HYDESS Project

HYDESS Consortium

IHA 2A Feasibility Report

Funded by the Department for Energy Security and Net Zero

Department for Energy Security & Net Zero

Document approval

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Executive summary

Introduction

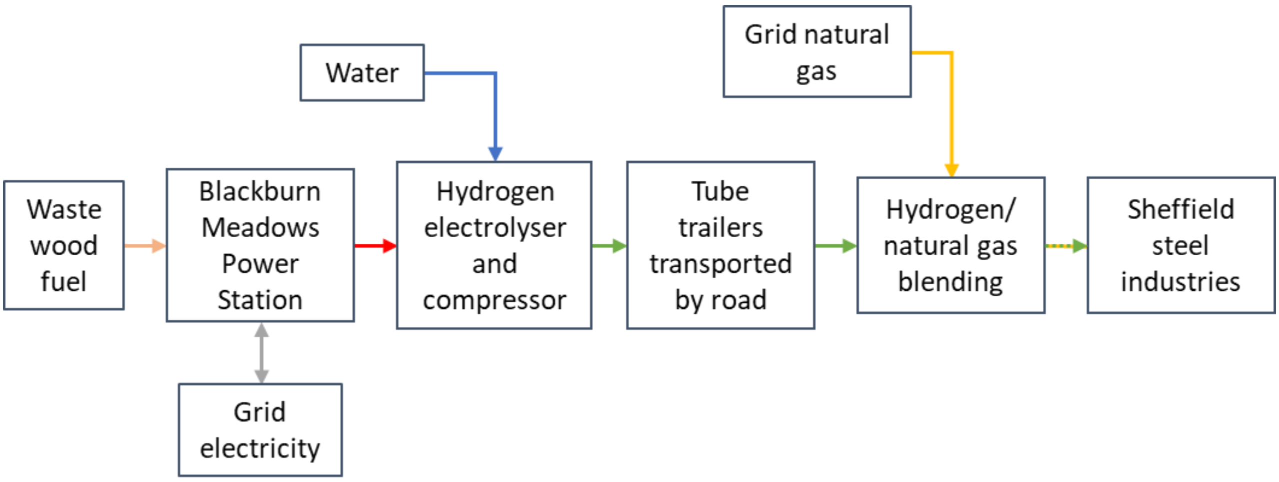
The HYDESS (Hydrogen for the Decarbonisation of Sheffield Steel) project seeks to decarbonise steel manufacturing sites across Sheffield. The consortium executing the project consists of:

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

The Department for Energy Security & Net Zero (DESNZ) (formerly BEIS) awarded funding to the consortium to carry out this feasibility study under the Industrial Hydrogen Accelerator (Stream 2A).
E.ON has engaged Fichtner Consulting Engineers (Fichtner) to support on aspects of the project, including the production of this report.

Process overview

The end-to-end process for the HYDESS project is summarised below. Low carbon electricity produced by E.ON's Blackburn Meadows Biomass Plant will feed (via private wire) an electrolytic hydrogen production plant. 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). Three end users have been identified: Sheffield Forgemasters; Forged Solutions; and Chesterfield Special Cylinders.



Hydrogen production

Hydrogen will be produced using an electrolysis plant located at Blackburn Meadows. The plant will require electricity and towns water, both supplied from Blackburn Meadows. The plant is assumed to run 80% of the time, considering downtime of the electrolyser plant and Blackburn Meadows (the plant will only run when low carbon power is available).

Six potential electrolysis plant suppliers have been identified, with a power input between 8 and 10 MWe. The exact solution and supplier is to be determined but is likely to be a 10 MWe plant. This would have the following approximate main inputs and outputs, in year 1.

- 77,438 MWh/y power input
- 17,520 m^3/y water input
- 1,242 t/y hydrogen produced (48,904 MWh_{HHV}/y)
- 7.1 MW H_2 HHV production at full load

In the levelised cost of abatement and emissions savings calculations reported below, it is assumed that the end users are able to consume all hydrogen produced.

Hydrogen transport

Hydrogen from the electrolyser plant will be produced at typically 20-40 barg pressure. A compressor will be used to increase the pressure to typically 200 barg, suitable for onward transport via tube trailers. Various types of tube trailers (at different capacities and pressures) have been assessed. The preferred option is the smallest capacity (400 kg and 200 barg), for economic and safety reasons.

The filled tube trailers will then be towed by electric vehicle (EV) tractor units to the end user. The carbon intensity of the transport solution is estimated to be 0.051 $gCO_2e/MJ_{LHV}H_2$. The hydrogen losses (fugitive emissions) in the end-to-end process are assumed to be 0.5%.

End use

The filled tube trailers will connect into the Sheffield steel manufacturer's gas distribution systems for use in steel primary heat treatment, quality heat treatment, and reheat operations. If necessary, hydrogen will be blended with natural gas to achieve the correct furnace conditions (e.g. temperature and emissions).

To evaluate the performance of hydrogen and hydrogen-natural gas blends in the steel manufacturers' furnaces, Computational Fluid Dynamics (CFD) modelling and trials were carried out. The trials were carried out in Glass Futures' Combustion Test Bed furnace (CTB), which also formed the basis of the modelling carried out by the University of Sheffield.

The CTB trials showed that hydrogen is capable of replacing natural gas for degas, reheat, and titanium heating cycles. The trials showed that hydrogen is able to replicate the necessary heating profile very precisely. CFD modelling demonstrated a good agreement with the trials.

In both the trials and CFD modelling, NOx production when using higher blends of hydrogen was higher than with natural gas. This was based on the standard burner design with no mitigation. Further steps should be taken in the FEED (Front End Engineering Design) study to engage burner and furnace equipment suppliers to understand how NOx could be mitigated.

Overall, the trials and modelling showed a good method for the development of an accurate furnace model. The same approach will be used in the FEED study to evaluate the performance of hydrogen in industrial furnaces and may be used to evaluate modification as necessary to reduce NOx.

The estimated annual demand for hydrogen for three of the potential end users is as follows.

End user	Units	2025	2030
Sheffield Forgemasters	t/y	31.5	1,782
	MWh_{HHV}	1,241.1	70,210.8
Forged Solutions	t/y	-	30,000
	MWh_{HHV}	-	1,182,000
Chesterfield Special Cylinders	t/y	15.6	60
	MWh_{HHV}	614.6	2,364

The figures in the table above are only the confirmed hydrogen demand figures from the consortium. E.ON is engaged in discussions with a variety of other steel manufacturers across the Don Valley area which would boost hydrogen demand.

Regulatory feasibility

E.ON (the proposed hydrogen producer) and Sheffield Forgemasters, Glass Futures and Liberty Steel (potential end users) have all carried out initial safety assessments governing the production, storage, and use of hydrogen. These initial safety assessments will form the basis of safe process design during the 2B FEED studies.

E.ON made a pre-application enquiry to Sheffield City Council (SCC) and Highways England to understand high-level planning requirements for the production site and transport solution. SCC stated it would support the proposal in principle and noted that the key risks to be considered in the planning application would be flood risk and car parking. Highways England noted that the application should include a detailed traffic assessment with regard to the additional traffic raised on the M1 J34 section of the Strategic Road Network.

Emissions saving potential

At the point of use, the hydrogen will have an estimated carbon intensity of 32.90 $gCO_2e/MJ_{LHV}H_2$, considering intensity of production (Low Carbon Hydrogen Standard methodology), fugitive H_2 emissions, and transport.

This compares to a carbon intensity of 56.19 gCO_2e/MJ_{LHV} (from UK Government emissions factors) for the natural gas currently used on site. By displacing this natural gas, approximately 3,468 tonnes of CO_2e will be abated in year 1 of production (41.8% reduction compared with natural gas).

Cost of solution (all values on real 2022 basis)

A commercial model was built using technical (e.g., efficiencies, availability) and economic (e.g., capital costs, forecast power prices) data from equipment suppliers and consortium members. The model covers production and transport, and estimates that the initial plant will have:

- a Levelised Cost of Hydrogen production (LCOH) of £198.0/MWh_{HHV} (£7.80/kg);
- a required delivered sales price (to the end users) of £237.3/MWh_{HHV} (£9.35/kg H_2), to give an E.ON post-tax project IRR of 12%; and
- a Levelised Cost of Abatement (LCOA) of £2,977/tCO_2e.

Following successful demonstration, by 2035 a larger (20 MWe) electrolyser may be considered. Using BEIS assumptions for improvements in efficiency and capital costs:

- the LCOH reduces to £144.1/MWh_{HHV} (£5.88/kg);
- the required delivered sales price reduces to £176.1/MWh_{HHV} (£6.94/kg H_2); and

- the LCOA reduces to £1,927/tCO2e.

Scalability

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.

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 sectors. 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.

Project risks

The key residual risks at the end of the feasibility study are as follows.

1. Most fuel switch companies will require end customer approval. Changing the critical process is a risk if they are not bought in.
2. Multiple entities have different decision-making processes and funding processes impacting ability to reach a Final Investment Decision (FID) across the consortium to simultaneously enable a demonstrator.
3. Preferred Electrolyser suppliers' lead time has recently increased to 18-24 months; further increases could delay installation of demonstration scale plant.
4. UK gas network providers' ability to construct and deliver a pipeline-based hydrogen network, in mid-term, as road transport is seen as short to mid-term.
5. The delivered hydrogen costs may not allow this to turn into a longer term commercial solution for the offtakers. However, it will progress the development of IP and knowledge that is essential for the earliest decarbonisation of UK steel production. The risk is that decision makers do not value this sufficiently and FID is delayed.
6. Hydrogen produces potentially more NOx emissions than natural gas and there is a risk that the raised levels cannot be mitigated or reduced below site or regulatory maximum levels.

Mitigations for the risks have been identified and are included in this report. Any residual risks will be considered through the scope of works of the future FEED study.

Next steps

Next steps for the development of the HYDESS project during the IHA 2B (FEED) are as follows.

1. Progress the design for the hydrogen production, transport, and end-use to front-end engineering design (FEED) level of detail.
2. Engage with burner and furnace equipment suppliers to demonstrate burners available to reduce NOx production.
3. Apply the method for simulation and testing of hydrogen firing to the furnaces of an industrial partner to verify hydrogen's effectiveness.
4. Carry out further materials testing on materials treated in a hydrogen fired furnace following forging.

Following completion of the FEED studies the consortium will take a joint FID to achieve demonstration of the project by 2026.

Contents

Glossary and Units

Abbreviation	Meaning
ALARP	As Low As Reasonably Practicable
BEIS	Department for Business Energy and Industrial Strategy
BSUoS	Balancing Services Use of System
CFD	Computational Fluid Dynamics
COMAH	Control Of Major Accident Hazards
CTB	Combustion Test Bed
CTMP	Construction Traffic Management Plan
DESNZ	Department for Energy Security & Net Zero
DSEAR	Dangerous Substances and Explosive Atmospheres Regulations
ECH	East Coast Hydrogen (pipeline)
ERP	Emergency Response Planning
ETS	Emissions Trading Scheme
EV	Electric Vehicle
FEED	Front End Engineering Design
FID	Final Investment Decision
FRA	Fire Risk Assessment
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HAZID	Hazard Identification Study
HAZOP	Hazard and Operability Study
HAZID	Hazard Identification Study
HGV	Heavy Goods Vehicle
HHV	Higher Heating Value
HV	High voltage
HYDESS	Hydrogen for the Decarbonisation of Sheffield Steel
IFS	Industrial Fuel Switching scheme
IRR	Internal Rate of Return
LCHS	Low Carbon Hydrogen Standard
LCOA	Levelised Cost Of Abatement
LCOH	Levelised Cost Of Hydrogen
LHV	Lower Heating Value
LoS	Letter of Support
LRVC	Long Run Variable Cost
MOU	Memorandum of Understanding
NG	Natural Gas
NOx	Nitrogen Oxides (NO_2 and NO)
O&M	Operations and Maintenance
PEM	Proton Exchange Membrane
P&ID	Piping and Instrumentation Diagram

Abbreviation	Meaning
PLC	Programmable Logic Controller
RAID	Risks, Actions, Issues, Decisions
RCRC	Residual Cashflow Reallocation Cashflow
REGO	Renewable Energy Guarantee of Origin
RFI	Request For Information
SCC	Sheffield City Council
SRN	Strategic Road Network
SSOV	Safety Shut-Off Valve
T&D	Transmission and Distribution
TRL	Technology Readiness Level

Item	Units (abbreviated)	Units
Power	MWe or MW_e	Megawatt (electrical)
Energy	MWh	Megawatt hour
	MJ	Megajoule
Time	h	hour
	y	year
Mass	g	gram
	kg	kilogram
	t	tonne

Compound	Name
O_2	Oxygen
H_2	Hydrogen
CO_2	Carbon Dioxide
CO_2e	Emissions in CO_2 equivalent
CH_4	Methane
N_2O	Nitrous Oxide

1 HYDESS feasibility

1.1 Introduction

The HYDESS consortium has been awarded funding from the Department for Energy Security & Net Zero (formerly Department for Business, Energy, and Industrial Strategy) under the NZIP Industrial Hydrogen Accelerator Programme to investigate the feasibility of producing green hydrogen to displace natural gas in steelmaking. The consortium in 2A comprised the following organisations:

- E.ON UK;
- The University of Sheffield – Advanced Manufacturing Research Centre (AMRC);
- Glass Futures;
- Sheffield Forgemasters;
- Chesterfield Special Cylinders;
- Forged Solutions;
- Outokumpu (the Sheffield operations have since been bought by Marcegaglia Steel Group); and
- Liberty Steel.

The proposed design will produce green hydrogen using renewable electricity from the Blackburn Meadows Biomass Power Plant. The hydrogen produced will displace natural gas usage in heat treatment and reheat furnaces at local steel manufacturing sites.

The project has been developed through six work packages as summarised below.

1. Engagement and legal – led by E.ON.
2. Customer demand and commercialisation – led by E.ON.
3. Furnace system combustion modelling – led by University of Sheffield.
4. Hydrogen furnace simulation & trials – led by Glass Futures.
5. Design & operations – led by Sheffield Forgemasters.
6. Project management & dissemination – led by E.ON.

E.ON has engaged Fichtner Consulting Engineers (Fichtner) to support on aspects of the project, including the production of this report.

1.2 Objectives

The objectives of the feasibility study are as follows.

1. Demonstrate the feasibility of using hydrogen to decarbonise steel processes.
2. Create a technical design concept for the end-to-end production and use of hydrogen.
3. Develop a commercial model to demonstrate the commercial viability of hydrogen production and potential delivered price for customers.
4. Evaluate emissions savings potential from the conversion of steel furnaces from firing on natural gas to hydrogen.
5. Understand the technical roadmap and barriers to be overcome for the decarbonisation of consortium furnaces.
6. Gain signed offtake Memorandum of Understanding (MOU) agreements for supply of hydrogen.

1.3 Conclusions

The conclusions (against each numbered objective listed above) are as follows.

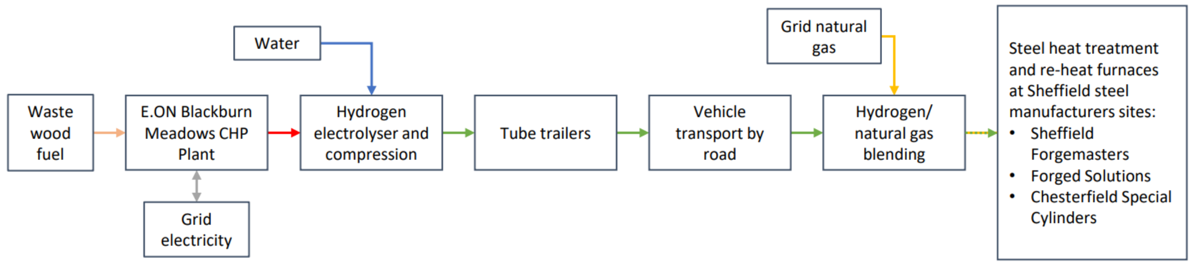
1. Modelling and testing have shown that it is technically feasible to use hydrogen blends of up to 100% to decarbonise steel manufacturing processes. Combustion was stable and complete, and the heating efficiency was at least comparable with natural gas. Work will be required (in conjunction with equipment suppliers) to minimise NOx formation, which can increase due to the higher flame temperatures when burning with hydrogen.
2. A technical design concept for the end-to-end production and use of hydrogen has been created. Hydrogen will be:
   a. produced using a 10 MW_e electrolyser plant located at E.ON's Blackburn Meadows site, using water and low carbon electricity supplied by E.ON;
   b. compressed and transported by road in tube trailer units supplied by Chesterfield Special Cylinders; and
   c. combusted in the Sheffield steel sites (replacing natural gas) to fire the heat treatment furnaces.
3. A commercial model has been developed, with the following main outputs (all 2022 real prices):
   a. the Levelised Cost of Hydrogen production (LCOH) for the demonstrator plant is estimated to be £7.80/kg and £198.0/MWh_{HHV}, when using the methodology outlined in BEIS's Hydrogen Production Costs document; and
   b. the required delivered sales price (to the end users) is estimated to be £9.35/kg H_2 (£237.3/MWh_{HHV}), to give a post-tax project internal rate of return (IRR) of 12%.
4. The estimated carbon intensity of hydrogen delivered to the end users is 32.90 gCO_2e/MJ_{LHV}, compared to 56.19 gCO_2e/MJ_{LHV} for natural gas. The proposed 10 MWe electrolyser plant would deliver 1,242 tonnes of hydrogen in year 1, which would result in carbon abatement of 3,468 tonnes.

1.4 Technical feasibility

1.4.1 Process overview

The end-to-end process for the HYDESS project is summarised in Figure 1. Low carbon electricity produced by the Blackburn Meadows Biomass Plant 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.

Figure 1: HYDESS block flow diagram



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

1.4.2 Hydrogen production

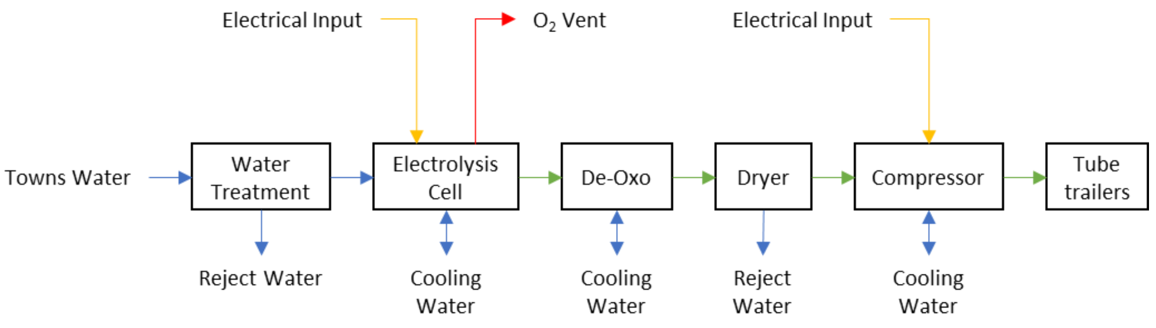
Hydrogen will be produced via electrolysis of water, using electricity from the Blackburn Meadows biomass power plant and water from the existing Blackburn Meadows towns water connection. The process includes the following steps.

1. Water is fed to a water treatment unit (typically reverse osmosis) which reduces the water conductivity to a level below that required by the electrolyser.
2. Treated water enters the electrolysis cell where electricity splits the water molecules into hydrogen and oxygen. The cells produce:
    a. an oxygen-rich stream; and
    b. a hydrogen-rich stream.
3. The hydrogen rich stream is purified in a de-oxo dryer to remove any oxygen or water carried over from the cell.
4. The resulting stream of hydrogen is typically >99.99% pure, and at typically low (20-40 barg) pressure. This stream is then compressed to the required final pressure (e.g. 200 barg) for transport in tube trailers.

Steps 1-3 are typically included within the scope of an electrolyser supplier. Step 4 is typically outside the scope, i.e. the compressor is purchased separately.

The steps above are summarised in Figure 2.

Figure 2: Block flow diagram of electrolysis and compression process.



Source: Fichtner

The production plant will have the following interfaces.

- Electricity, fed from the biomass power plant.
- Water, fed from the existing towns water connection.
- Waste water (water with elevated levels of dissolved salts, from the water treatment unit and the dryer), disposed of via the existing water treatment route.
- Control signals, exchanged to and from the existing Blackburn Meadows control system.

The planned operational strategy is to operate at full load throughout the year when power is available from Blackburn Meadows

Cooling for the electrolyser cells and de-oxo unit is typically provided by closed loop cooling water with heat rejected via air coolers, which are inside the electrolyser supplier's scope of supply. Cooling for the compressor can be either air-cooled (in the compressor scope) or water-cooled, depending on the unit selected.

E.ON will also investigate using the waste heat. Potential options for using the heat are described below.

1. Tie into District Heating Plant to supplement heat generated by existing boilers.
2. Provide heat to welfare cabins for delivery drivers.
3. Provide heat to adjacent stores building.
4. Provide heat to batteries for thermal regulation during winter months.

Oxygen produced from electrolysers is typically vented to atmosphere. However, E.ON will investigate options for using this oxygen during the FEED study. An air purification and compression unit might be required, depending on the end use. Potential options for using the oxygen are described below.

1. Sell to local companies including our consortium partners.
2. Use on E.ON sites, increasing E.ON's sustainability footprint.
3. Donate to vulnerable persons and hospitals.
4. Sell to adjacent Yorkshire Water site for use in its aeration process.

1.4.2.1 Electrolyser plants

There are various suppliers of electrolyser plants on the market, broadly fitting into one of the following two technology types.

1. Proton exchange membrane (PEM), in which water splitting is facilitated by a solid electrolyte which only allows H_2 to pass through it.
2. Alkaline, in which a liquid alkaline electrolyte is used to allow the current to pass through and split the water into H_2 and O_2.

The potential options were evaluated by sending a request for information (RFI) to various suppliers. The RFI returns are outlined in Table 1.

The electrolyser should ideally comply with the following criteria.

1. PEM is the most likely electrolyser type, as (compared to alkaline) it has faster start-up and ramp-up/down times.
2. 10 MWe is (at this stage) the most likely electrolyser capacity.

The actual electrolyser supplier chosen for the project will be subject to further project design and development. For the purposes of this study, supplier 4 has been assumed as it fits best with the above criteria.

The preferred suppliers that best fit E.ON's procurement preferences and the above criteria have a lead time of 18-24 months, which has been considered in the project plan (Sections 2.1.4 and 3.4).

Table 1: RFI returns from electrolyser suppliers for an 8 to 10 MWe installation.

Supplier		**1**	**2**	**3**	**4**	**5**	**6**
Technology type	-	Other	Alkaline	PEM	PEM	PEM	PEM
Electrical input (total)	MWe	8 MWe	8 MWe	8.1 MWe	10 MWe	10 MWe	10 MWe
Hydrogen output	kg/h	150	143.8	155	180	177	180
Availability	%	>98%	98%	99%	96%	97%	96%
Discharge pressure	barg	34	20	34	40	30	30
Hydrogen purity	%	99.999	99.999	99.999	99.999	99.999	99.999
Unit lead time	months	18-24	11	10-12	18	16	20-26
Approx. capital cost	£	£12.0M	£3.8M	£5.3M	£9.2M	£10.8	Not given

The information in the table above has been anonymised on request of the suppliers.

1.4.3 Hydrogen transport

1.4.3.1 Transport overview

Low pressure hydrogen from the electrolyser plant (approximately 30 barg) will be stored in buffer storage tanks/cylinders or in tube trailer units at the Blackburn Meadows site. The storage pressure will depend on the output volumes and delivery plan involved at the time and, if necessary, will be at a higher pressure (up to approximately 200 barg). The IHA 2B FEED work will explore the alternatives. The project team will try to store as little gas as possible, at the lowest pressure possible, in order not to waste energy or time in unnecessary compression, relative to the end use pressure. This is important, given the poor compressibility of hydrogen gas.

A suitable compound/restricted area will be provided for those trailers being filled (currently assumed to be up to two trailers at the same time). A similar compound/area will be provided at the offtake point(s), located at the required distance from buildings/walkways, for two trailers while one of them is connected/decanting. Chesterfield Special Cylinders has identified two potential areas on their existing site for such a compound, where traffic management will also be safely possible.

Electric vehicle (EV) tractor units will transport the filled tube trailers to the end users. EV units are currently assumed (instead of hydrogen fuel cell units, for example) as they are already available in the market. A brief review of the vehicles, including hydrogen vehicles, will be undertaken in the FEED study. Tube trailers (as shown in Figure 3) are a well-developed technology for transportation and storage of hydrogen.

Figure 3: Example of hydrogen tube trailer.

Source: Chesterfield Special Cylinders

Chesterfield Special Cylinders will supply the tube trailer units for the HYDESS project. Units with a hydrogen capacity of 400, 1000, and 1100 kg have been considered. For the proposed demonstrator 400 kg is considered the preferred option, for the following reasons.

- 400 kg is sufficient for a full heat treatment cycle at Sheffield Forgemasters.
- Smaller units will reduce the amount of inventory of a compressed flammable gas, therefore lowers the health and safety impact.
- Larger units will require more costly infrastructure to accommodate on site.

All options are potentially feasible. A larger unit capacity may be adopted in future once working practices with hydrogen are more established. The necessary equipment will be reviewed during the IHA 2B FEED study but may include higher pressure ratings for equipment.

The specific equipment required for trailer filling and unloading (e.g., valves, purging and protections) will be investigated during the IHA 2B FEED study. Specific tasks have been assigned to develop the process and civils design (see section 2.1).

E.ON will be the owners of the transportation commercial agreement, and therefore will be responsible for ensuring hydrogen trailer units are transported to the end-users.

During the FEED Study Chesterfield Special Cylinders will develop the plan for hydrogen piping from the trailer decant compound, into the production building and into an appropriate control, mixing and hydrogen gas detection system that leads into planned piping to the existing designated furnace and burner.

A distribution network operator, Cadent, has been engaged and will participate during the FEED to develop a plan for a hydrogen pipeline network as a longer-term transport solution. Cadent guarantees that it can share learning from its East Coast Hydrogen (ECH) pipeline pre-FEED study and has signed a Letter of Support with the consortium. It can also investigate the feasibility of a local hydrogen pipeline that may be quicker and/or more agile than through the ECH route, and it can help to publicise the project.

1.4.3.2 Carbon intensity of transport

The approximate carbon intensity of the transport solution has been calculated using the inputs in Table 2. To be conservative, we have assumed that the transport operator will charge the EV tractor units using grid electricity.

Table 2: Inputs into transport carbon calculation

Item	Units	Value
Tube trailer capacity	kg	400
LHV of hydrogen[1]	$MJ_{LHV}/kg\ H_2$	120
Tube trailer capacity (calculated from above)	MJ_{LHV}	30,000
UK electricity carbon intensity[2]	$kgCO_2e/kWh$	0.19338
UK electricity grid losses[2]	$kgCO_2e/kWh$	0.01769
EV tractor unit range[3]	miles	137
EV tractor unit battery capacity[3]	kWh	315
Distance from Blackburn Meadows to end users (typical)	miles	2.5

1 Lower Heating Value (LHV) is a measure of the energy content of a fuel excluding the latent heat of vaporisation of any water vapour in the combustion products. Higher Heating Value (HHV) is the same measure including the latent heat of vaporisation of water.

2 BEIS 2022 GHG Conversion Factors – UK generation, transmission, and distribution. Note that BEIS forecasts that the grid carbon intensity will reduce over time as the % share of renewables is increased.

3 Example EV tractor from EDT (DAF CF FT (4x2) EV tractor).

The emissions intensity of grid electricity is based on 2022 greenhouse gas conversion factors from BEIS. The emissions intensity of grid electricity is expected to decrease as time goes on therefore this forms a worst case scenario for the transport.

The outputs of the calculation are summarised in Table 3 below.

Table 3: Outputs of the transport carbon calculation

Item	Units	Value
Round trip distance	miles	5.0
EV tractor unit efficiency	miles/kWh	0.43492
Total carbon intensity of EV charging	$kgCO_2e/kWh$	0.21107
Carbon emissions per round trip	gCO_2e	2,426
GHG emissions from transport	**gCO_2e/MJ_{LHV} H_2**	**0.051**

1.4.4 Hydrogen end use

1.4.4.1 End use overview

Hydrogen will be used to displace natural gas at three Sheffield steel manufacturing sites:

- Sheffield Forgemasters;
- Forged Solutions; and
- Chesterfield Special Cylinders.

Hydrogen will be used in a range of heat treatment and reheat processes where steel alloys (and titanium) is heated and held at elevated temperatures for periods of hours to days. The processes where hydrogen will be used are described below.

- Reheat, in which components are heated to between 1,000 and 1,300°C then removed from the furnace for forging, then reheated again to the same temperature. This cycle continues until the forging of the component is complete.
- Primary heat treatment, which consists of three heating stages with a total duration of 170-440 hours:
  - Degassing, in which components are heated to 600 to 650°C for 80 to 350 hours to remove gasses from the alloy;
  - Austenitising, in which components are heated further to 800-950°C to achieve the desired crystalline structure; and
  - Stress relieve, in which the component is cooled (or quenched) then held at a high temperature to relieve internal stresses.
- Quality heat treatment, which consists of two heating stages (with a total duration of approximately 12 hours) to tailor the final balance of mechanical properties in a product:
  - Austenitising, in which components are heated to 800-900°C then water quenched to cool rapidly; and
  - Temper, in which components are heated to a lower temperature.

The exact temperatures, heating rates, and durations will depend on alloy composition, component geometry and manufacturing history.

For three of the potential end users, estimates of the annual hydrogen demand (for a given number of heat treatment furnaces) are shown in Table 4. Due to timing of retrofitting or replacing current Sheffield steel consortia manufacturers furnaces, any early/initial excess supply will be sold to alternative users. Alternative end users (other steel manufacturing sites in the Sheffield area and beyond) will be sought for any surplus production (i.e., production that is not met by the demand below) as the project progresses.

Table 4: Estimated annual hydrogen demand for two end users.

End User	Units	2025	2030
Sheffield Forgemasters	t/y	31.5	1,782
	MWh_{HHV}	1,241.1	70,210.8
Forged Solutions	t/y	-	30,000
	MWh_{HHV}	-	1,182,000
Chesterfield Special Cylinders	t/y	15.6	60
	MWh_{HHV}	614.6	2,364

Sheffield Forgemasters provided an indicative consumption of hydrogen for each heating cycle, shown in Table 5. Provision of hydrogen supply will focus initially on Quality Heat Treatment and Reheat only when a demonstration phase is reached for Sheffield Forgemasters.

Table 5: Hydrogen requirements for re-heat, primary and quality heat treatment operations

Process Type	Total Hydrogen Requirements (kg_{H2})
Primary Heat Treatment	2,400
Quality Heat Treatment	2,380
Reheat	22,000

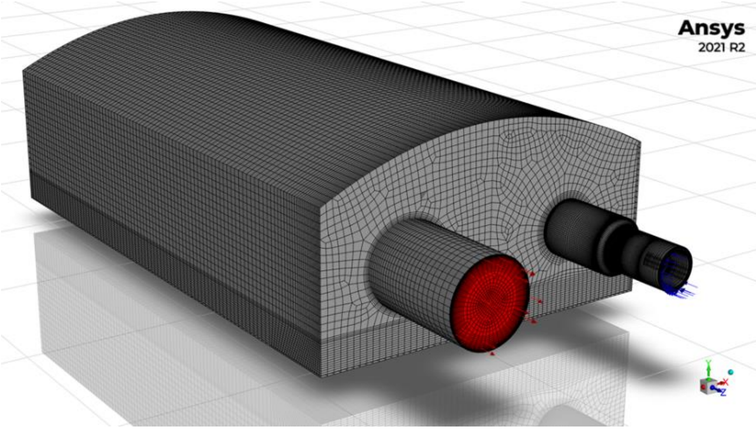
1.4.4.2 Furnace simulations

Furnace simulations were carried out using computational fluid dynamics (CFD) to investigate the initial performance of hydrogen as fuel. Following the simulations, trials were carried out on a real furnace to validate the conclusions of the simulations (Section 1.4.4.3). The aim of the furnace simulations was to:

- demonstrate the feasibility of using advanced CFD modelling techniques to simulate the combustion of blends of hydrogen and natural gas in a steel furnace; and
- to provide indicative furnace performance data for different blend ratios.

The work was based on Glass Futures' Combustion Test Bed (CTB, or "the furnace") as a representative steel furnace system fitted with a typical gas burner. The furnace in the CFD domain is shown in Figure 4.

Figure 4: CFD model of the furnace showing burner inlet (right) and exhaust outlet (left).



Source: University of Sheffield

The combustion of four different blends of hydrogen and natural gas were simulated using the commercial CFD software package ANSYS Fluent. Key furnace operating parameters such as the temperature distributions in the furnace, temperature around the steel samples, and emissions from the combustion were simulated and analysed. The four blend ratios of hydrogen and natural gas employed were 0%, 20%, 50% and 100% hydrogen (by volume). The same thermal input and excess oxygen were employed to make fair comparisons between the cases.

The main findings of the simulations were as follows.

1. The simulated flame shape and size for the four cases indicated stable combustion and complete combustion of the fuels. This indicates that the Glass Futures' existing furnace and burner design can operate successfully using hydrogen blends up to 100% hydrogen.
2. The temperature of the flame and the furnace increased with the hydrogen ratio. As a result, the temperatures of the steel samples increased as well. This indicates that hydrogen combustion has a similar heating efficiency than natural gas. Therefore, the fuel consumption of hydrogen is expected to be comparable with that of natural gas combustion (LHV basis).
3. Because of the increase in the flame temperature, a significant increase in nitrous oxide (NOx) emissions was observed. To limit the formation of large amount of NOx when switching to hydrogen firing, flame temperatures must be controlled to an appropriate level.

Overall, the simulations demonstrated that the CFD model can correctly predict the combustion, heat transfer and emissions that occurred in Glass Futures' CTB furnace and that a similar approach could be used to accurately simulate the performance of industrial scale steel furnaces. The model can provide critical information on furnace performance under various hydrogen blend ratios, which can assist in assessing and optimising the heating process and reducing NOx emissions when fuel switching to hydrogen.

1.4.4.3 Furnace trials

A set of trials was designed and executed in Glass Futures' Combustion Test Bed (CTB) at its Combustion Research Facility, located at Liberty Speciality Steel's site in Brinsworth (Rotherham). The CTB consists of a full-scale furnace test facility (with external furnace dimensions of approximately 2.2 m length and width and 2.3 m height). It comprises a burner, furnace, exhaust, and extensive instrumentation to measure performance throughout tests. Learnings from the CTB may then be applied to larger scale industrial furnaces.

The firing cycles were selected to represent key processes that take place in the steel industry, and to provide:

- an insight on material quality and properties of the metal sample sections after being fired with different hydrogen blends to investigate early potential showstoppers; and
- insights on possible next experimental or investigatory steps for the steel industry should hydrogen be selected as the main alternative fuel.

The steel manufacturers were interested in obtaining the following data from the trials.

1. Thermal profile of materials at different stages of the firing cycles.
2. Analysis of chemical composition and physical properties of the products including impact notch strength or toughness (measured using Charpy tests) and tensile strength (after firing).
3. Effect of hydrogen firing on hydrogen retention in steel products.

Table 6 shows the materials tested in the trials.

Table 6: HYDESS sample materials for furnace trials

Forged Solutions	Chesterfield Special Cylinders	Forgemasters	Liberty Steel
• Titanium 6-4 • CMV (chrome-molybdenum-vanadium) creep resisting aero steel • Maraging 250 (very high strength) steel • Hykro high strength high hardness aerospace steel	• 34CrMo4 low alloy (heat treatable high strength high ductility) steel • NiCrMo steel (corrosion resisting)	• SA508 steel alloy • 5Cr steel alloy • High sulphur containing steel	• 0533SM Leaded Steel

The original design of the CTB consists of a scalable replica of an end-fired regenerative glass furnace. The steel products were located on the left-hand side of the chamber to avoid flame impingement (i.e., avoid the flame directly touching the samples).

A summary of the experimental plan is shown in Table 7 below. The tests varied from 19 to 31 hours in duration, to replicate a realistic firing cycle. All the tests were cold combustion, meaning that cold air feeds the burner (hot combustion uses preheated air to feed the burner).

Table 7: Experimental test matrix for HYDESS in CTB

Firing Cycle No.	Fuel Type-1	Fuel Type-2	% Blend Fuel-1: Fuel-2	Cycle Type	Cycle Status
1	Natural gas	-	100	Degas	Complete
2	H_2	-	100	Degas	Complete
3	Natural gas	H_2	50:50	Degas	Complete
4	Natural gas	-	100	Re-heat	Complete
5	H_2	-	100	Re-heat	Complete
6	Natural gas	H_2	50:50	Re-heat	Complete
7	Natural gas	-	100	Titanium	Complete
8	Natural gas	H_2	50:50	Titanium	Complete

The main conclusions from the testing were as follows.

- Heating efficiency. In the degas and reheat tests when operating on pure hydrogen the furnace required 33% and 9% less energy respectively, than when operating on pure natural gas. Therefore, we can confidently say that hydrogen will be at least as efficient as natural gas.
- Equipment modifications. Burner design and potential control software modifications may be required in order to optimise furnace and fuel performance when switching from natural gas to hydrogen as a fuel.
- NOx emissions. NOx levels produced by hydrogen and air combustion are higher than for natural gas, therefore NOx control and/or mitigation will have to be investigated and implemented. NOx in this case comes from oxidation of nitrogen in the air, and is two kinds: Thermal and Prompt. There is no Fuel NOx with natural gas. Thermal NOx is dominant and the key strategy for its reduction is flame and furnace lining temperature control.

1.4.4.4 Decarbonisation alternatives

The current heating operations at the steel manufacturing consortium members use natural gas to provide heat to the furnaces. The following alternative decarbonisation options have been identified by the consortium.

1. Induction heating. Initial work by Chesterfield Special Cylinders on induction heating suggests there are further technical and cost challenges, compared to hydrogen fuelling. These challenges are summarised as follows.
   a. The shape of Chesterfield Special Cylinders' components changes over the heating-forging cycle for each piece, therefore several expensive coils (approximately £30k each versus approximately £2k for each burner) would be required. This is because the coil needs to mirror and be uniformly close to the surface shape of the metal to maintain effective and efficient heating.
   b. To get 'through-thickness' heating, a higher power and lower frequency would need be used, which also brings in production challenges of noise and tube vibrations.

   c. Substantial process optimisation is likely to be required to ensure the metal is heated uniformly, not melted, the process is repeatable, and can be controlled. The transition to hydrogen fuelling, from natural gas, will be more familiar to operators and end customers, therefore take less time and produce fewer rejects.
2. Liquid biofuels. This would require new furnace and oil storage infrastructure, for which there is insufficient space on some sites.
3. Biomethane. The supply of biomethane is limited for large scale consumption (e.g. the large furnaces operated by Sheffield Forgemasters, plus the 40 furnaces operated by Forged Solutions Group on their Sheffield sites).
4. Carbon capture. This is unlikely to be an economic option given the costs of carbon capture and of transport of CO_2 to a sequestration location. Sheffield-based industry is located a long way from any of the UK decarbonisation clusters. Many sites also do not have sufficient space to accommodate such equipment.

Based on the above assessment, for the scale of heating, and flexibility required, hydrogen appears to offer the best route for decarbonisation.

1.5 Regulatory feasibility

1.5.1 Planning permission

Nexus Planning ('Nexus') was engaged to investigate any likely blockers to the production site with regards to planning permissions. Nexus made a pre-application enquiry to Sheffield City Council (SCC). SCC's findings can be summarised as follows.

1. The proposal represents a development which would contribute towards both sustainable development and economic growth within the District and lie in an area identified for industrial facilities. The proposal would therefore be supported in principle by SCC Planning.
2. The location requirements of the development – in terms of being near to a significant energy generator and in a location with compatible surrounding development and appropriate access and other infrastructure – would be accepted to indicate that there is no alternative site for the development in sequential test terms and SCC Planning therefore have no concerns about the development's ability to pass the sequential test.
3. Given the likely specification of the electrolysis units we would not expect any air quality or noise issues to be raised. However, the following relevant technical reports would be required to be submitted if there were likely to be identifiable impacts in those respects:
   a. site and layout plans;
   b. details of the electrolysis units, including noise and other specifications;
   c. a planning statement, including a Design and Access Statement;
   d. a Transport Statement, addressing, amongst other things, on-site parking; and
   e. a Flood Risk Assessment.

SCC also assumes that the total storage of hydrogen on site is less than 2 tonnes (below the Planning (Hazardous Substances) regulations limit) and that Hazardous Substances Consent is not required.

In summary, 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 for operators and technicians.

1.5.2 Traffic assessment

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 Blackburn Meadows and Sheffield Forgemasters. JSJV (Jacobs SYSTRA Joint Venture) assessed the response from Highways England and noted the following points.

- The forthcoming planning application should be accompanied by a Transport Statement or Transport Assessment.
- With regards to the operation of the SRN (Strategic Road Network), it is important that the potential impact of the development be established at the M1 J34 north and south, and elsewhere on the SRN where traffic generation is considered to result in a material impact. This should include information on operational traffic as well as expected generation of employee trips.
- The trip generation methodology and its assignment on to the SRN should be discussed and agreed with National Highways.
- Due regard should be given to relevant regional and national planning policies. In terms of the impact on the SRN, the Transport Statement or Transport Assessment should make specific reference to the following policies:
  - DfT Circular 02/2013;
  - National Planning Policy Framework [NPPF] (2021); and
  - National Highways' guidance document 'The Strategic Road Network: Planning for The Future'.
- National Highways supports and requires the preparation and implementation of Travel Plans to limit the volume of private vehicle trips to and from developments and to promote sustainable modes of travel.
- A CTMP (Construction Transport Management Plan) should be prepared and will be a condition of a planning consent. It will need to be submitted and approved in writing by National Highways prior to the commencement of construction. The CTMP will need to include at least:
  - a dust management plan;
  - a noise management plan;
  - pollution prevention measures;
  - staffing numbers;
  - contractor parking;
  - construction traffic routes;
  - details of delivery arrangements (including for any abnormal loads); and
  - measures to limit and manage transfer of debris on to the highway.
- The Applicant should clearly outline the path of any pipeline and if this will cross the SRN, as this will likely require technical/operational approvals.

1.5.3 Safety assessment

1.5.3.1 Characteristics and properties of hydrogen

When compared to natural gas, hydrogen has a number of inherent differences that contribute to an increased operational risk when considered as an option for fuel switching.

The density of hydrogen is about seven times lower than that of natural gas. Therefore, in combination with a smaller molecule size, there is an increased potential for hydrogen leaks in any closed systems when compared to other gasses. Leaks, as well as being problematic for furnace operation, are of specific concern due to the ignition characteristics of hydrogen. However, hydrogen leaks can be mitigated better than natural gas by simply having good ventilation.

The steel processing industry tends to operate in buildings that have high roof levels, typically designed to accommodate overhead gantry cranes. Therefore leaking hydrogen gas would rise rapidly into a spacious under-roof void, with a natural dilution in large volumes of air with associated decrease of risk for ground-level operatives. Many of the roof spaces in this industry are also draughty and designed to 'leak' the heat of multiple furnaces and heat sources.

Whilst having a higher auto-ignition temperature than natural gas, hydrogen has lower ignition energy and wider ignition limits when in the air. The relatively low ignition energy increases the potential possibility and sources for ignition. For example, in venting scenarios, hydrogen can be ignited by a static charge in the air, especially in environments with low humidity. Other examples of possible sources of ignition that need to be considered include:

- static electricity;
- electrical discharge;
- impact or friction;
- sparks;
- hot surfaces; and
- open flames.

The wider ignition temperature range also must be accommodated in the system design. Whilst the lower limit is comparable to natural gas, the upper limit is much higher. The accidental inclusion of oxygen (which increases the upper limit of ignition to around 93%) or air into the system presents risks of ignition and explosion even at lower concentrations of hydrogen.

The governing mechanisms of heat transfer, such as the relative reduction in thermal energy transferred by radiation, are also different in hydrogen. Natural gas predominantly emits heat radiation within the infrared range of the spectrum, which is easily detected on the skin and by current standard flame testing equipment. Hydrogen provides a heat signature spread across the ultraviolet, red, and infrared spectrums, meaning flames are generally not visible or difficult to detect by the human eye. The heat signatures are not as evident at a distance. The characteristics of a hydrogen flame decrease the likelihood of accidental ignition being detected, thus increasing the potential for cascading system failures.

We will consider how to reduce the risk of jet flames by having road trailers/higher pressure piping outside at offtakers, well away from buildings and thoroughfares as regulations dictate, along with pressure reduction systems. Low pressure piping, with overhead hoods/sniffer sensing will be used internally to connect hydrogen road trailer supply into the furnace burner.

The above inherent risks associated with handling hydrogen have been considered in the site-specific safety reviews, which are described in the following sections. Further work on risk mitigation will be undertaken in the IHA 2B FEED.

1.5.3.2 EON HAZID (production and transport)

A HAZID (Hazard Identification) Study was performed on the E.ON UK component of the HYDESS Project for Blackburn Meadows on the 29th of November 2022. E.ON's scope will include the operation and maintenance of a Polymer Electrolyte Membrane (PEM) electrolyser at the Blackburn Meadows site, including the distribution of the produced hydrogen.

The HAZID workshop was an E.ON led workshop comprising a multidisciplinary team including representatives from engineering, process safety, project management as well as independent facilitation from outside the project team. The study focused on the construction, operation and maintenance and project implementation phases and concluded with a visit to the proposed development areas.

The review identified hazards which were not already known to the team, and highlighted several areas requiring further, more detailed, analysis in order to develop effective risk management controls during the evolution of the project.

In total, 78 recommendations were identified. A summary of the key risks is presented in Table 8.

Table 8: Key items with residual risk from the E.ON Blackburn Meadows HAZID study.

Cause	Consequence	Recommendations
High wind speed due to local conditions.	Unsafe operating conditions. Resulting in harm due to fall from height / drops from height.	High wind considerations to be included and reviewed within lifting plans. Restrictions for working at particular wind speeds should be clear and documented for construction and operational phases.
Loss of control impacting adjacent motorway or shopping centre.	Harm to third parties offsite.	Ensure dispersion modelling or equivalent is considered for the loss of containment of hydrogen and the impact on the adjacent motorway.
Live tie-ins to high voltage (HV) main.	Harm to employees via electric shocks, fires, or explosions.	Authorised Engineer to be informed of requirements for HV tie-in work prior to any work commencing and works controlled under a permit to work system.
Lack of Emergency Response Planning (ERP).	Harm to employees.	Ensure that site's ERP is updated to reflect construction risks and where support may be required or access/egress changes.
Lack of control over emergency response.	Ineffective emergency response.	Ensure that the site emergency plans are updated to reflect new risks introduced onto site, including Hydrogen filled lorries.

Cause	Consequence	Recommendations
Loss of control of stored H_2 resulting in fires.	Fires and escalating scenarios. Environmental harm. Asset damage.	Ensure that H2 tubes are stored in appropriate location. A fire wall is recommended based on the duration of storage, with a minimum separation distance based on 6m (NFPA requirements) or dispersion modelling (whichever is greatest).
		Ensure that the sites Fire Risk Assessments and DSEAR studies are updated accordingly to include additional risk from facility. It is recommended that results of dispersion modelling be considered as part of FRA and DSEAR.
Loss of control due to vehicle impacts.	Fires and escalating scenarios.	Consider the use of bollards and suitable vehicular protection around sensitive equipment and stored H_2.
Loss of control due to deviations in pressure.	Overpressure / loss of containment risk. Asset damage.	Ensure that components, fittings, joints are designed to appropriate British Standards and Pressure Systems Directive requirements.
		Ensure that appropriate pressure controls are in place to trigger a stop in gas production if set points are exceeded.

1.5.3.3 Sheffield Forgemasters HAZOP study (end-use)

To conduct the HAZOP study, an indicative Piping and Instrumentation Diagram (P&ID) for the demonstrator system was developed and split into the following parts:

- storage;
- furnace delivery systems;
- vent & purge; and
- furnace.

Each system was assessed by taking a guide word (e.g. no, more, less) and applying it to an element (e.g. pressure, temperature, hydrogen, air) to evaluate key deviations which may be likely to occur during operation. This allows a comprehensive review of the proposed system and safeguards in place to ensure safe and reliable operation. An example of a risk identified for the furnace is:

- Guide word: More.
- Element: Temperature.
- Deviation: Temperature of the furnace exceeds design limits.
- Possible cause: Increased rate of combustion.
- Consequence: Damage to furnace.
- Safeguards: Install a high temperature switch (protection device).

Through this methodology each system was examined and 58 deviations were noted. For each deviation a recommended mitigation/safeguard has been identified. The complete deviations list is available in Appendix A.

1.5.3.4 Glass Futures safety assessment

Glass Futures is already experienced at handling gaseous hydrogen. The following is a summary of the safety systems in place which may also form the basis of safe handling procedures across the consortium.

In regard to testing carried out at the Glass Futures Combustion Test Bed, other than the immediate area of the gas/fuel skids, the gas lines are not subject to hazardous area classification as the lines are mainly welded construction and located in a well-ventilated area, all raised above ground level. The area is subject to a high dissipation rate especially for gases such as hydrogen. The compound has no enclosed roof areas which would allow for build-up of trapped gases.

Hydrogen in the fuel skid is at high purity and therefore above the upper flammability level in air. The temperature of the gas is ambient and the pressure at which the hydrogen flows through the pipework of the skid is 0.5 barg, which is low pressure (pressure vessel regulations do not apply). The hydrogen is filtered, regulated down and passes through a double block gas safety shut off system to conform to EN 746. The flow is controlled by a Coriolis flowmeter and control valve and then passes through a limiting orifice valve (trim valve) and a non-return valve before combining, in this case, with natural gas in the mixer unit. The SSOV (Safety Shut-Off Valve) trip system is via the safety PLC (Programmable Logic Controller). Backflow is also prevented by a differential pressure switch linked to the shutdown system. The building where the fuel skid is installed has sufficient openings to allow free passage of air, therefore it is considered well ventilated. As an additional safety level, hydrogen sensors are installed at height in the building and at locations where potential accumulation could occur.

The furnace itself is not subject to hazardous area classification since there is a continuous source of ignition present in normal operation.

Area classification is applied to the gas skids where natural gas/hydrogen is present. The size of the zone is dictated by the gas pressure in the system. The size of zone around the gas skid is very small based on the amount of hydrogen generated in normal operation and the high level of ventilation. Thus, the zone is assessed to be zone 2 of “negligible extent” based on the guidance in BS EN 60079-10-1 (equivalent to not zoned).

1.5.3.5 Liberty Steel safety assessment

Liberty Steel carried out a Process Hazard Review to investigate site-specific safety issues surrounding the storage of pressurised hydrogen and hydrogen pipework from the gas compound to the annealing furnaces.

The study identified 10 scenarios of which:

- 0 were considered intolerable;
- 4 were considered tolerable if ALARP (as low as reasonably practicable); and
- 6 were broadly acceptable.

When the relevant safeguards and recommendations are applied none of the risks were intolerable and therefore will not prevent implementation.

A summary of the 4 items considered tolerable if ALARP is provided below.

Table 9: Key items with residual risk from the Liberty Steel Hazard Review study.

Cause	Consequence	Recommendations/Safeguards
Overpressure: Hydrogen storage bottles overfilled from high pressure source during delivery by BOC.	Rupture of hydrogen storage bottle and sudden release of high-pressure hydrogen. Potential for (near colourless) fireball and jet flame of significant size in and around hydrogen storage bottle compound. Potential for burns, knock-on fires, and fatality of personnel in vicinity, esp. BOC delivery driver.	BOC delivery procedures – Drivers fully trained on delivery procedure. Pressure relief valves set 151 bar. Hydrogen storage compound has a brick wall separating it from adjacent Liberty Speciality Steels site buildings. Outside area / ex compound / design of compound allows dissipation.
Long term weakening: Storage bottle / fittings integrity deteriorates, due to internal or external corrosion.	Rupture of hydrogen storage bottle / fitting and sudden release of high-pressure hydrogen. Potential for (near colourless) fireball and jet flame of significant size in and around hydrogen storage bottle compound. Potential for burns, knock-on fires, and fatality of personnel in vicinity, esp. BOC delivery driver.	Integrity assurance of hydrogen storage bottles To BS399 and changed every 10 years (cylinders date stamped with last change). BOC delivery procedures – Drivers fully trained on delivery procedure. Hydrogen storage compound has a brick wall separating it from adjacent Liberty Speciality Steels site buildings. Outside area / ex compound / design of compound allows dissipation.
Leak: From hose connection during hydrogen refilling due to ageing / wear.	Spontaneous ignition and significant (near colourless) jet flame likely. Potential for burns and major injury and even fatality of driver and other personnel in vicinity.	Hose integrity and BOC maintenance / inspection arrangements. Changed every 5 years and included in maintenance regime. Hoses are left hand thread connector complete with an O-ring that cannot be removed – capable of pressures up to 228 bar. Hose kept in gated hydrogen storage compound connected to pipework and away from the ground when not in use. BOC delivery procedures – Drivers fully trained on delivery procedure. Hydrogen storage compound has a brick wall separating it from adjacent Liberty Speciality Steels site buildings. Outside area / ex compound / design of compound allows dissipation. Non return valve prevents back flow to trailer inspected annually.

Cause	Consequence	Recommendations/Safeguards
Maloperation: Escape from hose connection during hydrogen refilling due to error in coupling.	Spontaneous ignition and significant (near colourless) jet flame likely. Potential for burns and major injury and even fatality of driver and other personnel in vicinity.	BOC delivery procedures – Drivers fully trained on delivery procedure. Hydrogen storage compound has a brick wall separating it from adjacent Liberty Speciality Steels site buildings. Outside area / ex compound / design of compound allows dissipation.

1.6 Performance of solution

1.6.1 Mass and energy balances

Table 10 shows the main annual input and outputs of the end-to-end hydrogen production and transport process. These values were derived using the following assumptions.

- The electrolyser operates (at full production) for 80% of the year. This considers the typical power availability from Blackburn Meadows and the typical availability of the hydrogen production plant.
- There will be 0.5% hydrogen losses from production to end use. The use of steel storage/transport cylinders shows no/negligible leakage, therefore losses are driven by the electrolyser and end-use operations.

Table 10: Annual throughputs

Parameter	Units	Year 1
Power input	MWh/y	77,438
Water input	m^3/y	17,520
Wastewater output	m^3/y	8,760
Hydrogen production	t/y	1,248
Hydrogen losses	t/y	6
Hydrogen delivered to end users	t/y	1,242

Note that the above values are for year 1 only. The following assumptions have been used for degradation, which affects year-on-year hydrogen production:

- the electrolyser efficiency degrades 2% (i.e., the tonnes hydrogen produced reduces by 2% for the same power input) per year; and
- after five years (i.e., when degradation reaches 10%), the electrolyser cell stacks will be replaced (this cost is included in the operating costs).

Funded by the Department for Energy Security and Net Zero NZIP Industrial Hydrogen Accelerator

1.6.2 Carbon intensity of hydrogen

1.6.2.1 Calculation method and system boundary

The carbon intensity of hydrogen produced has been calculated by following the Low Carbon Hydrogen Standard (LCHS). The total emissions considered in the calculation is a simplification of the equation given in Section 6.4 of the standard:

$$E_T = E_{energy\ supply} + E_{input\ materials}$$

The terms excluded from the Section 6.4 equation (and the reasons why) are described below.

- $E_{feedstock\ supply}$ – water is the only feedstock and is captured under input materials.
- $E_{process}$ – electrolysis produces no direct CO_2 emissions.
- $E_{fugitive\ non\ CO2}$ – electrolysis produces no emissions of methane, nitrous oxide, SF_6, PFCs, or HFCs.
- $E_{CO2\ sequestration}$ – carbon capture is not utilised.
- $E_{compression\ and\ purification}$ – hydrogen exits the electrolyser at over 3 MPa and 99.99% purity (compression above this pressure is outside the scope of the LCHS).

Based on the updates listed above, the system boundary used in the LCHS hydrogen emissions calculator was modified to represent hydrogen production at Blackburn Meadows. Figure 5 below shows the example system boundary from the LCHS, and Figure 6 shows the system boundary as applicable for Blackburn Meadows.

Figure 5: GHG emissions system boundary provided as example in the LCHS.

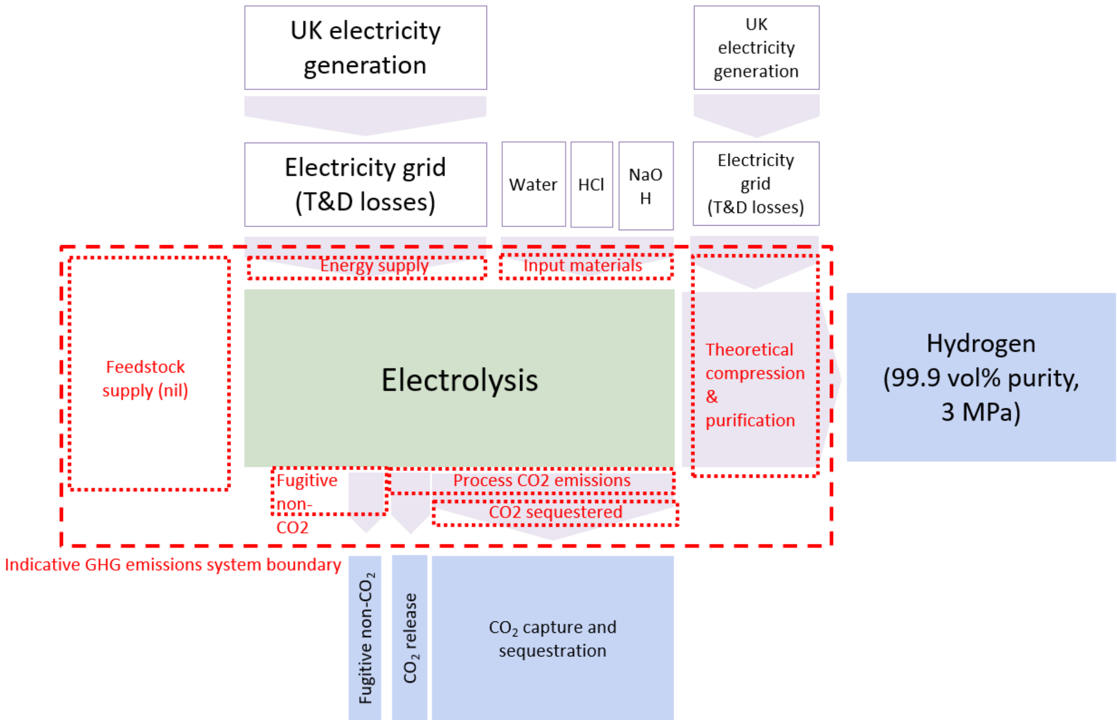


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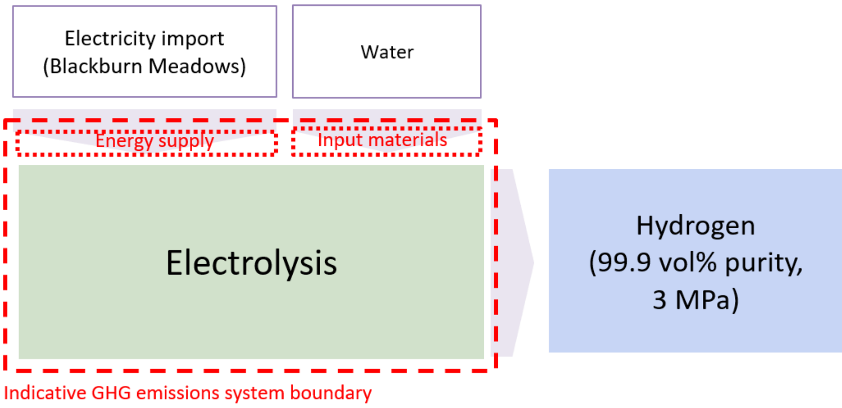
Figure 6: GHG emissions system boundary for hydrogen production at Blackburn Meadows.



1.6.2.2 Carbon intensity of energy supply

The total emissions from Blackburn Meadows was calculated using the 2021 Emissions trading Scheme (ETS) reported CO_2 emissions from Blackburn Meadows, plus the quantity of reported equivalent non-CO_2 GHG emissions (nitrous oxide and methane), as summarised in Table 11 below.

Table 11: 2021 Blackburn Meadows reported emissions.

Item	Quantity (tonnes)	GWP (kg CO_2e/kg)	Emissions (tonnes CO_2e)
CO_2	12,206.9	1	12,206.9
N_2O	17.4	265	4,615.5
CH_4	0.1	28	3.1
TOTAL			**16,825.4**

The carbon intensity of power produced from Blackburn Meadows was estimated from the emissions inventory outlined above and the total power generated in 2021, as reported in the ETS. Results presented in Table 12.

Table 12: Derivation of carbon intensity of power from Blackburn Meadows.

Item	Units	Value	Formula	Source
2021 annual emissions from Blackburn Meadows	tonnes CO2e	16,825	a	EON Reporting
2021 annual ETS reported power output	MWh	242,787	b	EON ETS Reporting
Proportion of emissions attributed to power	%	97.80%	c	EON ETS Reporting
Total carbon intensity of power from Blackburn Meadows	**g CO2e/kWhe**	**67.78**	**d = (a * c) / b**	**Calculation**

1.6.2.3 Carbon intensity of hydrogen

The following assumptions were applied in the LCHS hydrogen emissions calculator.

1. Blackburn Meadows supplies all the power for electrolysis i.e., there is no grid electricity import to the electrolyser.
2. Water is the only input material. The water supplied is typical towns (mains) water.
3. Hydrogen exits the electrolyser at a pressure greater than 30 bar (compression beyond 30 bar is outside the scope of the LCHS).

The key inputs given in Table 13 were used in the LCHS hydrogen emissions calculator. As discussed in section 1.4.2.1, the electrolyser type is assumed to be from Supplier 4.

Table 13: Inputs to Low Carbon Hydrogen Standard hydrogen emissions calculator.

Item	Units	Value	Source
Carbon intensity of power from Blackburn Meadows	gCO2e/kWhe	67.78	See Table 12
Carbon intensity of towns water	kgCO2e/t	0.149	BEIS GHG Conversions Factors 2022
Year of operation	-	2025	E.ON commercial model
Hydrogen production (first year)	t/a	1,345	E.ON commercial model
Operational hours (first year)	h/a	7,708	E.ON commercial model
Water consumption (first year)	t/a	19,272	E.ON commercial model
Power consumption (first year)	MWh/a	77,088	E.ON commercial model
Electrolyser outlet pressure	barg	40	Supplier RFI (Table 1)

Applying the figures above into the LCHS calculator yields the results given in Table 14.

Table 14: Outputs from Low Carbon Hydrogen Standard hydrogen emissions calculator

Item	Units	Value
GHG emissions of energy input	gCO_2e/MJ_{LHV} H_2	32.37
GHG emissions of water input	gCO_2e/MJ_{LHV} H_2	0.02
LCHS GHG emissions (TOTAL)	**gCO_2e/MJ_{LHV} H_2**	**32.39**

This report has assumed that 100% of power used by the electrolyser will be supplied by Blackburn Meadows. E.ON believes it is possible to alter the mix of electricity it uses to power the electrolyser through Power Purchase Agreements or Sleeving Agreements with green generators. For example:

1. a Power Purchase Agreement could be used to buy electricity from the market (which would include the price for Deep Green Renewable Energy Guarantee of Origin (REGO));
2. a Sleeving arrangement could be agreed with an external renewable counterparty; or
3. Blackburn Meadows could swap its Brown REGOs for Green REGOs to offset its carbon.

E.ON believes that all three of these options would reduce the carbon intensity of the electricity required and are currently exploring these possibilities in relation to the HYDESS project.

1.6.3 Emissions saving potential

The furnace simulations and trials concluded that the efficiency of hydrogen combustion is at least equal to the efficiency of natural gas combustion, on a lower heating value (LHV) energy basis. Therefore, every MJ of hydrogen used in the steel furnace will displace an equivalent MJ in natural gas.

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Table 15 shows the estimated GHG emissions from:

- hydrogen production (as stated in section 1.5.3.5);
- hydrogen transport (as stated in section 1.4.3);
- fugitive hydrogen emissions in the end-to-end process; and
- current natural gas usage (using UK Government GHG conversion factors[4]).

Fugitive hydrogen emissions have been calculated assuming a Global Warming Potential (GWP) of 11 gCO_2e/gH_2[5].

The results show that the total estimated net emissions reduction is 23.51 gCO_2e/MJ_{LHV} H_2, or 2.82 $kgCO_2e$/kg of hydrogen.

Table 15: Summary of GHG emissions performance of the HYDESS project.

Item	Units	Formula	Value	Source
GHG emissions from hydrogen production	gCO_2e/MJ_{LHV} H_2	a	32.39	Table 14
GHG emissions from transport	gCO_2e/MJ_{LHV} H_2	b	0.05	Table 3
GHG emissions from fugitive H_2	gCO_2e/MJ_{LHV} H_2	c	0.46	
GHG emissions from natural gas	gCO_2e/MJ_{LHV}	d	56.19	BEIS
Total GHG reduction (LHV Basis)	gCO_2e/MJ_{LHV} H_2	e = d – a- b – c	23.29	
LHV of hydrogen	MJ_{LHV}/kg H_2	f	120.0	BEIS
Total GHG reduction (Per kg H_2)	$kgCO_2e$/kg H_2	g = e * f / 1000	2.79	
Hydrogen used by end users in first year	tonnes	h	1,241	Table 10
CO_2e abated in first year	**tonnes**	**i = g * h**	**3,468**	

The data in Table 15 outlines an overall emissions reduction of 41.8% when converting from natural gas to hydrogen.

The UK Government has a legally binding target to reach net zero by 2050, with additional ambitions for carbon capture (as set out in the Net Zero Strategy) to capture 20-30 Mtpa of CO_2 by 2030, including 6 Mtpa of industrial emissions. The emissions reduction expected for the HYDESS demonstration phase project would contribute approximately 0.06%[6] to this target.

Following successful demonstration of the project it is likely that wider scale adoption of hydrogen for decarbonising steel furnaces will lead to increased demand. By 2035 a 20 MWe electrolyser may be required to fulfil this demand. By 2035, BEIS expects that the efficiency of electrolysis will increase while capital cost will decrease[7]. Factoring these changes in, a 20 MWe electrolyser at Blackburn Meadows could reasonably produce hydrogen at 29.81 gCO_2e/MJ_{LHV} H_2, which leads to an overall emissions reduction of 25.87 gCO_2e/MJ_{LHV} H_2 (an overall emissions reduction of 46.0%).

[4] BEIS GHG Conversion Factors 2022

[5] BEIS Publishing: Fugitive Hydrogen Emissions in a Future Hydrogen Economy

[6] Calculation: 3,468 / 6,000,000 = 0.06%

[7] https://www.gov.uk/government/publications/hydrogen-production-costs-2021

1.7 Cost of solution

All values in this section are reported in real 2022 prices unless stated otherwise. The commercial model has been created on the assumption that operations will start in 2025, however, due to lead times in signing contracts the real start date for operation may be pushed back to 2026.

1.7.1 Capital costs (hydrogen production)

The estimated capital costs for the demonstrator production plant are summarised in Table 16. Note that:

- this is based on a 10 MWe electrolyser from supplier 4, as stated in section 1.4.2;
- these costs are for hydrogen production only, i.e. they do not include any costs end users may incur in switching to hydrogen;
- there are no grid connection costs, as the electricity will be sourced directly from the Blackburn Meadows power plant; and
- compressor costs are based on discussions with two compressor suppliers and assume that two medium stage compressors (e.g. 40 to 240 barg) in parallel, and one high stage compressor (e.g. 240 to 500 barg), would be required.

Table 16: Estimated capital costs (production)

Item	Cost	Source
Electrolyser	£9,320,000	Supplier RFI
Compressor	£500,000	E.ON & Chesterfield Special Cylinders assumption
Cabling and enabling works	£500,000	E.ON assumption
Other (civils plus controlling software)	£500,000	E.ON assumption
Switchboard extension	£200,000	E.ON assumption
COMAH permits	£4,000	E.ON assumption
On-site storage	£100,000	E.ON assumption
Total	**£11,124,000**	

1.7.2 Operating costs (hydrogen production and distribution)

The estimated operating costs for the demonstrator plant are summarised in Table 17 below. This is based on a 10 MWe electrolyser from supplier 4, as stated in section 1.4.2.

E.ON has assumed that 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.

The alternative would be for the biomass plant to sell power to the electrolyser at a fixed price. However, the plant will lose export revenue by supplying the electrolyser with electricity. In order to maintain the biomass plant's 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 plant was to sell electricity to the electrolyser at a fixed price, there would be too much risk associated with lost export revenue.

Electricity prices used in the commercial model are based in E.ON's price forecasts.

Table 17: Estimated operating costs.

Item	Annual Cost	Source
Electricity (year 1)	£9,784,000	E.ON forecast prices
Production plant O&M costs[8]	£199,000	E.ON assumption
Distribution and storage costs	£131,000	Chesterfield Special Cylinders assumption
Water	£25,000	E.ON assumption (£1.49/m^3 and £30/year standing charge)
Wastewater	£27,000	E.ON assumption (£3/m^3)
Insurance	£14,000	E.ON assumption (0.12% of CAPEX, plus 12% premium)
Business rates	£76,000	E.ON assumption (0.72% of total CAPEX)
Total	**£10,256,000**	

Distribution and storage costs were estimated by Chesterfield Special Cylinders, which has decades of experience working with gas majors in the UK.

Business rates and insurance are the additional costs that the hydrogen plant would incur. These are proportional to the capital cost of the equipment on site.

1.7.3 End-user costs

The estimated capital costs for an end user are summarised in Table 18 below. This is a high-level estimate and applies for the demonstrator furnace infrastructure installation suitable for a large offtaker such as Sheffield Forgemasters only, i.e. for sufficient end-user modifications to consume approximately 1,250 t/y hydrogen.

8 This includes periodic replacement of electrolyser cell stacks (to minimise the effects of degradation over the project life).

Table 18: Estimated furnace offtaker capital costs

Item	Cost	Source
Storage system purchase	£135,000	Forgemasters estimate
Storage system installation	£100,000	Forgemasters estimate
Auxiliary instrumentation, controls, and systems	£460,000	Forgemasters estimate
Auxiliary system installation	£150,000	Forgemasters estimate
Furnace purchase	£2,700,000	Forgemasters estimate
Furnace foundations and civils	£300,000	Forgemasters estimate
Furnace installation & commissioning	£800,000	Forgemasters estimate
Total Forgemasters costs	**£4,645,000**	**(sum of above)**
Initial furnace development and hydrogen infrastructure fitting costs	£200,000	Chesterfield Special Cylinders estimate
Hydrogen infrastructure costs for other potential furnace offtaker sites	£1,200,000	Chesterfield Special Cylinders estimate
Burner retrofit modifications at other furnace offtaker sites	£187,500	Chesterfield Special Cylinders estimate
Total	**£6,232,500**	**(sum of above)**

1.7.4 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 document[9]. 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.

1.7.4.1 Demonstrator plant

Table 19 below shows the estimated LCOH for the demonstrator plant. Note that:

- the electricity costs vary year-on-year, depending on the E.ON forecast for wholesale electricity price;
- the project start date affects the electricity costs only (all other costs are assumed to remain flat in real terms); and
- the hydrogen production also varies year-on-year due to degradation (see section 1.6.1).

[9] https://www.gov.uk/government/publications/hydrogen-production-costs-2021

Table 19: LCOH estimation for the demonstrator plant

Item	Units	Value	Formula	Source
Capital costs	£	£10,524,000		Table 16 (exc. Compression & storage)
Electricity costs (year 1)	£	£8,854,000		Table 17 (exc. Compression)
Operating costs	£	£251,000		Table 17 (O&M plus water and wastewater)
Hydrogen produced (year 1)	Tonnes	1,248		Table 10
Discount rate	%	10%		BEIS Hydrogen Production Costs 2021
Project life	Years	30		
Production start date	Months	01/04/2025		E.ON assumption
Total discounted costs	£	£88,447,144	a	Calculated from above
Total discounted hydrogen production	Tonnes	11,340	b	Calculated from above
Levelised cost of hydrogen	**£/kg**	**£7.80**	**c = a / b**	**Calculated from above**
HHV of hydrogen	MWh_{HHV}/kg	0.0394	d	Literature
Levelised cost of hydrogen	**£/MWh_{HHV}**	**£198.02**	**e = c / d**	**Calculated from above**

1.7.4.2 Commercial plant (2035)

Table 20 below shows the estimated LCOH for the 2035 commercial plant. The following assumptions have been used.

- The electrolyser size will be 20 MW_e, compared to 10 MW_e for the demonstrator plant.
- The electrolyser plant relative capital cost (£/MW_e) will reduce by 29% compared to the demonstrator plant. This is the capital cost reduction (from 2025 to 2035, for PEM electrolysers) assumed by BEIS in its "Hydrogen production costs 2021" document[10].
- The electrolyser efficiency (kg H_2 generated per kWh electricity consumed) will increase by 5.3% compared to the demonstrator plant. This is the efficiency improvement (from 2025 to 2035, for PEM electrolysers) assumed by BEIS in its "Hydrogen production costs 2021" document.
- The wholesale electricity price (the price of electricity to the electrolyser plant) will be equal to the central forecast for Industrial Long Run Variable Cost (LRVC), as published in the UK Green Book[11].
- Annual inflation is assumed to be as per the Gross Domestic Product (GDP) Deflators (referenced in the Green Book)[12]. Inflation is assumed to be 1.74%/y from 2027 onwards (2027 is the last year available in the GDP Deflators spreadsheet).

[10] https://www.gov.uk/government/publications/hydrogen-production-costs-2021

[11] https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

[12] https://www.gov.uk/government/statistics/gdp-deflators-at-market-prices-and-money-gdp-december-2022-quarterly-national-accounts

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Table 20: LCOH estimation for the 2035 commercial plant

Item	Units	Value	Formula	Source
Capital costs	£	£14,202,000		Appendix C
Electricity costs (year 1)	£	£12,881,000		E.ON forecast prices
Operating costs	£	£295,000		Appendix C
Hydrogen produced (year 1)	Tonnes	2,635		As 2025, scaled up and with efficiency improvements as stated above
Discount rate	%	10%		BEIS Hydrogen Production Costs 2021
Project life	Years	30		
Production start date	Months	01/04/2035		E.ON assumption
Total discounted costs	£	£135,550,954	a	Calculated from above
Total discounted hydrogen production	Tonnes	23,885	b	Calculated from above
Levelised cost of hydrogen	**£/kg**	**£5.68**	**c = a / b**	**Calculated from above**
HHV of hydrogen	MWh_{HHV}/kg	0.0394	d	Literature
Levelised cost of hydrogen	**£/MWh_{HHV}**	**£144.08**	**e = c / d**	**Calculated from above**

1.7.4.3 Uncertainties (and sensitivity analysis)

Table 21 below shows the main uncertainties for the demonstrator plant 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, as shown below, if the electricity price were to be 50% lower than assumed (over the project life), the LCOH would be £112.89/MWh instead of £198.02/MWh.

Table 21: LCOH uncertainties and impact, demonstrator plant

Parameter	Uncertainty	LCOH (low), £/MWh_{HHV}	LCOH (high), £/MWh_{HHV}
Electricity price	±50%	£112.89	£283.15
Electrolyser efficiency	±10%	£180.12	£219.89
Capital costs	-30%, + 50%	£191.36	£209.12
Operating costs	-30%, + 50%	£196.35	£200.80

1.7.5 Delivered price of hydrogen

E.ON has developed a commercial model to estimate the delivered price of hydrogen. In contrast to the LCOH value estimated above, this price:

- includes the costs for compression and transport from production plant to the end user;
- includes non-production-related operating costs such as insurance and business rates;
- includes non-production-related upfront costs such as legal costs; and

- is set to meet E.ON's required post-tax project internal rate of return (IRR).

The commercial model uses:

- the capital and operating costs as in sections 1.7.1 and 1.7.2;
- the hydrogen production as in section 1.6.1; and
- the additional assumptions in Table 22 below.

Table 22: Additional assumptions used to estimate the delivered price of hydrogen.

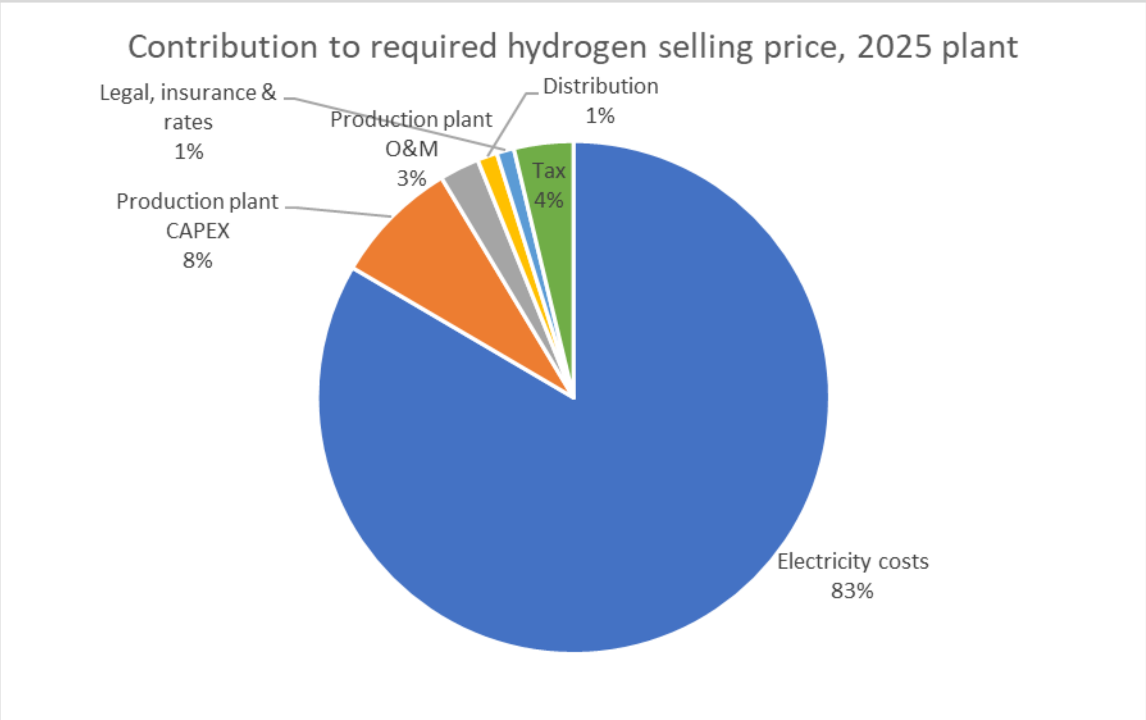
Item	Units	Value	Source
Upfront legal costs	£	£265,000	E.ON assumption
Corporation tax	%	17%	E.ON assumption
Capital allowances	%	6%	E.ON assumption
Required post-tax project IRR	%	12%	E.ON assumption

The estimated delivered price of hydrogen is:

- £9.35/kg H_2 (£237.31/MWh_{HHV}) for the 2025 demonstrator plant; and
- £6.94/kg H_2 (£176.07/MWh_{HHV}) for the 2035 commercial plant.

The breakdown (over the project life) of this delivered price is shown in Figure 7, for the 2025 plant.

Figure 7: Hydrogen selling price breakdown, 2025 plant



1.7.6 Levelised cost of CO_2 abatement

1.7.6.1 Demonstrator plant

The levelised cost of abatement (LCOA) has been estimated for the demonstrator plant, considering:

- the capital and operating costs for production, transport and end-use as per sections 1.7.1, 1.7.2 and 1.7.3;
- 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 carbon emissions abated as per section 1.6.3 (the emissions abated will vary year-on-year according to the degradation assumptions discussed in section 1.6.1); and
- the same assumptions for project life and discount rate as for the LCOH estimation in section 1.7.3.

This results in an estimated LCOA of **£2,977/tCO_2e**.

1.7.6.2 Commercial plant (2035)

The same approach was taken for the commercial plant, with the following additional assumptions.

- Electrolyser plant capacity, capital cost and efficiency as per section 1.7.4.2.
- Natural gas prices as per the UK Green Book forecasts for Long Run Variable Cost for Industrial users, central forecast.
- Increased end user costs of £562,500 (in addition to the end user costs for the demonstrator plant) to account for more burner modifications required.

This results in an estimated LCOA of **£1,927/tCO2e**.

1.8 Project risks

Throughout the development of the feasibility project, each work package owner has provided input to a project risk register. Risks identified for each work package are categorised by risk level (likelihood x severity), risk owner and risk type.

A summary of the key items with high residual risk at the end of the feasibility study is provided in Table 23.

Table 23: High residual risk items at the end of the feasibility study.

Risk and description	Mitigation
Most fuel switch companies will require OEM approval. Changing the critical process is a risk if they are not bought in.	Involve end user in change process, upfront agreement in validation.
Multiple entities have different decision-making processes and funding processes impacting ability to reach a FID across the consortium to simultaneously enable a demonstrator.	Business Steering Committee to be set up as part of project governance in 2B FEED to create alignment and progress to agree a mutual FID across the consortium.
Electrolyser lead time is 18-24 months which could delay installation of demonstration scale plant.	Engage with electrolyser suppliers during FEED to raise awareness of project and prepare for procurement.
Ability to construct and deliver a hydrogen network, as road transport is seen as short to mid-term.	FEED study will determine detail required. Cadent will support 2B FEED to investigate feasibility off hydrogen pipeline.
The hydrogen demand may not be enough to make this a commercially viable/sustainable solution, in comparison to natural gas costs.	Identify a plan as part of FEED to identify other routes of hydrogen supply as well as ways to reduce CO2e to reduce costs further.
Hydrogen is producing more NOx emissions than natural gas, this will need to be factored into the feasibility study with a view to address this as part of any FEED/demonstrator.	There are alternative solutions to this that have been identified and will need to factor in/costed and considered as part of 2B.

1.9 Scalability

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 metal (steel and aluminium) casting and other foundation industries such as ceramics and glass. Of the top ten industrial CO_2 emitters in the South Yorkshire region, six are steel manufacturers and three 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 sectors. 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 3.3).

The use of green 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 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 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 assets (for example at E.ON's biomass plant in Lockerbie) and developed in collaboration with local industry to deliver a similar project to decarbonised heavy industry such as steel, ceramics, glass, and other high consumers of natural gas.

The HYDESS project will first deliver hydrogen to a selected industrial partner 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.

1.10 Lessons learned

The lessons learned for each work package are summarised below.

Customer demand and commercialisation.

1. It was difficult to construct a commercial model with limited input assumptions on the end-to-end process. In future specific technology experts and knowledge from historic projects should be brought in earlier to guide the process.
2. Supply chain issues across the hydrogen end-to-end process mean that this project is unable to support a demonstration scale installation within the period supplied by DESNZ (formerly BEIS). As a result, the next phase will be a FEED study.
3. The commencement of DESNZ's Industrial Fuel Switching scheme (IFS) at the same time as the IHA made the IHA 2B less attractive. As a result, significant planning and changes were required to look at how the scheme could be rolled out across different consortium members.

Furnace system and combustion modelling

4. NOx levels are significantly increased when using hydrogen as a fuel. Further work is required to test different burner and furnace arrangements to reduce NOx. This will require engaging with burner manufacturers early in the next phase of design.

Simulation and trials

5. Mechanical properties from material samples were as expected but no subsequent mechanical or processing work was carried out on the samples, therefore they are not representative of final products. Further investigation is needed on the material properties of final products manufactured with hydrogen as fuel.
6. The CTB was designed for glass manufacturing temperatures (~1,500°C) which is significantly hotter than the temperatures seen in the steel heating tests. This meant that the CTB was not optimized for lower fuel flowrates used in the tests. The next phase of testing will focus on higher temperature cycles, for which the CTB will be better suited.

Design and operations

7. Identifying assumptions for the design of the end-to-end process was difficult and some only became apparent late in the project. In future the design should focus on engaging earlier with hydrogen experienced user groups to support the end-to-end process. Chesterfield Special Cylinders plans to include HyEnergy Consultants (whose senior team has more than 40 years

hydrogen road trailer delivery senior management experience with Air Products) as sub-contractors in future FEED study.

Other

8. Each consortium member showed varying degrees of readiness to support the project and as such it was difficult to stay aligned as a consortium. In future senior level management should be more involved at the consortium level.
9. Project management was very intensive. In future the roles and responsibilities should be divided more efficiently.

2 FEED Delivery plan

2.1 Detailed plan

2.1.1 Aims

The engineering FEED study should remove some remaining uncertainties, improve understanding of risk and reward for particular offtakers, with the specific aims listed below.

1. Establish and quantify amendments to the commercial model (and therefore to the delivered price of hydrogen) based on details of engineering/capex requirement being confirmed and offtake quantities being confirmed.
2. Understand and characterise any potential changes in heat transfer characteristics to discuss with end customers any potential modifications to standard process instructions.
3. More completely understand the specific steel maker's furnace environment (e.g. NOx, water vapour) by using an upgraded, more tailored CFD model.
4. Demonstrate the commercial viability of hydrogen fuels for the expected offtakers (volumes and price assumptions, plus transport cost details being more fully understood).
5. Provide a baseline for future hydrogen demand from the primary offtakers (in the consortium) and then further potential offtakers (there are many further furnaces in the local area, which might be retro-fitted with hydrogen-ready burners)).
6. Assess induction heating as an alternative to hydrogen. This assessment will include identification of suppliers, high level process engineering, cost assessment, environmental assessment, and evaluating the overall business impact.
7. Establish safe working practices in the transportation, storage, and use of hydrogen as a fuel on site at Blackburn Meadows and also a steel-maker's site.
8. Identify technology gaps ahead of full-scale adoption of hydrogen fuels.

2.1.2 Organogram

The 2B FEED project will be carried out with oversight from three levels.

1. Business FID (Financial Investment Decision) Steering Committee.
   a. Consists of executive level directors from E.ON, Chesterfield Special Cylinders, Sheffield Forgemasters, and Forged Solutions.
   b. This group will meet every 4-6 weeks and will ensure that each member is able to take a joint FID at the end of the 2B FEED study.
2. Technical Steering Committee.
   a. Consists of technical experts from E.ON, Forged Solutions, Chesterfield Special Cylinders (supported by HyEnergy), University of Sheffield, Sheffield Forgemasters, and Glass Futures.
   b. This group will meet every 3 weeks to ensure the project progresses on track and that technical learnings are shared throughout the consortium.
3. Project Governance.
   a. Consists of the work package leaders.
   b. This group will meet weekly to ensure the project deliverables stay on track.

2.1.3 Work package plan

The 2B FEED project will be split into six work packages (WP). Each work package will be led by a relevant expert from the consortium. The work packages are described below.

- WP1 – Commercial, legal and demand – Led by E.ON
  - Scope includes financial reporting and governance, commercial model development, customer demand model development, policy/regulation support, completion of consortium agreement, agreeing directional offtaker agreements, agreeing electricity (or feedstock) supply agreement, and market orientation development.
- WP2 – Furnace and burner modelling and optimisation – Led by Glass Futures
  - Scope includes installation of up to 4 burners from UK or European manufacturers (e.g. from Global Combustion Services Ltd, Limpsfield Combustion Engineering, Dunphy Combustion, and possibly Kromschroder) in the CTB. Each burner will undergo initial commissioning at low temperatures, once stabilised, optimise combustion, and characterise combustion performance for hydrogen/natural gas blends of 100/0, 80/20, and 50/50. University of Sheffield will model the best performing burners (max of three) and apply each one to a model of the Chesterfield Special Cylinders furnace to evaluate potential performance.
- WP3 – Blackburn Meadows FEED – Led by E.ON
  - Scope includes process engineering works, safety and environmental works, equipment selection, civils design work, and implementation planning.
- WP4 – Chesterfield Special Cylinders FEED – Led by Chesterfield Special Cylinders
  - Scope includes process engineering works, safety and environmental works, equipment selection, civils design work, implementation planning, collaboration across WPs to agree outcomes for reports, and alternative decarbonisation route (induction heating) assessment.
- WP5 – Storage and logistics FEED – Led by E.ON (supported by Chesterfield Special Cylinders)
  - Scope includes agreeing offtakers and loads, detailed operating model, signed offtaker and backup supply contracts, agreed MOU/outline contract for tractor/driver provision, implementation plan, agree compression and decanting processes, process engineering works, safety and environmental works, implementation & procurement.
- WP6 – Project management – Led by E.ON
  - Scope includes implementation of Stream 2B work scope, project plan, milestone reporting, RAID (Risk, Actions, Issues, Decisions) log, and delivery of FEED reports.

2.1.4 Gantt Chart

E.ON has prepared a Gantt chart to outline the key milestone dates to ensure the 2B FEED project is delivered on time and on budget. The plan shows the key tasks to be completed in each work package and the estimated duration of each task. A summary of the overall duration of each work package is provided in Table 24 below.

Table 24: Key dates for the 2B FEED plan.

Work Package	Start Date	End Date
OVERALL	**May-23**	**Jun-24**
1 – Commercial, legal and demand	May-23	May-24
2 – Furnace and burner modelling and optimisation	May-23	Jan-24
3 – Blackburn Meadows FEED	Jun-23	Apr-24
4 – Chesterfield Special Cylinders FEED	Jun-23	Apr-24
5 – Storage and logistics FEED	May-23	Feb-24
6 – Project management	May-23	Jun-24

Following successful completion of the overall FEED project the consortium members will be in a position to take a joint FID.

2.2 Cost estimate

The cost for the 2B FEED project has been estimated from each consortium member. A summary of the total costs for the 2B FEED project are provided by member in Table 25 below.

Table 25: Cost breakdown for 2B FEED project by consortium member.

Member	Total Costs
E.ON	£691,534
Chesterfield Special Cylinders	£281,055
University of Sheffield	£158,390
Sheffield Forgemasters	£21,658
Glass Futures	£358,161

Cadent, Forged Solutions, and Liberty Steel will be supporters in the 2B FEED and will participate on a no-cost basis.

Government funding enables E.ON to bring in the support of Glass Futures and University of Sheffield to address many technical risks. As well as providing access to its equipment, modelling capabilities and expertise, this will also enable E.ON and the steel manufacturers to build closer links with counterparts in the glass and ceramics sectors, creating opportunities for future collaborations between the three sectors, to share R&D costs, and to facilitate knowledge exchange in areas such as furnace management, health and safety, and engineering requirements. This will increase the rate of development of hydrogen technologies across both sectors and increase the impact of government funding for this and any follow-on projects in the Sheffield-region and across the UK.

The models and insights from Glass Futures and University of Sheffield potentially de-risk Chesterfield Special Cylinders' FID decision on the adoption of hydrogen, but also can also translate into a lower-cost modelling approach which can be used by the burner makers to help other steel makers to understand costs and benefits of retrofitting/installing UK-made hydrogen burners on other furnaces nationally. The work for this one project, focused on Chesterfield Special Cylinders' furnace, can therefore be extended to many other companies in the UK steel sector.

The best performing burner from Stream 2B may be used to conduct initial trials on one of the two Chesterfield Special Cylinders furnaces, post IHA 2B funding. This would involve some temporary solution, prior to FID/installation of the permanent hydrogen trailer decant-furnace mixing/piping solution.

2.3 Planning

The 2B FEED project will develop the planning process for the production and end-use facilities. Key deliverables from the work packages that will support any future planning processes are:

1. plot plans;
2. general arrangement drawings;
3. 3D models;
4. construction execution plans; and
5. traffic management assessments.

The deliverables list presented in Section 2.1.3 is a high level plan for the completion of the engineering FEED studies. The exact requirements for planning, permitting, and interfaces will be established at the commencement of the FEED design stage.

3 Value, future plans, and dissemination

3.1 Social value

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.

During the feasibility project the HYDESS consortium supported jobs and training in the local economy. At Sheffield Forgemasters, a placement student supported the feasibility study and gained an insight in decarbonisation of industrial processes. The same student has been offered the opportunity for employment after completion of their degree.

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 the 2B FEED study.

3.2 Benefits

Throughout the feasibility study the consortium maintained a benefits table to measure the performance of the project against a list of key performance indicators (KPIs). Table 26 shows a summary of some of the key metrics assessed.

Table 26: IHA 2A HYDESS benefits table.

KPI area	KPI description	Start of feasibility	End of feasibility
Technology readiness level	What is TRL of the proposed technical solution?	2	4
Publications	How many publications has the project resulted in?	0	3
Dissemination	How many events for sharing knowledge have been produced?	0	0
Dissemination	How many events for sharing knowledge have been participated in?	0	3
Dissemination	How many other products or activities for sharing knowledge have been generated?	0	15
Commercial readiness level	What is the commercial readiness level of the proposed solution?	1	2

3.3 Dissemination and engagement

To develop a sustainable dissemination plan, the consortium members are engaging with their marketing and communications teams to develop the communications infrastructure which will effectively manage and build ongoing activities for the duration of the project.

The activities cover local, regional, and national stakeholders. It will be of benefit for local communities to:

- understand developments being made to improve air quality and the local environment;
- engage young people in sustainability, innovation, and science through schools; and
- engage regional and national organisations and institutions in the communication of approach and findings to further understanding and progress in the decarbonisation of heavy industry.

A stakeholder map and engagement plan have been developed. As part of this we are considering developing a project website, which will provide the public with key information such as our vision, who we are, what we want to achieve, as well as news updates and ways that we can be contacted.

Planned dissemination activities focus on two types of recipients:

1. industry; and
2. public sector.

Dissemination to industry focusses on social media engagement and dissemination to industrial information channels relevant to production of hydrogen and use of hydrogen in the steel industry.

The public dissemination plan includes local interest groups and wider communities who may be interested in the scheme but may not directly apply the findings.

So far, 15 dissemination activities have been carried out. The complete list of proposed and completed activities can be found in Appendix B.

3.4 Post funding plan

E.ON has developed a plan to take the HYDESS project from the end of the FEED studies (May 2024) to successful operation of the system (May 2026). The plan for Stream 2B will result in the consortium members being able to take a joint FID on the contract award for the design, construction, and commissioning of the production, transport, and end-use systems.

The operational plant will trial the solution outlined in Section 1.4. An 8-10 MWe electrolyser will be built at Blackburn Meadows for the production of hydrogen. To use the hydrogen, new hydrogen ready burners will be retrofitted to existing furnace(s) at Chesterfield Special Cylinders.

Key dates for the post funding plan are provided in Table 27.

Table 27: Simplified high level post-funding plan.

Activity	Start	Finish
OVERALL	May-24	Mar-26
Key Contract Milestones		
Build-out contract award	May-24	May-24
Client design specs available	May-24	Aug-24
Long lead time items (LLIs) ordered	May-24	Jun-24
Start main civils	Jan-25	Jun-25
LLIs delivered on site	Oct-25	Jan-26
Site go live	Feb-26	Mar-26
Detailed Engineering		
Process engineering	May-24	Jul-24
Process drawings	Jun-24	Jul-24
Civils/structural	May-24	Sep-24
Piping	Jun-24	Aug-24
Mechanical	Jul-24	Aug-24
Electrical	Jun-24	Jul-24
Safety and environmental	May-24	Jul-24
Procurement		
Electrolyser	May-24	Jul-24
Compressor	Aug-24	Sep-24
Bulk equipment	May-24	Sep-24
Construction		
Site general	Oct-24	Mar-26
Main install	Jul-25	Dec-25
Completions		
Power systems	Jan-26	Jan-26
Commission process units	Feb-26	Mar-26

Appendices

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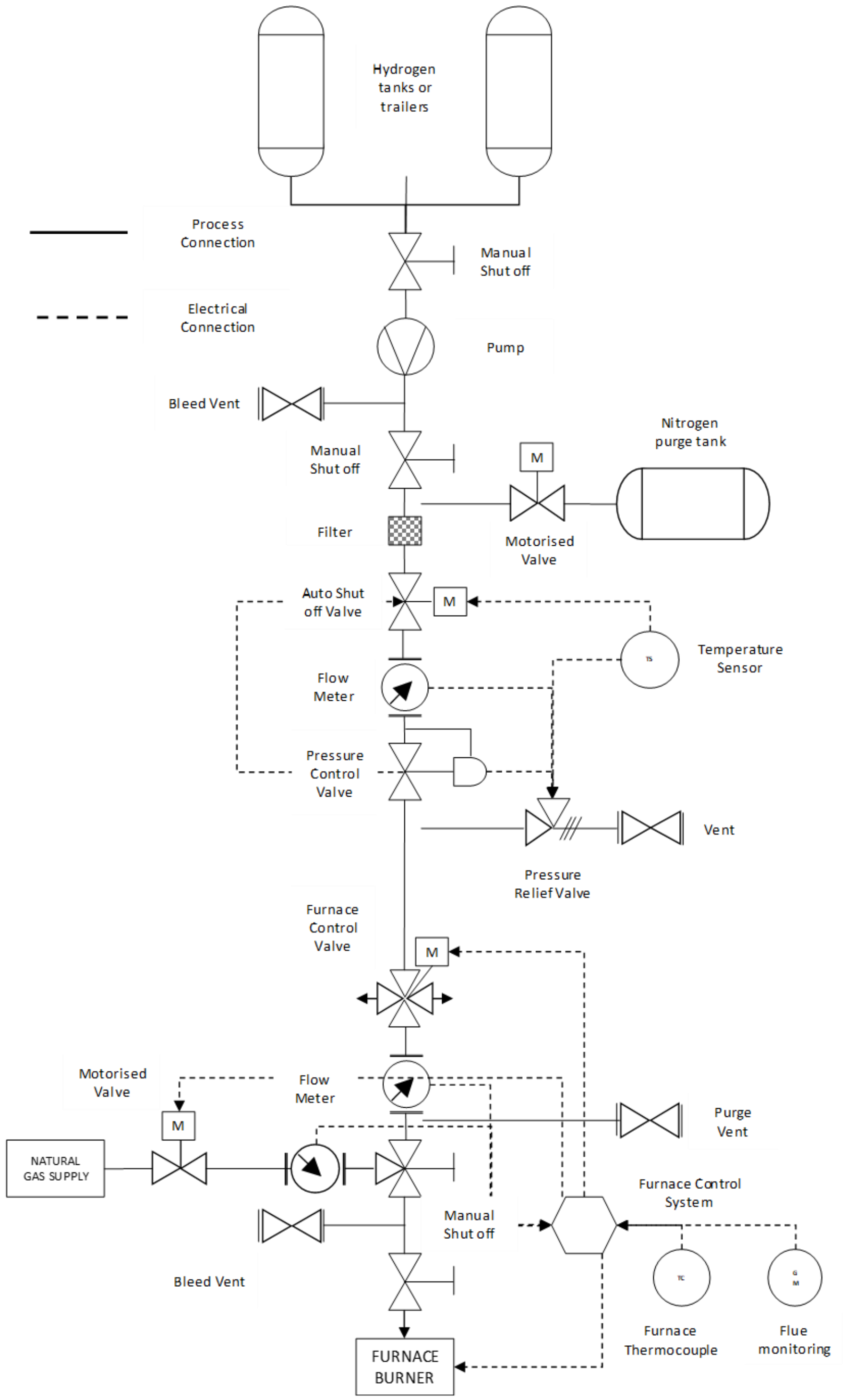
A Sheffield Forgemasters HAZOP Study

Figure 8: Indicative P&ID used for Sheffield Forgemasters HAZOP study



Deviations List: Storage - Design Intent: Store hydrogen at a pressure

#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
1	No	Hydrogen	Hydrogen not flowing from storage containers	No hydrogen in the tank Blockage of valve Loss of power to pump Control system failure High downstream pressure	Flame extinction	Tank monitoring Flame detectors Define start-up procedures Preventative maintenance
2	No	Hydrogen	The storage container is empty	Late or missed delivery Leak Consumption larger than planned	Flame extinction Cannot operate furnace as planned	Operating two tank/trailer systems ensures one is replaced on empty Calculate usage rates for larger storage systems Possible use of natural gas or blend if hydrogen is depleted
3	No	Access	No clear, direct access to hydrogen storage in furnace operation	System designed with buried or elevated systems. Inappropriate location of storage causing system congestion Blockages cause by third party Event leading to changes in the environment, e.g. power cuts, smoke etc	Unable to inspect and maintain systems without deconstruction Unable to access equipment and systems in an emergency	Assessment of storage location Pipework above ground Access plans/equipment for systems and pipework above head height Exclusion zones, including appropriate access paths Visual management/mapping Safe operating procedures Backup power or battery unit Design system fail-safes Emergency lighting around

#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
4	No	Access	No clear, direct access to storage when delivering hydrogen	Inappropriate location of the storage. Inappropriate design of the system. Inappropriate use of storage area, e.g. trailers parked incorrectly. Third-party blockages	Failure to deliver hydrogen as required. Blockages to other production and site operations	Proper assessment of storage location Exclusion zones around critical equipment, including appropriate access paths Visual management/system mapping Safe operating procedures Design system fail-safes. Emergency lighting around key points Design delivery systems with three distinct bays, guarding and bump stops
5	More	Pressure	Hydrogen delivered and stored at higher than intended pressure	Failure of pressure control systems in filling Heating of storage tank	Catastrophic failure of storage tank Explosion/ignition/fire Damage to the system Leak	System pressure relief valve Pressure monitoring System/joint damage inspection Exclusion zones Emergency fire procedures Physical fencing within the exclusion zone
6	More	Temperature	The temperature of the tank is heated beyond the design temperature	Exposure to an external heat source	Catastrophic failure of storage tank Explosion/ignition/fire Damage to the system Leak	System/joint damage inspection Tank temperature monitoring Exclusion zones Emergency fire procedures Physical fencing within the exclusion zone

#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
7	Less	Hydrogen	Less than required hydrogen contained in the storage tank	Late or missed delivery. Leak Consumption larger than planned	Flame extinction Cannot operate furnace as planned	Operating two tank/trailer system ensure one is replaced/refilled on empty Accurately calculate usage rates for larger storage systems Possible use of natural gas or blend if hydrogen is depleted
8	Less	Pressure	Hydrogen delivered and stored at lower than intended pressure	Failure of pressure control systems on filling Cooling of storage tank	Catastrophic failure of storage tank Ignition/fire Damage to the system Leak	System/joint damage inspection Tank temperature monitoring Exclusion zones Emergency fire procedures Physical fencing within the exclusion zone
9	Less	Flow	Flow from storage tank lower than expected	Low pressure Blockage Leak	System damage, e.g. pumps	Regular system inspection and maintenance Monitoring and recording flow rates from the storage tank

#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
10	Part of	Hydrogen	Contamination with other gases	Contamination of delivered product Accidental gas injections	Flame extinction Cannot operate furnace as planned Formation of explosive mixture Contamination of systems Changes in furnace emissions/accidental environmental discharge	Composition Monitoring/sampling Exclusion zones Emergency fire procedures System venting procedure emissions monitoring
11	Part of	Hydrogen	Contamination with particulates	Contamination of delivered product Accumulation of particulates due to system environment and usage	System blockages Changes in furnace emissions/accidental environmental discharge	Composition Monitoring/sampling Usage of filtration system System maintenance and cleaning
12	Other Than	Hydrogen	Hydrogen not stored safely in tanks/trailer	Physical damage caused by impact to tank. Failure caused by tank/trailer degradation, e.g. corrosion. Incorrect design and/or manufacture Catastrophic failure	Flame extinction Cannot operate furnace as planned Explosion/ignition/fire Asphyxiation	System/joint damage inspection Regular maintenance Tank monitoring Exclusion zones Emergency fire procedures Physical fencing within the exclusion zone Impact protection Suitable outdoor location

#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
13	Sooner Than	Hydrogen	Hydrogen is delivered into the downstream system sooner than expected	Accidental discharge Failure of safety systems, e.g. isolation valves Inaccurate or failure of monitoring systems	Explosion/ignition/fire Asphyxiation Venting of hydrogen system damage	Regular system maintenance and inspection Established safe working procedures Automated safety systems Alarms Sensor redundancy (multiple monitoring sensors) Shut off valve located close to furnace operations
14	later Than	Hydrogen	Hydrogen is delivered into the downstream system later than expected	Leak Low pressure Pump failure Control system failure blockages	Flame extinction loss of furnace control Changes in furnace emissions/accidental environmental discharge	Regular system maintenance and inspection Established safe working procedures Automated safety systems Alarms Sensor redundancy (multiple monitoring sensors)

Deviations List: Furnace delivery system - Design Intent: Transport hydrogen from storage to furnace systems at atmospheric pressure

#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
1	No	Hydrogen	No or reduced flow of hydrogen in the delivery system	Low or no flow from storage Blockages Leaks Failure of control systems False flow monitor reading Valves unexpectedly closed	Flame extinction in the furnace	Calibrated flow monitoring Maintenance and inspection regimes Multiple flow meters
2	No	Process Control	No KPI was recorded or monitored by the system	Failure of control systems Failure of sensors Loss of power Accidental removal of sensor or system	Excess or unexpected fuel delivery. Explosion/ignition/fire Asphyxiation Leaks	Maintenance and inspection regimes Design system fail-safes Alarms Backup power or battery unit

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#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
3	No	Access	No clear access to delivery systems and pipework	System designed with Buried or elevated pipework. Inappropriate location of causing system congestion Blockages caused by a third party, e.g. inappropriate storage etc Event leading to changes in the environment, e.g. power cuts, smoke etc	Unable to inspect and maintain systems without deconstruction Unable to access equipment and systems in an emergency	Assessment of furnace location Locating pipework above ground Access plans/equipment for systems above head height Exclusion zones Visual management mapping System purge capability Safe operating procedures Backup power or battery unit Design system fail-safes emergency lighting
4	Not	Pump	Pump not providing the required work	Pump breakdown External system failures, e.g. power cut System leaks	Flames extinction in the furnace Unable to use the furnace	Maintenance and inspection regimes Design system fail-safes Backup power or battery unit

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#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
5	Not	Safety valves	Pressure relief valve and or auto-shutoff valve not working	Failure of equipment due to mechanical, electrical faults or physical damage Blockages Failure of control & monitoring systems	Explosion/ignition/fire Asphyxiation Leaks System damage Changes in furnace emissions Furnace inoperable	Maintenance and inspection regimes Design system fail-safes Backup power or battery unit Appropriate system design and tests (FATS) Alarms System purge capability Manual relief valves
6	Not	Control systems	Control systems failure	Failure of equipment due to mechanical and electrical faults Failure of control & monitoring systems loss of power	Unexpected or uncontrolled delivery of hydrogen Flame extinction Hydrogen venting Explosion/ignition/fire	Maintenance and inspection regimes Design system fail-safes Backup power or battery unit Alarms System purge capability Manual relief valves

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#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
7	Not	Material	Materials used in pipework are not compatible with the use of hydrogen	Inappropriate material choice in design Mistake in system fabrication	Leaks Catastrophic failure of the system	Use of quality systems and processes in system design System documentation, e.g. certification of conformity Selection of suitably experienced systems integrator Maintenance and inspection regimes
8	More	Hydrogen	More hydrogen entering the delivery system than expected	Over-pressurised hydrogen contained in storage Fault in flow monitoring and control systems	Flame extinction System damage Explosion/ignition/fire Hydrogen venting to the environment Changes in furnace environment and emissions	System monitoring Design system fail-safes Pressure relief valves Automatic shutoff valve Locate venting to the external environment Fire safety systems Alarms
9	More	Temperature	Delivery system environment temperature exceeds design temperature	External heat sources from other production operations occurring on site External heat source from emergency event, e.g. fire	System damage Explosion/ignition/fire Hydrogen venting to the environment	Environment Monitoring Appropriate fire regulations and suppression systems Locate delivery systems externally where appropriate Design system fail-safes Alarms

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#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
10	Less	Hydrogen	Less hydrogen entering and supplied by the delivery system than expected	Low-pressure hydrogen in storage System or equipment failure Blockages Leaks	Flame extinction Changes in furnace environment & emissions	Emissions monitoring Maintenance and inspection Alarms
11	Part of	Hydrogen	Presence of particulates in stream	Filtration system failure, leaks in pipework	Jamming of control or emergency release valves, partial pipe blockage reducing hydrogen flow	Use of welded pipe joins wherever possible, sampling/monitoring of stream, Maintenance, and cleaning regimens for filtration systems
12	Other Than	Hydrogen	Containment of hydrogen within the pipe	Leaks in pipework, corrosion of pipework, damage to pipes caused by machinery/ usage	formation of the explosive mixture around pipework, asphyxiation	Pipes to be above ground with welded joints where possible. Ventilation around pipes is to be increased as much as practicable. Where pipes are underground, place them in a protective sleeve. Hydrogen distribution pipework to be at or close to atmospheric pressure. Maintenance and inspection procedures before use Exclusion zones, armouring or pump protection to be designed around key infrastructure Environmental oxygen monitoring of internal and confined areas Alarms/Fail safes

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#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
13	Other Than	Hydrogen	Hydrogen cannot be delivered to the furnace, so hydrogen is effectively stored in the system	Failure of the control system Blockages Failure of the downstream system	Unintended storage of hydrogen in the delivery system	Establish safe purging capability for the removal of hydrogen

Deviations List: Vent and Purge - Design Intent: Safe removal of gases from all systems

#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
1	No	Nitrogen	No nitrogen is available for the purging delivery system	Empty nitrogen tank Failure of the injection system	Unable to purge hydrogen from the system	Use an alternate/temporary purge source to remove hydrogen from the system. Create safe working practices for the removal of hydrogen from the system with alternate purge gas
2	Not	Vent	Purge ventilation does not allow for the removal of hydrogen from the system	Inoperable vent/valve for system purge	Ventilation of the system through the pressure release valve	Regular system maintenance and inspection
3	More	Nitrogen	More nitrogen than expected entering the demonstrator system	Faulty purge injector. Faulty flow metering or control system	Ventilation of the system through the pressure release valve	Regular system maintenance and inspection

#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
4	Less	Nitrogen	Less nitrogen than expected entering the demonstrator system	Faulty injection or control system Blockage Leak	System not adequately purged, leaving residual hydrogen	Maintenance and inspection Safe working practices for demonstrator usage, e.g. repeated purge cycles System monitoring
5	Part of	Nitrogen	Nitrogen gas contaminated with other gases, e.g. air	Leaks Mistaken delivery of purge gas System contamination	Fire, Ignition, explosion	A sampling of gas delivery before system purge. Maintenance and inspection regimes
6	Other Than	Vent	ventilation of hydrogen from purge is to an internal or confined area	Inappropriate location of system vent Third-party blockage or introduction of confinement	Fire, Ignition, explosion Inadequate system purging	Locate ventilation outside to an area with no overhanging structures. Limit access by third parties and assess for the possibility of accidental blockages

Deviations List: Furnace - Design Intent: Controlled heating of the furnace up to 900°C

#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
1	No	Air	Airflow stopped	Blocked valves, blocked inlets, control system fault, lack of power	If hydrogen is not fully combusted in the furnace, it may combust within the flue.	Add hydrogen monitors within the flue

#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
2	No	Hydrogen	Hydrogen flow stopped	Loss of power, failure of the control system, hydrogen supply tank depleted, failure of control valves to open	Flame extinction, if the flow is restored, an explosive mixture may be formed within the furnace.	Addition of a purge system to be operated in the event of flame extinction
3	No	initial ignition	no pilot flame	Pilot flame system fault, control system fault	The subsequent failure of the main ignition leads to the formation of an explosive mixture within the furnace.	Flame detection in UV and IR ranges, Proof of pilot flame ignition prior to H2 injection
4	No	Power	No Power	Power cut, severing of wires	No airflow, hydrogen flow and data from monitoring systems.	Emergency power system implementation. Fails to safe conditions
5	No	Combustion	Flame extinction	Loss of airflow Loss of hydrogen flow Dust quenches flame	Hydrogen enters the flue system, where it may combust.	H2 detectors within the flue system to detect build-up before LEL reached
6	More	Temperature	The temperature of the furnace exceeds the design limits	increased rate of combustion	Damage to the furnace.	Installation of a high-temperature switch
7	More	Hydrogen	Hydrogen flow	Failure of the control system, Failure of control valves	increased rate of combustion	Installation of a high-temperature switch
8	More	Pressure	Excess pressure within the furnace	Failure of pressure control systems	physical damage to the furnace,	high combustion air pressure switch

#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
9	More	Hydrogen	The quantity of hydrogen in the furnace before the flame is established is too high	Failed ignition attempts allowing excess H2 build up in the furnace	Explosion.	Purging 5x furnace volume between ignition attempts. Igniter flame establishing a period timer
10	More	Airflow	Airflow greater than the required levels	Failure of the control system, Failure of control valves, obstruction to blower inlet, blower failure	Flame extinction	low combustion air pressure switch
12	Less	Hydrogen	Hydrogen injection velocity is lower than hydrogen flame speed	Failure of the control system, failure of pumps (if used)	Flashback.	Installation of flame arrestors
13	Less	Pressure	Pressure within furnace lower than 1atm	Failure of control systems, failure of blowers, obstruction of blower inlet	Flame extinction, if the flow is restored, an explosive mixture may be formed within the furnace.	Installation of flame detectors, installation of low combustion air pressure switch
14	Less	Hydrogen flow	Hydrogen flow is lower than anticipated	Failure of the control system, failure of pumps (if used)	Flame extinction	low combustion air pressure switch
15	Less	Airflow	Airflow lower than required to combust hydrogen with a desired excess air ratio	Failure of control systems, failure of blowers, obstruction of blower inlet	Flame extinction, formation of an explosive atmosphere in the flue system	Add hydrogen monitors within the flue

#	Guide Word	Element	Deviation	Possible Causes	Consequences	Safeguards
16	Less	purging	The furnace purge system is not capable of 5 volume changes in one hour	Failure of purge blowers	Explosion when combustion reattempted	At a minimum, proof of purging after 5 volume changes in an hour with a portable hydrogen sensor
17	Other Than	flame	Flame quenched	dust cooling sides of flames	Increased levels of hydrogen within the furnace, potential explosion in the flue system	Add hydrogen monitors within the flue
18	As well as	Hydrogen	Static charge	Bagging plants, phones etc.	Explosion if hydrogen leak occurs	Adherence to minimum exclusion distances. Installation of hydrogen detectors around and above the furnace
19	As well as	Hydrogen	Hydrogen discharge around the furnace due to incomplete combustion	Incomplete combustion, flame extinction	Explosion if hydrogen concentration exceeds LEL.	Hydrogen detectors around equipment and wearable hydrogen detectors for personnel

B Dissemination plan

Table 28: Industry dissemination plan

Opportunity	Objective	Lead	Timings
LinkedIn	Communicate press release and follow-ups	E.ON	Q4 2022 onwards
Make UK	Communicate press release with the association and publish in Member news. Publish follow-up findings	TBC	Q1 2023
UK Steel	Communicate press release with the association and publish in Member news. Publish follow-up findings	TBC	Q1 2023
Decarbonisation Leaders Network	Communicate press release with the association and publish in Member news. Publish follow-up findings	TBC	Q1 2023
Institute of Materials	Communicate press release with the association and publish in Member news. Publish follow-up findings	TBC	Q1 2023
Institute of Mechanical Engineering	Communicate press release with the association and publish in Member news. Publish follow-up findings	TBC	Q1 2023
World Steel Association	Communicate press release with the association and publish in Member news. Publish follow-up findings	Liberty Steel	Q1 2023
Advanced Forging Research Forum	Communicate feasibility, key findings, and implications/opportunities	Chesterfield Special Cylinders	31/01/2023
UK Steel Climate Change Committee 7th December 2022	Communicate project approach, organisation, and learnings to date	E.ON/ Liberty	07/12/2022
Energy Intensive Users Group Meeting	Communicate project approach, organisation, and learnings to date	Liberty Steel	January 2023 TBC
Decarbonisation Catalyst Conference	Project update, hydrogen business model discussion	E.ON	21-23 Feb, 2023
Sheffield Forging and Forming Forum	Overview on project progress/plans	Chesterfield Special Cylinders	31/1/2023
LinkedIn post - Chesterfield Special Cylinders	Detail on Chesterfield Special Cylinders, the project bens and decarb	Chesterfield Special Cylinders	Jan 2023

Opportunity	Objective	Lead	Timings
H2View trade press	Mention as part of storage and distribution editorial piece	Chesterfield Special Cylinders	December 2022
Annual Report case study	Project synopsis	Chesterfield Special Cylinders	March 2023
Made In Sheffield Newsletter	Funding and project announcement	Chesterfield Special Cylinders	December 2022
UnLtd trade press	Funding and project announcement	Chesterfield Special Cylinders	December 2022
Sheffield star local media	Funding and project announcement	Chesterfield Special Cylinders	December 2022

Table 29: Public sector dissemination plan

Opportunity	Objective	Lead	Timings
Sheffield City Council	Quarterly progress updates	E.ON	Jan-23
South Yorkshire Combined Authority	Quarterly progress updates	E.ON	Jan-23
Sheffield - education	Communicate project, consider link to STEM activities	TBC	H1 2023
Sheffield - community groups	Communicate project, expected future benefits (cleaner air, innovation, economy)	TBC	H1 2023
AMRC Regional Network	Communicate feasibility, key findings, and implications/opportunities	E.ON	Quarterly
AMRC monthly newsletter	Communicate press release and follow-ups	AMRC/ University of Sheffield	Q1 2023
University stakeholder newsletter	Communicate press release and follow-ups	AMRC/ University of Sheffield	Q1 2023

Table 30: Dissemination activities completed during 2A feasibility study.

Date	Lead	Type	Dissemination	Participants
Sep-22	E.ON	Quarterly Update Meeting	2A Update on progress to date	Sheffield City Council, SYCA
Sep-22	E.ON	Meeting	2A overview	E.ON AG Green fuels team
Nov-22	E.ON	Meeting	2A Update on progress to date	Sheffield City Council
Nov-22	E.ON	Press Release	2A overview	Consortium partners
Nov-22	E.ON	Network sharing	2A overview	3500+ post impressions
Nov-22	E.ON	Quarterly Review Meeting	2A Update on progress to date	E.ON AG/UK Board members
Nov-22	Fichtner	Social media announcement	LinkedIn post	
Nov-22	E.ON	Meeting/ Presentations	Update on 2A Objectives	
Nov-22	E.ON	Quarterly Review Meeting	2A Update on progress to date	
Nov-22	Chesterfield Special Cylinders	Project announcement	LinkedIn post	Chesterfield Special Cylinders
Q4 2022	E.ON	LinkedIn	Communicate press release and follow-ups	
Jan-22	Chesterfield Special Cylinders	Advanced Forging Research Forum	Communicate feasibility findings and opportunities	
Jan-23	E.ON	Sheffield City Council	Quarterly progress updates	
Jan-23	E.ON	South Yorkshire Combined Authority	Quarterly progress updates	
Oct-23	E.ON	MP's update - Louise Haigh	Site visit and hydrogen update	EON/CSC

C 2035 capital and operating costs estimation

Table 31: Estimated capital and operating costs for 2035 commercial deployment

Item	Units	Value	Formula	Source
Electrolyser capital costs (2025, 10 MW)	£	£9,320,000	a	Table 16
Electrolyser capital costs (2025, 20 MW)	£	£18,640,000	b = a * 2	Assumption that electrolyser costs scale linearly
Reduction in electrolyser capital costs (2025 to 2035)	%	29%	c	BEIS Hydrogen Production Costs 2021
Electrolyser capital costs (2035, 20 MW)	£	£13,234,400	d = b * (1-c)	
Cabling and enabling works	£	£500,000	e	Table 16
Other (civils plus controlling software)	£	£500,000	f	Table 16
Switchboard extension	£	£200,000	g	Table 16
COMAH permits	£	£4,000	h	Table 16
Total capital costs	**£**	**£14,438,000**	**d+e+f+g+h**	
Production plant O&M costs	£/y	£191,000	i	E.ON assumption
Water and wastewater costs (10 MW)	£/y	£52,000	j	Table 17
Water and wastewater costs (20 MW)	£/y	£104,000	k = j * 2	Water and wastewater generation is proportional to electrolyser capacity
Total operating costs	**£/y**	**£295,000**	**l = i + k**	

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