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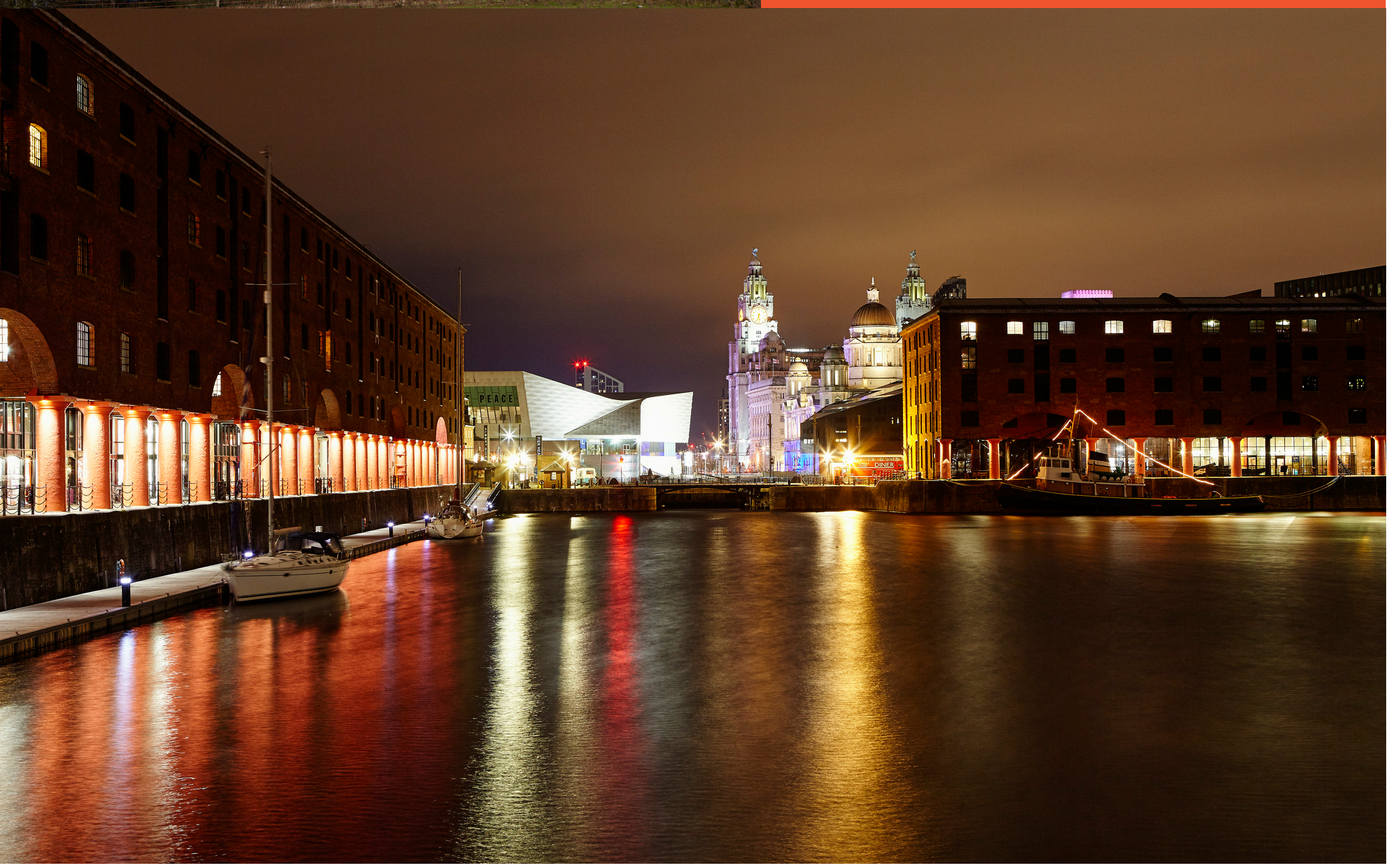
HyNet Industrial Fuel Switching

Feasibility Study



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GLOSSARY

ATR	Autothermal Reformer
BECCS	Bio-Energy Carbon Capture and Storage
BEIS	Department for Business, Energy & Industrial Strategy
CAG	CCS Advisory Group
CAPEX	Capital Expenditure
CCC	Committee on Climate Change
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
CHP	Combined Heat & Power
CO_2	Carbon Dioxide
EPC	Engineering, Procurement and Construction
EPCM	Engineering, Procurement and Construction Management
FEED	Front End Engineering Design
FID	Final Investment Decision
GT	Gas Turbine
GVA	Gross Value Added
HGV	Heavy Goods Vehicle
OPEX	Operational Expenditure
PEL	Progressive Energy Limited (also Progressive)
RIIO	Revenue = Incentives + Innovation + Outputs
ROG	Refinery Off-Gas
SMR	Steam Methane Reformer

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1.0 Introduction And Objectives

This report summarises the Feasibility Study for the HyNet Industrial Fuel Switching (IFS) project, which was funded under Lot 2 ('clusters') of the Department for Business, Energy and Industrial Strategy's (BEIS) Phase 2 IFS Competition. This work was undertaken by a consortium comprising project developer Progressive Energy Limited (PEL) and Pilkington Technology Management Ltd (part of the NSG Group), and supported by Jaguar Land Rover, Unilever, Ibstock Brick, Essar and Solvay. The core goal of the Phase 2 work was to develop technical evidence to support the site operators in progressing towards switching to hydrogen fuel, including hosting practical demonstrations of hydrogen firing at a selection of sites under Phase 3 of the BEIS IFS Programme.

The six sites considered in the Feasibility Study, were as follows:

1 NSG (glass furnace) at St Helens;

2 Unilever (boiler) at Port Sunlight;

3 Solvay (boiler) at Warrington;

4 Jaguar Land Rover (boiler) at Halewood;

5 Ibstock (brick kiln) at Ravenhead; and

6 Essar (process heaters and gas turbine) at Stanlow Refinery.

These sites were split into three work packages; 'Direct Firing', 'Boiler' and Refinery', as described further in Section 4.0.

Conversion to hydrogen of the above sites is core to the HyNet project[1]. HyNet is an integrated hydrogen and carbon capture, utilisation and storage cluster (CCUS) in the North West of England. PEL is working on a range of activities necessary for the development and delivery of HyNet; some of which have also received funding from BEIS, under its Hydrogen Supply and CCUS Innovation Competitions. With partners, PEL plans to deploy operational hydrogen and CCUS networks in the region by 2025.

The work proposed, therefore, is not a theoretical exercise, but relates to sites which have a realistic chance of being converted to hydrogen in the short-to-medium term. Such conversion will be enabled by the supply of bulk low cost, low carbon hydrogen from the HyNet project, which is why this work has concentrated on sites in the North West. The work was designed to be applicable to other similar industrial sites, both within the North West, across the wider UK and globally, enabling wider conversion and hydrogen use. This approach will not only help achieve the Government's decarbonisation goals but is also aligned with both its Industrial and Clean Growth Strategies[2].

2.0 Overview Of HyNet

HyNet North West is a significant clean growth opportunity for the UK. It is a low cost, deliverable project which meets the major challenges of reducing carbon emissions from industry, domestic heat and transport.

HyNet is a complete system of hydrogen production, hydrogen distribution, hydrogen utilisation, and carbon capture, transportation and sequestration located in a confluence of industry, existing technical skill base, and suitable geology. The close proximity of hydrogen production, utilisation, and carbon sequestration, coupled with substantial re-use of existing assets, means that the HyNet system offers substantially lower capital cost and development risk compared to other potential hydrogen clusters around the UK.

The new infrastructure for HyNet is also readily extendable beyond the initial project and provides a replicable model for decarbonisation of other UK clusters.

2.1 HyNet Rationale

The UK is committed to legally binding emissions reduction targets with the 2008 Climate Change Act requiring an 80% reduction from 1990 levels by 2050. In June 2019 this target was extended to net-zero requiring a 100% reduction in emissions. Progress against the 2050 target is measured in 5-year carbon budgets, set by the independent Committee on Climate Change (CCC). Successful performance against carbon targets to date has been achieved by a focus on power generation with a substantial growth in renewable generation and the closure of coal stations.

However, little meaningful progress has been made in reducing emissions from industry and heating and the UK is not on track to deliver the 4th and 5th Carbon Budgets (2023-27 and 2028-2032). The CCC and the UK Government (HMG) agree that hydrogen and CCUS are essential technologies for substantial decarbonization of these sectors.

The CCC has recommended the urgent deployment of CCUS on a cluster basis with integrated hydrogen production to address decarbonisation of a range of sectors, including industry, heat, transport and power generation. To achieve the net-zero 2050 target, the CCC has determined that 75-175MtCO_2/annum of CCUS will be required across these sectors[3].

2.2 HyNet Elements

HyNet directly addresses the above policy need. It takes a cluster-based approach to large scale regional decarbonisation in the North West of the UK. Anchored with low cost industrial CO_2 capture, it will develop and construct the CO_2 transport and storage infrastructure which will then also be used to capture emissions from large scale hydrogen production. The HyNet project is split into four main elements:

1) Element 1 - Final Investment Decision (FID) 2022, operational 2024

a. Focuses upon construction of the CCUS infrastructure (using largely re-purposed oil and gas assets) to capture, transport and store CO_2 from industrial anchor sources. These anchor sources, an oil refinery and an ammonia production plant, are amongst the UK's largest industrial emitters and provide immediate capture opportunities of 1.2MtCO_2/annum. Pipeline infrastructure will be sized at up to 10MtCO_2/annum to facilitate future phases. Storage will be in the Liverpool Bay gas fields currently nearing depletion and owned and operated by Eni;

2) Element 2 - FID 2022, operational 2024

a. Being developed in parallel with Element 1, but separated due to different regulatory regimes, this involves construction of a number of hydrogen production units at the Stanlow oil refinery site. These are based on the 350MWth (HHV) plant design, which has received feasibility support under by BEIS Hydrogen Supply Programme. Hydrogen will be used for industrial fuel switching and gas distribution network blending to reduce the carbon intensity of domestic and commercial heat use, which is the subject of an engineering development programme as part of the HyDeploy Hydrogen Blending Project. Up to 3MtCO_2/annum will be captured in this phase.

3) Element 3 - North West expansion

a. This phase of the project will enable further industrial capture and further expansion of hydrogen production and distribution across the North West region to include hydrogen bulk storage underground to accommodate seasonal demand variation for heat and flexible power generation. The North West region has the UK's largest concentration of existing underground gas storage assets, and studies are underway (Project Centurion and Project HySecure) to assess the feasibility of converting these for hydrogen storage. Up to 10MtCO_2/annum will be captured in this phase from 2025 onwards.

4) Element 4 - development of a 'Western Mega-cluster'

a. The subsequent phase involves shipping of captured hydrogen production and industrial CO_2 emissions from South Wales to the East Irish Sea for storage. Storage can be expanded from Liverpool Bay to Morecambe Bay, which is forecast to cease gas production in 2030 and has capacity for over 1.5BtCO_2. By 2050, the total amount of CO_2 captured from the Mega-cluster (comprising, Wales, the Midlands and the North West) could be up to 47.3MtCO_2/annum; from power generation, industrial capture, industrial fuel switching, hydrogen mobility and hydrogen network blending. Of this potential total, we consider 20MtCO_2/annum a useful upper bound estimate for HyNet project capacity.

The HyNet project was conceived in 2016 and has been formulated and driven by PEL. Two substantial feasibility studies have been published to date, funded by the Gas Distribution Network (GDN), Cadent Gas Limited. These have demonstrated the potential for a very competitive CCUS project with low start-up costs compared to other candidate projects in the UK and a pathway to expand significantly with relatively low start up and development risk.

HyNet continues to be actively developed. Elements 1 and 2 are being pursued in parallel streams, with pre-FEED activities underway for Element 1 and recently completed for Element 2. PEL has assembled a team of plant owners and key sub-contractors as the basis for the project consortium and secured funding from HM Government to contribute to development costs.

Pre-FEED activities on Element 1 are led by PEL and currently funded by project partners Essar Oil (which owns and operate Stanlow Oil Refinery which provides 16% of UK transport fuels), CF Fertilisers (which supplies ~50% of all UK fertilisers), Cadent Gas (which owns and operates four of the eight UK gas distribution networks), Peel Environmental (a major land and infrastructure owner in the region) and the University of Chester. Eni (owners of the offshore gas fields in which CO_2 storage is planned) are funding their own concurrent engineering activities and co-operating closely with PEL and the onshore project team which will assist the definition of an integrated full chain project.

Pre-FEED activities on Element 2 are led by PEL with funding from HMG. Hydrogen production utilises Johnson Matthey Low Carbon Hydrogen (LCH) technology with SNC Lavalin undertaking the engineering, procurement and construction (EPC) role and Essar providing the site at Stanlow Refinery. In addition to the work undertaken in Phase 2, and proposed under Phase 3, of the IFS programme, PEL is undertaking demonstration testing on the use of hydrogen blends up to 20% in the existing gas network through the HyDeploy project[4]. This £22.5M programme is funded through Ofgem's Network Innovation Competition (NIC) by Cadent Gas and Northern Gas Networks, two of the four GDN Operators. Cadent is also funding the development of a hydrogen distribution network in the North West through a further Network Innovation Allowance (NIA) project to undertake the system and physical design of a pipeline system to connect hydrogen production, storage facilities and end-users.

Taken together, Elements 1 & 2 constitute the leading approach to the decarbonisation of an industrial cluster in the UK. The project is anchored on industrial emissions capture but with hydrogen production at the heart of future expansion, enabling the decarbonization of a wide range of energy-intensive industries, directly aligning with HMG's cluster-based approach to CCUS deployment.

3.0 Site Down-Selection Process

As a result of the limited budget associated with Phase 3 of BEIS IFS Programme, the first part of the Feasibility Study was focused upon an initial review and down-selection of sites to a set of projects which delivered maximum transferable benefit, but which fell within the £7.5M maximum budget eligible for support from BEIS. Whilst the three boilers located at each site (Unilever, Jaguar Land Rover and Solvay) initially included within the Boiler Work Package are very different design, much of the learning from a single site can be transferred to the other sites. So, although ultimately any site converting to hydrogen will require a 'demonstration' phase, a demonstration at more than one site could not be justified within the scope of the BEIS budget.

Consequently, as presented in Table 3-1, a set of assessment criteria were designed by which to 'score' and down-select some of the sites for the Phase 3 bid to BEIS. These are largely strategic criteria, but with also a focus on 'deliverability' of a meaningful demonstration, which represents the criterion with the highest weighting, and includes a number of technical sub-criteria.

Using this matrix, the following sites were selected for inclusion in the Phase 3 bid for further funding:

- Work Package 1 – Direct Firing:
  - NSG - Greengate Works, St Helens;
  - Demonstration of hydrogen-firing in a 50MWth glass-making furnace.
- Work Package 2 – Boiler:
  - Unilever – Port Sunlight;
  - Demonstration of hydrogen firing in an 7MWth package boiler;
- Work Package 3 – Refinery:
  - Essar – Stanlow Refinery;
  - Front-end Engineering and Design (FEED) study for installation of a new hydrogen Gas Turbine CHP.

The feasibility work and Phase 3 project design relating to each of the above sites is summarised in Sections 4.0 and 6.0.

It is important to emphasise that whilst the Phase 3 work will be focused on the above three sites, our engagement during Phase 2 suggests that Solvay, Ibstock Brick and Jaguar Land Rover understand the decarbonisation benefits of hydrogen conversion and will all will remain very much engaged in the programme and benefit from the project's proposed knowledge sharing scope of work. This approach will enable such 'non-host' sites to be ready to convert to hydrogen in a far shorter timescale than would otherwise have been the case. Consequently, we believe this approach is of significant benefit to Government in respect of its goals to decarbonise all industrial sites across the UK.

As shown in Table 3-1, the highest weighting ascribed to the 'deliverability' sub-criteria related to the practicality and availability of sufficient hydrogen supply. At an early stage in the project we identified that delivery of hydrogen for site trials was one of the key challenges of a demonstration project. A range of options was considered, including road transport of hydrogen gas, onsite production of hydrogen from electrolysis, road transport of hydrogen as ammonia and on-site cracking, and, in the case of Essar, upgrading of existing 'high hydrogen' refinery fuel gas (RFG). The conclusion of this assessment was that road transport of hydrogen gas from an existing industrial gas provider was the most cost effective and deliverable solution, but this imposed volume constraints on trial design.

The hydrogen demand from some of the larger plant to facilitate a meaningful demonstration was in excess of the potential budget available from BEIS for a single site within a Lot 2 'cluster' bid for Phase 3. In one specific case, this would have been greater than the capacity of all of the hydrogen tube trailers currently operating in the UK. As such, the deliverability of hydrogen has proved a significant factor in the selection of sites and the design of the trials.

In the case of the proposed process heater demonstration at Stanlow Refinery, sufficient hydrogen could have been supplied via upgrading of the RFG, but the cost of related equipment would again have exceeded the budget available from BEIS. However, significant work was undertaken to determine the costs and feasibility of this option, along with the costs of full conversion of all process heaters at Stanlow. Consequently, whilst not described in the context of the sites selected for the Phase 3 bid in Section 6.0, we have summarised the findings of the feasibility work in Appendix A.1.0.

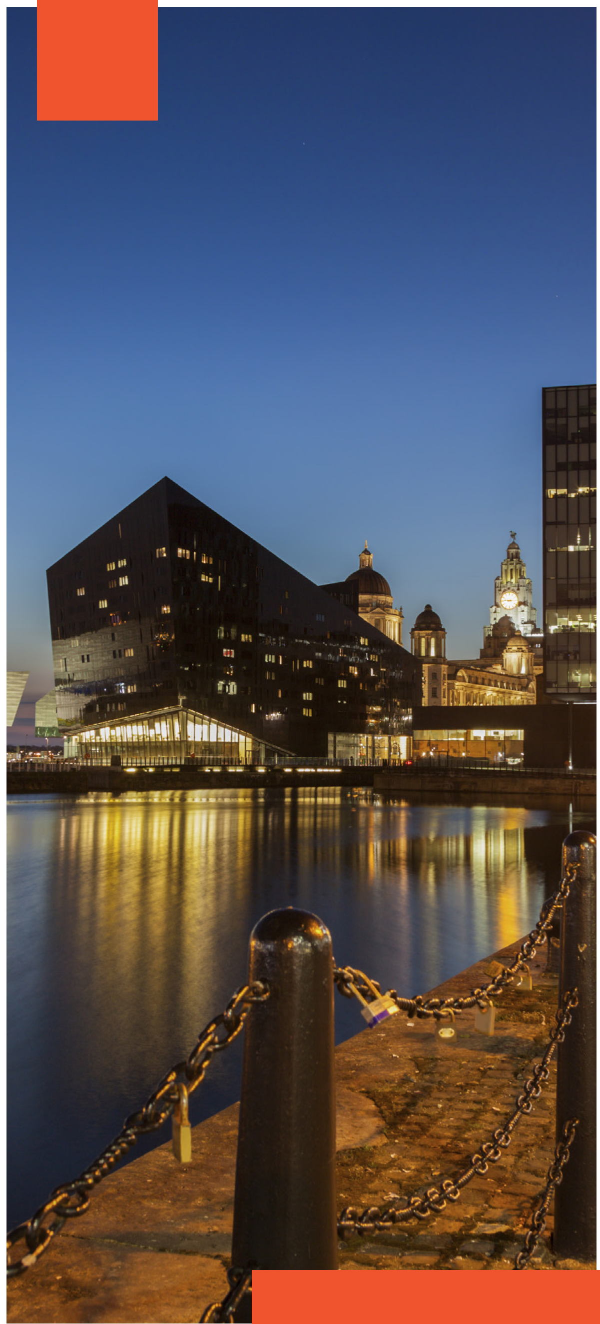


Table 3-1: Site Assessment Matrix

Assessment Criteria	Sub-Weighting	Weighting
1. Applicability and significance to wider UK How applicable is the technology to the wider UK? Is the industry sector of significant size in a UK context? How nationally significant is the plant itself, in respect of size and strategic importance?		6
2. Operator commitment Is there good buy-in from the operator such that it will be possible to sign a collaboration agreement for Phase 3?		7
3. Global/national status and size of operator Does the status of operator help further the wider objectives of HyNet? What opportunities does operator bring for technology export overseas?		4
4. Location relative to HyNet hydrogen production and pipeline Is the site well-located in terms of early connection to the planned HyNet hydrogen pipeline network?		5
6. Deliverability of meaningful demonstration		10
Ease of meeting safety requirements, e.g. distances	6	
Ease of scheduling burner replacement work / maintenance windows	6	
Ease of compliance with NOx limits	7	
Practicality and availability of sufficient hydrogen supply[1]	10	
Consenting issues, e.g. plumes and traffic	4	
Ease of gaining guarantee from burner OEM	7	
Plant redundancy and risk to operations/plant/product	9	
7. Likely cost of Phase 3 Based on the information gathered via the initial site characterisation, how much is the demonstration likely to cost? How does this relate to the total maximum bid of £7.5m across the cluster of the projects?		8

4.0 Comparison With Counterfactuals

The counterfactuals to hydrogen conversion of the three selected sites could be considered as:

1. The current status quo, i.e. for the sites to remain fuelled by natural gas; or
2. Alternative solutions to decarbonising the sites.

Given the UK's 'Net Zero' obligations, it is most meaningful to consider the latter, and therefore for each work package we have presented comparative analysis of hydrogen conversion versus these other options. Essentially, the two core alternative decarbonisation solutions for industrial heat provision are a switch to either:

- Renewable or 'low carbon' electricity, which might be provided via a 'direct' local grid connection to a co-located power generation plant or procured via a 'virtual' power purchase agreement (PPA) from generation at alternative location; or
- Biomass, either in the form of solid or gaseous fuel, which due to the significant volumes required, might be imported from outside the local geography, and potentially in the case of the former, from outside of the UK.

Taking into consideration both technical and commercial criteria, Table 4-1 to Table 4-3 present comparative analysis for each of the three work packages. This analysis suggests that hydrogen performs very well compared with the two main alternatives. In reality, however, the relative merits of each option will depend upon the specific nature and location of the site.

Table 4 1: Comparative Analysis for Direct Firing Technologies

Criteria	Hydrogen	Electrification	Biomass
Impact on product quality	✓	✓	✓x[1]
Process efficiency	✓	✓	✓x[1]
Plant lifetime	✓	✓	✓x[1]
Operational reliability	✓	✓	✓
Availability of fuel	✓[2]	✓x[3]	x
Ease of implementation[4]	✓	x	✓x[1]

Notes:
1. The use of solid biomass would have a negative impact, but biomethane would have zero impact
2. Sufficient natural gas is currently available to supply the UK's industrial kilns and furnaces, and as the proposed HyNet ATR plant operates at a high level of conversion efficiency, it is assumed that sufficient levels of hydrogen can be generated to service the same plant
3. Whilst there is not sufficient low carbon electricity available to supply the UK's industrial kilns and furnaces, it is assumed that sufficient additional low carbon electricity could be generated to meet this potential level of demand
4. As gaseous fuels, both hydrogen and biomethane can effectively function as 'drop-in' fuels for natural gas without the need for significant plant reengineering

Table 4 2: Comparative Analysis for Boilers

Criteria	Hydrogen	Electrification	Biomass
Impact on product quality	✓	✓	✓
Process efficiency	✓	✓	✓x[1]
Plant lifetime	✓	✓	✓x[1]
Operational reliability	✓	✓	✓
Availability of fuel	✓[2]	✓x[3]	x
Ease of implementation[4]	✓	x	✓x[1]

Notes:
1. The use of solid biomass would have a negative impact, but biomethane would have zero impact
2. Sufficient natural gas is currently available to supply the UK's industrial boilers, and as the proposed HyNet ATR plant operates at a high level of conversion efficiency, it is assumed that sufficient levels of hydrogen can be generated to service the same plant
3. Whilst there is not sufficient low carbon electricity available to supply the UK's industrial kilns and furnaces, it is assumed that sufficient additional low carbon electricity could be generated to meet this potential level of demand
4. As gaseous fuels, both hydrogen and biomethane can effectively function as 'drop-in' fuels for natural gas without the need for significant plant reengineering

Table 4 3: Comparative Analysis for Refinery CHP

Criteria	Hydrogen	Electrification[1]	Biomass[2]
Impact on product quality	✓	n/a	✓
Process efficiency	✓	n/a	✓
Plant lifetime	✓	n/a	✓
Operational reliability	✓	n/a	✓
Availability of fuel	✓x[3]	n/a	x
Ease of implementation	✓	n/a	✓

Notes:
1. Electricity is a co-product of CHP (alongside heat) and so industrial CHP plant cannot be 'electrified'
2. Assumes use of biomethane (not solid biomass) as a fuel for the gas turbine
3. Sufficient natural gas is currently available to supply the UK's industrial boilers, and as the proposed HyNet ATR plant operates at a high level of conversion efficiency, it is assumed that sufficient levels of hydrogen can be generated to service the same plant

5.0 Uncertainties Relating To Hydrogen Conversion

5.1 Work Package 1: Direct Firing

The glass industry uses 6.5TWh of heat annually in the UK, the vast majority from fossil fuel sources. Heat is used in both the melting and refining elements of the process. The operating furnace at NSG's Greengate works is designed to use 50MW of natural gas at any given time and the emissions associated with this combustion lead to Greengate works being one of the highest industrial emitters in the North West. Given the direct-firing nature of the application and high temperatures required, hydrogen is an ideal low carbon energy source.

Switching to hydrogen fuel would enable Greengate works to significantly reduce its CO_2 emissions. However, during the Phase 2 work programme, the following concerns were identified, with associated modelling being undertaken to explore them:

- Whether heat transfer from the flame to the melt will be satisfactory:
  - Thermodynamic modelling suggested that there will be sufficient heat transfer to the melt at hydrogen inputs up to 100%. The models were validated at low hydrogen concentrations (up to 30%) using operational data. However, similar data does not currently exist to validate the models at higher hydrogen concentrations.
- Whether NOx emissions can be maintained below permitted limits:
  - NSG has developed a new empirical model for NOx emissions. This model suggests that NOx emissions at 100% hydrogen will be within the capability of the existing pollution control plant. Again, data is not currently available to validate models at 100% hydrogen operation.
- Whether the existing furnace refractories will be damaged by increased soda volatilisation:
  - Glass furnaces are shut down and overhauled approximately every 15 years. Consequently, for Greengate works to use hydrogen in the short-to-medium term, the existing refractory must be suitable. Modelling indicates that hydrogen firing will cause an increase of approximately 30% in sodium hydroxide (NaOH) levels, but this would not be sufficient to cause problems.

The Phase 2 modelling strongly indicates that the above concerns will not be realised. However, it is critically important that the models are validated by operational data, hence the proposed demonstration programme described in Section 6.1.

5.2 Work Package 2: Boilers

Unilever's Port Sunlight manufacturing facility currently uses up to 15 tonnes per hour (tph) of steam, primarily raised from natural gas boilers, which were installed in 2011. This steam is used to manufacture home and personal care products. Switching to hydrogen-fuelled boilers would allow the site to significantly cut CO_2 emissions, with no change to manufacturing operations.

The steam produced by the boiler is critical to manufacturing operations. While there are a limited number of examples of hydrogen-fuelled boilers worldwide, these are largely new-build designs[5]. Unilever requires a demonstration to provide sufficient confidence to convert an existing natural gas boiler to run on hydrogen.

The Phase 2 work resulted in the following concerns being identified:

- Whether steam can be consistently produced at the required temperature and pressure;
- Whether the boiler can operate reliably to avoid any unexpected downtime; and
- Whether NOx emissions limits can be met.

During Phase 2, these concerns have largely been addressed via work undertaken by Dunphy Combustion, which manufactured the burners fitted to the boilers at Unilever and through work concerning emissions limits. Danstoker, which manufactured the boilers themselves, has also been consulted. This work has provided confidence that each of the above concerns can be addressed, but that demonstration is required to provide firm evidence to enable future full conversion to hydrogen.

5.3 Work Package 3: Refinery CHP

The Stanlow Refinery CHP system currently generates around 50MW of power, from fossil-derived sources of varying carbon intensity, which include different grades of RFG alongside natural gas. Up to 500tph of steam is also generated. The existing CHP system cannot be converted to hydrogen and therefore, rather than hydrogen conversion, as is being explored in respect of the Direct Firing and Boiler work packages, installation of a new hydrogen-fuelled gas turbine (GT) CHP system would be required.

The Phase 2 study resulted in the following uncertainties being identified:

- Whether the new CHP system would be backed by manufacturer guarantees;
- Whether it could meet the required duty whilst operating within NOx emissions limits; and
- Whether it would not come at 'excessive' cost (compared with a natural-gas fired system).

There is not sufficient budget under BEIS' IFS programme to fund a new hydrogen-fuelled CHP. It is therefore proposed that a Front-End Engineering Design Study (FEED) study is undertaken to address the above concerns and also to determine a sensible schedule, plot plans, utility connections and costs in relation to the potential installation.

Under business as usual planning, Essar is currently procuring a FEED study for a replacement CHP system, fuelled by natural gas and RFG. However, the business case for a concurrent study on a hydrogen-fuelled solution cannot currently be made due to the fuel price differential with natural gas. Ahead of any financial support mechanism for hydrogen, therefore, public sector funding is required to fund a FEED to enable Essar to make a related investment decision.

6.0 Phase 3 Design

A large part of Phase 2 work has been focused upon designing the approach to the proposed Phase 3 tasks, in addition to determining the feasibility of fuel switching options. Phase 3 has been designed to provide firm, practical evidence to enable future full conversion to hydrogen.

6.1 Work Package 1: Direct Firing

Due to the relatively large scale of the furnace (approximately 50MWth) and related fuel demand, limitations to both BEIS' IFS budget and the current UK hydrogen supply chain it is not feasible for the majority of the fuel fired in the furnace at any one time during Phase 3 to be hydrogen. However, the demonstration is being designed, such that it will provide sufficient confidence to NSG that it could commit to converting the majority of the burners to hydrogen in the future, once low-carbon hydrogen is available at scale.

The demonstration project has been designed to provide sufficient data to validate the conclusion of the modelling described in Section 5.1. The Greengate furnace is a multi-port cross-fired furnace. The upstream ports are concerned with melting glass, and use >60% of total gas consumption. During the demonstration, a hydrogen-ready burner will be installed in port 1.

The programme will begin by firing hydrogen at 20% (the remainder being natural gas), with this percentage being increased over several days up to 100% (Test 1). Measurements will be taken of gas temperatures, NOx levels, thermal profiles within the furnace and NaOH levels. This allows full validation of the modelling work (which made predictions across the full range of hydrogen input percentages).

Test 1 will be repeated (Test 2) to provide further confidence in the results, and, if necessary to resolve contradictory observations, the test will be performed a third time.

Following these tests, 100% hydrogen will be fired through the port for 8 hours (Test 3). This will provide a powerful demonstration that hydrogen is suitable for glass production.

Each of these tests will be conducted during normal operation of the glass furnace, and the product will be inspected to verify that there are no adverse effects on quality.

The data gathered will be sufficient to validate NSG's models, and will enable NSG, in principle, to commit to firing 100% hydrogen on the upstream ports of the furnace using clean hydrogen from HyNet, and to consider further expanding hydrogen use to the downstream ports. The hydrogen for the demonstration will be provided by tube trailer deliveries from a hydrogen production facility in the North West.

6.2 Work Package 2: Boiler

The demonstration has been designed in the following two phases:

1. Stage 1 comprises a trial on a representative boiler system at Dunphy Combustion's test site in Rochdale. This phase includes a two-day ramp-up to 100% hydrogen followed by a week of continuous operation. This test period is an essential part of the risk-mitigation process for Unilever to run the subsequent demonstration at Port Sunlight, which will be undertaken in a 'live' manufacturing environment. The test will demonstrate that the required steam can be consistently produced at the required temperature and pressure, and that the boiler can operate reliability. The test will also confirm the design of the flue gas recirculation (FGR) system to be implemented at Unilever to ensure NOx limits are met.
2. Following successful execution of the test at Dunphy, Stage 2 of the Boiler Work Package involves the installation of a new 7MW tri-fuel (hydrogen, natural gas and gas oil) burner in one of Unilever's boilers. The proportion of hydrogen fuel gas will be increased from 0 to 100% over four days, during which steam quality and NOx emission performance will be verified. This will be followed by a period of up to 6 weeks where the boiler will operate on 100% hydrogen for 8 hours per day, providing the steam needs of the Unilever site. The Unilever test will therefore demonstrate successful provision of the required site steam demands while meeting emissions limits and providing evidence that there are no long-term ill-effects from operation with hydrogen (as the boiler will be undergo a detailed inspection both before and after the demonstration).

Following Stage 2, sufficient evidence will have been established to enable Unilever to commit, in principle, to a contract to use hydrogen supplied by HyNet, once this becomes available. As per Work Package 1, hydrogen will be provided by tube trailer deliveries.

6.3 Work Package 3: Refinery CHP

The requirement for flexible operation and servicing of future demand growth associated with the wider HyNet project (Essar will be hosting the associated hydrogen production plant) necessitates the construction of up to four GTs, each at approximately 20MWe scale. Through engagement with manufacturers during the Phase 2 Feasibility study, a survey of GTs which are available at appropriate scale was conducted. This survey identified a single GT that will, on the timescale of the project, be both available with manufacturer guarantees and capable of meeting NOx limits.

During Phase 2, a specification for the FEED study on a hydrogen-fuelled CHP system was produced and issued to bidders as part of a competitive procurement exercise. The tenders received set out a FEED programme to be performed during Phase 3 and to enable FID in 2021. The key outputs from the study can be summarised as follows:

- Confirmation of primary technology selection;
- Process flow and piping and instrumentation diagrams;
- HAZOP and Environmental Impact reports;
- Equipment and instrumentation list;
- Preliminary plot plan;
- Execution programme; and a
- Capital cost estimate.

The objective of this exercise is to deliver a 'shovel-ready' project, which can attract investment as soon as both bulk, low cost hydrogen is available from HyNet and a suitable policy framework is in place.

7.0 Scalability And Applicability To Other Sites

7.1 Work Package 1: Direct Firing

The proposed technical solution to be demonstrated at NSG's Greengate Works is applicable to all other float (or 'flat') glass manufacturing plants around the UK and globally. Such plant in the UK are largely of relatively similar scale, and are operated by St Gobain and Guardian Glass. Alongside NSG, these two companies are responsible for 70-80% of output from the sector. However, a number of smaller sites are also operating and the proposed solution is likely to be equally applicable to these plants.

The solution is also applicable to container glass manufacturers, as the majority use a similar furnace to that at Greengate Works; for example, that operated by Encirc at Elton (near Ellesmere Port), which is currently fuelled by around 800GWh/annum of natural gas. This plant is directly adjacent to Stanlow Refinery, where the HyNet Hydrogen Production plant will be situated, making Encirc an ideal candidate for early hydrogen conversion

PEL estimates that there is a total of around 55 glass-making sites in the UK, including those manufacturing fibre glass products. In principle, once demonstrated, the solution could be applied to all of these sites, albeit furnace-specific CfD modelling would need to be undertaken. This equates to potentially converting up to 650-700MWth (approximately 6 TWh/annum) of energy demand from natural gas to low carbon hydrogen, reducing UK emissions by approximately 1.2MtCO_2/annum.

The Direct Firing Work Package is also relevant to the brick-making kiln operated by Ibstock at Ravenhead (and to the wider brick-making sector, which includes around a further 40 sites in the UK), which was included in the first phase of the analysis. Glass and brick-making are, in some respects, similar processes in that both use refractory materials and there is direct contact between the flame and the product via multiple burners over a relatively long period of time. Consequently, there are some commonalities in respect of the impact of a switch from hydrogen to natural gas upon the manufacturing process and the product.

7.2 Work Package 2: Boiler

Package boilers such as that proposed for the hydrogen demonstration at Unilever are ubiquitous across the UK. Consequently, once demonstrated at Unilever, the solution can be applied to other sites, potentially without the need for further practical demonstration. PEL estimates that there are around 1,300 high pressure steam package boilers between 1MW and 10MW in scale, and around 600 hot water package boilers currently in operation in the UK. Collectively, these equate to around 8GWth of capacity, which might be converted to hydrogen as a result of the proposed solution at Unilever.

These steam and hot water boilers are spread across a range of market sectors, which require 'indirect' heat for manufacturing; including chemicals, food and drink, paper and automotive. Furthermore, there are potentially another 3-4GWth of low pressure, hot water boilers in the commercial sector, many of which could also, in principle, be converted to hydrogen based on evidence from the demonstration at Unilever.

The proposed solution therefore represents a major opportunity for decarbonisation of a major swathe of the UK economy. If the full 12GWth of potential opportunity was converted to hydrogen, this would represent national emissions savings of approximately 20MtCO_2/annum. This is a major contributor to future carbon budgets and clearly illustrates the benefit of the proposed programme in demonstrating the potential for large-scale industrial fuel switching to hydrogen.

7.3 Work Package 3: Refinery CHP

The major product processes carried out in UK refineries include distillation, vacuum distillation, reforming, catalytic cracking, alkylation, isomerisation, hydrocracking, coking and calcining, desulphurisation and hydrotreatment. No two refineries are quite the same. UK refineries each have their own particular characteristics and idiosyncrasies, which is a reflection of how they have needed to evolve over many years to meet the growing and changing demand for fuels and other products.

The hydrogen-fuelled GT proposed for Phase 3 at Stanlow is fully scalable and applicable to a range of industrial sites across the UK, not solely refineries. GTs are used in CHP systems in a number of sectors, which have a need for significant amounts of both heat and power, such as chemicals, paper and pulp, food and drink and automotive. Some manufacturers are investing heavily in ensuring their fleet of GTs are hydrogen ready by the mid-2020s, but need engagement from industry to justify ongoing work to bring these models to commercial readiness. The proposed work in relation to Stanlow will, in part, fulfil this role and also provide evidence to enable other sites across multiple sectors to justify undertaking similar work, which will result in earlier and far greater deployment of hydrogen-fuelled CHP systems.

8.0 Project Development Plan

The ultimate benefit of deployment of the solutions proposed for development and demonstration on Phase 3 will be in helping enable the UK meet its 'Net Zero' target and in ensuring the ongoing competitiveness of the UK in global low carbon manufacturing. Realisation of this benefit is intimately tied to deployment of the wider HyNet hydrogen production, distribution and CCUS infrastructure. Consequently, the approach to commercialisation of the solutions is intrinsically linked to the wider HyNet project. At the same time, for this reason, the proposed demonstrations are far more likely to lead to full commercialisation of the associated solutions as they are linked to a real project, rather than being purely theoretical or academic exercises.

The specific approach, which moves the solutions towards commercialisation can be summarised as follows:

1 Development of technical and commercial evidence to enable an investment decision in relation to the HyNet infrastructure (2019-2021):

a. The proposed solutions will first be deployed at the three host sites in summer/autumn 2020. This will provide evidence in relation to impacts upon product quality, process efficiency, plant lifetime, operational reliability, and practical implementation. This evidence can subsequently be used by the three sites as a basis for an investment decision in respect of future conversion to hydrogen and connection to the HyNet network;

b. During 2020/21, at the same time as delivery of Phase 3 of the Fuel Switching programme, PEL will be leading FEED studies (funded by Partners and Government) in respect of the hydrogen supply and CCUS elements of HyNet. This is such that an investment decision on these elements of the HyNet infrastructure can be made at the same time as those relating to industrial use of hydrogen, which will influence the hydrogen pipeline route.

2 Commencement and securing of relevant consents for all elements of HyNet project infrastructure (2019-2022):

a. Alongside the required technical evidence, relevant consents must be secured for all infrastructure. Such consents, particularly those relating to hydrogen and CO_2 pipelines, require Development Consent Orders (DCOs), which can take several years to secure. Preliminary work has therefore commenced in this respect and will continue through 2020, 2021 and into 2022;

3 Engagement with Government and additional relevant stakeholders in respect of a long-term support mechanisms for hydrogen and CCUS (2019-2021):

a. Neither the proposed solutions nor any other element of the HyNet project will be deployed without long-term support mechanisms for hydrogen and CCUS. PEL has played a key role in engaging with Government, as part of the CCUS Advisory Group (CAG), which helped shape the current consultation on CCUS (and hydrogen). PEL also led much of the CAG engagement in respect of hydrogen and industrial CCUS and continues to provide informal support.

b. PEL also continues to work closely with Cadent, the local gas network operator, to support its interactions with Ofgem in respect of funding the HyNet hydrogen distribution network under a Regulated Asset Base (RAB) model similar to that currently used for the existing natural gas network. It is likely that an allowance for this network will be included as a re-opener option within Cadent's business plan for the next RIIO Price Control Period, running from 2021-2026. Such an approach will provide a funding route for this element of the HyNet project.

4 Securing investment for deployment of Phases 1 of HyNet (2019-2022):

a. Private sector investment in HyNet cannot be secured in the absence of the above long-term support mechanisms. However, PEL continues to engage closely with the investment community, such that the relevant funders are primed and ready to allocate suitable finance as soon as the suitable long-term support mechanisms are in place such that the solutions (as part of HyNet) become credible investment propositions. Based on informal engagement with Government, we expect sufficient policy certainty to enable FID by end-2022, which will facilitate deployment of the proposed solutions by 2024/25;

5 Securing investment for deployment of Phases 2 and 3 of HyNet (2024-2030):

a. Following deployment and successful operation of the solutions at NSG, Unilever and Essar as part of Phase 1 of HyNet, there will be sufficient evidence to enable Phase 2 deployment of the proposed solutions at other similar sites within the North West industrial cluster. For example, at Encirc Glass, which is located adjacent to Stanlow Refinery, at Jaguar Land Rover, Ibstock Brick and Solvay, which participated in this Phase 2 Feasibility Study, and at various sites which have existing CHP systems; for example, Cereal Partners, located adjacent to Unilever on the Wirral.

b. As other low carbon industrial clusters mature in the second half of the decade, there is potential to extend the deployment of the solutions to neighbouring regions of the UK, which would be supplied with low carbon hydrogen from HyNet; for example, the Midlands and West Yorkshire.

9.0 Cost Assessment

Lifetime costs for fuel switching can be broken down into capital costs and operational costs. The operational costs are dominated by the cost of fuel, but also include maintenance. During the Phase 2 Feasibility Study, no evidence has been identified to suggest a substantial difference in the long-term maintenance regimes between natural gas and hydrogen fired boilers, furnaces or heaters. Consequently, for the purpose of this assessment no difference has been assumed in respect of maintenance costs. For clarity, all costs outlined in this section are for full site conversion to be undertaken at a future point when pipeline hydrogen is available from HyNet. This section does not cover the specific costs related to the Phase 3 work.

9.1 Capital Costs and Comparison with Natural Gas

Cost assessments have been undertaken based on estimates for conversion of existing facilities, rather than new-build; indeed, this is one of the benefits of a hydrogen solution over either biomass or electrification, in that conversion costs are limited to replacement burners and control systems, rather than the full system replacement that would be required with these alternative fuels.

Capital cost assessments for conversion of the NSG and Unilever sites are therefore presented below, based on the work undertaken during the Phase 2 Feasibility Study. However, it is possible to compare the hydrogen CHP system proposed for Stanlow Refinery with a new system fuelled by natural gas, as presented in Section 9.1.3.

9.1.1 NSG (Greengate Works): Glass Furnace

Greengate Works in St Helens has two furnaces, although only one is still in active production. The Phase 2 study suggests that there are no modifications required to the furnace structure or existing materials to facilitate full conversion to hydrogen. It is therefore modifications to burners that form the main challenge to conversion.

The active furnace at Greengate Works has two rows of eight main burner ports horizontally opposite each other. Each row is fired in sequence to ensure an even heat distribution and minimise the potential for convective currents within the glass melt. Following the Phase 2 study, which included site visits and engagement with the NSG R&D team as well as the manufacturing team, it has been concluded that the existing burners do not need to be wholly replaced. Rather it is only the nozzles and controls which require replacement.

Based on eight burners per furnace, the total cost for parts manufacture and installation is estimated at £0.4M for the operating furnace. A further £1.3m is estimated for ancillaries and another £0.6M for the cost of pipework and pressure let-down station to the curtilage of the site, where, in principle, it would join to the main HyNet hydrogen pipeline. Total estimated costs for the conversion of one furnace at Greengate Works to hydrogen are therefore estimated at £2.3M. This is considerably less than the £6M estimated in the Phase 2 bid, which demonstrates the value of the work undertaken during this Phase 2 Feasibility Study.

9.1.2 Unilever (Port Sunlight): Boilers

Unilever's Port Sunlight site has two 7MW Danstoker OPTI 1200 gas fired waste heat boilers each providing process steam and hot water to the site. The existing boilers are fitted with multi-fuel Dunphy burners configured to run on natural gas and light fuel oil. The existing burners will require replacement to enable them to burn hydrogen, whilst additional flue gas recirculation (FGR) and controls are also required.

The costs of this equipment and its installation are estimated at £0.24M. A further £0.08M is estimated for ancillaries and another £0.35 for the cost of pipework and pressure let-down stations to the curtilage of the site, where, in principle, it would join to the HyNet hydrogen main. Total estimated costs for the conversion of the two boilers at Port Sunlight to hydrogen are therefore estimated at £0.67M. This is considerably less costly than the estimate of £1.5M in the Phase 2 bid submission, which again demonstrates the value of the work undertaken during this Phase 2 Feasibility Study.

9.1.3 Essar: CHP (Gas Turbine)

Essar's refinery complex at Stanlow processes over 9 million tonnes of crude oil feedstock each year, to produce around 16% of the UK's transport fuel. The refinery uses a range of forms of heating as part of the fuel production process. The energy use at the refinery proposed for switching to hydrogen relates to the installation of a new 80MWe CHP system to replace the current system.

The preferred solution for the hydrogen-fuelled gas turbine CHP is to install a new dual-fuel hydrogen / natural gas turbine along with associated and waste heat recovery boilers. Based on the Phase 2 Feasibility Study, the capital and installation costs for this system are estimated at £252M. This estimate will be further refined during the FEED Study proposed for Phase 3.

9.2 Operating Cost Assessment

A study published in May 2018 by Cadent in respect of the HyNet project, modelled a LCOH (Levelised Cost of Hydrogen), which included all aspects of the associated CCUS infrastructure[6]. If, as is expected, existing industrial emissions are also captured from further local industries (including process emissions from Stanlow Refinery's catalytic cracker unit), then the capital costs of the CCUS infrastructure would be amortised over considerably higher flow rates of CO_2, therefore reducing this LCOH. PEL is currently leading a 'pre-FEED' study of the CCUS element of the project, which is being funded by BEIS' CCUS Innovation Programme. This will help refine cost estimates for this element of the project.

Phase 1 of the PEL-led HyNet Hydrogen Supply Project has recently concluded[7]. The LCOH calculated as an output from this study is £43/MWh for the 100Nm3/hr reference plant (whilst the 500Nm3/hr scale up plant has an estimated LCOH of £36/MWh). Taking a 2019 wholesale natural gas price of £18/MWh, an operating cost differential between hydrogen and the reference case of natural gas can be calculated as presented in Table 9 1. This shows that the annual cost of hydrogen fuel for the three converted sites would be around £68M, which is around £40M greater than the current annual cost of equivalent natural gas.

Table 9 1: Initial Estimates of Energy Use and Costs

Company	Application(s)	Peak energy demand (MWth)	Max H_2 Substitution (Energy)	Peak H_2 demand (MWth)	Annual H_2 Demand at 80% utilisation (MWh)	Annual H_2 cost (£)	Annual Cost above Natural Gas (£)
Essar	CHP (Gas Turbine)[1]	160	100%	160	1,121,280	48,775,680	28,497,985
NSG	Glass Furnace	50	80%	40	280,320	14,327,856	8,371,283
Unilever	2 x Boilers	22	100%	22	154,176	6,706,656	3,918,473
Total		232	n/a	222	1,555,776	67,676,256	39,540,955

Notes:
1. The CHP at Stanlow is currently fuelled largely by RFG. If it was not currently available, RFG would need to be replaced by natural gas and hence it is appropriate to assume it is of similar value (or cost)

9.3 Addressing uncertainty via Phase 3 work

9.3.1 Capex

As part of the Phase 2 study, accurate cost estimates for the demonstration programme have been developed, which are backed by firm quotes from a range of suppliers. To a large extent, therefore, this data can be extrapolated to estimate the costs of conversion of the wider site (or at least in respect of similar equipment at that site) as has been presented above. For example, at Unilever, the Phase 2 work provides accurate data on the costs of replacement burners and associated equipment, which largely reflects the costs of full conversion, minus pipework for the eventual pipeline supply of hydrogen.

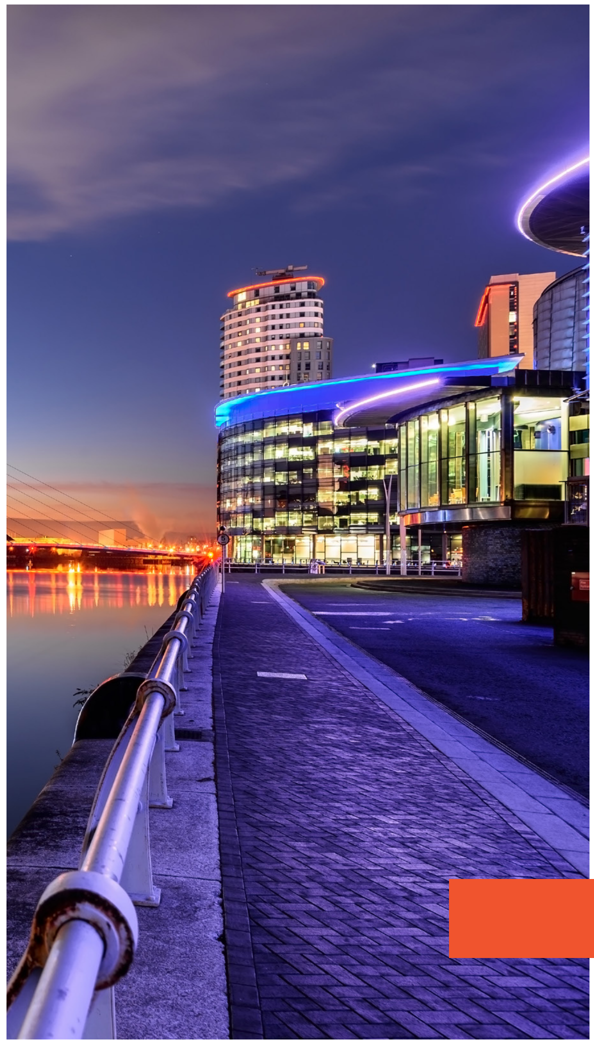
However, greater certainty on the costs of full conversion will come from actual delivery of the demonstration. This is because detailed design will be undertaken at the start of Phase 3, which will refine the estimates made thus far. Actual running of the demonstration will further inform the likely costs of full conversion as any potential impacts of fuel switching to hydrogen, for example, upon materials of construction can be viewed in actuality. Consequently, the proposed demonstration programme is a critical step towards addressing cost uncertainty.

In specific respect of the CHP system at Essar, the proposed FEED study will fully address Capex uncertainty by providing a 'Class 2' estimate for equipment and installation costs. In this context, it should be noted that the price quoted in Section 9.1.3 was developed by a contractor employed as part of the Phase 2 study. The same contractor will lead the FEED study (should it secure funding) and subsequently the build (on an EPC or EPCM basis) of the CHP plant.

9.3.2 Opex

As mentioned above, the proposed demonstrations at NSG and Unilever will not provide further insights in respect of fuel costs, but will inform wider O&M cost estimates for full conversion[8]. As part of the demonstration programmes, all 'normal' operating procedures will be reviewed and any additional requirements, which would apply under a situation of full permanent conversion, documented and reported in the Phase 3 report. This would subsequently enable any 'hidden' costs to be identified and so allow the full cost of hydrogen conversion to be recorded.

Monitoring of the demonstrations will inform what permits are required and how headroom for NOx limits will be affected should full conversion to hydrogen be deployed. This will not only inform Capex estimates in respect of any additional abatement equipment that might be required to operate within emissions limits, but also the additional Opex required to run and monitor the abatement equipment, both in respects of energy use and manpower.



A.1.0 Feasibility Of Process Heater Demonstration

During Phase 2, the feasibility of demonstrating 100% hydrogen fuelling on both a 5MWth and 20MWth process heater at Stanlow refinery during Phase 3 was investigated. By selecting two heaters that were broadly representative of the wide range of heaters operating at the refinery, this was intended to facilitate a future switch to hydrogen fuel for a total of around 390MWth of heater capacity.

The feasibility study reviewed and identified the main burner and combustion issues, impact on heat transfer performance, NOx emissions, and approaches to mitigation. Based on responses to budget enquiries to fired heater and burner suppliers, the scope of modifications was identified and total installed cost determined. Engineering implications of hydrogen supply to the selected process heaters were also identified, and a plant configuration was developed for providing hydrogen to the two selected process heaters.

Based on the information provided to them, heater suppliers generally confirmed the feasibility of firing hydrogen. From a process point of view, it was determined that heater performance would not be substantially affected by the change of fuel. In this respect, the following points should be noted with regard to operation with hydrogen as the main fuel:

- There will be a lower air requirement compared to refinery gas, which should be considered against turndown capability of fans:
  - This is expected to be manageable and solved without requiring major modifications;
- Potential difficulties/limitations to turndown capability of the heater:
  - Hydrogen has a significantly higher flame velocity than hydrocarbon gases. With high hydrogen concentrations in the fuel gas, the degree of turndown possible can be limited;
- Main temperatures (flue gas bridgewall, stack temperature) as well as heat fluxes (and therefore skin/film temperatures) are not significantly affected;
- Impact on the requirements on tightness of the shutdown valves considering the higher potential for leakage of hydrogen compared to hydrocarbons:
  - The tightness class of the valve should be evaluated against the required SIL level and potentially increased.

The main modifications to be addressed for fuel switching to pure hydrogen relate to the burners, fuel gas and control system. The scope of heater modifications consists of:

1. New burners and relevant modifications to the floor;
2. Combustion air ducts and piping;
3. New fuel skid;
4. Replacement of existing flame scanners; and
5. Modification of the feed piping to allow change of fuel from pure hydrogen to refinery gas when needed (dual fuel system).

Due to change of burner size (and possibly number/position), modifications to the heater floors and combustion air distributors may be required. It was assumed that fire box, coils, convection box and stack are suitable for operation with hydrogen and therefore allowance in the cost estimate was not made for modifications to these items.

The major equipment cost relating to modifications to the heaters was estimated at £1.1 million. However, total installed costs of all modifications, including a PSA for purification of refinery hydrogen, a residue gas compressor, pipework, engineering and construction costs were estimated at £7.4 million. The costs of providing the infrastructure and sufficient hydrogen for demonstration of hydrogen-

firing on the two heaters were therefore regarded as prohibitive in the context of the funding available.

Ultimately, the amount of hydrogen required for a meaningful demonstration with the larger 20MW heater, was such that this could not be supplied by the tube trailer market, hence the need for a PSA and associated equipment to purify refinery hydrogen for use in the demonstration, and the prohibitive cost. However, further work was undertaken to determine whether it would be feasible to undertake solely a demonstration on the smaller 5MW heater. Whilst this was deemed possible in respect of costs and hydrogen supply, given the fact that such heaters have already operated on relatively high levels of hydrogen, Essar did not regard the proposed demonstration of sufficient value to merit its inclusion in a Phase 3 bid.

References

1 See www.hynet.co.uk

2 HM Government (2017) Industrial Strategy: Building a Britain fit for the future, November 2017
https://www.gov.uk/government/topical-events/the-uks-industrial-strategy
BEIS (2017) The Clean Growth Strategy: Leading the way to a low carbon future, October 2017
https://www.gov.uk/government/publications/clean-growth-strategy

3 Committee on Climate Change (2019) Net Zero – The UK's contribution to stopping global warming
https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

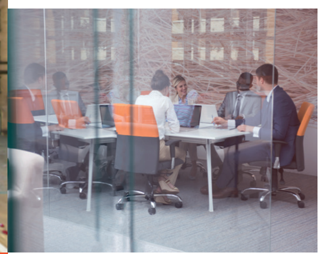
4 See https://hydeploy.co.uk/

5 Inovyn has converted an existing boiler to hydrogen in Runcorn, which it is understood, previously ran on both oil and gas

6 Cadent (2018) HyNet North West: From Vision to Reality, May 2018
https://hynet.co.uk/app/uploads/2018/05/14368_CADENT_PROJECT_REPORT_AMENDED_v22105.pdf

7 PEL (2019) BEIS Hydrogen Supply Programme – HyNet Low Carbon Hydrogen Plant: Phase 1 Report for BEIS, December 2019

8 However, greater certainty in relation to fuel costs will be gained via the parallel HyNet Hydrogen Supply FEED study



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