Refuelling the Humber Refinery

Public Report
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Humber Refinery, North Lincolnshire, UK

PROVIDING ENERGY. IMPROVING LIVES.

Authors

This report has been prepared by Phillips 66 Limited.

The Phillips 66 Limited Humber Refinery, located in North Lincolnshire, UK, has a crude oil processing capacity of 221,000 barrels per day. It is one of the most complex refineries in Europe, supplying approximately 15% of the UK demand for fuels used for transport, heating and power.

As well as producing fuels such as petrol and diesel (approximately 14 million litres a day, some of which is sold at JET® branded petrol stations), plus LPG, kerosene and jet fuel, the refinery also produces products that are raw materials to be transformed into essential products used by society, ranging from household products, pharmaceuticals and plastics.

The Humber Refinery is one of the most complex refineries in Europe and is leading the way in the production of lower-carbon fuels. It was the first in the UK to produce, at scale, high-performing, advanced second-generation biofuels from waste, when used cooking oil (UCO) was introduced to its refining processes in 2017. In 2020, Phillips 66 Limited invested significantly, trebling this capacity with the addition of a new lower-carbon fuel module.

One of the most exciting opportunities for the Humber Refinery lies in the electric vehicle revolution. At the refinery, we produce speciality graphite coke; this already has a vital role in supporting advanced manufacturing in the steel recycling and aluminium smelting industries. Through unique coke formulations, it is now increasingly being used in the manufacture of anodes for lithium-ion batteries used in consumer electronics and electric vehicles. The Humber Refinery's role in the electric vehicle battery manufacturing supply chain was recognised in the UK Government's Industrial Decarbonisation Strategy.

Acknowledgements

The Department for Business, Energy and Industrial Strategy (BEIS)[1] provided co-funding for the Phillips 66 Limited Refuelling the Humber Refinery (RtHR) feasibility study through the **Industrial Energy Transformation Fund (IETF)** Phase 1 programme which was delivered by **UK Research and Innovation (UKRI)**. UKRI provided an independently appointed monitoring officer to support project management and coordination through the life cycle of the study.

Worley Europe Limited provided engineering services supporting the study's execution. This covered all major areas of the project execution (general engineering, thermal-rating studies, support of burner testing), as well as overall project coordination and final technical report writing. Worley Europe Limited is a subsidiary of the Worley group, a worldwide team of consultants, engineers, construction workers and data scientists all with one thing in common; they love to be challenged. Every day, they come to work to solve the complexity of the energy, chemicals and resources sectors.

References:
1

John Zink Hamworthy Combustion provided engineering support regarding burner functionality and capability to be fuel switched. Workstreams included detailed engineering studies and computational fluid dynamic studies of burners and heater fire-side operation, along with physical burner testing at their Luxembourg facility. John Zink Hamworthy Combustion, a Koch Engineered Solutions company. Koch is one of the largest privately held companies in the U.S. As a result, they are able to support development of industry-leading innovations and are ideally suited to support a study of this nature.

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ERM acquired Element Energy and E4tech in 2021, which are now fully integrated in ERM's Sustainable Energy Solutions (SES) team. The team consists of over 150 specialists bringing deep expertise in the development, commercialisation, and implementation of emerging low-carbon technologies across a wide range of sectors, including industrial decarbonisation (hydrogen, carbon capture utilisation and storage, electrification), low carbon fuels and chemicals, the built environment, smart energy systems, electricity and gas networks, low carbon transport and funded project management.

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Executive Summary

The Refuelling the Humber Refinery (RtHR) feasibility study was commissioned by Phillips 66 Limited and co-funded by the Department for Business, Energy and Industrial Strategy's (BEIS's [now DESNZ]) Industrial Energy Transformation Fund (IETF) Phase 1 programme between September 2021 and November 2022, which was delivered by UKRI. The feasibility study provided a broader evidence base on which industrial-scale fuel switching of fired heaters from refinery fuel gas (a fuel similar to natural gas) to up to 100% lower-carbon hydrogen* could be undertaken.

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Key Findings

- The study demonstrated it is technically feasible to fuel switch industrial fired heaters from refinery fuel gas to up to 100% hydrogen through relatively cost-effective retrofit modifications to the heaters, which in most cases is a simple burner replacement.

- This first-of-a-kind study for a UK refinery has provided a broader evidence base with the learnings directly applicable across a range of process services, heater types and configurations (e.g. firebox shape, firebox size, thermal duty, burner orientation, air provision). Conventional heater analysers (fuel-rich atmosphere detection) require replacement when approaching 100% hydrogen. Flame detector and total flammability analyser technologies are at commercial deployment for use with 100% hydrogen. Due to the low-volumetric energy density of hydrogen compared to other fuels:

  - There is an exponential relationship between the vol% hydrogen in the fuel gas and the reduction in CO_2 emissions. For example, 20vol% and 90vol% hydrogen results in approximately 7% and 74% CO_2 reductions, respectively, as shown in Figure 12.

  - To maintain burner duty, the flow rate of hydrogen must be around three times higher than refinery fuel gas. The hydrogen supply pipework must, therefore, be larger in diameter and operate at a higher pressure.

- Modification/replacement of burners should be assessed on a case-by-case basis considering targeted hydrogen content, current burner technology, nitrous oxides (NO_x) limitations, noise emissions and required fuel gas pressure. Early engagement with burner vendors and other key supply chain providers is critical to undertake these assessments.

- For a given burner, NO_x generation will be higher when burning hydrogen fuel than refinery fuel gas. The highest NO_x generation will be around 75vol% to 100% hydrogen concentration and is subject to burner design.

- A low NO_x burner in hydrogen service will generally produce less NO_x than a conventional burner in refinery fuel gas service. Therefore, where conventional burners are replaced with burners optimised for hydrogen service, a reduction in NO_x emissions can be achieved relative to the conventional burner operating in refinery fuel gas service.

- When operating on hydrogen fuel, the heat is generated lower down in the radiant section than when operating on refinery fuel gas. There is a reduction in heat recovered in the heaters' convection sections of approximately 5% to 15% when firing 100% hydrogen. The convection sections of heaters are typically used for steam generation or preheat of process streams. The impact of which would need to be assessed on a case-by-case basis, depending on the service.

- Pilot burners suitable for high-hydrogen content fuels (> 50vol%) are not commercially available. It is recommended to supply pilot burners with the current refinery fuel gas supply until pilot technology has been developed and proven in service. The fuel gas supply by the pilot burners is small in relation to the overall heater duty, typically around 1%, and depends on burner design, firing rate and heater duty.

- Heater simulations (thermal rating tool – FRNC-5PC and computational fluid dynamics – CFD modelling) indicated that key heater mechanical integrity parameters, such as bridge wall temperature and tube metal temperature (TMT), remain within design limits at 100% hydrogen firing.

- The total capital investment for the fuel switching proposed by the RtHR project is in the region of 15% (today) to 40% of the installation cost for an electrolytic hydrogen production facility. This is therefore a small marginal component in the levelised cost of energy but may present a barrier to undertaking fuel switching for some UK industrial sites.

***Reference to 'hydrogen' throughout the report is referring to lower-carbon hydrogen.**

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Contents

1. Introduction

The UK Government is committed to efforts to keep global temperature rise since preindustrial levels[2] to below 2°C and to pursue best efforts to limit the increase to 1.5°C as a signatory of the Paris Agreement in 2015. This ambition has since been strengthened in:

- **June 2019:** The UK Government updated the Climate Change Act requiring a 100% reduction in net greenhouse gas emissions by 2050[3].
- **December 2020:** The UK Government enshrined a new target in law to reduce greenhouse gas emissions by 78% by 2035 relative to 1990 levels[4], committing to reduce emissions at the fastest rate of any major economy.

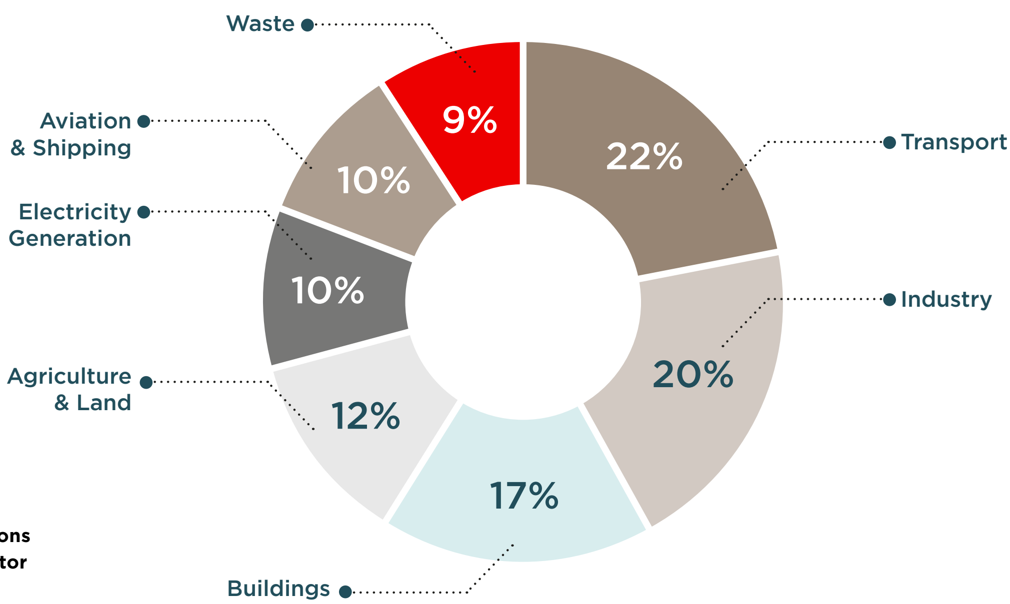

Figure 1: UK Emissions Distribution by Sector 2019[6]

Approximately

20%

of the UK's total annual emissions

The UK's industrial sectors account for approximately 20% (2019)[5] of the UK's total annual emissions of 522MtCO_2/year[6](2019), as shown in Figure 1. It is essential that the industrial decarbonisation challenge is prioritised to manage the UK's CO_2 target, as well as maintain international competitivity and jobs across the UK. Decarbonising industry presents challenges, as industrial processes are well established and require associated high-capital investments to modify. Any decision to transition away from the use of traditional fossil fuel industrial-based processes must, therefore, be informed and evidence driven to ensure the efficient use of capital and other resources.

References:
2, 3, 4, 5, 6

Industry has two main sources of CO_2 emissions that need to be addressed:

1. **Production processes:** Abating emissions is complex and production process-specific. Different approaches and techniques are required across such a diverse range of industrial processes requiring abatement, e.g. oil and gas refining, petrochemicals, cement production, steel production, glass production.

2. **Combustion of hydrocarbon-based fuels for industrial heating:** This process is similar across many industries. Therefore, lessons learnt at one industrial site are more easily and widely exploited. This allows supply chains for equipment to develop and value chains for the supply of hydrogen, biomass, renewable electricity or CCUS to be established.

This report focusses on fuel switching for industrial heating applications using lower-carbon hydrogen.

1.1. The Role of Hydrogen in Decarbonisation

Hydrogen has been identified as having a key role to play in the transition to a net-zero future (Figure 2). This was formally recognised in the UK Government's Hydrogen Strategy[7], published in August 2021.

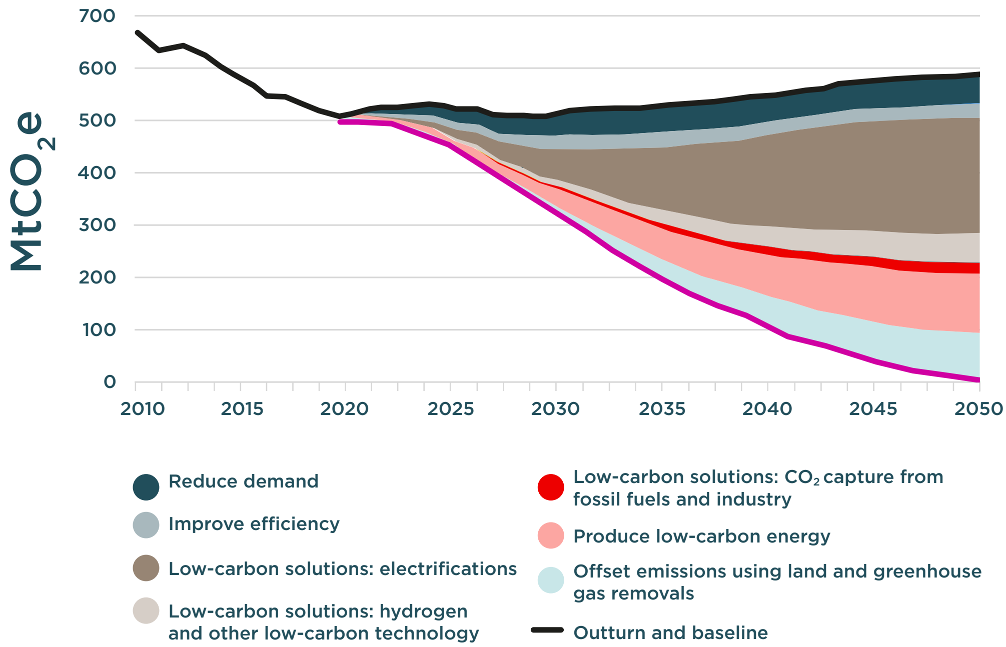

Figure 2:
UK Decarbonisation Pathway and Technologies[6]

References:
6, 7

1.1.1. Hydrogen Production Pathways and UK Deployment Plans

There are two main lower-carbon hydrogen production options:

Electrolytic Hydrogen

- Produced when lower-carbon (renewable) electricity splits water into hydrogen and oxygen via electrolysis (commonly known as **green hydrogen**).

- Requires both a new electrical connection and a supply of water (~17-31l/kgH_2[8,9]). These present regulatory challenges, especially in industrial clusters, where there may be electrical grid constraints and/or water supply constraints. This could be overcome through collaboration with renewable power supply developers and integration considerations with neighbouring industrial sites for water supply.

Such collaboration has the potential to ease the regulatory burden associated with implementing electrolytic hydrogen production.

CCUS-Enabled Hydrogen

- Derived from transforming primarily natural gas into hydrogen and using carbon capture to collect CO_2 emissions produced during the transformation process (commonly known as **blue hydrogen**).

- Requires a supply of natural gas and water (22-31l/kgH_2[8,9]), as well as access to a CCUS network/other CO_2 transportation means. Access to water can face similar challenges as electrolytic hydrogen whilst access to natural gas remains a relatively low hurdle in industrial settings.

- The UK Government is supporting the development of CO_2 transport and storage networks across UK industrial clusters through its Cluster Sequencing programme[10], which are de-risking access to these networks.

The UK Government is supporting both CCUS-enabled hydrogen and electrolytic hydrogen, with a target of 10GW_{th} production capacity by 2030, put forward in the UK's Energy Security Strategy[11]. This includes at least 5GW_{th} of electrolytic hydrogen and 5GW_{th} of CCUS-enabled hydrogen, which is financially supported by BEIS's (now DESNZ) Net Zero Hydrogen Fund[12] and the Cluster Sequencing programme[10]. These programmes are already gaining traction in the UK, with widespread ambitions to deploy both hydrogen production technologies at scale across the country.

Many of these projects are found around the UK's six industrial clusters. Over 50% of the UK's industrial emissions are produced from Humber, South Wales, Merseyside, Teesside, Grangemouth and Southampton. A heat map of 2018 emissions from large sites correlates directly to the corresponding locations of the UK's six major industrial clusters (emission values derived from the National Atmospheric Emissions Inventory (NAEI) database – 50km radius).

References:
8, 9, 10, 11, 12

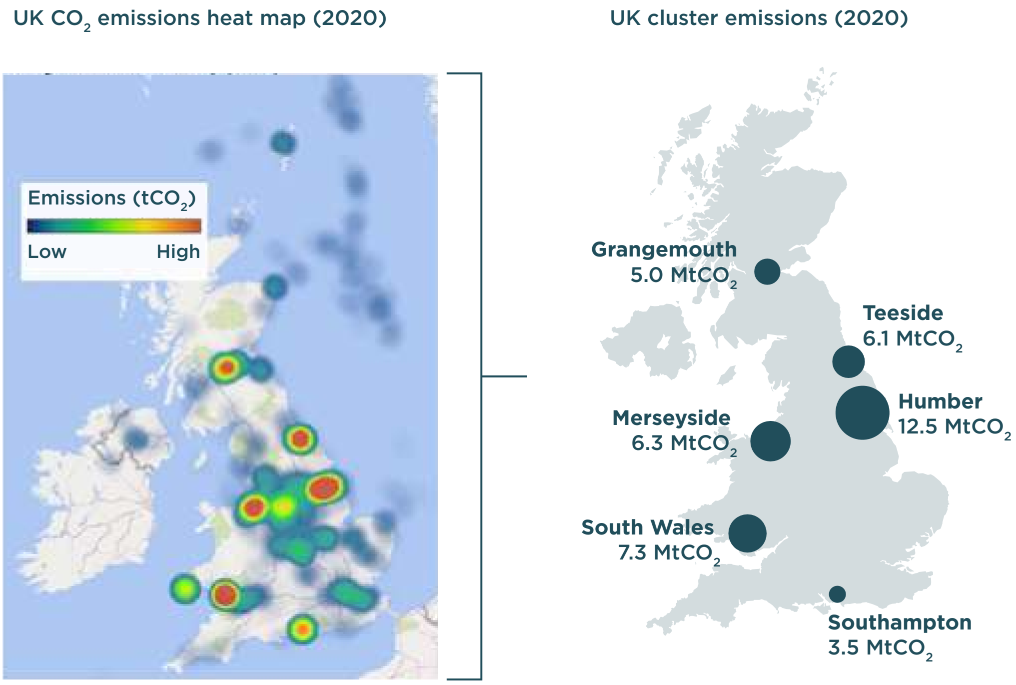

Figure 3:
The UK's Industrial Clusters[5]

The Humber region is the UK's largest industrial cluster emitting 12.5$MtCO_2$/year. This is due to the high density of energy-intensive industries, such as refineries, power stations and steel works located on the banks of the River Humber, which traditionally receive their hydrocarbon-based fuel feedstocks and export products via the ports of Immingham and Hull.

The RtHR project supports Phillips 66 Limited's long-term vision, which includes a plan to reduce carbon emissions at the Humber Refinery and develop a UK electric vehicle battery supply chain. Currently, the Humber Refinery emits approximately 2$MtCO_2$/year. Subject to obtaining all necessary consents, permits and approvals (including all necessary internal management approval), Phillips 66 Limited intends to abate these emissions through a combination of carbon capture and storage, energy efficiency measures, and the use of lower-carbon energy sources such as hydrogen.

The Humber Refinery is one of the most complex refining facilities in Europe and is pivoting to deliver lower-carbon products that are vital in a net-zero world. The Humber Refinery is Europe's only producer of specialty graphite coke, a key component in lithium-ion batteries for electric vehicles and consumer electronics. Additionally, it is the UK's only at-scale producer of sustainable aviation fuels (SAF) and also produces advanced biofuels, attaining the Department for Transport's Development Fuels classification.

Through a combination of planned carbon emission reduction measures and further development of lower-carbon products, Phillips 66 Limited intends to transition the Humber Refinery to a refinery that is fit for the future.

References:
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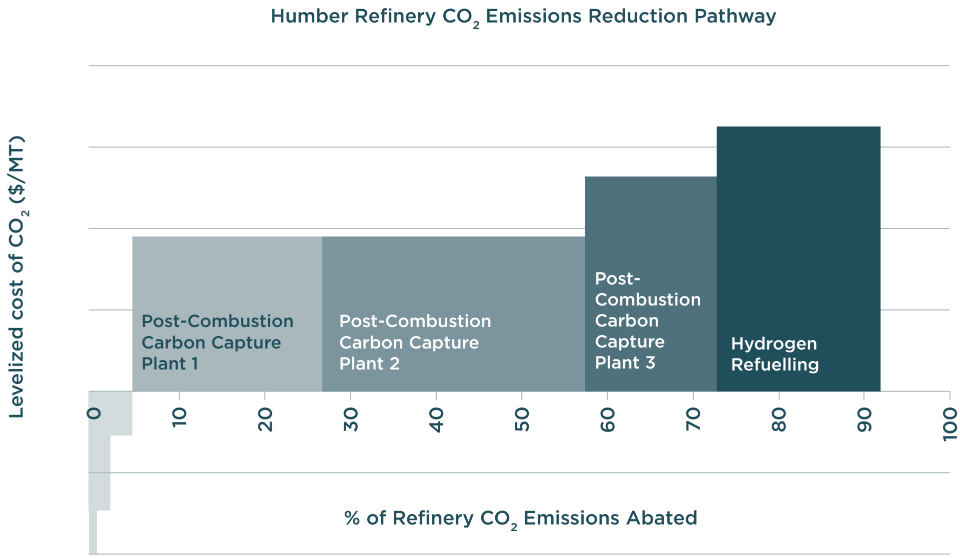

Figure 4:
Refinery Pathway for CO_2 Emissions Reduction

1.1.2. Industrial Process Applications of Hydrogen

Hydrogen traditionally plays a key role in several industrial applications, providing a feedstock for sulphur removal processes in oil refining and chemical processes, such as the production of ammonia and methanol. However, the importance of decarbonisation means that hydrogen is being evaluated for new industrial applications. This includes the use of lower-carbon hydrogen in the aforementioned processes and the production of other lower-carbon products such as steel (direct reduction of iron) and using hydrogen for heat through combustion.

Hydrogen has not traditionally played a part in industrial heating due to the abundance of low-cost hydrocarbon-based fuels such as natural gas. A reduction in carbon emissions from carbon-intensive industrial heating can be achieved through either post-combustion carbon capture, electrification or hydrogen refuelling. The choice between these technologies is not solely down to cost (levelised cost of abatement) but also logistical factors, such as asset location, scale and operational profiles. Hydrogen is particularly useful as high temperatures required for many industrial processes cannot currently be achieved by electrification. Phillips 66 Limited has conducted a decarbonisation feasibility assessment at its Humber Refinery (as part of the BEIS [now DESNZ] Industrial Energy Transformation Fund) and determined that fuel switching is the only viable option to decarbonise geographically remote heaters.

This report concerns a feasibility study on fuel switching for the identified geographically remote groups of heaters and was funded through the UK Government's Industrial Energy Transformation Fund.


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2. Industrial Energy Transformation Fund (IETF) – Refuelling the Humber Refinery (RtHR)

Strategically, the IETF sits within the context of the Government's long-term plans toward net-zero carbon emissions by 2050, as set out in the Government's Energy White Paper (2020)[13], 10-Point Plan (2020)[14] and the Industrial Decarbonisation Strategy (2021)[15]. **The objective of the IETF is to help businesses with high energy use to cut both their energy bills and carbon emissions through investing in energy-efficiency and lower-carbon technologies.**

BEIS (now DESNZ) provided a total of £289m in grant funding for the IETF Phase 1 and 2 projects in England, Wales and Northern Ireland. This was delivered by UK Research and Innovation (UKRI). The funding pot is catalysing projects and supporting the IETF's objectives. This will further establish UK companies as world leaders in technology deployment for decarbonisation.

The IETF Phase 1 competition provided grant funding for feasibility and engineering studies and for industrial energy efficiency deployment projects. The competition opened in 2020, with applicants requesting funding for projects scheduled to begin by 2021 and conclude by 2025[16].

The RtHR project was selected for funding in Phase 1 of the IETF. This feasibility study explored fuel switching in the refinery's industrial fired heaters, displacing fossil-derived fungible refinery off-gases with lower-carbon hydrogen. **These findings are directly applicable to sites exploring fuel switching from natural gas to hydrogen as natural gas is considered to be comparable and interchangeable with refinery fuel gas.**

As a large-scale producer and consumer of hydrogen, Phillips 66 Limited is ideally placed to develop and implement the technology required for fuel switching to hydrogen. The Humber Refinery has over 50 years of experience with the design, operation and maintenance of high-purity hydrogen systems and industrial fired heaters, with particular expertise in the safe handling of this material.

References:
13, 14, 15, 16

The Humber Refinery fuel gas used in the facility's fired heaters already has a hydrogen content of up to 30%. This has multiple key benefits for testing new hydrogen contents since, i) the impact of current hydrogen concentration is already known through constant monitoring of the fuel gas composition and heater performance, and ii) hydrogen safety and control systems are well established and in use at the refinery.

The RtHR project has furthered Phillips 66 Limited's understanding of the requirements to significantly reduce carbon emissions from the Humber Refinery's industrial fired heaters, while also demonstrating the suitability of hydrogen for wider applicability for industrial fuel switching, which supports the UK to achieve its net-zero ambition.

The project aimed to identify:

- The requirements for any new or modified equipment to enable successful heater refuelling with hydrogen.
- The extent of modifications required to existing equipment to meet the duty requirements of the new systems.
- A recommended maximum practical and cost-effective hydrogen content for each individual heater.

2.1. Project Methodology

The RtHR feasibility study was conducted over a 12-month period, between Q4 2021 and Q4 2022, using a work package approach as follows:

- **Work Package 1 – Piping and Equipment Study**

Provide a design and cost estimate for the hydrogen and refinery fuel gas supply pipework and associated equipment needed for fuel switching, including blending stations and heater shutdown system/ flame detection.

- **Work Package 2 – Fired Heaters Studies**

Conduct thermal modelling on a range of fired heaters using industry-standard software. Models produced for current conditions and high-hydrogen firing to assess performance when fuel switching.

- **Work Package 3 – Firebox Computational Fluid Dynamics (CFD) Modelling**

Conduct detailed CFD modelling of a selection of fired heaters to assess burner performance and firebox conditions across a range of hydrogen concentrations.

- **Work Package 4 – Burner Testing**

Test the technical performance of a selection of burners at the vendor facilities (John Zink Hamworthy Combustion – JZHC) at a range of hydrogen concentrations.

- **Work Package 5 – Report Writing**

Reporting of Work Package outputs, recommendations for future work and dissemination activities.

- **Work Package 6 – Project Coordination**

Coordinate between dependencies of different work packages and track progress against KPIs.

Table 1:
RtHR IETF Award

Descriptor	Value
Project Title	Refuelling the Humber Refinery
Project ID	96873
Sector	Industry (Refinery)
Primary Activity	Oil refinery (SIC Code 5541)
Location	Immingham, North Lincolnshire
Lead Organisation	Phillips 66 Limited
Subcontractors	Worley (Engineering) John Zink Hamworthy Combustion (Burner specialists)
Grant Offered	£509,605
Project Costs	£1,019,209
Start Date	September 2021
End Date	November 2022

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3. Literature Review of Previous Hydrogen Fuel Switching Studies

Industrial fuel switching is a sector-wide technical challenge. To ensure the RtHR study built upon the existing knowledge base, Phillips 66 Limited commissioned Element Energy (now part of ERM) to conduct a literature review to further inform the deliverables of the study and the following sources were used:

1. Lowe, Cliff, et al. (2011) "Technology assessment of hydrogen firing of process heaters"[17].
2. HyNet (2020) Industrial Fuel Switching (IFS) feasibility study[18].
3. Ditaranto, Mario, et al. (2013) "Performance and NO_x emissions of refinery fired heaters retrofitted to hydrogen combustion"[19].
4. H-vision (2019) "Feasibility Study: Blue hydrogen as an accelerator and pioneer for energy transition in the industry"[20].

RtHR furthered knowledge enhancement from the studies in the following ways:

1. Performance of New Hydrogen Burners: These studies present findings about hydrogen fuel switching feasibility at a high level, which are difficult to translate to the multiple burner designs and the industrial fired heaters (which have differing types and uses). RtHR addressed this by utilising thermal rating, CFD modelling and physical testing of a selection of burners representing a range of heaters in the study scope (see Figure 8).

2. Health and Safety: The RtHR study reviewed requirements to analyse the combustible atmosphere within the heaters and how this would be impacted by fuel switching. This was particularly important to understand integration with required safety instrumented shutdown systems.

3. Hydrogen Blending Opportunities: RtHR considered a full spectrum of hydrogen volumes (from 0% to 100%). This allowed RtHR to give deeper technical insights and investigate the impact of fuel-blending on a variety of operational, cost and safety factors. This holistic approach meant RtHR could establish blending limit volumes based on several variables before substantial burner and heater modifications are required.

References:
17, 18, 19, 20

4. NO_x and CO_2 Emissions: RtHR considered NO_x emissions across the heaters studied to gain a deeper understanding of NO_x response to fuel switching. Phillips 66 Limited's operating experience and NO_x models, developed during this study, along with physical burner testing, were used to determine NO_x response through fuel switching. This helped to produce detailed reports on NO_x emissions and how they would be impacted by different blends of hydrogen. RtHR also produced a detailed analysis of verified CO_2 emissions savings from switching to 100% hydrogen to determine the total emissions savings. Infrastructure requirements were also assessed.

5. Hydrogen Infrastructure: The RtHR study considered hydrogen supply pressure requirements and fuel-blending configurations to deliver flexible fuel switching. Additionally, hydrogen pipeline infrastructure requirements were also assessed.

6. Supply Chain: RtHR worked with both Worley and JZHC throughout the project. Key learnings were discovered on the capabilities of retrofitting existing burners or replacing them with models that are optimal for hydrogen.

4. Study Approach

4.1. Introduction

RtHR was a first-of-a-kind feasibility study for a UK refinery exploring refuelling a range of large-scale industrial fired heaters with blends of up to 100% hydrogen. The study was split into four technical work packages and a report-writing and dissemination package, as shown in Figure 5. These work packages were selected to advance the technical understanding of fuel switching at different hydrogen blend ratios on industrial fired heaters, including consideration on the potential emission levels, options for fired heater safeguarding and the scope of plant modifications required at the Humber Refinery. Key learnings from the technical work packages have been disseminated in this report to support the wider UK industry in successfully fuel switching to hydrogen. The RtHR work packages also serve to fill literature gaps identified in Section 3 and to progress the project through the preliminary stages of Phillip 66 Limited's internal project stage gate process.

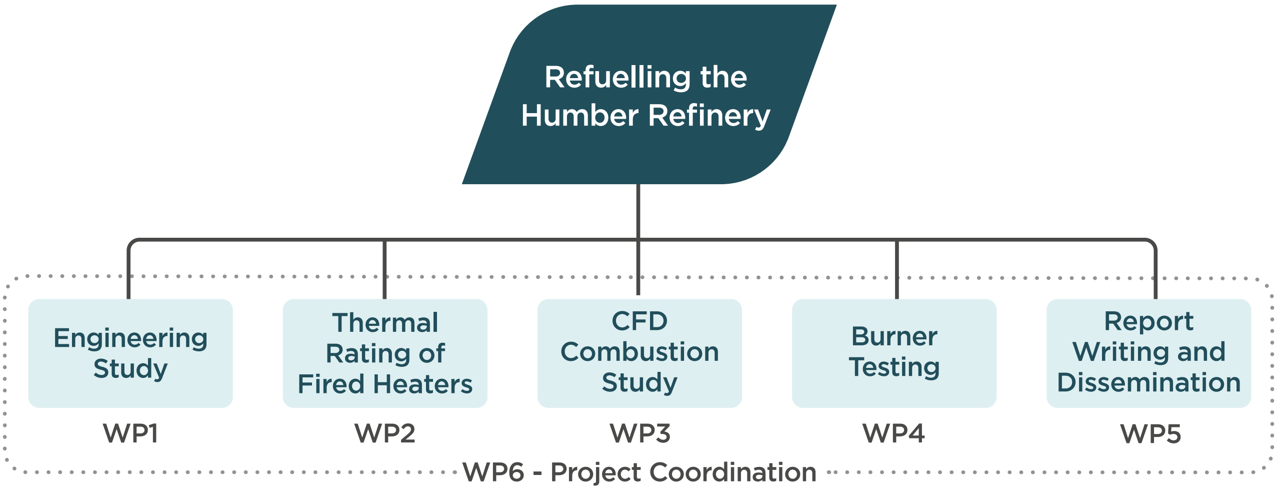

Figure 5: RtHR Work Package Breakdown (WP = Work Package)

The four technical work packages ran from September 2021 to November 2022, with intermediate results collected and regularly reviewed with the Phillips 66 Limited, Worley and JZHC project team. Quarterly reviews were conducted with UKRI and an independently-appointed monitoring officer covering the status of project activities, emerging learnings and project management/coordination.

The range of fired heaters evaluated in this feasibility study are summarised in figure 8. The heaters selected covered a broad range of process services, heater and burner configurations, and natural versus balanced drafts with a range of design duties from 2 to 51MW.

To provide context, a simplified process flow diagram and heater schematic can be found below.

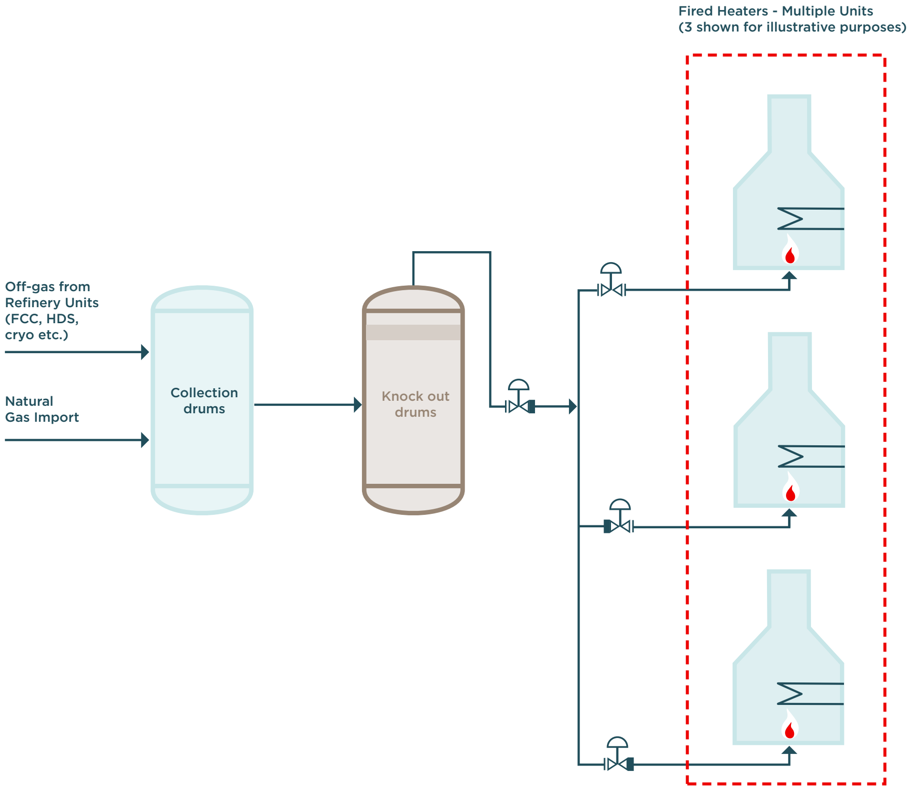

Figure 6:
Simplified Process Flow Diagram

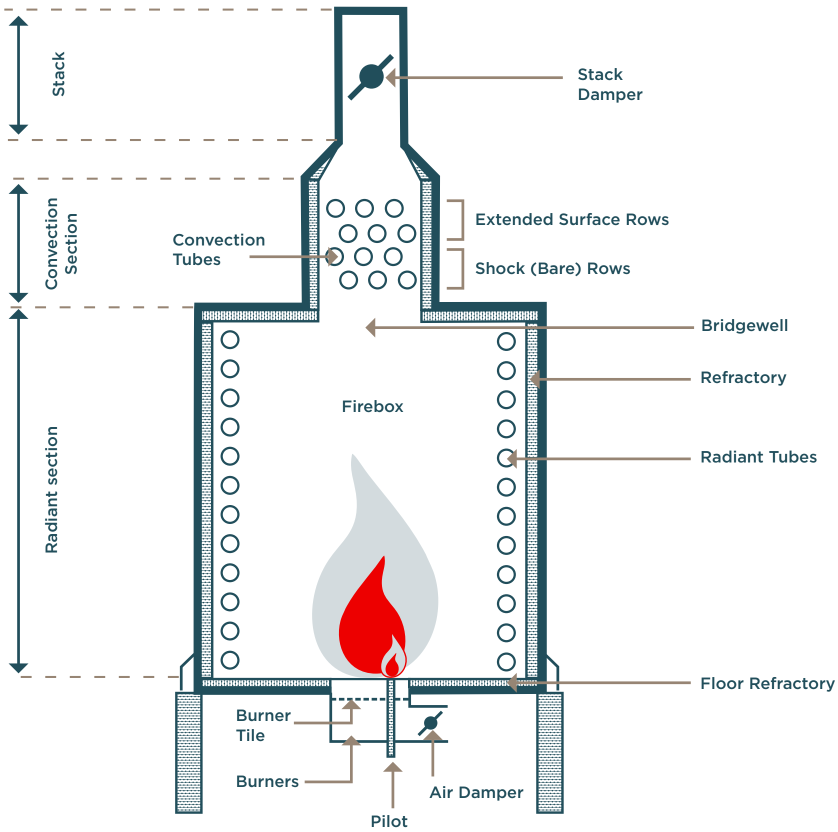

Figure 7:
Simplified Heater Schematic

Note: Instrumentation and Controls omitted for clarity

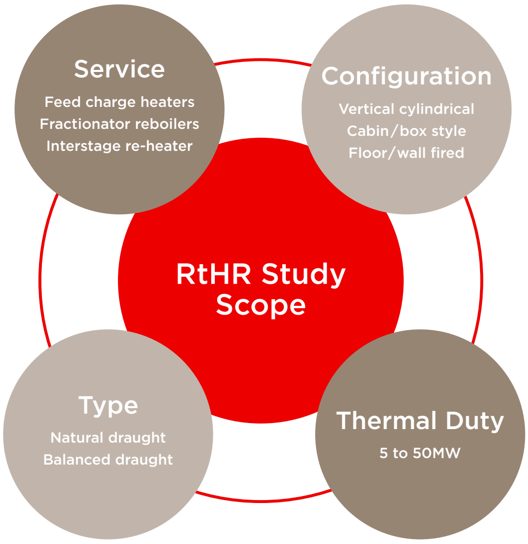

Figure 8:
Humber Refinery's Fired Heaters Considered in RtHR.

4.2. Basis of Design

The basis of design for any fuel switching project will be unique to a particular industrial off-taker and its proposed hydrogen supply. Below are some considerations unique to the Humber Refinery, which informed the scope and key deliverables of the work packages to give a wider context to the RtHR study.

- Refinery fuel gas is predominantly methane-based in composition with similar combustion properties to natural gas; the study findings are, therefore, applicable to other industrial sites exploring fuel switching from natural gas to hydrogen.

Table 2:
Currently Used Fuel

Refinery Fuel Gas		Current
Fuel Temperature	°F	60
Fuel Pressure at Burner Tip	psig	22
Specific gravity		0.64
Density (kg/m^3)		2.0
Molecular Weight		18.5
Lower Heating Value (LHV)	Btu/scf	1012
Cp/Cv @ T		1.3
hydrogen sulfide in ppm	H_2S	40
Component	**Formula**	**vol%**
methane	CH_4	43
ethane	C_2H_6	22
Other hydrocarbons	C_3+	10
hydrogen	H_2	23
oxygen + nitrogen + carbon dioxide	$O_2 + N_2$	2
	Total	**100**

- Hydrogen supply pressure was assumed to be 30barg (420psig), typical for a polymer electrolyte membrane (PEM) electrolysis process.

- Retain capability to provide each fired heater with a unique fuel blend between refinery fuel gas and 100% hydrogen for the below reasons:

    1. Maintain turnaround maintenance independence of refinery process units and hydrogen supply.

    2. Allow fired heater startup and shutdown operational procedures to be carried out on refinery fuel gas.

    3. At the point of setting the basis of design, the maximum permissible hydrogen content in the fuel gas was expected to vary across the fired heaters.

- JZHC recommendation of fuel gas supply pressure to the burner for optimal burner performance.

Further optimisation of this design basis will be undertaken at later stages of project development using the findings of this feasibility study.

4.3. Work Package Scope and Key Deliverables

The methodology for each of the four technical work packages is given in Table 3, including scope and key deliverables.

WP1 – Engineering Study	
Scope	Produce an initial design and capital cost estimate covering the process equipment/piping, process control and instrumentation and burner technologies required to refuel fired heaters with blends up to 100% hydrogen. Worley and JZHC were selected as the engineering contractor and Burner Technology Specialist, respectively.
Key Deliverables	**Worley Engineering Scope** 1. Define hydrogen and refinery fuel gas distribution and supply network to the fired heaters studied. 2. Design key process equipment and instrumentation to maintain the flexibility such that all heaters studied are capable of firing on refinery fuel gas up to 100% hydrogen.

Table 3:
RtHR Work Package Descriptions

WP1 – Engineering Study	
Scope	**3.** Conduct high-level hazardous area classification to assess the impact of proposed RtHR modifications. **4.** Engage analyser vendors and provide technology readiness level assessments for new safety shutdown systems and flame and combustibles detection for blends up to 100% hydrogen. **5.** Complete preliminary assessment of operational transitions from current refinery fuel gas blends up to 100% hydrogen and vice versa. **6.** Consolidate capital cost estimate inclusive of Worley and JZHC engineering scope. **JZHC Engineering Scope** **1.** Provide recommendations for burner modifications/replacements for burners capable of firing on refinery fuel gas up to 100% hydrogen. **2.** Assess the hydraulic impact of varying fuel gas compositions and flow rates up to 100% hydrogen. **3.** Provide updated burner data, capacity curves, general assembly drawings and suggested trip-setting values for up to 100% hydrogen. **4.** Calculation of predicted NO_x emissions considering refinery fuel gas blends up to 100% hydrogen. **5.** Provide recommendations for modifications on the air-side of the burner. **6.** Provide recommendations in terms of flame detection systems (main flame and pilot flame). **7.** Provide recommendations for burner testing. **8.** Estimation of the single burner noise impact of increasing hydrogen for each heater studied. **9.** Deliver budget proposals for all burner upgrade requirements determined by the engineering study.
WP2 – Thermal Rating of Fired Heaters	
Scope & Objectives	Conduct a thermal rating assessment of each of the in-scope fired heaters using FRNC-5PC software for refinery fuel gas and 100% hydrogen boundary cases. Summarise the impacts of fuel switching to 100% hydrogen and identify any limitations to the fired heaters. Thermal rating assessments were carried out by Worley fired heater subject-matter experts (SMEs).
Key Deliverables	**1.** Construct a refinery fuel gas base case FRNC-5PC simulation for each of the fired heaters based on heater geometry, original design data and current process information. **2.** Conduct a "fuel switch" in the FRNC-5PC simulations to 100% hydrogen for each of the fired heaters. **3.** Assess any changes in key operating parameters between refinery fuel gas and 100% hydrogen cases, such as firing rate, heater efficiency, tube skin temperatures, gas-side temperatures, draft, process temperatures, pressure drop, heat duties and fluxes. **4.** Assess the impact on absorbed duty in both the radiant and convection sections (if applicable) for each of the heaters at 100% hydrogen. **5.** Conduct mechanical integrity assessment of fired heater stacks, tubes, tube sheets and refractory.

Table 3:
RtHR Work Package Descriptions

WP3 – CFD Combustion Study	
Scope & Objectives	Conduct 3D CFD modelling for refinery fuel gas and 100% hydrogen boundary cases for four sample heaters across coking, catalytic reforming and hydrodesulphurisation services. JZHC was selected to carry out all CFD modelling.
Key Deliverables	**1.** Build CFD models of selected heaters using fired heater geometry, burner geometry and heater-specific process information. **2.** Predict and assess the flame shape and size, evaluate flame interaction, flame rollover and flame impingement on the process coils for refinery fuel gas and 100% hydrogen cases. **3.** Determine the radiative heat flux distribution (average and maximum), absorbed duty and tube metal temperature contours (average and maximum) on radiant tubes for refinery fuel gas and 100% hydrogen cases. **4.** Assess the flow regime inside the radiant section, including flow direction, areas of turbulence, flow separation, stagnant flow zones, high-velocity zones, overall velocity profiles and streamlines for refinery fuel gas and 100% hydrogen cases. **5.** Produce an overall flue gas temperature, O_2 concentration and carbon monoxide (CO) concentration profile for refinery fuel gas and 100% hydrogen cases.
WP4 – Burner Testing	
Scope & Objectives	Conduct eyewitness testing of existing and modified burners for coking and hydrodesulphurisation services and replacement burners for catalytic reforming service at JZHC's test centre in Luxembourg. Observe performance of burners at increasing percentages of hydrogen from refinery fuel gas up to 100% hydrogen.
Key Deliverables	**1.** Conduct testing for each burner at refinery fuel gas, 75%, 85%, 95% and 100% hydrogen fuel gas blends. **2.** Test each burner with refinery fuel gas and 100% hydrogen for 5:1 turndown minimum duty, typical duty and maximum duty cases. **3.** Assess the difference in performance between current burner designs and modified burner designs optimised for high-hydrogen firing. **4.** Report pressure drop, noise, flame length and NO_x emissions for each burner for refinery fuel gas, 75%, 85%, 95% and 100% hydrogen fuel gas blends.

Table 3:
RtHR Work Package Descriptions

5. Performance Findings

The study's conclusions are broken down by work package, aligning with the methodologies and objectives listed in the previous section.

5.1. Work Package 1 – Engineering Study

5.1.1. Safety Considerations

The project team considered the following areas relating to process safety:

Hazardous Area Classification

Annex B of the Energy Institutes EI15[21] states any mixture containing more than 30vol% hydrogen should be gas group IIC rated. The gas group designation relates directly to the ignition potential (temperature) of a gas mixture. For context, gas group I relates to methane gases and coal dust, whilst gas groups IIA, IIB and IIC (and group III) are categorised according to their different ignition potential. Gas group IIC has a lower ignition temperature. The existing fuel gas system is classified as gas group IIA/IIB; hence, a switch to greater than 30vol% hydrogen content in a fuel gas mixture will require a higher gas group classification versus existing refinery fuel gas. Full hazardous area classification and zoning requirements will need to be reviewed and modified in line with this gas group change to satisfy code requirements.

Pilot Burners

Pilot burners are a primary safety device in fired heaters, which serve as an ignition source for the main burner designed to deliver the process duty. Pilot burners are premix designs that incur the risk of flashback with fuels with a hydrogen content typically greater than 40-50vol%. This is due to the limited velocity of the fuel-air premix and hydrogen having a higher flame speed and higher flammability limit, as shown in Table 4. Pilot burners suitable for hydrogen contents greater than 50vol% are currently not at commercial technology readiness level, and therefore it is recommended to leave pilot burners on the current fuel gas supply. The fuel gas supply to the pilot burners is small in relation to the overall heater duty, typically around 1%, and depends on burner design, firing rate and heater duty. Any CO_2 generated through pilot combustion would be similarly low and should be accounted for in any reported CO_2 reduction from fuel switching.

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Heater Safeguarding and Analysers

The purpose of the fired heater safety system is to prevent the formation of a fuel-rich, explosive atmosphere because of poor combustion or flame-out conditions. The safety system automatically takes action to keep a fired heater in a safe state or put it in a safe state when abnormal conditions are present. The RtHR feasibility study found that when fuelling Humber's fired heaters with a high-percentage hydrogen, there is a requirement to replace fuel-rich atmosphere detection analysers. Analyser technology used at the Humber Refinery focuses on firebox detection of i) low oxygen content, ii) potential combustibles, such as methane and carbon monoxide content. No modifications are anticipated on the oxygen analysers; this will be reviewed at later stages of project development. At 100% hydrogen, there would be no methane or carbon monoxide; therefore, any installed analysers to detect the presence of these combustibles would require replacement. RtHR engaged analyser vendors to assess available technologies commercially available today for 100% hydrogen. A summary of options is given below to be investigated and selected during the next engineering phase.

1. **Flame Detectors With Ultraviolet (UV) Detection –** Monitors for radiation emitted by a hydrogen flame in both the UV and infrared (IR) spectral ranges. Flame detectors are widely used across industry and have been assumed as the base case for RtHR as Humber Refinery currently uses tuneable diode lasers (for detection of methane and carbon monoxide), which are not suitable for 100% hydrogen.

2. **Total Flammability Analysers –** Metered hydrogen pilot flame technology incinerates the extracted sample; the resulting change in flame characteristics is proportional to the total concentration of flammable vapours.

5.1.2. Hydrogen and Refinery Fuel Gas Supply, Distribution and Blending

An assessment of several options for the supply of hydrogen and refinery fuel gas to the fired heaters was undertaken using the basis of design outlined in Section 4.2.

Hydrogen

Due to the low-volumetric energy density of hydrogen compared to other fuels, to maintain burner duty, the flow rate of hydrogen must be around three times higher than refinery fuel gas. The hydrogen supply pipework must, therefore, be larger in diameter and operate at a higher pressure. Therefore, a new hydrogen header with subheaders to each of the fired heaters will be required. Distributing hydrogen to the fired heaters at the highest available supply pressure reduces the line sizing requirements, making routing of pipework through congested areas easier and minimising capital costs.

As a result of Work Package 1, a preliminary hydrogen supply route was established with the main header entering at the eastern boundary of the Humber Refinery before splitting off to each of the fired heater groups, as shown in Figure 9. The hydrogen subheaders have been designed to utilise existing pipe racks to minimise capital cost for civil and structural infrastructure.

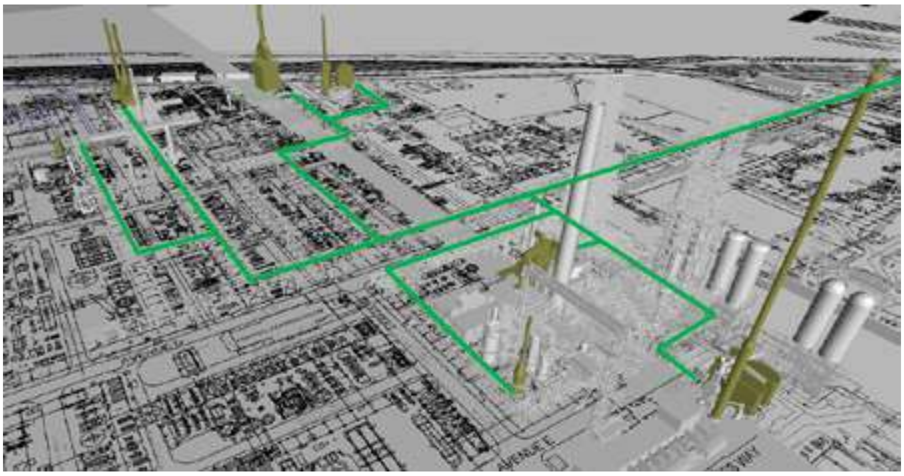

Figure 9: RtHR Hydrogen Pipeline Suggested Route

Refinery Fuel Gas

Humber Refinery's current fuel gas system operates below the JZHC recommended fuel gas supply pressure to the burner in a hydrogen blend firing case, and therefore it would not be possible to achieve the required pressure at the burners for high-hydrogen blends. To maintain the design flexibility required for high-hydrogen firing, a higher pressure refinery fuel gas distribution header will be included as part of the project scope and will also use existing pipe racks. It is important to note that (i) 85vol% hydrogen in the fuel blend is the point where the highest supply pressure to the burners is required based on the provisional heat release capacity curves provided by JZHC and (ii) modifications to the current fuel gas supply should be considered on a case-by-case basis for fuel switching. An example heat release capacity curve of an existing burner in the study is shown below for illustrative purposes.

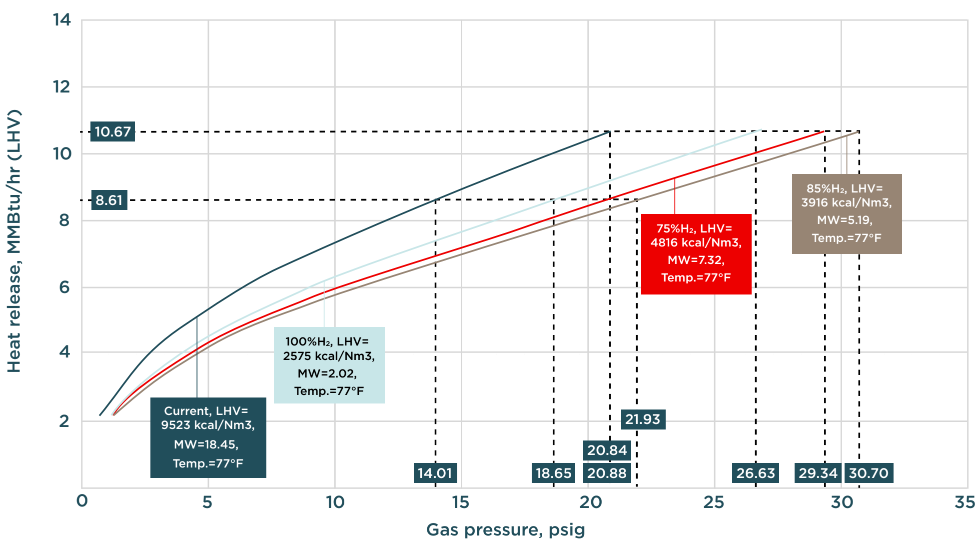

Figure 10: Example Heat Release Capacity Curve for an Existing Humber Refinery Burner

Blending

The new hydrogen and refinery fuel gas headers would deliver fuel locally to each fired heater group, having its own dedicated hydrogen and refinery fuel gas let-down arrangement and a dedicated blending control station. Ratio control would be used to deliver the required hydrogen blend. Providing dedicated blending stations locally to each fired heater provides operating flexibility to supply different hydrogen/refinery fuel gas ratios to each heater or set of heaters as required. Prior to the blending stations, new knockout drums would be installed on the refinery fuel gas supply to recover liquid hydrocarbons and prevent liquid slugs from reaching the burners.

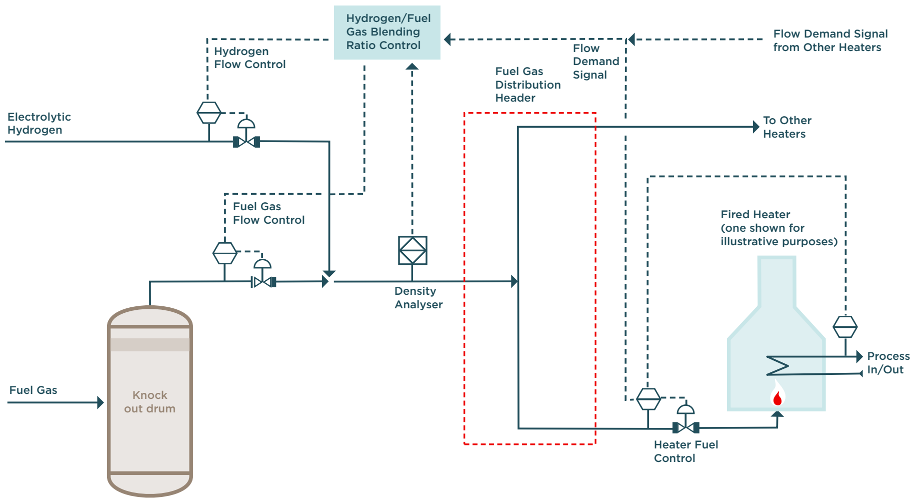

Figure 11: Typical Blending Station Arrangement

Note: Typical for overall blending station; may utilise individual blending arrangements per heater or group of heaters

A single centralised blending station and distribution header was also considered to supply all fired heaters with the same hydrogen blend; this would reduce the piping/instrumentation requirements and, thus, the capital costs. At this stage, the operational flexibility of dedicated blending stations for each fired heater group is the preferred engineering option for use within the cost estimate. Further optimisation of this design basis will be undertaken at later stages of project development using the findings of the RtHR feasibility study.

The sizing of piping downstream of the blending station is based on 100% hydrogen due to the low volume-based heat release of hydrogen versus refinery fuel gas. Piping local to the fired heaters is expected to be a similar configuration as today, with pipe diameters increasing by approximately 50% to 100% to accommodate the additional volumetric flow rate to the burners.

Plot Space Considerations

Work Package 1 produced an initial design demonstrating that the site plot space required for fuel switching industrial fired heaters is relatively small and can be accommodated within congested sites such as the Humber Refinery. Plot space should be considered on a case-by-case basis for any industrial fuel switching application.

5.1.3. Burner Engineering Study

General Considerations for Hydrogen Firing

Hydrogen has specific properties that differentiate it substantially from hydrocarbon fuels. Below are some of the key considerations:

- Hydrogen has a lower LHV on a volume basis when compared to refinery fuel gas. Thus, the fuel flow to achieve the same heat release is higher, approximately 3.3 times.
- As the volumetric flow rate of hydrogen is higher, a higher burner supply pressure is required to achieve the same duty.
- Hydrogen has a higher flame speed and higher flammability limit, which increases the stability of diffusion burners. These properties make premix burners and pilots unsuitable for hydrogen contents, typically above 40-50vol%.
- Hydrogen burns at a higher temperature, which has the potential to impact mechanical integrity and, thus, material selection of both the burner and fired heater internals.
- Due to hydrogen burning at a higher temperature, thermal NO_x generation directionally increases. The hydrogen percentage with the highest NO_x generation is dependent on the burner technology in service and should be considered on a case-by-case basis.
- Hydrogen has a lower stoichiometric air requirement versus methane; the higher the hydrogen content in the fuel gas, the lower the amount of air to be provided to the burner.
- Increasing the hydrogen percentage in the fuel gas impacts the fuel gas pressure required at the burner due to changes in fuel gas molecular weight and the fuel amount required. Burner testing by JZHC showed that 85vol% hydrogen is the case where the highest delivery pressure is required (based on the compressible flow equation the fuel gas pressure is dependent to the ratio between the fuel gas mass flow and molecular square root).
- Hydrogen combustion produces higher noise levels at the burner compared to hydrocarbon fuels due to the higher generated flame speed and increased volumetric flow rates in piping systems.

Variable	Methane (CH_4)[1]	Hydrogen (H_2)
Molecular Weight	16	2
LHV (MJ/Nm3)	36	11
LHV (MJ/kg)	46	120
Adiabatic Flame Temperature (°C)	1880	2050
Max Flame Speed (cm/s)	45	325
Flammability Range (vol% air)	5-15	4-74
Air Consumption (Nm3/Gcal)	1111	870

Table 4:
Key Property Comparison of Methane Versus Hydrogen

[1] Note methane has been used as a proxy for refinery fuel gas.

Retrofitting Versus Replacement of Burners

The RtHR study has determined the burner modifications required for each of the heaters studied at the Humber Refinery. Of the fired heaters studied, five heaters' burners could potentially be retrofitted with modified tips, with the remaining 11 fired heaters requiring full burner replacements. This is site-specific and should, therefore, be considered on a case-by-case basis, exploring burner technologies deployed and any regulatory operating requirements; for example, those detailed by the Large Combustion Plant Best Available Technology Reference documents. Some general considerations for retrofit versus replacement of burners are outlined below:

- Burners with premix technologies may not be suitable for hydrogen contents typically above 40-50vol% and could require full replacement.

- Certain burner technologies are unable to achieve the desired site-specific NO_x targets or flame stability and may require full replacement for high-hydrogen content firing.

- Burners capable of achieving the desired NO_x targets may require modifications to the gas tips to ensure the fuel gas pressure at maximum heat release of the limiting case (85vol% hydrogen) is within the maximum available site pressure.

- Generally, for a given burner, firing high-hydrogen contents results in increased NO_x due to increased generation of thermal NO_x. However, replacing previous generations of burner technology (premix, low NO_x) with the latest generation ultra-low NO_x burners can result in a reduction of NO_x generation across all fuel gas blend compositions. Upgrading previous generation burner technology to latest ultra-low NO_x burners presents a betterment opportunity in terms of reduced NO_x generation.

5.1.4. Summary of Potential CO_2 and NO_x Emissions Savings

In this feasibility study, Phillips 66 Limited considered refuelling the fired heaters with up to 100% hydrogen, which could potentially reduce Humber Refinery's carbon emissions by 350,000 to 450,000Mt CO_2 per annum, depending on refinery operation. This represents approximately 20% of the overall refinery's carbon emissions. Figure 12 demonstrates the exponential relationship between the hydrogen content in the fuel gas and the associated reduction in CO_2 emissions. Referring to Figure 12, a high level of carbon dioxide reduction through hydrogen fuel switching requires a very high-hydrogen percentage; for example, to achieve a 90% reduction in CO_2 emissions, it is necessary to refuel to 97vol% hydrogen in the fuel gas blend. This is due to low volume-based heat release of hydrogen versus refinery fuel gas. It is important to note that the Humber Refinery typically operates at approximately 23vol% hydrogen in the refinery fuel gas.

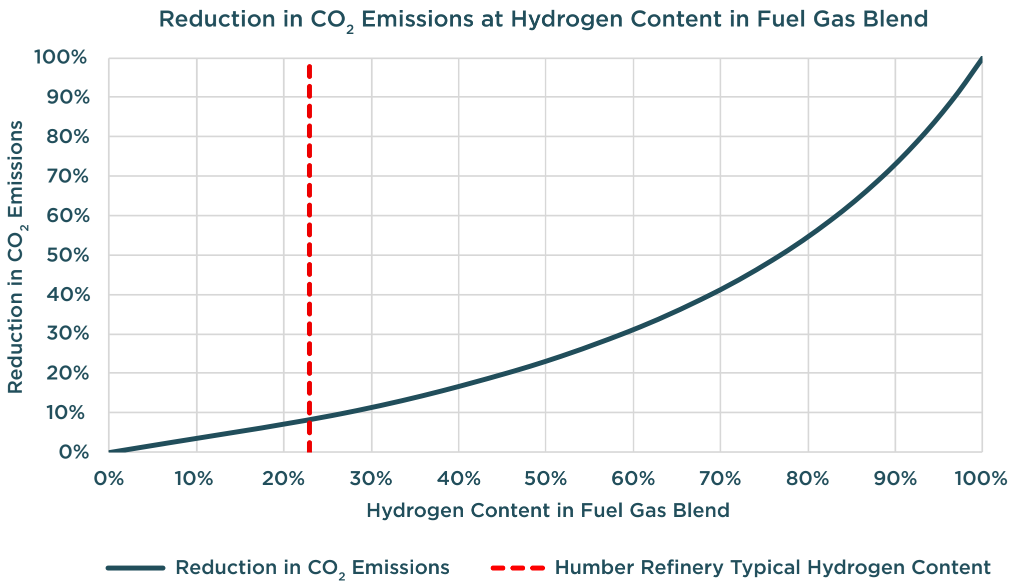

Figure 12: Reduction in CO_2 Emissions at Hydrogen Content in Fuel Gas Blend With Humber Refinery's Typical Hydrogen Content Shown at 23vol%

Regarding NO_x the RtHR feasibility study indicates that Humber Refinery would remain within the permissible NO_x levels specified in the refinery's environmental permit to operate.

5.2. Work Package 2 – Thermal Rating of Fired Heaters

Work Package 2 included thermal rating assessments of each of the fired heaters using FRNC-5PC software for refinery fuel gas and for 100% hydrogen boundary cases. A base case simulation was developed for each of the fired heaters using heater geometry measurements, original design data and current process information. The model was calibrated, simulating refinery fuel gas, and then used to model a fuel switch to 100% hydrogen. The FRNC-5PC modelling was configured to match the radiant section duty to ensure the required process duty was met. A summary of key findings is given below. The percentage change in key fired heater parameters from refinery fuel gas to hydrogen is given below in Table 5. FRNC-5PC modelling does not address the impact of fuel switching on the burner and for the purpose of FRNC-5PC modelling, it is assumed the burners are capable of operating at 100% hydrogen.

- The results of the FRNC-5PC modelling determined that it is thermally possible to fuel switch fired heaters from refinery fuel gas to 100% hydrogen firing.

- In all heaters modelled, the radiant section (process) duty could be matched to required performance, with a slight increase in thermal efficiency of up to 2% with 100% hydrogen firing.

- The flue gas mass flow rate decreases in all cases by approximately 15% to 25%, resulting in a reduction in convection section duty of 5% to 15%. This would reduce convection section duty for services, such as process preheat, boiler feedwater preheat, steam generation, steam superheat or air preheat. The wider impact of this change should be considered in any fuel switching project.

- Options to reduce the impact on convection section duty could include i) running at higher excess air ii) modifying the fired heater to allow recirculation of flue gas. Both options increase the mass flow rate to the convection section but increase fuel consumption. The impact on NO_x emissions should be assessed for both options.

- Key physical parameters, such as bridge wall temperature (temperature measured at the transition point from radiant to convection section in a fired heater) and tube metal temperature (surface temperature of radiant tubes), remained within specified design parameters; thus, indicating minimal impact on mechanical integrity of the fired heater internal trim. This will be reviewed further at later stages of project development.

Table 5: Key Property Comparison of Methane Versus Hydrogen

Parameter	% Change Refinery Fuel Gas Versus Hydrogen
Thermal Efficiency	+ 0.5% to + 2%
Flue Gas Mass Flow Rate	- 15% to - 25%
Radiant Section Duty	+/- 0.5% (Matched)
Convection Section Duty	- 5 to -15%
Bridge Wall Temperature	+ 0.5 to + 3%
Tube Metal Temperature	+/- 2%

5.3. Work Package 3 – CFD Combustion Study

5.3.1. General Findings

JZHC was selected to carry out CFD combustion studies on four fired heater groups across coking, catalytic reforming and hydrodesulphurisation services. The CFD models were built using fired heater geometry, burner geometry and heater-specific process information. The models were run for refinery fuel gas and 100% hydrogen boundary cases. The findings of this CFD study are unique to each burner and heater configuration. A summary of general findings applicable across all heaters is outlined below:

- A 100% hydrogen flame is more compact and has a shorter flame length versus a refinery fuel gas flame for a given set of operating conditions. This is a result of hydrogen having a higher flame speed, as discussed previously. No significant differences in flame interaction were observed between refinery fuel gas and 100% hydrogen cases.

- Reviewing the CFD results, no impingement of the flame approximation on the process tubes and fired heater walls has been observed across all fired heaters modelled. This was indicated by using a reasonable flame approximation for refinery fuel gas and hydrogen firing, combined with an in-depth investigation of flue gas recirculation patterns and flue gas temperature profiles within the radiant section.

- For a given burner heat release, there is an increase in radiant section thermal efficiency for each heater, as seen in the FRNC-5PC modelling in Work Package 2.

- For some fired heater cases, upgrading to the latest generation of burner technology improved flue gas recirculation, firebox velocity/oxygen profiles and gave a more uniform heat flux distribution across the firebox.

- Average and peak tube metal temperatures were within +5% delta from refinery fuel gas to the 100% hydrogen case, with all heaters modelled remaining within metallurgy design limitations, albeit with some potential impact on tube life introduced by operating at higher tube metal temperatures (TMT).

5.3.2. Distillate Hydrodesulphurisation Fractionator Reboiler Example Case Study

An example CFD case study is presented below for Humber Refinery's distillate hydrodesulphurisation fractionator reboiler. This fired heater is a vertical, cylindrical, natural draft heater with 15 floor fired burners. The design has six vertical radiant passes and three rows of bare shock tubes prior to the convection section located at the outlet of the radiant section. A summary of the heater geometry is given in Figure 13 below. Figure 14, Figure 15 and Figure 16 show an infographic summary of the distillate hydrodesulphurisation fractionator reboiler, demonstrating the above general findings.

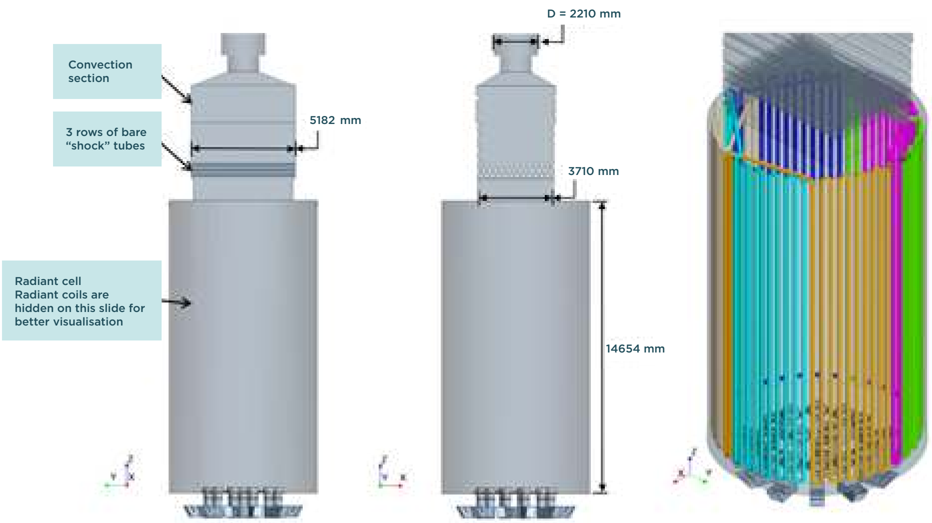

Figure 13: Heater Geometry for Distillate Hydrodesulphurisation Fractionator Reboiler

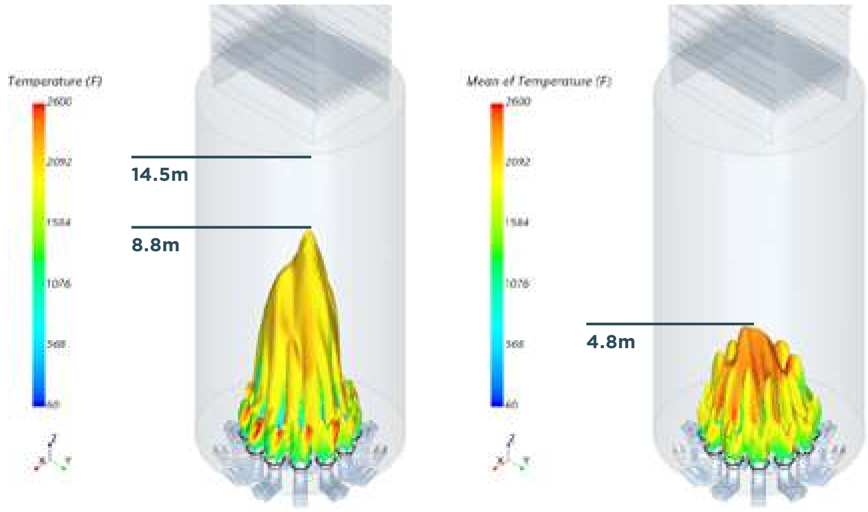

Figure 14:
Comparison of Flame Temperature, Length and Shape for Refinery Fuel Gas (left-hand side) and 100% Hydrogen (right-hand side)

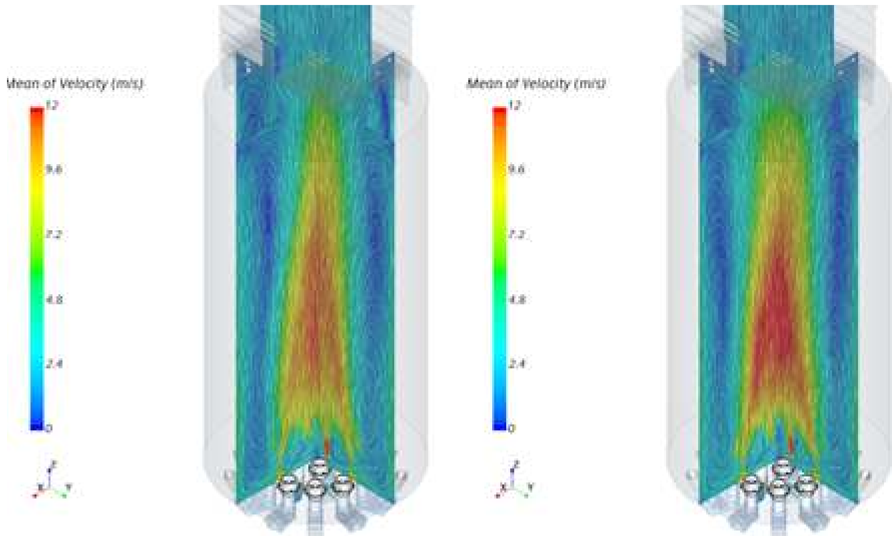

Figure 15:
Comparison of Flue Gas Velocity and Recirculation Pattern for Refinery Fuel Gas (left- hand side) and 100% Hydrogen (right-hand side)

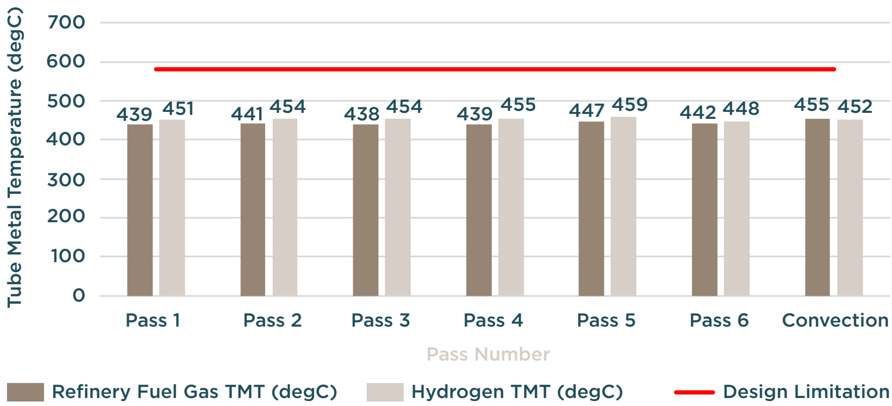

Figure 16:
Comparison of Maximum Tube Metal Temperature (TMT) for Refinery Fuel Gas and 100% Hydrogen

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5.4. Work Package 4 – Burner Testing

The project team conducted eyewitness testing of modified burners for coking and hydrodesulphurisation services and replacement burners for catalytic reforming service at JZHC's test centre in Luxembourg.

A summary of the testing findings is given below:

- Confirmed CFD modelling results show that a 100% hydrogen flame burns hotter with a more compact and shorter flame length versus a refinery fuel gas flame.
- Flames remain largely visible when operating in high-hydrogen firing cases, albeit with a different colour with some loss of peripheral definition as shown in Figure 17 .
- All burner models tested met performance expectations across refinery fuel gas, 75vol%, 85vol%, 95vol% and 100% hydrogen fuel gas blends.
- All burner flames demonstrated stability across minimum (5:1 turndown), typical and maximum duty firing cases for refinery fuel gas and 100% hydrogen fuels.
- Key test parameters remained within defined objectives for all fuel blends considered:
    - Burner air-side pressure drop <15.2mm H_2O at maximum firing rate with register fully open.
    - Noise <85dBA at 1m.
    - NO_X emissions <80mg/m^3 at maximum and normal firing rate when corrected to 3vol% O_2 dry.
- Modifications to existing burners are required to optimise them for high-hydrogen blends in terms of delivering the fuel gas pressure requirements predicted in the engineering study, refer to Figure 18.

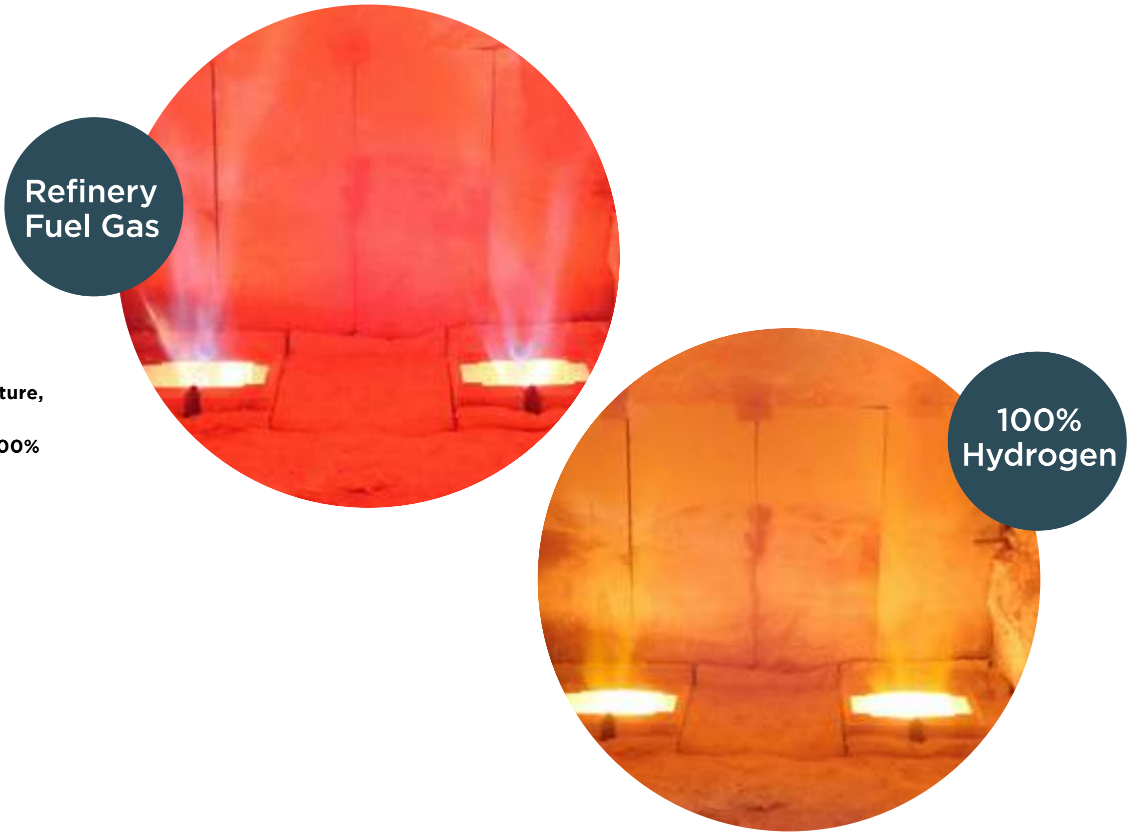

Figure 17:
Comparison of Flame Temperature, Length and Shape for Refinery Fuel Gas (left-hand side) and 100% Hydrogen (right-hand side)

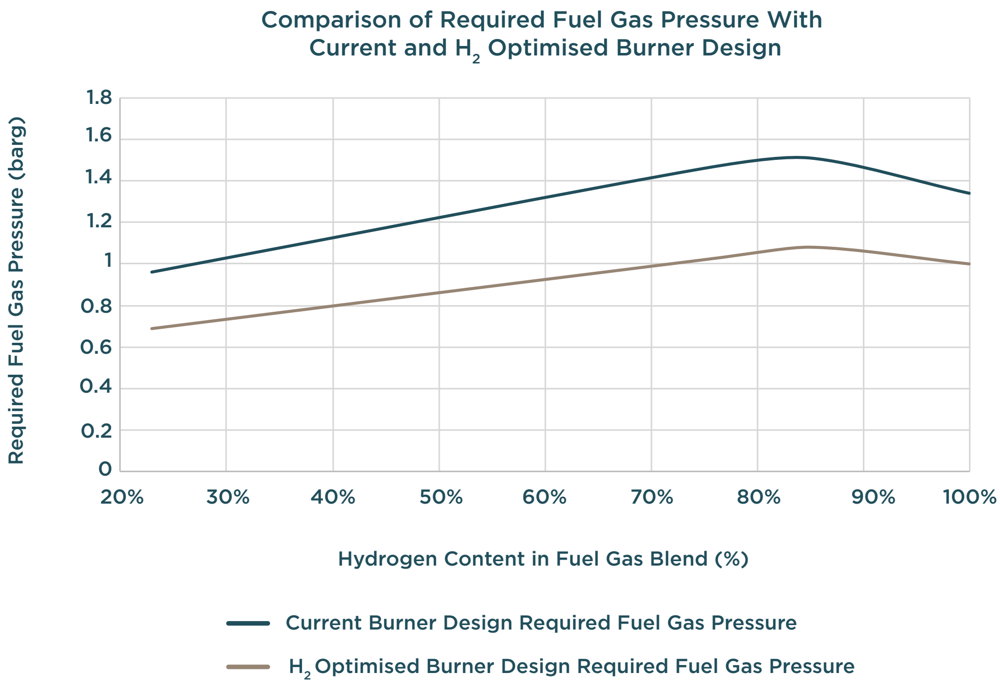

Figure 18:
Example Comparison of Required Fuel Gas Pressure With Current and H_2 Optimised Burner Design

6. Techno-Economic Assessment

Relative to the capital and operating costs associated with electrolytic and CCUS-enabled hydrogen production facilities, the costs of industrial refuelling are of a lesser scale. However, such costs are still significant and represent a key uncertainty to UK industry, given that they sit outside of the proposed Hydrogen Business Model (the business model). This business model de-risks and incentivises the production of hydrogen, but not the off-take and usage.

Under the business model, the hydrogen off-taker receives the hydrogen at a price that is at the energy-based equivalent of its existing fuel (the counterfactual). However, there is a floor which represents the lowest price that the hydrogen producer can sell to the off-taker. This will be set on a natural gas price equivalence basis. For the Humber Refinery, this represents a financial debit as its existing fuel - which would be replaced by hydrogen - is valued at below natural gas, as the existing fuel is produced as a "by-product" of refinery operations. On an energy equivalent basis, hydrogen to the Humber Refinery (under the business model) is expected to be significantly higher per unit (£/MWh) than today.

This additional cost for the hydrogen fuel, as well as the capital costs within the refinery system boundary, are not covered within the Government funding mechanism. Therefore, the incentive for the off-taker is in the CO_2 emissions reduction related to the hydrogen refuelling.

In addition to supporting Phillips 66 Limited and other industrial users in reaching their decarbonisation goals, it is expected that these emission reductions will create value under the UK Emissions Trading Scheme (ETS). It is anticipated that the hydrogen consumers will retain their free allowances relating to gas firing and, where refuelled with hydrogen, will be able to monetise these against other emissions. This value can then be used to offset the higher costs highlighted above. It is Phillips 66 Limited's expectation within RtHR that the associated free allowance value generated by hydrogen refuelling will be sufficient to cover both the capital costs at the refinery and the higher fuel pricing.

6.1. System Boundaries

The system boundaries for this assessment are given in Figure 19 and align with the boundaries of the industrial site used within this study. This shows the incumbent business case with natural gas (NG) feeding the industrial heaters, with CO_2 and heat as the products. The new business case includes a dedicated hydrogen supply and a new pipeline that feeds the modified heaters. Once 100% refuelled, no CO_2 emissions are generated from the heaters[22].

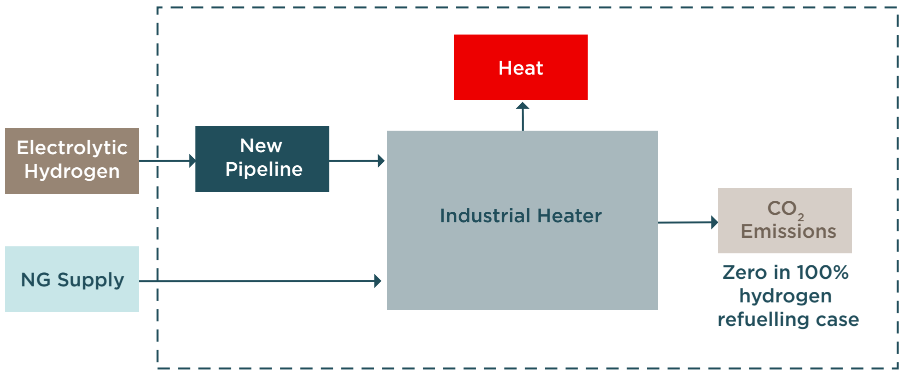

Figure 19: Techno-Economic System: System Boundaries

6.2. Analysis

6.2.1. Capital Expenditure (CAPEX)

The CAPEX to achieve 100% hydrogen firing includes new heater equipment (e.g. burners, instrumentation and flame scanners), heater modifications (e.g. refractory reconfiguration), as well as new hydrogen and refinery fuel gas distribution pipelines. The breakdown by component for the proposed RtHR deployment is presented in Figure 20 relative to the total installed cost. The physical materials and equipment costs represent 28% of the total installed costs, whereas the remaining 72% comprises the costs associated with engineering design and execution of the project scope of works to deliver fuel switching.

Some of the key findings from the project were:

- In all cases, Phillips 66 Limited expects that the industrial heaters can be retrofitted to fuel switch with hydrogen; thus, avoiding the large capital (approximately 10 times more expensive) to fully replace the heater.
- As a percentage of the capital costs for an electrolytic hydrogen production facility, the additional costs associated with industrial refuelling are in the order of 15% to 40%.

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- Upgrading all heaters to utilise flame detector and total flammability analyser technologies, essential for safe operation, may represent a significant proportion of the total material costs for refuelling. In the Humber Refinery's case, this is in excess of 50% of the materials cost to fuel switch.

- Capital expenditure with respect to specialist technology providers (burners, analysers) is relatively modest and a considered prudent investment for de-risking the fuel switching of heaters.

Whilst the cost of delivering fuel switching to hydrogen is a relatively small cost component compared to the cost of installing a dedicated hydrogen production facility, the initial investment to fuel switch may present a significant hurdle for many industrial sites.

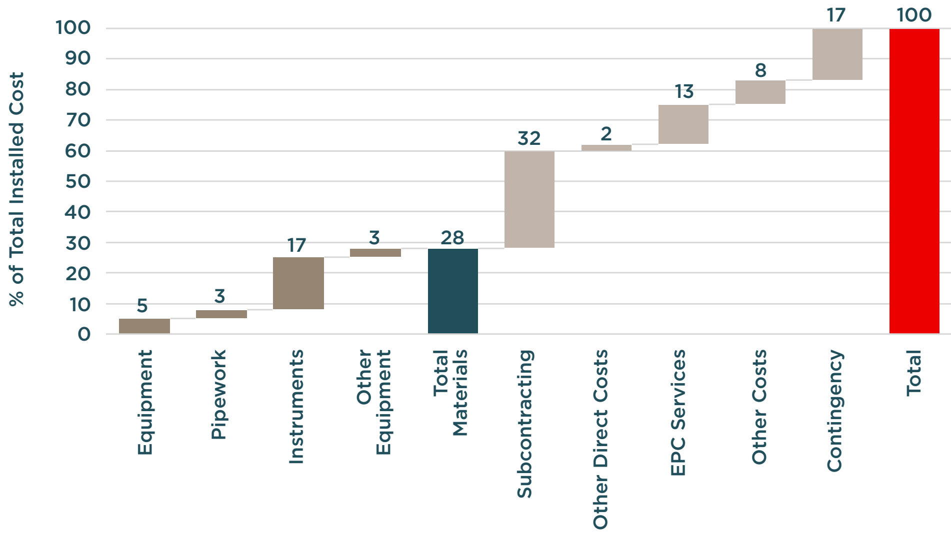

Figure 20:
Total Installed Cost by Component (other equipment includes electrical, control systems, spares and packaging and delivery)

6.2.2. Cost of Abatement

As mentioned in section 5.1.4., 100% refuelling of the 16 fired heaters, considered within this study with hydrogen, could potentially reduce the Humber Refinery's carbon emissions by approximately 350,000 to 450,000Mt CO_2 per annum. Based on the total estimated capital for heater conversions and provision of hydrogen delivery infrastructure (piping from hydrogen supply and fuel blending stations), the cost of CO_2 abatement is around £10/Mt. It should be noted that this represents purely the within-refinery boundary cost of abatement and excludes the cost of production for the hydrogen source to refuel the heaters.

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7. Supply Chain, Skills and Technology Readiness

Through the development of the RtHR study, it has become apparent that the majority of the scope of work and skill base required to deliver fuel switching on large-scale fired heaters is within current industry capabilities. Hydrogen supply infrastructure and controls are commonplace and widely used throughout the refining and petrochemical industry. Advances in burner technology are at a level of maturity that will allow conversion of existing systems to fire high-hydrogen fuel mixes and designs are continuing to be optimised. Note that the pilot burners suitable for high-hydrogen-content fuels (> 50vol%) are not currently commercially available.

In summary, the study has shown that no special or new technology is required to deliver large-scale fuel switching.

One area that does require further development is advancing technology options for firebox combustion analysis. The use of flame scanners is well-established technology for monitoring and safe operation of fired heaters and such scanners can be adapted or replaced to work with high-hydrogen flames. Applications that currently utilise fuel-rich atmosphere detection analysers in the firebox to initiate safety shutdown systems require additional considerations and technology development to provide equivalent functionality in high-hydrogen firing. This is a key area where the end users can work with the technology providers to enhance and develop atmospheric detection analysers.

As a large-scale producer and consumer of hydrogen, Phillips 66 Limited is ideally placed to develop and implement the technology required for fuel switching to hydrogen. The refinery has over 50 years of experience with the design, operation and maintenance of high-purity hydrogen systems and industrial fired heaters, with expertise in safe handling of this material. It is anticipated that other facilities similar to the Humber Refinery would have in-house hydrogen expertise and that this can be leveraged for similar fuel switching applications.

Humber Refinery

8. Further Advancing Hydrogen Fuel Switching

Phillips 66 Limited is progressing to the next stage of project development following the successful outcomes from this feasibility study.

The commercial justification for implementation of fuel switching at the Humber Refinery is contingent on a further review being carried out on the economic case. Hydrogen refuelling will reduce the refinery's carbon dioxide emissions and should lower its costs incurred through the UK Emissions Trading Scheme (ETS); however, hydrogen is likely to be a more expensive energy vector than refinery fuel gas for the foreseeable future. The hydrogen business model is focused on hydrogen producers and does not provide support for the investment required by off-takers to enable fuel switching. The capital investment required to convert the heaters to hydrogen firing would need to be assessed and balanced against the benefits from lower-carbon emissions under ETS. The economic case for this technology needs further review in the next stage of the project. Additional grant funding or revenue support for the capital investment would support the economic case and would reduce the risk associated with early deployment of the technology, as well as reduce the risk around uncertainty in the carbon market and lower-carbon products market.

The following technical items have been identified as requiring further consideration as the project progresses:

1. Conduct an operability review to assess heater operational transitions (planned and unplanned) from refinery fuel gas to hydrogen firing and vice versa. The transition between fuels needs careful consideration due to the change in combustion air requirement which, if not controlled, could result in low-firebox oxygen contents and subsequent activation of the heater safety shutdown system. Assess the feasibility of 100% hydrogen-fired heater startup/shutdown procedures.

2. Further detail the implications of hydrogen fuel switching on hazardous area classification and heater safeguarding systems.

3. Assess the impact of the reduction in fired heater convection section heat duties and the wider implications to Humber Refinery's sitewide utility balance.

4. Conduct a detailed constructability review to further optimise locations of additional process equipment, such as knock-out drums and blending stations. Assess how construction timelines can be optimised to minimise the impact on maintenance turnaround timings and durations.

5. Review the feasibility of a single, centralised blending station and distribution header as opposed to heater group dedicated blending stations to reduce the piping/instrumentation requirements and thus the capital cost.

6. Consider changing hydrogen blends in step increments to minimise risk, increasing hydrogen blends in a planned campaign, rather than binary switch.

7. Conduct a further constructability review. Minimise duration for required modifications.

"In addition to the evaluation of the cost-benefit (capital-ETS savings) associated with heater fuel switching, the Humber Refinery (hydrogen off-taker) takes on the operational risk associated with converting the heaters to hydrogen firing. Any project should consider this operational risk in conjunction with the cost-benefit of fuel-switching, and ensure end-to-end consideration between hydrogen provider and off-taker."

References

1 Now known as The Department for Energy Security and Net Zero (DESNZ).

2 The International Panel on Climate Change (IPCC) uses the reference period 1850-1900 to represent preindustrial temperature. This is the earliest period with near-global observations and is the reference period used as an approximation of preindustrial temperatures in the IPCC Fifth Assessment Report.

3 HMG, UK becomes first major economy to pass net-zero emissions laws, 2019

4 HMG, UK enshrines new target in law to slash emissions by 78% by 2035, 2021

5 Element Energy Deep Decarbonisation Pathways Report 2020

6 CCC, UK Sixth Carbon Budget, 2020

7 BEIS, UK Hydrogen Strategy, 2021

8 Element Energy, HICP Water Study, 2022

9 Water demand for hydrogen production varies based on the amount of water needed for cooling and the degree of water pre-treatment before use. The in-text values account for water losses from raw water pre-treatment and the water demand for cooling. This results in a much higher actual water demand than the stoichiometric limits for hydrogen production from each route, which are: electrolytic hydrogen: ~9l/kgH_2; CCUS-enabled Hydrogen: ~4.5l/kgH_2.

10 BEIS, Cluster Sequencing Programme, 2021

11 British Energy Security Strategy 2022

12 BEIS, Net Zero Hydrogen Fund, 2022

13 UK Government Energy White Paper

14 UK Government 10 Point Plan

15 UK Industrial Decarbonisation Strategy

16 Phase 2 of the IETF provided grant funding for feasibility and engineering studies, and for the deployment of industrial energy efficiency and deep decarbonisation projects. These projects will build on the lessons learnt from Phase 1. The competition began in 2022, and projects are scheduled to begin by 2023 and conclude by 2025.

17 Lowe, Cliff, et al., Technology assessment of hydrogen firing of process heaters, 2011

18 HyNet, Industrial Fuel Switching Feasibility Study, 2020

19 Ditaranto, Mario, et al., Performance and NOx emissions of refinery fired heaters retrofitted to hydrogen combustion, 2013

20 H-vision, Feasibility Study: Blue hydrogen as an accelerator and pioneer for energy transition in the industry, 2019

21 EI Model Code of Safe Practice, Part 15

22 This Techno-Economic Assessment details the requirements within the system boundaries as shown and does not address refinery off-gases displaced by the new hydrogen supply.

Glossary

°C
Degrees Centigrade

°F
Degrees Fahrenheit

ATR
Auto Thermal Reformer

barg
Unit for the measurement of gauge pressure

BEIS
Department for Business, Energy and Industrial Strategy

Btu/scf
British thermal unit per standard cubic foot, measure of energy density

CAPEX
Capital expenditure

CCC
Climate Change Committee

CCUS
Carbon Capture, Utilisation, and Storage

CFD
Computational Fluid Dynamics

CH_4
Methane

cm/s
Centimetres per second, unit of flame speed

CO
Carbon monoxide

CO_2
Carbon dioxide

Cp/Cv @ T
Specific heat ratio

dBA
Unit of measurement for noise, decibels absolute

ECITB
Engineering Construction Industry Training Board

ETS
(UK) Emissions Trading Scheme

EU
European Union

FRNC-5PC
Thermal rating tool used for heater modelling

GHR
Gas Heated Reformer, can work in combination with ATR

GW
Gigawatt, unit of electrical power

GWth
Gigawatt unit of thermal power

H_2
Hydrogen

H_2O
Water

H_2S
Hydrogen Sulfide

HHV
Higher heating value, gross thermal energy produced by the complete combustion of fuel

IETF
Industrial Energy Transformation Fund

IFS
Industrial Fuel Switching

IR
Infrared

JZHC
John Zink Hamworthy Combustion (burner specialist)

kg
Kilogram, unit of mass

kg/m^3
Kilograms per metre cube, unit for the measurement of density

kWh_{HHV}
Kilowatt hour, rate of power/energy, higher heating value basis

LHV
Lower heating value, net thermal energy produced by combusting a specified quantity of fuel

MJ/kg
Megajoules per kilogram, specific energy density mass basis

MJ/Nm³
Megajoules per normal cubic metre, specific energy density volume basis

MMbtu/hr
Million British thermal units per hour, energy release/input rate

Mt
Metric tonne

MW
Megawatt, unit for the measurement of power/energy

MWe
Megawatt electric, unit for the measurement of electrical power

MWh
Megawatt hour, rate of power/energy

MWh_{HHV}
Megawatt hour, rate of power/energy, higher heating value basis

NAEI
National Atmospherics Emissions Inventory

NG
Natural Gas

Nm³/Gcal
Normal cubic metre per giga calorie, volumetric air consumption per energy input

NO_x
Nitrogen/nitrous oxides

NZHF
Net Zero Hydrogen Fund

O_2
Oxygen

OPEX
Operating expense

PEM
Polymer electrolyte membrane

ppm
Parts per million, fractional unit of measure for concentration

ppmvd
Parts per million volume dry, fractional unit of measure for concentration on a dry basis

psig
Pounds per square inch gauge, unit for the measurement pressure

RtHR
Refuelling the Humber Refinery

SAF
Sustainable Aviation Fuel

SME
Subject-matter expert

SMR
Steam methane reforming

tCO_2
Metric tonnes of carbon dioxide

TMT
Tube metal temperature

tpd
Metric tonnes per day, unit of measurement of mass flow

UK
United Kingdom

UKRI
United Kingdom Research and Innovation

UV
Ultraviolet

vol%
Volumetric percentage

Contact decarbonisation@P66.com
for more information.

Humber Refinery

PROVIDING ENERGY. IMPROVING LIVES.