HyNet CCUS Pre-FEED

Key Knowledge Deliverable

WP2: Hydrogen Production Plant

HyNet North West

EXECUTIVE SUMMARY

The CO_2 Specification Achievement Report was generated as part of the Preliminary Front End Engineering and Design (pre-FEED) study for the HyNet Industrial CCUS Project. The HyNet CCUS pre-FEED project commenced in April 2019, and was funded under grant by the Department for Business, Energy and Industrial Strategy (BEIS) under the Carbon Capture Utilisation and Storage (CCUS) Innovation Programme.

Delivery of the project was through a consortium formed between Progressive Energy Limited, Essar Oil (UK) Limited, CF Fertilisers UK Limited, Peel Environmental Limited, University of Chester, and Cadent Gas Limited.

The main project objectives are as follows;

- To determine the technical feasibility of a full chain Industrial CCUS scheme comprising anchor loads from Stanlow Refinery and Ince Fertiliser Plant and storage in Liverpool Bay fields.
- To determine the optimised trade-off position between lowest initial cost and future scheme growth
- To determine capital and operating costs for the project to +/- 30% to support HMG development of a policy framework and support mechanism
- To undertake environmental scoping and determine a programme of work for the consent process

This document is one of a series of Key Knowledge Deliverables (KKD’s) to be issued by BEIS for public information, as follows;

- HyNet CCUS Pre-FEED KKD WP1 - Basis of Design
- HyNet CCUS Pre-FEED KKD WP1 – Final Report
- HyNet CCUS Pre-FEED KKD WP2 - Essar Refinery Concept Study Report
- HyNet CCUS Pre-FEED KKD WP2 - Hydrogen Production Plant
- HyNet CCUS Pre-FEED KKD WP3 - Fertiliser Capture Report
- HyNet CCUS Pre-FEED KKD WP4 - Onshore CO2 Pipeline Design Study Report
- HyNet CCUS Pre-FEED KKD WP4 - CO2 Road Rail Transport Study Report
- HyNet CCUS Pre-FEED KKD WP5 - Flow Assurance Report
- HyNet CCUS Pre-FEED KKD WP6 - Offshore Transport and Storage
- HyNet CCUS Pre-FEED KKD WP7 - Consenting and Land Strategy

The hydrogen production plant is core to the proposed HyNet North West project. The objective, under HyNet is to provide a foundational reference design for a hydrogen production plant that can be replicated elsewhere in the UK and internationally. The Low Carbon Hydrogen (LCH) process, developed by Johnson Matthey (JM), based on AutoThermal Reforming (ATR) of Natural Gas has been selected. A flowscheme and site layout has been developed to pre-FEED level, undertaken by the companies responsible for the design, JM, SNC-Lavalin and Progressive Energy Limited. This was funded by BEIS under the Phase 1 Hydrogen Supply Programme (HSP) and the final report is attached in Appendix 1.0

The work in the HyNet Industrial CCUS Project with respect to the LCH was always intended to be minimal (and, as such, had no separate line in our budget plan), and was put in place to demonstrate that the output of the LCH process could meet the CO_2 pipeline specification with minimal levels of additional heat required in the LCH process. H_2 levels in the CO_2 stream are critical as it significantly impacts the phase envelope, and hence the operability of the transport and storage system.

A range of technology options are available to meet this CO_2 specification, any of which could theoretically be integrated into the flowscheme. The CO_2 removal technology choice has not yet been optimised and finalised, but a Benfield process has been modelled, as this is considered a 'worst case' for heat load requirement, and is considered well-proven, and hence represents a low risk. The output of this modelling has confirmed that the required CO_2 specification can be met using the Benfield process, and that there is sufficient heat available from the LCH process that no further (external) heat input is required. The Benfield process has therefore been used as the basis for the LCH plot plans/cost assessments etc.

BEIS has awarded a HSP Phase 2 contract for the undertaking of the LCH FEED which will include the finalisation of this choice.

David Parkin

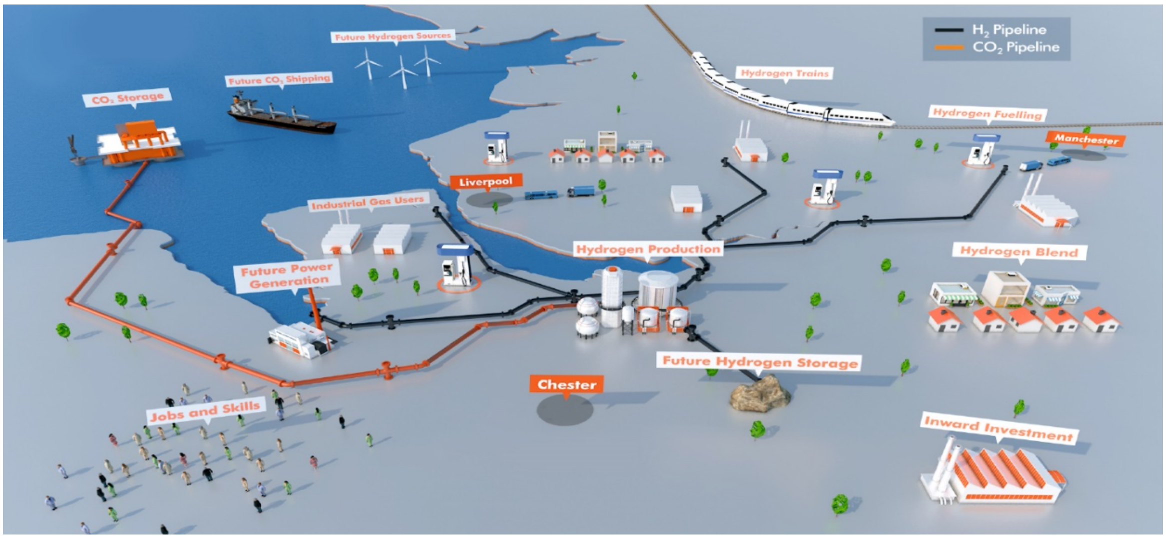
Dave Parkin
HyNet Project Director

CONTENTS

1.0 Introduction

The HyNet North West project (see Figure 1.1) comprises the development and deployment of a 100,000 Nm³/hr hydrogen production facility with associated carbon dioxide capture and storage. It will deliver low cost, low carbon production of bulk hydrogen supplies.

Figure 1.1: Schematic of HyNet North West project



The hydrogen production plant is core to the proposed project. It will also provide a foundational reference design that can be replicated through multiple lines in the north-west (the site design has provision for three lines, with opportunity for further lines in region), elsewhere in the UK and internationally.

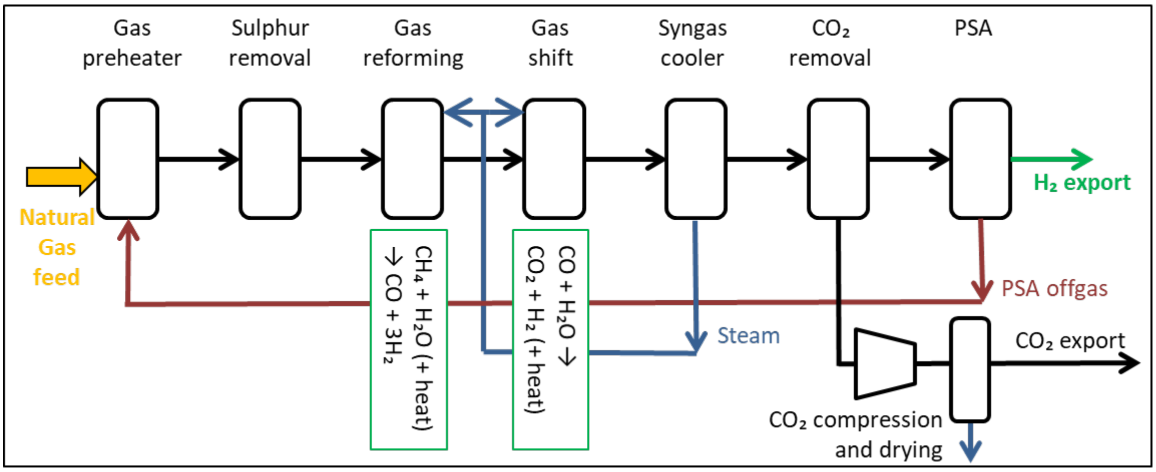
When associated with the CO_2 transport and storage infrastructure integral to the HyNet North West project, it delivers low carbon hydrogen for key industrials alongside non-disruptive blending to over 2 million households in line with the Climate Change Committee's recent hydrogen report. This plays a vital role in the Clean Growth Strategy, to safeguarding existing industry and attracting inward investment into the region and the UK more widely in line with the Industrial Strategy. In addition, it unlocks low carbon transport solutions for transport as well as dispatchable low carbon power generation to complement intermittent renewable generation.

The project is based on employing Johnson Matthey's LCH (Low Carbon Hydrogen) process, which includes a Gas Heated Reformer (GHR), based on Auto-Thermal Reformer (ATR) technology, followed by a Shift Converter and a CO_2 removal plant.

The GHR unit uses predominantly natural gas as a feedstock and is sized to produce 100,000 Nm³/h of hydrogen product suitable for industrial use, blending in to the gas network and for power generation. The CO_2 is to be suitable for export, transportation and long-term geological storage.

A block flow diagram of the hydrogen production process is shown as Figure 1.2.

Figure 1.2: Block flow diagram of LCH process



Unusually, both of the product streams (hydrogen and CO_2) are required, for different reasons, to conform to specific requirements with regards to their chemical composition. This report considers the production of CO_2 to the required specification.

The LCH process has been the subject of a Pre-FEED process undertaken by Progressive Energy, Johnson Matthey and SNC Lavalin, concluding in September 2019. This has produced flowschemes, plot plans, preliminary execution plans and cost estimates. A 15-month FEED programme is scheduled to commence in December 2019, subject to successful award of grant funding.

2.0 CO_2 removal requirements

2.1 Chemical

The minimum target CO_2 capture rate required is >95% with a target of 97%[1] (defined as the ratio of CO_2 export over the total CO_2 potential in the feedstock). Not all of the impurities within the CO_2 export stream are of equal importance downstream (see Table 2.1) in the CO_2 Transport and Storage network.

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[1] Ref. P-1133-HYN-SP-001 'BEIS Hydrogen Supply Programme, HyNet Hydrogen Plant, Basis of Design' 190523 rev. 06

Table 2.1: Most sensitive impurities within the CO_2 stream

Impurity	Sensitivity issue
Hydrogen	Affects the thermodynamic properties of the CO_2 stream, enlarging the two-phase envelope thus reducing the effective operational envelope
Nitrogen	Affects the depressurisation velocity of the CO_2 stream, increasing the potential for running ductile fracture when operating in the dense phase
Oxygen	Stimulates the formation of Sulphur Reducing Bacteria (SRB) in the pores of the reservoir, leading to reduced permeability and loss of storage volume
Water	Corrosion of carbon steel components (e.g. pipeline), and increased potential for CO_2 hydrate formation. The presence of water in the CO_2 stimulates other effects such as the formation of nitric acid from NOx, sulphuric acid from SOx, and elemental sulphur deposition.
H_2S	Potential for symptoms of nausea, headaches, delirium, disturbed equilibrium, tremors, convulsions, and skin and eye irritation in the event of an escape of CO_2
H_2S and SO_2	Potential for sulphur induced stress corrosion cracking (SISCC) in the presence of “free water[2]”

This led to the development of a HyNet system level CO_2 specification in the Basis of Design, which is common to all capture plants, based mainly on ISO27913, and is reproduced as Table 2.2.

Table 2.2: CO_2 Specification from Basis of Design

Species	Indicative levels (volumetric composition, ppm, unless stated as mole%)
CO_2	>95%
H_2O	≤ 50
H_2	<0.75%
N_2	<2%
CH_4	Not specified
CO	$\leq 0.2\%$

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[2] “Free water” implies the presence of H_2O within the CO_2 at sufficient level that some H_3O^+ (or OH^-) ions are available to take part in chemical reactions. This is usually in the >200 to 250ppmv range.

O_2	≤10
H_2S	<200
SO_2	<100
NO_2,	<100
N_2O_4	<25
NaOH	Not specified
HCl	Not specified
Amine	Not specified
Methanol	Not specified
Ethanol	Not specified
PEG	Not specified
C_2+	<2.5% °

With Table 2.2 as the composition requirements, JM developed an LCH flowscheme specifically for the HyNet project, based on work previously carried out on their patented GHR (Gas Heated Reforming) technology. The resulting CO_2 composition, derived from the Heat and Mass Balance, meets or exceeds all of the requirements shown Table 2.2, with the exception of:

- Water content
- Temperature
- Pressure

These may be addressed most effectively downstream of the CO_2 removal plant.

2.2 Post-capture processing

To raise the pressure from about 2bara to 35barg the CO_2 stream will have to be compressed, as shown in Figure 1.2. Isothermal compression occurs when the gas pressure and volume vary such that the temperature remains constant. The preferred type of compression is that which is close to isothermal, because that requires the least amount of work compared with other forms of compression. Delivering a gas stream that is close to constant temperature implies cooling and in practice the compressor will have a number of stages with inter-stage cooling between each.

As the compressed gas cools moisture from within the gas will drop out, producing a CO_2 stream with a gradually decreasing moisture content. This will not be as low as the required <50ppmv, but the reduction is achieved without introducing any additional stages into the process that would not be required anyway.

A final CO_2 stream cooler will be necessary (not shown in Figure 1.2) to bring the temperature down to the required 20°C, possibly utilising some of the 'coolth' from the nitrogen stream of the air separation unit.

A separate moisture removal stage may be necessary.

2.3 Energy consumption

Reducing the energy penalty associated with CO_2 capture will reduce the operating costs associated with producing clean hydrogen. Hence, those technologies with minimum thermal and electrical energy demands are preferred.

3.0 CO_2 removal technologies

CO_2 is considered to be a relatively stable compound, insoluble and chemically unreactive. However, it is not totally stable, insoluble and unreactive and a number of technologies have been identified to enable its separation from the other components of syngas. In this instance it helps that its properties are very different from those of hydrogen, the main species from which it is desired to separate the CO_2. Some of these differences are summarised in Table 3.1

Table 3.1: Some differences between hydrogen and carbon dioxide

Factor	Unit	Hydrogen	Carbon dioxide
Boiling point	°C	-252.9	-78.46
Molecular weight		2.0148	44.0095
Density	g/litre	0.08988	1.96
Reaction with oxygen		Very rapid	None
Reaction with water		None	Forms H_2CO_3
Solubility in water[3]	mg/litre@20°C	1.57	1496.43

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[3] "Concentration and Solubility Of H_2", Molecular Hydrogen Institute

These differences (and others) can be exploited to separate the two gasses, as shown in Table 3.2 below.

Table 3.2: Technology types available to separate CO_2 and hydrogen

Technology Type	Property exploited
Cryogenic distillation	Differences in boiling point
Physical solvent	Differences in solubility
Chemical solvent	Difference in chemical reaction rates
Molecular sieve	Difference in molecule size

3.1 Cryogenic distillation

Cryogenic distillation is used by CF Fertilisers (owner and operator of Ince Fertiliser plant, one of the CO_2 capture sources for the HyNet project), to separate CO_2 from the small amount of residual hydrogen (less than 3vol%) that is in the process vent from the plant, downstream of the main separation. The objective in this instance is to produce high purity (Food Grade, 99.99% pure) CO_2. The stream is cooled, initially to below the water dew point, when the moisture is removed. The moisture-free stream is further cooled to the CO_2 dew point, and the carbon dioxide bled off. The remnant gas, mostly hydrogen, is then vented. Were the hydrogen to be a higher proportion of the incoming stream, it could be utilised beneficially, or, following further processing, form a saleable by-product.

3.2 Physical Solvents

In physical chemistry, Henry's law is a gas law that states that the amount of dissolved gas in a liquid is proportional to its partial pressure above the liquid. Thus, the higher the pressure the greater the potential for dissolving gas in the liquid.

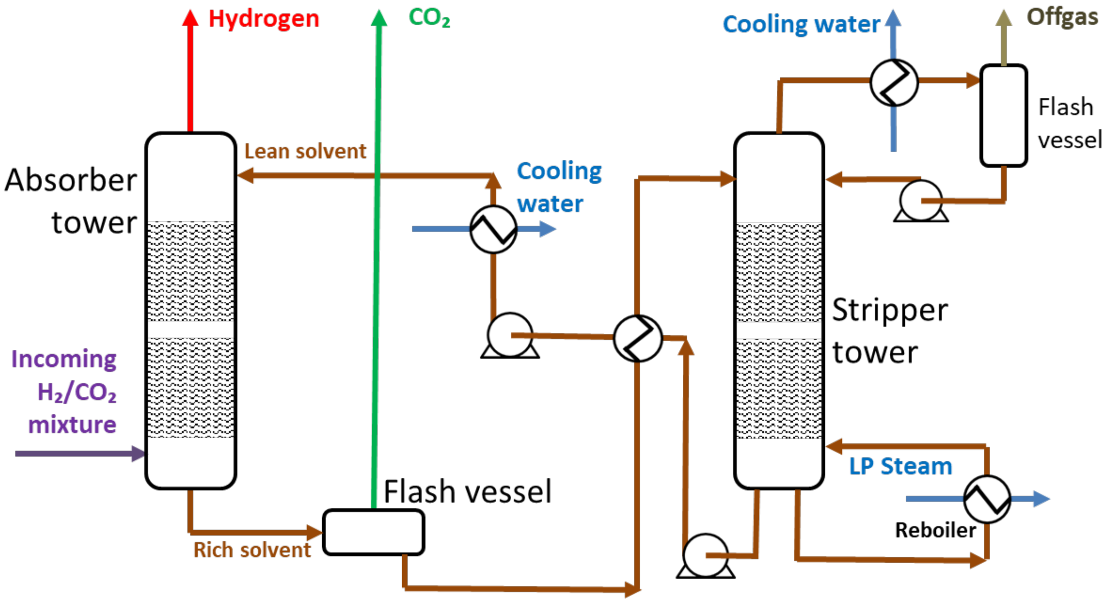
As a result, physical solvent separation processes take place under pressure. Dissolving CO_2 out of a CO_2/hydrogen mix is not particularly difficult: Table 3.1 suggests that the stream could simply be bubbled through water. The hydrogen would barely dissolve and would rise to the surface, and the CO_2 would be retained within the water. More effectively the CO_2/hydrogen mixture would flow upward against a downward flowing stream of water droplets (providing maximum surface area) or bubbling through trays in an absorber tower. The hydrogen would exit through the top, and the CO_2-rich water from the bottom.

Pumping the water away and releasing the pressure would allow the CO_2 to vaporise out of solution in a flash vessel: the water could then be returned for re-use. A schematic of a physical solvent process is given as Figure 3.1. The amount of CO_2 released in the flash vessel is a function of the pressure drop: the greater the pressure differential, the more CO_2 is released from the solvent. Often the flashing is multi-stage. Thus, the CO_2 emerges at low pressure and may require compression before it can be utilised.

There are better solvents than water, which absorb more CO_2 more readily and, unlike water, which would react with the CO_2 to form carbonic acid (H_2CO_3), are more resistant to chemical reactions. (N.B. the chemical reaction between CO_2 and water is, for simplicity at this point, ignored, but becomes more important when considering chemical solvent technologies).

Table 2.2 shows that there are gasses other than CO_2 and hydrogen in the incoming mixture, and these are removed from the solvent in a stripper tower and emerge as an offgas as shown.

Figure 3.1: Schematic of physical solvent removal process



Physical solvent processes have a low energy requirement (mostly pump power to return the solvent to the absorber under pressure), but the segregation between the incoming component gasses is not always high enough to deliver high purity products, nor high end capture rates. However, there is almost no pressure drop through the absorber tower, thus the hydrogen emerges at high pressure.

The solvents can be chosen such that no chemical reactions will take place, leading to long solvent life and hence reduced environmental impact, and lower operational costs.

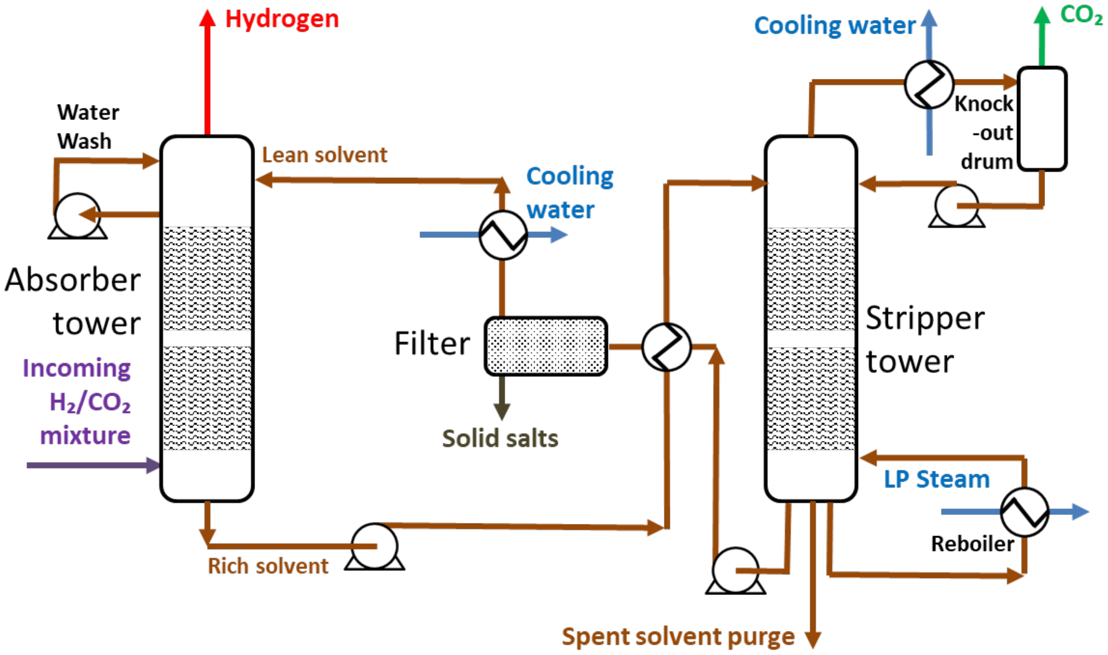
3.3 Chemical Solvents

All chemical reactions, to a greater or lesser extent, are reversible. However, reversing some reactions where stable molecules are formed, can take a great deal of energy, and present technological challenges. This fact is used in chemical solvent processes.

Table 3.1 shows that CO_2 will react with water (to form carbonic acid, H_2CO_3, which would be described here as an intermediate product) more readily that hydrogen, which has no reaction. This time, for simplicity, the physical absorption phenomenon, which was described in section 3.2 is ignored. This reaction could then be reversed, the CO_2 released from the intermediate product, and the water re-used. Heat is usually used as the energy source to release the CO_2.

As with physical processes, there are better solvents than water, which both react and release more CO_2 more readily. A schematic for a chemical solvent removal process, shown as Figure 3.2.

Figure 3.2: Schematic of chemical solvent removal process



Unlike a physical solvent process, there is no offgas; however, there are intermediate salts formed from reactions other than those that are reversible by the heating and stripper tower. Solid salts are filtered out, and liquid salts are either processed out from a spent solvent purge, or destroyed separately if reprocessing is not cost-effective.

Chemical solvent processes do not require the same pressures as physical solvents to operate, and are thus suitable for near-atmospheric applications, such as flue gas processing. Both the hydrogen and CO_2 emerge at very low pressure and may require compression before they can be utilised.

By choosing the chemical solvents carefully, the processes can offer a very high degree of separation of the incoming mixture, but the reboiler heat requirement to reverse the chemical reaction can be very high.

3.4 Molecular Sieve

A molecular sieve is a material which contains very small pores of uniform size. These pore diameters are similar in size to small molecules, and thus large molecules cannot be adsorbed, whilst smaller molecules can. Molecular sieve adsorbents are crystalline aluminosilicates, known as zeolites, whose pores, or cages, have a high affinity to re-adsorb water or other polar molecules. As a mixture of molecules (hydrogen and CO_2 in this case) pass through the bed of the sieve the component with the highest molecular weight (i.e. the CO_2, see Table 3.1) is unable to be absorbed and exits at a pressure similar to that of the incoming gas. The smaller molecules (hydrogen) are absorbed into the pores.

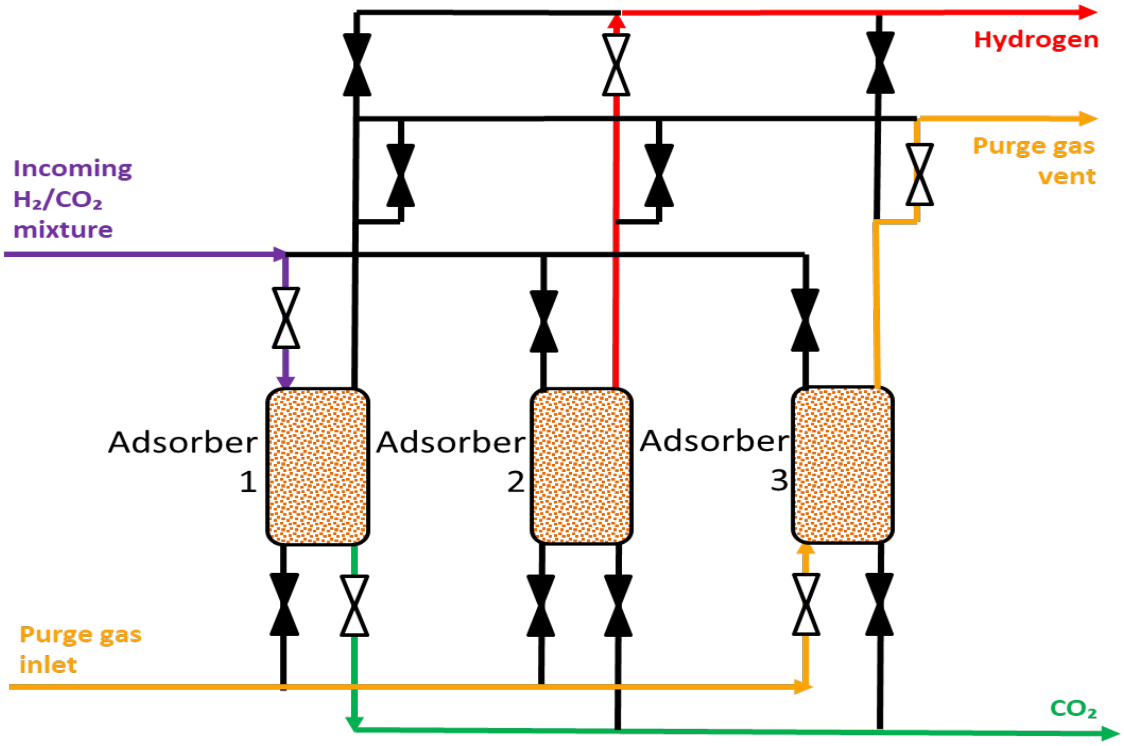
Once pore saturation has been reached the gas supply is switched off and pressure reduced, allowing the adsorbed molecules (hydrogen) to be released. The zeolite is purged, repressurised and is then ready for duty again. The purge may be product gas (e.g. hydrogen from upstream

This is essentially a ‘batch’ process, so to ensure a continuous stream of processed gas, multiple sieves are used in sequence, such that there is always one carrying out the adsorption part of the process. A multi-sieve design is able to utilise the depressurising part of the cycle for one unit to provide some of the repressurising cycle of another, thus saving energy and minimising gas wastage.

A schematic of a molecular sieve arrangement is shown as Figure 3.3, noting that only three sieves are shown for simplicity. Adsorber 1 is shown in the adsorption part of the cycle: the hydrogen from the incoming mixture (purple line) is filling the pores within the zeolite and the CO_2 molecules, too big for the pore size, are passing straight through (green line) at a pressure similar to that of the incoming mixture. Other pipes (shown as black) are valved off. Adsorber 2 is shown in the desorption part of the cycle: the hydrogen, extracted from the incoming mixture, is leaving the pores within the zeolite at a decaying pressure (red line). Other pipes are valved off. The hydrogen from Adsorber 3 has gone as the driving force of pressure has decayed, and the associated valves are now closed (black lines). The vessel is now purged (orange lines), and the purge gas vented. The purge gas may be compressed hydrogen, or it may be nitrogen or another inert gas. Following the purge, the valve to the purge gas vent line is closed and the adsorber is repressurised ready for adsorption, at which point adsorber 2 will be put into the purge cycle and adsorber 1 will start to desorb the hydrogen it has captured in the pores.

Whilst the CO_2 will emerge at pressure, the hydrogen does not and would require compression. If other gasses within the incoming hydrogen/CO_2 mixture have small molecules, they will appear with the hydrogen: other larger-sized molecules, too big for the pores, will exit with the CO_2. Based on molecule size, the sieve designer can decide where the trace gasses will appear by engineering the appropriate pore size.

Figure 3.3: Schematic of molecular sieve arrangement



The ability to engineer the pore size can give very good separation between the species within the incoming gas. However, molecular sieves are expensive and are therefore more suited to polishing duties than bulk gas separation.

4.0 PRE-FEED STAGE OF HYNET PROJECT

For the pre-FEED stage of the LCH project, a preliminary screening process was carried out to assess the application of commercially available removal systems to separate CO_2 from a syngas feed stream ex-shift, containing hydrogen, CO_2, unshifted CO and water, and trace amounts of other species, as shown in Table 2.2.

This provided a reference design with a high confidence in the performance in terms of capture rate and product stream separation. It was assessed to ensure that sufficient heat could be delivered from the upstream process. However, it is recognised that during the full FEED it is likely to be possible to further optimise this with detailed engagement with specific CO_2 process vendors and licensors.

4.1 Discussion

Many CO_2 separation applications are aimed at producing a single saleable or usable product gas and a 'waste gas' into which as many as possible of the other species within the feed stream should be directed. Most common is the purification of Natural Gas, in which the methane is the saleable product, and the 'waste gas' contains the nitrogen, the H_2S, and the CO_2 for instance. Exclusive selectivity becomes the driving parameter in the choice of a particular technology or solvent.

Coal gasification applications require the syngas feed to be split into three, hydrogen, CO_2 and H_2S, and the process designer has to balance the specific compositions, e.g. how much H_2S can the CO_2 contain and how does changing this affect the amount of CO_2 in the hydrogen.

For the HyNet project, there are essentially two product gasses, since both the hydrogen and the CO_2 are required to meet specified compositions, with hydrogen-in-CO_2 probably being the most critical parameter, as this determines the operability envelope of the Transport and Storage system due to its contribution to the phase envelope. Thus, in the choice of both technology and solvent, the degree of separation between the CO_2 and the hydrogen is likely to be the driving characteristic.

The separation between the species is not as well defined for physical processes as it is most chemical solvent processes, thus chemical solvent technology may be more appropriate for this application.

It is intended in the LCH flowscheme to 'polish' the hydrogen product gas through a PSA (Pressure Swing Absorber) to remove the small amount of unshifted CO that will be present. The PSA tail gas would ideally contain residual hydrogen together with all of the unreacted CO and methane, and trace amounts of nitrogen and ammonia. Since it is intended to include this additional step into the hydrogen stream, the separation process can be designed to allocate these products into the hydrogen, leaving the CO_2 "pipeline ready" (except for pressure and water content, see Section 2.1).

In terms of technology selection, the design should:

- Provide a very high degree of separation between CO_2 and hydrogen, and
- Allocate non-CO_2 species to the hydrogen stream

4.2 HyNet Modelling for hydrogen plant

It was agreed that a default case should be used, which was expected to require the greatest level of external heat provision, as this provides an upper-bound envelope to the process specification. If these heat requirements could be met from within the hydrogen production flowscheme, then confidence would exist that no external energy would be required to provide heating for alternative technologies. The Benfield process typically has the highest parasitic heat load, so was chosen as the default case.

In the event, careful integration demonstrated that the LCH flowscheme could service the heat requirement from the Benfield process. The modelling also showed that the Benfield process is able to produce CO_2 of the required purity, with the exception of water content, which would be addressed in the compression/dehydration stages downstream.

5.0 RECOMMENDATIONS FOR LCH FEED

It is recommended that in the FEED phase of the LCH project a number of candidate CO_2 removal processes should be evaluated to assess and optimise the application of commercially available CO_2 removal system to separate CO_2 from a hydrogen and CO_2 containing feed stream (as defined in the Basis of Design, or as subsequently amended). Assessment is to inform and advise the developers to select the most appropriate technology.

The minimum target CO_2 capture rate required is 97%, but the assessment should consider higher rates if this can be achieved on a cost-effective basis.

Because reducing the energy penalty associated with CO_2 capture will reduce the operating costs associated with producing clean hydrogen, the technologies with minimum thermal and electrical energy demands would be preferred. The assessment process will evaluate the thermal and electrical requirements of the proposed process along with design optimisation opportunities. For example, this may include improvements to solvent, reductions in solvent regeneration and improved heat integration.

It is critical that the selected process can be delivered commercially with appropriate performance guarantees on the timeframe required. This requires evidence of operation at appropriate scale.

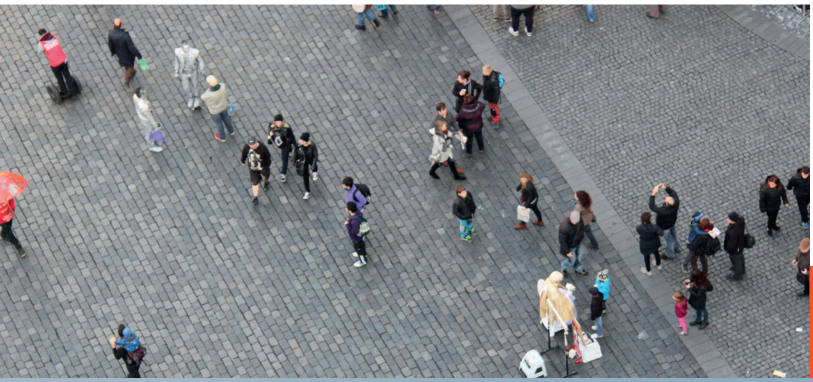
Specifically, final technology selection will be based on:

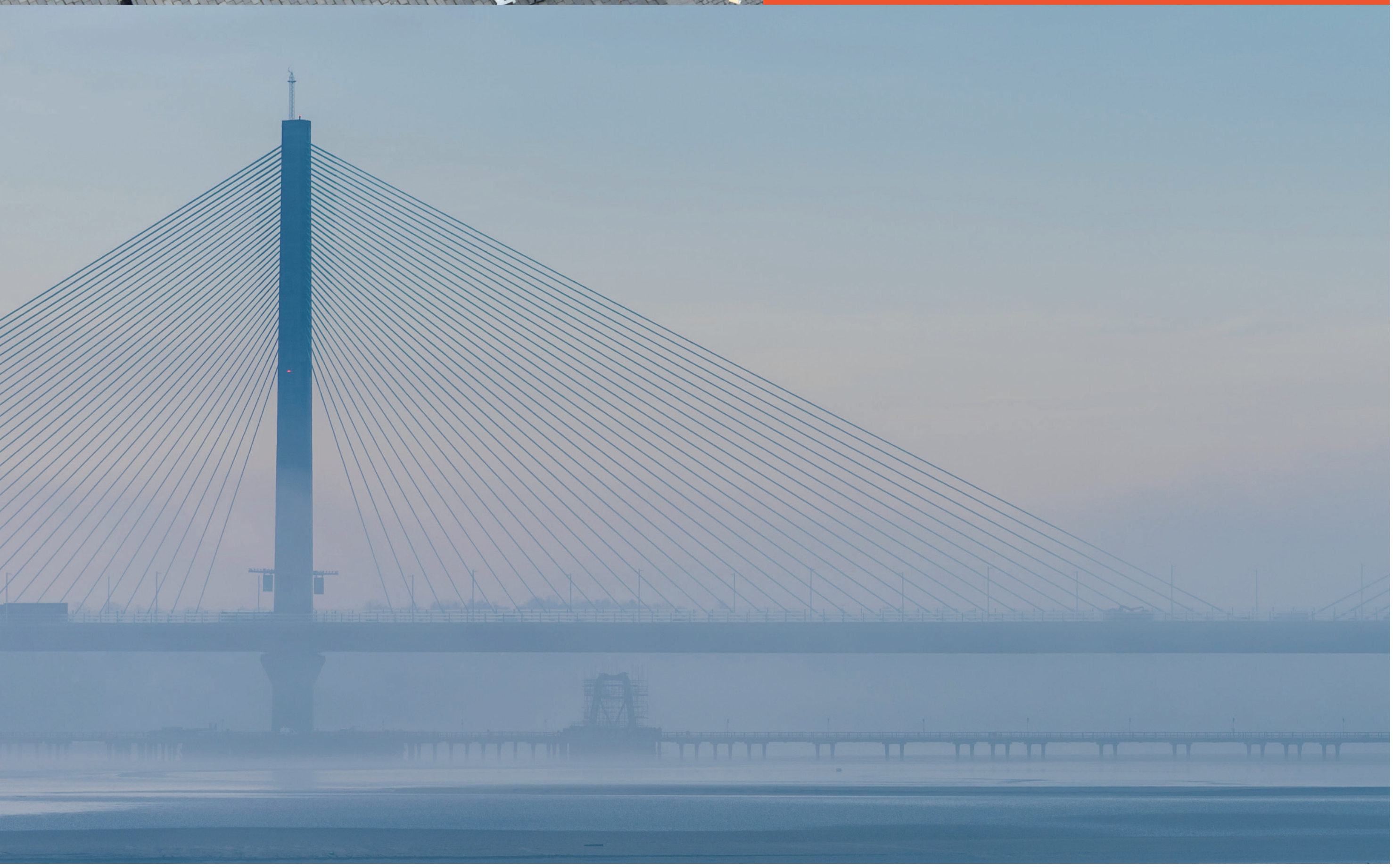
1. A Heat and Mass Balance demonstrating that the required product specifications temperature, pressure, and capture rate are met or exceeded.
2. Utility requirements including:
    - Power requirement
    - Thermal duty (steam conditions and quantities)
    - Cooling duty
3. The plant footprint being able to be contained within the area shown on the plot plan
4. The CAPEX and OPEX (including initial fill and yearly make-up costs), specified to within ±20%
5. The turndown capability & ramp rate
6. A HAZOP assessment

BEIS Hydrogen Supply Programme

HyNet Low Carbon Hydrogen Plant

Phase 1 Report for BEIS





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CONTENTS

Figures

Tables

1.0 Executive Summary

The HyNet Low Carbon Hydrogen Project comprises the development and deployment of a 100kNm^3/hr hydrogen production and supply facility to be sited at Essar Oil's Stanlow refinery utilising Johnson Matthey's Low Carbon Hydrogen (LCH) technology which includes carbon capture. It will represent the first deployment of a technology proven in other sectors to the production of clean hydrogen and will achieve this at scale, at a higher efficiency than other reforming technologies and with a very high carbon capture rate. It therefore will deliver low-cost, low carbon bulk hydrogen.

This plant is core to the North West HyNet project being led by Progressive Energy Ltd and provides a foundation reference design for replication through multiple units in the North-West, elsewhere in the UK and internationally. When associated with the HyNet carbon dioxide (CO_2) transport and storage infrastructure, this delivers low-cost, low carbon hydrogen for key industrials alongside non-disruptive blending to over two million households as part of delivering a net-zero industrial cluster in the region.

This report details the work undertaken on the project in 2019 as part of Phase 1 of the BEIS Hydrogen Supply Programme.

Hydrogen delivers energy without carrying carbon and therefore with no carbon dioxide emissions at the point of use. Hydrogen can be used to supply many parts of the energy system, often advantageously, for example: high temperature heat for industrial applications; rapid fill and range benefits for mobility; as well as the potential for low-cost diurnal or seasonal energy storage. Hydrogen is recognised as playing an important role in industrial transformation and delivering clean growth.

Conversion of fossil resources to hydrogen with Carbon Capture, Utilisation, and Storage (CCUS) is a practical means of bulk production, offering scale and cost benefits compared with alternatives such as electrolytic or bio-hydrogen. Advanced Reforming, and specifically Johnson Matthey's LCH technology delivers at a higher efficiency than other reforming technologies and with a very high carbon capture rate, therefore delivering low-cost, low carbon bulk hydrogen.

The HyNet cluster is based on the production of hydrogen from natural gas integrated with CCUS infrastructure. In its 2019 Progress Report, the Committee on Climate Change (CCC):

> **'In order to develop the hydrogen options, which are vital in our net-zero scenarios, significant volumes of low-carbon hydrogen must be produced at multiple industrial clusters.'**

HyNet is a complete system of hydrogen production, hydrogen supply, hydrogen utilisation, carbon capture, transportation, and carbon sequestration located in a concentration of industry, existing technical skill base, and suitable geology. The close proximity of hydrogen production, utilisation, and carbon sequestration means that the HyNet system offers substantially lower capital cost and development risk compared to other potential clusters around the UK. The new infrastructure for HyNet is readily extendable beyond the initial project and provides a replicable model for decarbonisation of other UK clusters.

The total demand for hydrogen is assessed in this report to be around 135TWh/yr regionally and over 550TWh/yr nationally by 2050, assuming that dispatchable power is delivered via hydrogen. Accounting for hydrogen production by electrolysis and biomass gasification, based on assumptions by Imperial College in its work supporting the CCC, there is a regional and UK demand of LCH hydrogen of 94 and 378TWh/yr respectively. This equates to between 30 and 120 LCH units depending on whether they are at the capacity of the initial unit or the larger unit, which would be expected during roll out.

A grounded business development plan provides an immediate and deliverable route to market, and a platform for expansion to provide a core aspect of meeting the UK's 2050 net-zero requirements.

In the short-term, the business plan is based on the construction of a 100kNm^3/hr hydrogen plant built on the Essar's Stanlow Refinery, with hydrogen customers for the full capacity. To maximise deliverability, sufficient customer offtake has been identified which minimises the number of independencies, and therefore risk to the Final Investment Decision (FID). The first plant produces around 3000GWh/yr of hydrogen.

The HyNet LCH project is able to deliver rapidly. Early adoption of low-cost, low carbon bulk hydrogen production is required by the early-mid 2020s; it provides a low-cost solution to meeting our imminent carbon budget shortfalls, it unlocks opportunities for early cost reductions through deployment, it provides the basis for clean growth and export, and critically safeguards existing industry much of which is vulnerable to carbon price increases and free allowance reductions, risking substantial carbon flight.

The plant is located on the refinery with sufficient land to deliver the first unit rapidly, with low planning risk, but also the capability for expansion up to six times capacity on the first site, allowing for zoning, constructability, tie-in and operational requirements. In addition, the North West has the chemical industry skills and political support to deliver the project within the wider HyNet scheme. CO$_2$ removal is through the low-cost, low risk HyNet CO$_2$ infrastructure with an initial infrastructure of 10MtCO$_2$/yr, expandable to over 20MtCO$_2$/yr, that is 30 times the capacity of the initial unit.

The project has been configured to use best practice engineering delivery. The consortium formed to deliver this is equipped and has the skills and experience to bring this plant to reality. The technology is delivered by Johnson Matthey plc (JM), a £11bn chemicals and catalyst technology company. SNC-Lavalin UK Ltd (SNCL) is an experienced £6bn international EPC contractor, well experienced in delivering chemical processing plant. Essar Oil (UK) Ltd is a £5bn international conglomerate that owns and operates the Stanlow refinery and sees this project as an opportunity to take an international lead in revisioning the refining sector, whilst reducing the carbon intensity of existing operations. In parallel Cadent will further develop the hydrogen distribution infrastructure for wider regional role out. The project is being led and co-ordinated by Progressive Energy Ltd (Progressive), who have been undertaking project development of CCUS and low carbon hydrogen-based solutions since 1998.

This project offers the lowest cost option for a first UK hydrogen project because:

- It uses the LCH technology delivering maximum efficiency hydrogen production capacity with CO$_2$ capture;
- The HyNet CO$_2$ infrastructure delivers low-cost, low risk CO$_2$ transport and storage (T&S) due to its location and relocation of assets;
- The refinery location offers operational synergies; and
- The opportunity to utilise an element of refinery off-gas (ROG) to reduce costs.
- This makes it the premier project to establish bulk low carbon hydrogen production in the UK under this programme.

The Phase 2 programme will complete the full FEED (Front-End Engineering Design) by March 2021, along with the full commercial framework for delivery, such that an FID can be expedited once the support regime has been put into place. On the basis of a timely delivery of a support regime, the plant can be operational in mid-2024, based on the

Phase 3 execution programme and so delivering low carbon hydrogen into the cluster by mid-2020s commensurate with the CCC recommendations.

The HyNet vision is a grounded development plan to facilitate roll out in the UK to enable the longer-term business plan. The CCUS capacity, hydrogen distribution infrastructure including storage as well as hydrogen consumers in the region provide a basis for expansion. It delivers a low carbon industrial cluster which can both expand regionally, as well as be replicated at other clusters. There are few technical barriers to commercialisation, as it is established chemical process engineering with the operation of the initial plant providing operational evidence. The main risk is considered to be an appropriate support regime. The build rate can deliver 90TWh/yr of capacity by 2035 (nine times the stretch target identified by BEIS in this programme) and over 250TWh/yr by 2045 only requiring about one larger plant to come on line per year. Supply chain assessment indicates there is more than adequate capacity to achieve this and could be delivered at a greater rate.

A Basis of Design (BoD) was developed, laying out all the technical parameters that applied to the inputs to and outputs from the LCH plant together with certain key requirements of scope and performance for the plant itself. As well as being a basis for the Phase 1 work, during Phase 1 these bases were tested for their appropriateness, both internally to the LCH project and as part of the interface to the wider HyNet project and the BoD was appropriately updated.

The project is based upon JM's LCH technology as this will provide the lowest cost for low carbon hydrogen at the scale required for HyNet. The project has also identified the specific location where the plant will be located, Area 4 of Essar's Stanlow Refinery.

The viability of the LCH technology to produce low carbon hydrogen has been confirmed through a range of Phase 1 engineering assessments. In addition, the operating conditions of the LCH technology have been optimised in comparison to previous studies and this has increased the CO_2 capture rate. The technology can be constructed to meet all regulatory requirements including air quality. The fired heater has been split into two to simplify the start-up and shut down of the LCH technology and to offer CAPEX savings.

The technology is also flexible enough to meet the varying demand of the end-users quickly. As part of Phase 1, a review of the LCA and LCM plants operation was conducted and found that the LCH plant can be started up in 6 to 8 hours to reach 40% and ramped up from 40% to 100% in 30 to 60 minutes. The process can be also ramped down from 100% to 40% in about 10 minutes.

Whilst the focus has been on a single unit at 100kNm^3/hr capacity, a 500kNm^3/hr scheme has been developed and assessed in terms of site layout and indicative costs to provide the basis for roll out.

A key attribute of this project is the participation of an international EPC contractor, SNCL, who have produced the capital cost estimate for the plant. The process plant information is based on quotations obtained by JM. The equipment throughout the remainder of the plant has been priced based on vendor quotations, licensor estimates, recent project data, and SNCL internal database information. Building on from the costs for major equipment packages or stick built equipment, the estimates for installation, bulk materials and labour, commissioning, and contractor's and owner's costs were developed. This provides a capital cost estimate of £253M for a single unit of 100kNm^3/hr hydrogen. The OPEX estimate has been built up from information available from the Phase 1 design, covering fixed costs (including staffing) and variable costs. This includes catalyst change out from proprietary equipment as well as maintenance, utilities and consumables based on capital cost estimates.

On this basis, the plant delivers a levelised cost of hydrogen of £43.46/MWh (HHV basis). The estimated equivalent cost for a 5x unit is £35.62/MWh. By way of comparison, this is lower than the equivalent cost of natural gas, accounting for the cost of carbon in 2035, which is assumed to be £37.16/MWh, in line with BEIS data, with a rising trajectory beyond this due to increasing carbon price.

A project delivery plan has been developed to execute a programme to reach a "shovel ready" project (Phase 2) and then into construction and operation (Phases 3 and 4).

To achieve this requires a firm policy framework. Without the cost of carbon fully internalised in our energy markets, delivering low carbon solutions will require some form of revenue support. Whilst grant funding may be of assistance in terms of addressing aspects of risk allocation for early projects, there will be a requirement to address the increased operational costs of low carbon hydrogen production. Therefore, it is imperative that there is an appropriate and timely revenue support regime. Whilst it is important to establish enduring support regimes, the legislative processes to deliver these can be considerable. In order to create a new market and achieve timely delivery of early hydrogen facilities and infrastructure it is likely to be important to put in place interim support regimes, similar to "FID-Enabling" contracts under the CfD regime.

The consortium will deliver a "shovel-ready" FEED package for the 100kNm^3/hr LCH plant for Essar's Stanlow Refinery. The objective of the Phase 2 FEED is to "define" the project based on the selected concept to allow successful project sanction.

To achieve this requires a firm policy framework.

To achieve the objective the project team's delivery will include all the necessary site characterisation, basic engineering packages for the core process and associated vendor packages and the full FEED. This will be used to provide the total installed cost estimate. The definition of design and specification will be developed in order to handover to EPC phase with the engineering, procurement and construction strategies defined. In parallel, applications for planning, permit and consents will be submitted and heads of terms and draft contracts developed as a basis to progress to FID, on the basis of an appropriate and delivered policy framework.

A levelised cost of hydrogen of £35.62 to £43.46/MWh depending on scale, lower than the cost of natural gas by 2035, accounting for the price of carbon.

The roles and responsibilities for each project partner have been defined with appropriate organisational and governance arrangements to enable delivery.

The non-engineering project development work undertaken during FEED is critical to delivering a "shovel ready" enterprise which is capable of being sanctioned for build following this phase of the project. This includes establishing the entity that will own and operate the LCH plant, expected to be a Special Purpose Vehicle (SPV) company including Essar, and terms for Land and Wayleaves will be negotiated. To support financing, and on the basis of a policy framework from BEIS a detailed financial model will be developed. During Phase 2 the consortium will identify an appropriate and cost-effective project delivery strategy for the LCH facilities and develop the contract for delivery of engineering, procurement and construction. In order for the plant to operate it requires a variety of supplies and off-takes. It will not be possible to finalise many of these negotiations until the support arrangements for low carbon hydrogen have been agreed and put in place by HMG. The Phase 2 work will include a number of workstreams to engage with the wider HyNet project and the key stakeholders involved. Whilst not being undertaken as a funded part of this project, in parallel to the Phase 2 work Cadent Gas Ltd will undertake a Pre-FEED study of the hydrogen distribution system needed for the wider HyNet vision. In the longer term it is expected that storage will play an important role in balancing hydrogen production and use in the wider HyNet area and the technical requirements for hydrogen storage will be established. A key responsibility during Phase 2 is the transfer of knowledge and learning from the project to wider industry. As part of encouraging financial investors it is important that the consortium can show a business plan that extends beyond the first project.

> The HyNet Low Carbon Hydrogen Project accelerates the development of bulk low carbon hydrogen.

The objective of the execution phase of the project is to deliver safely a facility for handover to the operator. The phase comprises four primary activities: detailed engineering, procurement of equipment and materials, construction and commissioning. The project, engineering, procurement, and construction management will be based in the UK and will relocate to site to support construction. Detailed design will be managed by offices within the UK. The project organisation is planned to be run by Essar as the owner and operator of the final asset through an SPV, with overall project management by Progressive and Essar, SNCL the contractor for the execution phase and JM, licensor of the LCH technology.

The LCH Plant is designed for continuous operation with maximum uptime (availability) in order to generate the best economic return on investment. The LCH Plant will be operated by a dedicated operations team of suitably qualified and trained personnel. The operations team will operate on a shift pattern to provide continuous operational coverage of the plant and will be supported by a day shift who will cover management and routine maintenance of the plant and provide administration for the operation of the plant as a business. Non-routine maintenance will be supported by outside contractors and equipment manufacturers. Planned outages for significant maintenance will be organised at set durations through the plant life and will be campaigned to reduce the impact (downtime) on the plant economic operation. The plant availability has been assessed at 95.1%.

The HyNet Low Carbon Hydrogen Project accelerates the development of bulk low carbon hydrogen.

Technically, the approach is based on chemical processing engineering, designed to operate at scale; enabling carbon reductions for industry, dispatchable power, domestic heating and transport. It can provide the volumes required through a relatively small number of plants. It delivers at a cost base at half that achievable through electrolysis, and lower than that projected from bio-hydrogen from biomass. Capture rates are at 97%, with developments that could increase this further.

In the future combining an element of the feedstock stream from gasification of biogenic sources would deliver net-zero hydrogen. Alternatively, co-location with bio-hydrogen production can deliver net-zero clusters, with the fossil derived hydrogen production providing the volumes of CO_2 to amortise the infrastructure.

Bulk hydrogen production enables the development of both the market and infrastructure for hydrogen distribution, storage and use. Beyond 2050, as international markets and sources of renewable hydrogen develop, established UK hydrogen infrastructure positions it to take advantage of such sources to complement reformed gas.

2.0 Introduction

The HyNet Low Carbon Hydrogen Project comprises the development and deployment of a 100kNm^3/hr hydrogen production and supply facility to be sited at Essar Oil's Stanlow refinery utilising Johnson Matthey's LCH technology which includes carbon capture. It will represent the first deployment of a technology proven in other sectors to the production of clean hydrogen and will achieve this at scale, at a higher efficiency than other reforming technologies and with a very high carbon capture rate. It will, therefore, deliver low-cost, low carbon bulk hydrogen.

This plant is core to the North West HyNet project[1] being led by Progressive Energy Ltd (Progressive). It is not simply a theoretical plant design but one that meets the specific regional demands, delivered on a specific project site. It will provide a foundation reference design for replication through multiple units in the North West, elsewhere in the UK and internationally. When associated with the HyNet CO_2 transport and storage infrastructure, this delivers low-cost, low carbon hydrogen for key industrials alongside non-disruptive blending to over two million households as part of delivering a net-zero industrial cluster in the region.

This report summarises the output of the work carried out under the BEIS Phase 1 Hydrogen Supply Competition. This work was undertaken by a consortium of Johnson Matthey plc (JM), as the technology provider, SNC-Lavalin UK Limited (SNCL), as project delivery specialists, and led by project developer Progressive. Essar Oil (UK) Limited (Essar) has confirmed interest to join the consortium as owner/operator of the hydrogen production unit. Appendix 1 gives more detail of the work packages executed under Phase 1.

3.0 Rationale

Hydrogen is a vector which delivers energy without carrying carbon and therefore with no carbon dioxide (CO_2) emissions at the point of use.

Hydrogen is not itself an energy source and must be produced using other sources of energy, such as wind generated electricity used to split water via electrolysis or conversion of hydrocarbon sources (e.g. reforming of natural gas, or potentially conversion of renewable biomass). Where the source is from fossil resources, then no carbon benefit is conferred unless the carbon is captured such that CO_2 is not released to the atmosphere, i.e. Carbon Capture Utilisation & Storage (CCUS). Where the source is biogenic, then conversion to hydrogen with CCUS is also a mechanism to remove carbon from the biosphere, known as BECCS (Bio-Energy Carbon Capture & Storage), a form of geoengineering.

Conversion of fossil resources to hydrogen with CCUS is a practical means of bulk production. In the context of CCUS, hydrogen as a vector allows the centralised capture of CO_2 for sequestration via transport and storage (T&S) infrastructure, whilst providing distributed low carbon energy to multiple users.

Hydrogen can be used to supply many parts of the energy system, often advantageously, for example: high temperature heat for industrial applications; rapid fill and range benefits for mobility; as well as the potential for low-cost diurnal or seasonal energy storage. Hydrogen is recognised as playing an important role in industrial transformation and delivering clean growth, and therefore has a role in the UK's industrial strategy. Hydrogen should be pursued where it offers the potential for economic advantages compared with other low carbon solutions, or where it unlocks benefits that cannot readily be delivered through alternatives.

The Committee on Climate Change (CCC) has recognised the important role that hydrogen plays in decarbonising the energy system in its net-zero report[2]. For the UK to deliver a net-zero carbon energy system, it has explicitly identified the requirement for 225TWh/yr of low carbon hydrogen production with CCUS[3]. The CCC also identifies 148TWh/yr electricity from 'gas with CCS plants', which could potentially be hydrogen fired. The CCC concludes that:

> In order to develop the hydrogen option, which is vital in our scenarios, significant volumes of low-carbon hydrogen must be produced at one or more CCS clusters by 2030, for use in industry and in applications that would not require initially major infrastructure changes (e.g. power generation, injection into the gas network and depot-based transport).

Hydrogen plays a role in all the emerging UK CCUS clusters. It is integral to the HyNet and Western Cluster for delivery to industry and as a blend to the gas network as well as unlocking mobility and dispatchable power benefits[4] and synergistic links to the steel industry in South Wales.

3.1 Hydrogen Sources

Low Carbon hydrogen can be produced via three primary routes; electrolytic splitting of water using renewable electricity, reforming of fossil resources with CCUS, or conversion of renewable biomass with or without CCUS. Hydrogen produced from renewable resources is commonly referred to as 'Green Hydrogen', and from fossil resources with CCUS as 'Blue Hydrogen'.

3.1.1 Electrolytic Hydrogen

Production of hydrogen by electrolysis is a mature technology and is widely deployed internationally at scales of 100s of kWth capacity[5]. In the UK there are examples of operational hydrogen filling stations at this capacity, and ITM is supplying a similar electrolyser for the HyDeploy project[6]. Projects are underway to scale up production such as Project Centurion[7] which is targeting around 75MWth of installed hydrogen capacity.

The cost of electrolytically-produced hydrogen depends on the capital cost of the equipment and crucially the cost of electricity and utilisation of the plant. Operating at high load factor reduces the capital cost element of the levelised cost, but means that at typical scales, electricity will need to be purchased at market prices, meaning that the input energy cost alone may be in excess of £100/MWh of hydrogen. Using constrained renewable resources will lower the cost of electricity and the carbon intensity, but the capital cost element rises with low utilisation. For example, offshore wind has a load factor of around 40%, but it is unlikely it could deliver economically with >10% constraint, which is a utilisation of the electrolysis plant of <4%. In this case, the capital cost element of electrolytic hydrogen production would be significant. Therefore, whilst electrolytic hydrogen has a role to play, particularly where it can assist with balancing the electricity network, it is expected to be a costly route.

3.1.2 Biohydrogen

Bioenergy with CCS (BECCS) is widely recognised as playing an important role in meeting our 2050 obligations. As identified by the CCC in its net-zero report, this means combining bioenergy with CCS, "whether for power generation, hydrogen production or production of biofuels"[8]. However, this requires development of reliable and financeable biomass gasification at scale, capable of delivering a syngas suitable for subsequent conversion (shifting) to hydrogen. It also depends on the consolidation of significant volumes of biomass supply chains to support financing and delivery of conversion plants. There is no doubt that production of biohydrogen will form an important part of delivering Net Zero, although these factors are likely to delay the uptake of biohydrogen, and potentially constrain capacity relative to reforming of gas with CCUS.

3.1.3 Conversion of Natural Gas with CCUS

Conversion of natural gas to hydrogen is a mature technology deployed internationally. It offers the potential for bulk low carbon hydrogen production considerably more cost effectively than electrolytic or biohydrogen. Therefore, whilst it is expected that there will be a mixture of hydrogen sources in the future, “blue hydrogen” is expected to be the dominant source, as assessed by the CCC.

Two principal technologies are available: Steam Methane Reforming (SMR) and Advanced Reforming including Autothermal Reforming (ATR) or Gas Heated Reforming coupled with an ATR. Where there is a requirement to capture CO$_2$, it is recognised that Advanced Reforming is a more appropriate technology, as SMR gives rise to two separate CO$_2$ streams, one of which is at low pressure and low CO$_2$ concentration, while Advanced Reforming produces a single high-pressure stream for CO$_2$ capture.

JM’s LCH technology offers lower cost, higher CO$_2$ capture rate, and scalability advantages. The technology also can process feeds other than natural gas. The performance characteristics are presented in more detail in Section 6.0.

4.0 HyNet & The Future of Hydrogen

4.1 HyNet Overview

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.

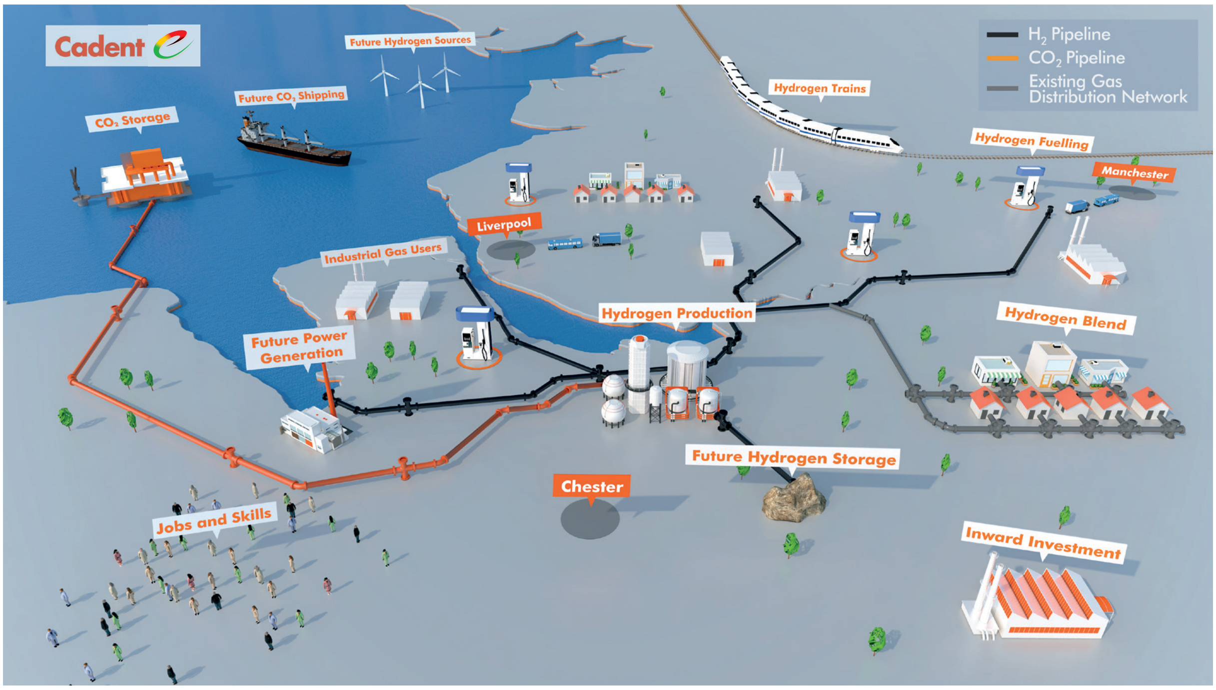
The HyNet cluster is based on the production of hydrogen from natural gas integrated with CCUS infrastructure. In its Progress Report, the CCC concludes that:

‘In order to develop the hydrogen options, which are vital in our net-zero scenarios, significant volumes of low-carbon hydrogen must be produced at multiple industrial clusters.’

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

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

Figure 4-1 - HyNet Infographic



4.1.1 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, virtually no 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.

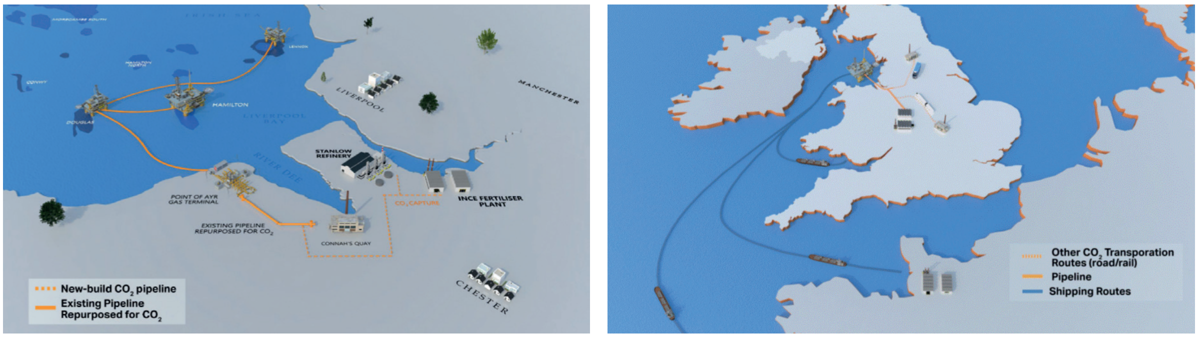
The CCC has recommended the urgent deployment of CCUS on a cluster basis with integrated hydrogen production to address decarbonisation of a range of sectors, including industry, heat, transport and power generation. To achieve the net-zero 2050 target, the CCC has determined that up to 178MtCO_2/yr of CCUS will be required across these sectors.

4.1.2 HyNet Elements

HyNet is an integrated Hydrogen / CCUS project that directly addresses this policy need. It takes a cluster-based approach to large scale regional decarbonization in the North West of the UK. Anchored with low-cost industrial 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 project is split into elements:

- Element 1 of the project (FID 2022, operational 2024) will construct 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 plant, are amongst

Figure 4-2 HyNet Infographic



the UK's largest industrial emitters and provide immediate capture opportunities of 1.2MtCO$_2$/yr. Pipeline infrastructure will be sized at up to 10MtCO$_2$/yr to facilitate future phases. Storage will be in the Liverpool Bay gas fields currently nearing depletion and owned and operated by Eni.

- Element 2 of the project (FID 2022, operational 2024), which is being developed in parallel with Element 1, but is separated due to different regulatory regimes, will construct a number of hydrogen production units at the Stanlow oil refinery site. These are based on the 350MWth (HHV) hydrogen plant being developed under this Hydrogen Supply Project. Hydrogen will be used for industrial fuel switching and distribution network blending to reduce the carbon intensity of domestic and commercial heat use. Both of these areas are the subject of engineering development programmes, namely the HyNet Fuel Switching Project and the HyDeploy hydrogen blending project. Up to 3MtCO$_2$/yr will be captured in this phase.
- Element 3 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 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. This underpins further hydrogen production and introduction of BECCS, potentially producing biohydrogen. Up to 10MtCO$_2$/yr will be captured in this phase from 2025 onwards.
- Element 4 will see the development of a 'Western Megacluster', with industrial emissions and emissions from hydrogen production in South Wales being shipped to the North West 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 a Western Megacluster (comprising, Wales, the Midlands and the North West) could be up to 47.3MtCO$_2$/yr, from power generation, industrial capture, industrial fuel switching, hydrogen transport, and hydrogen network blending. Of this 47.3MtCO$_2$/yr potential, we consider 20MtCO$_2$/yr a useful upper bound estimate for HyNet project capacity.

The HyNet project was conceived in 2016 and has been formulated and driven by Progressive. Two substantial feasibility studies have been published to date, funded by the Gas Distribution Company, 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 to the storage of >20MtCO$_2$/yr 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. Progressive has assembled a team of plant owners and key subcontractors as the basis for the project consortium and secured funding from HMG to contribute to development costs.

Pre-FEED activities on Element 1 are led by Progressive and currently funded by project partners Essar Oil (who own and operate Stanlow Oil Refinery which provides 16% of UK transport fuels), CF Fertilisers (who provide ~50% of UK fertilisers), Cadent Gas (who own and operate four of the eight UK gas distribution networks), Peel Environmental (who are major land and infrastructure owners in the region) and the University of Chester, together with support from HMG. Eni (owners of the offshore gas fields in which CO_2 storage is planned) are funding their own engineering activities and co-operating closely with Progressive 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 Progressive with funding from HMG. Hydrogen production utilises JM LCH technology with SNCL undertaking the EPC activity and Essar providing the site at the Stanlow Refinery. Hydrogen demand activities underway involve six major companies with significant manufacturing activities in the area (Essar, Unilever, Solvay, Pilkington Glass, Ibstock Brick and Jaguar Land Rover) who see the potential to substitute gas by low carbon hydrogen in a range of heating applications. These cover use in high temperature furnaces, boilers and direct firing applications across a range of industries. Progressive is undertaking demonstration testing on the use of hydrogen blends up to 20% in the existing gas network through the HyDeploy[9] project. The £22.5M OFGEM NIC supported programme is sponsored by Cadent Gas and Northern Gas Networks, two of the four Gas Distribution Operators. Cadent is also sponsoring the development of a hydrogen distribution network in the North West to service existing natural gas end-users.

Taken together, Elements 1 & 2 constitute the leading approach to the decarbonization 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.

4.2 Hydrogen Market Assessment

A detailed bottom up analysis of UK hydrogen demand by sector has been undertaken. It assesses the market opportunity for the initial LCH unit to underpin the delivery of the first project. Hydrogen demand is assessed both regionally and nationally with maximum demand being provided on a 2050 basis. Given the reliance on CCUS infrastructure a "cluster model" is assumed; the North West regional assessment is based on data from the North West, with the national assessment assumed to follow a similar pattern building out from other CCUS clusters.

This modelling expects hydrogen demand to be dominated by industrial use and low carbon dispatchable power generation to enable deeper deployment of intermittent renewables. Blending into the gas grid provides an important means to reduce the carbon intensity of domestic and commercial heat demand, with the potential for conversion of elements of the gas grid to full hydrogen. For transport, hydrogen enables decarbonisation of HGVs and fleet (depot-based) vehicles and the non-electrified rail sectors.

Delivery to these markets will require associated development of hydrogen distribution, potentially conversion of elements of the existing gas network as well as hydrogen storage to provide efficient matching of supply and demand. This infrastructure development is enabled by delivering to specific sectors, which is identified in the assessment.

The total demand for hydrogen is assessed in this report to be around 135TWh/yr regionally and over 550TWh/yr nationally by 2050, assuming that dispatchable power is delivered via hydrogen. Accounting for hydrogen production by electrolysis and biomass gasification, based on assumptions by Imperial College in its work supporting the CCC, there is a regional and UK demand of LCH hydrogen of 94TWh/yr and 378TWh/yr respectively. This equates to between 30 and 120 LCH units depending on whether they are at the capacity of the initial unit or the larger unit, which would be expected during roll out.

The UK enjoys a number of key advantages in relation to hydrogen and CCUS clusters: it has an extensive gas network, indigenous sources of natural gas, suitable sites for LCH development and high quality, large scale geological storage sites for carbon sequestration in the Irish Sea and the North Sea. This may allow the UK to develop, over time, a low-cost hydrogen production industry, capable of economically exporting hydrogen to customers around the world.

Table 4-1 - UK Hydrogen Demand

H_2 Demand (TWh/yr)	Initial	Regional	National
Industrial	2.4	16.7	135.0
Dispatchable Power	0.7	91.4	308.0
Transport	0.0	20.0	82.0
Distribution Grid Blending	0.3	9.7	29.0
Total	**3.4**	**137.8**	**554.0**

There is also a range of international hydrogen opportunities that can flow from this; either for export of hydrogen or for construction of indigenous LCH plants.

Together, the above market assessment provides the basis for the business development plan summarised in Section 4.3.

4.2.1 Summary of UK Demand for Hydrogen

The total low carbon hydrogen demand for the UK in 2050 has been assessed to be around 554TWh/yr as summarised in Table 4-1.

This is broadly consistent with the Imperial College Hybrid 10 scenario. The CCC's 2019 Progress report identifies 270TWh/yr of hydrogen demand, although they have generally not assumed that the dispatchable generation demand is supplied by hydrogen. Imperial College in its underlying work assumed all dispatchable power was from hydrogen, consistent with the above assessment.

4.2.2 Summary of UK Sources of Hydrogen

As identified in Section 3.0, there are a variety of potential sources, although supply is dominated by LCH hydrogen production.

Imperial College's Hybrid 10 scenario anticipates 48TWh_e/yr of electrolysis capacity is available by 2050. Based on an efficiency of 80% this equates to an output of 38TWh_{th}/yr.

The Committee on Climate Change estimates that 200TWh/yr of biomass is available which should be used with CCS. The models used by Imperial supporting the CCC report model chose to use BECCS to produce hydrogen in all cases. At the (conservative) 69% conversion efficiency identified the Imperial report suggests, this indicates 138TWh/yr of bio-hydrogen in 2050.

This suggests a combined hydrogen production of 174TWh/yr from these sources by 2050, therefore a balance of demand of 378TWh/yr of hydrogen from LCH production facilities. It is assumed that the

Table 4-2 - UK Hydrogen Demand Supplied by LCH

LCH H_2 Demand (TWh/yr)	Initial	Regional	National
Industrial	2.4	11.4	92.1
Dispatchable Power	0.7	62.4	210.2
Distribution Grid Blending	0.3	6.6	19.8
Transport	0.0	13.6	55.9
Total	3.4	94.0	378.0
LCH Units (350MWth)	1	31	126

regional and national scenarios have the same pro-rata split of hydrogen production by electrolysis, biomass and LCH, although the initial demand is assumed to be from the first LCH unit, as any production by either electrolysis or biomass is likely to be negligible on the timeframes considered.

Total LCH demand is converted to numbers of units, based on a reference capacity of 100kNm^3/hr (350MWth HHV), although it is recognised that as hydrogen demand develops, larger unit sizes up to 500kNm^3/hr (1750MWth HHV) may be deployed to deliver economies of scale.

This analysis indicates a UK LCH demand of around 120-130 equivalent units on a 2050 timeframe, although this could be delivered with ~25 larger units, which equates to a build out of around one plant per annum to 2050, which is deliverable with the right policy framework.

4.2.3 International Opportunities for Hydrogen

The UK's challenges in decarbonising its energy system are not unique. All other countries currently have obligations to reduce greenhouse gas emissions under the Paris Agreement. International demand for hydrogen from industrial users in major international business, which has grown three-fold over the last four decades to around 4000TWh/yr. This hydrogen is predominantly sourced from fossil resources, consuming around 6% of global natural gas and 2% of global coal supply. It is responsible for over 800 million tonnes of CO_2 emissions per annum. Globally, hydrogen has a potential role addressing chemicals manufacture, high-temperature industrial heat, iron and steel production, long-distance and urban road transport, shipping and heat for buildings. Because hydrogen can be stored, burned or used chemically in ways that are similar to conventional fossil resources, it is believed to provide a deliverable low carbon solution.

To deliver this requires low carbon sources of hydrogen at scale. Whilst there is likely to be a role for hydrogen from renewables, there is no doubt that to deliver the volumes required, continued use of fossil resources is necessary – providing that the CO_2 emitted in their production is permanently sequestered.

Two principal international opportunities may emerge from the creation of a low-cost decarbonised hydrogen supply chain in the UK:

- Roll out of hydrogen production technology to other jurisdictions. This includes the deployment of equipment but also export of skills and services necessary for delivery; and

- International supply of hydrogen from UK facilities. In addition, the development of associated CO_2 storage infrastructure in the UK provides mirrored opportunities in this sector.

The number of countries with hydrogen-supporting policies is increasing across different sectors including transport, power generation, and industry. Around US$800 million of national research and development budgets are focused on this sector. IEA[10] has identified nine facilities around the globe which have started to capture CO_2 from fossil-based hydrogen production for industrial applications. Key jurisdictions for low carbon hydrogen are: The European Union, China, The United States, Korea, and Japan.

The UK enjoys a number of key advantages in relation to hydrogen and CCUS clusters: it has an extensive gas network, indigenous sources of natural gas, suitable sites for hydrogen production development and high quality, large scale geological storage sites in the Irish Sea and the North Sea. This may allow the UK to develop, over time, a low-cost hydrogen production industry, capable of economically exporting hydrogen to customers around the world, as well as providing an export of skills and services.

4.3 Business Development Plan

This LCH solution addresses a critical market need for decarbonisation, with an approach which offers deeper carbon reductions at a lower cost than alternatives. A grounded business development plan provides an immediate and deliverable route to market, and a platform for expansion to provide a core aspect of meeting the UK's 2050 net-zero requirements.

Therefore, there are two elements to the business plan:

- A short-term business plan addresses the key commercialisation risks to unlock wider deployment; and
- A longer-term business plan to deliver roll out of bulk low carbon, low-cost hydrogen.

The following outlines the commercialisation risks that the plan needs to address as well as both the short- and longer-term business plans.

4.3.1 Commercialisation Risks to be Addressed

The risks implicit in commercialising the technology are assessed as follows:

Technical: This is a well-developed technology which has been used internationally for ammonia and methanol production and the LCH technology has now been optimised for hydrogen production. The technical risks relate to the robust ability to meet the high capture rates and efficiency design points, and product specifications over the operating conditions required, particularly through start-up and shut down as well as under turn down conditions. Whilst any plant will operate most economically at baseload, it is important to establish that it can meet turndown, and ramp-rate requirements to meet market demand.

Commercial: The outturn costs of the facility and its operation will dictate the market merits of the technology. Delivery can only be achieved with the appropriate policy framework. Until the costs of environmental damage due to carbon emissions are fully internalised, there will be a requirement for some form of support regime to address out-of-market costs. Without this, it will not be possible to deliver projects. This is addressed in more detail in Section 8.2.1.

Deliverability: The design is based on a standardised unit, which has been assessed for manufacture and the ability of the supply chain to produce and deliver the necessary key elements. Construction of the first plant will validate this to enable roll out and expansion.

Timescales: To meet 2050 requirements, the early project must be operating rapidly to evidence the role that the technology can play in meeting the targets.

To commercialise the technology, construction and operation of a full-scale facility are required.

Based on the standardised design, a first full FEED must be undertaken based on a real project to take to FID on the first at-scale project. Commercial operation will demonstrate that full chain operation can be delivered matching customers' requirements and plant performance and costs. It must also be capable of expansion, as outlined in Section 4.3.3.

4.3.2 Short Term Business Plan

The short-term business plan is based on the construction of a 100kNm³/hr hydrogen plant built on the Essar Site, with hydrogen customers for the full capacity.

4.3.2.1 Deliverable Short-term Market

To maximise deliverability, sufficient customer offtake has been identified which minimises the number of independencies, and therefore risk to Financial Close. The first plant produces around 3000GWh/yr of hydrogen.

The dominant customer is the refinery itself, which consumes around 700MWth of heat, predominantly serviced by ROG. The refinery will take hydrogen for fuel switching of various process heaters and is currently participating in an Industrial Fuel Switching Programme, funded by BEIS to establish the basis for conversion to full hydrogen operation. Over 800GWh/yr of demand from individual units have been identified, with potential for further conversion if hydrogen is available. Essar also currently run a CHP which they are evaluating for replacement. As part of the fuel switching programme feasibility work is being undertaken on replacing this with a hydrogen fuelled facility. This would require potentially 1400GWh/yr of fuel demand.

HyNet infrastructure itself requires low carbon generation. New hydrogen-fuelled dispatchable power plant capacity will deliver low carbon electricity to the HyNet infrastructure, demonstrating the operation of a gas turbine (GT) operating flexibly on hydrogen. This requires at least 700GWh/yr of capacity.

The site is located adjacent to two large industrial users of gas within 2km of the plant, with the opportunity to use existing pipelines for delivery. These have the capacity of taking over 200GWh/yr without intervention and could take higher levels with conversion.

To ensure deliverability, the initial industrial users have been selected to minimise the reliance on extensive hydrogen distribution and use hydrogen in a way which maximises confidence in ability to adopt hydrogen. However, to roll out wider adoption across other industrial users and at higher levels of hydrogen utilisation requires technical and commercial market confidence. In that regard it is imperative that demonstration of successful industrial fuel switching is delivered in parallel with development of hydrogen supply.

The Local Transmission System (LTS) passes along the edge of the site, and so the facility is able to blend into the gas grid based on the outcome of the HyDeploy project. This connection alone could take 250GWh/yr. Across the region, with the pipeline proposed by Cadent Gas, there is capacity of taking over 3000GWh/yr.

Together this is over 3350GWh/yr of firm demand, and double this with connectivity to the regional gas network and adoption of other industrial users on the refinery alone.

The primary customers are baseload, and therefore the initial unit does not require storage, keeping costs low and utilisation high, however, the region has hydrogen storage capacity for the future (as is currently being demonstrated by Projects Centurion and HySecure).

The hydrogen production plant will take an element of refinery gases as part of the feedstock. By doing so, it enables the refinery to maintain its energy balance, keeping costs low and maximising deliverability.

4.3.2.2 Plant Location

The project is located on the refinery with sufficient land to deliver the first unit rapidly, with low planning risk, but also the capability for expansion to six times capacity on the first site (see Section 6.1.1) allowing for zoning, constructability, tie-in and operational requirements. The North West has the chemical industry skills and political support to deliver.

4.3.2.3 CO_2 Removal

CO_2 removal is through the low-cost, low risk HyNet CO_2 infrastructure with an initial infrastructure of 10MtCO_2/yr, expandable to over 20MtCO_2/yr, that is 30 times the capacity of the initial unit. See Section 4.1 for further information on the HyNet Infrastructure.

4.3.2.4 Plant Delivery

The project has been configured to use best practice engineering delivery, with an EPC contractor as part of the project consortium using well proven contractual structures, delivered in a high skills region and supply chain assessed for delivery capacity. See Section 8.0 which addresses the Project Execution Plan for all phases of the project, as well as the approach to contracting and financing.

4.3.2.5 Delivery Team

The consortium is equipped and has the skills to deliver this plant. The technology is delivered by JM, a £11bn chemicals and catalyst technology company. SNCL is an experienced £6bn international EPC contractor, well experienced in delivering chemical processing plant. Essar is a £5bn international conglomerate that owns and operates the Stanlow refinery and sees this project as an opportunity to take an international lead in revisioning the refining sector, whilst reducing the carbon intensity of existing operations. In parallel Cadent will further develop the hydrogen distribution infrastructure for a wider regional roll out. The project is being led and co-ordinated by Progressive, who have been undertaking project development of CCUS and low carbon hydrogen-based solutions since 1998.

4.3.2.6 Competitive Costs for Delivery

Lowest cost of bulk hydrogen production is from fossil resources with CCUS. This project offers the lowest cost option for a first UK hydrogen project because:

- It uses the LCH technology delivering maximum efficiency hydrogen production capacity with CO_2 capture;
- The HyNet CO_2 infrastructure delivers low cost, low risk CO_2 T&S due to its location and relocation of assets;
- The refinery location offers operational synergies; and
- The opportunity to utilise an element of ROG to reduce costs.

This makes it the premier project to establish bulk low carbon hydrogen production in the UK under this programme.

4.3.2.7 Financing

Delivery is predicated on the establishment by HMG of a suitable policy architecture, which provides an appropriate return to investors into hydrogen production.

The Carbon Capture and Storage Advisory Group (CAG) has worked to develop financing models for hydrogen production and carbon capture and storage[11]. This provided supporting material to a consultation by BEIS into CCUS[12] launched in July 2019, with a government response expected by the end of 2019 and with recommendations expected to be incorporated into a policy framework during 2020.

The models considered by the CAG include a Regulated Asset Base (RAB), Contract for Difference (CfD), a Hydrogen obligation, incentives or grants. Although policy clarity is not yet available, the principles being applied aim to deliver lowest cost hydrogen without inadvertently introducing any distortions which might result in any excess returns resulting for any individual market participant or sector. Given these challenges, it is likely that for timely delivery of early hydrogen facilities and infrastructure it will be important to put in place interim support regimes, similar to “FID-Enabling” contracts under the CfD regime. These options are discussed in more detail in Section 8.2.1.

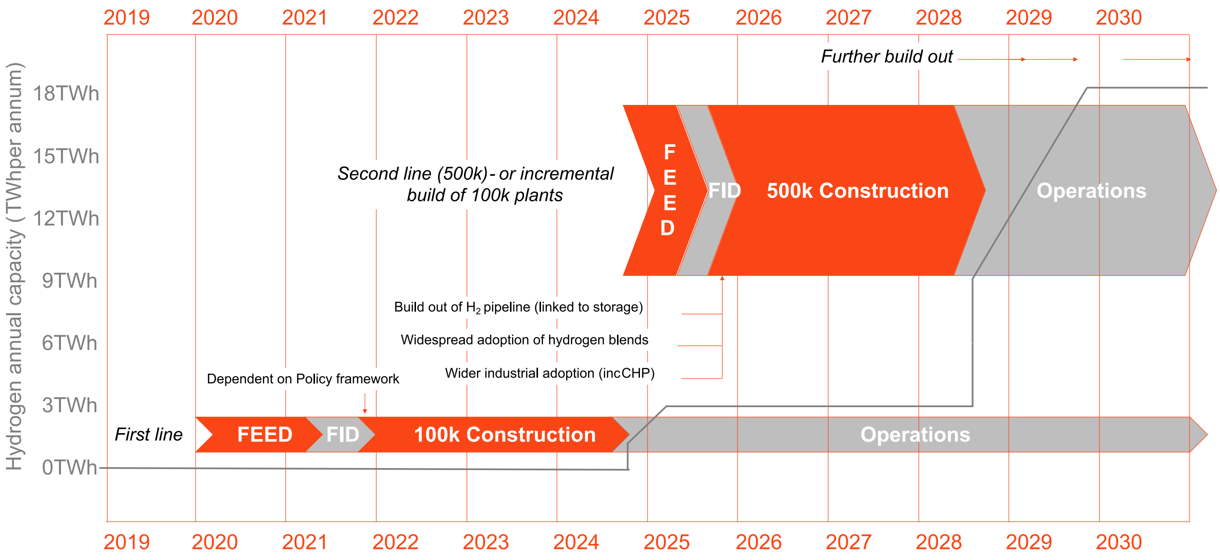
It is fundamental to progress that an appropriate regime is put in place which provides appropriate revenue support and risk allocation, including that associated with CCUS in order to enable investment. With an appropriate regime, it is expected that finance can be secured, similar to that directed to offshore wind and other renewables.

4.3.2.8 Timescales – Ability to Deliver

The Phase 2 programme will complete the full FEED by March 2021, along with the full commercial framework for delivery, such that FID can be expedited once the support regime has been put into place. On the basis of a timely delivery of a support regime, the plant can be operational in mid-2024, based on the Phase 2 execution programme, and so delivering low carbon hydrogen into the cluster by the mid-2020s, commensurate with the CCC recommendations.

Figure 4-2 shows the timeline for the initial facility, as well as the potential construction of the next unit, consistent with the longer-term business plan discussed in 4.3.3. It is assumed that the initial facility can ramp up to full capacity relatively quickly with local offtakers being scheduled to utilise the hydrogen. It assumes that an appropriate support regime has been put in place, and that this would allow for market-making hydrogen to come onstream up to a year ahead of CCUS infrastructure. The economic advantages of the second unit being of larger capacity would favour the follow-on plant to be of this scale. This would require the hydrogen distribution network to be in place, targeted for delivery under RIIO GD-2, delivering hydrogen to multiple users and linking to hydrogen storage. Hydrogen market development is critical. With successful delivery of HyDeploy blending could become more widely adopted, with similar confidence being provided by industrial

Figure 4-3 - Timescales for Early Facilities



fuel switching trials. In theory the second facility could go through development and come on stream earlier than shown; it is market development that is considered to be the constraint, rather than technical performance. It is assumed that there would be a ramping up of offtake from the facility, tying into industrial shut-down and refurbishment cycles.

Together this would deliver 3.6 million tonnes of carbon stored in the region via hydrogen production and around 5.0 million tonnes accounting for industrial capture, contributing meaningfully to both the 4th and 5th carbon budget shortfalls.

4.3.2.9 Timescales: The Need for Action

As shown above, the HyNet LCH project is able to deliver rapidly. Early adoption of low-cost, low carbon bulk hydrogen production is required by the early-mid 2020s;

- It provides a low-cost solution to meeting our imminent carbon budget shortfalls,
- It unlocks opportunities for early cost reductions through deployment,
- It provides the basis for clean growth and export, and critically
- It safeguards existing industry much of which is already vulnerable to carbon price increases and free allowance reductions, risking substantial carbon flight.

The Committee on Climate Change identifies hydrogen as unequivocally required to meet our legislated carbon targets. It also emphasises the urgency, in its latest Progress Report[13], stating a necessary milestone of "Industrial Hydrogen and CCS clusters operational from mid-2020s". At present the CCC identifies a significant shortfall in our 4th and 5th carbon budgets. By delivering operation in by 2024, cost effective carbon savings across a range of sectors are unlocked to deliver meaningful contribution to these shortfalls.

Given that hydrogen is necessary, there is an urgent need to develop both the nascent market and the associated infrastructure. Both of these take time to deliver; early production into low risk markets enables deployment. As is exemplified by offshore wind, deployment enables cost reduction. Scale is an important element of this; moving to larger facilities is necessary to drive down costs and ensure supply chain capacity. This can only be achieved by delivering the first unit. Early adoption drives the costs down sooner and allows a mature and balanced supply chain to deliver cost effectively on our legal obligations. Establishing infrastructure sooner on our journey to net-zero maximises its utilisation over the period.

Facilitating production of bulk low-cost, low carbon hydrogen, safeguards industry and enables wider adoption of low-cost low carbon energy solutions. As carbon prices rise and free allowances fall away, many of the UK's remaining key industries are under threat. Assessment of profitability and carbon exposure shows that companies exposed to the Emissions Trading System will be under threat during the 2020s, even under fairly conservative carbon price assumptions, as profitability is overwhelmed by carbon price exposure[14].

Accelerating deployment low-cost, low carbon hydrogen provides an opportunity through fuel switching to safeguard these industries during the 2020s; further delays would jeopardise this and further prejudice UK GDP with carbon flight elsewhere, often increasing net global carbon emissions.

Excellent progress has been made in reducing the carbon intensity and cost of electricity production, as exemplified by the latest CfD prices for offshore wind. The ability to adopt increasing levels of intermittent wind generation will be curtailed without low-cost solutions to balance the network and provide generation during periods of low wind and solar. Gas turbines provide the lowest cost capacity for dispatchable intermittent generation. These can be fuelled by low-cost, low carbon hydrogen, thereby unlocking otherwise unfeasible amounts of low-cost wind generation whilst maintaining secure supply for customers.

Hydrogen also has a key role in both the heating and transport sectors. For heating, it provides an opportunity for early carbon reduction based on blending, saving carbon in the short term and as a pathway to deeper decarbonisation. The HyDeploy programme is making excellent progress, providing the basis to adopt blending in the early 2020s; bulk hydrogen production allows immediate adoption of this, reaping the benefit of the work undertaken. Similarly, there is strong progress being made with hydrogen use in transport, particularly for trains. In general across all sectors there is a shortage of bulk low-cost, low carbon hydrogen to enable development and early deployment; bulk supply in an industrial heartland with access to industry, power sector, transport and domestic markets, enables the market and milestone that the CCC identify as being necessary – industrial hydrogen clusters operational by the mid-2020s.

The role of hydrogen is increasingly recognised internationally. Due to a combination of its oil and gas experience both on and offshore, as well as its geology the UK is extremely well placed to lead development of low-cost low carbon bulk hydrogen production. Early adoption in the UK enables both export of technology, skills and services as well as inward investment in the UK. Conversely, given the rate of market change internationally, delayed adoption in the UK risks other jurisdictions taking the lead and therefore GVA (Gross Value Add) opportunity globally.

4.3.3 Longer-Term Business Plan

Bulk hydrogen production from fossil resources with CCUS is recognised to be the dominant source of low carbon hydrogen to 2050. The LCH approach delivers the low-cost reforming solution due to its high efficiencies and integration with capture. It is a scalable technology, enabling roll out in the UK and internationally, with JM as the technology provider and engineering contractors such as SNCL able to deliver commercial plants. The HyNet vision is a grounded development plan to facilitate roll out in the UK. The CCUS capacity, hydrogen distribution infrastructure including storage as well as hydrogen consumers in the region provide a basis for expansion. It delivers a low carbon industrial cluster which can both expand regionally, as well as be replicated at other clusters. There are few technical barriers to commercialisation, as it is established chemical process engineering with the operation of the initial plant providing operational evidence. The main risk is considered to be an appropriate support regime. The build rate can deliver 90TWh/yr of capacity by 2035 (nine times the stretch target identified by BEIS in this programme) and over 250TWh/yr by 2045 only requiring about one plant coming online per year. Supply chain assessment indicates there is more than adequate capacity to achieve this and could be delivered at a greater rate.

4.3.3.1 Regional Hydrogen Demand

Work under this programme has established that the total demand for hydrogen is assessed to be around 135TWh/yr regionally and over 550TWh/yr nationally by 2050 (see Section 4.2), assuming that dispatchable power is delivered via hydrogen. Accounting for hydrogen production by electrolysis and biomass gasification this equates to a regional and UK demand of thermally reformed hydrogen of 94TWh/yr and 378TWh/yr respectively. Whilst the early plants are expected to be at the 100kNm^3/hr capacity (3TWh/yr), JM have developed the LCH technology at 500kNm^3/hr (15TWh/yr) offering cost savings. The national demand could be satisfied by just 25 larger plants. The business plan provides deliverable incremental expansion and addresses the national and international situation - initial plants will be at the smaller scale providing flexibility when hydrogen requirements are very low and larger plants, enabling economies of scale to be achieved, will be used once the hydrogen infrastructure develops.

Building on the short-term business plan to deliver hydrogen to established early users on or adjacent to the Stanlow site from a single unit, the wider region demand has been assessed in terms of industrial, dispatchable power, hydrogen blend into the network and transport. Due to the industrial, population and power generation density of the region, equates to a demand of 147TWh/yr across the full Western Cluster, dominated by the North West and West Midlands, making it an ideal location to grow hydrogen production.

Industrial: Initially there are 41 user sites in the Warrington, Liverpool, Chester and Manchester areas with a conservative demand of 8TWh/yr. These users will build on the confidence delivered by an effective Industrial Fuel Switching demonstration programme. Further expansion towards the West Midlands area adds an additional 4.6TWh/yr across another 34 sites, equating to a total demand of 12.6TWh/yr. Incorporating South Wales as part of the wider Western Cluster adds an additional 4.1TWh/yr from another 24 users. In total, this represents 16.7TWh/yr of demand from less than 100 sites.

Power: (Based on mid-merit demand to support intermittent generation). Repowering of Fiddler's Ferry (due for decommissioning imminently) would require 11.5TWh/yr of hydrogen. The four nearby CCGTs of Carrington, Connah's Quay, Deeside and Rocksavage will reach the end of their operating lives over the next decade and the CCGTs at West Burton A & B and Rugeley could also convert to hydrogen. Combined this would equate to hydrogen demand of 57.7TWh/yr. The potential repowering of South Wales generation capacity at Aberthaw, Baglan Bay, Barry, Pembroke and Uskmouth A & B would add a further 33.7TWh/yr of demand.

Blending: The demonstration work being undertaken by HyDeploy enables blending at 20%vol (6.5%energy) into the grid. The North West is a region of high population density enabling cost effective delivery of hydrogen to key nodes on the distribution network. Assessment of the demand at these shows a demand of 8TWh/yr in the region, with additional demand from South Wales as part of the Western Cluster would add an additional 1.7TWh/yr.

Transport: Work undertaken under the HyMotion programme[15] has estimated hydrogen demand from fuel cell electric vehicles in the North West of up to 2.4TWh/yr. In the longer term, this demand would be expected to grow across the full region 20TWh/yr as HGVs and, to a limited extent, trains decarbonise using hydrogen fuel cell technology.

4.3.3.2 Hydrogen Supply

Of the 147TWh/yr of regional demand, it is assumed that 36% is supplied by electrolysis and biohydrogen consistent with the Imperial University and CCC assessments, indicating a demand of 94TWh/yr from reforming which is lower cost so may take higher share. The attributes of the LCH technology are expected to establish a strong market position for the technology as discussed below.

Much of the demand for the North West could be supplied from the Stanlow area, given its location at the heart of the cluster and suitability. The initial plot on the refinery site deliberately has the capacity for expansion to service 18TWh/yr, storing 3.6MtCO$_2$/yr, which would be delivered through the construction of a 500kNm^3/hr unit, expected to be constructed during the mid-late 2020s, subject to appropriate policy frameworks.

Further capacity could be constructed elsewhere on the refinery site and elsewhere in the region, building on the local skills and capabilities. It is expected that the South Wales element of the cluster would be serviced by local hydrogen production, such as at the Tata Steelworks, or the Milford Haven refinery, with CO$_2$ shipped to the North West. Across the region it is assumed that 94TWh/yr of the hydrogen demand is delivered by reforming. With an overall penetration of LCH at 70-75% this represents 65TWh/yr which could be serviced from as few as five facilities, although some sites and locations would be more suited to smaller capacity plants. This level of production with 13MtCO$_2$/yr stored, is well within the capacity of the HyNet planned infrastructure.

On a national basis, clusters could be replicated, utilising local CO_2 T&S infrastructure, most readily adopted at industrial sites such as refineries, steelworks and chemical facilities. Market assessment for this indicates a total demand of 378TWh/yr for reforming. With an overall penetration of 70% for LCH this would be 265TWh/yr of capacity, which could be delivered by as few as 18 units, although more with a mix of 100kNm^3/h and 500kNm^3/h units.

International demand for hydrogen from industrial users has grown threefold over the last four decades to around 4000TWh/yr. This hydrogen is predominantly sourced from fossil resources, consuming around 6% of global natural gas and 2% of global coal supply. It is responsible for over 800Mt of CO_2 emissions per annum.

Internationally, countries currently have obligations to reduce greenhouse gas emissions under the Paris Agreement, with particular focus on the US, Japan, China, Korea as well as EU countries Belgium, France, Germany, Italy and the Netherlands. This provides the opportunity for sales of further plants, export of skills and services as well as the potential to export hydrogen from UK facilities.

4.3.3.3 Hydrogen Distribution and Storage

Delivery to users requires the establishment of a distribution system. Pre-FEED work will be undertaken in parallel with Phase 2 of this programme by Cadent to establish optimum routing as well as system optimisation and costings. The wide range of users with intermittent demand is enabled by the establishment of hydrogen storage. Salt storage capacity is available in the region, with work being undertaken by Storenergy and Innovyn, with which the consortium is engaged and supportive. The hydrogen distribution system connects to this. Similar distribution and storage arrangements can be replicated elsewhere in the country, dictated by geological capacity (for both hydrogen and CO_2).

4.3.3.4 Build-Out Rate

The chart below summarises the expected build-out programme, subject to appropriate policy frameworks being in place. Based on an assumed

Figure 4-4 - LCH Build-Out Rate

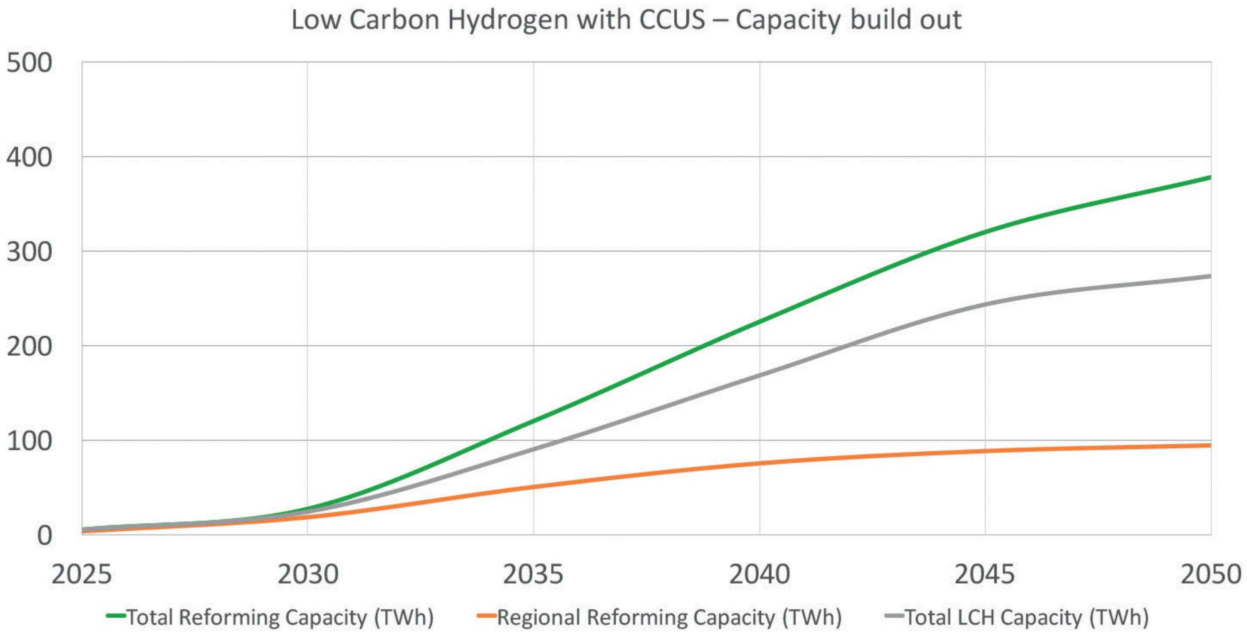


Table 4-3 - LCH Build-Out Rate

	2025	2030	2035	2040	2045	2050
Total Reform. Capacity (TWh)	5	27	120	225	320	378
Regional Reform. Capacity (TWh)	3	18	50	75	88	94
Total LCH Capacity (TWh)	5.0	24.0	90.0	168.0	243.0	273.0
LCH Assumed Market Share	100%	89%	75%	75%	75%	72%
LCH 100k Units Cumulative	2	3	5	6	6	6
LCH 500k Units Cumulative	0	1	5	10	15	17
Total Build per 5 Year Period	2	2	6	6	5	2

mix of larger and some smaller units this equates to the construction of four units during the 2020s and approximately one unit coming on stream each year over the 2030s and early 2040s. This is well within the supply chain capability; a more aggressive build out programme could be adopted if the market required. Construction is anticipated to tail off as the net-zero target is met, although if the market demand is delayed then build rate during the 2040s would be higher but could be sustained. On this trajectory the technology would be delivering around 90TWh/yr of low carbon hydrogen by 2035, an order of magnitude greater than requirements proposed by BEIS in this programme of 10TWh/yr. However, the consortium is of the view that the 2050 targets could not be met if only BEIS' "stretch" target were achieved. This would contribute up to 7% of the 4th Carbon budget shortfall and up to 15% of the 5th.

4.3.3.5 Route to Market

The route to market replicates that of the initial project, based on conventional engineering contracting practice. The LCH technology is provided by JM and is delivered by EPC contractors such as SNCL. Like other parts of the energy sector, developers will be required to conceive and undertake early development with key strategic investors from the refinery/industrial/energy sectors, similar to Essar, potentially supported by financials. Given the low technology risk profile, it is expected that relatively high levels of debt finance can be applied, subject to the structure of the policy support regime. There is sufficient technical and financial capacity to deliver this requiring <£700M/yr of investment.

4.3.3.6 Key Challenges to Commercialisation at Scale & Key Barriers

Given the nature of the LCH technology and having delivered the initial unit which will have confirmed plant performance under operational conditions, there are few technical or engineering challenges to commercialisation at scale. This is conventional chemical engineering, being delivered at an appropriate market scale. Whilst the expectation that the plant unit will increase in size fivefold, this is a partially modular scale up for practical reasons

(4 GHRs, 2 ATRs) which minimises scale-up risk. The key risk will be policy in terms of an appropriate support regime. Whilst reductions in hydrogen price through scale-up and learning and increase in carbon price over this period will assist in reducing the level of support required, it is expected there will still be a requirement for an appropriate regime. The nature of this support will also dictate the level of market risk, i.e. whether users are appropriately incentivised to decarbonise and procure hydrogen. Supply chain ability to deliver is not considered to be a challenge.

4.3.3.7 Development Costs

Once the first plant is operating, and with an appropriate revenue support regime, the market can deliver projects conventionally. Projects would go through early inception and FEED against a commercial framework for private sector investment through both development and construction. Through FEED programmes for each project, incremental improvements and learning would be applied, as with any roll out of established technologies.

4.3.3.8 Supply Chain Constraints

Supply chain constraints have been assessed by SNCL and JM and considered not to represent a risk to the build out rate anticipated, with considerable capacity for a higher rate.

Design, Engineering and Procurement (DEP) Capacity: The current UK based process industries contractors employ approximately 50,000 personnel. The DEP resourcing requirement is a fraction of this.

Equipment: The majority of the equipment can be procured on a global market if required, and the fabrication capacity for the specialist equipment such as the GHR has been confirmed as being more than sufficient to meet the requirement.

Construction, Trade/Craft Labour: There is plenty of capacity across the industry. The peak manning of projects is circa 700 people per facility, assuming a 3-year delivery requires 2,100 people in parallel to deliver one train per annum. Due to the decline in the oil, gas and hydrocarbon sector there have been considerable job losses over the last few years. Therefore, there should be the skills required, and indeed an opportunity to reverse this decline.

4.3.3.9 Future Innovation and Learning Rates

Having established the operation of the core technology, there are a range of further developments and innovations which can deliver cost and carbon savings.

Cost improvements: The dominant factor is a scale-up of the technology to the 500kNm^3/hr plant which equates to a 30% reduction in the capital cost element. In line with the deployment of relatively new technology, incremental improvements and value engineering are expected to deliver further capital cost savings. OPEX and CAPEX savings will be realised and staff reductions are also to be expected over time as shown by current UK Hydrogen plants. The use of industrial off-gases for feedstock from steelworks and refineries are expected to offer further cost benefits.

Technical improvements: Further optimisation of capture rate is expected, as the sector develops. Heat integration has been deployed on this project, but with increasing confidence in start-up/shutdown and operational flexibility, further integration may be feasible. Air Separation Unit (ASU) operation may also be optimised maximising co-product sales and offering grid services.

Financial improvements: Increased reference plant operation reduces risk, reducing costs, lowering hurdle rates for investors and potentially higher debt ratios.

Accelerate the Development of Bulk Low Carbon Hydrogen and Meeting Net-Zero

Combined these factors accelerate the development of bulk low carbon hydrogen:

- Technically, the approach is based on chemical processing engineering, designed to operate at scale; enabling carbon reductions for industry, dispatchable power, domestic heating and transport;

- It can provide the volumes required through a relatively small number of plants;
- It delivers at a cost base at half that achievable through electrolysis, and lower than that projected from bio-hydrogen from biomass; and
- Capture rates are at 97%, with developments that could increase this further.

In the future combining an element of the feedstock stream from gasification of biogenic sources would deliver net-zero hydrogen. Alternatively, co-location with bio-hydrogen production can deliver net-zero clusters, with the fossil derived hydrogen production providing the volumes of CO_2 to amortise the infrastructure.

Bulk hydrogen production enables the development of both the market and infrastructure for hydrogen distribution, storage and use. Beyond 2050, as international markets and sources of renewable hydrogen develop, established UK hydrogen infrastructure positions it to take advantage of such sources to complement reformed gas.

5.0 Basis of Design

Prior to commencement of the Phase 1 Pre-FEED, the consortium established a Basis of Design (BoD) laying out all the technical parameters that applied to the inputs to and outputs from the LCH plant together with certain key requirements of scope and performance for the plant itself. As well as being a basis for the Phase 1 work, during Phase 1 these bases were tested for their appropriateness, both internally to the LCH project and as part of the interface to the wider HyNet project, and the BoD was appropriately updated. The BoD will continue to be reviewed during Phase 2 and any changes will be approved through a formal consortium change procedure.

This section describes the key elements of the BoD as finalised at the end of Phase 1 and provides the rationale for a number of the key decisions that were made.

5.1 Key Input Parameters

The plant shall be designed to run on natural gas as its main feedstock. The gas shall be in compliance with the specification required by the Gas Safety (Management) Regulations 1996 (GS(M)R) which shall be delivered at a pressure of between 34bara and 77bara. The latter is based upon the expected range of supply pressures in the local NTS at Rocksavage.

It is recognised, however, that there are commercial and greenhouse gas benefits to being able to accommodate a level of ROG as supplied from the Essar refinery. The work by JM in Phase 1 showed that the LCH plant can accept proportions of ROG dependent on its quality. As the quality of ROG is very variable, further work on this will be undertaken in Phase 2 to confirm what quantum of different specifications can be accepted by the plant.

5.2 Key Output Parameters

For both the product low carbon hydrogen and the off-take CO_2 full specifications have been established by the work in Phase 1.

5.2.1 Hydrogen

The specification for the hydrogen and the acceptable ranges thereof has been defined by the approach to place the same concentration limits on certain species in the hydrogen as are in place for the natural gas, ensuring that any mixed stream will remain within the natural gas specification.

It should be noted that carbon monoxide (CO) content is not specified in the GS(M)R despite its safety implications. The HSE guidance on domestic exposure to CO (the only context currently being combustion) states[17]:

> “Current criteria for room CO have to be taken into account. The chief criterion is the World Health Organisation 8-hour time weighted average figure of 10 ppm. Most appliances would not be operated for as long as 8 hours at a time, so the adoption of the 10 ppm standard is probably correct.”

If the hydrogen/NG blend contained 10 ppm then it would be possible to guarantee to be within the HSE guidance levels. Assuming a blend level of 20 vol% means that the hydrogen could contain up to 50 ppmv CO. This project will use the conservative limit of 50 ppmv.

The GS(M)R specification also places no restrictions on the non-combustible content of natural gas; limits on inert content are, in effect, controlled by the Wobbe number specification. A 2% limit on non-combustibles is considered an appropriate reference for design purposes. This allows up to 20% hydrogen blending while meeting the GS(M)R Wobbe Number limits.

The BoD requires the hydrogen to delivered at >46bara. This requirement will be finalised in FEED following consultation with end users and the work on hydrogen distribution by Cadent Gas.

5.2.2 Carbon Dioxide

The required specification of the CO_2 to be captured from the hydrogen plant and injected into the CO_2 pipeline given in Table 5-1. This is driven by the necessary specifications for both transport and storage (the latter is the determinant for the oxygen content only).

Table 5-1 - CO_2 Specification

Species	Limit
Ash	<1mg/Nm^3, <1µm
C_2+	<2.5mol %
Carbon dioxide (CO_2)	>95 mol%
Carbon Monoxide (CO)	0.2%
Hydrogen (H_2)	<0.3 mol%
Water (H_2O)	<250 ppmv
Hydrogen Sulphide (H_2S)	<200 ppmv
Non-condensables (N_2, Ar, CH_4, etc.)	<4 mol%
Nitrogen Oxides (NOx)	<50 ppmv
Sulphur Oxides (SOx)	<50ppmv
Oxygen (O_2)	<10ppmv
Temperature	0°C to 20°C

As noted in the table, the temperature specification for the compressor outlet has been set at 20°C for all capture plants and also as a system maximum for the pipeline. 20°C has been set as the upper limit for the onshore pipeline for environmental reasons, in line with previous projects.

The plant is to be designed to be able to deliver all the CO_2 it captures at a fixed pressure of 26 bara (25 barg) throughout the life of the plant.

5.3 Key Plant Requirements

5.3.1 Technology & Size

Given the basis of the project it is a requirement that the plant is based on JM LCH technology. The plant size was set at their standard size of 100kNm^3/h of hydrogen output as this aligned both to the development work JM has undertaken on the LCH technology prior to the Phase 1 and it represents a realistic volume of hydrogen to place with the first unit.

5.3.2 Output Variability

Whilst there is no requirement for the first project to design in significant variability in the output of the plant, the Phase 1 work did look at the flexibility that could be achieved by the LCH technology so that this could be applied, if necessary, to future plants.

There is no requirement to design for seasonal variation in plant output as it is anticipated that demand will be managed downstream of the plant by using the distribution network for ‘overspill’ if the industry has lower demand than anticipated. However, a turndown ability might be required for occasions when the above management strategy is not available and so the plant shall be capable of turning down to 40% of maximum hydrogen output.

There is no requirement for significant short-term demand variation management as this will be managed through linepack in the hydrogen pipeline. However, a ramping ability might be required for occasions when the above management strategy is not available and so the plant shall be capable of a ramp rate of 2%/minute. This rate is a balance between needing flexibility on hydrogen production whilst having a rate of variation of CO_2 production that can be accepted by the transport and storage system.

5.3.3 Plant Performance Requirements

A number of factors relating to plant performance have been established in the BoD either as absolute requirements or targets to be aimed at through the design process. The most significant of these are as follows:

Efficiency: The conversion efficiency shall be greater than the target set by the BEIS counterfactual model. The work in Phase 1 shows that this will be substantially exceeded and further value engineering work will be undertaken in FEED to see if greater efficiency can be cost-effectively delivered.

Capture Rate: The plant shall capture as carbon dioxide a minimum of 95% of the total carbon entering the plant with a target of 97%. The lower figure is set as this is regarded as the current level expected within the industry. A higher target has been set given the value, both economically and in terms of net-zero, of achieving higher capture rates. In FEED further value engineering work will be done to see if the achieved rate can exceed the above target.

Availability: The plant shall be designed to have an availability of at least 95% averaged over its lifetime. Availability is to take account of both planned and unplanned maintenance and shall be calculated with respect to hydrogen production as a proportion of total requested hydrogen production assuming 8760 hr/y operation. The plant shall be designed so that no planned outage is greater than 20 days from hydrogen off to hydrogen on (full load to full load).

Design Life: The plant shall be designed to have an operational life of 25 years with specific maintenance intervals for key equipment.

Staffing: It shall be assumed that the plant is a stand-alone facility and will not be integrated into other facilities from either an operations or maintenance perspective. The plant shall not be designed for remote operation.

5.3.4 Interface to Stanlow Refinery Area 4

The work in Phase 1 confirmed that Area 4 of Essar's Stanlow refinery is suitable for the construction of the LCH plant and for expansion with further units in the future (up to 3 x 100kNm^3/h or 1 x 100kNm^3/h plus 500kNm^3/h). The engineering analysis identified which existing buildings would be retained and re-used/re-purposed and what site clearance would be required. It also investigated the options for using existing services and identified, where services are not available or not of sufficient quantity/ quality/ reliability, the utilities that would need to be generated within the LCH plant. The BoD identifies the specification of all utilities that must pass between the core LCH plant engineered by JM and the balance of plant engineered by SNCL.

The following services will be provided from the wider Essar site:

- Electrical power at 6.6kV
- Potable water
- Foul water
- Storm water
- Telecoms

The Essar site may also be able to provide MP steam and demineralised water but the analysis in Phase 1 indicated that these would not be cost-effective to use. This will be confirmed in FEED. Phase 1 studies also showed that there are not effective options for raw water supply or for process waste discharge without prior, on-site, treatment.

The current design assumes that the ASU generating the required oxygen and nitrogen for the process will be co-located with the core LCH equipment. During FEED it will be assessed whether it would be commercially advantageous to have this as an "over-the-fence" supply from an established industrial gas company and, if so, where an appropriate location for the facility might be.

The BoD also provides full meteorological data for the site on which the plant design shall be based.

5.3.5 Design Philosophies

A number of design philosophies have been agreed and laid down in the BoD. These cover; heat integration, cooling, power integration, rotating device driver selection, flaring, winterisation and equipment sparing. The BoD also addresses the codes & standards to be used and units to be used.

6.0 Low Carbon Hydrogen Plant

The project is based upon JM's LCH technology as this will provide the lowest cost for low carbon hydrogen at the scale required for HyNet. The project has also identified the specific location where the plant will be located, Area 4 of Essar's Stanlow Refinery.

The viability of the LCH technology to produce low carbon hydrogen has been confirmed through a range of Phase 1 engineering assessments. In addition, the operating conditions of the LCH technology have been optimised in comparison to previous studies and this has increased the CO_2 capture rate. The technology can be constructed to meet all regulatory requirements including air quality. The fired heater has been split into two to simplify the start-up and shut down of the LCH technology and to offer CAPEX savings.

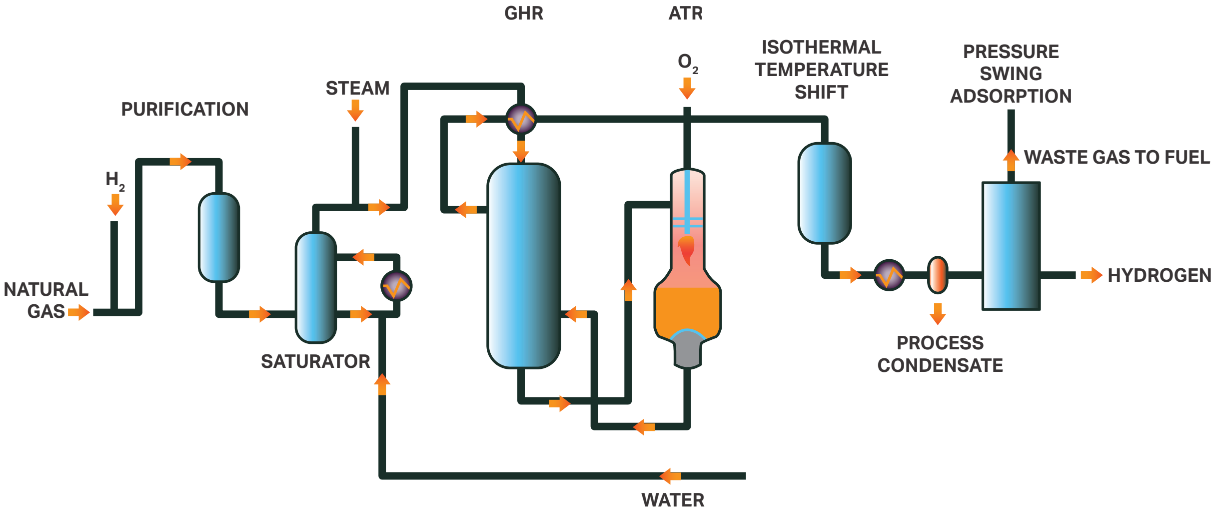
6.1 Plant & Process Description

The hydrogen production facility is built around JM's LCH technology which recovers heat at maximum exergy (ie,: the highest possible quality) and which offers efficiency benefits by coupling a Gas Heated

Reformer (GHR) with an Autothermal Reformer (ATR). The main difference between the LCH and Steam Methane Reforming (SMR) flowsheets is that the energy to drive the reaction is provided by introducing oxygen to the ATR as opposed to burning natural gas in the SMR. At the scales envisaged, this oxygen would come from an air separation unit (ASU). GHRs and ATRs are already used in the production of syngas and are part of most modern schemes for production of methanol and liquid fuels from Fischer-Tropsch processes. These plants are very large and demonstrate that the technology is capable of producing hydrogen at large scale and therefore the scale-up risk is minimised.

At a basic level, a flowsheet showing hydrogen production using LCH technology is shown in the following Figure.

Figure 6-1 - LCH Flowsheet



Purified natural gas is pre-heated and reformed in the GHR before entering the ATR. In the GHR, 30% of the total hydrocarbon is reformed by reaction with steam to form syngas. In the second stage, the ATR, oxygen is added and combusts some of the partially-reformed gas to raise the process gas temperature. The resultant gas then passes through a bed of reforming catalyst inside the same vessel for further reforming. Since the reaction is limited by equilibrium, operation at high temperature and steam flows minimises the methane content of the product gas which in turn minimises overall carbon dioxide emissions. The hot gas exiting the ATR passes back to the GHR providing the heat necessary to drive the reforming reaction in the GHR tubeside.

For the LCH flowsheet, all of the carbon dioxide is within the product stream and therefore is at high pressure and can be easily removed using standard industry removal technologies. For an SMR coupled with CCS, the CO_2 stream is at low pressure and diluted with nitrogen and hence requires a large and hence expensive CO_2 capture system.

6.1.1 Site Location: Stanlow Refinery Area 4

Stanlow Refinery is located centrally to the industrial area of the North West making it an ideal location for generating hydrogen to reduce the carbon footprint of industry. Sited on a 770 hectare industrialised area of Ellesmere Port, Cheshire, Stanlow benefits from its close proximity to major North West metropolises, a robust configuration and reliable, well maintained assets.

The refinery plays a strategic role in the UK economy, supplying 16% of all road transport fuels. It is also a major regional employer with over 900 staff, an additional 800 on site contractors and a further 5,000 people employed indirectly through the extended value chain.

The Stanlow site has a readily available development space in Area 4 for a new LCH plant, has the knowledge and experience to safely operate process units, and is an appropriate brownfield site to develop as it already has a long history of operating processing assets.

Area 4 is located on the eastern side of the refinery. It has an 800m frontage along Oil Sites Road providing good construction, operation, and maintenance access to the site. The site location is adjacent to the pipelines routing for natural gas, hydrogen, and carbon dioxide.

The short-term business plan is for the establishment of a single 100kNm^3/hr unit, however the plot has been selected to be expandable. Figure 6-2 and Figure 6-3 show the plant layout for either 3x100kNm^3/hr units (9TWh/yr of hydrogen and captures 1.8mt/yr of CO_2) or 1x100 plus 1x500kNm^3/hr (18TWh/yr of hydrogen and captures 3.6mt/yr of CO_2). The longer-term build-out approach will depend on policy framework and therefore rate of market development as well as operation of the initial unit.

Figure 6-2 - Stanlow Refinery Area 4 with 3 x 100kNm^3/hr Plants

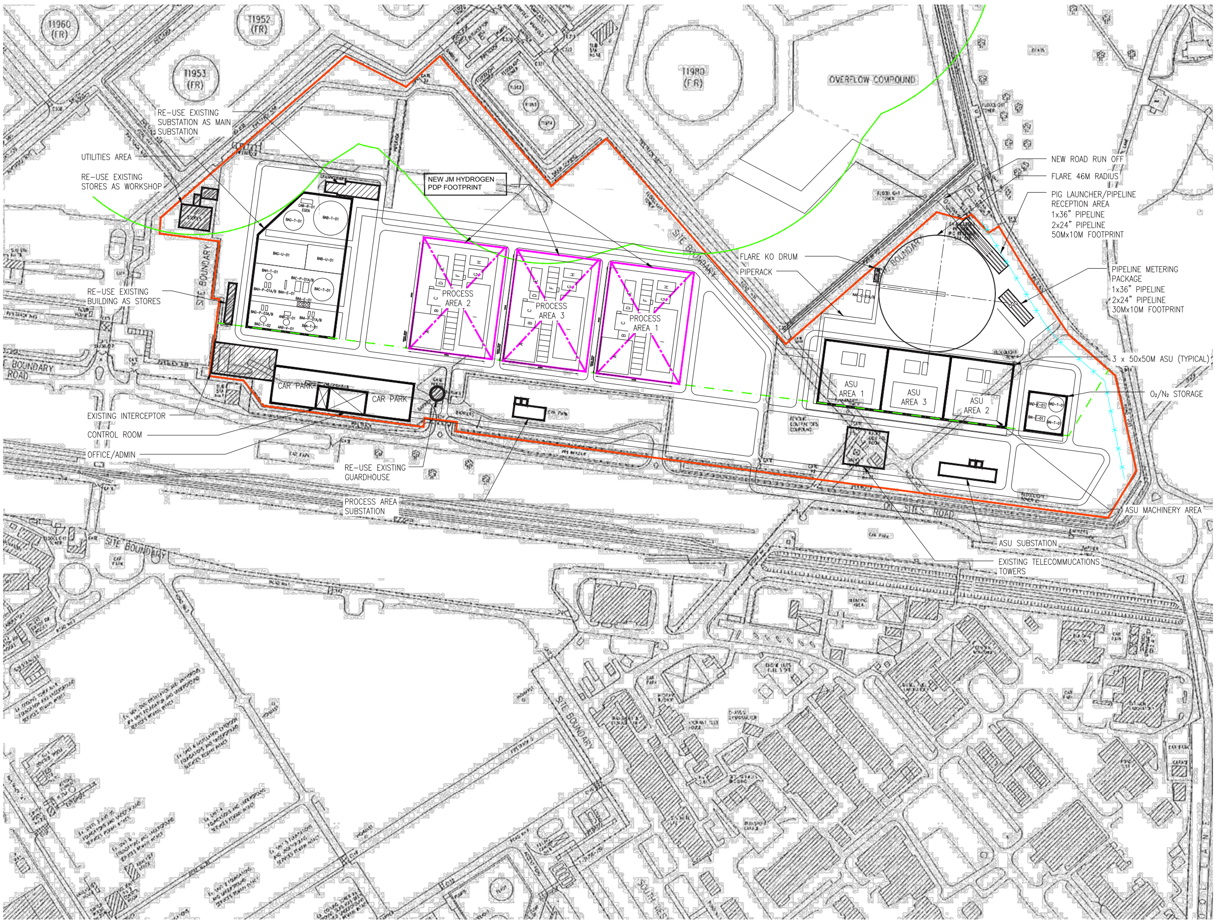
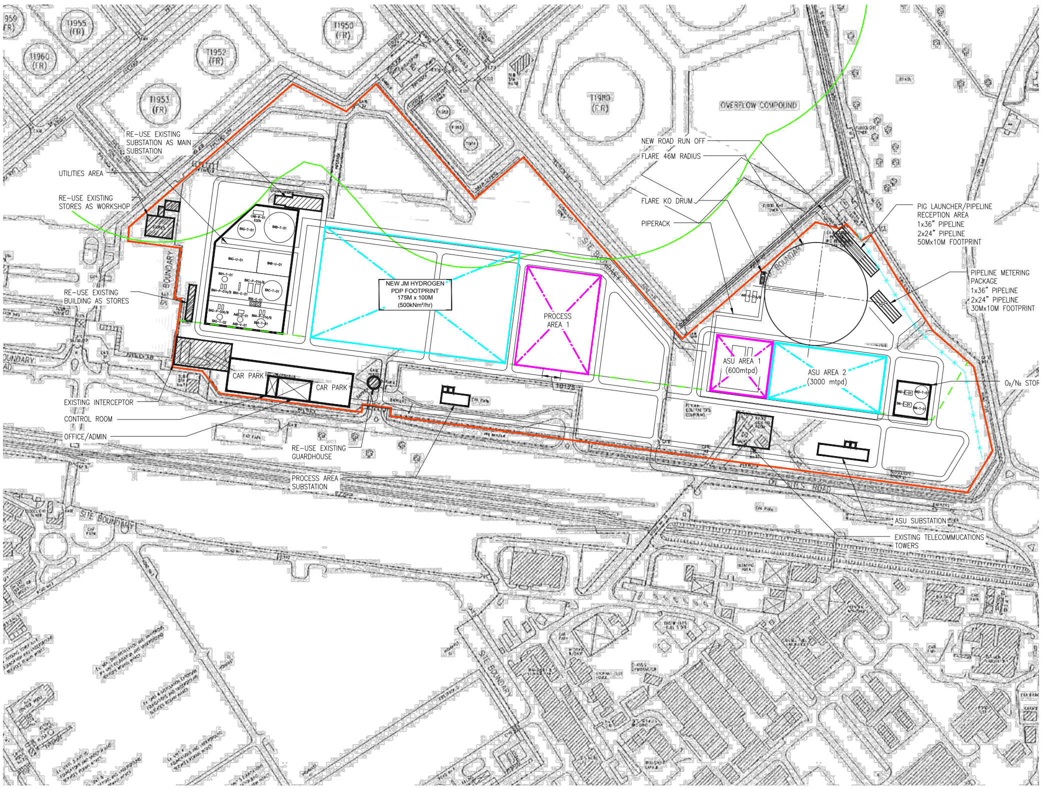


Figure 6-3 - Stanlow Refinery Area 4 with 1 x 100kNm³/hr Plant & 1 x 500kNm³/hr Plant



The plant is laid out to maintain a safety distance between the new LCH and the storage tanks to the north, the public road to the west, and pipe rack & road to the south. The manned area of the plant is located to the south west with utilities to the west. The LCH plant is located in the centre of the site with flare & oxygen production to the east of the site. The pipelines will follow an existing pipeline route running along the eastern edge of Area 4 with existing connections to other plants and refinery along the southern and eastern edges of the site.

The reuse of existing areas and routes (brownfield) reduces the development risk and there is opportunity within Area 4 for future phases of hydrogen production plants. These, combined with additional opportunities for hydrogen production facilities within Stanlow Refinery, will permit the creation of a mega hub for hydrogen production supplying the whole region.

6.2 Plant Performance

JM's Efficient Natural Resources sector has been a leading developer of catalysts and process design to produce chemicals from synthesis gas since the 1930s. JM aims to apply this knowledge to decarbonising natural gas by providing the best in class technology to produce high purity hydrogen with greater than 97% CO_2 being captured.

The LCH technology builds upon the knowledge and experience of JM around the Leading Concept Ammonia (LCA) and Methanol (LCM) commercialised flowsheets.

The BEIS Hydrogen Supply Competition establishes a counterfactual based on SMR+CCS. In assessing, during Phase 1, the improved performance of the LCH technology it has been done so against this counterfactual plant.

Compared to the counterfactual, the LCH technology uses a number of technologies that are not commonly used on hydrogen plants in order to maximise conversion efficiency and hence minimise energy consumption. These include:

- A GHR to recycle heat at the highest possible level as opposed to downgrading to medium pressure steam as is done in the counterfactual;
- An oxygen blown ATR to minimise methane slip by operating the ATR at high temperature;
- A high efficiency water gas shift converter that recovers medium grade heat as steam; and
- A saturator circuit to recycle process condensate and use heat to generate steam.

These unit operations have been proven in other areas:

- The JM GHR is used in three LCA plants and one LCM plant
- The JM ATR is used in the LCA/LCM plants and in over 20 other plants
- The isothermal shift has been used in the LCA plants
- The saturator circuit has been used in the LCA, LPM (Low Pressure Methanol) and LCM plants.

Table 6-1 - Plant Performance

Parameters	Units	Counterfactual	LCH
Product Flow Rate	MWth (LHV) / (HHV)	300 / 355	300 / 355
	kNm³/hr	100	100
Hydrogen Purity	%	99.9	99.999
Efficiency (LHV) & (HHV) Basis	%	67.2 / 71.7	79.7 / 84.7
CO_2 Capture Rate	%	90.1	97.2
CO_2 Output Stream Purity	%	96	99.7
CO_2 Generated	t/hr	82.03	77.49
CO_2 Captured	t/hr	73.91	75.27
CO_2 Emitted	t/hr	8.12	2.22
	kg/kNm³	81.2	22.2

6.2.1 Energy Efficiency

Due to the high temperatures used exit the ATR, the methane slip within the LCH technology is significantly lower than the 4.35mol% dry in the counterfactual. The use of a GHR allows for heat to be recovered at significantly higher temperatures than the raising of steam at 250°C in the counterfactual. As a result of these, the LCH technology uses less natural gas for every unit of hydrogen produced and therefore by implication produces less overall CO_2.

As with the counterfactual, the LCH technology requires a significant amount of steam to be added to the feed natural gas. Around 60% of the steam is raised through the use of the saturator circuit, with an additional 20% from the ITS and the remainder from the steam boiler. The former two methods of raising steam are more efficient ways of generating steam in terms of quality compared to the counterfactual which uses high temperature stream exit the reformer at 860°C to raise medium pressure steam thereby degrading the quality of the heat.

Therefore, LCH technology is more efficient than the counterfactual with an energy efficiency of 84.7% compared to 71.7% (HHV basis) as shown in the table below. As feedstock costs dominate the OPEX, the LCH technology has a lower operational cost than the counterfactual.

6.2.2 CO_2 Emissions and Capture

The LCH technology has very low CO_2 emissions of 2.2t/hr compared to the counterfactual of 8.1t/hr (see table below) because of:

- Operating the ATR at high temperatures, which minimises the methane slip and hence the CO_2 emissions when the PSA tail gas is combusted
- Utilisation of a highly efficient shift converter which minimises the CO slip and CO_2 emissions when the PSA tail gas is combusted

CO_2 can be also removed cheaper and with a higher capture rate in the LCH technology than in the counterfactual (see table below) as it is captured from the process gas as opposed to the CO_2 containing dilute low pressure fluegas stream in the counterfactual. The reason for this is that oxygen is used in the LCH technology to provide heat for the reforming reaction, and this eliminates a diluted, ambient pressure fluegas stream that is produced in the counterfactual.

Further work is envisaged In Phase 2 to refine the CO_2 Removal Unit performance figures and hence optimise the flowsheet.

6.2.3 System Flexibility and Operating Rates

The HyNet project users include a number of industrial users alongside network blending which meaning that the LCH plant will operate at a higher load than envisaged for other projects, as the industrial users demand is steadier and less intra-seasonal. The technology is also flexible enough to meet the varying demand of the end-users quickly. As part of Phase 1, a review of the LCA and LCM plants operation was conducted and found that the LCH plant can be started up in 6 to 8 hours to reach 40% and ramped up from 40% to 100% in 30 to 60 minutes. The process can be also ramped down from 100% to 40% in about 10 minutes. As part of Phase 2, discussion will be held with vendors and their ramp rates will be confirmed. This level of flexibility is not required for the initial project due to the mix of users, and hydrogen storage capacity for local roll-out. However, this is expected to be an important attribute for deployment in other geographies.

During Phase 1, discussions with ASU vendors have found that they are working on units that can track renewable energy generation and provide buffer storage of O_2 during times of reduced electricity generation.

Shutting down and restarting an SMR, either cold or hot, can lead to a reduction in the useful life of the SMR tubes and, depending on how well controlled the shutdown is, can lead to catalyst damage shortening its useful life. SMRs are also prone to both minor and catastrophic failure during transient operations such as start-up or changes in plant rate.

The LCH technology eliminates these as potential causes of poor reliability due to its inherent design.

Shutdowns and start-ups can also lead to some refractory damage, especially when the shutdown is not done in a well-controlled manner. The LCH technology has less refractory than an SMR and therefore such damage will be limited.

As all unit operations have been operated at scale, the consortium is assuming an onstream factor of 95%. The LCA and LCM plants have demonstrable onstream factors of in excess of 95%.

6.2.4 Product Purity

Phase 1 has confirmed product purities as follows:

Table 6-2 - Product Purities

Parameters	Units	Counterfactual	LCH
Hydrogen Product Purity	%	99.9	99.999
CO_2 Product Purity	%	96.0	99.74

These purity levels support deployment across a range of industrial and domestic uses. Although LCH provides a product purity for fuel cell applications, additional purification may be required to address pipeline debris etc at point of use.

6.2.5 Alternative Feedstock

The LCH technology can also be configured, with appropriate pre-treatment to use a ROG from the Stanlow site. This offers the prospect of further decarbonising the Stanlow refinery and maintaining the energy balance, whilst providing some potential saving in feed costs. The implications of using alternative feedstock will be further evaluated as part of Phase 2.

6.2.3 Plot Plan

The LCH technology offers a smaller plot area than the counterfactual. The work carried out during Phase 1 indicates an ISBL plot plan of 67m x 111m for the LCH plant compared to an estimated plot area of 110m x 150m for the counterfactual.

6.2.7 Maximum Plant Size

The LCH technology can produce 500kNm³/hr of hydrogen in a single train. This is significantly bigger than the largest hydrogen plants based on SMR technology (i.e. Air Products 2 x 90kNm³/hr plants at the Bharat Petroleum Corporation facility at Kochi).

7.0 Costs

During Phase 1 SNCL have produced both capital coast (CAPEX) and operational cost (OPEX) estimates based on data from across the Phase 1 workstreams. By the very nature of being undertaken at this stage of the project with limited levels of technical definition available they have significant error bands in accordance with normal project development procedures. During Phase 2 these estimates will be significantly improved to allow contracts to be negotiated and, eventually, investment decisions to be made.

7.1 CAPEX

A capital cost estimate has been produced by SNCL for the HyNet Hydrogen Supply Program. The estimate was built up using the methodology presented in the Basis of Estimate. In line with the Association for the Advancement of Cost Engineering International (AACEI) 18R-97 guidelines, the Phase 1 work has produced a Class 4 estimate.

The estimate has been built up based on the Basis of Design, Major Equipment List, and Site Plan as major contributing sources of information. The OSBL equipment has been priced based on vendor quotations, licensor estimates, recent project data, and SNCL internal database information. The ISBL information is based on quotations from JM. Building on from the costs for major equipment packages or stick built equipment, the estimates for installation, bulk materials and labour, commissioning, and contractor's and owner's costs were developed. The overall costs were assessed and benchmarked against Lang factors, metrics for other process facilities, and publicly available data for other UK-based and international projects.

Table 7-1 - CAPEX Summary

	Plant Element	1 Unit (£Million)	2 Units (£Million)	3 Units (£Million)
000	Site Preparation, Enabling and Facilities	£12.5	£12.5	£12.5
100	Low Carbon Hydrogen Plant	£55.0	£109.0	£163.4
200	Air / Gas Systems	£137.3	£227.0	£330.8
300	Water Systems	£14.3	£14.6	£15.6
400	Flare Systems and Infrastructure	£8.6	£8.6	£8.6
500	Buildings	£6.4	£6.4	£6.4
600	Connections and Common Systems	£19.8	£25.7	£32.5
	TOTAL	£253.9	£403.8	£569.8

7.2 OPEX

The OPEX estimate is based on generic numbers. It can only be evaluated on a limited basis at this stage without further engineering work done. The main areas of interest in the OPEX estimate are related to the proposed staffing levels and the change out of catalyst from propriety equipment. This is required on a two/four-year cycle.

Two significant aspects of the OPEX are feedstock natural gas and power. For the purpose of this analysis, they are shown separately in the levelised cost assessment in Section 7.3. Similarly, the cost of CO_2 transport and storage has been identified separately in the levelised cost assessment.

Generic labour rates for similar positions in similar geographies have been assumed for operations, maintenance and G&A staff. The number of staff considered to operate and maintain the business has been kept to a minimum by assuming that the plant will be built to modern control and automation standards.

Further analysis is required during further stages of this project for a better definition of the OPEX adjustments associated with availability, reliability, and the cost of restarting the plant following shutdowns.

Other Expenses include insurance, business rates/local taxes, small tools and maintenance consumables, and personal protective equipment. Land lease is excluded from the OPEX calculations. All OPEX costs are present value as no escalation has been applied for future operating years. Whilst the total OPEX cost does vary by year dependent on the maintenance activities and total shutdown periods it averages out at £13.2m/yr.

7.3 Levelised Cost Assessment

Phase 1 has delivered a high level of cost certainty for the proposed solution, based on an optimised flowsheet developed by JM, whole plant cost and performance estimates by the SNC as an EPC contractor with the capability of delivering the project and site-specific information. Phase 2 will provide further performance and cost certainty by undertaking the full FEED. Based on the CAPEX and OPEX figures above[18], and the performance below a levelised cost assessment has been undertaken. Costs were also estimated for a 5x unit.

Table 7-2 - Parameters for Levelised Cost Assessment

Performance	Units	HyNet HSP 100kNm^3/hr	HyNet HSP 500kNm^3/hr
Output H_2 Capacity	kNm^3/hr	100	500
Output H_2 Capacity	MWth (LHV)	300	1,500
	MWth (HHV)	355	1,775
Thermal Efficiency	%eff (LHV)	79.4%	79.4%
	%eff (HHV)	84.7%	84.7%
Input Feedstock	MWth (LHV)	378	1,890
	MWth (HHV)	419	2,094
CO_2 Potential	t/hr	77.49	387.45
CO_2 Captured	t/hr	75.27	376.35
CO_2 Emitted	t/hr	2.22	11.10
CO_2 Capture Rate	% Capture	97.1%	97.1%
Electrical Demand	MWe	22.9	114.5
Plant Utilisation	%	95%	95%
Plant Utilisation	Hrs/yr	8,322	8,322
Economic Parameters			
Total Project Cost	£000	253,000	887,000
OPEX (Ex Feedstock, Power & CO_2)	£000/yr	13,194	41,620

Underlying energy prices over the period have been taken from BEIS 2018 Updated Energy & Emissions Projections (published May 2019)[19], although it is noted that these only go up to 2035, and so the following years have been maintained at the 2035 values. The cost of CO_2 T&S has been taken from HyNet at £12/tonne. A discount rate of 10% has been assumed for the purposes of levelised cost calculations consistent with BEIS's assessments and work of the CCUS Advisory Group.

On this basis, the plant delivers a levelised cost of hydrogen of £43.46/MWh (HHV basis), comprising £10.66/MWh of capital, £21.63/MWh of feedstock and the balance of £11.16/MWh of operational costs. The estimated equivalent cost for a 5x unit is £35.62/MWh. By way of comparison, this is lower than the equivalent cost of natural gas, accounting for the cost of carbon in 2035, which is assumed to be £37.16/MWh, in line with BEIS data, with a rising cost due to the carbon price trajectory beyond this.

7.3.1 Future Improvements

The biggest factor is scale-up. As part of Phase 1, a CAPEX estimate for a 500kNm³/hr LCH plant was developed which saves around 30% on the capital cost element of the levelized cost, with corresponding savings to OPEX, as shown above.

The above costs are all based on a first of a kind design. When considering Nth of a kind plants, there will be a number of further cost savings:

- A reduction in the engineering design work;
- Improvements to the supply chain reducing material costs;
- Selection of preferred vendors for key equipment items which will reduce fabrication costs;
- A reduction in construction costs;
- A reduction in time to commission the plant;
- Learning from the first plants would be used to improve the design of subsequent plants;
- Reductions in project contingencies; and
- Reduced hurdle rates required by investors due to increased operational and market confidence.

8.0 Project Development Plan Summary

As part of the work undertaken by the consortium in Phase 1, the timeline for delivering the LCH plant project has been reviewed and this has established a possible timeline through the next three phases; the FEED (leading to FID), execution (plant construction) and operations. This section lays out that overall timeline and the work content of each of the phases with most focus on Phase 2 as that is the next to be delivered.

8.1 Overall Timeline

Phase 1 (Pre-FEED) completes with the delivery of this report to BEIS in October 2019.

Phase 2 (FEED) will commence when a contract is agreed with BEIS for the FEED and associated work. This will be subject to the project being selected to continue in the Hydrogen Supply Competition. It is anticipated that such a contract will be awarded, and Phase 2 will commence, at the end of November 2019. Phase 2 is anticipated to last for 16 months with an end date of March 2021.

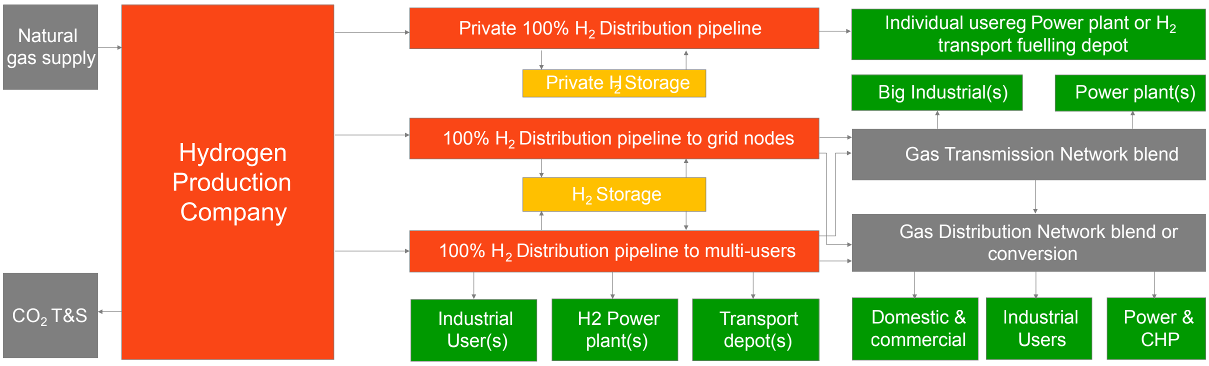
Phase 3 (Execution) will only commence once an FID has been taken by the investors in the project. As noted elsewhere, such an FID will be dependent on HMG having delivered an appropriate policy framework and support mechanism to allow investment to be made with the expectation of an acceptable return. It is not clear, at present, when HMG will complete their work on this but it is anticipated that consultations and legal drafting will be undertaken in parallel to Phase 2 such that an FID, and Phase 3 commencement, can be achieved soon after the completion of Phase 2, say mid-2021. The project development work undertaken in Phase 1 shows that the plant will take some 37 months to design, build, commission and bring into commercial operation. That will allow the first low carbon hydrogen to be delivered to customers in mid-2024. (Note: Dependent on the support regime(s) put in place by HMG it may be necessary, for the FID to occur for the LCH Plant, that there would need to be a simultaneous FID for the CO_2 transport and storage development. It is, however, possible to envisage support regimes where this is not necessary).

Phase 4 (Operations) will continue until the plant is no longer economic to run. This could be determined by the condition of the equipment or the cessation of the commercial contracts that permitted the original FID. The plant has a design life of 25 years and, as with most process plants, will be able to operate long beyond that point with suitable renewal investments. For FID to occur, the initial commercial contracts would be of a length that provide a satisfactory return with an acceptable cost of low carbon hydrogen. It is expected that those contracts would be for at least 20 years.

8.2 Phase 2

Whilst Phase 2 is known as FEED and, indeed, the technical work to underpin an FID will form the majority of the activity in the phase, there are other workstreams that will be undertaken during Phase 2 which are essential to the success of the project. The two principal ones of these are engagement with HMG on the policy framework and support mechanism and developing the range of necessary commercial arrangements with appropriate counterparties that are needed for the plant to be an operating, commercial enterprise. These three principal Phase 2 workstreams are described in more detail below.

Figure 8-1 – Full Chain Business Structure



8.2.1 Policy Framework

A firm policy framework is required in order to enable FID. The business model to support low carbon hydrogen must take account of the full range of users and producers of hydrogen across the hydrogen supply chain, as set out in Figure 8-1.

Without the cost of carbon fully internalised in our energy markets, delivering low carbon solutions will require some form of revenue support. Whilst grant funding may be of assistance in terms of addressing aspects of risk allocation for early projects, there will be a requirement to address the increased operational costs of low carbon hydrogen production. Therefore, it is imperative that there is a revenue support regime.

The mechanism by which support is delivered has a significant impact on the cost of the support, and on the benefits to the energy system. The following lays out the functional requirements of such a revenues support regime and considers six possible models. Given the legislative timetable to establish an enduring regime, it is likely to be appropriate to put in place an 'enabling' support regime to deliver early projects.

8.2.1.1 Functional Requirements of a Revenue Support Regime

Appropriate revenue mechanisms should:

Enable multi-use: A key benefit of low carbon hydrogen is that it can deliver to multiple energy sectors. Any support regime should enable this and not artificially constrain the opportunities for other parts of the energy system, particularly where hydrogen can deliver cost-effective decarbonisation compared with alternatives.

Establish new infrastructure: Low carbon hydrogen is a new vector. The revenue mechanism should enable the bulk production of low carbon hydrogen and enable the establishment of infrastructure to enable the market to develop.

Be cost effective: The business model should provide the necessary support efficiently to be cost effective: (a) the mechanism should efficiently deliver the revenues to the actors requiring it, and (b) given the capital-intensive nature of production and infrastructure, models which allocate risk appropriately to minimise the cost of capital are important.

Be financeable in a nascent market: The use of low carbon hydrogen is an emerging market, dependent on early adopters. Like any nascent market, the low carbon hydrogen supplier faces higher volume and price risk than a fully established market. The appropriate actors must have the appetite to participate, and the commercial risk profile must be suitable for financing.

Avoid unintended consequences: It should not create perverse incentives nor encourage actors to develop projects which are not aligned with policy objectives or undermine cost-effectiveness.

Be deliverable on an appropriate timeframe: Avoiding catastrophic impacts of climate change requires urgent action. Each year that action is not taken, increases the global inventory of CO_2 by 40 billion tonnes. The CCC states that hydrogen is an area where progress has been too slow. Early progress on low-cost no-regrets applications allows 'learning by doing', which the CCC identifies as important. The support regime should be deliverable on an appropriate timeframe to deliver initial projects by the mid-2020s. Given construction, FID is needed 2-3 years beforehand. Financing actors must also have sufficient confidence in a new regime following its implementation before they will make an FID decision; this takes time. Timely delivery is addressed by a regime which uses existing frameworks. New primary legislative pathways take considerable time which, in the case of new frameworks, would have to be in place ahead of FID, with an associated risk of delay.

Be suitable for an enduring regime: It is recognised that in order to meet the timelines advised by the CCC it is unlikely that an enduring regime can be put in place in time for FID on this project. By enabling early projects to deliver, it allows 'learning by doing' for both plant delivery and also in terms of support regime structuring. However, ideally the 'interim arrangements' would be compatible with expected future developments. Changes to the landscape may be general, or specific. Given the range of potential opportunities hydrogen offers and wider developments in the user sectors, the balance of uses will change over time. Any regime should be able to accommodate the implications of such changes, at a minimum for the projects already funded, even if new projects are supported differently.

Accommodate the price of carbon: This will change over time, and the regime should be consistent with this. As carbon prices rise, the quantum of additional revenue support for low carbon solutions relative to fossil counterfactuals should reduce.

8.2.1.2 Potential Funding Models

The following lays out six potential funding models;

A Hydrogen RAB model

A licensed entity is permitted to make a regulated return on the investment and operation of the assets. Based on the permitted regulated return, they are licensed to collect socialised funds from the supply/shipping of commodities, accounting for all the revenue streams they are receiving (for example - regulated gas, electricity, water infrastructure). The largest, and most relevant energy flow in the UK is gas which is supplying domestic, commercial, industrial and power users. This could be a new hydrogen licence or potentially an extension of the existing gas distribution/transmission licence. The RAB model is capable of accommodating higher value revenues from individual users or end market sectors, reducing the socialised cost to all gas users.

Individual revenue support to end market sectors (Individual Sector Support)

This assumes that revenue support mechanisms are set up for specific end user sectors. This allows these users to pay a premium value for the low carbon fuel, hydrogen. Examples could be a low carbon Electricity CfD which supports hydrogen fuelled power generation, or Industrial user support for use of low carbon hydrogen. This premium value would need to be set to enable the hydrogen producer to make its return from the end users it sells to, and to be financeable.

Low Carbon Gas (Hydrogen) CfD

A body is set up by HMG to run an auction process for supply of low carbon gas (hydrogen) to use the market to find the private sector pricing and provide a contract at a Strike Price. The body would be authorised to collect the necessary socialised funds from gas shippers/suppliers and would be the counterparty to the contract with the private entities providing the low carbon hydrogen. (Analogous to EMR CfDs in the electricity sector). Under contract the producer would receive a payment for each unit of low carbon hydrogen produced. It would receive revenue support based on the difference between the Strike Price and the 'Reference Price' the assumed value of the underlying commodity.

Low Carbon Gas (Hydrogen) Obligation
An obligation is imposed by HMG on gas suppliers to secure low carbon gas (hydrogen); This incentivises them to buy a specified proportion of low carbon gas, but to secure this at lowest cost compared with competitors, with the ability to trade or buy out if they are unable to meet their obligation. This is the basis of the former electricity Renewable Obligation, and the current Renewable Transport Fuel Obligation.

Direct taxpayer support: Revenue Incentive
A direct revenue premium made to the producer from the Exchequer funded by the taxpayer. This would supplement the commodity price secured for the hydrogen. It is analogous to the Renewable Heat Incentive. This premium value would need to be set to enable the hydrogen producer to make its return from this plus the sum of the individual market revenues streams secured by the user, and be financeable.

Direct taxpayer support: Grant Funding
A grant payment made to the producer from the Exchequer funded by the taxpayer. This could cover a proportion of the capital cost of the facility.

These options can be evaluated against the functional requirements above.

- Whilst Grant Funding may be helpful, it cannot alone support delivery of a project.
- Taxpayer support may be an appropriate interim measure for early projects, but an enduring regime where the beneficiary (energy users) pays is likely to be preferable.
- A Gas CfD or Low Carbon Obligation on Gas (or even energy) could be a long-term option, but this is expected to take considerable time to implement. Of these a CfD is preferred as for an emerging market. An obligation does not readily provide a secure income stream and is dependent on the headroom between the obligation and delivery.
- Individual Sector Support mechanisms do mean that costs are transparently borne by the individual users receiving the benefit and can build on specific markets to establish early production. However, it does rely on various individual sector revenue support regimes to be put in place (in heating, power, industrial, & transport) which would need to be co-ordinated to ensure that policy objectives are met and avoid unintended consequences.
- A RAB structure is configurable to encourage multi-users and provides revenue certainty and therefore low-cost of capital. In a nascent market it gives revenue risk management and is an established approach in the energy sector. It is also able to accommodate higher value streams, so could work in tandem with individual sector support mechanisms.

The final structure and delivery of support regime will dictate the FID on the first project and the pipeline. It will determine the risk allocation, and therefore appetite of investors, and the cost of capital. It will also impact the timing of project delivery.

In order to enable creation of a hydrogen market, and as an important part of underpinning adoption of CCUS cluster delivery by mid-2020, it is likely that it will be necessary to pursue a regime focused on supporting early projects. This would allow the market to develop before an enduring regime is put in place. There is precedent for such as regime with the FID-Enabling contracts under Electricity Market Reform. Clearly the objective is that such contracts are reasonably consistent with the enduring regime. This would address the timescale issues associated with major legislative programmes and would also allow government and the private sector to establish and experience the impact of such support regimes ahead of widespread roll out. The call-out box below considers the impact of three hydrogen projects of this scale, assuming that the cost is socialised nationally across key gas consumers.

Bulk Hydrogen Production: Case Study

Assume that in the first instance, three clusters each build out a single unit of bulk hydrogen production from Natural Gas. This equates to 3x3TWh per annum of hydrogen requiring a support requirement for bulk production of ~£20/MWh. Across the total gas consumption in the UK assumed to be 800TWh this equates to a socialised increase of £0.22/MWh, well within the recent fluctuations in wholesale gas price (over 15p/therm = £5/MWh over the last 18 months). Note that the following is the socialised cost of production across all users on the network.

- On the basis of around 300TWh of domestic consumption and 23.5 million households, this equates to a typical usage of 13MWh/yr and increase of around £2.90/yr on a bill. Typical delivered price of gas per annum is £550/yr, so this equates to ~0.5% increase, and well within the fluctuations in gas bills due to wholesale price fluctuations (up to £65/yr, based on the £5/MWh variation).
- On the basis of 200TWh/yr of commercial and industrial consumption, this equates to an increase of £0.22/MWh. A medium scale facility (BEIS category) consuming 10GWh of gas would face an increase of £2,200/yr.
- On the basis of 280TWh/yr of power generation, this equates to an increase of ~£0.40/MWh on the electricity price borne by the electricity consumer.

Some users may take a ‘full’ hydrogen stream directly or via a hydrogen distribution system. In some cases, this could have a higher value to the user. Under a RAB, a Single Till regime could be used to accommodate this, with correspondingly lower socialised costs across the gas sector.

8.2.2 Technical FEED

The consortium will deliver a “shovel-ready” FEED package for the 100kNm^3/hr LCH plant for Essar’s Stanlow Refinery. The objective of the Phase 2 FEED is to “define” the project based on the selected concept to allow successful project sanction.

To achieve the objective the project team’s delivery will include:

- Site characterisation of a topographical survey, soil investigations, geotechnical report, contamination investigations, unexploded ordnance (UXO) desk top survey, existing utilities and services investigations, condition surveys of buildings and infrastructure slated for reuse;
- Core LCH Flowsheet Basic Engineering Package (BEP);
- Licensor BEP for CO_2 capture unit;
- Integrated FEED package;
- Total Installed Cost (TIC) estimate, including main vendor procurement and main construction subcontractors;
- Definition of design and specification in order to handover to EPC phase (relied upon information to form the basis of EPCM contract) including overall project execution, constructability, construction execution, commissioning programme, performance tests and guarantees, maintenance and operability, and compliance with UK regulations;
- Planning application to permission, permits, and consents;
- Manage risk to acceptable level for sanction/ investment.

8.2.2.1 Project Team

The project team will execute the work from offices based in the UK. The team is made up of the following team members, who have the following responsibilities on the project:

Table 8-1 - Partner Responsibilities

Partner	Overall Responsibility	Specific Responsibilities
Johnson Matthey	Process Technology Engineering: - Delivery of Basic Engineering Package (BEP) for core LCH technology (inc. GHR-ATR)	■ Delivery of Basic Engineering Package (BEP) for core LCH technology (inc. GHR-ATR) ■ Delivery of BEP for core technology together with associated capital cost estimate ■ Key engagement with PSA & CO_2 Capture licensors in early FEED to agree process design ■ Support to EPCM contractor on Balance of Plant (BOP) and overall process safety design ■ Support to owner on Operations and Maintenance strategy ■ Support to stakeholder engagement and regulatory framework as required ■ Support for planning and consents
SNC-Lavalin	EPCM Contractor: - Overall co-ordination of FEED and responsible for all BOP not covered by JM BEP	■ Overall co-ordination of technical FEED work ■ Engineering of BOP (including co-ordination with Services providers) ■ Deliver BEP and commercials for PSA & CO_2 Capture packages ■ Lead on construction, commissioning and on-site project delivery (interfacing with specialist subcontractors as required inc. surveys) ■ Overall process safety design ■ Lead on CAPEX and OPEX estimates ■ Counterparty to owner for EPCM contract negotiation ■ Support to owner on O&M strategy ■ In-house consenting and permitting specialist services ■ Support to stakeholder engagement and regulatory framework as required ■ EPCM offer
Essar	Owner/Operator: - Owner's Engineering, O&M and financing development	■ Review of FEED definition ■ Owner's engineer role to review JM/SNCL design ■ Engineering and design of interfaces with the existing Stanlow assets ■ Operator role in design (HAZOP etc.) ■ Operations and Maintenance (O&M) Strategy (including support to SNCL's OPEX cost estimate) ■ Lead on commercial negotiations for EPCM, third party off-take/supply and land ■ Develop financing arrangements for project with Progressive ■ Support on planning and other consents ■ Support on regulatory framework, stakeholder engagement
Progressive Energy	Overall Project Co-ordinator	■ Overall project management (provision of Project Director) ■ Interface to BEIS and regulatory bodies on funded project ■ Technical lead on wider HyNet project system definition and integration, including; ■ Interface to associated work on hydrogen distribution, storage and use ■ Interface to associated work on CCUS transport and storage system ■ Lead on hydrogen economy policy/regulatory framework ■ Lead on stakeholder engagement (including the wider HyNet project) ■ Financial modelling (initial project and future expansion projects as cluster grows) ■ Develop financing arrangements with Essar ■ Support to Essar on commercial agreements (EPCM, third party off take/supply and land) ■ Lead on planning and other consents

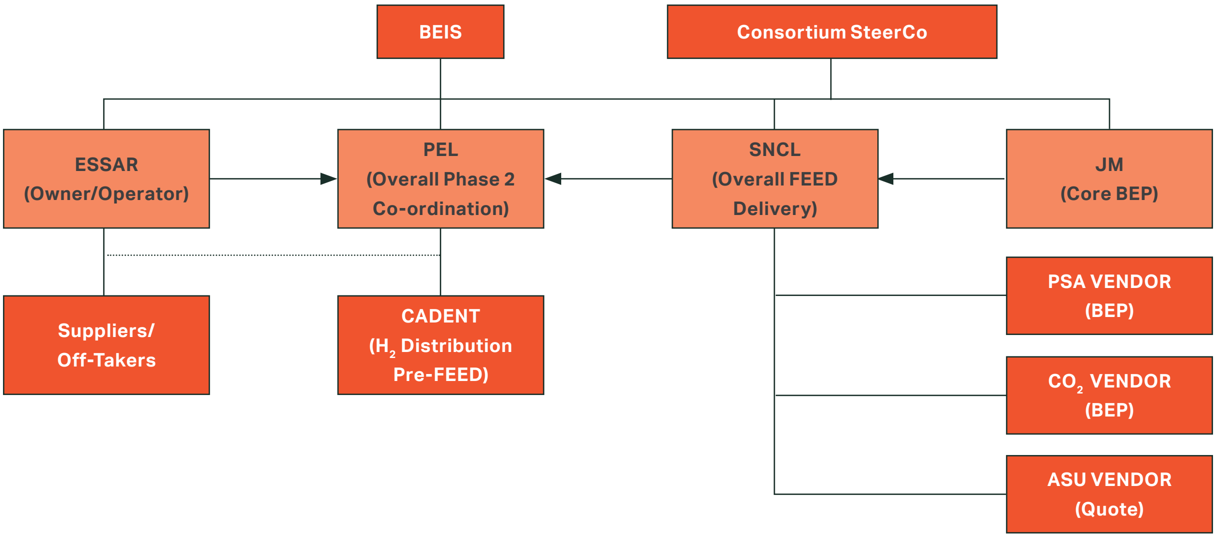
8.2.2.2 Client Requirements

The client for the Phase 2 of the Hydrogen Supply Programme is BEIS although it is recognised that the Phase 2 outputs must also satisfy the needs of the Phase 3 client which will be the SPV.

8.2.2.3 Project Structure

The project is a consortium with a structure as shown in the following organisation chart:

Figure 8-2 - Phase 2 Organisational Structure



8.2.2.4 Engineering Strategy

The technical content of the FEED will be coordinated by SNCL. The core of the technical delivery will be the BEP produced by JM for their LCH technology supported by a BEP produced by the Licensor for the Carbon Capture Package.

The interface with Area 4 will be dictated by the condition of the site. The work will commence with a detailed site visit followed by a range of site surveys. The site condition information will then be used to develop the construction, ground works, and civils engineering designs.

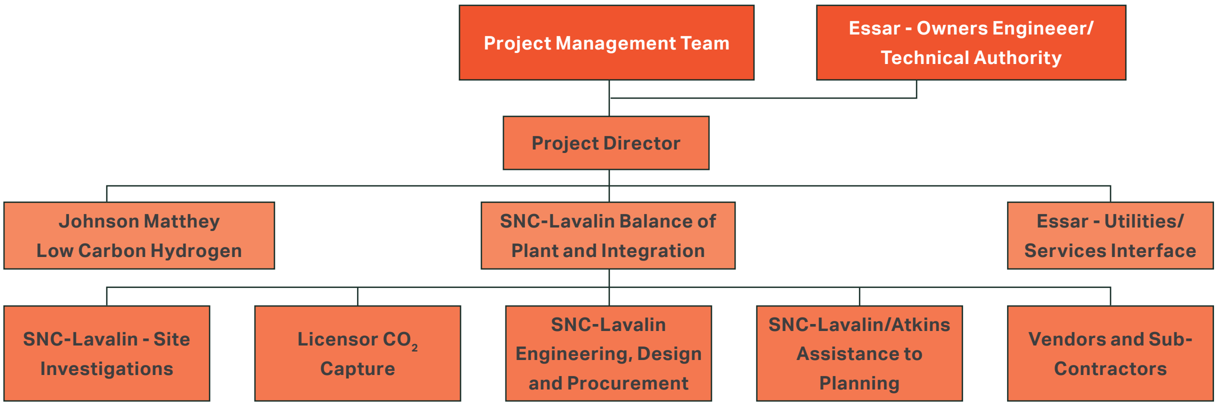
The FEED design, including utilities, services, amenities, and infrastructure will be built up around the BEPs. Complex equipment will be supported by information from previous projects or information solicited from Vendors.

The FEED design will be developed to a level to support a cost estimate suitable for sanction (both within consortium companies and for the overall project). This will require design definition of all significant aspects of the project (>1% CAPEX or approximately >£250,000). It is expected that tenders for significant aspects will have been technically and commercially evaluated against engineering requisitions (with clarifications concluded as required), and terms & conditions negotiated to a reasonable degree in order to increase the accuracy and reliability of the cost estimate. This work will require a suitable development of 3D model design in order to develop a material take offs for bulks to support main construction sub-contracts, and suitable development of equipment and package data sheets and specifications to obtain equipment pricing. The extended level of development will also include lower value items for which the technical characteristics on which the guaranteed performance of the plant depends.

The engineering shall also be developed to a level suitable for supporting safety and environmental studies, and for supporting applications for planning, permits, and consents.

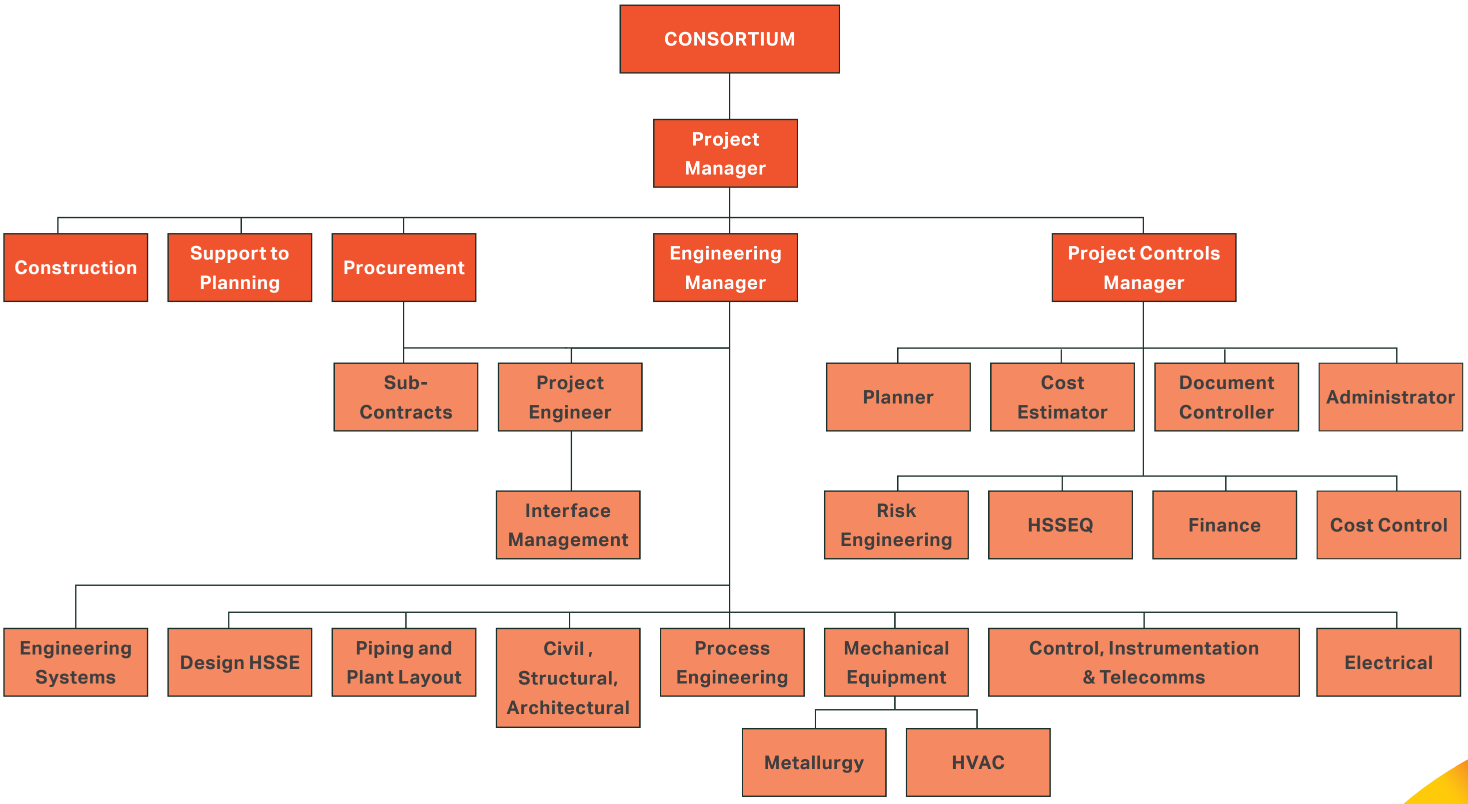
The following is the FEED organisation.

Figure 8-3 - FEED Organisation



The following shows the FEED team. Areas of the Engineering Organisation will be replicated in JM and the Carbon Capture Licensor's teams.

Figure 8-4 - FEED Team



8.2.2.5 Procurement Strategy

The procurement team will manage sub-contracts to be placed during the FEED phase (e.g. invasive parts of surveys, carbon capture licensor). Procurement scope is to enquire for sufficient pricing to provide the required accuracy for the cost estimate and to provide the required assurance for SNCL's EPCM proposal, price, terms, and the transition into the EPC phase of the project.

Pricing will therefore be required for:

- Licensors;
- Packages and equipment > £250k;
- Sub-contracts > £250k;
- Critical technical information (items to be identified by engineering management at the end of the FEED preparation phase); and
- Long Lead Items > 12 months

The procurement team, with support of Essar, is expected to negotiate agreements on terms (principals) on major value items and sub-contracts:

- Licensors, packages, and equipment where there are project critical process performance guarantees (either up to main contract or within regulatory compliance); and
- Sub-contracts > £1m.

Procurement of equipment will be worldwide (but in compliance with EU Directives and UK Regulations – i.e. CE Marked). Construction sub-contractors shall be UK specific preferably with a bias towards those in geographic proximity to the job site. Enquiry sub-contract packages will be targeted to scope and purpose for project (generalised packages used on previous projects were a lesson learned on poor performance).

8.2.2.6 Project Controls Strategy

Project controls will be executed close to the project and engineering management for the project in order to provide close control on cost and schedule. The project controls team will compute cost budgets per discipline and monitor cost and man hours against the delivery progress using principles of earned value management and will also manage project services (admin, DCC, etc).

Document control will be executed by SNCL for the whole project with input and access to the different consortium members.

8.2.2.7 Construction Strategy

The construction team will be responsible for managing the site for the project (under Essar control) during invasive aspects of the FEED work – site visits, site surveys, condition surveys.

The construction work will be developed to support the required level of cost estimate such as construction design, construction welfare design, construction philosophy and construction execution planning. Construction will also provide the construction scopes of work and specifications for the construction sub-contract enquiries and support the requisitioning process during FEED.

The construction strategy for execution will be multi-contract maximising the direct control of the contractor over sub-contractors by eliminating further tiering where possible.

8.2.3 Project Development and Commercial Activities

The non-engineering project development work undertaken during FEED is critical to delivering a "shovel-ready" enterprise which is capable of being sanctioned for build following this phase of the project. The following project development activities will be undertaken during Phase 2.

8.2.3.1 Owner/Operator

During Phase 2 the project will establish the entity that will own and operate the LCH Plant. At the end of Phase 2 it will need to be clear who will be the owning entity, who will be responsible for operations and maintenance and the relationship between the two.

Establishment of Owning Entity

It is anticipated that Essar will take the lead in this but it may not be the sole owning entity and so it is also anticipated that a Special Purpose Vehicle (SPV) company will be established, owned by those who are investing the finances to build the project. The SPV will be the counterparty for all the contracts required to build and operate the facility. Progressive will work with Essar and the other consortium parties to establish the financing and the resulting SPV. If Essar were established as the only investing party then the SPV may, indeed, be a new or existing trading company of Essar Oil (UK) Ltd.

Establishment of Operator

During Phase 2, Essar will provide operator input to the engineering design (HAZOP, RAM etc.) however, also during this Phase, the consortium partners, led by Progressive, will identify the entity that will be responsible to the SPV for the operation and maintenance of the facility. It is anticipated that this will be an Essar led entity but whether it is wholly Essar owned or whether it is an existing entity will be determined during Phase 2. Phase 2 will also seek to establish the contractual arrangements between the operations entity and the SPV.

Land/Wayleaves

As determined during Phase 1, the LCH Plant will be situated on Area 4 of Essar's Stanlow refinery. Essar have undertaken to reserve this land for the project on the expectation that HMG will establish a suitable support framework that will allow the project to go ahead. They are providing the option cost as an in-kind contribution to the project. There will need to be an appropriate lease agreement established between Essar and the SPV for the use of this land. Progressive will represent the consortium in those negotiations with Essar.

The various pipelines and cables that will be necessary to bring fluids, power and signals to and from the main site will need to have appropriate wayleaves negotiated to establish their rights to be constructed and operated. It is anticipated that the majority, if not all, these will be located in existing utility corridors which will make the task more straightforward but legal agreements will still be required. These will also need to cover any necessary railway crossings and the like. Progressive will lead for the consortium in negotiating these, working with Essar where appropriate.

Financial Modelling

In order to establish the investment case a full financial model covering the whole life and whole scope of the investment will need to be created and validated. The model will be owned by the SPV. Progressive will support the SPV in the establishment of the model. A specification for the model will be established early in Phase 2.

Capital Financing

The work in Phase 1 established an estimated capital requirement for the project of £253m. The sources of this finance plus appropriate financial contingency will need to be identified during the execution of Phase 2. It is recognised that any financing will be subject to the establishment of a suitable support regime from HMG for low carbon hydrogen production and, therefore, the financing will all be conditional until that support regime is securely in place. Progressive will work with Essar on sourcing the necessary finance.

8.2.3.2 Project Delivery Strategy

During Phase 2 the consortium will identify an appropriate and cost-effective project delivery strategy for the LCH facilities. The form of this will depend on the nature of the SPV. It could require a single EPC contractor to provide a "fully-wrapped", lump sum, turnkey price. Equally, the SPV may wish to pay a lower capital cost by sharing risk with the contractor. It is, however, anticipated that a single entity will be responsible to the SPV for the delivery of the project and, currently, it is anticipated that this entity will be SNCL with JM responsible for the delivery of the core LCH technology equipment.

Once the main technical work of FEED is completed SNCL will adopt the role of negotiating counterparty for the EPC work. It is anticipated that Essar, supported by Progressive, will represent the interests of the SPV. The SPV will draw upon industry standard practices and benchmarks to ensure that the arrangements put in place represent the best value for money for the SPV.

8.2.3.3 Supply/Off-Take Contracts

Contracting Strategy

In order for the plant to operate it requires a variety of supplies and off-takes. These will need to be negotiated during Phase 2 in order that the financial model can be developed. It will not be possible to finalise many of these negotiations until the support arrangements for low carbon hydrogen have been agreed and put in place by HMG. The extent to which these arrangements will impact upon the ability to finalise the contract will vary with the type of contract. Some (e.g. water and waste) should be little impacted but others (e.g. hydrogen off-take) will be significantly dependent on the arrangements. Those identified so far as being required are listed below. The client counterparty for all these will be the SPV. It is anticipated that Essar, supported by Progressive, will lead the negotiation of these contracts. Where Essar is the other counterparty then Progressive will lead. (Note: currently the ASU providing oxygen and nitrogen for the process is considered to be built as part of the LCH plant. During Phase 2 it will be investigated as to whether it is more cost effective for those supplies to be provided "over-the-fence". If so, then supply contracts for these will need will to be negotiated also). It is recognised that some engineering FEED work (different amounts for different agreements) will need to be done first to establish the technical specification for the contracts.

Natural Gas Supply

Natural gas is the main feedstock for the LCH plant and this will be sourced from the local NTS. This contract will need to address volumes, pressures, specification, off-take location and reliability amongst other factors.

Refinery Off-Gas Supply

It is anticipated that certain streams of ROG will be diverted to be used as feedstock for the plant. The same issues as for natural gas of volumes, pressures, specification, off-take location and reliability will need to be addressed in the contract. There will likely be interactions between any ROG contract and that for hydrogen off-take in order for the refinery to maintain its overall energy balance.

Electricity Supply

The LCH plant will require high voltage electrical supply. It is anticipated that this will be provided by a private wire from a local generating source.

Hydrogen Off-Takes

During Phase 2 the customers for the 100kNm^3/hr of hydrogen will be finalised. This contract will need to address volumes, pressures, specification, supply location and reliability amongst other factors. For the first plant it is hoped that all these customers will be relatively close to the LCH plant to minimise the cost of distribution. Indeed, it is anticipated that some of the major users will be on Stanlow refinery. One of the off-take contracts will be for blending into the LTS gas main.

CO_2 Off-Take

In parallel to this project, the wider HyNet project will be developed further so that it can offer a CO_2 off-take service for transport and storage. This service will depend significantly on the support regimes established by HMG.

Services

A range of other services (water, wastewater, telecoms, security etc.) will be required for the operation of the plant and contracts will need to be negotiated during Phase 2.

8.2.3.4 Stakeholder Engagement

The LCH plant project does not exist in isolation but is part of the wider HyNet project. The plant will not be able to be built unless key parts of the wider HyNet vision are delivered. The Phase 2 work will include a number of workstreams to engage with the wider project and the key stakeholders involved with it to ensure that the LCH plant is a suitable component of the whole. This work will be led for the consortium by Progressive and the key elements of it are listed below.

BEIS/HMG - Policy Framework/Support Mechanism

Without a suitable policy framework that leads to a viable support mechanism for low carbon hydrogen and its associated CCUS then neither the project nor the wider HyNet project can proceed to delivery.

The consortium will work with BEIS and, through them, with Treasury to ensure that such policy and framework are delivered in a timely manner. Progressive will lead this work for the consortium.

HyNet Integration

It is essential that the LCH plant wholly integrates technically into the wider HyNet project. Progressive will liaise with the wider HyNet project to ensure this is the case, establishing appropriate technical discussions between the teams as necessary. This liaison will also be necessary for establishing the CO$_2$ Off-Take agreement.

Cadent: Hydrogen Distribution Pre-FEED

Whilst not being undertaken as a funded part of this project, in parallel to the Phase 2 work Cadent Gas Ltd (Cadent) will be responsible for a Pre-FEED study of the hydrogen distribution system needed for the wider HyNet vision and will liaise with the technical and commercial teams establishing the hydrogen off-takes to the initial LCH plant project. This work is being funded by Cadent from other sources. Progressive will provide appropriate liaison on this work.

Hydrogen Storage

Whilst not anticipated as being necessary for the first LCH plant hydrogen production project, in the longer term it is expected that storage will play an important role in balancing hydrogen production and use in the wider HyNet area. It is, therefore, important that the technical requirements for any potential hydrogen store are understood by the LCH Plant project. Progressive will lead for the consortium in liaising with those investigating hydrogen storage options in the region.

Regional Engagement

The support of the North West region is essential for the success of the HyNet project. This support comes from MPs, regional mayors, councils, LEPs, CoCs and the like. Progressive will lead for the consortium in engaging with these stakeholders as part of the wider HyNet effort.

Knowledge Transfer

A key responsibility during Phase 2, as required by the contract with BEIS, is the transfer of knowledge and learning from the project to wider industry. The requirements will be identified in the contract with BEIS and Progressive will lead for the consortium to ensure the necessary work is done. This will involve publications, conferences and other events during and immediately after the Phase 2 work is complete.

8.2.3.5 Cluster Growth / Business Development Plan

As part of encouraging financial investors it is important that the consortium can show a business plan that extends beyond the first project. During Phase 2, working with the wider HyNet team, Progressive will lead for the consortium in establishing the future hydrogen business plan for the North West cluster as it moves to become the first Net-Zero cluster in the UK.

8.3 Phase 3 - Execution

8.3.1 Objective

The objective of the execution phase of the project is to safely realise an operational facility for handover to the operator.

This phase is composed of four primary main activities:

Detailed Engineering: The detailed design of the plant. Management and coordination activities related to design activities conducted by others, and technical supervision of equipment procurement. The detailed engineering team will also be responsible for all the integration within the plant design between client, landowner, permits & consents, licensors, vendors, site, construction, and commissioning teams.

Procurement: The procurement of all equipment and materials for the construction of the plant. This will include expediting data for engineering, expediting material inspection and certification, and witness of testing. The procurement team will manage the logistics of delivery of material, equipment, and modules / skids to site, and management of material on site until its installation.

Construction: The mobilisation and execution of construction work. This will include the securing of the site, provision of temporary facilities, demolition of structures not required for the project and refurbishment of buildings and facilities that would be retained, management of main sub-contractors, supervision / control / monitoring of construction.

Commissioning: The checking of all systems on the plant, start-up and operation of the plant, followed by availability and performance tests.

8.3.2 Project Team

The project, engineering, procurement, and construction management teams will be based in the UK and will relocate to site to support construction once temporary offices are available and mechanical installation commences.

Detailed design will be managed by offices within the UK. There will be detailed design work that will be undertaken overseas in order to provide a competitive price for the project.

Commissioning personnel tend to be transitory by the nature of their work, and will move with projects, and will locate to site as required to support construction, pre-commissioning, and take over the plant at commissioning.

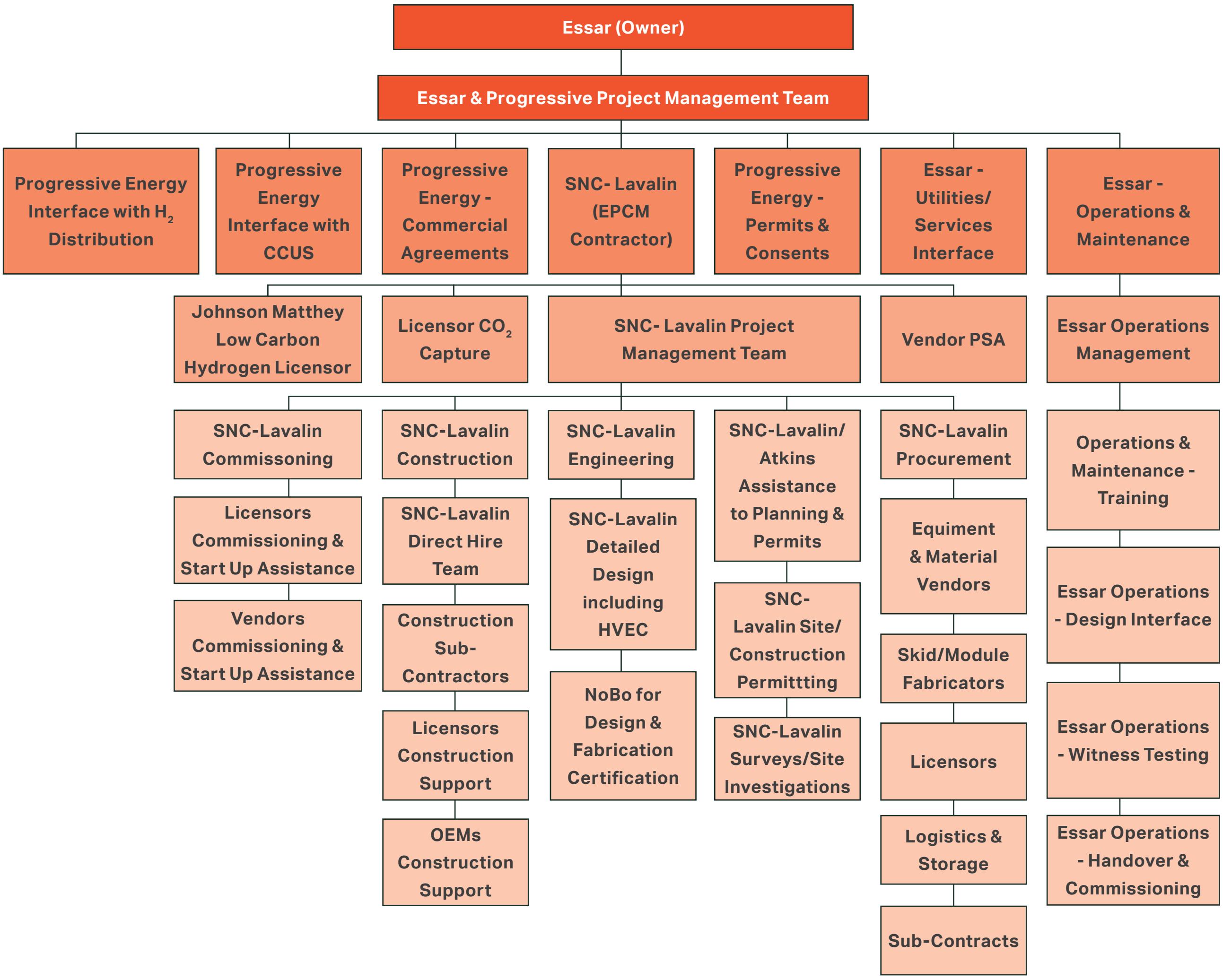
8.3.3 Organisation

The precise form of the organisation put in place to execute the project will be finalised in Phase 2. The current expectation for this is as follows.

The project organisation will be run by Essar as the owner and operator of the final asset. It is anticipated that there will be a SPV specific to the LCH Plant which Essar would lead. Progressive and Essar will provide the overall management team for the Project under the SPV. SNCL would be the EPCM contractor for the execution phase with a contractual relationship with the SPV. JM, licensor for the LCH technology, will be contracted through the EPCM to the SPV.

The organisation is shown in the following organisation chart.

Figure 8-5 - Proposed Execution Organisation



8.4 Phase 4 - Operations

8.4.1 Operations and Maintenance Strategy

The LCH Plant is designed for continuous operation with maximum uptime (availability) in order to generate the best economic return on investment. It will be operated by a dedicated operations team of suitably qualified and trained personnel. The operations team will operate on a shift pattern to provide continuous operational coverage of the plant.

The operations team will be supported by a day shift to cover management and routine maintenance of the plant, and to provide administration for the operation of the plant as a business. Non-routine maintenance will be supported by outside contractors and equipment manufacturers.

Planned outages for significant maintenance will be organised at set durations through the plant life and will be campaigned to reduce the impact (down-time) on the plant economic operation.

8.4.3 Operations Staff

The plant will be operated on a 24 hours a day, 365 days a year basis. It has been assumed that a four-team shift rotation pattern will be used with each shift worker working 2184 standard hours per year.

Each shift will consist of 24 operations members as follows:

- The plant operators shift team will consist of one off Shift Superintendent and two off Operators per shift
- The maintenance team will consist of two Maintenance Fitters per shift
- A security guard will be on each shift

8.4.3 Operations Support Staff

The office day workers will consist of the following staff members:

- An Operations Manager/Site Manager
- A Maintenance Manager
- Two Mechanical Technicians
- One Electrical Technician
- A Control & Instrumentation Technician
- A Storeperson who will also do the procurement of spare parts etc.
- Two Administrator/Receptionists
- Part time support from HR, Accounts, IT and document control

8.4.4 Maintenance

For each item of equipment, pressure vessels, pumps, tanks etc the required statutory and preventative maintenance schedules have been spread out across the working life of the plant. Even in the first few years of operating a brand new plant it is prudent to open up certain key items of equipment to check for corrosion levels, scale build up, catalyst degradation etc. Pressure vessels require inspection every five years, but it is good practice to spread out the inspections and perform some inspections each year to minimise the staff levels and down time for an annual shutdown.

The process technology requires that some vessels require the catalyst to be changed out every two years and other units are scheduled to run for two to four years between catalyst changes. It is anticipated that this will lead to a shorter minor shutdown for years 1,3,5, etc. and longer major shutdowns in years 2,4,6, etc. The preferred schedule of shutdowns will be agreed with the operations team in Phase 2.

8.4.5 On-Site Facilities

On-site facilities are provided to assist in operations and maintenance. A control room is provided as a central point for operators to control the entire plant. Welfare (messing, lockers, showers, WCs, first aid), offices and workstations are provided for staff working on the site. A dedicated stores building and a workshop are provided on site to support site based maintenance and to provide routing spares required to keep the plant operational.

8.4.6 Plant Availability

Due to the change out of the catalyst from some of the process equipment it has been assumed that the plant will have an annual shutdown and on alternate years this shutdown will be either a minor or a major shutdown. It has been assumed that a minor shutdown will be 11 days and that a major shutdown will take 14 days.

In addition to the planned down time of the plant there are often unplanned events such as instrument/valve failures which will cause the plant to stop production. With sufficient equipment sparing and an on-site maintenance team operating a well-designed planned maintenance schedule these unplanned outages can be kept to a minimum. It has been assumed for the cost estimate that unplanned outages will account for five days or 1.4% of the downtime.

In addition to the time for catalyst change out analysis has been undertaken of the shutdowns required for other key equipment maintenance. These calculations show an estimated plant availability over 20 years of 95.1%.

9.0 Glossary

Acronym	Full Name
AACEI	Association for the Advancement of Cost Engineering International
ASU	Air Separation Unit
ATR	Autothermal Reformer
BECCS	Bio-Energy Carbon Capture and Storage
BEIS	Department for Business, Energy & Industrial Strategy
BEP	Basic Engineering Package
BoD	Basis of Design
BoP	Balance of Plant
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
CfD	Contract for Difference
CHP	Combined Heat & Power
CO_2	Carbon Dioxide
CoC	Chamber of Commerce
DCC	Document Control Centre
DEP	Design, Engineering and Procurement
EMR	Electricity Market Reform
EPC	Engineering, Procurement and Construction

Acronym	Full Name
EPCM	Engineering, Procurement and Construction Management
ENVID	Environmental hazard Identification
FEED	Front End Engineering Design
FID	Final Investment Decision
G&A	General & Administration
GDP	Gross Domestic Product
GHR	Gas Heated Reformer
GS(M)R	Gas Safety (Management) Regulations 1996
GT	Gas Turbine
GVA	Gross Value Add
HAZID	Hazard Identification
HAZOP	Hazard & Operability study
HGV	Heavy Goods Vehicle
HHV	Higher Heating Value
HMG	Her Majesty's Government
HSE	Health & Safety Executive
HSP	Hydrogen Supply Programme
IEA	International Energy Agency
ISBL	Inside Battery Limit (LCH core technology)
ITS	Isothermal Shift
JM	Johnson Matthey plc
LCA	Leading Concept Ammonia
LCH	Low Carbon Hydrogen
LCM	Leading Concept Methanol

Acronym	Full Name
LEP	Local Enterprise Partnership
LHV	Lower Heating Value
LPM	Low Pressure Methanol
LTS	Local Transmission System
MP	Member of Parliament
NTS	National Transmission System
OPEX	Operational Expenditure
OSBL	Outside Battery Limit (i.e. BoP)
PEL	Progressive Energy Limited (also Progressive)
PSA	Pressure Swing Adsorption
RAB	Regulated Asset Base
RAM	Reliability, Availability & Maintainability study
RIIO	Revenue = Incentives + Innovation + Outputs
ROG	Refinery Off-Gas
SMR	Steam Methane Reformer
SNCL	SNC-Lavalin UK Limited
SPV	Special Purpose Vehicle company
T&S	Transport & Storage
TIC	Total Installed Cost
UXO	UneXploded Ordnance

Appendix 1: Summary of Work Undertaken in Phase 1

Work Package Number	Work Package Name	Project Partner Lead for Work Package	Brief Description of Work Package, Including Key Tasks
WP1	Project Initiation	PEL	All partner activity to issue Phase 1 Execution Plan and review and confirm the Basis of Design prior to undertaking process design for the project.
WP2	Site Visit Report	SNCL	Construction manager visit to site; to ensure that the project design can be built; to identify battery limits, to identify likely topology/geotechnical issues (desktop only – no survey work), to provide feedback for constructability and construction costs. The area surrounding the site will be reviewed for logistics constraints in order to develop a strategy for modularisation and prefabrication. Report produced to support Phase 2 scope definition.
WP3	Process Design	JM	Design and performance assessment of the plant. Includes assessing; impacts of variable demand, scalability, process risks and comparison to the counterfactual model. Interim and final reviews by partners.
WP4	Plot Plan & Tie-ins	SNCL	Concept level Plot Plan for the project. To be developed from information provided by the site owner and JM's process design. Will utilise SNCL's "Basis for Site Layouts" to ensure sufficient maintenance and safety distances for hazard control.
WP5	Cost Estimates	SNCL	Capital cost: An AACEI Class 4 estimate will be developed for the plant using; the major equipment list, plot plan, CAPEX items from JM, SNCL data bases and estimating tools. OPEX cost: An operational design will be created for the Plant as a basis for the cost estimate. This will include; an organisation chart and shift pattern, maintenance schedule and % allowances for areas which can't be quantified at this stage. An AACEI Class 4 OPEX estimate will be created for the plant.

Work Package Number	Work Package Name	Project Partner Lead for Work Package	Brief Description of Work Package, Including Key Tasks
WP6	Project Execution Plan	SNCL	Project Execution Plan including: ▪ a Level 3 Schedule for the project (inclusive of; front end, engineering, design, procurement, construction, constructability, commissioning, and testing activities);and ▪ a Risk Management Plan. This will be derived from a risk management workshop which will result in a risk register for the project together with a Monte Carlo analysis for the capital risk allowance for the project and a contingency register.
WP7	Future Capacity Delivery Rate	SNCL	Supply chain capability for technology delivery.
WP8	Market Assessment	PEL	Market size and export opportunities.
WP9	Detailed Plan for Phase 2	PEL	Scoping and Execution Plan for Phase 2. FEED Definition.
WP10	Development Plan Definition	PEL	Identify key development steps to commercialisation. Develop a business plan for the deployment of the technology and identify barriers and risks.
WP11	Phase 1 Report	PEL	Production of Phase 1 Report.
WP12	Project Management	PEL	Overall project management including the interface to BEIS. Management of JM scope of delivery. Management of SNCL scope of delivery.

In addition to the work managing the effort, with respect to output documentation, this work covered five broad categories:

- The technical work undertaken by JM on the core of the LCH plant. This work has built on previous general development work on the technology undertaken by JM and provided a core process design for the plant for HyNet application.
- The design of the balance of plant to embed that core technology into a project that can be constructed and operated at the Stanlow refinery. This work was undertaken by SNCL and covered the assessment of Area 4, the designated location for the LCH plant on the refinery and identifying how the plant would integrate with existing and new services.

- CAPEX and OPEX costs for the facility have been developed, led by SNCL but with input from JM and Progressive.
- A high level business plan covering both the initial development and the future expansion of hydrogen production has been developed based upon a market assessment for low carbon hydrogen. This work was led by Progressive.
- Preparation for Phase 2 in the form of HAZID/ENVID, risk assessments and execution plans in which the whole consortium has been involved.

More specifically the work undertaken in Phase 1 included the following.

Technical Work – Core Plan
The LCH core process design was undertaken by JM and delivered a process design package consisting of a full set of process flow diagrams, equipment and catalyst details and supporting analyses and write-ups. This work, building on earlier work developing the LCH concept, showed that the LCH technology would be suitable for the HyNet application, provided engineering detail to allow BoP design by SNCL and provide cost and performance data for inclusion in the cost estimates and financial modelling.

Technical Work – Balance of Plant
SNCL undertook a detailed (non-invasive) site visit to identify the significant constraints and issues that would need to be addressed in developing Area 4 of the Essar Stanlow Refinery as the chosen location for the project. They also undertook the design of the BoP equipment (that required to provide all the necessary utilities to the core process and to connect the core process with the external tie-in points) sufficient to complete an overall site layout and to provide cost and performance data for inclusion in the cost estimates and financial modelling.

Cost Estimation
Based on design data input from both JM, for the core LCH technology, and SNCL, for the BoP, SNCL developed an AACEI Class 4 capital estimate together with a full risk and contingency analysis for the project.

The consortium agreed on a likely staffing model for the plant and that, together with the LCH plant performance parameters as provided by JM, were used by SNCL to provide an operational cost estimate for the project. They were also able to undertake an initial reliability, availability and maintenance modelling exercise to derive a likely overall availability for the plant and a view on the turnaround schedule over its 20 year operation.

Business Planning
Progressive led a review of the future UK and, indeed, the worldwide market for hydrogen and, in particular, low carbon hydrogen. This review was then used to set the scene for the business plan for developing LCH technology facilities in the HyNet project area and for identifying what barriers there might be (concluding that there were none of any significance) to rolling out the technology as part of achieving net-zero by 2050.

Business planning was undertaken by Progressive on two time horizons, the plan to develop and deliver the first LCH plant unit at the Essar Stanlow refinery and that to develop further LCH production in the HyNet area. This work looked at issues specific to the project and also those external issues necessary to allow a Final Investment Decision (FID) to be taken in due course. This identified that having a suitable regulatory framework and support mechanism from HMG are essential to FID.

Preparation for Phase 2
The consortium agreed on a Basis of Design for the project. This document was agreed at the start of Phase 1 for the purposes of Phase 1 and, at the

end of that Phase, was updated based on the work and learnings that were developed by the team to establish a BoD for commencing the FEED in Phase 2.

A HAZID/ENVID review was undertaken, participated in by all consortium partners and overseen by an independent chair. This identified a number of hazards that will need to be managed in the Phase 2 FEED but none that were regarded as casting doubt on whether the plant can be constructed at the proposed location.

The consortium team met together on two occasions to undertake and complete a risk review for the project. This risk review covered all aspects; technical, commercial and stakeholder and was in two sections, one covering Phase 2 and one the execution phase. The later was undertaken at this stage to ensure that, where there are major risks in execution that can be mitigated in Phase 2, those mitigations were included in Phase 2 planning.

A key element of the Phase 1 work was to plan for executing Phase 2. This involved a full, bottom-up, estimating exercise based on work package identification and Cost, Time and Resource sheet completion. This allowed SNCL to complete a full cost estimate for the Phase 2 work and a detailed execution programme. The team also produced a project execution plan covering all the work (technical and commercial) that will need to be undertaken in Phase 2 and a first pass schedule for the execution phase.

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Progressive energy

hynet.co.uk

Progressive Energy Ltd
Swan House,
Bonds Mill,
Stonehouse
GL10 3RF
+44 (0)1453 822444
www.progressive-energy.com

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