caledonian Sleepers and TransPennine Express. Combined, these operators consumed 108 GWh of electricity in 2019/20 and this is assumed to remain constant until 2027, when electrification of lines north of the Central Belt will allow the LNER services to Aberdeen and Inverness, which are currently operated by bi-mode Class 800 units, to operate an increased proportion of their journey using overhead electric in place of diesel. The combined energy usage of these TOCs is anticipated to have increased to 125 GWh once Cross Country Trains switch from diesel to electric overhead use in Scotland.

As the lines on which TOCs other than ScotRail operate are all either currently electrified or overhead electrification is planned, it is not envisaged that that there will be a need for battery electric or hydrogen powered trains, which is reflected in Tables 41 to 46.

Table 41. Forecast Electric and Hydrogen Energy Demand for TOCs Under Scenario 1: LH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	108	108	117	118	125	125

Table 42. Forecast Electric and Hydrogen Energy Demand for TOCs Under Scenario 2: ML (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	108	108	117	118	125	125

Table 43. Forecast Electric and Hydrogen Energy Demand for TOCs Under Scenario 3: MH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	108	108	117	118	125	125

Table 44. Forecast Electric and Hydrogen Energy Demand for TOCs Under Scenario 4: HL (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	108	108	117	118	125	125

Table 45. Forecast Electric and Hydrogen Energy Demand for TOCs Under Scenario 5: HH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	108	108	117	118	125	125

Table 46. Forecast Electric and Hydrogen Energy Demand for TOCs Under Scenario 6: MM (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	108	108	117	118	125	125

4.2.4 Freight Operating Companies

Rail freight services into and within Scotland are operated by several different Freight Operating Companies including DB Cargo (UK), Direct Rail Services (DRS), Freightliner, Freightliner Heavy Haul, GB Railfreight and Rail Operations Group. In aggregate, these companies consumed 20 GWh of electricity in 2019/20, principally by services into central Scotland from England via the West Coast Mainline (WCML).

However, there are still a significant number of diesel-hauled trains on the WCML, presumably due to gaps in electric overhead infrastructure either at their origin or destination terminal or on route within England and almost all freight trains on the East Coast Mainline (ECML) are also diesel hauled despite the presence of a 25kV overhead.

It has been assumed that all cross-border services will switch from diesel to electric haulage between now and 2045 linearly as the existing constraints to switching are eliminated. For services within Scotland, principally between Aberdeen, Inverness and the Central Belt, it has been assumed that these will switch from diesel to electric traction and overhead electrification schemes are complete post 2030.

In addition, it has been assumed that electrification upgrades provide the capacity to run a further four freight trains in each direction each weekday on both the routes to Aberdeen and Inverness, with corresponding paths to the ECML and WCML. This results in a significant increase in electricity usage for freight services, with energy requirements increasing from 31 GWh in 2022 to 264 GWh by 2045. As indicted in Tables 47 to 52, this assumption is constant across all scenarios.

Table 47. Forecast Electric and Hydrogen Energy Demand for FOCs Under Scenario 1: LH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	31	49	94	151	208	264

Table 48. Forecast Electric and Hydrogen Energy Demand for FOCs Under Scenario 2: ML (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	31	49	94	151	208	264

Table 49. Forecast Electric and Hydrogen Energy Demand for FOCs Under Scenario 3: MH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	31	49	94	151	208	264

Table 50. Forecast Electric and Hydrogen Energy Demand for FOCs Under Scenario 4: HL (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	31	49	94	151	208	264

Table 51. Forecast Electric and Hydrogen Energy Demand for FOCs Under Scenario 5: HH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	31	49	94	151	208	264

Table 52. Forecast Electric and Hydrogen Energy Demand for FOCs Under Scenario 6: MM (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	0	0	0
Battery Electric	0	0	0	0	0	0
Overhead Electric	31	49	94	151	208	264

4.3 Implications

The principal barrier to the transition to electric trains is the significant cost of overhead electrification infrastructure. Approximately 29% of the total route length of the Scottish Rail network is already electrified. As the lines that are currently electrified are double track routes this equates to 40.7% of single-track kilometres and as at early 2020 and these routes carry approximately 76% of all passenger journeys in Scotland. Further overhead electrification works are currently planned. With numerous different classes of Electric Multiple Units (EMUs) in operation - there are no technological constraint to overhead electrification.

By contrast, alternative traction solutions are less developed. Although few hydrogen and battery electric demonstrator trains are present in the UK, both technologies are anticipated to be viable by the time the existing fleet of Diesel Multiple Units (DMUs) operated by ScotRail need to be replaced. The choice of technology used to decarbonise the sections of the network without a 25 kV overhead is therefore driven by the range of the engines of potential units. The current Battery Electric Multiple Units (BEMUs) have a range of up to 80 miles between charges and are therefore most suited to use on relatively short railway lines or sections of the rail network where discontinuous overhead electric catenary is provided. For longer rural routes, hydrogen fuel cell technology is considered the most promising technology.

Although some hydrogen freight locomotives are currently being developed, it is considered that the rail freight market is most likely to rely on overhead electrification, albeit there may be a need for bi-mode locomotives that include lithium oxide batteries, like Stadler Rail’s Class 93 scheduled for delivery in 2023 - to address short gaps in electrification and at freight terminals.

There may be requirement for grid reinforcement in terms of localised supply to provide overhead electrification. Hydrogen usage is likely to be minor and a small-scale introduction, but infrastructure will be required to support the services identified as being most likely to use hydrogen technology.

Chapter 5: Maritime

5.0 Introduction

According to Scottish Transport Statistics 2020, shipping emissions accounted for approximately 15% of all transport emissions in 2019. This is following a downward trend in emissions over the past two decades, with an average annual reduction of 3% between 1999 and 2019.

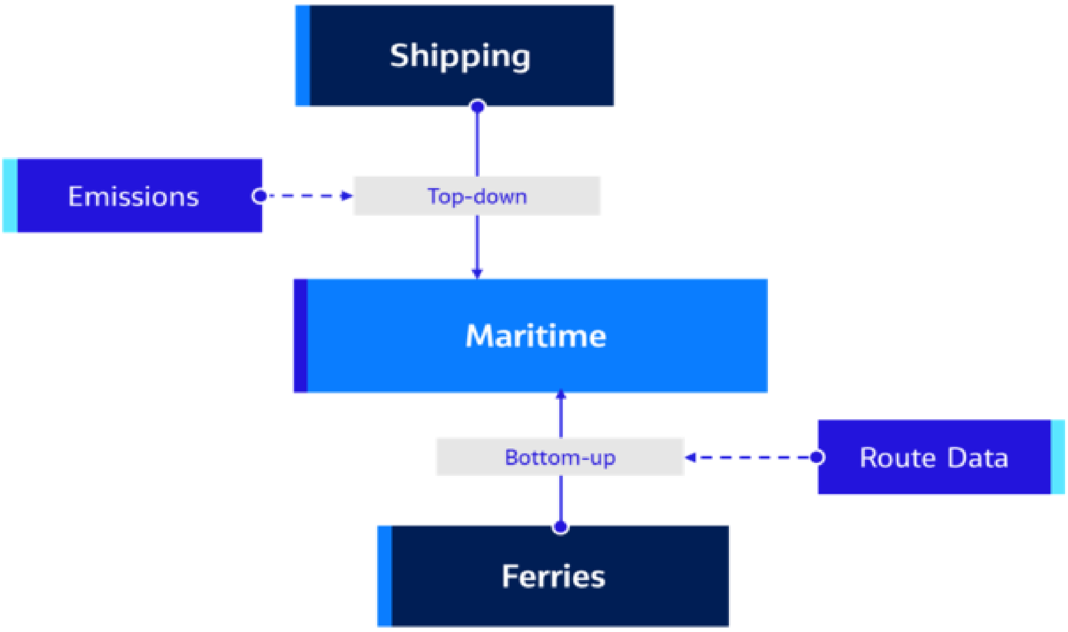
However, the International Maritime Organisation (IMO) goal of at least 50% reduction in GHG emissions by 2050 (relative to 2008 levels) will still pose significant challenges for the shipping industry, as ships are highly capital-intensive assets with typical operating lives of approximately 20 to 30 years. This means decisions made in the near term on vessel types and their energy sources will have implications for decades to come.

Options to reduce emissions in the maritime transport sector include: technology improvements, operational or behavioural changes, increases in energy efficiency, solutions that capture or treat exhaust emissions, as well as alternative fuels and energy sources. This study focuses on the latter, examining the potential of energy sources such as electric, Ammonia (Ammonia), and hydrogen technology for maritime transport in Scotland.

5.1 Methodology

The forecast electricity and hydrogen demand for maritime transport for Scotland, has been constructed using a mix of top-down and bottom-up approaches for shipping and ferries respectively – this was required due to the availability and granularity of data (or lack thereof) of emissions and route information, as described in Figure 10 below:

Figure 10. Maritime Methodology Approach



In terms of applying these approaches, transport demand projections were first considered according to data availability (Section 5.1.1), before constructing, technology transition scenarios (Section 5.1.2) based on available information on uptake of electricity and hydrogen technology for different vessel types.

An energy demand analysis was then undertaken (Section 5.1.3) to provide overall results, as well as split by Shipping and Ferries. Finally, the limitations of this approach are discussed in Section 5.1.4.

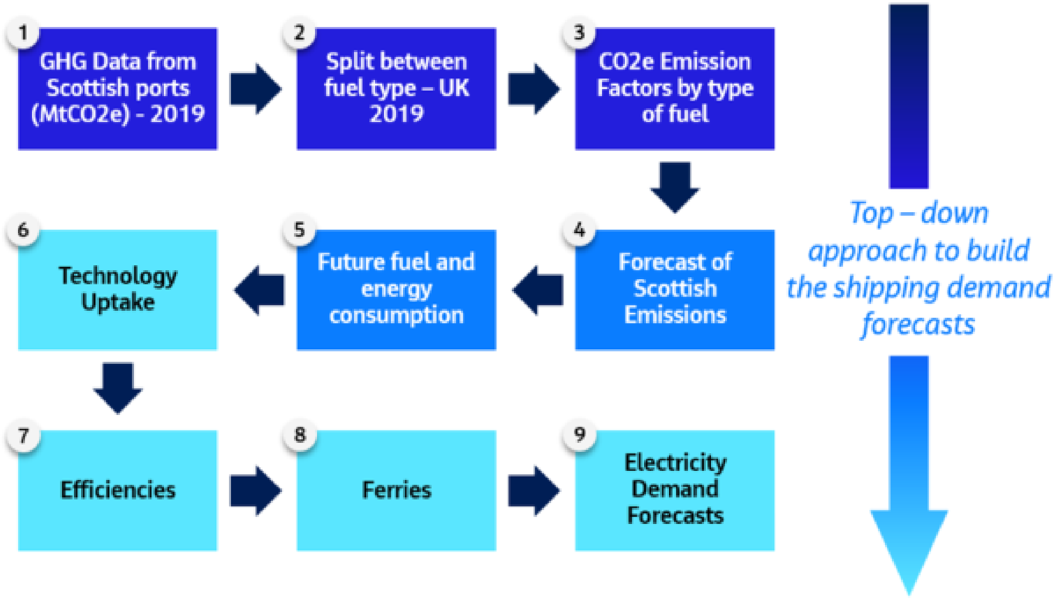
5.1.1 Maritime Transport Demand Forecasts

Transport demand forecasts for shipping were undertaken using a detailed nine-step process as described in **Figure 11**, while for Ferries the method required 12 steps, as per **Figure 12**. In line with the scope in Section 1.2 these forecasts have been produced annually until 2030 and then at five-year intervals, in 2035, 2040 and 2045.

Shipping Transport Demand Forecasts

The shipping modelling was developed following a top-down approach due to the current absence of a centralised publicly available database on the annual routes, kilometres, tonnage by route or vessel and other detailed data required in order to undertake a bottom-up approach, as shown in **Figure 11**:

Figure 11. Shipping Methodology



The steps in this process and sources of data are summarised below:

1. **GHG Emissions:** The key dataset used to develop the shipping maritime forecasts was the annual *Scottish Greenhouse Gas* (GHG) emissions from 2019. The Scottish government reports GHG emissions from all sectors, including shipping, on an annual basis. The following emissions were considered to develop the shipping forecasts:
    - **Domestic Navigation:** Includes emissions from inland goods-carrying vessels, motorboats and workboats, personal watercraft, sailing boats with auxiliary engines and shipping coastal.
    - **Fishing vessels:** Emissions from fishing vessels.
    - **Shipping Naval:** Emissions from military shipping.
    - **Marine Bunkers:** Includes emissions from international shipping, shipping between UK and Bermuda, between UK and Crown Dependencies, between UK and Gibraltar and between UK and Other Territories.

Given that international shipping emissions are calculated using international fuel bunker sales, they are considered an adequate proxy of the fuel demand at Scottish ports for the purpose of constructing transport demand forecasts for energy directly.

However, further steps were undertaken to make future estimates more precise, as follows:

2. **Fuel Type:** This involved converting the 2019 annual emissions into fuel consumption using the UK Government's *Greenhouse gas reporting conversion factors 2021*. As the conversion factors are specific to sector and type of fuel, and Scotland does not report on emissions at this level of granularity, the UK shipping fuel split (by proportion) was instead applied to Scottish shipping. All the fuel used for deep sea fishing in non-UK waters was assumed to be gas oil sourced in the UK, as per the *UK Greenhouse Gas Inventory Report*.
3. **Emissions by Fuel Type:** Emissions from 2019 were separated by fuel type based on the fuel type split discussed in Step 2.
4. **Forecast of Emissions:** To forecast future emissions, the forecast annual tonnage growth for each type of cargo at UK ports was used. These individual annual growth rates were multiplied by the market share of each cargo type as reported at Scottish ports. This calculation gave an overall 'tonnage' annual growth that was then applied to the 2019 Scotland reported emissions. It is recognised that the tonnage annual growth does not have a linear relationship with the annual growth of the emissions, as these will depend upon various other factors including vessel size, engine type, efficiency, and distance. However, it was used as a proxy.
5. **Future Fuel & Energy Consumption:** The forecast emissions were then converted into fuel and energy by using the relevant factors from *Greenhouse gas reporting conversion factors 2021*.

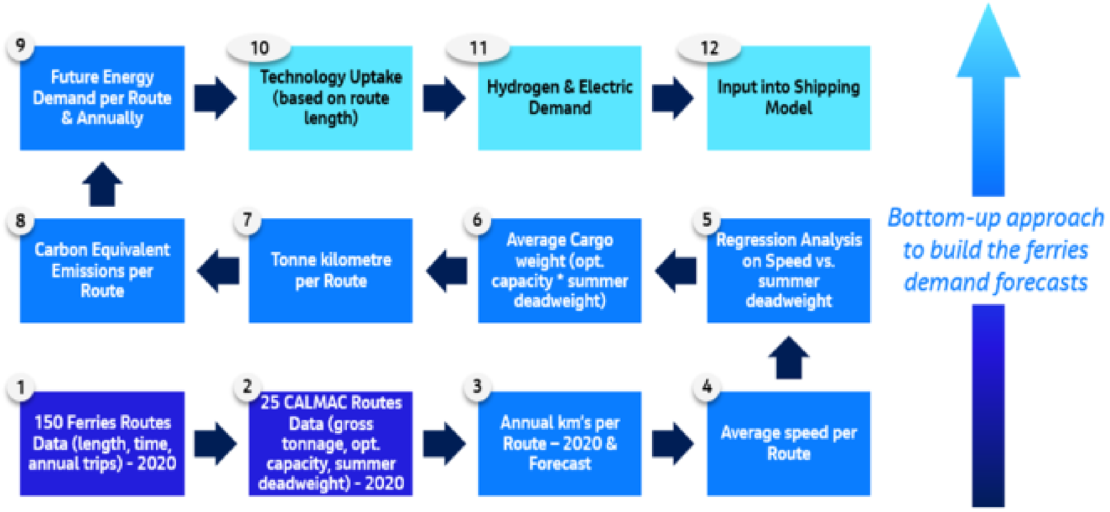
Ferry Transport Demand Forecasts

The methods applied to conduct the ferry transport demand required converting a series of different datasets, assumptions, and variable inputs into meaningful forecasts, as presented in **Figure 12** below.

A total of 150 intra-Scotland routes were identified and included in this study, which included a combination of ferry services that Transport Scotland is responsible for, recognised as essential services - as well as privately operated routes.

Transport demand forecasts were developed which predicted the total distance that would be travelled along each of these routes, for each of the modelled years between 2022 and 2045.

Figure 12. Ferries Methodology



As described in Steps 1-3 in **Figure 12** above, the calculation of ferry demand forecasts was based on several key data sources. The first was a dataset constructed by Jacobs specifically for this study, which collated publicly available data on each of the 150 ferry routes identified and developed as follows:

- For each route, information on the operating company, route length (km), estimated journey time per trip, and the number of annual trips was collected.
- The number of annual trips was multiplied by the total route length, the total number of kilometres travelled along each route in the 'base' year (2020) was then calculated as shown in the equation below:

$$Annual\ km_{Route\ x} = \#\ Annual\ Trips_{Route\ x} * km_{Route\ x}$$

- In terms of future demand, it was assumed that the total annual distance travelled along each route was constant between 2020 – 2045. That is, the total distance travelled in each modelled year will be the same as 2020, due to the uncertainty with the future of ferry services across future years.
- Using the length and average journey time data included within Jacob's constructed dataset, average speed of the primary vessel travelling along each of the 150 routes was calculated (Step 4).

However, further to total distance travelled and average speed - tonne kilometres per route were also required to be calculated. A tonne kilometre is a unit of measure of freight transport which represents the transport of one tonne of goods by a given transport mode:

Tonne Kilometre: multiplying the average load per trip by the total annual mileage

Calculating tonne kilometres would later enable conversions to carbon equivalent emissions, and thereby back calculate energy demand (discussed in **Section 5.1.3.2**). The steps to calculate tonne kilometres are as follows:

- Using data from Transport Scotland *Scottish ferry emissions analysis and pathways to carbon reduction (internal)* the characteristics of Caledonian MacBrayne (Calmac) Ferries and the routes which they operated were determined.
- The Calmac Vessel Replacement Deployment Plan (Calmac VRDP), was then used to assign each of the Calmac ships to the routes they were operating.
- Using public information from VesselFinder, the gross tonnage and summer deadweight for each of the Caledonian MacBrayne (Calmac) Ferries was then calculation.

The collation of this information produced a dataset with information on the average speed, gross tonnage and summer deadweight of each of the 25 Caledonian MacBrayne (Calmac) Ferries, along with the route they predominantly operate.

Using this data, it was possible to conduct a regression analysis for this sample of 25 Caledonian MacBrayne (Calmac) Ferries (Step 5). This regression identified a relationship between deadweight and speed. That is, speed was identified as a moderate-strong predictor of summer deadweight (Adjusted $R^2 = 0.75$). This meant:

- Given a vessels speed, the regression equation allowed the estimation of the summer deadweight for that vessel.
- As the average speed of the vessels operating each of the ferry routes was already calculated (Step 4), it was possible to predict the summer deadweight of each of these vessels.

The Calmac VDRP also provided information on the average operating capacity for many of their vessels. The multiplication of this average operating capacity by the summer deadweight yielded an estimate of the average cargo weight carried by each of the Calmac vessels (Step 6).

This process was then repeated with the non-Calmac vessels, however, in the absence of specific data on operating capacity for the remaining ferry fleets, a 54% operating capacity was assumed. That is, the estimated summer deadweight of each of the non-Calmac vessels was multiplied by 54% to generate an estimate of the average load per trip. The exception was the P&O and Stena Line ferries that operate between Cairnryan and Loch Ryan to Northern Ireland for which information was available.

Finally, by estimating the load carried by the vessels operating each of the 150 routes was calculated using ‘tonne kilometres’ for each route (Step 7), which would enable energy demand to be estimated (**Section 5.1.3.2**).

5.1.2 Technology Transition Scenarios

This section presents the key technology uptake assumptions considered for each of the six scenarios, for the purposes of forecasting future electric and hydrogen energy demand for maritime transport. Due to the different approaches (top-down versus bottom-up) the scenarios for shipping and ferries are presented separately for clarity.

5.1.2.1 Shipping

Given the top-down approach, the technology uptake has been calculated based on the adoption of technology for a percentage of vessels each year, also considering the year of entry into service, the retirement cycle of the current vessels, and the fuel mix by the end of the cycle as follows:

> End of cycle = entry into service + retirement cycle

For shipping, Ammonia (Ammonia) has been selected as the dominant zero-carbon fuel type based on the scenarios set out in the UK’s 6th Carbon Budget and accompanying literature review, of which the key assumptions on the dominance of Ammonia are based on:

- The potential to retrofit ship engines at relatively low cost
- Its higher energy density compared to hydrogen (and therefore requiring less space to store and smaller fuel tanks)
- The lower cost of production compared to methanol – an alternative biofuel.

For electricity demand, two types of sources have been considered: electric-battery vessels and shore power, that is ships temporally connected to grid electricity when docked in port to power onboard systems. Aside from the energy, other assumptions were made as follows:

- A retirement cycle of 15 years has been considered for all vessels and scenarios, with an entry into service in 2030 for Ammonia and 2025 for electric-battery and shore power. The operating life of ships is between 25-30 years, however, many of the current operating vessels have been in service for some years now, and so, the remaining operating life has been assumed to be 10-15 years less. The entry into service year is based on various studies carried out to date, including the UK's 6th Carbon Budget, the Fuel EU Maritime and supplementary UK's Clean Maritime Plan.

- Given the large size of the shipping vessels and the long distances, especially for the international market, battery-electric technology is expected to be used in a limited number of vessels.
- Shore power, however, is expected to be more widely used.

Moreover, the technology take-up projections used to develop **Table 53** were based on the Clean Maritime Plan technical annex (scenario analysis). This report presents several scenarios with different levels of Ammonia uptake by 2050 but similar levels of shore power and battery-electric uptake. For this analysis, a mix between the Clean Maritime Plan's scenarios B, C and D of that study were used for low, high and medium hydrogen scenarios respectively.

The 6th Carbon Budget and the Fuel EU Maritime reports were also used to adjust the technology take-up assumptions of this study. However, as former relies on the UMAS shipping modelling, similar assumptions were used on both assessments. The Fuel EU Maritime, on the other hand, presents considerably lower Ammonia and electrification take-up projections. Therefore, the latter was used to refine the low scenario assumptions.

The combined percentage of zero emission fuel by 2045 was calculated multiplying each percentage by the market share of domestic (Dom) and international (Intl) shipping activity respectively, as follows:

$$\begin{aligned}\boldsymbol{Fuel\ Mix}\ (\%) &= \%\ \boldsymbol{Dom} * \left(\boldsymbol{Ammonia\ Dom}\ (\%) + \boldsymbol{Battery\ Dom}\ (\%)\right) \\ &+ \%\ \boldsymbol{Intl} * \left(\boldsymbol{Ammonia\ Intl}\ (\%) + \boldsymbol{Battery\ Intl}\ (\%)\right)\end{aligned}$$

Because the domestic market share of Scottish shipping is higher compared to the international, the total fuel mix by 2045 will be largely driven by the domestic fuel mix as shown **in Table 53** below:

Table 53. 2045 Fuel Mix % Share projections by vessel type

Vessel type	High Scenarios	Medium Scenarios	Low Scenarios
Ammonia Domestic	76%	40%	20%
Ammonia International	52%	32%	8%

Vessel type	High Scenarios	Medium Scenarios	Low Scenarios
Battery-Electric & Shore Power Domestic	9%	6%	4%
Battery-Electric & Shore Power International	5%	4%	4%

Overall, technology transition scenarios estimate Ammonia is represents between 20-76% of domestic, and 8-52% of the international fuel mix by 2045, while electrification only represents between 4-9% of domestic and 4-5% of the international fuel mix respectively.

This figures for domestic shipping represent assumptions for an earlier transition to zero-emission alternatives and a higher uptake of battery-electric, shore power and Ammonia technology - due to the usage of smaller vessels and shorter routes.

In terms of comparison between these projections and other studies, Scenario 5 (HH) presents similar figures to a number of the 6th Carbon Budget scenarios, in which electricity represents 12%-13% of the fuel demand - while Ammonia represents 60-83% in 2045.The following sections summarise the assumptions for the six different scenarios and how they compare to other scenarios in greater detail:

Shipping Scenario 1 (LH)

This scenario is based on Ammonia uptake assumptions in the UK’s Clean Maritime Plan Scenario C, in which the main transition occurs in the early-mid 2030s. Additionally, battery-electric uptake is based on the UK’s Clean Maritime Plan Scenario B, in which the main transition occurs in the mid-late 2040s.

As described in **Table 54** below, this scenario is characterised by a high Ammonia (76%) share of fuel used in 2045. This is largely driven by the assumptions of high use of Ammonia in the domestic shipping market in Scotland – driven by the domestic policy agenda.

In terms of electrification, electric-battery and shore power uptake within the domestic and international shipping markets are similar, representing less than 5% of the total fuel mix by 2045 - in line with existing government policy analysis as aforementioned.

Table 54. Scenario I (LH) Fuel mix % share projections by vessel type

Vessel Type	2030	2035	2040	2045
Ammonia Domestic	5%	29%	52%	76%
Ammonia International	3%	20%	36%	52%
Battery-Electric & Shore Power Domestic	1%	2%	3%	4%
Battery-Electric & Shore Power International	1%	2%	3%	4%

Shipping Scenario 2 (ML)

In Scenario 2, only 24% of fuel use by 2045 would be zero emission, due to the low use of Ammonia. Scenario 2 assumes that Ammonia will represent 20% of the domestic market and less than 10% of the international market. Electric-battery and shore power uptake within the domestic and international shipping markets is very similar, representing circa 10% of the total fuel mix by 2045.

Ammonia uptake is based on the UK's Clean Maritime Plan Scenario B, in which the main transition occurs in the mid-late 2040s. Therefore, the uptake before 2045 is relatively small. Battery-electric uptake is based on the UK's Clean Maritime Plan Scenario D, in which the main transition occurs in the mid-late 2030s for the domestic market and early 2040s for the international market.

Table 55. Scenario 2 (ML) Fuel mix % share projections by vessel type

Vessel Type	2030	2035	2040	2045
Ammonia Domestic	1%	8%	14%	20%
Ammonia International	0.5%	3%	6%	8%
Battery-Electric & Shore Power Domestic	2%	3%	5%	6%
Battery-Electric & Shore Power International	1%	2%	3%	3.5%

Shipping Scenario 3 (MH)

In Scenario 3, 78% of the fuel use by 2045 would be Net Zero as shown in Table 56. This is slightly higher than Scenario 1 due to the higher usage of battery-electric vessels and shore power.

Ammonia uptake is based on the UK's Clean Maritime Plan Scenario C, in which the main transition occurs in the early-mid 2030s. Therefore, by 2035, Ammonia represents 20% and 29% of the fuel mix for domestic and international vessels respectively. Battery-electric uptake is based on the UK's Clean Maritime Plan Scenario D, in which the main transition occurs in the mid-late 2030s for the domestic market and early 2040s for the international market.

Table 56. Scenario 3 (MH) Fuel mix % share projections by vessel type

Vessel Type	2030	2035	2040	2045
Ammonia Domestic	5%	29%	52%	76%
Ammonia International	3%	20%	36%	52%
Battery-Electric & Shore Power Domestic	2%	3%	5%	6%
Battery-Electric & Shore Power International	1%	2%	3%	3.5%

Shipping Scenario 4 (HL)

Scenario 4 presents similarly to Scenario 2, due to the same assumptions on Ammonia uptake and similar electrification uptake, with 27% of the fuel zero emission by 2045. However, even in the high electrification scenario, electric-battery and shore power vessels still represents a small proportion of the fuel mix by 2045, less than 10% of the domestic fuel mix and 5% of international.

Adoption of Ammonia is based on the UK's Clean Maritime Plan Scenario B, in which the main transition occurs in the mid-late 2040s. Therefore, the Ammonia uptake before 2045 is relatively small. Battery-electric uptake is based on the UK's Clean Maritime Plan Scenario C, in which the main transition occurs in the early-mid 2030s.

Table 57. Scenario 4 (HL) Fuel mix % share projections by vessel type

Vessel Type	2030	2035	2040	2045
Ammonia Domestic	1%	8%	14%	20%
Ammonia International	0.5%	3%	6%	8%
Battery-Electric & Shore Power Domestic	3%	5%	7%	9%
Battery-Electric & Shore Power International	1.5%	3%	4%	5%

Shipping Scenario 5 (HH)

In Scenario 5, the highest technology take-up with 81% of the fuel zero emission by 2045. Ammonia and battery-electric uptakes are based on the UK's Clean Maritime Plan Scenario C, in which the main transition occurs in the early-mid 2030s.

Table 58. Scenario 5 (HH) Fuel mix % share projections by vessel type

Vessel Type	2030	2035	2040	2045
Ammonia Domestic	5%	29%	52%	76%
Ammonia International	3%	20%	36%	52%
Battery-Electric & Shore Power Domestic	3%	5%	7%	9%
Battery-Electric & Shore Power International	1.5%	3%	4%	5%

Shipping Scenario 6 (MM)

Scenario 6, being a medium transition of both electric and hydrogen is therefore a hybrid of all other scenarios, where approximately half of the shipping fuel used by 2045 would be zero emission is circa 45%. In light of this, Ammonia and battery-electric uptakes are based on the UK's Clean Maritime Plan Scenario D, in which the main transition occurs in the mid-late 2030s (domestic) and early 2040s (international).

Table 59. Scenario 6 (MM) Fuel mix % share projections by vessel type

Vessel Type	2030	2035	2040	2045
Ammonia Domestic Vessels	3%	15%	28%	40%
Ammonia International Vessels	2%	12%	22%	32%
Battery-Electric & Shore Power Domestic	2%	3%	5%	6%
Battery-Electric & Shore Power International	1%	2%	3%	3.5%

5.1.2.2 Ferries

For the technology transition scenarios for ferries, an overarching assumption has been made that the zero emission fuel technology adopted for each route is dependent on the route length for simplicity and clarity – based on assumptions provided in Transport Scotland's *Scottish ferry emissions analysis and pathways to carbon reduction* (internal document).

As such, when transitioning away from Internal Combustion Engine (ICE) ferries, it has been assumed that journeys of less than 40km in length will be powered by electric ferries. Alternatively, journeys equal to or greater than 40km have been assumed to be powered by hydrogen apart from the large ferries operated between Cairnryan and Loch Ryan to Northern Ireland which due to their significantly higher tonnage were projected to use Ammonia as a fuel source, matching the Shipping model.

It is acknowledged that the technology used to power each vessel will be dependent on the vehicle weight as well as the journey length. However, due to the granularity of data required to complete this calculation, it has not been undertaken for this study.

In all scenarios, it has been assumed there are zero hydrogen vessels operating before 2030. This assumption is based on the limited technological readiness of hydrogen which means these vessels are unlikely to be commercially viable prior to that time.

At the same time, all scenarios assume 100% of journeys over 40km in length will be operated by hydrogen ferries in 2045 – in line with Scottish Government objectives. Therefore, the variation between each of the different scenarios is according to the speed of uptake.

As such, in all scenarios there is assumed to be a 'straight-line' uptake of electric vessels between 2022 and 2032, and between 2032 and 2045 at a different rate. It is assumed there are no electric vessels in 2022.

Importantly, the scenarios for ferries do not consider technology uptake rates for each route individually. That is, for a given route, it does not consider at what point the vessel operating that route will switch from an ICE powertrain electric or hydrogen.

Instead, the scenarios estimate the percentage of all miles that are going to be undertaken by alternatively fuelled vehicles in a given year. To determine whether these will be battery electric or hydrogen services the criteria of journey length (+/-40km) is applied.

> **Each of the six technology transition scenarios are summarised in further detail in the following sections, however due to the 'straight line' uptake of electric vessels, detailed breakdowns are provided for hydrogen uptake only:Ferry Scenario 1 (LH)**

In Scenario 1, the rate of battery electric uptake between 2022 and 2032 is slow by comparison with the other scenarios. This means by 2032 only 30% of services on routes shorter than 40km are operated by electric vessels.

Table 60. Percentage of trips completed by hydrogen ferries for routes longer than 40km, by Year

2030	2031	2032	2035	2040	2045
0%	12%	23%	48%	87%	100%

Therefore, there is a high rate of uptake from 2032 - with the percentage of electric vessels increasing from 30% to 100% over this period. It also assumes a rapid straight-line rate of hydrogen uptake from 2030, as per Table 19 above.

Ferry Scenario 2 (ML)

In Scenario 2, the rate of battery electric uptake between 2022 and 2032 is moderate. By 2032, 65% of services on routes that are shorter than 40km are operated by electric vessels.

Table 61. Percentage of trips completed by hydrogen ferries for routes longer than 40km by Year

2030	2031	2032	2035	2040	2045
0%	7%	13%	33%	67%	100%

Therefore, there is a moderate rate of uptake from 2032 to 2045, with the percentage of electric vessels increasing from 65% to 100% over this period. Scenario 2 assumes a slow rate of hydrogen uptake, as seen in Table 61 above.

Ferry Scenario 3 (MH)

Scenario 3 has the same rate of battery electric uptake as Scenario 2 and assumes a rapid rate of hydrogen uptake, as seen in 62 below.

Table 62. Percentage of trips completed by hydrogen ferries for routes longer than 40km by Year

2030	2031	2032	2035	2040	2045
0%	12%	23%	48%	87%	100%

Ferry Scenario 4 (HL)

In Scenario 4, the rate of battery electric uptake between 2022 and 2032 is high, meaning by 2032, 100% of services on routes that are shorter than 40km are operated by electric vessels. This means no further uptake required from 2032 to 2045, and thereby a slower rate of hydrogen uptake, as seen in Table 63 below:

Table 63. Percentage of trips completed by hydrogen ferries for routes longer than 40km by Year

2030	2031	2032	2035	2040	2045
0%	7%	13%	33%	67%	100%

Ferry Scenario 5 (HH)

Scenario 5 has the same rate of battery electric uptake as Scenario 4, however it assumes a rapid rate of hydrogen uptake, as seen in Table 64 below.

Table 64. Percentage of trips completed by hydrogen ferries for routes longer than 40km by Year

2030	2031	2032	2035	2040	2045
0%	12%	23%	48%	87%	100%

Ferry Scenario 6 (MM)

Scenario 6 has the same rate of battery electric uptake as Scenarios 2 and 3, and assumes a moderate rate of hydrogen uptake, as seen in Table 65 below.

Table 65. Percentage of trips completed by hydrogen ferries for routes longer than 40km

2030	2031	2032	2035	2040	2045
0%	11%	19%	41%	77%	100%

5.1.3 Maritime Energy Demand Analysis

The Energy Demand Analysis utilises the transport demand forecasts discussed in **Section 5.1.1**, the technology transition scenarios discussed in **Section 5.1.2**, and a series of additional modelling assumptions relating to energy usage to forecast future energy demand.

5.1.3.1 Shipping

As shown in the shipping methodology outlined in Figure 14, Step 7 considers various future technology efficiency improvements, which in form the forecast energy demand in each scenario of this study.

In terms of shipping, in 2011, the IMO adopted a set of energy efficiency requirements for new ships, known as the *Energy Efficiency Design Index* (EEDI). These EEDI sets the requirements efficiency improvement of 10% by 2015, 20% by 2020 and 30% by 2025 compared to a baseline of ships built between 1999 and 2009.

Therefore, based on the IMO targets and review of forecast sea transport efficiency gains, the model considers a 1% efficiency gain per year from 2014 to 2045.

In terms of future alternative technology efficiency, battery-electric technology has been considered to be 50% more efficient compared to ICE technology based on the UMAS modelling and reporting on electric container ships. Similarly, a conservative efficiency of 92% for electric batteries has been assumed, based on the standard efficiency shown by lithium-ion batteries that are currently commercially available.

Conversely, Ammonia engines have been assumed to be as efficient as the current shipping fuel engines, at approximately 50% efficiency. This assumption is based on a report published by MAN Energy Solutions on a research they are undertaking on Ammonia engines for vessels.

For reporting purposes, Ammonia has been converted into hydrogen considering an efficiency factor of 85% - that is, when converting Ammonia to hydrogen, 15% more hydrogen than Ammonia is required according to *Sailing on Solar, EDF*.

Further details are provided in Chapter 7: Appendices for specific efficiencies and energy parameters considered in the shipping model.

5.1.3.2 Ferries

In order to calculate the energy demand for Ferries, as outlined in Figure 12, the following steps were undertaken:

- Using tonne kilometres for each ferry as described in **Section 5.1.1** the carbon equivalent emissions for each route were calculated using the *UK Greenhouse Gas Inventory Report* and assumptions of the physical size of the vessels in the sample.
- From there, it was possible to estimate the annual carbon emissions produced by vessels operating along each route.

- It was assumed that each ferry in the dataset produces 0.053kg of CO2 equivalent per tonne kilometre and that they were assumed to be Ro-Ro ferries of the average linear metres (LM).
- It was assumed that the three large vessels operating between Cairnryan and Loch Ryan to Norther Ireland produce 0.377kg of CO2 equivalent per tonne kilometre as they were assumed to be Large RoPax ferries.

Once the carbon equivalent emissions were calculated, the forecast emissions were then converted into the relevant fuel type and energy equivalent by using the relevant factors from *Greenhouse gas reporting conversion factors 2021*. It was assumed that all ferries in the dataset are powered by marine fuel oil and therefore a conversion factor of 0.262 was used. That is, every kWh of energy generated by marine fuel oil produces 0.262kg of CO_2 equivalent.

Using this information, it was possible to estimate the annual kWh energy requirement for each route (Step 9 in Figure 12). Where necessary, this was divided through by the total annual distance to calculate a constant kWh/km requirement to be considered for all modelled years.

In instances where a ferry route has a terminal located outside Scotland (e.g. Northern Ireland), only half of the energy required to operate this route has been attributed to the Scottish port. It has been assumed that other half of the energy required will be supplied by the destination port and should therefore not be considered in the Scottish energy demand forecast.

The overall annual energy demand forecast from ferries was then calculated as follows:

- Aggregating the multiplication between the estimated annual mileage travelled along each route (by each traction type) by the rate of energy consumption for the respective traction type (specific to each route) (Step 11 in Figure 12).
- As the technology transition pathways are different for each scenario, this generates different annual energy demand forecasts for each.
- Where necessary, the kWh energy values calculated for hydrogen powered vessels were converted to a hydrogen equivalent value using the 0.03kg/kWh conversion factor (HLHV).

The energy demand from ferries was subtracted from the energy demand of shipping to avoid double counting (Step 12 in Figure 12). However, there are several limitations which could be improved in further work, detailed in Section 5.1.4.

5.1.4 Limitations

The primary limitation to the energy demand forecasts for maritime transport relate to the availability and granularity of data on which to build the forecast set of assumptions.

In terms of the shipping, a lack of data regarding annual kilometres made by Scottish vessels meant forecast rely on a top-down approach to estimate energy demand through forecast Scottish shipping emissions. Moreover, future Scottish emissions were calculated applying the annual growth forecasted for the UK tonnage due to the lack of data on forecasted emissions from Scottish vessels.

Although these provide a good proxy for fuel consumption, the results may have been more precise if data on fuel sales and/or kilometres by port were readily available – in order to adopt a more granular, bottom-up approach.

For ferries, the central limitation was lack of availability of data regarding the summer deadweight for the ferry operating each of the circa 150 routes and the commission date of the vessels - from which a decommissioning profile could have been developed to better predict when the vessels will be replaced by a low emission alternative.

Importantly, due to data availability and time constraints, the model does not consider changes in ferry engine efficiency, nor the precise decommissioning or replacement profile for each route. However, given the lack of data, applying a percentage in terms of the technology transition as outlined in **Section 5.1.2.2**, was considered the most appropriate approach.

Finally, ferries and shipping calculations are based on two different methodology approaches and therefore, there are also some differences on the energy parameters used in the modelling.

- **Technology efficiencies:** The shipping model considers a higher technology efficiency over time, whereas the ferries model assumes a constant energy consumption.
- **Type of fuel:** The shipping forecasts are based on a top-down approach utilising GHG emissions and type of fuel, this means different types of fuel have been considered for the different navigation classes. Ferries calculations, on the other hand, use only marine fuel oil for clarity and simplicity.
- **Hydrogen vs. Ammonia:** The shipping forecasts Ammonia as the alternative zero-emission fuel while the ferries modelling considers hydrogen.

However, Ammonia requirements have been converted into hydrogen requirements for reporting purposes.

5.2 Maritime Energy Demand Forecasts

This section presents the energy demand forecasts for maritime. Table 66 presents the electricity demand from hydrogen ferries, Ammonia ships, shore power and battery-electric ferries and ships. Ammonia demand has been converted into hydrogen for reporting purposes only. It should be noted that the electricity demand required to produce hydrogen has not been considered within the calculations.

Table 66. Electric and Hydrogen Energy Demand for Maritime according to year for Scenario 1: LH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	525	3,182	5,906	8,715
Electric	0	15	77	143	211	281

Table 67. Electric and Hydrogen Energy Demand for Maritime according to year for Scenario 2: ML (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	132	793	1,470	2,166
Electric	0	28	178	330	486	647

Table 68. Electric and Hydrogen Energy Demand for Maritime according to year for Scenario 3: MH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	525	3,073	5,750	8,715
Electric	0	28	178	330	486	647

Table 69. Electric and Hydrogen Energy Demand for Maritime according to year for Scenario 4: HL (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	132	793	1,470	2,166
Electric	0	50	312	580	854	1,136

Table 70. Electric and Hydrogen Energy Demand for Maritime according to year for Scenario 5: HH (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	525	3,182	5,906	8,715
Electric	0	50	312	580	854	1,136

Table 71. Electric and Hydrogen Energy Demand for Maritime according to year for Scenario 6: MM (GWh)

Vehicle Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	282	1,702	3,159	4,660
Electric	0	28	178	330	486	647

Transition to battery-electric vessels will have significant technology barriers, and battery-electric powered vessels are expected to only serve a small part of the domestic shipping market and the shortest ferries routes (below ~40km). Hydrogen and Ammonia ships have not either largely penetrated the market as yet, however, the technology is expected to be suitable to all type of vessels, including large vessels operating in international routes. Therefore, all forecast scenarios, including Scenario 4 (HL), show a higher transition to hydrogen vessels with a relatively small role for electrification.

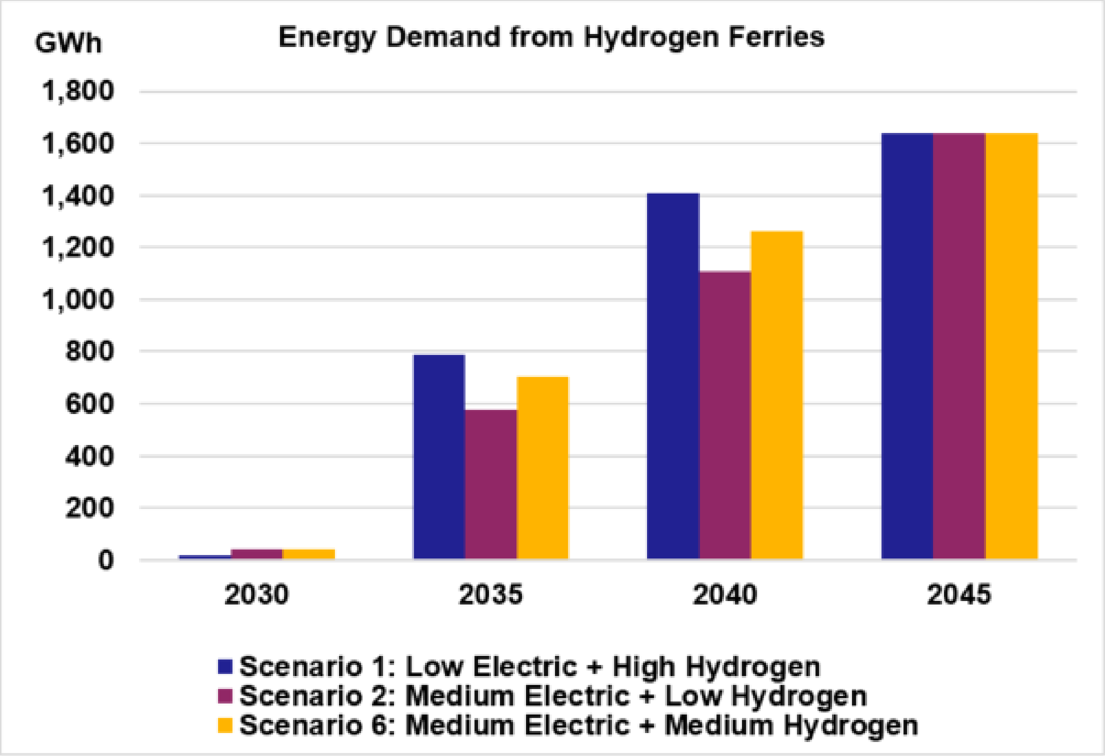
Tables 66 to 71 above show a fast ramp up of hydrogen and electric vessels from 2030 as hydrogen, Ammonia and battery-electric technologies will not be widely ready for commercial purposes for at least 10 years.

Sections 5.2.1 Ferries and 5.2.2 Shipping present more detailed results for different types of maritime transport respectively.

5.2.1 Ferries

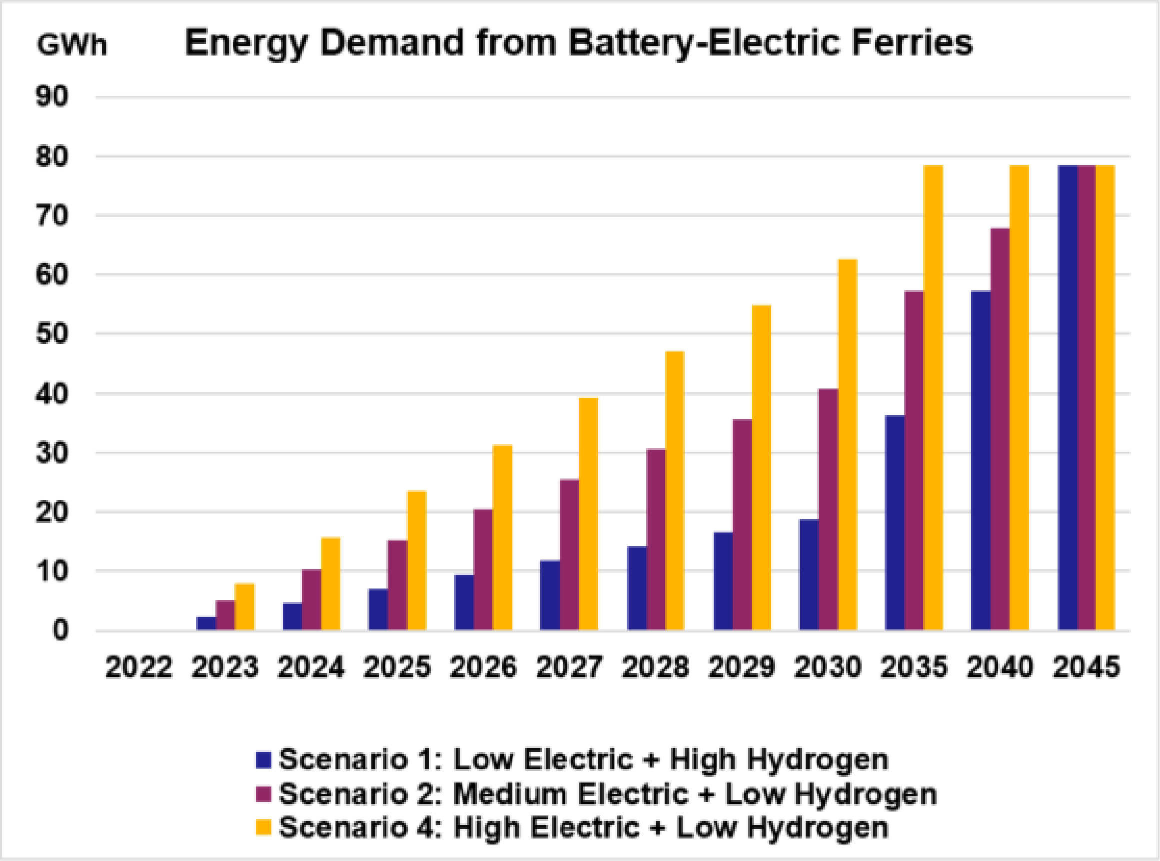
Figure 13 shows the energy demand from hydrogen ferries, for the high, medium and low scenarios. All scenarios have the same hydrogen demand by 2045, as it was considered that all routes longer than 40km will have been converted to hydrogen by then. The key difference between the high, medium and low scenarios is how fast hydrogen technology is adopted prior to 2045. All scenarios show a hydrogen demand starting in 2031.

Figure 13. Energy Demand from Hydrogen Ferries



Conversely, Figure 14 shows the energy demand from battery-electric ferries. Again, by 2045, the energy demand from all three scenarios is the same, as it was assumed that all routes below 40km would be operated by battery-electric ferries. The high scenario presents the same energy demand from 2035, as the assumption was that by 2032, all routes below 40km would be Net Zero. The low scenario was built so that the government target of achieving 30% of Scottish Ferries to be low emissions by 2032 was accomplished. The low scenario shows a slower take-up before 2030 and a faster take-up from 2030. The medium scenario presents demand figures in-between the high and low scenarios and a smoother hydrogen take-up.

Figure 14. Energy Demand from Battery Electric Ferries



5.2.2 Shipping

Figure 15 shows the energy demand from hydrogen ships for the high, low and medium scenarios. Domestic shipping accounts for ~90% of all the demand given the higher Ammonia take-up and the higher proportion of domestic shipping activity than international in Scotland sea territories (85% vs 15%).

There is no hydrogen demand before 2030 in any of the three scenarios.

Figure 15. Energy Demand from Hydrogen Ships

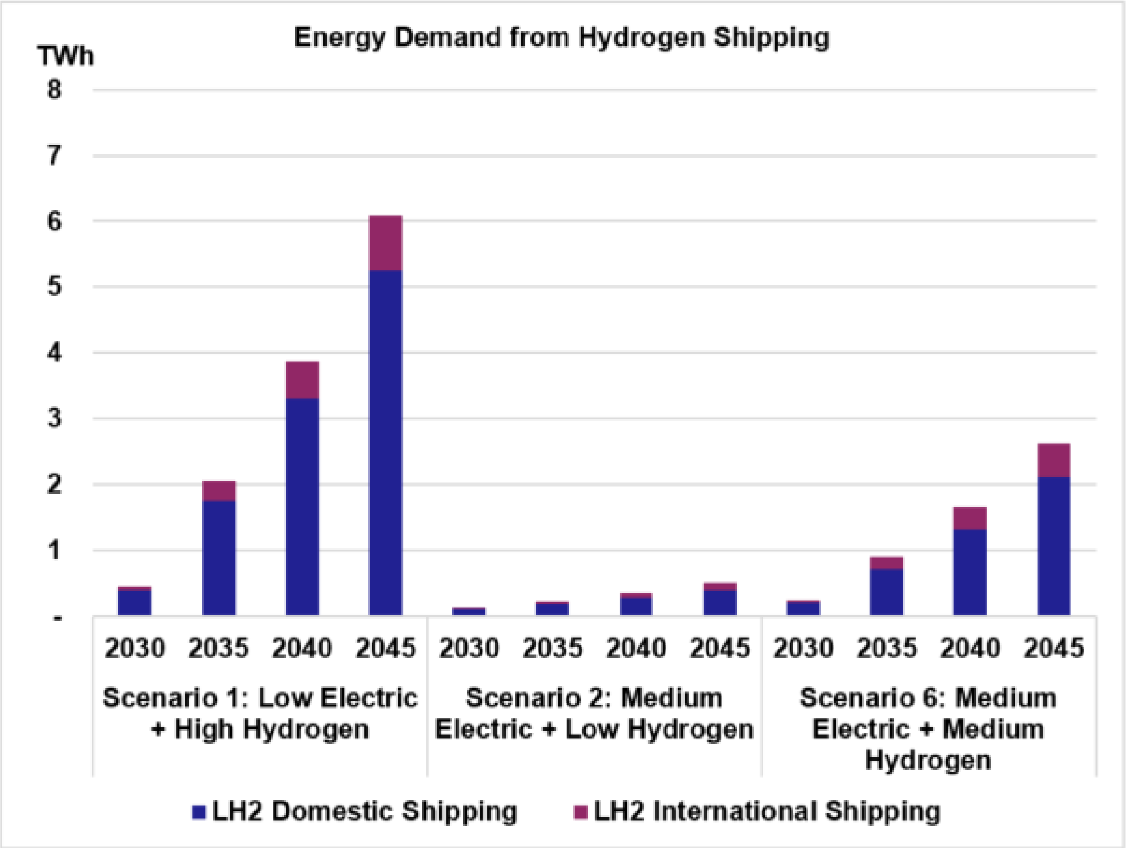
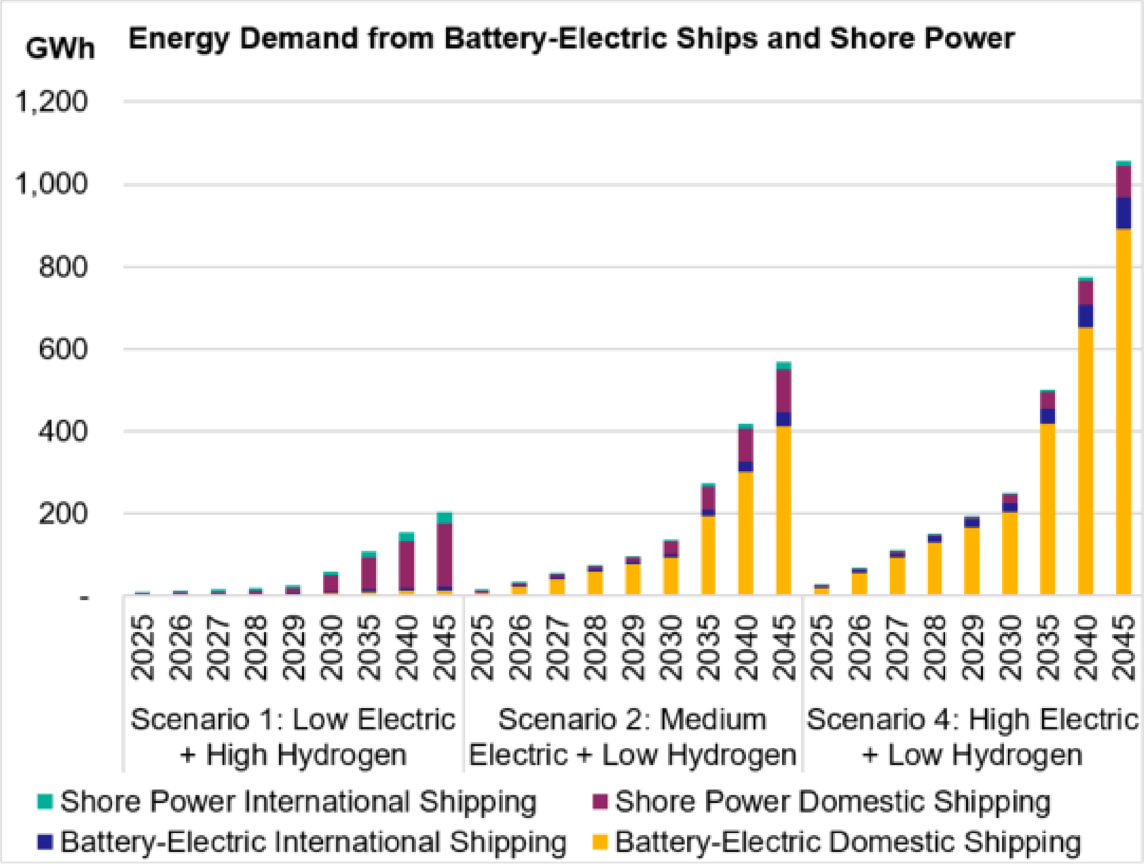


Figure 16 presents the energy demand from battery-electric vessels and shore power. Scenario 1 represents the low electric demand, which is largely driven by shore power, as it has been considered that battery-electric technology will represent only small niches of the domestic market. Scenario 2 and 4 represent the medium and high electric demand. The demand for shore power is similar in magnitude to the total demand for this under the low scenario. This indicates that the largest sensitivity in the estimation of power electricity demand is the share of full battery electric ships in the future. Demand is mainly driven by the domestic market, as it has been estimated to be more cost-effective to convert ships to full electric due to its smaller size and shorter routes than international shipping.

Battery-electric and shore power demand starts in 2025 for all three scenarios with a faster take-up from 2030, especially in the high scenario.

Figure 16. Energy Demand from Battery Electric Ships and Shore Power



5.3 Implications

There are a number of different solutions which are not yet widely used for abating emissions from domestic and international shipping. With the exception of batteries, hydrogen and Ammonia could, from a technical standpoint, be applied to all ship types. Batteries, due to their low energy density, may be technically infeasible to use for international shipping.

Hydrogen, Ammonia and battery-electric technologies are expected to be available in the near term (e.g., the next 10 years). However, in order to achieve competitive implementation costs, significant levels of take-up would be required. Results presented in the assessment above are based on a technology uptake aiming at achieving the national target of reducing annual emissions from international shipping by 50% by 2050 as well as the shorter-term goal of achieving a proportion of low emission Scottish ferries of 30% by 2032. Therefore, strong policy drivers have been considered to be in place to incentivise transition towards zero emission technologies. Should the suitable regulation not be in place, full penetration in the sector of zero emissions could be delayed until 2050 onwards.

Basis of this assessment have been the *6th Carbon Budget* and *UMAS Modelling Reports*. Outcomes from this study, therefore, are similar as these two studies. However, because the objective of this assessment was to provide a range of energy demand depending on different technology penetration rates, the high, medium and low scenarios present significant different results. Jacobs' high scenario presents similar hydrogen and electricity requirements as the *6th Carbon Budget* (Figure 17), whereas the Jacobs low and medium shipping scenarios present similar battery-electric and shore power demand as the *UMAS modelling* (Figure 18).

Figure 17. Comparison between Jacobs and the 6th Carbon Budget

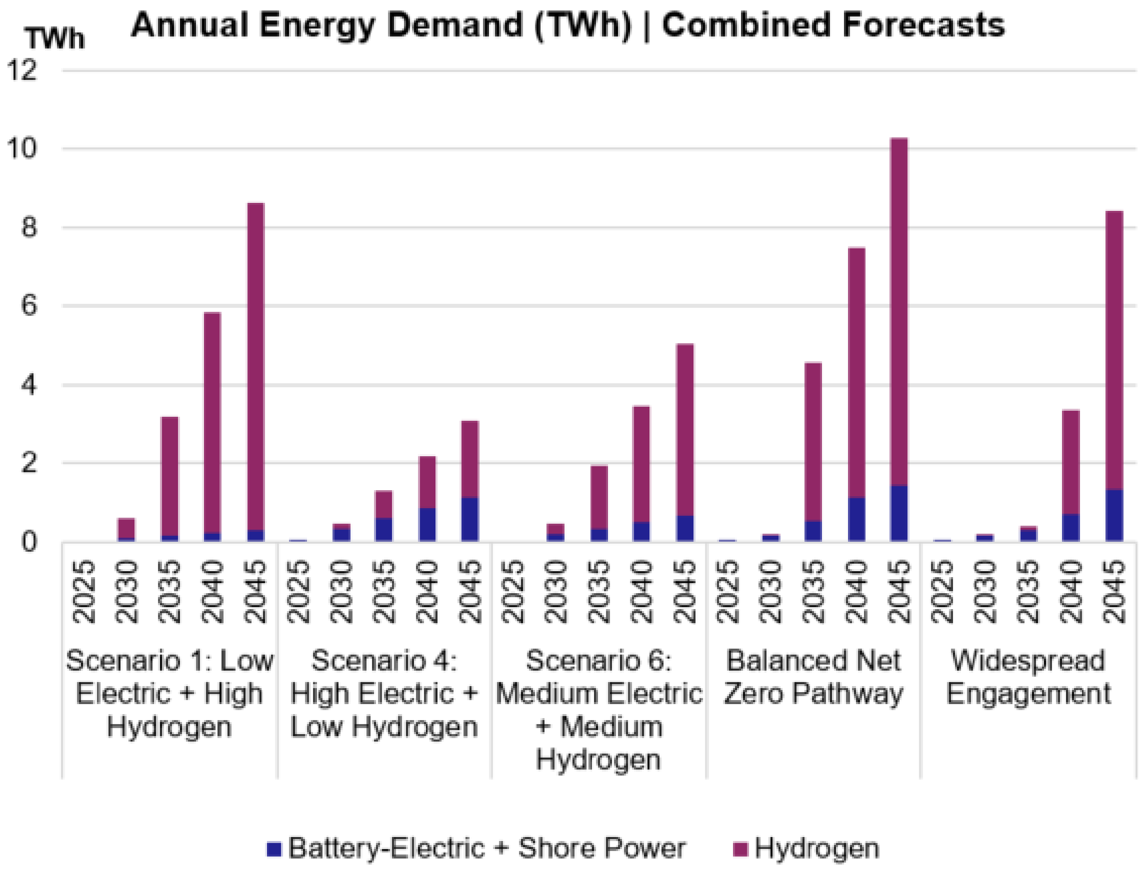
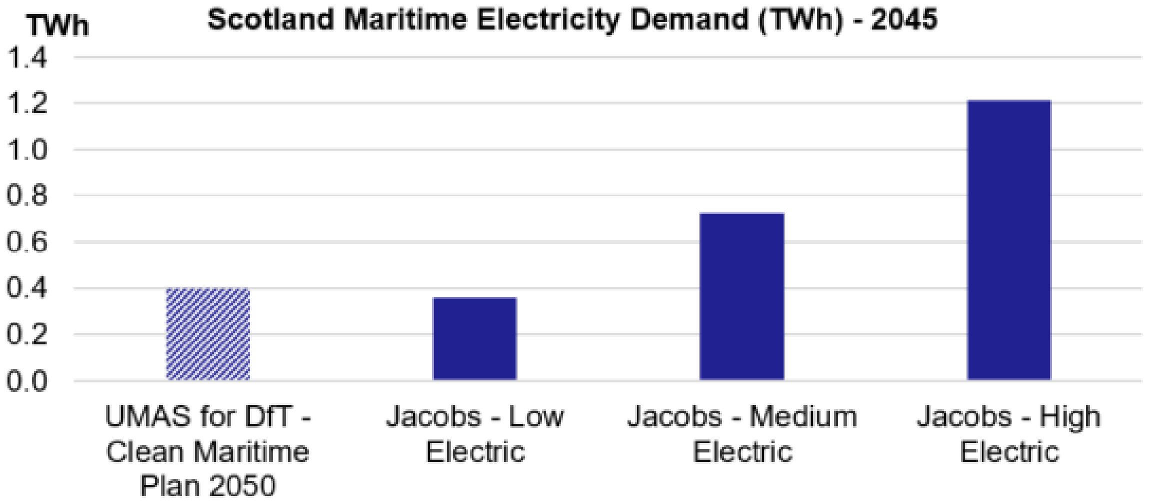


Figure 18. Comparison between Jacobs and UMAS modelling



Results presented in Section 5.2 Maritime Energy Demand Forecasts, show that if a port were to offer shore power and ship battery charging, this can greatly increase its electricity requirements. Exploring whether the distribution network connection requires to be enhanced would then be required.

For ammonia (or hydrogen) the main implication will be on the land-side infrastructure. In order to enable a section of the fleet to use hydrogen or ammonia, the land-side infrastructure and supply chains for these fuels will need to be in place and widely available. Assessment above presents unrestricted energy demand forecasts, meaning that no infrastructure neither hydrogen and/or electricity supply limitations have been considered.

Chapter 6: Aviation

6.0 Overview

Aviation is one of the sectors with more limited progress towards decarbonisation due to the technical challenges in developing and deploying new fuels and the long lifetimes of aircraft, which could delay implementation of new technologies and fuels. GHG emissions from aviation currently represent around 15% of all Scottish transport sector emissions.

Several key pieces of work have been undertaken to investigate how the aviation industry could meet both Scottish and UK emission targets. Among these include The Jet Zero Consultation and The 6th Carbon Budget – which identify pathways on how emissions could be reduced in aviation by improving existing technology efficiency, using alternative fuels (including hydrogen-electric and battery-electric) and by optimising operations, amongst others.

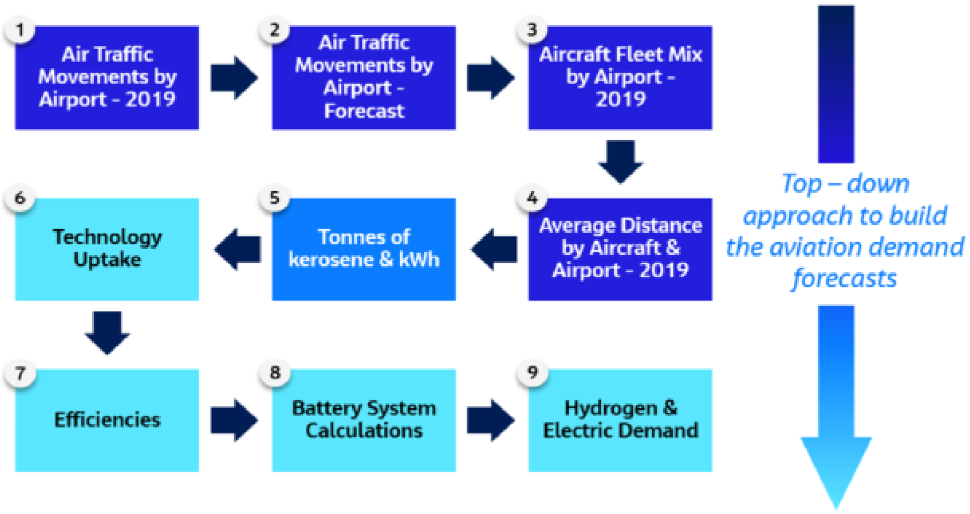
Both the Jet Zero Consultation and The 6th Carbon Budget have been used as guidance in the formulation of technology transition scenarios in this study, however both highlight that by 2050 there will still be residual in-sector emissions and that significant in-sector abatement is only possible if substantial progress is made on new technologies and appropriate policies are in place.

6.1 Methodology

Due to the availability and granularity of data available, a top-down approach has been undertaken in order to develop electricity and hydrogen demand forecasts for aviation, as shown in **Figure 19**. This approach is understood to be consistent with other concurrent zero emission fuel studies being undertaken within the aviation sector.

In terms of applying this approach, aviation transport demand projections were first considered according to data availability (Section 6.1.1), before constructing, technology transition scenarios (Section 6.1.2) based on available information on uptake of electricity and hydrogen technology for aviation.
An energy demand analysis was then undertaken (Section 6.1.3) to provide overall results, as well as split by aircraft type. Finally, the limitations of this approach are discussed in Section 6.1.4.

Figure 19. Aviation Methodology



6.1.1 Aviation Transport Demand Forecasts

This following section explains Steps 1-5 as indicated in **Figure 19,** carried out in order to calculate future demand for aviation – in terms of average distance by aircraft and airport in 2019, and then forecast forward their associated fuel requirements to 2045.

1. **Air Traffic Movements (ATMs) by airport**: The ATMs from all the Scottish airports in 2019 were taken as the baseline year for aviation transport demand.
2. **ATMs by Airport Forecast**: The aviation forecast published by the DfT was then used to forecast future ATMs. Because the DfT does not provide forecasts for each airport individually, the forecasted annual growth of the *Other Regional Airports – Central Demand* was applied to all Scottish airports. Given that the forecast from the DfT was developed in a pre-pandemic scenario, to reflect the impact of Covid-19 on the demand; 2019 levels were assumed to be recovered by 2025.
3. **Aircraft Fleet Mix:** The 2019 aircraft fleet mix by airport was also taken as the baseline mix. Future fleet mix was then estimated, considering a modest annual growth in narrow body and wide body (circa 0.1%) aircraft services and flat growth for large turboprops and regional services, as per the future fleet outlooks from the industry as well as the nature of operations at Scottish airports. Smaller airports, such as those serving the islands (e.g., Eday, Fair Islands or Tingwall airports) were also considered to remain served by 100% small turboprop aircraft.
4. **Average Distance by Aircraft and Airport:** The average distance (km) flown in 2019 by each aircraft type by airport was taken as the baseline. Future average distance was assumed to remain close to flat, with only a modest growth in narrow body aircraft of 0.4% and 0.1% for all the other services.
5. **Fuel Consumption:** The International Civil Aviation Organization (ICAO) fuel consumption formula (see below) was used to calculate the total tonnes of fuel burnt by each aircraft type and from each airport. The ICAO publishes tables with the C1 and C2 parameters as per the below formula for each specific aircraft. However, for simplicity only a single representative design for each aircraft category (regional, narrow body, wide body, small turboprop and large turboprop) was selected. As such, a total of five fuel consumption formulas were calculated, before the kerosene energy density (12 kWh/kg) was applied to convert fuel consumption into energy demand (kWh). Importantly, ATMs were applied as per Step 1, as were average km per air traffic movement – as per Step 3.

$$\boldsymbol{Fuel\ per\ ATM\ [kg] = C1 * km + C2}$$

$$\boldsymbol{Energy\ [kWh] = Fuel\ per\ ATM * Total\ ATM's * Energy\ Density}$$

6.1.2 Technology Transition Scenarios

This section presents the key technology uptake assumptions considered for each of the six scenarios, for the purposes of forecasting future electric and hydrogen energy demand for aviation transport in Scotland.

The technology uptake was undertaken on a percentage basis and defined as the percentage of zero emission ATMs at the end of the aircraft lifecycle, this being:

> End of lifecycle = entry into service + retirement cycle

As a result of these lifecycles, there are some common assumptions for all scenarios which are outlined below, before a discussion of individual technology transition scenario assumptions in the remainder of this section:

All scenarios:

- Small turboprops are considered to adopt electric technology only.
- Narrow body and wide body aircraft are considered to adopt hydrogen technology only.
- **Table 72** below shows the assumptions regarding the entry into service year considered for each aircraft type technology (electric or hydrogen) for all the high, medium or low scenarios respectively.
- Assumptions regarding the entry into service of electric aircraft are based on the International Air Transport Association (IATA) Optimistic Technology Roadmap for 2050, which forecasts electric aircraft enter into service between 2035 and 2050.
- For hydrogen aircraft, an entry into service of between 2030 and 2040 for small and larger aircraft respectively was assumed. These figures are similar to those considered in the UK's Jet Zero Consultation, which considers small aircraft (<150 seats) being replaced by zero emission aircraft from 2030 and larger zero emission aircraft (150-200 seats) to enter into service from 2040.

Table 72. Entry into Service Assumptions for various aircraft

Aircraft Type	Entry into Service		
	High Scenarios	**Medium Scenarios**	**Low Scenarios**
Hydrogen Regional	2030	2032	2035
Hydrogen Large Turboprop	2030	2032	2035

Aircraft Type	Entry into Service		
Hydrogen Narrow Body	2033	2035	2038
Hydrogen Wide Body	2035	2037	2040
Electrical Regional	2040	2045	2050
Electrical Large Turboprop	2040	2045	2050
Electrical Small Turboprop	2035	2037	2040

In terms of ATMs, **Table 73** below shows the assumed percentage share of movements to be zero emission by 2045 for each aircraft type, technology, for each scenario.

Importantly, as shown in **Table** the percentage of hydrogen movements are more optimistic than those presented by The 6th Carbon Budget. This higher hydrogen utilisation reflects the potential limitation on feedstocks to produce Sustainable Aviation Fuels (SAFs) and therefore an increased hydrogen demand is assumed.

The percentage of movements done by electric aircraft are based on various sources including The 6th Carbon Budget and The Jet Zero Consultation Report.

For example, for the high hydrogen and high electric scenario, regional aircraft movements would be 64% hydrogen powered, 16% electric and the remaining 20% would use either kerosene, SAF or another fuel. The same logic applies to all other aircraft types.

Table 73. 2045 Net Zero ATMs % Share Assumptions

Aircraft Type	2045 ATM's % Share		
	High Scenarios	**Medium Scenarios**	**Low Scenarios**
Hydrogen Regional	64%	47%	24%
Hydrogen Narrow Body	46%	33%	18%
Hydrogen Wide Body	22%	14%	5%
Hydrogen Large Turboprop	21%	14%	6%

Aircraft Type	2045 ATM’s % Share		
Electrical Regional	16%	3%	0%
Electrical Large Turboprop	28%	4%	0%
Electrical Small Turboprop	59%	45%	17%

Following the outline of assumptions across all scenarios above, the individual technology transition assumptions are summarised for each of the six scenarios below:

Aviation Scenario 1 (Low Electric – High Hydrogen)

In this scenario, 37% of all Scottish air traffic movements are assumed to be zero emission by 2045, driven largely by hydrogen aircraft. This translates into approximately 42% of the total aircraft kilometres, given that narrow body and wide body hydrogen aircraft are assumed to operate some of the longest routes within all ATMs.

In this scenario, only 2% of all ATMs are assumed to be electric by 2045. This is underpinned by the assumption that, by that time, only small turboprops will be capable of adopting electric technology and therefore, serving only short domestic routes, this translates to only 0.5% of the total aircraft kilometres.

Table 74. Scenario 1 (Low Electric – High Hydrogen) Zero Emission Aircraft Assumptions

Aircraft Type	2045 ATM % Share	2045 km’s % Share
Hydrogen Aircraft	35%	41%
Electrical Aircraft	2%	0.5%
Total	**37%**	**41.5%**

Aviation Scenario 2 (Medium Electric – Low Hydrogen)

In this scenario, 19% of all Scottish ATMs are assumed to be zero emission by 2045, again driven by hydrogen aircraft. This translates into approximately 18% of the total aircraft kilometres. While 6% of the ATM's would be electric, because these are assumed to be operated by small turboprops and therefore, only serving short domestic routes - this translates into only 2% of the total kms, as shown in **Table** below:

Table 75. Scenario 2 (Medium Electric – Low Hydrogen) Zero Emission Aircraft Assumptions

Aircraft Type	2045 ATM % Share	2045 km's % Share
Hydrogen Aircraft	13%	16%
Electrical Aircraft	6%	2%
Total ZE Aircraft	**19%**	**18%**

Aviation Scenario 3 (Medium Electric – High Hydrogen)

In this scenario, 41% of the ATMs or 43% of the kms are assumed to become zero emission by 2045 as shown in **Table** below, given that narrow body and wide body hydrogen aircraft are assumed to operate some of the longest routes.

Table 76. Scenario 3 (Medium Electric – High Hydrogen) Zero Emission Aircraft Assumptions

Aircraft Type	2045 ATM % Share	2045 km's % Share
Hydrogen Aircraft	35%	41%
Electrical Aircraft	6%	2%
Total ZE Aircraft	**41%**	**43%**

Scenario 4 (High Electric – Low Hydrogen)

This scenario considers 29% of the ATMs or 23% of the total aircraft kilometres being zero emission by 2045. The assumed electric kilometres are broadly in line with the electric uptake assumed by The 6th Carbon Budget, which assumes approximately 9% of the ATM kilometres being electric powered by 2050. These assumptions are shown in **Table** below:

Table 77. Scenario 4 (High Electric – Low Hydrogen) Zero Emission Aircraft Assumptions

Aircraft Type	2045 ATM % Share	2045 km's % Share
Hydrogen Aircraft	13%	16%
Electrical Aircraft	16%	7%
Total ZE Aircraft	**29%**	**23%**

Aviation Scenario 5 (High Electric – High Hydrogen)

This scenario presents the most optimistic assumptions from a technology uptake perspective. By 2045 approximately half of the aviation would be zero emission. This translates into 51% of the ATMs or 47% of the total aircraft kilometres being zero emission by 2045, as show in **Table** below:

Table 78. Scenario 5 (High Electric – High Hydrogen) Zero Emission Aircraft Assumptions

Aircraft Type	2045 ATM % Share	2045 km's % Share
Hydrogen Aircraft	35%	41%
Electrical Aircraft	16%	6%
Total ZE Aircraft	**51%**	**47%**

Aviation Scenario 6 (Medium Electric – Medium Hydrogen)

This scenario intends to reflect a middle ground situation in terms of technology uptake. It is assumed that by 2045 a third of the aviation would be zero emission. This translates into 31% of the ATM's or 32% of the total aircraft kilometres, as shown in **Table** below:

Table 79. Scenario 6 (Medium Electric – Medium Hydrogen) Zero Emission Aircraft Assumptions

Aircraft Type	2045 ATM % Share	2045 km's % Share
Hydrogen Aircraft	25%	30%
Electrical Aircraft	6%	2%
Total ZE Aircraft	**31%**	**32%**

Having specified the six technology transition scenarios, the following section discusses the steps undertaken to convert these assumptions combined with forecast transport demand into potential energy demand.

6.1.3 Aviation Energy Demand Analysis

This section discusses the steps undertaken to calculate energy demand, based on the previous 2 sections. Methodology corresponds to Steps 7-9 in **Error! Reference source not found.** as follows:

7. **Efficiencies**:
    - Future energy demand was calculated first on the basis that all aircraft remain kerosene powered as described using the ICAO fuel consumption formula described in Section 6.1.1 and then converting kg of kerosene to kWh/kg.
    - Importantly, existing kerosene internal combustion engines have an efficiency between approximately 25% and 50%, depending on engine age. For example, a typical turboprop aircraft equipped with a not-new engine has an efficiency of approximately 27%.
    - As a large proportion of movements from Scottish airports are operated by turboprops and regional aircraft, and these aircrafts are considered to have been operated for some years now, a 27% efficiency was applied for all existing kerosene engines.

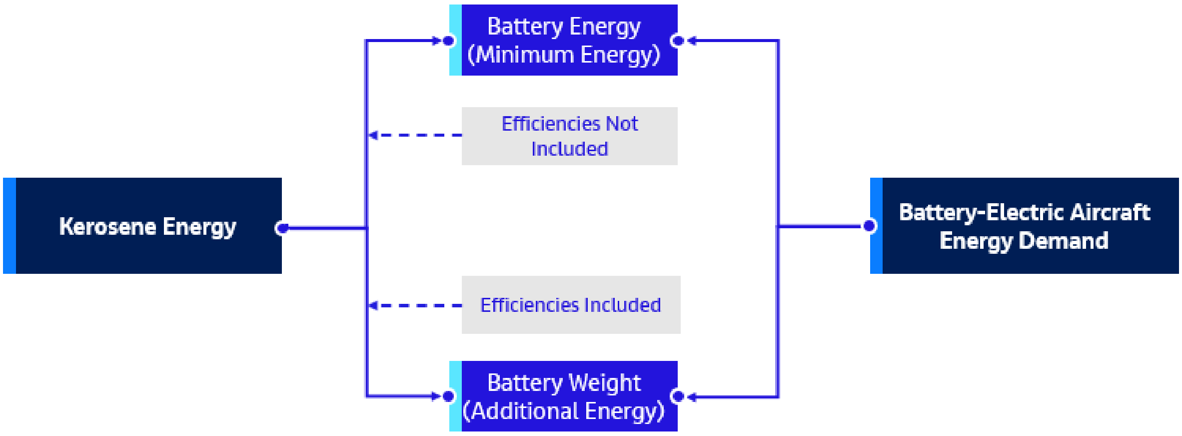
- No future efficiency improvements were considered on kerosene engines to account for the worst-case scenario.
- The next step was to apply the technology take-up profiles previously described in Section 6.1.2.
- Energy demand from hydrogen aircraft assumes an efficiency increment of between 40% and 60% for hydrogen powered aircraft compared to kerosene powered aircraft.

8. **Battery System Calculations**:

- Kerosene energy was first converted into battery energy (which represents the minimum energy the aircraft needs to fly).
- An additional calculation was then undertaken to estimate the energy required due to the additional weight from the batteries by converting kerosene energy into kilograms of battery.
- This was undertaken by assuming a battery energy density of approximately 0.15kWh/kg until 2030 (as per the energy density of existing batteries), and future energy density of approximately 0.5kWh/kg - based on an estimate of aircraft electrical propulsion consistent with several recent studies on aircraft batteries.
- In addition, it was assumed an energy density of lower than 0.5kWh/kg would almost make electric aircraft unfeasible due to the enormous additional weight that would be required to deliver the same energy as kerosene engines.
- Therefore, the additional weight of the batteries was calculated by applying the 27% kerosene efficiency and then converted into energy assuming a battery efficiency of 92%

This process is illustrated in **Figure 20** below:

Figure 20. Battery-electric aircraft energy demand process



Importantly, efficiencies were only applied to calculate the additional energy required due to the additional weight of the batteries. This approach was taken as weight is the most crucial parameter for aircraft, and an increase in the aircraft weight not only implies a higher energy demand due but also reduces the maximum altitude aircraft can reach. At the same time, flying at a lower altitude leads to a higher energy consumption as it increases the drag and lengthens fly times.

Therefore, in order to reflect this additional energy consumption, the higher efficiency of the batteries compared to the kerosene engines was only applied when calculating the additional energy required due to the additional weight of the batteries and not to convert kerosene energy into battery energy.

Finally, the results of these calculations were compared against the electrical power requirements from electric aircraft prototypes from IATA's technology roadmap for Airbus and Zunum Aero as shown in **Table** below:

Table 80. Comparison of Electric Aircraft Consumptions between Jacobs Modelling and IATA Technology Roadmap

Aircraft Type	MW per ATM – Jacobs	MW per ATM - IATA
Regional Aircraft	17 (Average 84 pax)	18 – 22 (> 100 pax)
Large Turboprop Aircraft	9 (> 20 pax)	8 – 16 (100 pax)
Small Turboprop Aircraft	2 (< 20 pax)	4 – 5 (50 pax)

As **Table** shows above, the power demand (MW) per ATM is generally consistent with the electric aircraft currently being developed by the industry, according to IATA's technology roadmap. Further detail on these assumptions can be found in Chapter 7 - Appendices energy tables, which show the full list of efficiencies and energy parameters considered as part of the aviation forecast.

The results of these calculations are presented in Section 6.2, however, there are several limitations which could be improved in further work, as detailed below.

6.1.4 Limitations

The methodology followed to calculate future energy demand for aviation transport in Scotland has several limitations pertaining to its assumptions. Foremost, power consumption of future electric aircraft will depend upon the performance of each specific flight. As such, a more precise energy demand calculation for battery-electric aircraft could be performed, which would need to apply individual assessments for each flight and each individual aircraft – a level of granularity outside the scope of this study. For hydrogen aircraft, an efficiency of between 40% and 60% compared to kerosene aircraft was assumed, based on literature review. A more precise energy demand calculation for hydrogen aircraft would imply individual assessments for each individual aircraft type – again, a level of granularity outside the scope of this study.

Second, assumptions on technology uptake in this study have been based on aircraft type only and are not dependent on whether the flight is a domestic or international flight. However, because aircraft type and flight type are related (that is, small turboprops are only used in domestic services), it is considered not be a major limitation on the assumptions.

6.2 Aviation Energy Demand Forecasts

The Energy Demand forecasts for aviation utilises the transport demand forecasts discussed in Section 6.1.1, the technology transition scenarios discussed in Section 6.1.2, and a series of additional modelling assumptions relating to energy usage to forecast future energy demand.

Tables 81 to 86 present the total GWh of forecast demand results for hydrogen and electric aircraft by Scottish airports from 2022 to 2045. Results by airport are presented in Section 7.4. Electricity demand required to produce hydrogen has not been considered within the calculations below. This was considered separately in Section 2.

Table 81. Forecast electric and hydrogen energy demand for aviation under Scenario 1: LH (GWh)

Aircraft Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	6	359	1085	1969
Electric	0	0	0	0	2	11

Table 82. Forecast electric and hydrogen energy demand for aviation under Scenario 2: ML (GWh)

Aircraft Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	3	242	736
Electric	0	0	0	0	12	57

Table 83. Forecast electric and hydrogen energy demand for aviation under Scenario 3: MH (GWh)

Aircraft Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	359	1085	1969
Electric	0	0	0	0	12	49

Table 84. Forecast electric and hydrogen energy demand for aviation under Scenario 4: HL (GWh)

Aircraft Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	3	242	736
Electric	0	0	0	3	49	222

Table 85. Forecast electric and hydrogen energy demand for aviation under Scenario 5: HH (GWh)

Aircraft Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	6	359	1085	1969
Electric	0	0	0	3	43	173

Table 86. Forecast electric and hydrogen energy demand for aviation under Scenario 6: MM (GWh)

Aircraft Type	2022	2025	2030	2035	2040	2045
Hydrogen	0	0	0	105	678	1393
Electric	0	0	0	0	12	53

In reflecting on the above results, consideration should be given to the fact that the transition to electric aircraft will have significant technology barriers, and electric powered aircraft are expected to only serve the intra-island and domestic market.

Although hydrogen aircraft have not yet penetrated the market, the technology is developing and expected to be suitable to all aircraft types, including narrow body and wide body aircraft. For this reason, all forecast scenarios show a higher transition to hydrogen aircraft with only small role for electric – as per **Tables 81 to 86**.

The Scottish Government's net-zero by 2045 target includes emissions from domestic and international aviation and they have also committed to work to decarbonise schedule passenger flights within Scotland by 2040. The UK Government has also made commitments to reduce the environmental impact of aviation, focusing on technological development. This ambition is reflected in these forecasts by the fast ramp up of hydrogen and electric aircraft from 2030 and 2040 respectively.

Additionally, **Figure 21** shows the energy demand from hydrogen aircraft by each aircraft type. Narrow body aircraft account for 80% - 85% of the total hydrogen demand by 2045. This is explained by the high proportion of narrow body movements (44% of total ATMs in 2019) with longer distances and higher energy consumption rates compared to regional aircraft.

Figure 21. Energy Demand from Hydrogen Aircraft

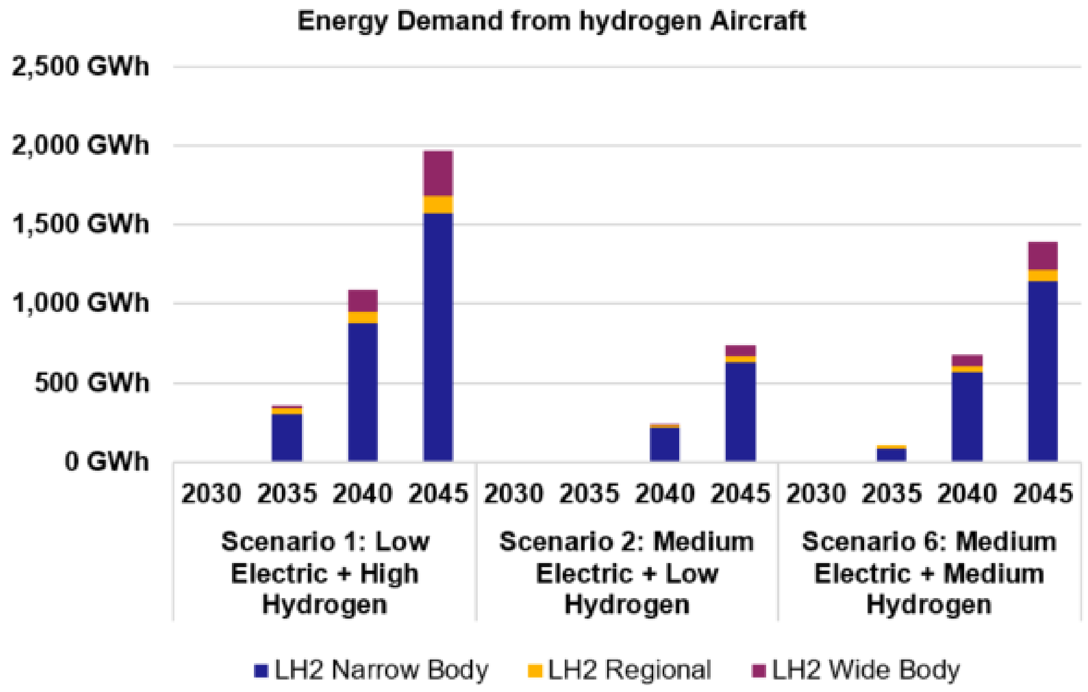
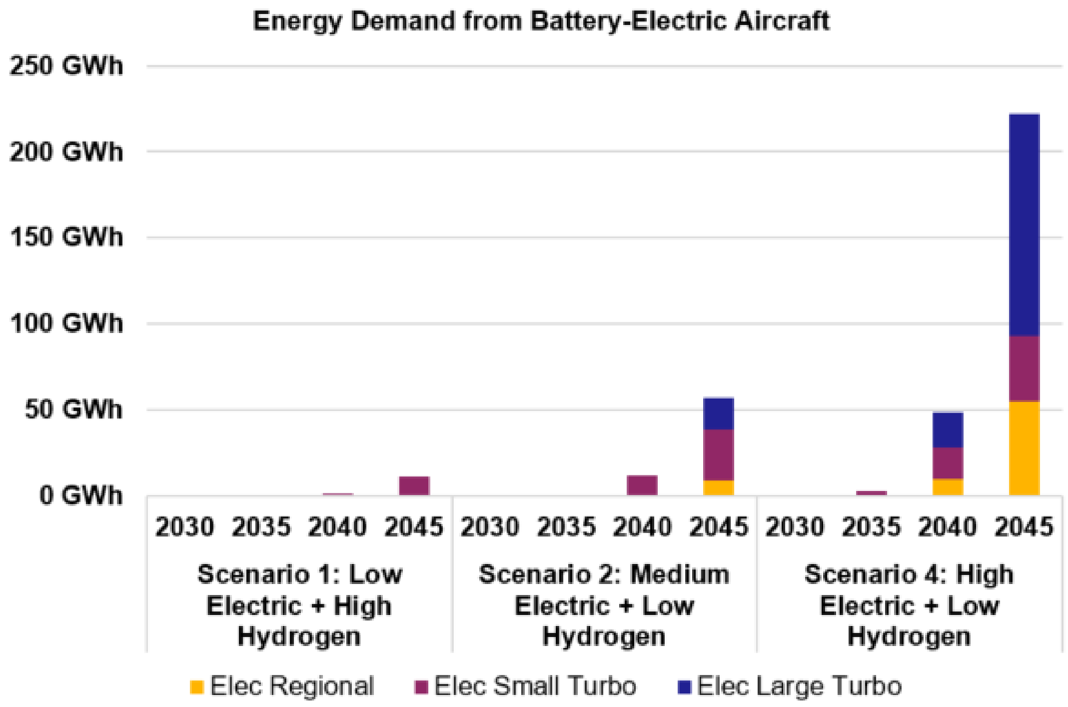


Figure 22 shows the energy demand from electric aircraft by aircraft type. The low battery-electric demand comes solely from small turboprop aircraft, with almost no demand until 2045. This is due to the low entry into the market, the low consumption of the small turboprops and the longer replacement cycles of the aircraft.

The high electric scenario shows a significant demand from 2040, mainly from the large turboprop aircraft, due to the higher number of movements and a higher consumption.

The medium electric scenario sits between the low and high scenarios.

Figure 22. Energy Demand from Battery-Electric Aircraft



6.3 Implications

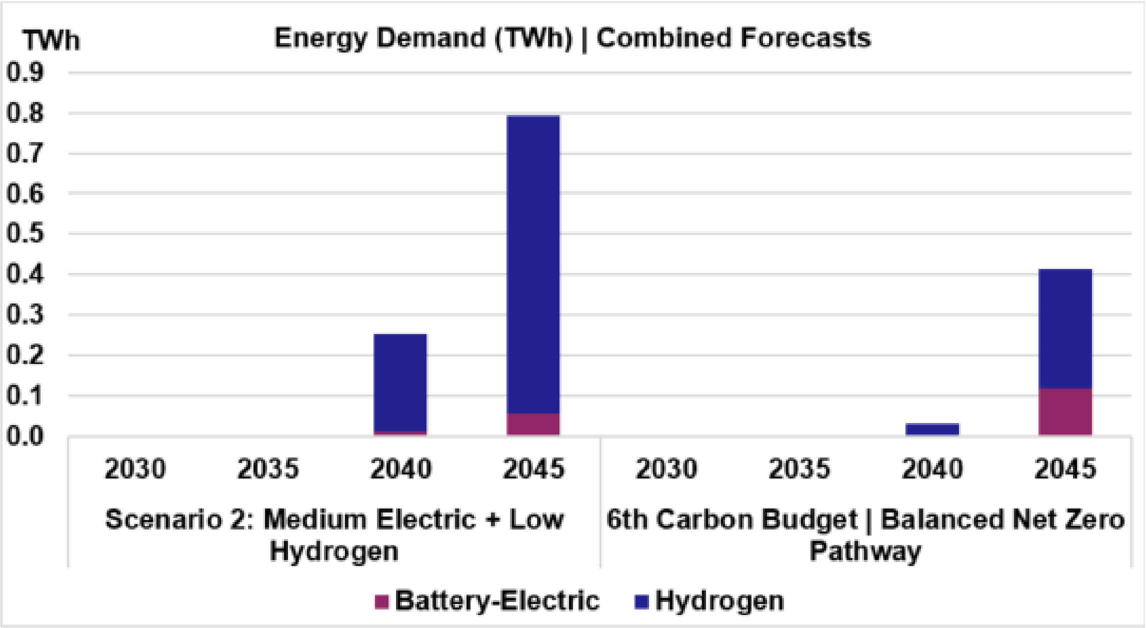
The results presented in the preceding section have numerous implications. Technology uptake rates are driven by government targets and the total potential energy demand remains ambitious, yet consistent with respective government ambitions.

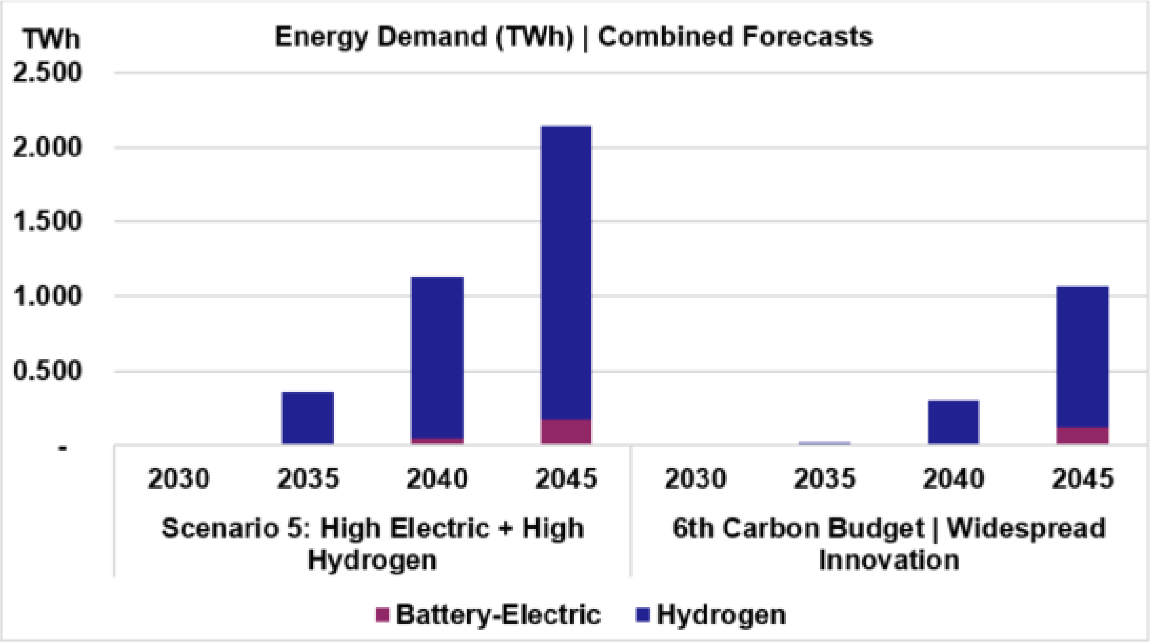
Therefore, the results must be tempered with consideration that hydrogen and electric aircraft are still in the early stages of development. Substantial innovation is still required to bring them to market, which leads to a high uncertainty about the timing of their availability. Additionally, consideration must also be given to the role of Sustainable Aviation Fuels in the future zero emission aviation energy demand trajectory.

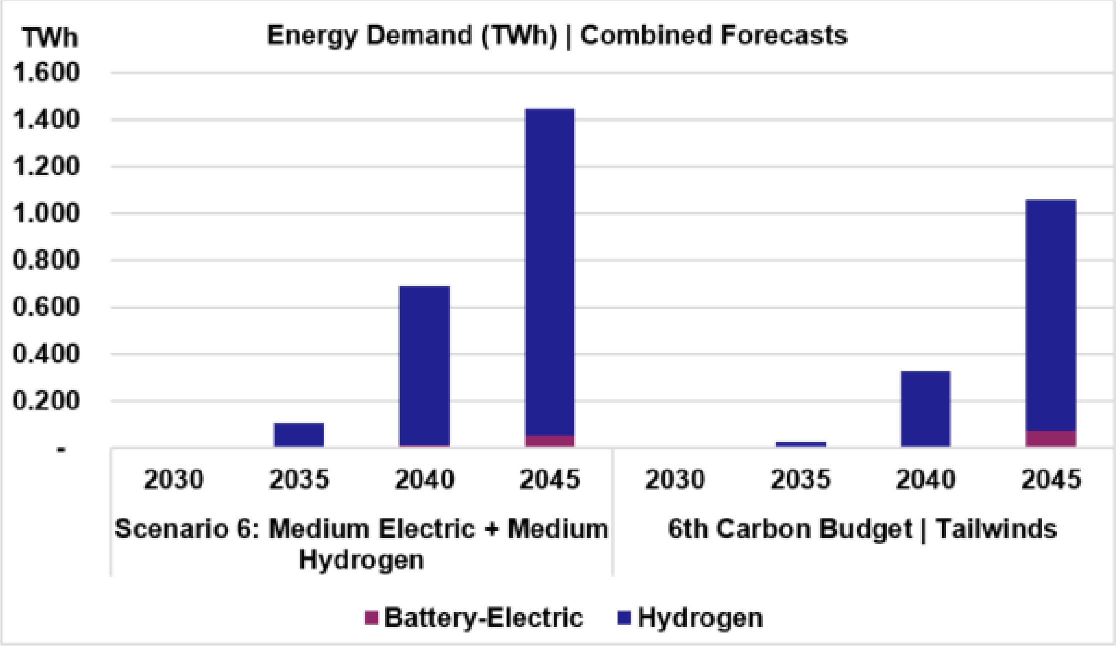
Nevertheless, other recent studies assume similar levels of aviation decarbonisation by 2045, involving a mix between expected technology readiness and compliance with the net zero ambitions. For example, energy demand for hydrogen and electric aircraft forecasted by The 6th Carbon Budget present results in the same range to Jacobs' low and medium scenarios (**Figure 23. Comparison between Jacobs' and the 6th Carbon Budget scenarios**).

This similarity in these scenarios is because [The 6th Carbon Budget] considers hydrogen and electric aircraft will occupy only small niches by 2050, with SAF having the largest fuel mix in their forecasts, between 20% to 50%.

Figure 23. Comparison between Jacobs' and the 6th Carbon Budget scenarios







Usage of SAF is one of the pathways more broadly adopted to reduce aviation emissions. However, there is also a high uncertainty around the availability, efficiency to reduce emissions and cost of SAF in the future. For this reason, for the purpose of this study, a future limited feedstock availability to produce SAF has been considered, which has resulted in a higher hydrogen demand.

As previously discussed in Section 6.1.4 Limitations, technology penetration rates will also highly depend upon the flight type (i.e., domestic, or international). At this project stage, assumptions on technology uptake have been based on aircraft type only. Although aircraft type and flight type are closely related (e.g., small turboprop fly only domestic), a further step on this modelling should include different assumptions based on flight type to assess feasibility of the aviation decarbonisation targets for Scottish intra-domestic flights and required international policies to achieve the international targets.

Chapter 7: Appendices

The following sections summarise the comprehensive set of assumptions and parameters that form the basis of this study and its energy demand forecasts - building on the explanations for their selection across the previous Chapters. These details are also presented separately in the accompanying Tool to enable exploration of the study's results.

Wherever possible, external links to sources of these assumptions have been provided, unless assumptions have been derived from or adjusted from reference values based on internal data or reports.

7.0 Overarching Parameters

The following table first show the key assumptions used to combine the hydrogen and electricity figures and the key data points used in generating the comparative supply curves. Then the overarching assumptions used for the energy demand forecast are shown.

Table 87. Overarching Energy Calculation Parameters

Parameter	Value	Units	Notes / Reference
Hydrogen to Electricity Conversion	0.03	kg/kWh	Based on the LHV of hydrogen (33.46 kWh/kg)
Electrolyser Efficiency	65.4%	N/A	Based on UK Hydrogen Production Costs 2021 and comparison to standard data sheets
Current Renewables Utilisation	30.5%	N/A	Based on comparison of current capacity and output from Scottish Energy Statistics Hub
Future Hydrogen Capacity - 2030	5.00	GW	50/50 mix of Green and Blue in 2030 with a 27.5TWh output. 107.5TWh output in 2045 from 5 GW Blue and 20GW Green. Based on Draft Hydrogen Action Plan
Future Hydrogen Capacity - 2045	25.00	GW	50/50 mix of Green and Blue in 2030 with a 27.5TWh output. 107.5TWh output in 2045 from 5 GW Blue and 20GW Green. Based on Draft Hydrogen Action Plan
Current Renewables Capacity	11.90	GW	Based on Scottish Energy Statistics Hub and estimations from Onshore and Offshore Wind Policy Statements.

Parameter	Value	Units	Notes / Reference
			8 GW onshore wind by 2030 and upper estimate of 12 GW by 2045 8GW offshore wind by 2030 and 11 GW by 2045 Small increase in other sources but considered negligible
Future Renewables Capacity - 2030	27.9	GW	Based on Scottish Energy Statistics Hub and estimations from Onshore and Offshore Wind Policy Statements. 8 GW onshore wind by 2030 and upper estimate of 12 GW by 2045 8GW offshore wind by 2030 and 11 GW by 2045 Small increase in other sources but considered negligible
Future Renewables Capacity - 2045	34.9	GW	Based on Scottish Energy Statistics Hub and estimations from Onshore and Offshore Wind Policy Statements. 8 GW onshore wind by 2030 and upper estimate of 12 GW by 2045 8GW offshore wind by 2030 and 11 GW by 2045 Small increase in other sources but considered negligible

Overarching Energy demand Forecast Parameters

Assumptions common to all Scenarios

While scenarios are consistent across all transport modes, the assumptions for high, medium and low transition to electric (or battery) and hydrogen (or fuel-cell) vary. This is because the consensus of technological readiness and suitability of different energy sources varies both across and even within each mode (e.g. shipping versus ferries). Where applicable, Policy Scenario 3 is applied to guide Transport Demand.

Alignment to Scottish Government Targets and Policy Commitments

GHG targets: All forecasts align to 100% emissions reduction relative to 1990 by 2045.

Road: 20% reduction in distance travelled by car by 2030; phase out of new petrol and diesel cars and vans by 2030 and heavy vehicles by 2035; majority of public service buses zero emission by 2023

Rail: Passenger rail decarbonisation by 2035; and UK commitment to Net Zero emission rail network by 2050.

Aviation: Decarbonisation of intra-Scotland scheduled flights by 2040.

Maritime: 2032 low emission solutions at Scottish Ports, proportion of low emission Scottish Ferries 30% by 2032, IMO and UK commitment for annual emissions from international shipping reduced by 50% by 2050.

7.1 Transport Demand Assumptions

In this section the assumptions used to calculate the demand in each of the transport modes is presented as a summary of the detail in prior sections.

Road Demand Assumptions

Cars

As per Transport Model for Scotland (TMfS:18 STPR2 Low Growth Do Minimum) for trunk and principal roads. Department for Transport Statistics for 2019 have been used to estimate the non modelled demand on minor roads not represented in TMfS:18. Car demand on minor roads is assumed to fall to 80% of the 2019 demand by 2030.

Vans/LGVs

As per Transport Model for Scotland (TMfS:18 STPR2 Low Growth Do Minimum) for trunk and principal roads. Department for Transport Statistics for 2019 have been used to estimate the non modelled demand on minor roads not represented in TMfS:18. LGV demand on minor roads is assumed to be unchanged through to 2045.

Coaches and Scheduled Buses

Buses: As per Transport Model for Scotland (TMfS:18 STPR2 Low Growth Do Minimum) for trunk and principal roads. Department for Transport Statistics for 2019 have been used to estimate the non modelled demand on minor roads not represented in TMfS:18. This data is for scheduled services, assumed as an approximation to be served entirely by buses.

Coaches: Department for Transport Vehicle Licensing Statistics have identified additional vehicles not included in the above demand and it has been assumed that these are all coaches.

Total distance travelled by bus and coach is approximately constant, rising slightly throughout the period to 2045.

HGVs

As per Transport Model for Scotland (TMfS:18 STPR2 Low Growth Do Minimum). No minor road adjustment required.

Other Notes

As agreed with Transport Scotland, the TMfS:18 model was utilised to estimate demand for road transport, which assumes: Reduce Private Demand and increased public transport demand under the Low Scenario as it reflects the current policy ambitions of the Scottish Government and is consistent with STPR2 and other recent modelling undertaken on behalf of the Scottish Government by external consultants.

Rail Demand Assumptions

2023

- **Electrification Complete**:
  Glasgow Central to Barrhead

2024

- **Electrification Complete:**
  Glasgow Central to East Kilbride
- **Service Introductions and Rolling Stock Notes:**
  Glasgow Central to Barrhead
  Using existing EMUs - Class 156 units withdrawn

2025

- **Service Introductions and Rolling Stock Notes:**
  Glasgow Central to East Kilbride
  Some services use existing EMUs - Class 156 units withdrawn

2026

- **Electrification Complete:**
  Edinburgh to Tweedbank
- **Service Introductions and Rolling Stock Notes:**
  Edinburgh to Tweedbank (Battery Electric for Scenarios 4 and 5)
  Class 158 units transferred to West Highland lines; all Class 156 units withdrawn from West Highland

2027

- **Electrification Complete:**
  Fife Circle / Dundee / Perth; and Barrhead to Kilmarnock
- **Service Introductions and Rolling Stock Notes:**
  Edinburgh / Glasgow to Perth / Dundee and Fife Circle (Battery Electric for scenarios 4 and 5)
  Class 158 units transferred to South West Scotland; all Class 156 units withdrawn from South West Scotland

2028

- **Service Introductions and Rolling Stock Notes:**
  In 2028 it is assumed that all Diesel Multiple Units running under overhead electric wires are removed from Glasgow Queen Street to Cumbernauld, Falkirk, Alloa and Dunblane and from Edinburgh Waverley to Dunblane.
  Inverness to Wick / Thurso (hydrogen in all Scenarios) - Class 158 units withdrawn

2029

- **Electrification Complete**:
  Glasgow Queen Street / Edinburgh Waverley to Perth / Dundee / Arbroath
- **Service Introductions and Rolling Stock Notes:**
  In 2029 it is assumed that all Diesel Multiple Units running under overhead electric wires are removed from Edinburgh to Glasgow, North Electrics, South Electrics, Argyle Line, Paisley Canal, Inverclyde, Glasgow Central to Ardrossan, Largs and Ayr and Edinburgh Waverley to North Berwick and Dunbar.

  Glasgow Queen Street / Edinburgh Waverley to Dundee / Arbroath (Battery Electric for Scenarios 4 and 5) **-** Some Class 158 units withdrawn / Class 170 units cascaded north
  Glasgow Queen Street to Anniesland (Battery Electric for Scenarios 4 and 5) - Class 158 units withdrawn

  Inverness to Kyle of Lochalsh (hydrogen in all Scenarios) - Class 158 units withdrawn

2030

- **Electrification complete**:
  Montrose to Aberdeen
- **Service Introductions and Rolling Stock Notes**:
  Aberdeen to Montrose (Battery Electric for Scenarios 4 and 5) – Class 158 units withdrawn / 170 units cascaded to Southwest Scotland
  Glasgow Queen Street / Edinburgh Waverley to Aberdeen (Battery Electric for Scenarios 4 and 5) - HST Fleet Withdrawn / Class 170 units cascaded north
  West Highland Line (hydrogen in all Scenarios) - Class 158 units withdrawn

2035

- **Electrification Complete**:
  Perth to Inverness; Ayr to Girvan & Kilmarnock to Carlisle via Dumfries
- **Service Introductions and Rolling Stock Notes**:
  Glasgow Queen Street / Edinburgh Waverley to Aberdeen / Inverness (Battery Electric for Scenarios 4 and 5) - Class 170 units withdrawn
  Glasgow Central to Stranraer, Dumfries and Carlisle via Kilmarnock - Remaining Class 158 and Class 170 units withdrawn

Other Notes

1. Cross Country train services from Berwick-upon-Tweed to Edinburgh Waverley, Glasgow Central and Aberdeen remain as Class 221 Voyager Diesel Multiple Units until after 2035. By 2040 these will be replaced by 5-car Class 800 units operating as per 2021 timetable.
2. London North Eastern Services will continue operating 9-car Class 800 units that will draw power from the 25 kV overhead line where available before switching to diesel. The date at which the service to Inverness and services to Aberdeen switch to electric haulage is dependent on the date of electrification of the relevant route (2027 as far as Perth / Dundee, 2030 to Aberdeen and 2035 to Inverness).
3. All other cross-border Train Operating Companies (TOCs) will continue to use the same amount of electricity each year as they used in 2019/20.
4. All ScotRail services currently operated by Electric Multiple Units (EMUs) will continue to be operated by EMUs.
   Following implementation of the May 2022 timetable, vehicle miles is anticipated to be approximately 92% of 2019/20 service levels, and this is assumed to increase at 1% per annum, returning to 2019/20 levels by 2030.

5. All electric hauled freight services, across all Freight Operating Companies (FOCs) will continue to operate and use the same amount of electricity as these services used in 2019/20.
6. Existing cross-border rail freight services, via both the East Coast Mainline (ECML) and the West Coast Mainline (WCML), that are hauled by diesel traction, are assumed to start transferring to electric traction from 2022, with all existing diesel hauled freight services switching to electric traction by 2045.
7. Existing rail freight services from the Scottish Central Belt terminals to Aberdeen and Inverness will remain diesel hauled until after 2030. These services will then gradually transition to electric traction, with all existing diesel hauled freight services to Aberdeen and Inverness switching to electric traction by 2045.
8. Existing diesel paths in Network Rail's Working Timetable for December 2021 are assumed to switch to electric on all days specified, unless marked as 'Runs as Required' in which case it was assumed that the path is used half of the time. All these new electric services assumed to be Class 92 with 1,800 tonne trailing load (even although most existing diesel services operate with a reduced load).

Maritime Demand Assumptions

Shipping

Scottish Greenhouse Gas statistics: 1990-2019

2019 UK greenhouse gas emissions: final figures – dataset of emissions by source

Greenhouse gas reporting: Conversion factors 2021

UK Port Freight Traffic – 2019 forecasts

Ferries

Ferry demand was kept constant across the period and compiled from publicly available data on length, journey time and number of trips (according to current timetables for each Ferry route).

Other Notes

Shipping: For shipping a top-down approach was adopted to estimate transport demand (for fuel) based on the Scottish government reporting on GHG emissions from all sectors on an annual basis and broken down by type of water-borne navigation.

- This data was then split using the UK Government's reporting on emissions by type of fuel on an annual basis - also broken down by type of water-borne navigation.
- The CO2e Emission factors for each type of fuel is applied to convert CO2e emissions to fuel consumption
- The tonnage growth forecasted for UK ports was applied to the 2019 Scotland reported emissions to forecast future emissions
- Fuel Source: All the fuel used for deep sea fishing in non-UK waters is assumed to be gas oil sourced in the UK. Type and share of fuel as per UK (no Scotland specific).
- Shipping Movements: All emissions will be used to calculate fuel requirements and assumes ships will refuel at Scottish ports. Energy demand from ferries is subtracted at the end.
- International Accounting: Bunker Fuel Sales are the currently agreed basis by which countries report international shipping emissions to the UN.
- Types of Journeys and Vessels: Classified according to the Scottish government reports on GHG emissions.
- Forecasted Emissions: Scottish future emissions growth as per the UK tonnage forecasted annual growth.

Ferries: For Ferries, total distance travelled by the vessel operating each route was determined and summer deadweight and average operating capacity was estimated for the primary vessel operating each of the routs withing the full domestic ferry dataset.

Due to a lack of information on efficiencies for Fuel Cell and Battery powered ferries, the assumption was made to maintain the same energy demand requirements as currently required, but adjusted for different route operating requirements

Aviation Demand Assumptions

Air Traffic Movements

OAG and Department for Transport – Aviation Forecast data was used to inform 2019 Air Traffic Movements taken as baseline. The Aviation Forecast from the DfT used to forecast future movements for Scottish Airports. Annual growth assumed as per the “Other Regional – Central Demand”.

Average Fleet Mix

OAG 2019 aircraft fleet by airport taken as baseline. Future aircraft mix based on fleet outlooks: modest growth in NB and WB services, flat growth or large turboprops and regional services and smaller airports remain 100% small turboprops served.

Average Sector Distances

OAG and data from literature review informed the average distance flown in 2019 by each aircraft type from each airport taken as baseline. Future average distance remains almost the same, only with a modest growth in Narrow Body and Wide Body distances.

Fuel Consumption

The ICAO fuel consumption per formula was used to calculate the total tonnes of fuel burnt by aircraft type and airport. The kerosene energy density was then used to convert into kWh.

Notes

2019 baseline Air Traffic Movements are assumed to be recovered by 2025; 2019 Baseline fleet mix by airport, forecast for modest growth in narrow body and wide body services; 2019 average distance by aircraft type and airport forecast modest growth in narrow body and wide body distances.

7.2 Technology Scenarios Assumptions

In this section a summary of the technology scenarios as used by each mode of transport is provided, again to summarise the descriptions provided in each relevant section.

Road Technology Scenario Assumptions

Cars

1. **Low transition to electric, high transition to hydrogen:** BEV uptake follows lower boundary of ZEV uptake rate in UK wide transition. Car fleet is assumed to follow the hydrogen uptake rates specified in PS3.
2. **Medium transition to electric, low transition to hydrogen:** BEV uptake follows middle boundary of ZEV uptake rate in UK wide transition. Car fleet is assumed to follow 1/3 the hydrogen uptake rates specified in PS3.
3. **Medium transition to electric and high transition to hydrogen:** BEV uptake follows middle boundary of ZEV uptake rate in UK wide transition. Car fleet is assumed to follow the hydrogen uptake rates specified in PS3.
4. **High transition to electric and low transition to hydrogen:** BEV uptake follows upper boundary of ZEV uptake rate in UK wide transition. Car fleet is assumed to follow 1/3 the hydrogen uptake rates specified in PS3.
5. **High transition to electric and high transition to hydrogen:** BEV uptake follows Upper boundary of ZEV uptake rate in UK wide transition. Car fleet is assumed to follow the hydrogen uptake rates specified in PS3.
6. **Medium transition to electric and medium transition to hydrogen:** BEV uptake follows middle boundary of ZEV uptake rate in UK wide transition. Car fleet is assumed to follow 2/3 the hydrogen uptake rates specified in PS3.

Vans/LGVs

1. **Low transition to electric, high transition to hydrogen:** BEV uptake follows lower boundary of ZEV uptake rate in UK wide transition. Van fleet follows the hydrogen uptake rates specified in PS3 capped at total ZEV rate.
2. **Medium transition to electric, low transition to hydrogen:** BEV uptake follows middle boundary of ZEV uptake rate in UK wide transition.Van fleet is assumed to follow 1/3 the hydrogen uptake rates specified in PS3.
3. **Medium transition to electric and high transition to hydrogen:** BEV uptake follows medium boundary of ZEV uptake rate in UK wide transition. Van fleet follows the hydrogen uptake rates specified in PS3 capped at total ZEV rate.

4. **High transition to electric and low transition to hydrogen:** BEV uptake follows upper boundary of ZEV uptake rate in UK wide transition. Van fleet is assumed to follow 1/3 the hydrogen uptake rates specified in PS3.
5. **High transition to electric and high transition to hydrogen:** BEV uptake follows Upper boundary of ZEV uptake rate in UK wide transition. Van fleet is assumed to follow the hydrogen uptake rates specified in PS3.
6. **Medium transition to electric and medium transition to hydrogen:** BEV uptake follows middle boundary of ZEV uptake rate in UK wide transition. Van fleet is assumed to follow 2/3 the hydrogen uptake rates specified in PS3.

Coaches and Scheduled Buses

1. **Low transition to electric, high transition to hydrogen:** Vehicle replacement rates as high battery cost, low fuel cell cost scenario.
2. **Medium transition to electric, low transition to hydrogen:** Vehicle replacement rates as baseline battery cost, high fuel cell cost scenario.
3. **Medium transition to electric and high transition to hydrogen:** Vehicle replacement rates as baseline battery cost, low fuel cell cost scenario.
4. **High transition to electric and low transition to hydrogen:** Vehicle replacement rates as low battery cost, high fuel cell cost scenario. Removes the majority of fossil fuel buses by 2023.
5. **High transition to electric and high transition to hydrogen:** Vehicle replacement rates as low battery cost, low fuel cell cost scenario. Removes the majority of fossil fuel buses by 2023. All buses zero emission by 2030.
6. **Medium transition to electric and medium transition to hydrogen:** Vehicle replacement rates as baseline scenario.

HGVs

1. **Low transition to electric, high transition to hydrogen:** Early lock-in of hydrogen as fuel source for HGVs.
2. **Medium transition to electric, low transition to hydrogen:** Early lock-in of batteries as fuel source for HGVs.
3. **Medium transition to electric and high transition to hydrogen:** Early lock-in of hydrogen as fuel source for HGVs.
4. **High transition to electric and low transition to hydrogen:** Early lock-in of batteries as fuel source for HGVs,
5. **High transition to electric and high transition to hydrogen:** Mixed trajectory where hydrogen and battery are allowed to compete.
6. **Medium transition to electric and medium transition to hydrogen:** Mixed trajectory where hydrogen and battery are allowed to compete.

Other Notes

1. For cars, due to the expected low hydrogen numbers, the expected ZEV vehicle numbers are calculated and then split into BEV and hydrogen, using the hydrogen figure from PS3 as a base line. The hydrogen figure vary by scenario
2. Due to the widely differing future implementation rates of the potential technologies, there is a different definition of High/Medium/Low across the modes
3. HGV only contains three scenarios, High BEV – Low hydrogen, Medium BEV-Medium hydrogen, Low BEV – High hydrogen. This represents the assumptions in the *Analysis to provide costs, efficiencies and roll-out trajectories for zero emission HGVs, buses and coaches*.
4. There is a different probability for the most likely scenario across the different modes. This is most likely to be High BEV-Low hydrogen for both Cars and Vans, and, potentially, Medium-Medium for HGVs
5. Buses and coaches are scrapped on average after 15 years of operation, unless other incentives or policies cause them to be removed from service sooner.
6. Van fleet is assumed to follow car fleet hydrogen uptake rates specified in PS3 capped at total ZEV rate - assumptions above for vans are based on this overarching assumption.

Rail Technology Scenario Assumptions

Scenarios

1. **Low transition to electric, high transition to hydrogen:** Hydrogen – Far North (2028 to Wick, 2029 to Kyleof Lochalsh), West Highland (2030), Stranraer & Inverness to Aberdeen (2035); Battery – None
2. **Medium transition to electric, low transition to hydrogen:** Hydrogen – Far North (2028 to Wick, 2029 to Kyle of Lochalsh) & West Highland (2030) only; Battery – Inverness to Aberdeen & Stranraer (2035)
3. **Medium transition to electric and high transition to hydrogen:** Hydrogen – Far North (2028 to Wick, 2029 to Kyle of Lochalsh), West Highland (2030), Stranraer & Inverness to Aberdeen (2035); Battery – None
4. **High transition to electric and low transition to hydrogen:** Hydrogen – Far North (2028 to Wick, 2029 to Kyle of Lochalsh) & West Highland (2030) only; Battery – Edinburgh to Tweedbank (2026), Fife Circle, Glasgow Central to Kilmarnock (2027), GLQ/EDB to Perth, Dundee and Arbroath (50% in 2027, 100% in 2029), Glasgow Queen Street to Anniesland (2029), Aberdeen to Montrose, GLQ/EDB to Aberdeen (2030), GLQ/EDB to Inverness, Inverness to Aberdeen & Stranraer (2035)

5. **High transition to electric and high transition to hydrogen:** Hydrogen – Far North (2028 to Wick, 2029 to Kyle of Lochalsh), West Highland (2030), Stranraer & Inverness to Aberdeen (2035); Battery - Edinburgh to Tweedbank (2026), Fife Circle, Glasgow Central to Kilmarnock (2027), GLQ/EDB to Perth, Dundee and Arbroath (50% in 2027, 100% in 2029), Glasgow Queen Street to Anniesland (2029), Aberdeen to Montrose & GLQ/EDB to Aberdeen (2030) and GLQ/EDB to Inverness (2035)
6. **Medium transition to electric and medium transition to hydrogen:** Hydrogen – Far North (2028 to Wick, 2029 to Kyle of Lochalsh), West Highland (2030) & Stranraer (2035); Battery – Inverness to Aberdeen (2035)

Other Notes: All other lines are assumed to be overhead electric

Maritime Technology Scenario Assumptions

Shipping

1. **Low transition to electric, high transition to hydrogen:** Electric + Shore Power: 2% (2% / 2%); Ammonia: 73% (77% / 53%); Fossil Fuel: 25% (21% / 45%)
2. **Medium transition to electric, low transition to hydrogen:** Electric + Shore Power: 5% (6% / 3%); Ammonia: 17% (18% / 8%); Fossil Fuel: 78% (75% / 89%)
3. **Medium transition to electric and high transition to hydrogen:** Electric + Shore Power: 5% (6% / 3%); Ammonia: 73% (76% / 45%); Fossil Fuel: 22% (18% / 45%)
4. **High transition to electric and low transition to hydrogen:** Electric + Shore Power: 10% (11% / 6%); Ammonia: 17% (18% / 8%); Fossil Fuel: 73% (71% / 86%)
5. **High transition to electric and high transition to hydrogen fuel cell:** Electric + Shore Power: 10% (11% / 6%); Ammonia: 71% (74% / 52%); Fossil Fuel: 19% (15% / 43%)
6. **Medium transition to electric and medium transition to hydrogen:** Electric + Shore Power: 5% (6% / 3%); Ammonia: 38% (39% / 32%); Fossil Fuel: 57% (55% / 65%)

Ferries

1. **Low transition to electric, high transition to hydrogen:** 30% Battery Electric by 2032, 100% Battery Electric by 2045; Straight line uptake 2022 ->

2032 (0%->30%); Straight line uptake 2032 -> 2045 (30%->100%); 0% Hydrogen by 2030, 100% Hydrogen by 2045*; Rapid uptake rate 2030 -> 2045, E.g. 87% by 2040

2. **Medium transition to electric, low transition to hydrogen:** 65% Battery Electric by 2032, 100% Battery Electric by 2045; Straight line uptake 2022 -> 2032 (0%->65%); Straight line uptake 2032 -> 2045 (65%->100%); 0% Hydrogen by 2030, 100% Hydrogen by 2045*; Low uptake rate 2030 -> 2045, E.g. 67% by 2040
3. **Medium transition to electric and high transition to hydrogen:** 65% Battery Electric by 2032, 100% Battery Electric by 2045; Straight line uptake 2022 -> 2032 (0%->65%); Straight line uptake 2032 -> 2045 (65%->100%); 0% Hydrogen by 2030, 100% Hydrogen by 2045*; Rapid uptake rate 2030 -> 2045, E.g. 87% by 2040
4. **High transition to electric and low transition to hydrogen:** 100% Battery Electric by 2032, 100% Battery Electric by 2045; Straight line uptake 2022 -> 2032 (0%->100%); 0% Hydrogen by 2030, 100% Hydrogen by 2045*; Low uptake rate 2030 -> 2045, E.g. 67% by 2040
5. **High transition to electric and high transition to hydrogen fuel cell:** 100% Battery Electric by 2032, 100% Battery Electric by 2045; Straight line uptake 2022 -> 2032 (0%->100%); 0% Hydrogen by 2030, 100% Hydrogen by 2045*; Rapid uptake rate 2030 -> 2045, E.g. 87% by 2040
6. **Medium transition to electric and medium transition to hydrogen:** 65% Battery Electric by 2032, 100% Battery Electric by 2045; Straight line uptake 2022 -> 2032 (0%->65%); Straight line uptake 2032 -> 2045 (65%->100%); 0% Hydrogen by 2030, 100% Hydrogen by 2045*; Moderate uptake rate 2030 -> 2045, E.g. 77% by 2040

Other Notes

1. % of energy (TWh) demand at 2045 (Domestic / International).
2. The uptake of battery electric vessels and shore power is relatively modest, between 2% and 10% of the energy demand by 2045.

3. The high electric scenarios present similar electricity uptake as the 6th Carbon Budget scenarios.

4. High electric scenarios assume a higher battery electric uptake and lower shore power demand, while low electric scenarios assume a higher shore power demand than battery electric demand.

5. Ammonia has been chosen as zero-carbon fuel. It represents between 16% and 73% of the total energy demand by 2045. The high Ammonia scenarios present similar Ammonia uptake as the 6th Carbon Budget scenarios.

6. It has been assumed a higher uptake of battery electric and Ammonia technology and an earlier transition to zero-emission alternatives for the domestic shipping due to the usage of smaller vessels and shorter routes.

Shipping Entry into Service

Battery electric vessels (and shore power): The earliest battery electric vessels are assumed to entry into service is from 2025.
Ammonia vessels: Ammonia powered vessels are considered to entry into service from 2030.
Retirement Cycle: A 15 year retirement cycle of existing vessels has been considered.

Shipping Emissions

International Emissions: IMO targets annual emissions from international emissions to be reduced by at least 50% by 2050 (compared to 2008 emissions).
Jacobs Medium-Low Scenario reduces by ~ 60% the 2008 international emissions by 2050.
Jacobs High-High Scenario reduces by ~ 88% the 2008 international emissions and by 98% the total emissions.

Ferries

Only routes with a length of <40km will be serviced by battery electric ferries. Therefore, the percentages are the % of total mileage, for routes <40km, which are covered by battery electric vessels.

It is assumed that due to the tonnage of the Vessels used for the Cairnryan to Larne and Loch Ryan to Belfast that Ammonia will be the zero-carbon fuel

Aviation Technology Scenario Assumptions

Scenarios

1. **Low transition to electric, high transition to hydrogen:** Electric: 4% (1%); Hydrogen: 47% (56%); Kerosene**: 49% (43%)
2. **Medium transition to electric, low transition to hydrogen:** Electric: 16% (7%); Hydrogen: 20% (25%); Kerosene**: 64% (68%)
3. **Medium transition to electric and high transition to hydrogen:** Electric: 16% (5%); Hydrogen: 47% (56%); Kerosene**: 37% (39%)
4. **High transition to electric and low transition to hydrogen:** Electric: 20% (12%); Hydrogen: 28% (25%); Kerosene**: 52% (63%)
5. **High transition to electric and high transition to hydrogen fuel cell:** Electric: 28% (9%); Hydrogen: 47% (56%); Kerosene**: 25% (35%)
6. **Medium transition to electric and medium transition to hydrogen:** Electric: 16% (6%); Hydrogen: 35% (42%); Kerosene**: 48% (52%)

Other Notes

1. % of ATM’s by 2050 (% of Kms by 2050).
2. ** (Part of) the kerosene could be replaced by Sustainable Aviation Fuels (SAF). SAFs are out of the scope of this study.

7.3 Energy Demand Analysis Assumptions

Here the assumptions used to convert the forecast demand and technology uptake scenarios into the required amount of electricity and hydrogen are detailed. Firstly the assumptions for rail are presented.

Table 88. Rail Energy Demand Assumptions

Parameter	Value	Units	Notes / Reference
Hydrogen Consumption	0.386	kg/mile	Based on values for Concordia iLint and ARUP route to market study
Overhead Electric (Existing Routes)	3.23	kWh/mile	Scotrail services, based on ScotRail's energy draw 2019/20
Overhead Electric (New Routes)	4.47	kWh/mile	Scotrail services, based on figures provided by Network Rail across different 4-car Classes
Battery Electric	5.60	kWh/mile	Scotrail services, based on Vivarail modelling of Class 365
Cross country services	18.04	kWh/mile	Network Rail data for a 5-car Class 800
LNER Services	31.99	kWh/mile	Network Rail data for a 9-car Class 800
Freight Trains	79.53	kWh/mile	Network Rail data for a Class 92 locomotive hauling 1,800 tonnes

Table 89. Road Energy Demand Assumptions

Parameter	Value	Units	Notes / Reference
Car BEV Energy Demand	0.220	kWh/km	Derived from TAG data book
Car PHEV Energy Demand	0.073	kWh/km	Based on assumptions from Real-world usage of PHEVs
Car Hydrogen Utilisation	0.011	kg H2/km	From Toyota Mirai
Car Annual Mileage	13,900	km	TMfS:18 Data
EV Van Energy Demand	0.260	kWh/km	Derived from TAG data book
Van PHEV Energy Demand	0.087	kWh/km	Based on assumptions from Real-world usage of PHEVs
Van Hydrogen Utilisation	0.013	kg H2/km	Assumption that H2 efficiency scales as EV
Van Annual Mileage	29,185	km	TMfS:18 Data
Electric HGV Energy Demand	1.440	kWh/km	Collation of varied sources
HGV Hydrogen Utilisation	0.072	kg H2/km	Assumption that H2 efficiency scales as EV
HGV Annual Mileage	77,856	km	TMfS:18 Data
Single Decker (SD) Electric Bus Energy Demand	1.100	kWh/km	Based on input data from Energy - HDV, HGV and buses Based on data from Scottish Bus electrification
Single Decker Bus Hydrogen Utilisation	0.055	kg H2/km	Calculated based on electricity figures and Fuel Cell 60% efficiency
Single Decker Bus Annual Mileage	80,467	km	Based on data from Scottish Bus electrification
Double Decker Electric Bus Energy Demand	1.400	kWh/km	Based on input data from Energy - HDV, HGV and buses
Double Decker Bus Hydrogen Utilisation	0.070	kg H2/km	As above for SD Bus
Double Decker Bus Annual Mileage	80,467	km	Based on data from Scottish Bus electrification
Coach Energy Demand	1.100	kWh/km	Based on input data from Energy - HDV, HGV and buses

Parameter	Value	Units	Notes / Reference
Coach Hydrogen Utilisation	0.055	kg H2/km	As above for SD Bus
Coach Annual Mileage	80,467	km	Based on data from Scottish Bus electrification

Table 90. Shipping Energy Demand Assumptions

Parameter	Value	Units	Notes / Reference
Marine Fuel Oil CO_2e emissions	3,160	kg/tonne of fuel	UK Greenhouse gas reporting: conversion factors 2021
Marine Gas Oil CO_2e emissions	3,250	kg/tonne of fuel	UK Greenhouse gas reporting: conversion factors 2021
Diesel	2,969	kg/tonne of fuel	UK Greenhouse gas reporting: conversion factors 2021
Motor Spirit	2,948	kg/tonne of fuel	UK Greenhouse gas reporting: conversion factors 2021
Current Shipping Fuel Efficiency	50%	N/A	Based on IEEE: Electric Container Ships Are Stuck on the Horizon
Ammonia Engine Efficiency	50%	N/A	Based on estimation from MAN Energy Solutions data
Battery Efficiency	92%	N/A	Based on The Future of Batteries in the Marine Sector
Battery Energy Density	0.30	MJ/Kg	Based on IEEE: Electric Container Ships Are Stuck on the Horizon
Ammonia Energy Density	22.50	MJ/Kg	Ammonia HHV value
Hydrogen Energy Density	120.00	MJ/Kg	Hydrogen LHV value
Hydrogen to Ammonia Conversion Efficiency	85%	N/A	Based on data in Sailing on Solar, EDF

Table 91. Ferries Energy Demand Assumptions

Parameter	Value	Units	Notes / Reference
Marine Fuel Oil CO_2e	0.262	kg CO_2e/kWh (gross CV)	UK Greenhouse gas reporting: conversion factors 2021
Ferry CO_2e Emissions	0.052	kg CO_2e/ tonne.km	N/A
Large RoPax Ferry CO_2e Emissions	0.377	kg CO_2e/ tonne.km	N/A
Energy Demand per km on Each Route	N/A	kWh/km	Each route was determined to have a different energy demand per route. This is based on an analysis of the individual ferry routes, then applying the operating capacity assumptions.

Table 92. Aviation Energy Demand Assumptions

Parameter	Value	Units	Notes
Specific Energy of Baseline Fuel	42.8	MJ/kg	Hypertextbook
Specific energy of LH_2	120.0	MJ/kg	Hydrogen LHV value
Increase in efficiency of using LH_2	57%	N/A	Based on various reports from literature review
Kerosene use Efficiency	27%	N/A	Leeham - Article: The true cost of electric aircraft
Battery Efficiency	92%		Leeham - Article: The true cost of electric aircraft
Battery Energy Density - Existing	0.146	kWh/kg	Roland Berger - Aircraft Electrical Propulsion - The next chapter of aviation? Energies - Study: Assessment of All-Electric General Aviation Aircraft
Battery Energy Density - Future	0.500	kWh/kg	Roland Berger - Aircraft Electrical Propulsion - The next chapter of aviation? Energies - Study: Assessment of All-Electric General Aviation Aircraft

7.4 Aviation Energy Demand – Airport Level

Table 93, Table 94, Table 95, Table 96, Table 97 and Table 98 show hydrogen demand at airport level for each scenario respectively.

Scenario 1 (LH)

Table 93: Hydrogen Demand (GWh) by Airport – Scenario 1

Airport	2022	2025	2030	2035	2040	2045
Aberdeen	0.0	0.0	1.7	30.1	81.5	155.6
Benbecula	0.0	0.0	0.0	0.3	0.5	0.9
Barra	0.0	0.0	0.0	0.0	0.0	0.0
Campbeltown	0.0	0.0	0.0	0.0	0.0	0.0
Coll	0.0	0.0	0.0	0.0	0.0	0.0
Colonsay	0.0	0.0	0.0	0.0	0.0	0.0
Dundee	0.0	0.0	0.0	0.3	0.5	0.9
Edinburgh	0.0	0.0	1.6	167.4	515.0	923.0
Eday	0.0	0.0	0.0	0.0	0.0	0.0
Fair Isle	0.0	0.0	0.0	0.0	0.0	0.0
Foula	0.0	0.0	0.0	0.0	0.0	0.0
Glasgow	0.0	0.0	1.3	136.1	418.1	756.7
Islay	0.0	0.0	0.0	0.2	0.3	0.6
Inverness	0.0	0.0	0.5	10.1	27.6	53.1
Kirkwall	0.0	0.0	0.1	0.8	1.5	2.6
Sumburgh	0.0	0.0	0.2	1.2	2.5	4.2
Tingwall	0.0	0.0	0.0	0.0	0.0	0.0
Sanday	0.0	0.0	0.0	0.0	0.0	0.0
North Ronaldsay	0.0	0.0	0.0	0.0	0.0	0.0
Oban	0.0	0.0	0.0	0.0	0.0	0.0
Glasgow Prestwick	0.0	0.0	0.0	11.4	34.3	66.5

Airport	2022	2025	2030	2035	2040	2045
Papa Westray	0.0	0.0	0.0	0.0	0.0	0.0
Papa Stour	0.0	0.0	0.0	0.0	0.0	0.0
Stronsay	0.0	0.0	0.0	0.0	0.0	0.0
Stornoway	0.0	0.0	0.2	1.4	2.9	5.0
Tiree	0.0	0.0	0.0	0.0	0.0	0.0
Wick	0.0	0.0	0.0	0.1	0.1	0.2
Westray	0.0	0.0	0.0	0.0	0.0	0.0

Scenario 2 (ML)

Table 94: Hydrogen Demand (GWh) by Airport – Scenario 2

Airport	2022	2025	2030	2035	2040	2045
Aberdeen	0.0	0.0	0.0	0.9	20.6	60.2
Benbecula	0.0	0.0	0.0	0.0	0.1	0.3
Barra	0.0	0.0	0.0	0.0	0.0	0.0
Campbeltown	0.0	0.0	0.0	0.0	0.0	0.0
Coll	0.0	0.0	0.0	0.0	0.0	0.0
Colonsay	0.0	0.0	0.0	0.0	0.0	0.0
Dundee	0.0	0.0	0.0	0.0	0.1	0.3
Edinburgh	0.0	0.0	0.0	0.7	115.4	348.1
Eday	0.0	0.0	0.0	0.0	0.0	0.0
Fair Isle	0.0	0.0	0.0	0.0	0.0	0.0
Foula	0.0	0.0	0.0	0.0	0.0	0.0
Glasgow	0.0	0.0	0.0	0.7	89.1	276.3
Islay	0.0	0.0	0.0	0.0	0.1	0.2
Inverness	0.0	0.0	0.0	0.3	7.0	20.8
Kirkwall	0.0	0.0	0.0	0.1	0.4	0.8
Sumburgh	0.0	0.0	0.0	0.1	0.6	1.2
Tingwall	0.0	0.0	0.0	0.0	0.0	0.0

Airport	2022	2025	2030	2035	2040	2045
Sanday	0.0	0.0	0.0	0.0	0.0	0.0
North Ronaldsay	0.0	0.0	0.0	0.0	0.0	0.0
Oban	0.0	0.0	0.0	0.0	0.0	0.0
Glasgow Prestwick	0.0	0.0	0.0	0.0	8.4	26.6
Papa Westray	0.0	0.0	0.0	0.0	0.0	0.0
Papa Stour	0.0	0.0	0.0	0.0	0.0	0.0
Stronsay	0.0	0.0	0.0	0.0	0.0	0.0
Stornoway	0.0	0.0	0.0	0.1	0.8	1.7
Tiree	0.0	0.0	0.0	0.0	0.0	0.0
Wick	0.0	0.0	0.0	0.0	0.0	0.1
Westray	0.0	0.0	0.0	0.0	0.0	0.0

Scenario 3 (MH)

Table 95: Hydrogen Demand (GWh) by Airport - Scenario 3

Airport	2022	2025	2030	2035	2040	2045
Aberdeen	0.0	0.0	1.7	30.1	81.5	155.6
Benbecula	0.0	0.0	0.0	0.3	0.5	0.9
Barra	0.0	0.0	0.0	0.0	0.0	0.0
Campbeltown	0.0	0.0	0.0	0.0	0.0	0.0
Coll	0.0	0.0	0.0	0.0	0.0	0.0
Colonsay	0.0	0.0	0.0	0.0	0.0	0.0
Dundee	0.0	0.0	0.0	0.3	0.5	0.9
Edinburgh	0.0	0.0	1.6	167.4	515.0	923.0
Eday	0.0	0.0	0.0	0.0	0.0	0.0
Fair Isle	0.0	0.0	0.0	0.0	0.0	0.0
Foula	0.0	0.0	0.0	0.0	0.0	0.0
Glasgow	0.0	0.0	1.3	136.1	418.1	756.7

Airport	2022	2025	2030	2035	2040	2045
Islay	0.0	0.0	0.0	0.2	0.3	0.6
Inverness	0.0	0.0	0.5	10.1	27.6	53.1
Kirkwall	0.0	0.0	0.1	0.8	1.5	2.6
Sumburgh	0.0	0.0	0.2	1.2	2.5	4.2
Tingwall	0.0	0.0	0.0	0.0	0.0	0.0
Sanday	0.0	0.0	0.0	0.0	0.0	0.0
North Ronaldsay	0.0	0.0	0.0	0.0	0.0	0.0
Oban	0.0	0.0	0.0	0.0	0.0	0.0
Glasgow Prestwick	0.0	0.0	0.0	11.4	34.3	66.5
Papa Westray	0.0	0.0	0.0	0.0	0.0	0.0
Papa Stour	0.0	0.0	0.0	0.0	0.0	0.0
Stronsay	0.0	0.0	0.0	0.0	0.0	0.0
Stornoway	0.0	0.0	0.2	1.4	2.9	5.0
Tiree	0.0	0.0	0.0	0.0	0.0	0.0
Wick	0.0	0.0	0.0	0.1	0.1	0.2
Westray	0.0	0.0	0.0	0.0	0.0	0.0

Scenario 4 (HL)

Table 96: Hydrogen Demand (GWh) by Airport – Scenario 4

Airport	2022	2025	2030	2035	2040	2045
Aberdeen	0.0	0.0	0.0	0.9	20.6	60.2
Benbecula	0.0	0.0	0.0	0.0	0.1	0.3
Barra	0.0	0.0	0.0	0.0	0.0	0.0
Campbeltown	0.0	0.0	0.0	0.0	0.0	0.0
Coll	0.0	0.0	0.0	0.0	0.0	0.0
Colonsay	0.0	0.0	0.0	0.0	0.0	0.0
Dundee	0.0	0.0	0.0	0.0	0.1	0.3

Airport	2022	2025	2030	2035	2040	2045
Edinburgh	0.0	0.0	0.0	0.7	115.4	348.1
Eday	0.0	0.0	0.0	0.0	0.0	0.0
Fair Isle	0.0	0.0	0.0	0.0	0.0	0.0
Foula	0.0	0.0	0.0	0.0	0.0	0.0
Glasgow	0.0	0.0	0.0	0.7	89.1	276.3
Islay	0.0	0.0	0.0	0.0	0.1	0.2
Inverness	0.0	0.0	0.0	0.3	7.0	20.8
Kirkwall	0.0	0.0	0.0	0.1	0.4	0.8
Sumburgh	0.0	0.0	0.0	0.1	0.6	1.2
Tingwall	0.0	0.0	0.0	0.0	0.0	0.0
Sanday	0.0	0.0	0.0	0.0	0.0	0.0
North Ronaldsay	0.0	0.0	0.0	0.0	0.0	0.0
Oban	0.0	0.0	0.0	0.0	0.0	0.0
Glasgow Prestwick	0.0	0.0	0.0	0.0	8.4	26.6
Papa Westray	0.0	0.0	0.0	0.0	0.0	0.0
Papa Stour	0.0	0.0	0.0	0.0	0.0	0.0
Stronsay	0.0	0.0	0.0	0.0	0.0	0.0
Stornoway	0.0	0.0	0.0	0.1	0.8	1.7
Tiree	0.0	0.0	0.0	0.0	0.0	0.0
Wick	0.0	0.0	0.0	0.0	0.0	0.1
Westray	0.0	0.0	0.0	0.0	0.0	0.0

Scenario 5 (HH)

Table 97: Hydrogen Demand (GWh) by Airport - Scenario 5

Airport	2022	2025	2030	2035	2040	2045
Aberdeen	0.0	0.0	1.7	30.1	81.5	155.6
Benbecula	0.0	0.0	0.0	0.3	0.5	0.9

Airport	2022	2025	2030	2035	2040	2045
Barra	0.0	0.0	0.0	0.0	0.0	0.0
Campbeltown	0.0	0.0	0.0	0.0	0.0	0.0
Coll	0.0	0.0	0.0	0.0	0.0	0.0
Colonsay	0.0	0.0	0.0	0.0	0.0	0.0
Dundee	0.0	0.0	0.0	0.3	0.5	0.9
Edinburgh	0.0	0.0	1.6	167.4	515.0	923.0
Eday	0.0	0.0	0.0	0.0	0.0	0.0
Fair Isle	0.0	0.0	0.0	0.0	0.0	0.0
Foula	0.0	0.0	0.0	0.0	0.0	0.0
Glasgow	0.0	0.0	1.3	136.1	418.1	756.7
Islay	0.0	0.0	0.0	0.2	0.3	0.6
Inverness	0.0	0.0	0.5	10.1	27.6	53.1
Kirkwall	0.0	0.0	0.1	0.8	1.5	2.6
Sumburgh	0.0	0.0	0.2	1.2	2.5	4.2
Tingwall	0.0	0.0	0.0	0.0	0.0	0.0
Sanday	0.0	0.0	0.0	0.0	0.0	0.0
North Ronaldsay	0.0	0.0	0.0	0.0	0.0	0.0
Oban	0.0	0.0	0.0	0.0	0.0	0.0
Glasgow Prestwick	0.0	0.0	0.0	11.4	34.3	66.5
Papa Westray	0.0	0.0	0.0	0.0	0.0	0.0
Papa Stour	0.0	0.0	0.0	0.0	0.0	0.0
Stronsay	0.0	0.0	0.0	0.0	0.0	0.0
Stornoway	0.0	0.0	0.2	1.4	2.9	5.0
Tiree	0.0	0.0	0.0	0.0	0.0	0.0
Wick	0.0	0.0	0.0	0.1	0.1	0.2
Westray	0.0	0.0	0.0	0.0	0.0	0.0

Scenario 6 (MM)

Table 98: Hydrogen Demand (GWh) by Airport – Scenario 6

Airport	2022	2025	2030	2035	2040	2045
Aberdeen	0.0	0.0	0.0	11.4	52.7	112.0
Benbecula	0.0	0.0	0.0	0.1	0.3	0.6
Barra	0.0	0.0	0.0	0.0	0.0	0.0
Campbeltown	0.0	0.0	0.0	0.0	0.0	0.0
Coll	0.0	0.0	0.0	0.0	0.0	0.0
Colonsay	0.0	0.0	0.0	0.0	0.0	0.0
Dundee	0.0	0.0	0.0	0.1	0.3	0.6
Edinburgh	0.0	0.0	0.0	47.4	322.3	654.6
Eday	0.0	0.0	0.0	0.0	0.0	0.0
Fair Isle	0.0	0.0	0.0	0.0	0.0	0.0
Foula	0.0	0.0	0.0	0.0	0.0	0.0
Glasgow	0.0	0.0	0.0	37.5	257.7	529.9
Islay	0.0	0.0	0.0	0.1	0.2	0.4
Inverness	0.0	0.0	0.0	3.7	17.9	38.4
Kirkwall	0.0	0.0	0.0	0.4	0.9	1.7
Sumburgh	0.0	0.0	0.0	0.6	1.5	2.7
Tingwall	0.0	0.0	0.0	0.0	0.0	0.0
Sanday	0.0	0.0	0.0	0.0	0.0	0.0
North Ronaldsay	0.0	0.0	0.0	0.0	0.0	0.0
Oban	0.0	0.0	0.0	0.0	0.0	0.0
Glasgow Prestwick	0.0	0.0	0.0	3.2	22.1	48.2
Papa Westray	0.0	0.0	0.0	0.0	0.0	0.0
Papa Stour	0.0	0.0	0.0	0.0	0.0	0.0
Stronsay	0.0	0.0	0.0	0.0	0.0	0.0
Stornoway	0.0	0.0	0.0	0.8	1.9	3.5
Tiree	0.0	0.0	0.0	0.0	0.0	0.0

Airport	2022	2025	2030	2035	2040	2045
Wick	0.0	0.0	0.0	0.0	0.1	0.2
Westray	0.0	0.0	0.0	0.0	0.0	0.0

Table 99, Table 100, Table 101, Table 102, Table 103 and Table 104 show electricity demand at airport level for the scenario respectively .

Scenario 1 (LH)

Table 99: Electricity Demand (GWh) by Airport – Scenario 1

Airport	2022	2025	2030	2035	2040	2045
Aberdeen	0.0	0.0	0.0	0.0	0.6	4.5
Benbecula	0.0	0.0	0.0	0.0	0.0	0.0
Barra	0.0	0.0	0.0	0.0	0.2	1.3
Campbeltown	0.0	0.0	0.0	0.0	0.1	0.4
Coll	0.0	0.0	0.0	0.0	0.0	0.1
Colonsay	0.0	0.0	0.0	0.0	0.0	0.1
Dundee	0.0	0.0	0.0	0.0	0.0	0.0
Edinburgh	0.0	0.0	0.0	0.0	0.0	0.0
Eday	0.0	0.0	0.0	0.0	0.0	0.0
Fair Isle	0.0	0.0	0.0	0.0	0.0	0.3
Foula	0.0	0.0	0.0	0.0	0.0	0.2
Glasgow	0.0	0.0	0.0	0.0	0.1	0.3
Islay	0.0	0.0	0.0	0.0	0.0	0.1
Inverness	0.0	0.0	0.0	0.0	0.0	0.0
Kirkwall	0.0	0.0	0.0	0.0	0.1	0.7
Sumburgh	0.0	0.0	0.0	0.0	0.0	0.0
Tingwall	0.0	0.0	0.0	0.0	0.1	0.4
Sanday	0.0	0.0	0.0	0.0	0.0	0.2
North Ronaldsay	0.0	0.0	0.0	0.0	0.0	0.2
Oban	0.0	0.0	0.0	0.0	0.1	0.5

Airport	2022	2025	2030	2035	2040	2045
Glasgow Prestwick	0.0	0.0	0.0	0.0	0.0	0.0
Papa Westray	0.0	0.0	0.0	0.0	0.0	0.2
Papa Stour	0.0	0.0	0.0	0.0	0.0	0.1
Stronsay	0.0	0.0	0.0	0.0	0.0	0.1
Stornoway	0.0	0.0	0.0	0.0	0.0	0.0
Tiree	0.0	0.0	0.0	0.0	0.1	0.6
Wick	0.0	0.0	0.0	0.0	0.1	0.5
Westray	0.0	0.0	0.0	0.0	0.0	0.1

Scenario 2 (LH)

Table 100: Electricity Demand (GWh) by Airport – Scenario 2

Airport	2022	2025	2030	2035	2040	2045
Aberdeen	0.0	0.0	0.0	0.0	4.7	20.9
Benbecula	0.0	0.0	0.0	0.0	0.0	0.3
Barra	0.0	0.0	0.0	0.0	1.4	3.6
Campbeltown	0.0	0.0	0.0	0.0	0.4	1.2
Coll	0.0	0.0	0.0	0.0	0.1	0.3
Colonsay	0.0	0.0	0.0	0.0	0.1	0.2
Dundee	0.0	0.0	0.0	0.0	0.0	0.4
Edinburgh	0.0	0.0	0.0	0.0	0.0	6.4
Eday	0.0	0.0	0.0	0.0	0.0	0.1
Fair Isle	0.0	0.0	0.0	0.0	0.3	0.8
Foula	0.0	0.0	0.0	0.0	0.2	0.4
Glasgow	0.0	0.0	0.0	0.0	0.7	5.9
Islay	0.0	0.0	0.0	0.0	0.1	0.6
Inverness	0.0	0.0	0.0	0.0	0.0	2.1
Kirkwall	0.0	0.0	0.0	0.0	0.7	3.3

Airport	2022	2025	2030	2035	2040	2045
Sumburgh	0.0	0.0	0.0	0.0	0.0	1.7
Tingwall	0.0	0.0	0.0	0.0	0.4	1.1
Sanday	0.0	0.0	0.0	0.0	0.2	0.5
North Ronaldsay	0.0	0.0	0.0	0.0	0.2	0.6
Oban	0.0	0.0	0.0	0.0	0.5	1.3
Glasgow Prestwick	0.0	0.0	0.0	0.0	0.0	0.0
Papa Westray	0.0	0.0	0.0	0.0	0.2	0.5
Papa Stour	0.0	0.0	0.0	0.0	0.1	0.2
Stronsay	0.0	0.0	0.0	0.0	0.1	0.2
Stornoway	0.0	0.0	0.0	0.0	0.0	1.2
Tiree	0.0	0.0	0.0	0.0	0.7	1.7
Wick	0.0	0.0	0.0	0.0	0.5	1.5
Westray	0.0	0.0	0.0	0.0	0.1	0.3

Scenario 3 (MH)

Table 101: Electricity Demand (GWh) by Airport – Scenario 3

Airport	2022	2025	2030	2035	2040	2045
Aberdeen	0.0	0.0	0.0	0.0	4.7	18.1
Benbecula	0.0	0.0	0.0	0.0	0.0	0.3
Barra	0.0	0.0	0.0	0.0	1.4	3.6
Campbeltown	0.0	0.0	0.0	0.0	0.4	1.2
Coll	0.0	0.0	0.0	0.0	0.1	0.3
Colonsay	0.0	0.0	0.0	0.0	0.1	0.2
Dundee	0.0	0.0	0.0	0.0	0.0	0.3
Edinburgh	0.0	0.0	0.0	0.0	0.0	4.7
Eday	0.0	0.0	0.0	0.0	0.0	0.1
Fair Isle	0.0	0.0	0.0	0.0	0.3	0.8

Airport	2022	2025	2030	2035	2040	2045
Foula	0.0	0.0	0.0	0.0	0.2	0.4
Glasgow	0.0	0.0	0.0	0.0	0.7	4.3
Islay	0.0	0.0	0.0	0.0	0.1	0.5
Inverness	0.0	0.0	0.0	0.0	0.0	1.4
Kirkwall	0.0	0.0	0.0	0.0	0.7	3.0
Sumburgh	0.0	0.0	0.0	0.0	0.0	1.4
Tingwall	0.0	0.0	0.0	0.0	0.4	1.1
Sanday	0.0	0.0	0.0	0.0	0.2	0.5
North Ronaldsay	0.0	0.0	0.0	0.0	0.2	0.6
Oban	0.0	0.0	0.0	0.0	0.5	1.3
Glasgow Prestwick	0.0	0.0	0.0	0.0	0.0	0.0
Papa Westray	0.0	0.0	0.0	0.0	0.2	0.5
Papa Stour	0.0	0.0	0.0	0.0	0.1	0.2
Stronsay	0.0	0.0	0.0	0.0	0.1	0.2
Stornoway	0.0	0.0	0.0	0.0	0.0	0.8
Tiree	0.0	0.0	0.0	0.0	0.7	1.7
Wick	0.0	0.0	0.0	0.0	0.5	1.5
Westray	0.0	0.0	0.0	0.0	0.1	0.3

Scenario 4 (HL)

Table 102: Electricity Demand (GWh) by Airport – Scenario 4

Airport	2022	2025	2030	2035	2040	2045
Aberdeen	0.0	0.0	0.0	1.1	16.3	73.0
Benbecula	0.0	0.0	0.0	0.0	0.3	2.3
Barra	0.0	0.0	0.0	0.3	2.2	4.7
Campbeltown	0.0	0.0	0.0	0.1	0.7	1.5
Coll	0.0	0.0	0.0	0.0	0.2	0.3

Airport	2022	2025	2030	2035	2040	2045
Colonsay	0.0	0.0	0.0	0.0	0.1	0.3
Dundee	0.0	0.0	0.0	0.0	0.4	2.5
Edinburgh	0.0	0.0	0.0	0.0	7.7	43.1
Eday	0.0	0.0	0.0	0.0	0.1	0.1
Fair Isle	0.0	0.0	0.0	0.1	0.5	1.0
Foula	0.0	0.0	0.0	0.0	0.3	0.6
Glasgow	0.0	0.0	0.0	0.3	7.1	34.4
Islay	0.0	0.0	0.0	0.0	0.4	2.2
Inverness	0.0	0.0	0.0	0.0	2.1	13.6
Kirkwall	0.0	0.0	0.0	0.2	2.5	12.0
Sumburgh	0.0	0.0	0.0	0.0	1.7	11.6
Tingwall	0.0	0.0	0.0	0.1	0.7	1.5
Sanday	0.0	0.0	0.0	0.0	0.3	0.7
North Ronaldsay	0.0	0.0	0.0	0.1	0.4	0.8
Oban	0.0	0.0	0.0	0.1	0.8	1.7
Glasgow Prestwick	0.0	0.0	0.0	0.0	0.0	0.0
Papa Westray	0.0	0.0	0.0	0.0	0.3	0.6
Papa Stour	0.0	0.0	0.0	0.0	0.1	0.2
Stronsay	0.0	0.0	0.0	0.0	0.1	0.3
Stornoway	0.0	0.0	0.0	0.0	1.2	8.1
Tiree	0.0	0.0	0.0	0.2	1.0	2.3
Wick	0.0	0.0	0.0	0.1	0.9	2.5
Westray	0.0	0.0	0.0	0.0	0.2	0.4

Scenario 5 (HH)

Table 103: Electricity Demand (GWh) by Airport – Scenario 5

Airport	2022	2025	2030	2035	2040	2045
Aberdeen	0.0	0.0	0.0	1.1	14.4	55.9
Benbecula	0.0	0.0	0.0	0.0	0.3	1.8
Barra	0.0	0.0	0.0	0.3	2.2	4.7
Campbeltown	0.0	0.0	0.0	0.1	0.7	1.5
Coll	0.0	0.0	0.0	0.0	0.2	0.3
Colonsay	0.0	0.0	0.0	0.0	0.1	0.3
Dundee	0.0	0.0	0.0	0.0	0.3	2.1
Edinburgh	0.0	0.0	0.0	0.0	6.3	32.4
Eday	0.0	0.0	0.0	0.0	0.1	0.1
Fair Isle	0.0	0.0	0.0	0.1	0.5	1.0
Foula	0.0	0.0	0.0	0.0	0.3	0.6
Glasgow	0.0	0.0	0.0	0.3	5.8	24.6
Islay	0.0	0.0	0.0	0.0	0.4	1.9
Inverness	0.0	0.0	0.0	0.0	1.6	8.9
Kirkwall	0.0	0.0	0.0	0.2	2.4	10.5
Sumburgh	0.0	0.0	0.0	0.0	1.5	9.7
Tingwall	0.0	0.0	0.0	0.1	0.7	1.5
Sanday	0.0	0.0	0.0	0.0	0.3	0.7
North Ronaldsay	0.0	0.0	0.0	0.1	0.4	0.8
Oban	0.0	0.0	0.0	0.1	0.8	1.7
Glasgow Prestwick	0.0	0.0	0.0	0.0	0.0	0.0
Papa Westray	0.0	0.0	0.0	0.0	0.3	0.6
Papa Stour	0.0	0.0	0.0	0.0	0.1	0.2
Stronsay	0.0	0.0	0.0	0.0	0.1	0.3
Stornoway	0.0	0.0	0.0	0.0	1.0	5.6
Tiree	0.0	0.0	0.0	0.2	1.0	2.3
Wick	0.0	0.0	0.0	0.1	0.9	2.4

Airport	2022	2025	2030	2035	2040	2045
Westray	0.0	0.0	0.0	0.0	0.2	0.4

Scenario 6 (MM)

Table 104: Electricity Demand (GWh) by Airport – Scenario 6

Airport	2022	2025	2030	2035	2040	2045
Aberdeen	0.0	0.0	0.0	0.0	4.7	19.4
Benbecula	0.0	0.0	0.0	0.0	0.0	0.3
Barra	0.0	0.0	0.0	0.0	1.4	3.6
Campbeltown	0.0	0.0	0.0	0.0	0.4	1.2
Coll	0.0	0.0	0.0	0.0	0.1	0.3
Colonsay	0.0	0.0	0.0	0.0	0.1	0.2
Dundee	0.0	0.0	0.0	0.0	0.0	0.3
Edinburgh	0.0	0.0	0.0	0.0	0.0	5.5
Eday	0.0	0.0	0.0	0.0	0.0	0.1
Fair Isle	0.0	0.0	0.0	0.0	0.3	0.8
Foula	0.0	0.0	0.0	0.0	0.2	0.4
Glasgow	0.0	0.0	0.0	0.0	0.7	5.0
Islay	0.0	0.0	0.0	0.0	0.1	0.5
Inverness	0.0	0.0	0.0	0.0	0.0	1.7
Kirkwall	0.0	0.0	0.0	0.0	0.7	3.1
Sumburgh	0.0	0.0	0.0	0.0	0.0	1.5
Tingwall	0.0	0.0	0.0	0.0	0.4	1.1
Sanday	0.0	0.0	0.0	0.0	0.2	0.5
North Ronaldsay	0.0	0.0	0.0	0.0	0.2	0.6
Oban	0.0	0.0	0.0	0.0	0.5	1.3
Glasgow Prestwick	0.0	0.0	0.0	0.0	0.0	0.0
Papa Westray	0.0	0.0	0.0	0.0	0.2	0.5

Airport	2022	2025	2030	2035	2040	2045
Papa Stour	0.0	0.0	0.0	0.0	0.1	0.2
Stronsay	0.0	0.0	0.0	0.0	0.1	0.2
Stornoway	0.0	0.0	0.0	0.0	0.0	1.0
Tiree	0.0	0.0	0.0	0.0	0.7	1.7
Wick	0.0	0.0	0.0	0.0	0.5	1.5
Westray	0.0	0.0	0.0	0.0	0.1	0.3

TRANSPORT
SCOTLAND
CÒMHDHAIL ALBA

Further copies of this document are available, on request, in audio and visual formats and in community languages. Any enquiries regarding this document / publication should be sent to us at info@transport.gov.scot

This document is also available on the Transport Scotland website: www.transport.gov.scot

Published by Transport Scotland, May 2022

Follow us:

transcotland

@transcotland

transport.gov.scot