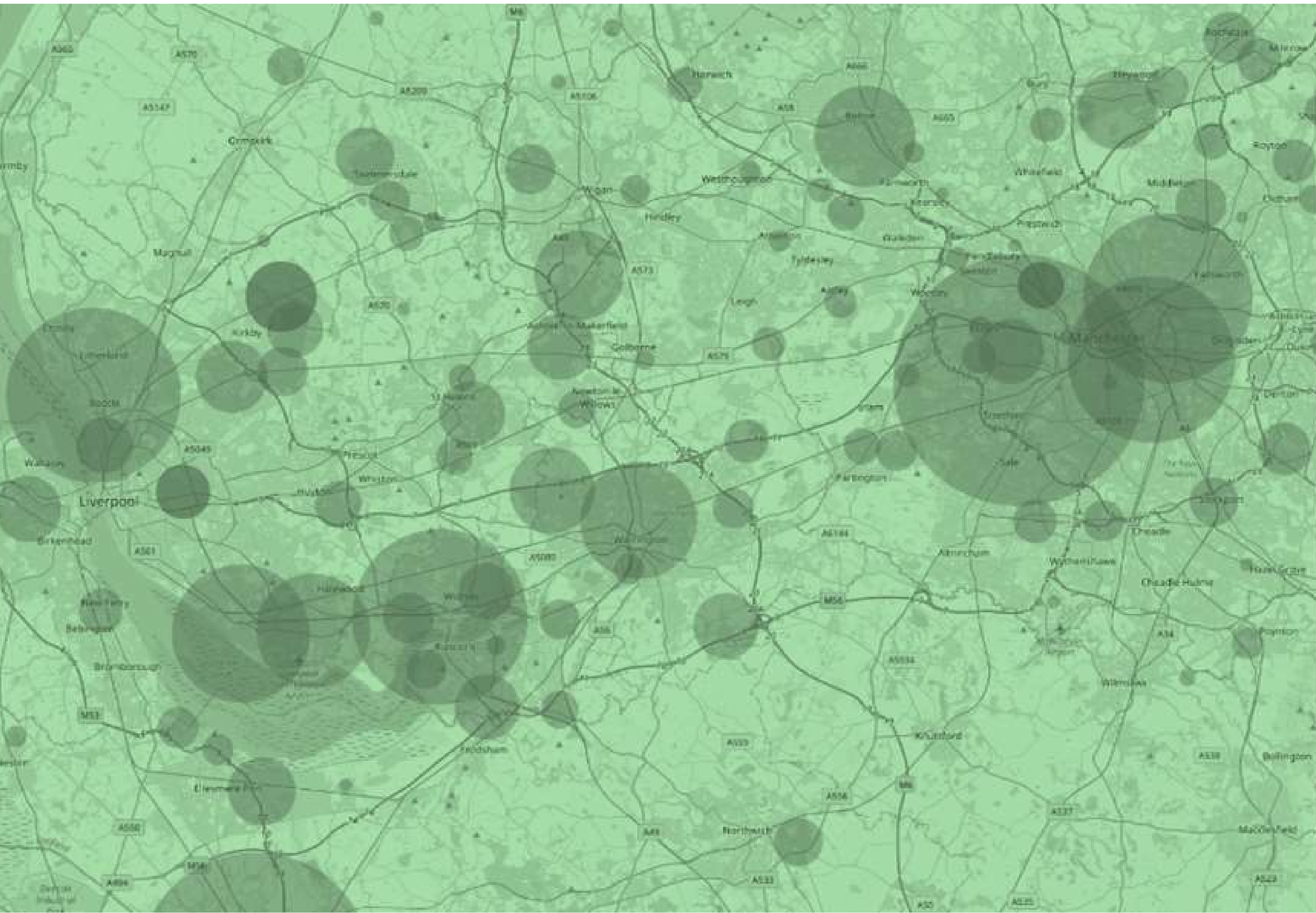
User guide

Using the Hydrogen Mobility Visualiser

1 March 2024



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1. INTRODUCTION AND TOOL PURPOSE

The Hydrogen Mobility Visualiser takes a cross sectoral approach to visualising the potential for hydrogen refuelling across the North of England.

The physics of hydrogen refuelling and electric vehicle (EV) charging are fundamentally different, and the levels of certainty and industry development in terms of both hydrogen production and hydrogen vehicles are several years behind the EV market. For this reason, this visualiser is not intended to pinpoint potential refuelling locations, but rather to identify the approximate areas where the potential for hydrogen refuelling is greatest and which are therefore *ripe* for building cross sectoral partnerships to further define and eventually implement the proposition.

The *potential* is a function of possible demand from several heavy-duty transport modes, namely trucks, buses and trains, and an assessment of certainty. The proximity to planned supply infrastructure is included within the tool outputs but does not determine modelled potential.

In the future, further demand information may be added to the tool, and further hydrogen supply and distribution plans can be tested/added.

The table below highlights potential use case, for the tool, across different users.

TABLE 1: USER BENEFITS

User	Benefit
Hydrogen suppliers (generation)	• The tool begins to paint a picture of where the potential demand is likely, when its likely to appear and who to start talking to about partnerships i.e. which transport modes, operators, and Local Authorities.
Gas Distribution Network Operators	• Building the case for hydrogen pipelines. • Visualising the potential mobility demand on new hydrogen distribution networks (e.g. East Coast Hydrogen).
Local Authorities	• Gaining an understanding of the hydrogen potential in their local boundaries. • Using this as a stimulus for conversations with hydrogen refuelling point operators and public transport operators (e.g. bus, taxi). • Informing council fleet renewal strategies (e.g. Refuse Collection Vehicles).
Freight operating companies, bus & train operating companies	• To give an indication of where go-first refuelling locations are most likely to be located. • Locations for partnership discussions (i.e. potential to commit to a certain level of offtake, helping business cases for hydrogen refuelling point operators and hydrogen suppliers). • Increase certainty when it comes to fleet renewal strategies

Section 2 of this guide includes a quick start for users.

Further information around the modelling method and key assumptions used within the visualiser can be found in Section 3.

2. HOW TO USE THE VISUALISER – QUICK START GUIDE

The guide below contains information on how to interpret the information displayed within the visualiser and the accompanying cluster information summary, as well as some useful hints on how to get the most out of the tool.

2.1 INTERFACE OVERVIEW

The visualiser's interface is divided into two main frames:

1. Map pane, which shows data and features against a geographic base. Various control panels can be found in each corner of the map, which are detailed later in this section: *Display and analyse*, *Select*, and *Period (years)*, plus three advanced filters and settings in the lower-right (*Modes included*, *Certainty minimum*, and *Range maximum*).
2. Result pane, which initially shows introductory and legal text, but once map features have been selected, will also summarise the demand associated with that selection. Proximity analysis and data download for that selection are also provided here.

On larger screens, the result pane sits to the right of the map. On smaller screens, the result panel is found below the map.

The map is interactive: One can zoom (for example using the +/- controls or mouse wheel) and pan around the map (for example, with a mouse, click, hold, and move), and select different features by clicking (or touching) them.

2.2 DISPLAY AND ANALYSE

This box allows you to select several different spatial features to be displayed on the map. Any number of these features can be displayed simultaneously.

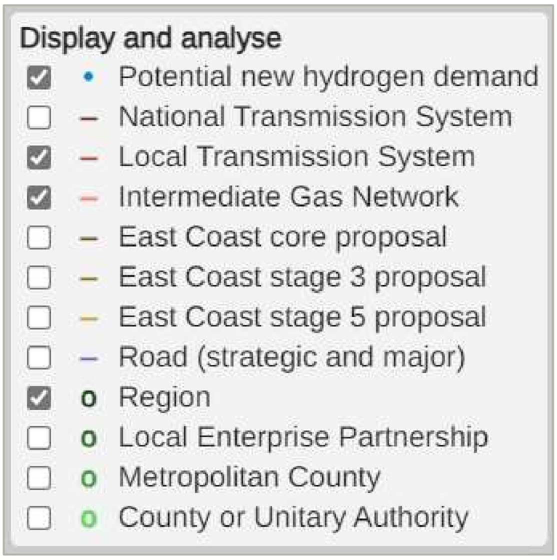


FIGURE 1: DISPLAY AND ANALYSE CONTROL

2.2.1 POTENTIAL NEW HYDROGEN DEMAND

Selecting this feature will display those areas where hydrogen transport fuel demand is possible for the transport modes considered in the tool. This is displayed via blue circles, known as *clusters*. The potential size of the hydrogen demand is indicated by the size of the circle, and the certainty of that hydrogen demand materialising is indicated by the transparency of the circles.

Hovering your cursor over a cluster will prompt a pop up giving you a summary of the potential total hydrogen demand and indication of certainty for each cluster.

Clicking on a cluster will open a *Potential new hydrogen demand* information breakdown on the right of your screen (at the bottom of your screen when using mobile devices). This provides the breakdown of that demand by mode and vehicle duty. Demand is shown as kilograms of hydrogen per day.

Allocation of Certainty

Vehicle duty types are assigned a *certainty* rating to convey the likelihood that the vehicle duty in question will convert to hydrogen when that duty type is decarbonised. Higher certainty means lower risk. Certainty encapsulates a range of non-local policy and price factors.

Please note that that when applying the % certainty to each mode and vehicle duty, the intention was not to be precise but rather to use professional judgement to:

- Indicate the relative levels of certainty of a mode/vehicle duty transitioning to hydrogen compared to other mode/vehicle duties.
- Indicate the relative chance of hydrogen being selected as a zero emissions solution for that mode/vehicle duty compared to other available alternatives (e.g. battery electric).

Vehicle Duty

The vehicle duty refers to the use of that vehicle (duty cycle), for example rural buses vs city buses, or domestic freight vs international freight.

2.2.2 EXISTING GAS NETWORK

The use of pipelines to distribute hydrogen may be key to making the fuel more cost-effective in the long term. For example, allowing green hydrogen to be produced directly using offshore wind, rather than being created at point of use via electrolysis, or being transported long distances by road tanker. Proximity of a vehicle depot to the existing pipeline network is no guarantee of a future hydrogen supply but is likely to make vehicle decarbonisation easier to achieve with hydrogen.

Decarbonisation of domestic heating implies a wholesale shift away from natural gas, which in turn frees the existing gas pipeline network to distribute hydrogen instead. While some pipelines may be possible to transition direct to hydrogen, domestic use of gas is expected to transition gradually over time, which will mean gradually changing the blend of gases in the pipeline network. This is already possible at low percentage blends, and technologies to support the use of higher ratios are actively being developed, notably in the context of Project Union.

Three separate gas network layers can be selected, which adds them to map, and in turn allows them to be selected for analysis, and automatically used in any proximity analysis:

- **National Transmission System** (highest pressure): The primarily inter-regional gas distribution network operated by National Gas, typically between 40 and 90 bar (multiples of atmospheric pressure).
- **Local Transmission System** (high pressure): The strategic backbone of gas distribution for the more local Gas Distribution Network Operators, typically between 7 and 16 bar.
- **Intermediate Gas Network** (medium pressure): The Gas Distribution Network Operators' more local strategic distribution pipelines, typically between 2 and 7 bar.

All offtakes would in practice require a compressor (typically a gas turbine engine). High pressure connections typically require higher capital investment, but then lower electricity operating costs to operate compressors.

Why does this matter?

It is important to distinguish between the different pressure levels of the network, as the different sections present different challenges in the context of a transition from natural gas to hydrogen.

Whilst blending and deblending poses one route to supply hydrogen to refuelling stations via the existing network, the different pressure tiers present unique challenges in the context of transitioning to pure hydrogen:

- The National and Local Transmission tiers are comprised of steel pipes which are not suitable for transporting hydrogen at high pressure due to the risk of hydrogen embrittlement, the process whereby hydrogen causes cracks to form in pipes. These tiers must be concerted to polymer pipes to be suitable for hydrogen transport. The higher-pressure tiers, however, comprise multiple parallel pipes. This inherent redundancy introduces the possibility of converting some pipes to hydrogen whilst minimising disruption of supply to natural gas users.
- The Intermediate network is comprised of polymer pipes so is not at risk of embrittlement. However, any transition to hydrogen must ensure minimal disruption to natural gas supply to downstream users (i.e. domestic consumers) if they are not able to transition to hydrogen for heat.

The sections of the network are converted to hydrogen first will depend on a range of planning and policy decisions on the part of government and network operators. The challenges outlined above could be overcome by constructing dedicated newbuild pipelines, which are likely to be built parallel to existing pipes to reduce planning and permitting issues. The location of existing pipelines therefore provides an indication as to where hydrogen may be available in future.

Pipeline route

Pipeline routes are intended to be indicative of proximity and should not be used as the basis for detailed local infrastructure planning.

Positioning of Clusters

Each cluster contains one or more transport depots that would be sufficiently close to each other to use a shared hydrogen fuelling station. Individual operators may not have sufficient scale to justify hydrogen, hence the need to build partnerships around local clusters. The centre point of the cluster approximately reflects the centre point between included transport depots and therefore does not suggest an exact refuelling location.

2.2.3 EAST COAST PROPOSAL

The East Coast Hydrogen project aims to repurpose parts of the higher-pressure gas transmission system to 100% hydrogen. This offers the same potential benefits as blending, but without the need to de-blend the hydrogen before use. However, the need for wholesale conversion of pipelines means most local pipeline infrastructure cannot be used.

Selecting this feature displays the new hydrogen pipeline network proposed by the East Coast Hydrogen partnership on the map, and in turn allows these pipelines to be selected for analysis, and automatically used in any proximity analysis. Three proposal stages are shown:

- **East Coast core proposal**: Main link between the Humber and the North East, via West Yorkshire. This is the transmission network developed by Northern Gas Networks, which is expected to go live by 2028.
- **East Coast stage 3 proposal**: Adds feeder pipelines, primarily between major industrial users and the main link. This is the initial distribution network developed by NGN, which is expected to go live by 2032.
- **East Coast stage 5 proposal**: Future network expansion, primarily towards Cumbria. This is the expansion of the distribution network developed by NGN, which is expected to go live by 2037.

Proposals may evolve

Proposed routes were provided by the partnership when announced at the end of 2023. Precise proposals may evolve in future.

2.2.4 ROAD (STRATEGIC AND MAJOR)

Selecting this feature displays the strategic and major road networks, as defined by Transport for the North. This is important in terms of understanding potential HGV flows, and thus potential opportunities for en-route fuelling. Of note is the spatial proximity between the highways network and the existing gas and proposed hydrogen pipeline networks.

2.2.5 REGION

Selecting this feature displays subregional boundaries for the North West, North East, and Yorkshire and Humber, allowing those subregions to be selected (using the *Select* function within the tool) and analysed.

2.2.6 LOCAL ENTERPRISE PARTNERSHIP

Selecting this feature displays existing Local Enterprise Partnership boundaries for the North, allowing those areas to be selected (using the *Select* function within the tool) and analysed. Note that potential hydrogen demand is only modelled for that part of Greater Lincolnshire that falls within the North of England (namely, the Humber).

2.2.7 METROPOLITAN COUNTY AND COUNTY OR UNITARY AUTHORITY

Selecting this feature displays existing Local Authority boundaries for the North, allowing those areas to be selected (using the *Select* function within the tool) and analysed, for example, aggregating cluster and demand information within those areas to understand the total demand for each authority.

2.3 SELECT FUNCTIONS

This box allows you to select single or multiple features displayed on the map for further analysis. When many features are displayed on the map, it may be easier to select all features within a defined area by using the *Draw box* function.

These functions are usefully used alongside the *Modes included*, *Certainty minimum*, *Range maximum* and *Period (years)* select functions.

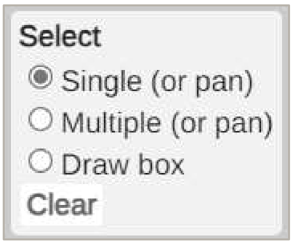


FIGURE 2: SELECT CONTROL

Selection defaults to the upper-most feature

Where map features overlap, only the upper feature can be selected. To select the lower feature, deselect the upper feature in the Display and analyse list.

Draw box disables map panning

Once *Draw box* has been selected, please note that you will be unable to pan the map using your cursor as the two functions are incompatible. You will need to ensure you have the desired section of the map within the visualiser area before using the *Draw box* function.

2.4 PERIOD (YEARS)

This function allows the user to visualise how potential cumulative demand for hydrogen may build up over 5-year periods to 2050. The whole 2025-2050 period is shown by default, which assumes all potential opportunities are taken in each period.

As the year periods progress, so do the size of the identified clusters, as well as new locations being identified for clusters.

FIGURE 3: YEAR PERIOD CONTROL

If a cluster or multiple clusters are selected, the *Potential new hydrogen demand* information breakdown on the right of your screen (at the bottom of your screen when using mobile devices), will indicate how that total cumulative demand is split between modes and vehicle duties.

Any of the features within the Display and analyse menu (see section 2.2) can be individually selected, or selected in multiples, with hydrogen for mobility demand related to those features displayed in the *Potential new hydrogen demand* information breakdown. Again, the time period can then be adjusted to understand the cumulative hydrogen mobility demand applicable to those features.

This functionality can be further enhanced by using the *modes included*, *certainty minimum*, and *range maximum* functions.

2.5 MODES INCLUDED

This function allows users to choose which of the modes must be represented within the demand clusters visualised. **Information about any other modes present in these clusters is retained, because these may remain important to the viability of the cluster.** This means that even if only one mode has been selected, the size of the cluster will not necessarily represent the size of the demand for that specific mode, but rather the total demand from all transport modes in clusters where this mode is included.

This function can be used alongside *period (years)*, *certainty minimum* and *range maximum* functions, for example, by selecting solely *Local buses* and then varying time period, users (typically local authorities) would be able to see where and when potential bus hydrogen demand could be generated.

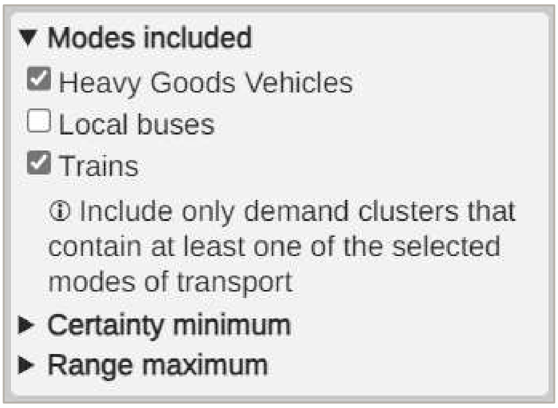


FIGURE 4: MODES INCLUDED

2.6 CERTAINTY MINIMUM

This tab allows the user to display only those clusters that achieve a minimum certainty of demand (for the modes specified within the *Modes included* function). This function allows users to focus on those demands with highest potential for successful partnerships and the lowest risks.

This function can be used alongside *period (years)* and *modes included* functions (see example box below), and with the *range maximum* function when a feature (e.g. a pipeline or road) is selected on the map.

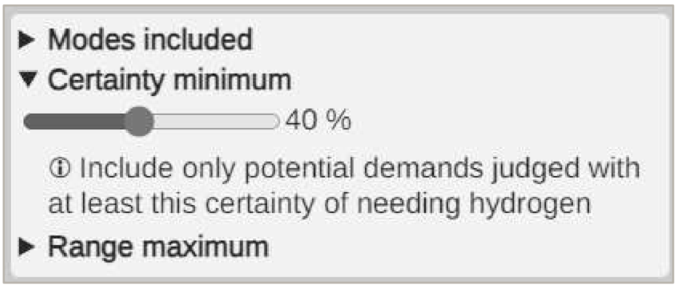


FIGURE 5: CERTAINTY MINIMUM

Certainty examples

- If selecting a certainty minimum of 50%, across all modes, this will exclude all Heavy Goods Vehicle demands, because all HGV demand is less than 50% certain.
- If selecting a very high certainty minimum, even across all modes, no clusters may be highlighted because no potential hydrogen transport demands have high certainty.
- If only local buses are selected with a certainty minimum of 30%, this would highlight only those clusters that include a bus demand with a certainty of 30% or mode. Note, however, that for those clusters shown in this case, the *potential new hydrogen demand* figure would reflect the demand both from those buses with a demand certainty of 30% or more, and any demand from the other modes in that cluster with a certainty of 30% or greater, so not all of the demand shown would necessarily be coming from buses.

2.7 RANGE MAXIMUM

This function allows users to introduce an area of interest around infrastructure features (pipelines or transport infrastructure) selected on the map. When a certain range is applied, the *Potential new hydrogen demand* information breakdown on the right of your screen (at the bottom of your screen when using mobile devices), will include only the demand information for only those clusters within the requested range of that selected infrastructure.

This function can be used alongside *period (years)* and *modes included* functions.

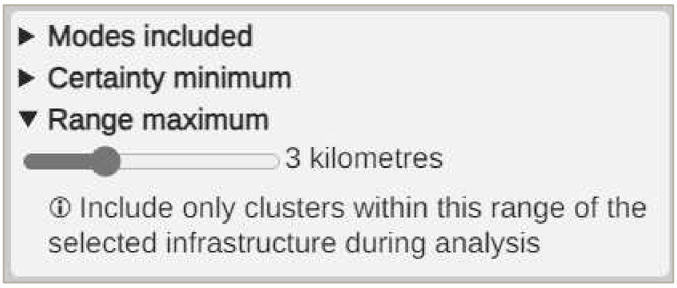


FIGURE 6: RANGE MAXIMUM

2.8 PROXIMITY TO INFRASTRUCTURE

Once a selection has been made, the results associated with that selection will be shown in the right-hand panel on larger screens, or below the map on smaller screens. If one or more infrastructure features are displayed, an option to show *Proximity to infrastructure* will be shown towards the bottom of those result. Clicking this will calculate the distance from each demand cluster in the selection to the nearest part of each infrastructure network visible then show a summary table.

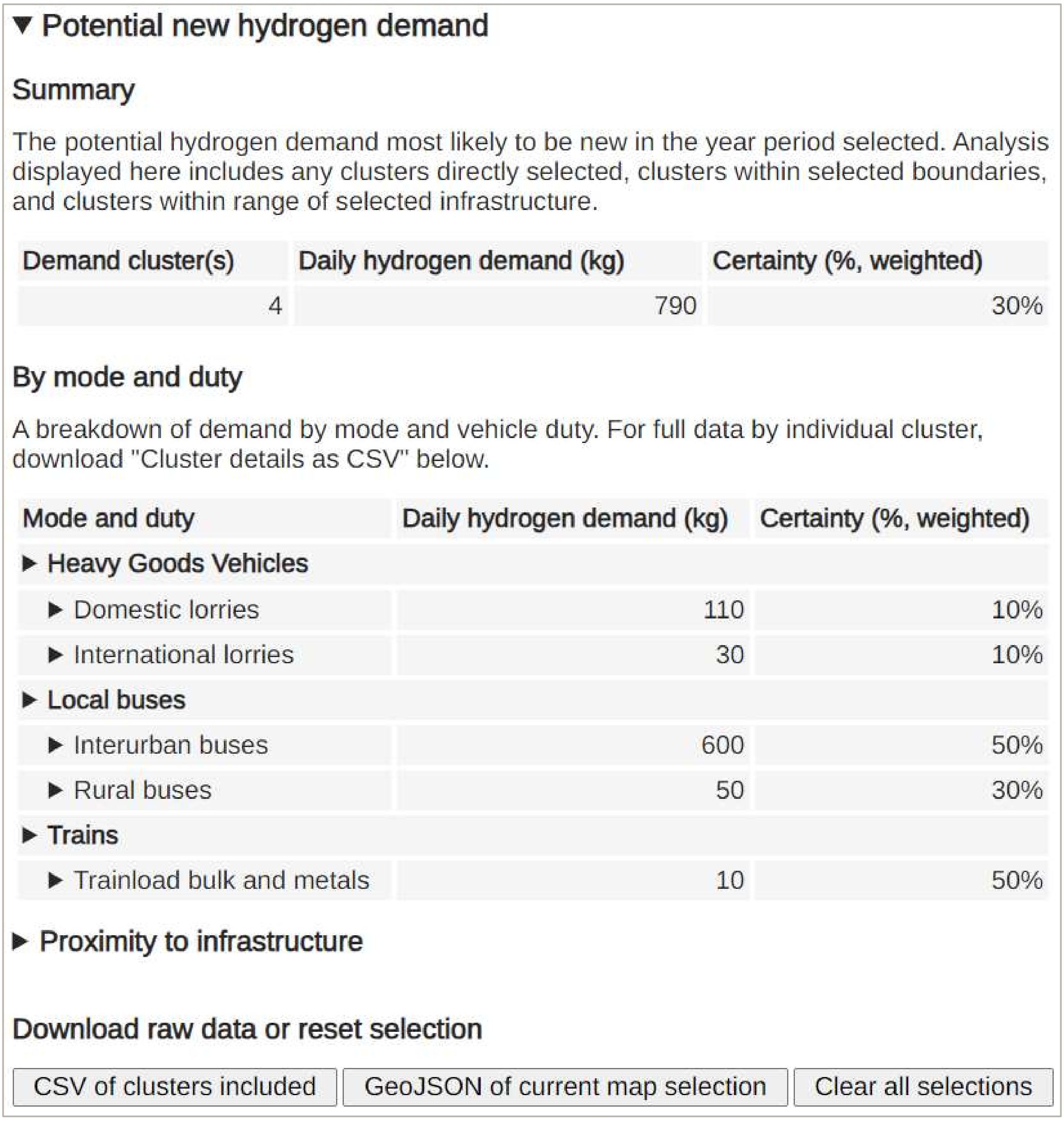
2.9 DOWNLOAD RAW DATA AND RESET SELECTION

These options, found at the bottom of the *Potential new hydrogen demand* information breakdown on the right of your screen, enable users to download the raw information related to a selected cluster or clusters in two different formats: the first reflects demand date in a CSV file (suitable for Excel) and the second reflects selection data in a GeoJSON file (suitable for Geographic Information System software).

The *Clear all selections tab* allows users to quickly clear any feature selections on the visualiser map. This does not clear any selections made within the *Display and analyse*, *modes included*, *certainty minimum*, and *range maximum* functions.

Data reuse

Please observe the Terms of use when reusing downloaded data. The Terms of use can be accessed from a subsection in the information panel on the right-hand side of the visualiser (or bottom of screen on mobile devices).



▼ Potential new hydrogen demand

Summary

The potential hydrogen demand most likely to be new in the year period selected. Analysis displayed here includes any clusters directly selected, clusters within selected boundaries, and clusters within range of selected infrastructure.

Demand cluster(s)	Daily hydrogen demand (kg)	Certainty (%, weighted)
4	790	30%

By mode and duty

A breakdown of demand by mode and vehicle duty. For full data by individual cluster, download "Cluster details as CSV" below.

Mode and duty	Daily hydrogen demand (kg)	Certainty (%, weighted)
▶ Heavy Goods Vehicles		
▶ Domestic lorries	110	10%
▶ International lorries	30	10%
▶ Local buses		
▶ Interurban buses	600	50%
▶ Rural buses	50	30%
▶ Trains		
▶ Trainload bulk and metals	10	50%

▶ Proximity to infrastructure

Download raw data or reset selection

CSV of clusters included | GeoJSON of current map selection | Clear all selections

FIGURE 7: RESULT PANEL SHOWING PROXIMITY AND DOWNLOAD BUTTONS

3. METHODOLOGY

Data for potential new hydrogen demand clusters has been modelled by ERM. The modelling method and key assumptions are outlined below. For further detail, including discussion of certainties and modes of transport that have not been included, please read the parallel *Modelling method* guide.

3.1 HYDROGEN TO DECARBONISE TRANSPORT VEHICLES

Unlike battery electric technologies, there is no clear trajectory for the future use of hydrogen in transport vehicles. The approach is therefore to model realistic opportunities for hydrogen in the transport sector, not to predict the future.

Hydrogen has been mooted as a fuel for a range of transport modes, from cars to ships. In practice hydrogen's technology development, cost, and supply of "green" fuel lags that for batteries. Hydrogen is highly unlikely to be competitive soon enough to decarbonise most mainstream vehicle duties.

However, there are niche vehicle duties which are challenging to decarbonise using battery technology, or where biofuel supply will rapidly become insufficient. This includes where battery electrification adds cost or complexity, for example requiring extra infrastructure or vehicles, or implies major changes to existing operating patterns. Likewise, non-aviation users of Hydrotreated Vegetable Oil can expect to be priced out of the market as demand for Sustainable Aviation Fuel grows. In these niches hydrogen may be one a few potential decarbonisation solutions.

3.2 POTENTIAL NEW HYDROGEN DEMAND

Each mode follows a specific method, introduced in later sections, but the broad approach is:

1. Isolate niches which are challenging for battery electric, where hydrogen is a potential alternative.
2. Estimate the 5-year period in which vehicle decarbonisation decisions are most likely to be taken.
3. Assign the energy requirement of each niche in each year period as potential hydrogen demand, expressed as kilograms of hydrogen on the busiest typical day.
4. Assess the chance of hydrogen being selected from the available alternatives as certainty.

The assignment is as geographically precise as is possible to model from available depot and duty data.

3.3 DEMAND CLUSTERING

Hydrogen allows vehicles to be fuelled for a full day's duty. This means fuelling infrastructure is expected to focus on home depots, with any en-route or at-destination fuelling function provided on a marginal basis.

Hydrogen has an inherent economy of scale, so is most viable where users cluster together. Individual locations, typically vehicle depots, have been clustered together using a hierarchical clustering algorithm. This algorithm groups individual locations within a circle of 3 kilometres radius (haversine distance). This should add no more than 5% to the distance these vehicles travel each day. In practice, one trip to fuel each day should add only a couple of percentage to total daily mileage, since all duties included in these clusters are relatively high mileage.

In practice not all clusters will be cost-effective to supply with hydrogen. For example, electrolysers are typically optimal only for daily volumes of over half a tonne. The inclusion of smaller clusters is intended to allow potential partners to better understand the local geographic distribution of demand. For example, perhaps to develop strategies which merge demand from neighbouring clusters in the knowledge that typical drive-times to refuel can be greater than 2-3 kilometres.

The notional centre point of the cluster is shown on the map, alongside the aggregate potential hydrogen demand for all users within the cluster. The point is indicative of surrounding demand: local partners and planners would need to identify a suitable site in the vicinity.

3.4 HEAVY GOODS VEHICLES (HGVS)

Battery electric vehicles are likely to dominate HGV decarbonisation, as explained here. However, two niches may provide a role for hydrogen:

- **Domestic lorries**: High mileage domestic duties, either with 2 drivers (and thus no natural stops to recharge en-route) or involving infrequent long-distance journeys. In both cases operators could be willing to pay a premium for the added operational flexibility granted by hydrogen. However, operators are unlikely to be prepared to pay more than an extra 30%, beyond which less convenient forms of battery operation will tend to be more viable. Domestic lorries are thus likely to be priced out of the market by the cost of green hydrogen production.
- **International lorries**: International duties, reflecting both long journey distances and the likelihood, or otherwise, of hydrogen becoming a more widespread truck fuel in continental Europe. While European policy has been supportive of hydrogen for international lorries, the deployment of high-power rapid charging stations is gaining momentum sooner, and ultimately at lower operating cost. The possibility of more trailer-only sea crossings, with alternative-powered tractors used to haul in Britain and in continental Europe, adds a further degree of uncertainty.

National patterns for these two duties have been assigned to known truck depots, from operator licence records, in proportion to the number of articulated trucks modelled to be based there.

3.5 LOCAL BUSES

Battery Electric Buses (BEBs) are likely to continue to dominate local bus fleet decarbonisation. Hydrogen's well-to-wheel energy conversion is far less efficient than that via batteries, making hydrogen fuel cell buses more costly to operate, a disadvantage that will remain even once the supply-chain difficulties experienced by early adopters have been resolved.

However, with current technology a BEB's battery capacity is limited by axle weight, in practice constraining the mileage possible with a single overnight charge. Where existing peak vehicle requirements exceed that required during the day, BEB operators may be able to manage their fleets to allow sufficient at-depot daytime top-up charging. For those that cannot, typically because all vehicles are active throughout the day, all viable alternatives add cost, and this is where hydrogen fuel cell buses have potential.

In these cases, hydrogen still competes against alternative solutions, such as extra buses to allow daytime at-depot charging, opportunity charging infrastructure to allow buses to charge while remaining in-service, and tri-axle buses capable of carrying greater battery capacity. Hydrogen is appealing to operators because hydrogen’s rapid fuelling time maintains the same operational flexibility as prior diesel vehicles. The appropriateness of each alternative would need to be evaluated locally in detail, but broadly differs by route archetype:

- **City buses**: Those core high-frequency urban duties that may be challenging to decarbonise with battery electric buses. On balance, many alternatives to hydrogen are relatively attractive: high frequency may favour investment in opportunity charging, and proximity to depot favours extra vehicles with daytime charging.
- **Interurban buses**: Those duties on routes to a regional centre from outside that centre that may be challenging to decarbonise with battery electric buses. While primarily serving urban markets, these relatively high frequency routes often form the backbone of services in rural areas. On balance, hydrogen is a strong contender, especially where roads are narrow (thus not suited to tri-axle buses), and frequencies are modest (thus not suited to opportunity charging).
- **Rural buses**: Those local rural or small-town duties that may be challenging to decarbonise with battery electric buses. Dispersed operational patterns will not favour fixed vehicle charging alternatives, while roads tend not to favour the use of longer vehicles, both factors strengthening the case for hydrogen fuel cell vehicles. However, the tight commercial margins on many rural services make hydrogen less likely to be adopted in practice due to hydrogen's higher fuel cost.
- **Suburban buses**: Those secondary urban duties (on routes operated at lower frequency than city buses) that may be challenging to decarbonise with battery electric buses. Lower frequencies than city routes weaken the case for opportunity charging infrastructure, while roads tend not to favour the use of longer vehicles. However, like city duties, suburban duties tend to operate relatively close to depots, favouring the option of extra BEBs with daytime charging, not necessarily hydrogen.

Modelling is of scheduled local bus services from May 2023 open data timetables. It excludes coach networks operated by or on behalf of Flixbus, Megabus, or National Express. ERM's national modelling suggests such coach operations could add about 15% to potential local bus hydrogen demand. There is a relatively high chance of hydrogen being adopted for scheduled coach due to high single-trip energy requirements and the geographic dispersion of many inter-regional coach routes. Home-to-school and contract routes are included only where they are available to the public, however these tend to be low-intensity duties and thus have no potential for hydrogen.

Routes have been allocated to depots based on sample real-time vehicle tracking data where data is available, or depot proximity to route termini where data is unavailable. Hydrogen demands are calculated from modelling of individual route operations. The likely year of conversion to Zero Emission operation reflects owning group fleet decarbonisation targets where known.

3.6 TRAINS

Overhead track electrification is generally the most effective, but also most capital costly way of decarbonising diesel train services. In the absence of long-term UK government funding for track electrification, the British rail sector may need to consider second-best decarbonisation options, such as hydrogen or battery electric.

Broadly, hydrogen is more space and weight efficient, but batteries are typically cheaper. So only the most demanding train duties, in terms of either distance or hauled weight, have a reasonable chance of adopting hydrogen. For heavy freight trains, hydrogen might be used as a combustion fuel, rather than the hydrogen fuel cells likely to be adopted by other transport modes. Five categories of railway service have the potential to adopt hydrogen:

- **Intercity passenger trains**: Long-distance trains operating at over a hundred miles per hour, with routes centred on London or Birmingham. Services operated primarily under overhead are likely to favour bimodal battery operation over hydrogen. Services which, even after Midland Mainline electrification, are still primarily operating on unelectrified track are likely to be more cost effective to operate bimodally with hydrogen fuel cells. These primarily operate to or from southwest England, so there is a risk that further track electrification in that region could tilt the entire fleet away from hydrogen towards bimodal battery.
- **Railfreight distribution**: Primarily intermodal, especially maritime container, freight trains. Cargos tend to be lighter than *Trainload bulk* trains, more likely to pass under overhead-electrified sections of track, and loads more evenly balanced in each direction, but the distances travelled tend to be further. While hydrogen is a realistic possibility for many of these hauls, especially by the 2040s when much of the existing diesel locomotive fleet will become life-expired, on some routes bimodal battery locomotives will be able to bridge gaps in track electrification.
- **Railway engineering**: Trains operated to move railway maintenance materials and equipment around the network, not the operation of that equipment to maintain infrastructure (which is outside the scope of this modelling). About a third of these trains are relatively light or short distance, so likely to convert to battery operation. The remainder are far heavier and mimic patterns of *Trainload bulk and metals*, which better suit hydrogen.
- **Regional passenger trains**: Mid-distance, excluding primarily local or suburban services, typically between regional towns and cities using short two or three carriage units and operating up to 90 miles per hour. These services are likely to favour bimodal battery operation over hydrogen. Most of this fleet is already approaching the end of its working life, and neither technology is likely to be optimised soon enough, nor cheap enough to suit what are often subsidised operations. This all adds to the uncertainty of decarbonisation pathway for regional passenger trains.
- **Trainload bulk and metals**: Primarily aggregates, including all the heaviest trains operated in Britain. These typically travel shorter distances than *Railfreight distribution*, with an empty return haul as low as a quarter of the net weight of the outbound loaded train. The relatively high power requirements of these trains, combined with limited running under overhead wires, make a strong case for hydrogen. Hydrogen may however raise operating cost to the point where alternative, especially maritime shipped, sources of material become more cost effective for customers.

Passenger trains have been modelled by summing the daily passenger train paths scheduled to leave non-passenger locations in the early morning, by Train Operating Company (TOC) and rolling stock class for diesel and bimodal trains. Each TOC's relevant fleet and energy use was distributed in proportion to that scheduled activity. Decarbonisation options were primarily evaluated through the value of revenue-earning potential lost due to the volume and weight of providing the required energy from battery or hydrogen.

Freight trains have been modelled more precisely from schedules, using exact origin and destination locations, train tonnage, and statistical probability of operating. Freight trains tend to serve industrial locations where both hydrogen and electricity is more likely to be present than at existing locomotive depots, so most fuelling is assumed to occur at each haul's origin, not necessarily existing depots.

In the absence of clear decarbonisation targets, railway vehicles have been assumed to decarbonise at the natural end of their 40-year life, or shortly before 2050, whichever is sooner. Aside from *Regional passenger*, most British train decarbonisation is not expected to occur until around 2040, by which time hydrogen and battery train technologies should have matured from their current novel or experimental status.

3.7 AVIATION

Hydrogen and hydrogen derivates (i.e. synthetic fuels produced using low-carbon hydrogen) are being considered as options to decarbonise the aviation sector. Potential aviation hydrogen demand has not been included in the visualiser tool. The rationale behind this decision is described in the *Modelling method* guide.

A more detailed methodology, including a full rationale of the certainty assumptions and reasons why other transport modes that have not been included, can be found in the parallel *Modelling method* guide.