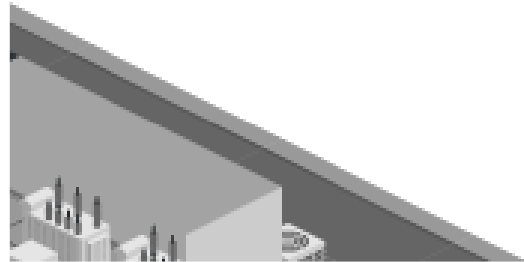
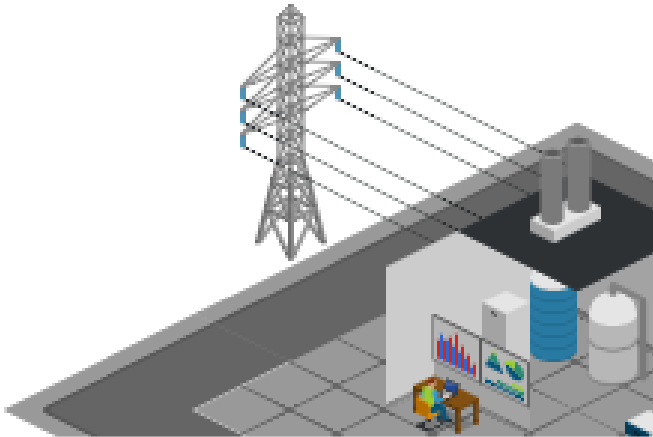
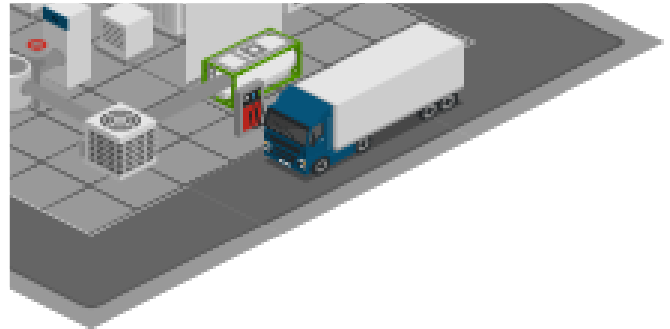


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HYDESS Project



E.ON

Hydrogen for the Decarbonisation of Sheffield Steel (HYDESS)

IHA 2B Feasibility Report

Document approval

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Executive summary

Introduction

The HYDESS (Hydrogen for the Decarbonisation of Sheffield Steel) project seeks to decarbonise steel manufacturing sites across Sheffield. The consortium executing the project consists of:

- E.ON UK;
- The University of Sheffield – Advanced Manufacturing Research Centre (AMRC);
- Glass Futures;
- Sheffield Forgemasters; and
- Chesterfield Special Cylinders (CSC).

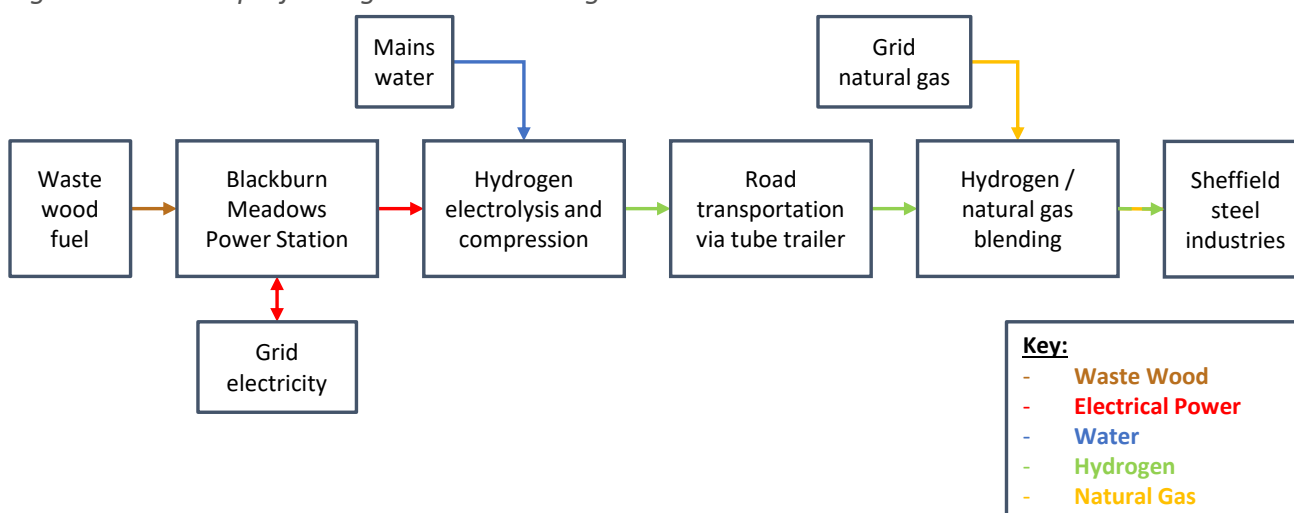
The HYDESS 2B project has the following stated objectives.

1. Assess the **techno-economic feasibility** of hydrogen fuel switching from natural gas in steel furnaces at leading UK steel manufacturers.
2. **Improve consortium partners' understanding** by assessing the design, implementation, and delivery of an end- to end hydrogen solution.
3. Provide the information required to **de-risk the technical challenges and provide a sound business case** for investing in fuel switching.
4. Develop new **commercial relationships** between the consortium and **assess expansion** of this network to other local industry (such as glass & ceramics).

Process overview

The end-to-end process for the HYDESS project is summarised in the block diagram below. Low carbon electricity produced by E.ON's Blackburn Meadows Biomass Plant and obtained through renewable energy power purchase agreement (PPA) will feed an electrolytic hydrogen production plant (via private wire). The plant will produce high pressure hydrogen, which will be stored in tube trailers before being transported via road to the end users (the Sheffield steel manufacturing sites). Multiple end-users were identified in the Sheffield and surrounding area with details of 2 potential customers being incorporated into this study.

Figure 1: HYDESS project high-level block diagram



Hydrogen production

Hydrogen will be produced using an electrolysis plant located at Blackburn Meadows. The plant will require electricity and towns water; both will be supplied from Blackburn Meadows, with any shortfall in electricity provided through a renewable energy guarantee of origin (REGO)-supported power purchase agreement (PPA). The plant is assumed to run for 8,000 hours a year, considering downtime of the electrolyser plant.

Market engagement determined that Proton Electron Membrane (PEM) was the most applicable electrolyser technology for the Blackburn Meadows site at time of report writing. E.ON will revisit this conclusion during detailed design. A mass and energy balance was developed based on details from a typical PEM supplier to provide indicative plant inputs and outputs.

Table 1: Main plant inputs and outputs

Parameter	Instantaneous	Annual
AC power (input)	10.59 MW	84,738 MWh
Mains water (input)	2.47 m ³ /h	19,752 m ³
Hydrogen produced	180 kg/hr	1,440 tonnes
Oxygen produced (vented to atmosphere)	1,528 kg/hr	11,520 tonnes
Wastewater (output)	0.68 m ³ /h	5,432 m ³

A full process design was developed for the Blackburn Meadows site, including preliminary piping and instrumentation diagrams (P&IDs). In addition, a plant layout, single line diagram (SLD) and 3D model were assembled for the full Blackburn Meadows site based on representative designs from supplier engagement.

Hydrogen transport

Hydrogen from the electrolyser plant will be produced at typically 20-40 bar(g) pressure. A compressor will be used to increase the pressure to typically 350 bar(g), suitable for onward transport via tube trailers to end users.

Two main transport options have been assessed: fixed storage (where there is interim fixed hydrogen storage between the compressors and the tube trailers) and mobile storage (where hydrogen is decanted directly into multi element gas containers (MEGCs) to be delivered when full).

Various types of storage options within these categories (at different capacities and pressures) have been assessed. Broadly, the annualised costs for fixed storage and mobile storage are comparable. However, mobile transport options have higher trailer transport capacities and a smaller footprint at site. Use of mobile storage also makes it easier to scale up operation if production is increased.

Process flow diagrams and process descriptions have been prepared for trailer loading and decanting processes to de-risk both operations.

A demand monthly profile has been assembled based on two potential customers within the Sheffield area. E.ON is in talks with additional potential customers and requires any potential new customers to submit granular demand estimates to allow for reasonable production planning.

End use

The filled tube trailers will connect into the Sheffield steel manufacturer's gas distribution systems for use in steel reheat operations. Equipment has been specified to be able to blend hydrogen with

natural gas to achieve satisfactory conditions (e.g. temperature and emissions) while firing the Chesterfield Special Cylinders steel reheating furnaces.

A full process design was developed for the CSC site, including preliminary process flow diagrams (PFDs), preliminary plant layouts and a 3D model. Dispersion modelling preparation was also undertaken to allow dispersion modelling to be completed at detailed design stage.

To evaluate the performance of hydrogen and hydrogen-natural gas blends in the steel manufacturers' furnaces, in particular to address concerns that combustion of hydrogen can lead to higher NO_x emissions, Computational Fluid Dynamics (CFD) modelling and trials were carried out. The CFD approach to combustion was validated against experimental data from both the CSC furnace and the Glass Futures' CTB furnace, using furnace wall temperatures and excess oxygen in the flue gas flow to show adequately predicted combustion conditions. Three 'low-NO_x' hydrogen burners were then obtained from existing suppliers and burner geometry characterised for use within the model. CFD simulations were finally carried out of the firing of the CSC furnace on blends of natural gas and hydrogen using each of the three hydrogen burners.

All three burners within the simulation could effectively heat the furnace to similar temperatures to those achieved by the existing natural gas burner using the same thermal input. Flue gas NO_x predictions for two of the burners indicate burning of up to 50% v/v hydrogen fuel blend would produce NO_x below the limit of 550 mg/m³ currently set for Forgemasters' Forge Heating Furnaces by the Environment Agency.

Emissions savings

The estimated greenhouse gas (GHG) emissions reduction from the project is approximately 180 ktCO₂e over the assumed 30-year project lifetime. This takes into account manufacturing, construction, operation, transport and end use. The emissions reduction derives from the displacement of natural gas at the end users by the hydrogen produced.

The annual emissions reduction is approximately 6 ktCO₂e/y. This equates to 1.4% of the 2022 UK iron and steelmaking fuel combustion emissions.

Cost of solution

The following capital costs were estimated.

- For the production plant, either:
 - £23.4m, up to and including hydrogen dispensers; or
 - £15.1m, up to and including LP storage (i.e. excluding compression, high pressure storage and dispensing, and their associated costs).
- £0.62m for a single tube trailer (400 kg capacity).
- £3.72m for end user costs at CSC's site.

E.ON has built a commercial model for the project. The model estimates that the project will have:

- a Levelised Cost of Hydrogen production (LCOH) of £195.51/MWh_{HHV} (£7.72/kg), when calculated according to BEIS methodology;
- a required delivered cost (to the end users) of £282.29/MWh_{HHV} (£11.15/kg H₂); and
- a Levelised Cost of Abatement (LCOA) of £1,212/tCO₂e, when calculated according to BEIS methodology.

Project learnings

The key findings from the HYDESS project, split between the relevant project objectives, are as follows.

1. Techno-economic feasibility

- a. Burner trials concluded that incorporating hydrogen into the fuel mix provided the same thermal requirement as using natural gas only.
- b. For 2 of the 3 burners tested, NO_x levels did not exceed existing environmental standards for 50:50 natural gas/hydrogen blends with 1 burner remaining below this standard at 100% hydrogen.
- c. At Chesterfield Special Cylinders (an end user), existing infrastructure can be adapted to utilise hydrogen at a capital cost of approximately £3.7m.

2. Knowledge enhancement

- a. Hydrogen production at E.ON's Blackburn Meadows site will benefit from a private wire connection with initial hydrogen production levels of approximately 180 kg/h or 1,440 tonnes per year with scope to increase as the market develops.
- b. Requirements, working design and timeline of how to mobilise E.ON's Blackburn Meadows towards hydrogen production have been developed.
- c. An end-to-end hydrogen solution has been developed, across production, delivery and supply, including requirements to enable it to become a reality.

3. Risk mitigation and business case development

- a. Risks associated with hydrogen production have been documented with mitigations developed or plan to address identified.
- b. Transportation of hydrogen using the road network is safe, provided the right controls and training are in place.
- c. Components needed to create a commercially sound proposition have been detailed, but capital cost support via Hydrogen Allocation Round 3 and price parity will be needed.

4. Commercial relationships and network expansion

- a. Interest is high within the steel industry with several positive relationships developed and two potential customers signing enhanced letters of interest.
- b. Aspirations to decarbonise is high across other industries with Sheffield demand exceeding supply.
- c. Mobilisation plan alignment is challenging considering the individual business requirements to satisfy when investment decisions can be taken.

Next steps

An assessment of how the process could be scaled and replicated more widely, and an exploitation and dissemination plan, have been produced. A post-FEED implementation plan (Gantt chart) has been produced for the production plant, with an estimated total project duration of 32 months.

De-risking outcomes

Safety studies were carried out and risk registers produced. The three biggest risks identified are as follows.

- **Steel industry hydrogen mobilisation.** The ability of the steel industry to accept hydrogen when production is likely might not be aligned (including alignment of financial investment decisions).
- **DESNZ price support.** The level of Government support which will be provided to early adopters is uncertain, i.e. whether this will be in place for the duration of a commercial contract.
- **Supplier long lead times.** Items such as electrolyzers, compressors and trailers all have long lead times (approximately 12-18 months). As interest in hydrogen grows, the lead times for these items may also increase.

Mitigations have been identified for all risks.

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1 Introduction

1.1 HYDESS consortium

The HYDESS (Hydrogen for the Decarbonisation of Sheffield Steel) project seeks to decarbonise steel manufacturing sites across Sheffield. The consortium executing this phase of the project consisted of:

- E.ON UK;
- The University of Sheffield – Advanced Manufacturing Research Centre (AMRC);
- Glass Futures (GF);
- Sheffield Forgemasters; and
- Chesterfield Special Cylinders (CSC).

1.2 Project background

The UK government previously awarded funding to the consortium to carry out a feasibility study under the Net Zero Innovation Portfolio (NZIP) Industrial Hydrogen Accelerator (IHA) Stream 2A (“the HYDESS 2A project”). This was completed in March 2023, with the final report published on the Government website¹.

Following this, the consortium was awarded funding under IHA Stream 2B for a front end engineering design (FEED) study (“the HYDESS 2B project”). The overall aim of the HYDESS 2B project is to understand the net benefits of decarbonising the Sheffield steel reheat processing using hydrogen produced locally, transported in road trailers, and used to replace natural gas (NG) in furnaces fired for reheating or heat treatment purposes. The project objectives are included in Section 1.4.

1.3 Project overview

The HYDESS 2B project is split into 6 work packages (WPs), laid out below, with each work package led by a relevant expert from the consortium.

Table 2: Work packages

WP	Package name	Led by
WP1	Commercial, legal and demand	E.ON
WP2	Furnace and burner modelling and optimisation	Glass Futures
WP3	Blackburn Meadows FEED	E.ON
WP4	Chesterfield Special Cylinders FEED	CSC
WP5	Storage and logistics FEED	E.ON (supported by CSC)
WP6	Project management	E.ON

¹ <https://assets.publishing.service.gov.uk/media/648089955f7bb7000c7fa666/iha-2a-eon-hydess-feasibility-report.pdf>

1.4 Project objectives

The HYDESS 2B project has the following stated objectives.

1. Assess the techno-economic feasibility of hydrogen fuel switching from natural gas in steel furnaces at leading UK steel manufacturers.
2. Improve consortium partners' understanding by assessing the design, implementation, and delivery of an end- to end hydrogen solution.
3. Provide the information required to de-risk the technical challenges and provide a sound business case for investing in fuel switching.
4. Develop new commercial relationships between the consortium and assess expansion of this network to other local industry (e.g. glass & ceramics).

2 System design and development

2.1 Testing & modelling (WP2)

2.1.1 Overview

The HYDESS 2B project's testing and modelling scope built on work carried out within the HYDESS 2A project. One of the concerns raised in the 2A study was that switching to hydrogen fuels could result in higher NO_x emissions which could exceed local limits set for Sheffield steel manufacturers, thus requiring additional investment into expensive abatement equipment. In 2B, the aim was to validate a computational fluid dynamics (CFD) modelling approach that allowed furnace models to accurately model combustion using a variety of natural-gas and hydrogen fuel blends, including the assessment of NO_x emissions. This will help to de-risk the use of fuel blending within the steel industry and provide insight into the combustion performance as well as emissions of natural gas-hydrogen blends and hydrogen against natural gas.

Testing of hydrogen-natural gas fuel blend combustion was undertaken using GF's Combustion Test Bed (CTB) at its Combustion Research Facility, located at Liberty Speciality Steel's site in Brinsworth (Rotherham).

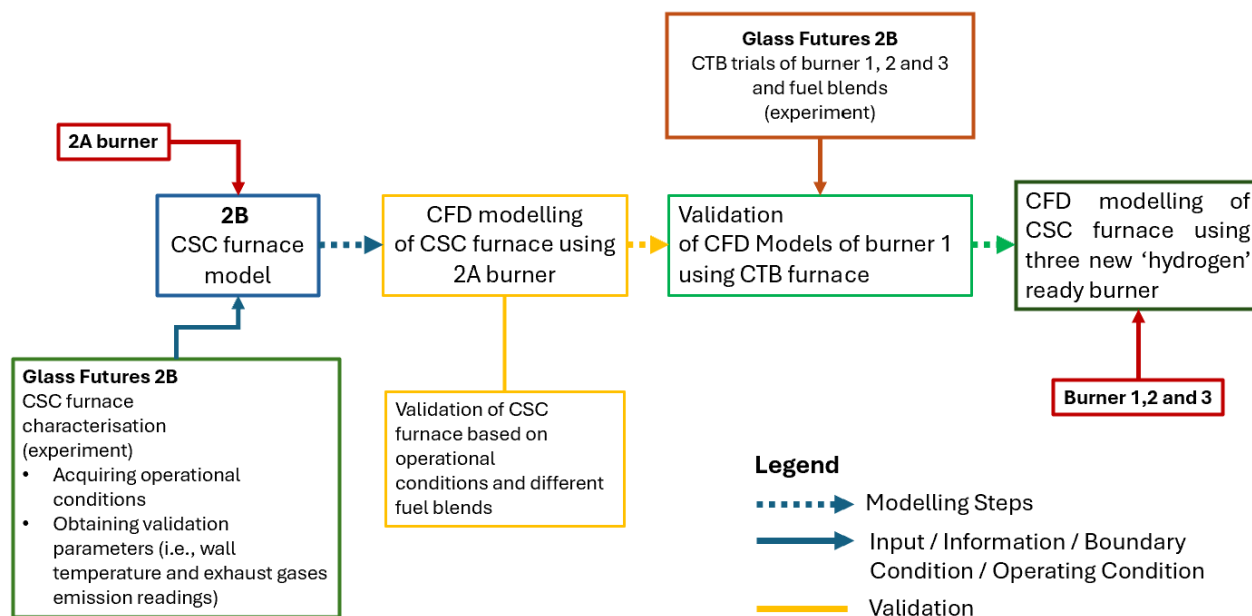
Modelling was also undertaken using a furnace ("the CSC furnace"), located at CSC's facilities north of Meadowhall Interchange (Meadowhall). The CSC furnace is a working furnace used to make seamless gas storage cylinders able to contain pressures of 150 – 700 bar(g).

Hydrogen burners and burner information were sourced from the burner suppliers Dunphy Combustion Ltd, Global Combustion Systems, Lanemark Combustion Engineering Ltd, and Limpsfield Combustion Engineering Co Ltd.

The work was split into the following tasks, explained visually in the block diagram included in Figure 2.

1. Characterisation experiments were conducted on the CSC furnace to acquire data for the furnace operational parameters (e.g. thermal power) and emissions.
2. A model of the CSC furnace fitted with a burner used in the HYDESS 2A project ("the 2A burner") was constructed. This was then validated using the experimental data from step 1.
3. Experimental trials were conducted on the CTB furnace to acquire data on the thermal performance and emissions of three new 'hydrogen-ready' burners.
4. The CFD model of burner 1 when fitted to the CTB was constructed and validated using this experimental data.
5. CFD models of the three new 'hydrogen ready' burners fitted to the CSC furnace were constructed and used to predict their thermal performance and NO_x emissions.

Figure 2: Block flow diagram of the Testing & Modelling work package, showing flow of information through each modelling and validation step



Source: University of Sheffield

2.1.2 CSC furnace characterisation and model formation

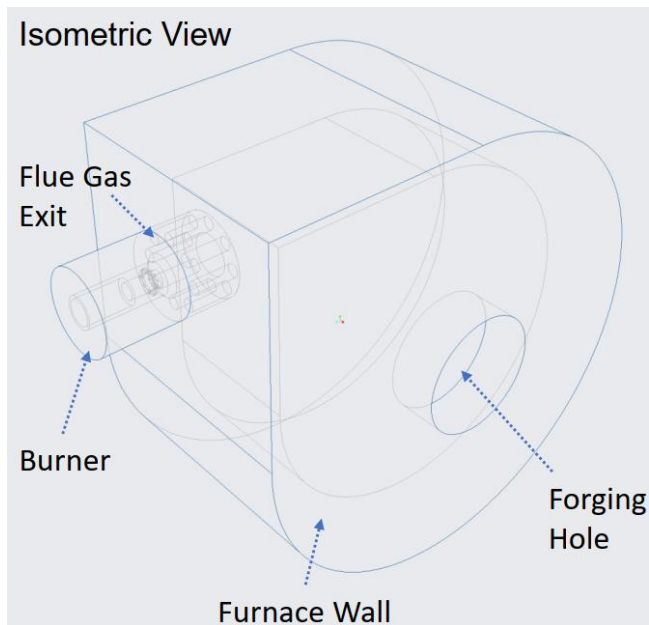
GF staff first characterised the CSC furnace by collecting data on gas emissions (NO_x , CO_2 and excess oxygen) and furnace wall temperatures during CSC furnace operation. A furnace 3D model and geometry were then constructed using CSC furnace measurements (see Figure 3 and Figure 4). Burner geometry was taken from a gas burner validated during the HYDESS 2A project (“the 2A burner”); it was not possible to model the original CSC burner due to the confidentiality of its geometry. The 2A burner is similar in size and power ($275 \text{ kW}_{\text{th}}$ capacity) to the existing CSC furnace burner ($270 \text{ kW}_{\text{th}}$).

Figure 3: CSC furnace front view, showing forging hole in the centre and burner/flue gas exit to top left (in red)



Source: University of Sheffield

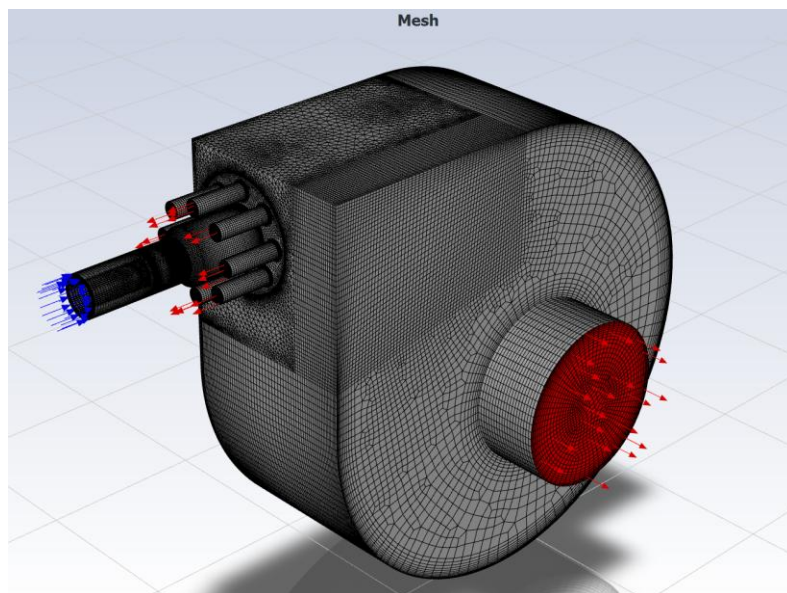
Figure 4: Isometric view of the CSC furnace geometry, including 2A burner



Source: University of Sheffield

2.1.3 CSC furnace model validation

Furnace (and 2A burner) 3D model and geometry were translated into the CFD software ANSYS Fluent to create a mesh and CFD model of the CSC furnace (see Figure 5). Mesh grade was modulated to be finer in areas with high anticipated flow velocity and temperature gradient, with CFD sub-modules chosen to better simulate fluid flow, heat transfer, turbulent flow and varied air-fuel premixing.

Figure 5: CSC furnace mesh in ANSYS Fluent

Source: University of Sheffield

The CSC furnace CFD model was then validated against characterisation data from five parameters: three optical temperature readings on the CSC furnace inner walls, one thermocouple reading from the top furnace wall, and excess oxygen readings from the flue gas analyser. These values are presented in Table 3.

Table 3: CSC model validation data – experimental versus predicted values

CSC furnace parameters	Units	Experimental data	CFD model predictions	Difference	Percentage difference vs experimental data
Temperature – left wall	°C	1277	1255	-22	-1.7%
Temperature – right wall	°C	1282	1255	-27	-2.1%
Temperature – top wall	°C	1292	1266	-26	-2.0%
Temperature – rear wall	°C	1267	1240	-27	-2.1%
Oxygen concentration at flue exit	%	10.77	10.74	-0.03	-0.3%
NOx emissions	ppm	52.70	681.60	+628.9	+1,193.4%

Source: University of Sheffield

Modelled values for furnace wall temperatures are within 2.1% of experimental values, indicating the model accurately replicates combustion conditions within the furnace. Oxygen concentration

modelling is 0.3% off experimental data, showing the model and experimental data are consistent with stoichiometric combustion conditions.

Conversely, NO_x emissions were overpredicted, with the CFD model predicting 681.60 ppm vs recorded values of 52.70 ppm. The University of Sheffield did not flag this as an issue with the model, suggesting this was due to their use of the 2A burner geometry, which is designed for hydrogen fuel, rather than the natural gas burner currently fitted.

2.1.4 Burner and gas blend experimental trials

Three hydrogen-ready, 'low-NO_x' burners were installed one by one within the GF CTB. The dimensions for each burner were also used to allow each burner to be applied to the CSC furnace CFD model post validation (see Section 2.1.6).

Once each burner was installed and commissioned, the furnace was fired with natural gas from cold up to 1,300 °C, then fired using the following fuel blends:

- 100% v/v natural gas;
- 20% v/v hydrogen blend;
- 50% v/v hydrogen blend; and
- 100% v/v hydrogen blend.

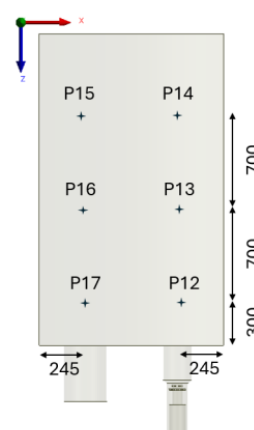
Each blend was used for three hours, with a one-hour changeover period between blend test periods. Experimental data was taken from temperature sensors placed throughout the furnace (see Figure 7) and sensors within the flue gas outlet.

Figure 6: Photo of Glass Futures' CTB interior, viewing the rear furnace wall from the opened back wall end



Source: University of Sheffield

Figure 7: Top-down plan of GF CTB showing experimental data measuring points



Source: University of Sheffield

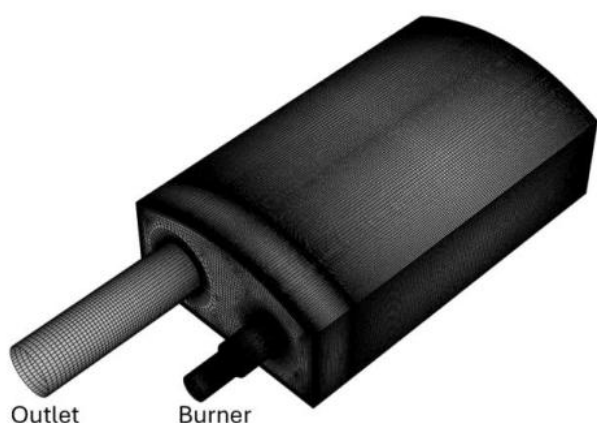
Furnace temperature and flue gas NO_x levels were taken forward and compared to the CTB CFD model (see Section 2.1.5).

2.1.5 Glass Futures CTB model validation

The University of Sheffield then tested a model of the GF CTB, previously created in ANSYS Fluent using the same approach as part of the HYDESS 2A project. This was done by passing inputs and gas blends through to match experimental data for all four hydrogen blend levels from burner 1 gas blend trials (see Section 2.1.4).

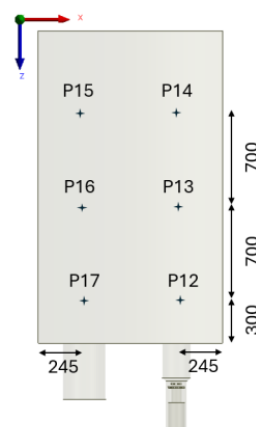
The furnace mesh is shown in Figure 8; Figure 9 shows the measuring points used within CTB burner and fuel blending trials.

Figure 8: Isometric view of Glass Futures CTB model with burner 1 fitted



Source: University of Sheffield

Figure 9: Top-down plan of GF CTB showing experimental data measuring points



Source: University of Sheffield

Again, model furnace wall temperatures closely tracked those six furnace wall points measured during the trials for all 4 hydrogen blends. As in Section 2.1.3, this therefore implies the model is accurately predicting furnace combustion conditions. Predicted NO_x values also largely matched those measured at lower hydrogen blends, while under-predicting at higher hydrogen levels (see Table 4).

Table 4: Comparison of model predicted NO_x in flue gas and experimental data, including fuel inlet temperature, thermal input, and NO_x production

Fuel blend	Experiment fuel inlet temp (°C)	Experiment thermal input (kW)	NO_x emission (ppm)		Difference from measured (%)
			Measured	Predicted	
100% natural gas	19.0	159.0	64.0	61.7	-3.6%
80% natural gas, 20% hydrogen	16.0	141.1	70.4	70.4	0.0%
50% natural gas, 50% hydrogen	12.0	118.8	87.3	73.1	-16.3%
100% hydrogen	5.0	96.7	215.0	143.0	-33.5%

Source: University of Sheffield

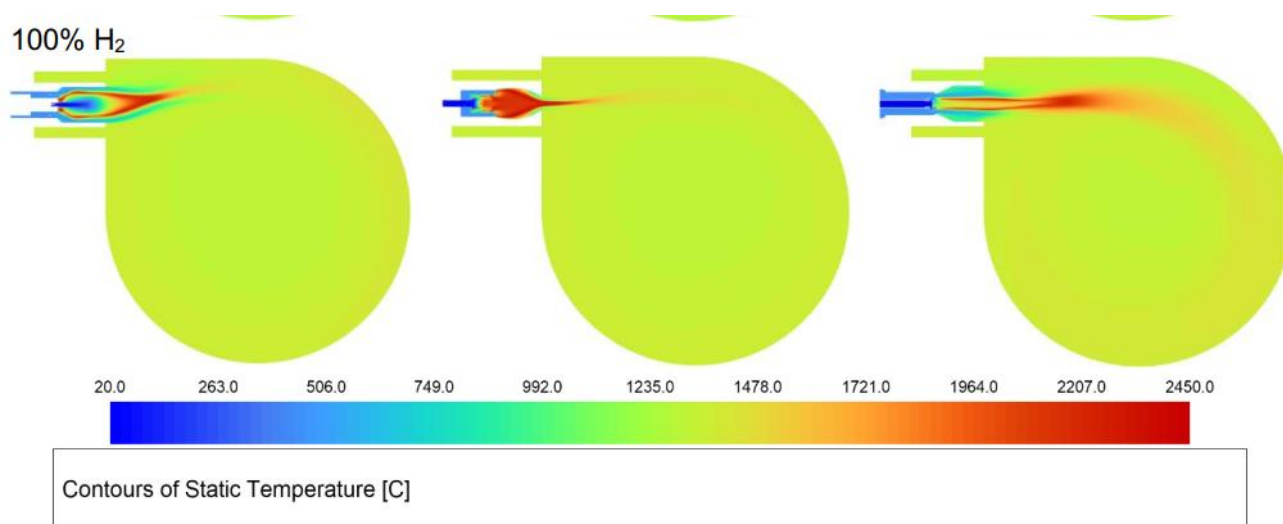
The reason of discrepancy is likely to be due to peak flame temperature: NO_x formation is highly sensitive to peak flame temperature, making it challenging to predict NO_x values using a model.

NO_x production rate increases with peak flame temperature, approximately doubling for every 90°C increase in peak flame temperature above 1900°C, and adding hydrogen to a natural gas fuel increases flame peak temperature (though likely inconsistently, unless the fuel blend has been very well mixed). Increasing the hydrogen fraction of a fuel blend will therefore increase NO_x production and NO_x measurement uncertainty.

2.1.6 CSC furnace simulations

The final step was to model all three of the hydrogen-ready burners fitted to the CSC furnace CFD model and to simulate the combustion of all four hydrogen blends (0%, 20%, 50% and 100% v/v hydrogen) as before. Unlike those tests conducted in Section 2.1.5, this time total burner thermal input and excess oxygen were kept the same across all simulated fuel blends. An example output, showing predicted side-on furnace temperature distribution for each burner simulation at 100% hydrogen fuel blend, is shown in Figure 10.

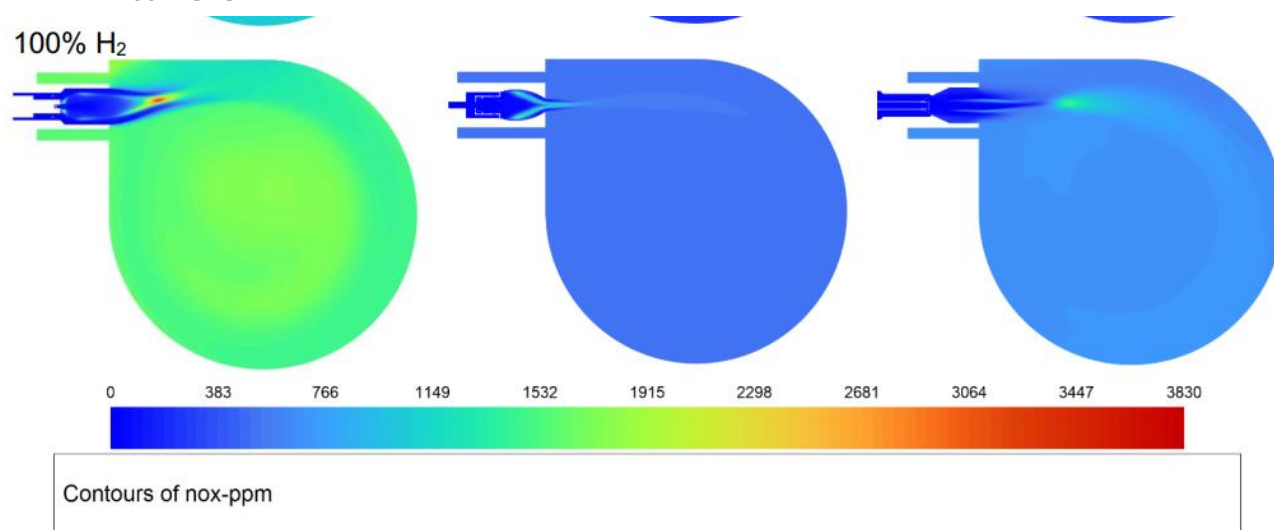
Figure 10: Example predicted temperature (°C) contour maps of CSC furnace fitted with hydrogen-ready burners using 100% hydrogen fuel. From left to right: burner 1, burner 2, burner 3



Source: University of Sheffield

Temperatures across the middle of the furnace (where the forge hole is located) were predicted to be uniform within the furnace and similar between burners, indicating that burner choice has a small impact on thermal profiling. Predicted NO_x concentration maps (see Figure 11 for an example) show that NO_x levels are higher at higher temperatures (shown around the point of combustion in each model), while burner 1 has significantly higher NO_x generation than burners 2 and 3.

Figure 11: Example predicted NO_x emissions (ppm) contour maps of CSC furnace fitted with hydrogen-ready burners using 100% hydrogen fuel. From left to right: burner 1, burner 2, burner 3



Source: University of Sheffield

Table 5 shows modelled NO_x levels at the flue gas outlet for each simulation variant. As can be seen, predictions for burner 1 are a lot higher than those for burners 2 and 3; however, of all three burners, only burner 2 is predicted to operate below a NO_x limit of 550 mg/m³ for all hydrogen blends. This is the limit currently set for Forgemasters' Forge Heating Furnaces by the Environment Agency, which provides a realistic expectation of NO_x limits for future fuel switching operation.

Table 5: Predicted NO_x emissions at flue gas outlet based on burner and fuel blend

Fuel blends	NO _x (ppm)		
	Burner 1	Burner 2	Burner 3
100% natural gas	823	186	164
80% natural gas, 20% hydrogen	860	202	181
50% natural gas, 50% hydrogen	1106	246	269
100% hydrogen	1622	531	655

Source: University of Sheffield

The above values are not adjusted to reflect differences seen in Table 4, such as the 16.3% under-prediction for 50% hydrogen fuel blends. After taking these under-predictions into account, burner 2 and burner 3 NO_x predictions still fall below the 550 mg/m³ limit for fuel blends of 50% hydrogen and below.

2.1.7 Conclusions

All three 'low-NO_x' burners demonstrated the ability to effectively heat the furnace to similar temperatures to those achieved by the existing natural gas burner using the same thermal input. Two of the burners demonstrated the ability to operate below the NO_x limits of 550 mg/m³ (currently set for Forgemasters' Forge Heating Furnaces by the Environment Agency) depending on

fuel blend used. The results proved to be very furnace/burner specific, so further trials would be recommended on a furnace-by-furnace basis once the exact operating conditions are known.

CFD simulations carried out on the firing of the CSC furnace on blends of natural gas and hydrogen using each of the three hydrogen burners confirmed that for 2 of the 3 burners, NOX should not be a concern for this furnace either, if it were to be fuelled with up to 50% v/v hydrogen.

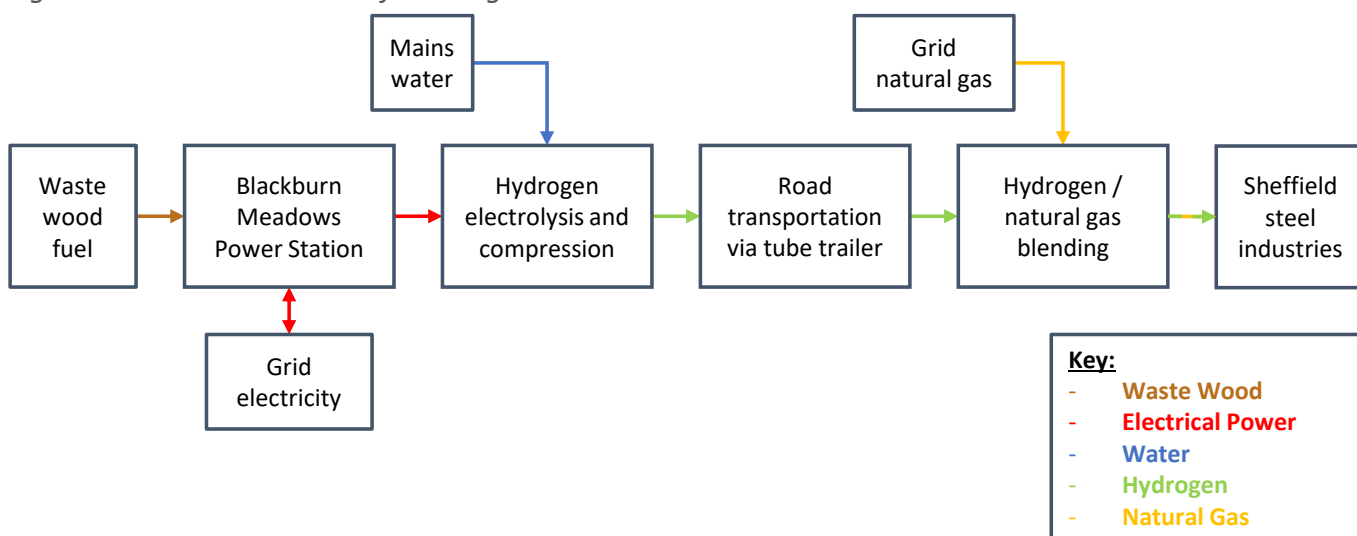
2.2 Front end engineering design

2.2.1 Overview

The end-to-end process for the HYDESS project is summarised in Figure 12. Low carbon electricity produced by the Blackburn Meadows Biomass Plant (and/or purchased via REGO-backed electricity tariffs) will feed (via private wire) an electrolytic hydrogen production plant. Water for the hydrogen plant will be provided from the existing Blackburn Meadows towns water connection.

The plant will produce pressurised hydrogen, which will be stored in tube trailers before being transported via road to the Sheffield steel manufacturing sites. At the manufacturing sites the hydrogen will be combusted in the heat treatment and reheat furnaces. The hydrogen may be blended with natural gas to achieve the correct flame and product characteristics.

Figure 12: HYDESS block flow diagram



The Front End Engineering Design (FEED) study aspect of the HYDESS 2B project was broken into three broad sections.

- **Production** – the production of clean, dry hydrogen at the Blackburn Meadows (BBM) site.
- **Application** – the handling and use of hydrogen on the CSC site.
- **Storage & logistics** – hydrogen compression, storage and transport on and between sites.

These are explored in further detail in the following sections.

Please note, these work package delineations are not consistently applied: hydrogen compression, storage and decanting equipment is included in design and high-level costing of the BBM production site.

2.2.2 Production (WP3)

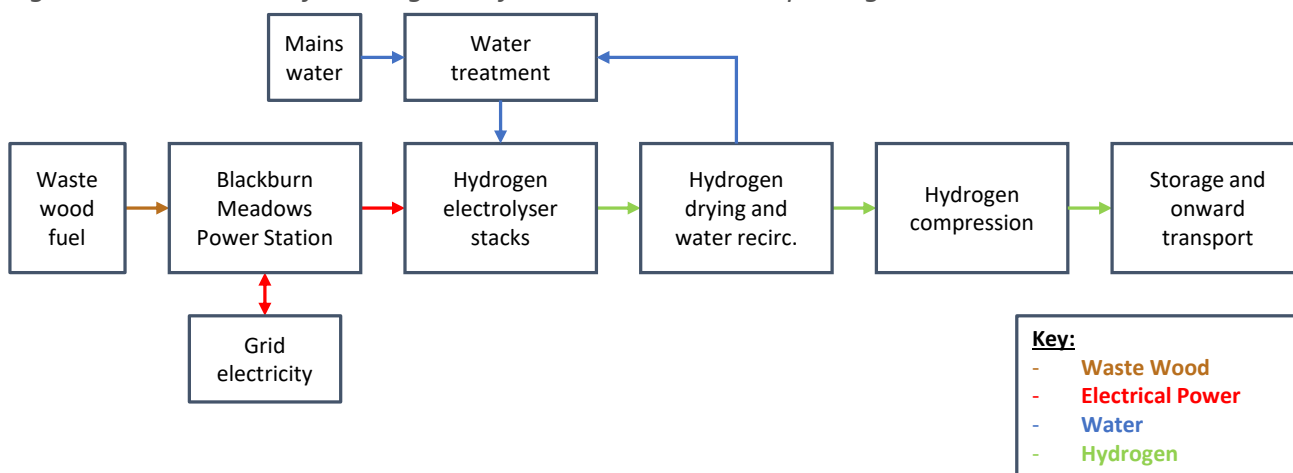
2.2.2.1 Overview

The wider scope of the production work package FEED study, which was carried out by Fichtner (except as indicated below), was split into the following tasks.

1. Electrolyser selection based on market engagement.
2. Process design for the site, including production of preliminary piping & instrumentation diagrams and process flow diagrams.
3. Formation of a mass and energy balance for the production site.
4. Preliminary production site layout, including production of preliminary civils calculations and electrical single line diagram.
5. Vent dispersion modelling.
6. Quantitative risk assessment (carried out by Cairn Risk).
7. Capital and operating cost estimates.

These tasks cover the production scope of the FEED study, laid out visually in Figure 13 below.

Figure 13: Process flow diagram of the Production work package



2.2.2.2 Electrolyser selection

A supplier engagement exercise was carried out to obtain technical proposals and indicative prices for electrolyser from six suppliers. A Basis of Design document was prepared, outlining the HYDESS 2B project and all information necessary for suppliers to provide budget prices for the electrolyser scope of supply. Once all budgets were received, and any gaps addressed, the following conclusions were drawn on which electrolyser technology types might be best used.

- **Proton electron membrane (PEM)** electrolyzers can modulate electrolyser load on a rapid (second-by-second) basis, for example according to power price variations.
- **Solid oxide electrolysis cell (SOEC)** electrolyzers operate with a relatively steady load, with the proviso that the engagement exercise found these to have the longest lead time, a more complex plant layout and the risk of using a technology which has a very limited track record.
- **Alkaline** electrolyzers operate with a relatively steady load, have the lowest capital cost, shortest lead times and the longest track record, and from the supplier engagement exercise appear to have a lower hydrogen production cost than PEM.

Based on this, E.ON selected PEM electrolyzers as the preferred technology type for progressing the rest of the FEED study due to the project need to be able to rapidly ramp up and down production as needed. E.ON will revisit this conclusion for the BBM site during detailed design.

In addition, a containerised production plant was assumed instead of a building-based plant. Use of a containerised solution is more typical at electrolyser capacities of up to at least 30 MWe, and the use of containerised equipment makes it easier to scale up plant production, if desired in the future.

2.2.2.3 Process design

With the main electrolyser technology chosen, the wider process design for the BBM site was developed. Broadly speaking, this can be split into three process areas: hydrogen production, hydrogen compression, and hydrogen dispensing. Venting is provided throughout to ensure the plant can be safely operated.

Hydrogen production

The hydrogen production plant consists of five electrolyser process containers, each housing three electrolyser stacks. Each process container has a nominal power input of 2 MWe, received via its own power supply unit (PSU) container. The PSU container houses the alternating current (AC) to direct current (DC) rectifier and is located adjacent to the process container. Each process container incorporates:

- water treatment plant;
- three electrolysis stacks;
- hydrogen purification and drying;
- water recovery and recirculation;
- compressed air supply for instrumentation; and
- control system.

Mains water is supplied from a tie-in to the existing Yorkshire Water supply to the BBM site. The water pressure is boosted via booster pumps (one running, one standby) and purified in the water treatment plant in the electrolyser process container. The purified water is stored in a buffer tank before being fed to the electrolyser stacks, where it is electrolysed into separate oxygen and hydrogen gas streams.

Oxygen is sent with the recirculated water stream to the oxygen/water separator, where it is separated and vented to the atmosphere. The recirculated water is then pumped back to the

electrolyser stacks via a heat exchanger, where it is cooled using a glycol circuit. This removes the heat generated during electrolysis.

The hydrogen product stream is first passed through a hydrogen/water separator, with the recovered water recycled back to the purified water buffer tank. The hydrogen stream is further treated in a deoxygenation reactor where the remaining oxygen reacts to form water. The product hydrogen stream is dried using desiccant dryers before exiting the electrolyser process container.

Hydrogen compression

At the hydrogen compression stage, the hydrogen exiting the electrolyser process containers is piped to two low pressure (LP) storage tanks. These provide approximately 8 minutes' storage (at 100% electrolyser load) which acts as a buffer before compression. The hydrogen is then compressed from ~30 bar(g) to 350 bar(g) through a two-stage compressor. There are three compressors in parallel (two running, one standby).

The compressed hydrogen is piped to high pressure (HP) storage, which consists of banks of storage cylinders. The HP storage provides approximately 12 hours storage (at 100% electrolyser load).

Hydrogen dispensing

The hydrogen is piped from the HP storage cylinders to the tube trailer filling area, where it is dispensed via one of two dispensers into tube trailers for delivery to end users.

Vent system

Vents are located throughout the process line to ensure safe operation and allow for process equipment and pipework purging if needed. At this stage of the plant design the vent system was not designed, except to carry out preliminary dispersion modelling (see Section 2.2.2.6) using initial assumptions of vent diameter and height. Final vent diameters and heights should be checked during detailed design to ensure the contents of the plant can be vented safely.

2.2.2.4 Mass and energy balance

The mass and energy balance (MEB) was developed using Thermoflex process modelling software based on assumptions from Fichtner's experience and assumptions provided by a typical electrolyser supplier.

The estimated plant inputs and outputs are summarised in Table 6 below. The first column gives instantaneous peak values, while the second column shows annual requirements assuming 8,000 hours availability and solely operating at 100% load year-round.

Table 6: Main plant inputs and outputs

Parameter	Instantaneous	Annual
AC power/energy (input)	10.59 MW	84,738 MWh
Mains water (input)	2.47 m ³ /h	19,752 m ³
Hydrogen produced	180 kg/hr	1,440 tonnes
Oxygen produced (vented to atmosphere)	1,440 kg/hr	11,520 tonnes
Wastewater (output)	0.68 m ³ /h	5,432 m ³

Values are provided with the following additional notes.

- All values are based on electrolyser beginning of life performance. Performance degrades over time at a rate dependent on running hours and percentage load, but can be up to 2%/year. The impact of degradation is that more electricity will be required to produce the same hydrogen output. Degradation is arrested by replacing the electrolyser stacks, typically every five to ten years.
- AC power has been built up based on an average of the nominated electrolyser supplier expected efficiency range (56.81 kWh/kgH₂, with a range of 55.64-57.98 kWh/kgH₂), and balance of plant power draw estimates.
- Mains water input has been built up using information from the nominated electrolyser supplier and is based on expected mains water quality from Yorkshire Water.
- The oxygen flowrates are for pure oxygen; the actual stream flowrates will be slightly higher due to the presence of water and trace hydrogen.
- Wastewater output has been built up using information from the nominated electrolyser supplier and is based on expected mains water quality. The characteristics of the wastewater produced will vary depending on the quality of the incoming mains water and will have seasonal variations.

2.2.2.5 Site layout

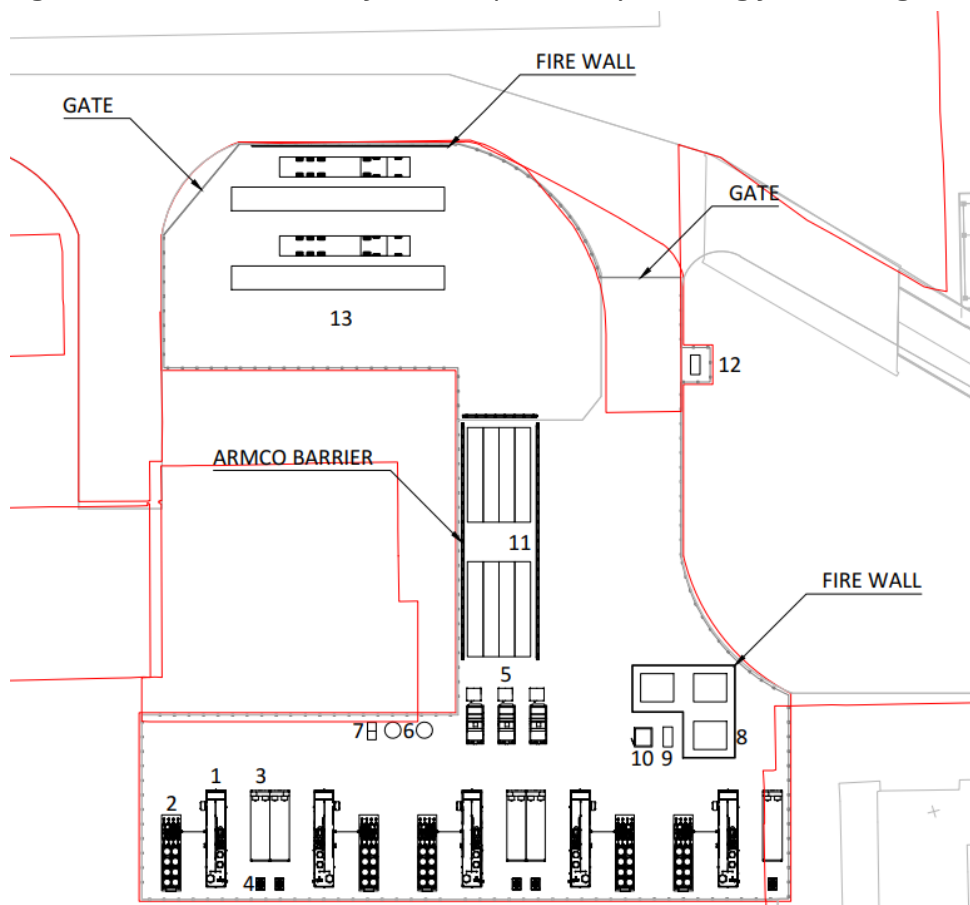
A layout was developed for the production site, including equipment for hydrogen production, treatment, compression and dispensing. The hydrogen production plant is located on the south-east portion of the existing visitors' car park with the hydrogen dispensing area located off the main site access road. The two areas occupy approximately:

- 3,040 m² for the production plant; and
- 1,290 m² for the dispensing area.

An example screenshot of the general arrangement is shown in Figure 14. Here, hydrogen production and treatment equipment is clustered to the south (points 1 – 4), with compressors (point 5) and high pressure fixed storage (point 11) located further northwards. Hydrogen is transferred via a high-level pipeline along the south-west side of the car park to the hydrogen dispensing area (point 13).

The plant will be controlled via control screens in the existing power plant control room.

Figure 14: Screenshot of an example site layout using fixed storage



In addition to 2D plans, a 3D model was developed showing the production and dispensing sites within the wider site context. A screenshot of this is shown in Figure 15.

Figure 15: 3D model screenshot of the BBM site, looking north, showing the production area in the centre and dispensing area to the top left



2.2.2.6 Dispersion modelling

A preliminary hydrogen dispersion modelling assessment was carried out in accordance with European Industrial Gases Association (EIGA) document “Hydrogen Vent System Guidance for Customers Applications”².

Vents and scenarios

The assessment considered the following vents and scenarios. A vent stack height of 6.328 m from the ground level was assumed, to provide a conservative base; mounting equipment on plinths will increase stack height from the ground and reduce any ground-level impacts from venting.

Table 7: Hydrogen vents and scenarios

Source	Number and location	Venting scenario(s)
Electrolyser start -up vents	1 vent per each of 5 electrolysers	During start-up, maximum 1-hour, max release 36 kg/hr per vent
Electrolyser emergency vents	1 vent per each of 5 electrolysers	Unplanned shut-down

² EIGA Hydrogen Vent Systems for Customer Applications – Doc 211/17, 2017.

Source	Number and location	Venting scenario(s)
Electrolyser operational vents ⁽¹⁾	1 vent per each of 5 electrolyzers	During operation
Compressor vents ⁽²⁾	1 vent per each of the 3 compressors, venting from a common stack	During start-up or unplanned shutdown
Low pressure (LP) storage vents ⁽³⁾	1 vent per each of the 2 storage vessels, vent stack located on top of each vessel	During site emergencies ⁽³⁾ , full inventory released
High pressure (HP) storage vents ⁽³⁾	3 vents per each of the 3 storage bank, total of 3 vent stacks each with 3 vents located immediately west of each storage bank	During site emergencies ⁽³⁾ , full inventory released
Note: (1) The release rate from the operational vent according to ITM is ~ 0.03 g/s, which is negligible. This source has not been considered in the dispersion modelling. (2) Only 2 compressors can vent simultaneously (as only 2 will be operational). (3) Venting of entire storage inventory from LP and HP storage will only occur in the event of a site-wide emergency that requires immediate venting to prevent explosion.		

A qualitative description of each potential venting scenario is given below.

1. Start-up (electrolyzers): no hydrogen will be vented until the system pressure has been reached and stack pressure can be maintained. When hydrogen generation starts the hydrogen quality will be monitored. If the hydrogen does not meet the required specification, it will be vented once the system is pressurised. The maximum duration of venting in this scenario is 1 hour, and the hydrogen release will be 36 kg/h per vent.
2. Start-up (compressors): when the compressors are started up, hydrogen is vented via a pressure relief valve as part of the compressor manufacturer's standard procedures.
3. Unplanned shut-down: if there is a technical issue that requires the Facility to shut down immediately, the emergency vents of the electrolyzers and the vents on the compressors will vent the hydrogen inventory in the relevant sections of the process.
4. Site emergency: if there is the potential for the LP and HP storage vessels to be compromised, for example by a fire on the site, the entire storage inventory will be vented as quickly as possible.

Assessment criteria

Hydrogen is potentially explosive in the atmosphere when between the lower flammability limit (LFL) of 4% by volume and the upper flammability limit (UFL) of 75% by volume³.

The probability of the hydrogen concentration exceeding the LFL at a height of 1.8 m above ground level was assessed. Consideration has not been given to the UFL, as if this is exceeded at any

³ Centre for hydrogen safety (via AIChE), Hydrogen Flammability. Available at: https://www.aiche.org/sites/default/files/docs/pages/the_elemental_-_hydrogen_flammability.pdf (accessed March 2024)

location at 1.8 m height, then the concentration at other locations will be between the LFL and UFL and hence potentially explosive.

For this purpose of this study, it was considered that if the dispersion model predicts that the probability of exceeding the LFL is less than 2% at any location during the worst-case meteorological conditions for dispersion, it is highly unlikely that the LFL will be exceeded in reality.

The 2% threshold for the probability of exceeding the LFL was selected due to the study being concerned with the extremes of the modelled probability distribution function. At these extremes the model tends to predict a low but non-zero probability of exceeding the LFL even when the average predicted concentration is well below the LFL. As such, if the probability of exceeding the LFL at any one location during the worst-case meteorological conditions for dispersion is less than 2%, the risk of exceeding the LFL in reality is considered negligible.

LP and HP storage vents

The vent flowrates for the LP and HP storage vents were estimated using the open-source Python package Hyddown⁴. Hyddown is specifically designed for simulating the filling and discharge of hydrogen storage tanks under a variety of conditions. The package allows for the calculation of vessel pressure, fluid inventory and vent flowrate as a function of time. The following assumptions were used in the Hyddown package to calculate the mass flow rate and efflux velocity of the hydrogen being vented.

Table 8: Assumptions for vent modelling

Descriptions	Units	Value	Notes
LP storage pressure	bar(g)	31	As per process flow diagram (reference S4009-8400-0001)
HP storage pressure	bar(g)	350	
Hydrogen temperature in LP storage	°C	30	
Hydrogen temperature in HP storage	°C	20	
Hydrogen gas density	kg/m ³	Variable	Calculated from operating pressure using https://cmb.tech/hydrogen-tools and ideal gas law
LP storage vessel diameter	m	2.9	Fichtner preliminary design (to give approximately 5 m ³ storage per tank)
LP storage vessel height	m	3	
No. of LP storage vessels		2	
LP vent diameter	mm	50	Fichtner preliminary design
HP storage vessel diameter	m	1.25	Provided by Chesterfield Special Cylinders
HP storage vessel length	m	11.47	Provided by Chesterfield Special Cylinders

⁴ Andreasen, A., (2021). HydDown: A Python package for calculation of hydrogen (or other gas) pressure vessel filling and discharge. Journal of Open Source Software, 6(66), 3695, <https://doi.org/10.21105/joss.03695>

Descriptions	Units	Value	Notes
HP vent diameter	mm	15	Provided by Chesterfield Special Cylinders
No of HP storage vessels		6	Six HP vessels will vent into a single DN15 vent

Vent heights

The electrolyser vents were assumed to discharge at a height of 6.328 m above ground, based on the preferred electrolyser supplier's design. The assessment showed that the probability of exceeding the LFL at this height was 0.1% or below.

For the initial assessment, the other vents were assumed to be located at the same height. For the LP storage vent, the the probability of exceeding the LFL at this height was less than 2%.

For the compressors, the probability of the compressor exceeding the LFL at this height was 2.9%. To reduce this to 2.0%, the vent height was increased to 8.0 m.

For the HP storage, the probability of the compressor exceeding the LFL at this height was 2.8%. To reduce this to 2.0%, the vent height was increased to 10.0 m.

Conclusions and recommendations

Preliminary hydrogen dispersion modelling showed a negligible chance that venting from the electrolyser plant will exceed the lower flammability limit of hydrogen in air. However, the model was subject to limitations and caveats and further analysis should be carried out in the detailed design phase.

2.2.2.7 Quantitative risk assessment

Cairn Risk Consulting Ltd carried out a quantitative risk assessment (QRA) on the production plant. The purpose of the QRA was to quantify the risk to people in the vicinity of the hydrogen plant, determining whether the level of risk meets E.ON criteria and if any addition risk reduction measures could be required. The QRA focused only on hydrogen process hazards.

E.ON's individual risk per annum (IRPA) criteria is $2\text{E}-05$, more conservative than the typical UK HSE expectation of $1\text{E}-04$. The results demonstrated that the IRPA for each worker group was below E.ON's IRPA criteria. The highest IRPA is experienced by the tube trailer driver due to spending approximately 2 hours per day in the dispensing area.

Hypothetically, to reach an IRPA of $2\text{E}-05$ a worker would have to spend approximately 3 hours per day working in the hydrogen plant area, equally distributed in the electrolyser, storage and dispensing areas (A3).

Based on the results from the study the following recommendations have been made:

1. As the design progresses, any opportunity to reduce the leak sources should be made. This could be through maximising welded connections rather than joints, as well as reducing pipework lengths (especially for high pressure inventories e.g. 350 barg).
2. As part of E.ON's Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR) assessments, it would be recommended to perform the following.

- a. Hazardous Area Classification (Regulation 7) studies could use the information presented in the QRA as well as developing additional venting releases to generate the hazardous area classifications.
 - b. A Fire and Explosion Risk Assessment could build upon the QRA to aid in the development of the required DSEAR assessments (Regulation 5). Topics like escalation could be further investigated to aid in demonstrating the required detection coverage and electrostatic discharge (ESD) philosophy. In addition, sensitivities could be performed to determine if further risk reduction measures could be required (e.g. fire suppression systems, fire and blast walls, increased separation distances).
3. The QRA only accounted for immediate fatalities. As part of future studies the potential impairment to escape routes should be investigated to reduce the risk of personnel being prevented from escaping before an event escalates.
4. As demonstrated, E.ON's risk criteria would be reached if personnel are exposed to process risks for approximately 3 hours per day every day for the whole year. The following measures could be further investigated to reduce this risk.
- a. Reduce the requirement for personnel to visit the hydrogen facility. If this is required for prolonged durations consider reducing the stored hydrogen inventory or shutting down hydrogen production or compression.
 - b. The largest contributor to the worker group's risk comes from the compressor package due to the high pressures and high leak frequencies associated with rotating equipment. Apart from ensuring leak sources are reduced (see recommendation 1) consider means of preventing the impact area of any consequence by using fire/blast walls or louvred barriers (to allow for ventilation but help reduce momentum from a release and facilitate dispersion upwards away from manned areas). Similar measures should be investigated for the High Pressure Storage areas.
 - c. If practicable consider relieving the pressure of the tube trailer manifold when not in operation, reducing this from the HP storage pressure of 350 barg.
 - d. Although the study has not accounted for escalation, if this were to occur (e.g. in the event of no detection and isolation) and personnel are unable to escape in time then measures like active fire protection should be investigated.

2.2.2.8 Cost estimates

Capital cost

The capital cost estimate was produced using elements of both the Association for the Advancement of Cost Engineering (AACE) Class 3 and Class 4 methods with a cost basis of January 2024. The main equipment costs, which form over 60% of the total project costs, were sourced from suppliers in the form of budgetary quotations. For the balance of the project costs, the estimate was based on:

- recent experience of similar projects;

- cost estimation reference sources (Cleopatra Cost Estimating software⁵ and 2024 Compass Front End/Conceptual Estimating yearbook⁶); and
- a quantity surveyor's estimate of the civil work costs.

Client costs are excluded from this estimate. These could include, for example:

- development costs (e.g. planning, permitting, legal);
- connection costs from utility providers (e.g. mains water, waste water); and
- client contingencies.

The total capital cost estimate is:

- £23.4m including compression, storage and dispensing; or
- £15.1m for production only (i.e. excluding compression, storage and dispensing, and their associated costs).

Table 9 shows a breakdown of the estimate by anticipated work package.

Table 9: Total capital cost estimate (by supplier/contractor) – cost basis Jan 2024

Item	Including compression, storage and dispensing	Production only
Electrolyser supplier	£8,962,000	£8,962,000
Compressor supplier	£4,374,000	-
HP storage supplier	£1,571,000	-
Dispenser supplier	£283,000	-
Mechanical & electrical contractor (inc. minor equipment)	£3,470,000	£2,988,000
Civil contractor	£2,729,000	£1,954,000
Equipment deliveries	£183,000	£71,000
EPCm contractor	£2,161,000	£1,107,000
Third party (certifications)	£37,000	-
Total	£23,365,000	£15,082,000

Operating cost

Operating and maintenance (O&M) costs for electrolyser plants are extremely difficult to forecast. There was no access to actual cost data from operating plants (due to the scarcity of worldwide electrolyser plants with several years of operating experience). Instead, an estimate was based on the extremely limited forecast data from suppliers. This translates into an assumed O&M cost equivalent to 5%/year of equipment capital cost, or approximately £1 m/year.

This operational cost excludes electricity, water and wastewater, which depend on utility unit costs.

⁵ <https://cleopatraenterprise.com/cost-estimating/>

⁶ <https://compassinternational.net/product/2024-front-end-conceptual-estimating-yearbook-pdf/>

2.2.3 Application (WP4)

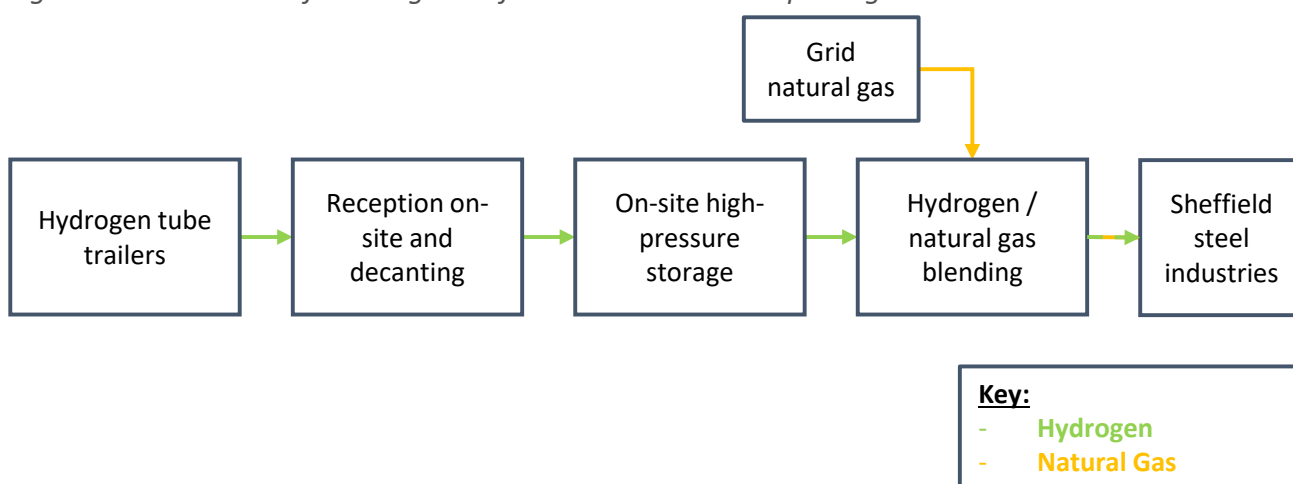
2.2.3.1 Overview

The work package FEED study scope included the design of the process and equipment required within CSC's factory limits to allow the safe offloading and distribution of hydrogen to supply two existing reheat furnaces. This wider scope was split into the following tasks.

1. Process design including production of preliminary process flow diagrams.
2. Site layout, including preparation of 2D plans and a 3D model.
3. Vent dispersion modelling.
4. A capital cost estimate for the CSC site.

These tasks cover the application scope of the FEED study, laid out visually in Figure 16 below.

Figure 16: Process flow diagram of the Production work package



2.2.3.2 Process design

The process design can be split into four process areas: hydrogen offload and storage, hydrogen pressure letdown, natural gas supply, and fuel blending and combustion control. A fixed/static storage arrangement was assumed for the CSC site (see Section 2.2.4.3) as it provided the shortest elapsed time for a delivery, removed the need to swap trailers, and provided larger storage buffer in case of trailer supply disruption. This assumption, and all assumed pressure levels in this section, shall be revisited at the detailed design stage.

Venting is provided throughout to ensure the plant can be safely operated. Low-pressure and high-pressure nitrogen systems supply nitrogen for pipework purging and tube trailer connection pressure testing. Low- and high-pressures are yet to be defined but are anticipated to be 0.5 bar(g) and 360 bar(g) respectively.

Hydrogen offload and storage

Hydrogen is transported to the CSC site by trailer and offloaded, using the process outlined in Section 2.2.4.5, into static storage cylinders with a working fill pressure value of 40-360 bar(g). The

cylinder bank shall be sized to store approximately 600 kg of hydrogen, based on consecutive filling and settling of each hydrogen storage cylinder, each of which shall be held at a different working pressure. Exact storage capacity of the buffer storage area, and pressure stages of the storage cylinders, shall be confirmed during detailed design.

Hydrogen pressure letdown and supply

When required, hydrogen is taken from the storage cylinders and passed through a pressure letdown station. This skid-mounted station shall comprise multiple stages of self-acting pilot operated pressure reducing valves (exact number of stages to be confirmed during detailed design), that will supply hydrogen at a reduced pressure of approximately 0.5 bar(g). The hydrogen supply will be continuous and uninterrupted.

Natural gas supply

Natural gas will be supplied from the existing site connection. If necessary, the pressure shall be boosted to meet the pressure requirements of the burner packages for blending and hydrogen co-firing.

Fuel blending and combustion

The existing burners will be replaced with new burners designed for firing blended hydrogen and natural gas over the range of 50% v/v to 100% v/v hydrogen, and 100% v/v natural gas. CSC has identified that this may require two sets of burner and/or nozzle positions – one able to fire hydrogen blends, and one able to fire 100% v/v natural gas – with furnace nozzle positions being adjusted as desired. Firing on 100% v/v natural gas is likely to be a non-routine operation, such as during unplanned maintenance activities or possibly as part of the initial furnace heat/soak period from cold.

Fuel blending and combustion control shall be managed within a control package. This package shall be capable of balancing fuel blend ratio (hydrogen to natural gas) and combustion air flow to maintain combustion conditions and the temperature set point within the furnace.

Flue gases from the existing burners are currently vented directly into the process building. This arrangement will be reviewed in line with anticipated flue gas compositions associated with the selected burners at detailed design stage.

2.2.3.3 Site layout

Two plots of land on the CSC facility site, one to the north of the main process building and one to the south, were evaluated as possible locations for the main CSC hydrogen infrastructure.

Figure 17: CSC site, showing main building and trailer offloading site location options

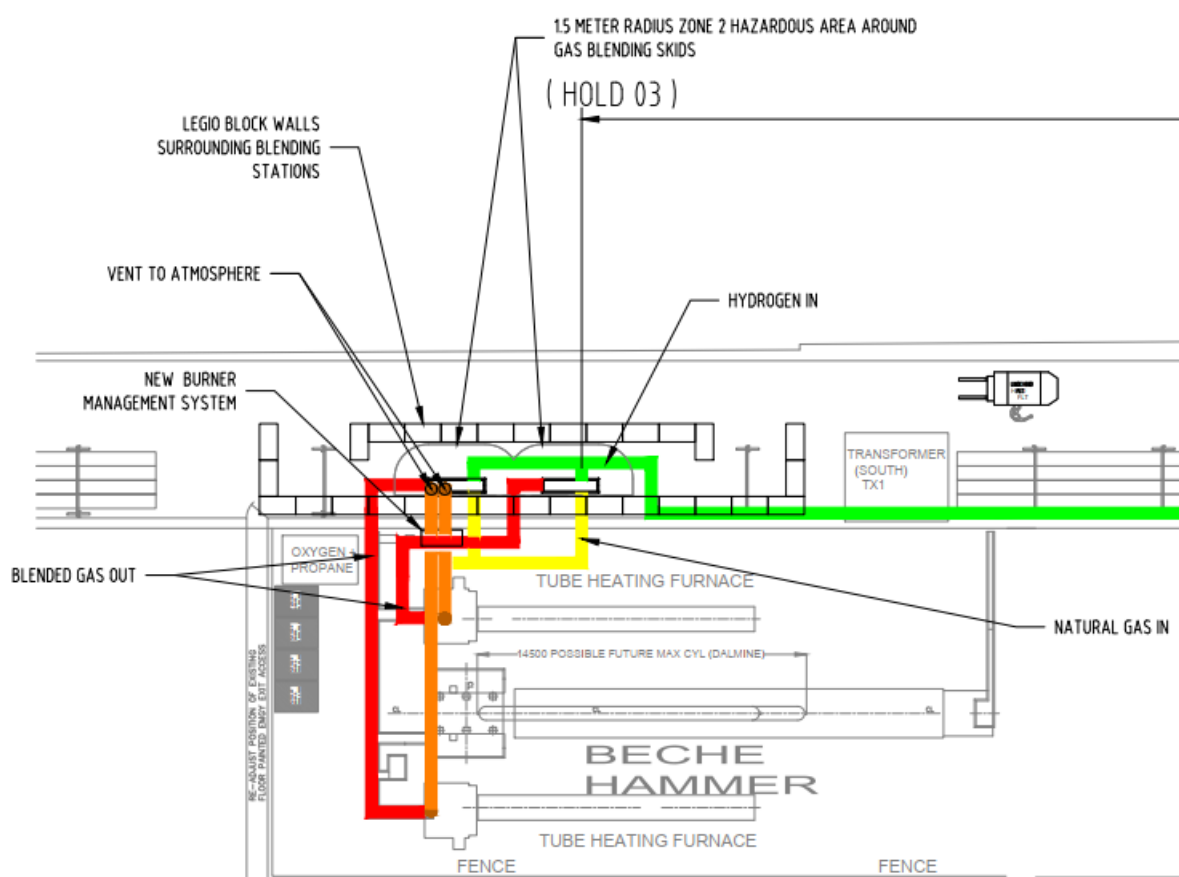


Source: Otto Simon

The north plot was chosen as it is further away from potential sensitive receptors (simplifying the planning process). Also, as of 10 May 2024, the south plot is also being leased out to another company, meaning there was deemed to be a higher risk of delays in the execution phase if the south side were chosen.

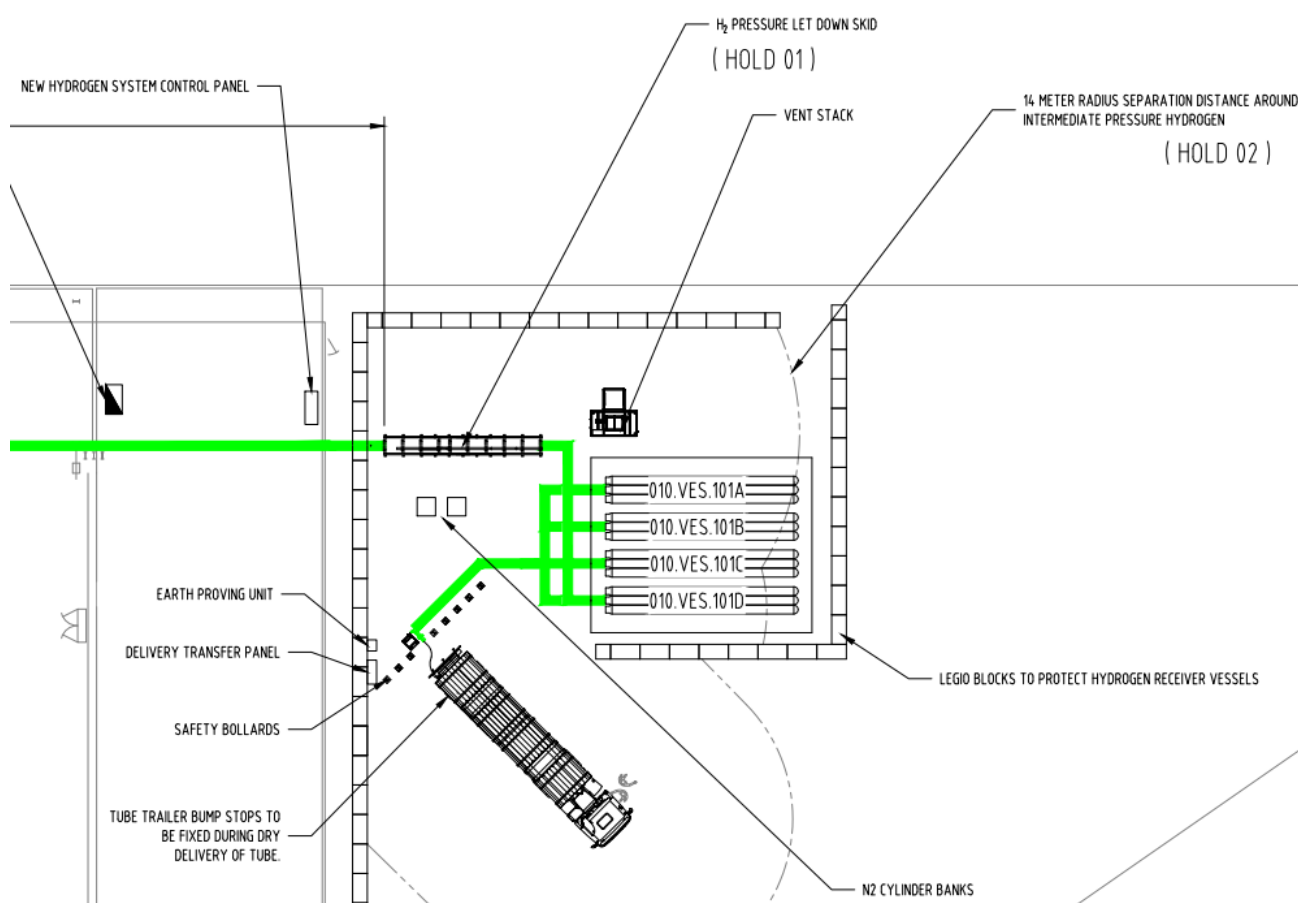
With the approximate location chosen, preliminary 2D location layout drawings were produced showing both trailer offloading and gas blending equipment. Gas blending equipment is located close to the furnace, which itself is approximately 210 m south of the offloading and buffer storage area. Example screenshots of each end of the preliminary layout are shown in Figure 18 and Figure 19.

Figure 18: Screenshot of example gas blending area layout close to furnace location (hydrogen pipework is green, natural gas pipework is yellow, blended gas pipework is red and venting is orange/brown)



Source: Otto Simon

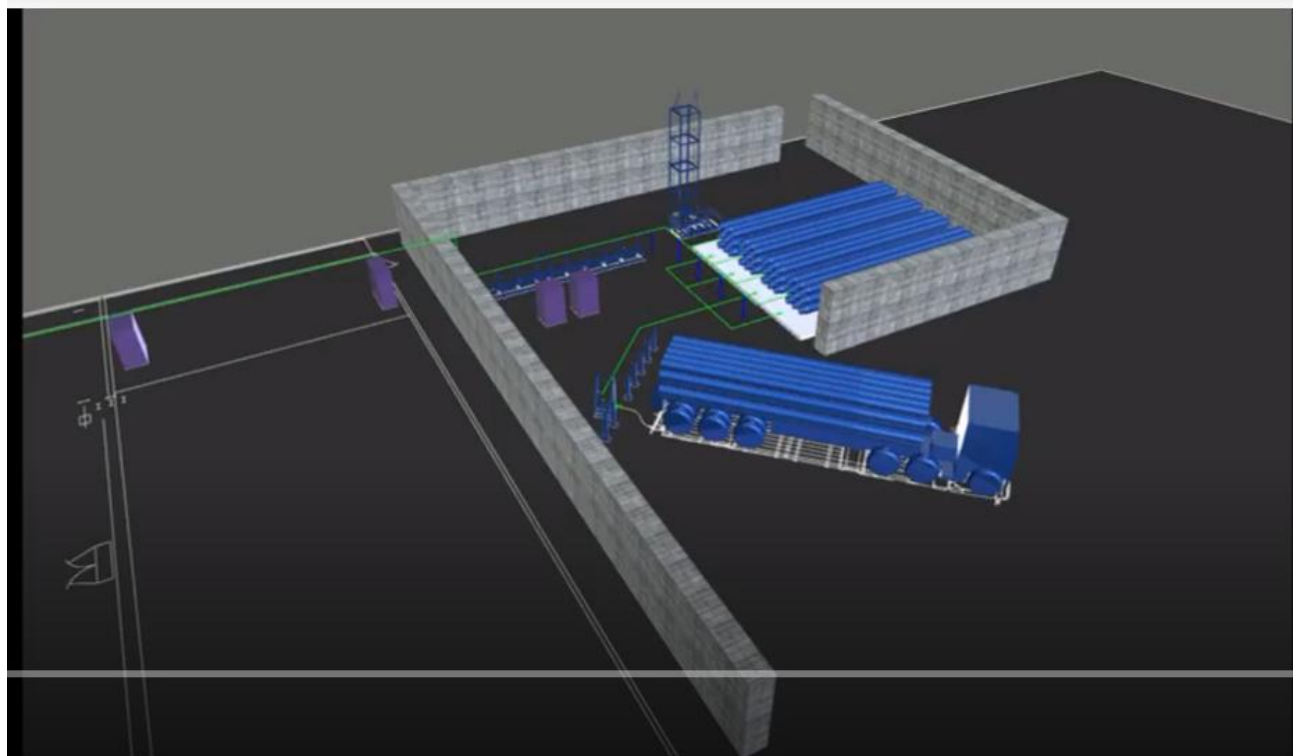
Figure 19: Screenshot of example trailer offloading area layout to north of main building (hydrogen pipework is green)



Source: Otto Simon

A 3D model has also been developed. A screenshot of the model, showing the hydrogen reception area and example tube trailer, is shown in Figure 20.

Figure 20: 3D model screenshot of the CSC site, looking west, showing hydrogen reception area



Source: HYDESS consortium

2.2.3.4 Hydrogen dispersion modelling

Full dispersion modelling was not conducted for the CSC site. Instead, high-level requirements were identified that will be needed for a full modelling at detailed design stage. These included:

- determination of hazardous zones and their sizes;
- confirmation of dedicated vent stack height and location; and
- determination of separation distances.

2.2.3.5 Capital cost estimate

A total installed cost estimate for works inside CSC's battery limit was produced. Table 10 shows a breakdown of the estimate. All values have been rounded to the nearest £1,000.

Main equipment costs were predominantly sourced from suppliers in the form of budgetary quotations. Other costs were based on recent experience of similar projects and cost estimation reference sources.

Table 10: Total installed cost estimate – CSC site

Item	Cost
Procured equipment costs	£2,065,000
Subcontract costs (civil works, installation, preliminary costs)	£645,000
Bought out services (certifications, dispersion modelling, studies, etc)	£19,000
Engineering costs	£287,000
Construction supervision and commissioning	£198,000
Escalation and contingencies	£448,000
Commissioning and scaffolding allowance	£53,000
Total	£3,715,000

Source: Otto Simon Ltd

In addition, an indicative monthly cash flow forecast was produced, showing how cash flow was likely to look over the estimated 14-month construction and commissioning process.

2.2.4 Storage & logistics (WP5)

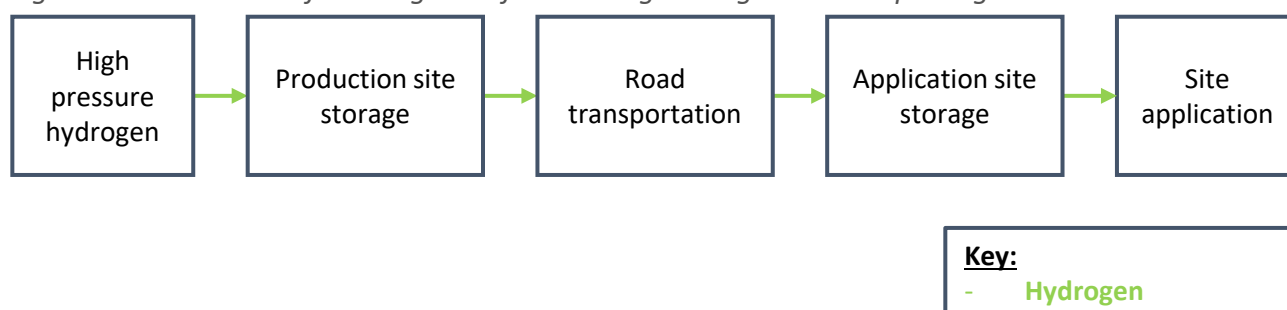
2.2.4.1 Overview

The wider scope of the storage and logistics work package FEED study, which was carried out by E.ON with support from Fichtner, was split into the following tasks:

1. creation of an approximate demand profile for two to four years;
2. discussion of possible road transportation options;
3. Investigation of road vehicle options to support project transport and logistics requirements; and
4. de-risking of the trailer filling and decanting processes.

These tasks cover the storage and logistics scope of the FEED study, laid out visually in Figure 21 below.

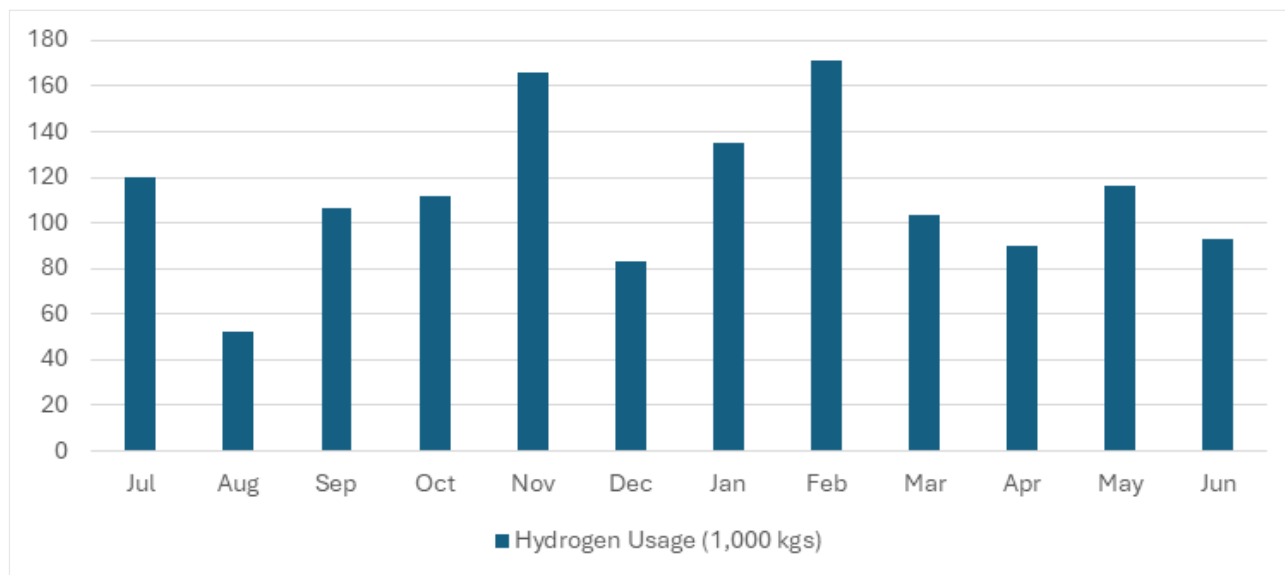
Figure 21: Process flow diagram of the Storage & Logistics work package



2.2.4.2 Demand profiling

Two primary customers provided monthly hydrogen demand predictions for three years. These were combined to form an annual demand profile (see Figure 22 for year one of three).

Figure 22: Estimated annual hydrogen demand for year one of three



Source: HYDESS Project

In this profile, demand varies from 50,000 kg/month to 170,000 kg/month, with an average demand of 110,000 kg/month. Annual demand is predicted to be approximately 1,348,000 kg.

This profile is not fixed across the full predicted time period, and HYDESS is currently in talks with other offtakers for the HYDESS 2B project. Any new customers will be required to provide annual forecasts to allow E.ON to manage any changes to expected demand.

While the annual hydrogen demand is achievable for the production site at BBM, monthly demand values over 120,000 kg/month exceed site production capacity (see Section 2.2.2.4). Where customer demand profiles cannot be reduced and exceed E.ON production capability, hydrogen will need to be acquired by the customer from third party sources.

2.2.4.3 Transportation cost options

Once produced at the BBM site, the hydrogen will need to be transported to where it is used. The options for hydrogen compression, storage, and transport to the offtakers were assessed.

When transporting via road, there are two broad options.

1. **Static storage** – the hydrogen is stored in high-pressure fixed storage vessels on the BBM site (Figure 23), before being dispensed into tube trailers (Figure 24) and connected to lorries for transport to offtakers.
2. **Mobile storage** – the hydrogen is stored in multi-element gas containers (MEGCs, Figure 25) on the BBM site, which are then connected to lorries (Figure 26) and transported to offtakers.

Figure 23: Example static storage tanks



Source: Chesterfield Special Cylinders

Figure 24: Example tube trailer



Source: Chesterfield Special Cylinders

Figure 25: Example MEGC render



Source: NPROXX

Figure 26: Example MEGC loading bays



Source: Hydros spider

Eight specific options were assessed, as described in Table 11 below. For the fixed storage options, Fix-1 includes the capital and maintenance cost of fixed storage at the offtaker's site, while Fix-2 excludes these costs. For mobile storage, six options were assessed across two transport pressures and three different MEGC container capacities.

Table 11: Storage and transportation options assessed

Option	Storage pressure (bar(g))	Transport pressure (bar(g))	Transport capacity (kg)	Offtaker storage capacity (kg)
Fix-1	350	200	400	440
Fix-2	350	200	400	-
Mob-1	-	300	402	-
Mob-2	-	300	626	-
Mob-3	-	300	848	-
Mob-4	-	380	486	-
Mob-5	-	380	756	-
Mob-6	-	380	1028	-

Cost models were constructed for each option, assuming four customers in the Sheffield area and considering capital and operating costs for:

- compressors;
- fixed storage (if applicable);
- MEGCs or tube trailers;
- MEGC/tube trailer filling bays; and
- transportation to and from user sites.

The costs for the different fixed and mobile storage options are similar; cost increases in one category tended to be balanced out by cost reductions in another category. On this basis, the preferred option is likely to be based on other considerations, such as the ability to fit within the site footprint, the frequency of vehicle movements, and the flexibility to implement a staged modular build-out.

Both the mobile and fixed storage concepts fit within the identified area for the hydrogen production plant, but a mobile concept would allow E.ON to retain most of the existing car park of the BBM site.

If E.ON intends a staged modular build-out approach, a mobile storage option would be more suitable than the fixed options.

2.2.4.4 Road vehicle options

E.ON has identified the following key points for road transportation to be successful:

- Low-emission transport – electric lorries to be utilised to help drive down the environmental impact of introducing additional vehicle movements in the Sheffield area.
- 24/7 deliveries – 24/7 operation of the BBM production plant means multiple trailer deliveries per day to locations across the Sheffield area. Production (and therefore delivery schedules) will scale up production as demand increases.
- Skilled personnel – drivers would be needed to fill, transport and decant hydrogen from a pressurised trailer to a storage vessel at the offtaker's site.

After reviewing the different options available in the sourcing and management of both lorries and drivers, the preference was to look at outsourcing providers. This was because outsourcing:

- makes good use of existing expertise in the haulage industry;
- minimises the impact on E.ON's BBM operations teams; and
- removes the costs associated with ownership, such as initial purchase and ongoing maintenance.

A high-level agreement template has been drafted to give a framework that E.ON can develop once demands and transport requirements are firmer.

BBM has received indicative hire costs for a lorry with driver as £650-850 /day depending on vehicle type (e.g. electric, diesel etc). These costs will be revisited, and the agreement template for delivery and logistics services further developed, upon detailed design and investment decision.

2.2.4.5 Hydrogen transportation de-risking

A risk assessment was undertaken for the hydrogen loading facilities and road transportation. This covered the following four steps.

1. **A HAZOP of the hydrogen loading facilities.** This identified the major loss of containment (LOC) scenarios and reviewed them against E.ON's risk matrix with and without potential safeguards.
2. **Consequence analysis.** The software SuperChems™ was used to model the ultimate consequence and show the severity of each LOC scenario.
3. **Preliminary LOC scenario analysis to calculate risk of truck filling.** This reviewed LOC scenarios with proposed safeguards against E.ON's risk matrix, identified any areas of improvement to reduce overall risk and recommended further safeguards/actions.
4. **Calculating risk of road transportation.** This reviewed road transportation frequency data to provide an overall risk categorisation for hydrogen road transportation.

The transportation risk assessment was performed on 3 different tube trailer options which included 400 kg at 200 bar, 1,000 kg at 500 bar and 700 kg at 380 bar. It was assumed that 6 deliveries would be done each day, 365 days per year.

Two headline risks were deemed "unacceptable" using E.ON's risk matrix. These risks were then minimised as low as reasonably practical. This is described below.

Risk: Hydrogen hose is not properly maintained, i.e. wear and tear, causing a loss of containment (LOC) of hydrogen

- As per the filling procedures outlined in Section 2.2.4.6, the filling hose will not be filled with hydrogen until the filling system has passed a pressure test using nitrogen. The pressure test will identify any wear and tear issues that result in an LOC, before hydrogen is passed through the hose as part of the filling process.
- A fire risk assessment and Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) assessment will be completed on site, which will include the hydrogen loading and decanting area. This is to remove any possible ignition sources in areas where hydrogen leaks may occur.
- A fire and gas detection system will be installed in the hydrogen loading and decanting area which will activate the emergency shut down valves and vent hydrogen to atmosphere if a fire or hydrogen gas is detected.
- Training will be provided to tube trailer drivers to ensure standard operating procedures are followed and the hazards of hydrogen are fully understood.

Risk: Overall risk due to road transportation

- The ignition likelihood of hydrogen following a LOC from a tube trailer was initially assumed to be 1. However, since hydrogen will be at high pressure and is also very buoyant, it is expected that hydrogen would quickly disperse upwards, meaning that the ignition likelihood is likely to be much lower.
- All tube trailer drivers will be trained in hydrogen hazards and how hydrogen should be safely transported by tube trailer.
- Traffic management plans will be implemented at Blackburn Meadows to manage and mitigate risks related to hydrogen transportation.

2.2.4.6 Trailer loading and decanting process

Process descriptions and process flow diagrams (PFDs) were produced to describe and de-risk how trailer filling and offloading will be conducted. For the sake of simplicity, these were prepared assuming the use of tube trailers filling from fixed storage at the production and decanting to fixed storage at user sites (i.e. the fixed storage option Fix-1 discussed in Section 2.2.4.3). This assumption shall be revisited, and other options (such as mobile storage and the use of MEGCs) considered at the detailed design stage.

When arriving to a site (either for filling or decanting), each trailer will first be earthed, before a leak test is performed on the connecting hose between the trailer and site storage. In this test, a site operator will use nitrogen from an onsite store to remotely pressurise a section of the hose connection to 100 – 200 bar(g). Once nitrogen supply is cut, and hose connections sealed, hose pressure will be monitored remotely for a prescribed length of time to confirm hose integrity. When the pressure test is successful, the hose is remotely purged and then hydrogen valves are remotely opened to start the trailer filling/decanting process. As an additional measure to prevent hydrogen leakage, tube trailer filling will follow a recognised protocol such as J2061.

Once hydrogen transfer is complete, the hose will be remotely purged using low pressure nitrogen, then vented to atmosphere. The driver will then be prompted by the operator to disconnect the flexible hose, after which the tube trailer is able to exit site. A breakaway coupling with integrated shut off valves will be installed between the dispensing pipework and the tube trailer. These are used to avoid spillage and damage associated with drive and/or pull away incidents when loading and unloading.

3 Costs and carbon savings

3.1 Expected cost of solution

All values in this section are reported in real 2024 prices unless stated otherwise.

3.1.1 Capital costs

The following capital costs have been estimated.

- For the production plant (see section 2.2.2.8), either:
 - £23.4m, up to and including hydrogen dispensers; or
 - £15.1m, up to and including LP storage (i.e. excluding compression, HP storage and dispensing, and their associated costs).
- £0.62m for a single 400 kg capacity tube trailer (from E.ON's project commercial model).
- £3.72m for end user costs at CSC's site (see section 2.2.3.5).

3.1.2 Operating costs

The estimated operating costs for the production plant are summarised in Table 12 below. These are all taken from E.ON's commercial model.

No operating costs have been estimated for the end users. End user operating costs are likely to be relatively low, and consist mainly of maintenance costs for any new plant and equipment.

Table 12: Estimated operating costs (from E.ON commercial model)

Item	Annual Cost	Source
Labour (logistics)	£280,000	E.ON assumption
Parts and maintenance	£123,000	E.ON assumption
Distribution costs	£163,000	E.ON assumption
Water and wastewater	£44,000	E.ON assumption (based on current prices)
Insurance	£28,000	E.ON assumption (0.12% of CAPEX, plus 12% premium)
Business rates	£153,000	E.ON assumption (0.72% of total CAPEX)
Rent	£155,000	E.ON assumption
Total	£666,000	

Table 12 excludes electricity costs. For electricity supply, E.ON has assumed the following.

- 60% of the electricity will be supplied directly from the BBM power plant. The electricity price to the electrolyser will be set to equal to the wholesale power price, adjusted for Balancing Services Use of System (BSUoS) and Residual Cashflow Reallocation Cashflow (RCRC) charges.

The principle is that the power plant sells to the electrolyser or to the grid at the same net price.⁷

- 40% of the electricity will be supplied via a power purchase agreement (PPA) with a renewable energy supplier.

3.1.3 Levelised cost of hydrogen

The Levelised Cost of Hydrogen (LCOH) has been estimated according to the methodology described in the BEIS Hydrogen Production Costs 2021 document⁸. As per the methodology:

- only the capital and operating costs associated with the production of hydrogen are included; and
- the battery limit for hydrogen produced is downstream of the electrolysis plant, and upstream of the compressor.

Table 13 below shows the estimated LCOH. Note that:

- all data has been taken from E.ON's commercial model (valid at 30th July 2024) unless stated otherwise;
- the electricity costs vary year-on-year, depending on the E.ON forecast for wholesale electricity price; and
- the hydrogen production also varies year-on-year due to electrolyser degradation.

Table 13: LCOH estimation

Item	Units	Value	Formula	Source
Capital costs	£	£15,082,000		Table 9
Electricity costs (year 1)	£	£8,854,000		E.ON (excludes compression)
Parts and maintenance	£	£123,000		Table 12
Water and wastewater	£	£44,000		Table 12
Hydrogen produced (year 1)	Tonnes	1,349		E.ON commercial model
Discount rate	%	10%		BEIS Hydrogen Production Costs 2021
Project life	Years	30		
Total discounted costs	£	£102,248,748	a	Calculated from above
Total discounted hydrogen production	Tonnes	12,332	b	Calculated from above
Levelised cost of hydrogen	£/kg	£7.72	c = a / b	Calculated from above
HHV of hydrogen	MJ/kg	141.8	d	Literature
Levelised cost of hydrogen	£/MWh_{HHV}	£195.51	e = c * d	Calculated from above

⁷ The biomass asset will lose export revenue by supplying the electrolyser with electricity. In order to maintain the biomass plants commercial position the price that the electricity is sold to the electrolyser must be the same as it would otherwise have achieved from selling the electricity to the grid. If the biomass assets were to sell electricity to the electrolyser at a fixed price, there would be too much risk associated with lost export revenue.

⁸ <https://www.gov.uk/government/publications/hydrogen-production-costs-2021>

3.1.3.1 Uncertainties (and sensitivity analysis)

Table 14 shows the main uncertainties for the LCOH. The assumed uncertainty level is shown (this is an approximate estimate only, at this stage of the project) together with the impact of this uncertainty on the LCOH. For example, if the electricity price were to be 50% lower than assumed (over the project life), the LCOH would be £115.73/MWh instead of £195.51/MWh.

Table 14: LCOH uncertainties and impact

Parameter	Uncertainty	LCOH (low), £/MWh _{HHV}	LCOH (high), £/MWh _{HHV}
Electricity price	±50%	£115.73	£275.30
Electrolyser efficiency	±10%	£177.74	£217.24
Capital costs	-30%, + 50%	£186.86	£209.93
Operating costs	-30%, + 50%	£194.10	£197.87

3.1.4 Levelised cost of CO₂ abatement

The levelised cost of abatement (LCOA) has been estimated, considering:

- the capital and operating costs for production, transport and end-use as in EON's commercial model;
- the cost savings from avoided natural gas usage, assuming:
 - each MWh_{LHV} of hydrogen displaces one MWh_{LHV} of natural gas; and
 - natural gas prices as per E.ON's internal forecasts.
- the annual net reduction in greenhouse gas (GHG) emissions as per section 3.2, amended to assume 40% input power provided from zero-emission renewable sources (as in section 3.1.2); and
- the same assumptions for project life and discount rate as for the LCOH estimation above.

This results in an estimated LCOA of **£1,212.49/tCO₂e**.

3.2 Carbon emissions savings potential and contributions to net zero targets

3.2.1 Project carbon emissions savings

A preliminary carbon assessment was produced, estimating the greenhouse gas (GHG) emissions produced across the following phases.

- Manufacturing and construction.
- Operation.
- End use of hydrogen mixed with natural gas as an alternative fuel to 100% natural gas within a steel manufacturing furnace.

The following assumptions and data sources were used in the assessment.

- DESNZ GHG conversion factors 2023 were used as emissions factors⁹.
- Global warming potential of emissions of specific gases in Table 15 were used.
- Material use in electrolyser plant manufacturing and construction was estimated using data in the paper *Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems* by Bareiß et al (2019)¹⁰. The “2017 state of the art” values from the paper were used.
- Material use for transformers was estimated using data in the paper *The greenhouse gas emissions of power transformers based on life cycle analysis* by Guo et al (2022)¹¹.
- It was assumed that 100% of the electricity for the production plant would be sourced from the Blackburn Meadows power plant, with electricity carbon intensity calculated based on official E.ON reporting.
- Hydrogen losses were estimated using data in the paper *Fugitive Hydrogen Emissions in a Future Hydrogen Economy* by Frazer-Nash (2022)¹². The 50% confidence interval values from the paper were used.
- All the hydrogen supplied to the end user is assumed to displace natural gas, irrespective of the blend ratio (i.e. the blend ratio did not affect the assessment).

Table 15: Global warming potential factors

Substance	Units	Value	Source
Carbon dioxide (CO ₂)	tCO ₂ e/t	1	IPPC Fifth Assessment Report, 2014
Methane (CH ₄)	tCO ₂ e/t	28	IPPC Fifth Assessment Report, 2014
Nitrous Oxides (N ₂ O)	tCO ₂ e/t	265	IPPC Fifth Assessment Report, 2014
Hydrogen (H ₂)	tCO ₂ e/t	11	N. Warwick, P. Griffiths, J. Keeble, A. Archibald, J. Pyle, and K. Shine, “Atmospheric implications of increased Hydrogen use,” 2021

The main conclusions from the assessment were as follows.

- The total emissions from manufacture, construction and shipping are estimated to be 678 tCO₂e.
- The total emissions per electrolyser stack replacement (typically every 5-10 years) are estimated to be 27 tCO₂e.

⁹ <https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2023>

¹⁰ Kay Bareiß, Cristina de la Rua, Maximilian Möckl, Thomas Hamacher, 2019, “Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems”, *Applied Energy*, Volume 237, pages 862-872

¹¹ Hong Guo, Yuting Gao, Junhao Li, 2022, “The greenhouse gas emissions of power transformer based on life system analysis”, The 5th International Conference on Renewable Energy and Environment Engineering.

¹² Frazer-Nash Consultancy (2022) *Fugitive Hydrogen Emissions in a Future Hydrogen Economy*, available at: <https://www.gov.uk/government/publications/fugitive-hydrogen-emissions-in-a-future-hydrogen-economy>

- The annual emissions from production plant operation are estimated to vary between 6,520 and 7,038 tCO₂e/y (depending on stack degradation). 99% of these emissions is from electricity usage.
- The total emissions over a 30-year project lifetime, including manufacturing, construction, shipping and operation is estimated to be 204 ktCO₂e.
- When allowing for emissions from hydrogen transport and the emissions savings from displacing natural gas usage at the end user, the net reduction in GHG emissions over a 30-year project lifetime is estimated to be 180 ktCO₂e.
- The annual net reduction in GHG emissions varies between 5,760 and 6,250 tCO₂e/year, depending on stack degradation.

3.2.2 Potential contributions to net zero targets

The UK has committed to achieving net zero GHG emissions by 2050, with an interim target of reducing industrial emissions by two thirds by 2035. Iron and steelmaking account for 14% of industrial GHG emissions in the UK, equivalent to around 2% of total UK emissions. The Climate Change Committee has recommended that steelmaking reaches near-zero emissions by 2035.¹³

In 2022, fuel combustion in iron and steelmaking produced 424 ktCO₂e of GHG emissions¹⁴. The annual emissions reduction from the HYDESS project is estimated to be approximately 6 ktCO₂e (see section 3.2.1). This equates to a 1.4% reduction in iron and steelmaking fuel combustion emissions.

E.ON has estimated that there is a potential demand from Sheffield steelmaking of approximately 174 TWh/y of hydrogen. This equates to approximately 4,410 tonnes per year. Assuming the same emissions reduction per tonne hydrogen produced as for the initial 10 MW_e HYDESS electrolyser, this would result in an annual emissions reduction of approximately 18.4 ktCO₂e, or a 4.3% reduction in iron and steelmaking fuel combustion emissions.

¹³ <https://researchbriefings.files.parliament.uk/documents/POST-PN-0672/POST-PN-0672.pdf>

¹⁴ [Report: Greenhouse Gas Inventories for England, Scotland, Wales & Northern Ireland: 1990-2022 - NAEI, UK \(beis.gov.uk\)](#)

4 Project learnings

4.1 Key lessons learned

4.1.1 People (interactions/resource)

- Understanding of the level of effort needed to deliver deliverables wasn't fully understood resulting in cost quoted being lower than actual cost incurred (labour especially).
- Varying levels of resource availability (additional resource required to complete deliverables being required across the whole consortium along with addressing delays in sharing key bits of information).
- Roles and accountability could have been more clearly defined as overlaps/gaps in task completion were evident. Potential work package re-structure focusing on technical and commercial may have been a better approach.
- More consideration should have been given for the change in relationship between consortium members from 2A to 2B (from conceptual to mobilisation).
- Key teams who were originally not part of the project were identified and involved at suitable times.
- Low carbon hydrogen standard calculations were 'clunky' due to not having a direct contact to clarify the direction of the information being requested. Considering the importance of this to the project, it would have been helpful if key contacts were easily identifiable.

4.1.2 Project (production of deliverables)

- Set aside time to share findings throughout the project rather than waiting for deliverables to be complete. This gives the potential benefit that more improved deliverables can be achieved.
- The project plan felt constrained i.e. needed to be more flexible to allow for findings and potential changes in direction.
- Obtaining contingency prices was a lot more time consuming and difficult than previously envisioned. This was compounded with misalignment of customer demand conversations (there is a need to understand customer requirements to support contingency conversations).
- Project risks identified concerns with elements such as hydrogen purity and dew point which diverted resources to investigate. The outcome was these risks were closed but consideration for these should have been incorporated as part of the technical objectives/scoping of the project.
- Wider consideration for logistics was required to determine the appropriate hydrogen transportation method i.e. pipe or other alternatives.

4.1.3 Process (project management)

- The original project plan 'front loaded' too many deliverables and didn't consider the relationship of deliverables across the project or timing on when key bits of information would be available.
- Greater clarity on end goals/objectives and what was needed to get there required at project inception, so that the project plan can be built around achieving these. This includes description/evidence and wording of deliverables.
- Introduction of enhanced procurement governance to help manage potential conflicts of interest, as this could have limiting effects on how the consortium can communicate effectively.
- Project governance good but introduction of 'stage gates' or 'review points' to understand progress and determine whether changes of direction were needed would have helped optimise time, resource and budget.

4.2 Environment, safety and regulatory considerations and requirements

4.2.1 General

The HYDESS project will need to ensure all aspects of the project hydrogen chain (production site, transport and use site(s)) comply with all relevant UK and international legislation and standards throughout the design life, including during construction. Below is a list of relevant legislation and guidance related to hydrogen production plants.

4.2.2 Legislation

5. Health and Safety at Work Act.
6. Construction (Design and Management) (CDM) Regulations.
7. Control of Substances Hazardous to Health Regulations (COSHH).
8. Control Of Major Accident Hazards (COMAH).
9. Planning (Hazardous Substances) Regulations.
10. Dangerous Substances and Explosive Atmospheres Regulations (DSEAR).
11. The Equipment and Protective Systems Intended for Use in Potentially Explosive Atmospheres Regulations (ATEX).
12. The Pressure Equipment (Safety) Regulations 2016.
13. Pressure Systems Safety Regulations 2000 (PSSR).
14. Dangerous Goods and Use of Transportable Pressure Equipment Regulations (CDG) 2009.
15. The Control of Noise at Work Regulations 2005 (Noise Regulations 2005).

4.2.3 Safety standards

1. BCGA Codes of Practices and Guidance, including BCGA Code of Practice 33 – The Bulk Storage of Gaseous Hydrogen at Users' Premises.

2. EIGA IGC Doc 15/03/E: Gaseous hydrogen stations – Minimum recommended horizontal safety-distances for hydrogen stations.
3. EIGA IGC Doc 75/07/E Determination of safety distances.
4. NFPA 2: Hydrogen Technologies Code.

4.2.4 Planning

At the feasibility study stage (under the HYDESS 2A project), Nexus Planning (“Nexus”) submitted a pre-application enquiry to Sheffield County Council for the BBM production site. SCC stated that the proposal would be supported in principle, and that the key matters to be considered in the application are:

- flood risk; and
- car parking.

4.2.5 Hazardous substance storage

Plants which produce, handle, or store hazardous substances, depending on the total inventory, may have to comply with:

1. The Planning (Hazardous Substances) Regulations 2015; and
2. Control Of Major Accident Hazards Regulations 2015 (COMAH).

The thresholds for each piece of legislation are summarised in Table 16. Values assume that sites have no other inventories of hazardous substances (i.e. only hydrogen is stored on site).

Table 16: Regulatory thresholds for hydrogen inventory

Legislation	Threshold
Planning Hazardous Substances Regulations	2 tonnes
COMAH (Lower Tier)	5 tonnes
COMAH (Upper Tier)	50 tonnes

In the planning pre-application enquiry (see section 4.2.4), Nexus assumed the total storage of hydrogen on the BBM site was less than 2 tonnes and that Hazardous Substances Consent was not required. However, calculations within work package 3 anticipate the site will include onsite high-pressure storage for at least 12 hours of electrolyser operation. This translates to approximately 2,200 kg of hydrogen at beginning of life electrolyser efficiencies, meaning the production site will at least be regulated under the Planning Hazardous Substances Regulations.

However, this value will not breach thresholds for a COMAH (lower tier) site, and so the final production site design is unlikely to require regulation under COMAH Regulations.

The above calculations and conclusions have been made assuming a fixed storage approach for the BBM and CSC sites (see Section 2.2.4.3). Site storage thresholds should be revisited and confirmed (and further planning conversations had with SCC) at detailed design stage.

4.2.6 Transport assessments

Under previous work for the HYDESS 2A project, E.ON made a pre-application advice request to Highways England to better understand the implications of the additional traffic arising from the HGV movements between the BBM site and Sheffield Forgemasters. A similar advice request should be submitted to Highways England for HGV movements between the BBM site and the CSC site at detailed design stage when transport logistics such as vehicle numbers are better defined (see Section 2.2.4.3).

4.3 Summary of social value derived through the contract (inc. emissions and environmental impacts)

The consortium members are highly committed to improving social measures in the Sheffield area. E.ON is currently committed to developing the local area by providing two community funds, each with a value of up to £25,000 per year. E.ON also intends to support Skills Street locally through the provision of site visits to approximately 16,000 students per year, allowing them to gain knowledge and insight on vocational and industry opportunities.

To ensure the safe and reliable operation of each stage of the end-to-end HYDESS project, new jobs and technical training are expected. The number of jobs created and training requirements will be quantified during detailed design.

The HYDESS project is also predicted to reduce carbon emissions from local industry (see section 3.2) which will improve local air quality, contribute to net zero targets and thereby reduce the harm done to the environment through global warming and the effects of climate change.

4.4 How the process could be scaled and replicated more widely

Many of the findings of the HYDESS project will be applicable to other heavy industrial users of natural gas. Similar high temperature industrial furnace applications within the Sheffield region include aluminium casting and other foundation industries such as ceramics and glass. Of the top 10 industrial CO₂ emitters in the South Yorkshire region, 6 are steel manufacturers and 3 are glass manufacturers.

The consortium considers there is significant potential to retrofit hydrogen-ready burners to many other local/South Yorkshire and UK-based heat treatment and re-heat furnaces in steel and other alloy sector. Initial estimates suggest more than 300 furnaces exist in the UK.

Findings will be communicated across other industry sectors through a range of channels, including industry workshops, conferences, articles in trade journals and the development of bespoke training courses (see Section 5.5).

The use of hydrogen to decarbonise local industrial companies like those in the consortium, supplied by road-based transport, will be an essential accelerator for UK decarbonisation.

Other aspects of this project will be applicable to other sectors (e.g. burners, ground- and transportable-storage designs, health & safety measures). Consortium members are well connected in relevant sectors. Glass Futures is already working with glass and ceramics sectors to investigate the feasibility of hydrogen fuels. Chesterfield Special Cylinders and the University of Sheffield are

working within the energy and chemicals sectors. This will ensure two-way knowledge exchange so that findings from this project benefit developments in other sectors. The project will aim to extend the use of the Glass Futures Combustion Test Bed (CTB) furnace to simulate other furnaces and kilns (e.g. aluminium and ceramics sectors).

Other E.ON operated assets could be potential targets for hydrogen production. A similar concept could be replicated at other E.ON assets (such as the Lockerbie biomass plant) and developed in collaboration with local industry to deliver a similar project to decarbonise heavy industry such as steel, ceramics, glass, and other high consumers of natural gas.

The HYDESS project will first deliver hydrogen to selected industrial partners for demonstration of the technical solution. Further industrial partners have signed Memorandums of Understanding (MOUs) and can easily be incorporated into the network upon successful demonstration.

5 Next steps

5.1 Post-FEED implementation plan

E.ON has assembled an indicative project programme assuming a project commencement date in October 2024. This is presented in Appendix A.

The plan includes all tasks from preliminary investment decision to commercial operation beginning in May 2027, and covers:

- detailed design and specification development;
- planning and permitting;
- competitive tendering processes for all packages;
- final investment decision; and
- full site construction and commissioning.

The full programme depends on the timing and outcome of the third Hydrogen Allocation Round (HAR3), which as of July 2024 is yet to be confirmed.

The programme in Appendix A assumes the following nominal dates, which are subject to change.

- Project commencement in October 2024.
- HAR3 funding application granted in February 2025.

5.2 Assessment of how process, technologies and knowledge will continue to be developed and commercialised

The project identified the following actions to aid the development and commercialisation of the process, technologies and knowledge.

- Continue to monitor electrolyser technological developments.
- Lobby Government on adaptations to the low carbon hydrogen standard with particular focus on biomass.
- Continue to explore future commercial relationships i.e. identification of potential offtakers and understanding their requirements
- Identify funding options and submit applications as appropriate.
- Develop the Hydrogen Storage as a Solution (HYSAAS) service offering to determine whether this can provide a suitable alternative to direct trailer purchases
- Extend the testing already completed on understanding whether adopting hydrogen has any impact on the steel produced by offtakers

5.3 How to address risks, challenges and uncertainties

A complete project risks, actions, issues and decisions (RAID) log for work packages 1, 3 and 5 has been assembled by E.ON (and is included in Appendix B) while a risks and opportunities register for work package 4 was assembled by Otto Simon (included in Appendix C).

A summary of the high-risk items (as defined in the risk register) for work packages 1, 3 and 5 is provided in Table 17 below.

Table 17: Summary of high-risk items noted in the E.ON RAID log

Risk Description	Proposed Mitigation
Fire and explosion risks due to the presence of hydrogen on site	Mitigated through reviewing current site fire and DSEAR risk assessments, considering installing a blast proof barrier to segregate the battery, and hydrogen plant, and through investigating the proximity of the batteries to the hydrogen plant when completing the site layout and hydrogen plant DSEAR assessment.
HV and steam (SOEC only) tie ins for the hydrogen plant	Mitigated through utilising a permit to work system, liaising with BBM electrical engineers to understand isolation requirements and schedules and further investigating how the steam tie-ins will be undertaken (if the SOEC electrolyser is chosen).
Inadequate fire protection systems in the hydrogen plant	This will be mitigated through ensuring fire protection systems are reviewed and updated, and confirming how the fire protection of the electrolyser system will be connected into the existing site fire system.
Lack of suitable emergency response for electrolyzers (during construction and operation)	Mitigated by updating all emergency procedures based on hydrogen plant location and associated auxiliaries.
Potential exposure to asbestos (particular attention should be paid to any underground services)	Mitigated through reviewing the site asbestos register.
During the operational phase there are health concerns around toxicity with regards to the refrigerant that is used in the electrolyser cooling system	To mitigate this the type of refrigerant being used should be identified (via the OEM) and suitable measures should be implemented to mitigate any risks.
Further hazard studies incl. a HAZOP, HAZID, DSEAR, FRA and consequence modelling/QRA need to be completed before the construction phase begins.	Include hazard studies completion as part of the project plan during detailed design phase.
Hose is not properly maintained (i.e. wear and tear) causing a loss of containment of hydrogen	Review maintenance regimes and automated control schemes.
Vehicle accident whilst transporting hydrogen via trailer on the road	Completion of a layers of protection analysis along with introducing journey safeguards.

Source: E.ON

A summary of amber level risk items (as defined in the risk register) for work package 4 is provided in below.

Table 18: Summary of amber risk items noted in the Otto Simon risks and opportunities register

Risk Description	Proposed Mitigation
Hydrogen supply price not established prior to study. Opex assessment therefore not complete.	Evaluate business case when the wider HYDESS project has established a hydrogen pricing structure.
Hazards were identified during the FEED Study in a HAZID study, however mitigation plans have not all been fully defined.	Implement mitigation plans during detailed design. The completed design must also be subject to a HAZOP review.
Poor response from burner suppliers during the FEED Study. Risk of delay and possible cost increases.	A conservative allowance has been made in the TIC estimate. Approaching burner suppliers outside the original nominated list should be considered in the detailed design phase of the project.
Delays to start-up if hydrogen not available at planned time from E.ON as part of the wider HYDESS project.	Develop a co-ordinated overall plan with other HYDESS members, allowing reasonable float in the programme.
Poor quality supply of equipment and delays in delivery.	Vendor assessments and early engagement with approved vendors to confirm suitable quality and lead times. Schedule has sufficient float to allow for level of delays.

Source: Otto Simon

In addition to risks, Otto Simon identified the following possible opportunities within work package 4.

Table 19: Summary of opportunity items noted in the Otto Simon risks and opportunities register

Opportunity Description	Proposed Action
The proposed solution of 4 x 10 m ³ static storage cylinder banks is based on the assumptions on tube trailer costs, availability and demurrage. There may be an opportunity to optimise Opex vs. Capex when this information is available.	Re-examine this part of the design when information from the E.ON part of the HYDESS Project is available.
The project execution programme could potentially be reduced by optimised the critical path to subcontract placement and completion.	Programme should be re-baselined against supplier and subcontractor information before optimising.
Prices obtained at FEED Study were budgetary only and from a limited pool of bidders. More suppliers and	More suppliers and contractors to be considered in detailed design.

Opportunity Description	Proposed Action
contractors are entering the hydrogen market, giving opportunities for costs reduction through competitive tendering.	Opportunities to reduce costs by simplifying vendor package offerings to be considered (i.e. sharing equipment between the 2 burners)

Source: Otto Simon

Project- and package-wide risks and opportunities shall be re-assessed at the HYDESS project detailed design stage.

5.4 Benefits plan

The HYDESS 2B project aims to provide key benefits to its project partners and the wider UK hydrogen development ecosystem. Table 20 lays out:

- each anticipated headline benefit;
- a breakdown of this benefit into smaller progress points (if required);
- the measure(s) each benefit is judged by (where possible, measures are quantitative to allow for concrete progress review); and
- progress against the plan.

Table 20: HYDESS 2B project benefits plan KPIs

Benefit	Benefit breakdown / description	Measure / unit	Progress
Increased knowledge stimulating innovation	Provide evidence and knowledge to support future hydrogen and industrial decarbonisation policy	Successful completion and publication of project reports (2 anticipated)	Completed via this report (public and confidential versions)
	Increased awareness, understanding and confidence in end-to-end hydrogen fuel switching solutions for industry to facilitate future deployment	Amount of domestic interest in the technology	Engaged with a number of prospective offtakers and have obtained two signed memorandums of understanding.
		Feedback from key stakeholders reading project reports or listening to project presentations	In progress
		Amount of media/research coverage, including announcement of new projects/partnerships (6 anticipated)	1 completed at project start, 1 likely at project completion. Dissemination events also planned.
		Number of project reports/documents published (1 anticipated)	Completed via this report
	Knowledge spillovers, where discoveries made from undertaking this project have other applications/ enable developments in other sectors	Number of partnership/projects planned in other sectors/applications which apply the innovation from the project (1 anticipated)	Steel FEED (alternative decarbonisation route milestone) completed and presented to DESNZ on 5 th July.

Benefit	Benefit breakdown / description	Measure / unit	Progress
Reduction in carbon emissions	Reduction in carbon emissions of a specific industrial process	Carbon intensity of process before and after innovation is applied / e.g. kT CO ₂ e/yr or kgCO ₂ e/Kwh heat or equivalent	Completed for CSC
		Potential volume of CO ₂ saved for this particular site / kT CO ₂ e/yr	Completed for CSC
Demonstrating UK leadership on the innovation	Emphasise UK's position and reputation as a world leader in low-carbon energy	Amount of domestic interest in the technology e.g. Number of site visits by interested parties <i>(2 anticipated)</i>	Complete. E.ON hosted Lord Callaghan on 11 th January and DESNZ project team on 25 th April. Project closure event planned for 4 th October with DESNZ, MPs and local councillors invited.
		Amount of media coverage <i>(1 article anticipated as baseline)</i>	See fourth row above.
		Number of invitations to speak at international events e.g. International Energy Agency (IEA e.g. TCP), Mission Innovation <i>(none expected, but included in case)</i>	None completed
		Number of international collaborations and/or projects <i>(none expected, but included in case)</i>	None completed

Source: E.ON

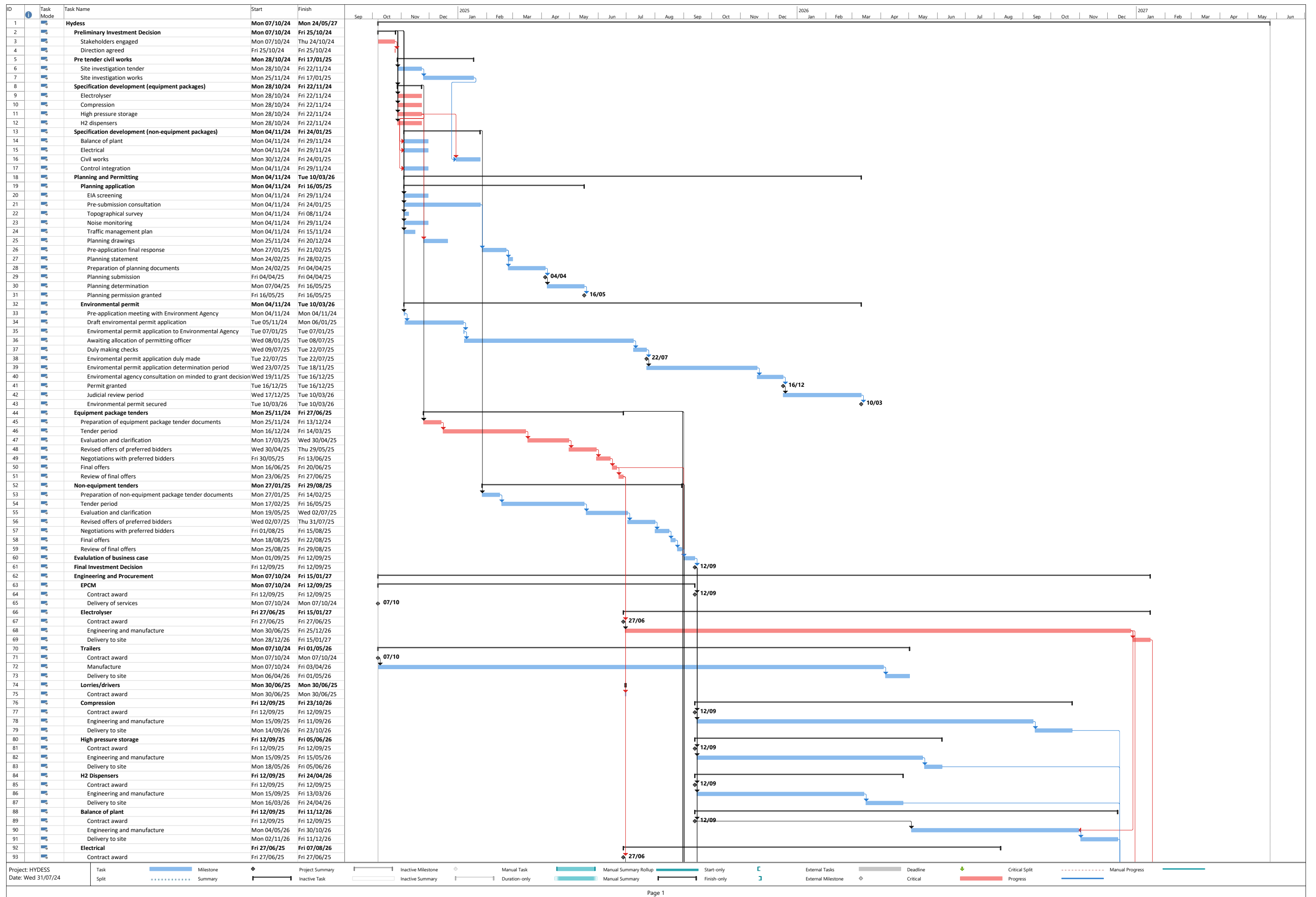
5.5 Exploitation and dissemination plan

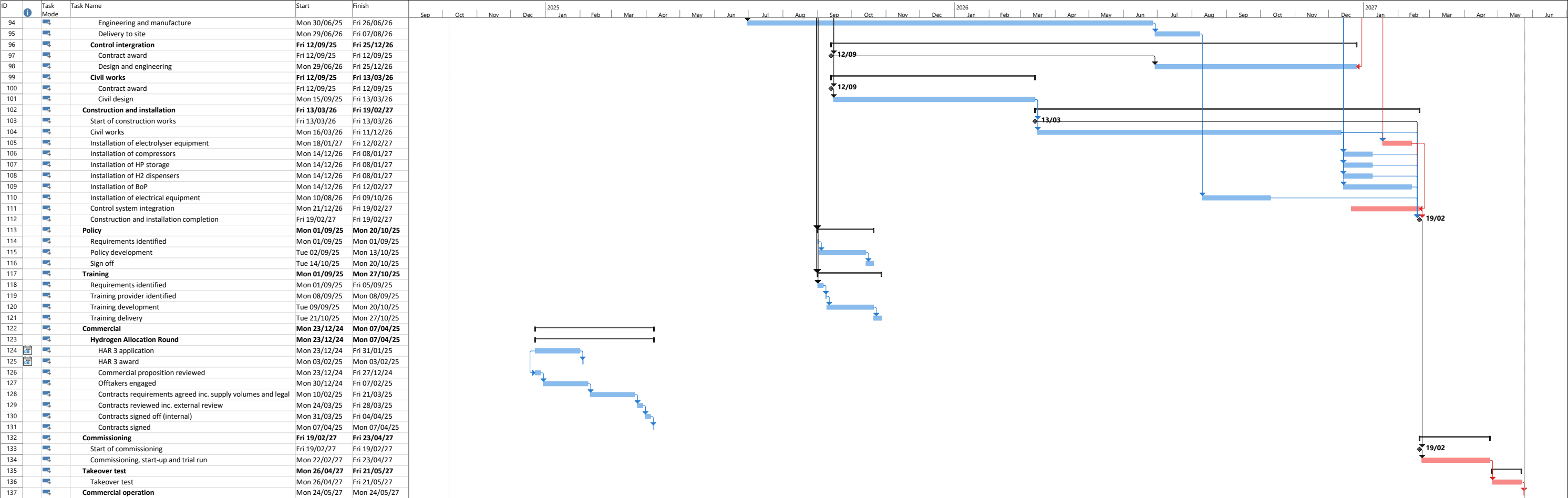
Planned dissemination activities are given in Table 21, showing those already undertaken as of July 2024 and those to be held later in the year.

Table 21: HYDESS 2B project dissemination events plan

Dissemination event	Form of action	Planned/achieved date
Completed dissemination events		
HYDESS press release	Press release	14 September 2023
Foresight: Netzero Live	Presentation	12 June 2024
South Yorkshire Sustainability Centre	Panel discussion	13 June 2024
Hydrogen Innovation Showcase	Presentations (2x)	2 July 2024
HYDESS - Alternative Decarbonisation Assessment	Presentation	5 July 2024
Planned/estimated dissemination events		
Glass Futures Member Update (confirmed)	Newsletter	August 2024
Steel Forging and Forming Forum (to be confirmed)	Presentation	3 September 2024
UK Metals Expo (to be confirmed)	Speaker/panellist	11 September 2024
HYDESS Project Closure Event (confirmed)	Presentation	4 October 2024
FT Energy Transition Summit (to be confirmed)	Presentation	22 October 2024
AMRC Decarbonisation Summit (confirmed)	Presentation	December 2024
AMRC Journal (confirmed)	Newsletter	March 2025

A HYDESS indicative project plan





B E.ON RAID log

Risk and Opportunity Log																
Entry ID	Risk or Opportunity?	Risk Description	Risk Owner	Raised by	Date Raised	Score	Risk Strategy	Management action(s) identified	Action taker	Target date	Latest date	Next Review date	Escalated to TO (date)	Comments	Date Resolved	Status
1	Operational Risk	Fire and explosion risks due to the presence of Hydrogen on site	Jess Dhariwal	Zac Gaiqui	17/10/2023	High	Reduce	Mitigated through reviewing current site fire and DSEAR risk assessments, considering installing a blast proof barrier to segregate the battery, and hydrogen plant, and through investigating the proximity of the batteries to the hydrogen plant when completing the site layout and hydrogen plant DSEAR assessment.	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open
2	Construction Risk	HV and steam (SOEC only) tie ins for the Hydrogen plant	Jess Dhariwal	Zac Gaiqui	17/10/2023	High	Reduce	Mitigated through utilising a permit to work system, liaising with BBM electrical engineers to understand isolation requirements and schedules and further investigating how the steam tie-ins will be undertaken (if the SOEC electrolyser is chosen)	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the construction phase is complete.		Open
3	Operational Risk	Inadequate fire protection systems in the hydrogen plant	Jess Dhariwal	Zac Gaiqui	17/10/2023	High	Reduce	This will be mitigated through ensuring fire protection systems are reviewed and updated, and confirming how the fire protection of the electrolyser system will be connected into the existing site fire system.	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open
4	Operational and Construction Risk	Lack of suitable emergency response for electrolyzers (during construction and Operation)	Jess Dhariwal	Zac Gaiqui	17/10/2023	High	Reduce	Mitigated by updating all of the emergency procedures based on the location of the hydrogen plant and associated auxilleries.	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open
5	Construction Risk	Potential exposure to asbestos (particular attention should be paid to any underground services)	Jess Dhariwal	Zac Gaiqui	17/10/2023	High	Reduce	Mitigated through reviewing the site asbestos register	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the construction phase is complete.		Open
6	Operational Risk	During the operational phase there are health concerns around toxicity with regards to the refrigerant that is used in the electrolyser cooling system	Jess Dhariwal	Zac Gaiqui	17/10/2023	High	Reduce	To mitigate this the type of refrigerant being used should be identified (via the OEM) and suitable measures should be implemented to mitigate any risks.	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open
7	Construction Risk	Most significant environment risks relates to spills to drain resulting in water pollution during the construction phase.	Jess Dhariwal	Zac Gaiqui	17/10/2023	Medium	Reduce	Mitigated by considering suitable bunding arrangements for temporary oil/chemicals on site, further inverstigating the nature of surface water run off and any associated environmental concerns and creating necessary spill prevention procedures.	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the construction phase is complete.		Open
8	Detailed Design Stage	Further hazard studies incl. a HAZOP, HAZID, DSEAR, FRA and consequence modelling/QRA need to be completed before the construction phase begins.	Jess Dhariwal	Zac Gaiqui	17/10/2023	High	Reduce	Include hazard studies completion as part of the project plan during detailed design phase.	Zac Gaiqui			01/09/2024		This risk will be kept open (and continuously reviewed) until the detailed design is complete.		Open
9	Detailed Design Stage	Upstream instrumentation/equipment malfunctions results in rapture of the piping/HP cylinders	Jess Dhariwal	ioMosaic	04/04/2024	Medium	Reduce	Review automated control schemes for shut off	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the detailed design is complete.		Open
10	Operational Risk	External fire caused by liquid pool or jet fire leading to a loss of containment	Jess Dhariwal	ioMosaic	04/04/2024	Medium	Reduce	Source tube trailers made from steel v. composite	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open
11	Operational Risk	Operator performs wrong operation (i.e. accidentally opening a valve during filling) leading to a loss of containment of hydrogen	Jess Dhariwal	ioMosaic	04/04/2024	Medium	Reduce	Review automated control schemes for shut off	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open
12	Operational Risk	Inadequate maintenance routine (i.e. corrosion or erosion) results in hydrogen leak from the system	Jess Dhariwal	ioMosaic	04/04/2024	Medium	Reduce	Review automated control schemes for shut off	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open
13	Operational Risk	Hose is not properly maintained (i.e. wear and tear) causing a loss of containment of hydrogen	Jess Dhariwal	ioMosaic	04/04/2024	High	Reduce	Review maintenance regimes and automated control schemes	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open
14	Operational Risk	Vehicle crashing into filling station causing damage to piping resulting in loss of containment of hydrogen	Jess Dhariwal	ioMosaic	04/04/2024	Medium	Reduce	Review volume of filling bays,vehicle movements, ensure adequate training and automated control schemes for shut off	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open
15	Operational Risk	Operator tripping while holding onto the hose, leading to hose damage and loss of containment	Jess Dhariwal	ioMosaic	04/04/2024	Medium	Reduce	Procurement of adequate equipment, introduction of housekeeping routines and automated control schemes	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open
16	Operational Risk	Vehicle moving away before hose is decoupled, causing the hose to break and resulting in loss of containment	Jess Dhariwal	ioMosaic	04/04/2024	Medium	Reduce	Procurement of adequate equipment, installation of barriers/equipment protection and automated control schemes	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open

Risk and Opportunity Log																
Entry ID	Risk or Opportunity?	Risk Description	Risk Owner	Raised by	Date Raised	Score	Risk Strategy	Management action(s) identified	Action taker	Target date	Latest date	Next Review date	Escalated to TO (date)	Comments	Date Resolved	Status
17	Operational Risk	Vehicle accident whilst transporting hydrogen via trailer on the road	Jess Dhariwal	ioMosaic	04/04/2024	High	Reduce	Completion of a layers of protection analysis along with introducing journey safeguards	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open
18	Commercial Risk	Offtaker mobilisation i.e. sites being prepared to accept hydrogen when E.ON is ready to provide (including alignment of financial investment decisions)	Sue Charlton	HYDESS 2B WG	01/05/2024	Medium	Remove	Regular commercial conversations to align mobilisation plans	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open
19	Commercial Risk	Government support being available throughout the duration of any agreements in place	Sue Charlton	HYDESS 2B WG	01/05/2024	Low	Remove	Confirm position of government support ahead of development to ensure appropriate decisions are made and to continuously monitor throughout	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open
20	Operational Risk	Long lead times for priority equipment e.g. electrolyzers, compressors and trailers	Procurement	HYDESS 2B WG	01/05/2024	Low	Remove	Orders to be placed as soon as a financial investment decision has been made and once made, implementation of effective contract management	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open
21	Commercial Risk	Alternative cheaper decarbonisation options becoming available within the market	Sue Charlton	HYDESS 2B WG	01/05/2024	Low	Reduce	Ongoing monitoring of technological advancements in supporting decarbonisation	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open
22	Commercial Risk	Contingency suppliers not being able to fulfill contingency supplies when needed	Sue Charlton	HYDESS 2B WG	01/05/2024	Low	Reduce	Consider wording for offtaker and contingent supplier contracts	tbc			01/09/2024		This risk will be kept open (and continuously reviewed) until the site is operational.		Open

C Otto Simon risks & opportunities register

Client:

Chesterfield Special Cylinders

Project Title

HyDESS Project

OSL Project Number:

5106

Document Title:

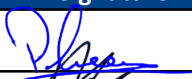
Risk and Opportunities Register

Document Number:

5106-PML-002

Document Revision:

P01

	Name	Signature	Date
Prepared By:	P.Creer		08/05/24
Checked By:	A.Cross		08/05/24
Approved By:	P.Creer		08/05/24

Revision History	
Issue Number	Description of and reason for revision(s)
P01	Preliminary issue for comment

Description
The purpose of this document is: - A record of projects risk identified while undertaking the design study, which should be evaluated and mitigated during - Potential opportunities that have not been evaluated during the deisng study, that may be considered during the next project phase. - This is intended as a high level project risk register. A safety risk register is maintained as a separate document. - At this preliminary (P01) issue of this document the proposed mitigation strategies are qualitative only and are specific to the CSC project only - i.e. a quantitative assessment of the mitigation measures has not been undertaken in isolation. This should be completed as part of the planning process for the next project stage, in cooperation with other HyDESS project participants.

References and Assumptions

Comments

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