Low Carbon Hydrogen Supply 2.

HYS2138: Production of low carbon hydrogen from high carbon heavy fuel oil via gasification with carbon capture and storage.

Feasibility Study Report

Date (07/10/22)

Contents

1 Executive Summary

Refineries play a significant role in the current carbon-based energy economy in processing crude oil into the many products that make our lifestyle possible. These oil-derived products reach well beyond the petrol, diesel and kerosene: they also include pharmaceuticals and vitamins, materials for garments, solvents, and plastics.

The substantial shift in the transport market with banning of new petrol and diesel cars in the UK from 2030 and deeper changes in 2035 will drive major change in demand for refined products. Similar-scale changes would be created by the global marine fleet moving away from burning heavy fuel oils. Refineries will be looking to adapt to these market changes as the economy progresses towards net zero. This feasibility study has evaluated an approach that refineries might adopt for processing heavy fuel oil and other refinery products in the transition away from carbon towards hydrogen.

The proposed core technology comprises building blocks of established commercial equipment, configured in a unique manner designed to maximise the carbon captured - to over 98%, deliver CO_2 to a pipeline and storage quality, whilst simultaneously maximising the hydrogen yield. The project uses Stanlow and its residual streams as an exemplar, but the technology is flexible and can be adapted to any liquid hydrocarbon stream.

The study has established that there is, however, one aspect of the design which would benefit from further development for a net zero environment, as existing solutions would give rise to carbon emissions without additional post combustion capture. The process would be best deployed with a different route for the disposal of gasifier ash and soot from those currently utilised elsewhere in the world. A possible route has been identified which, although low risk, has yet to be demonstrated. Proposals to demonstrate this at sufficient scale to permit a full-size plant to be considered are developed as a Phase 2 project.

The project economics are dominated by investment cost and the feedstock which together make up 60-80% of the levelised cost of hydrogen. Analyst opinion has been used to inform the basis used for modelling, and two extreme scenarios for feedstock pricing have been selected. The first represents existing markets for residual products remaining strong, the second, reduced marine transport demand. There is recognition that there could be a case where the cost of carbon globally is such that these residuals become distressed, and fall to low or zero value.

In the current market environment, with the price of residual feedstocks supported by demand for marine fuel blend stock, the project is unlikely to be commercially attractive. The levelised cost of hydrogen at around £120/MWh is high compared to some other potential sources. In the second the levelised cost of hydrogen falls to under £70/MWh which is much more competitive with other hydrogen manufacturing options, which attract global interest. If the feedstock is genuinely distressed, then the cost falls even further.

Under the right economic conditions, there is a credible path for deployment, leveraging CO_2 and hydrogen infrastructure under development in industrial clusters such as HyNet. It provides a pathway for decarbonisation, underpinning economic resilience, safeguarding existing jobs and industry, whilst supporting energy security through a diversity of hydrogen supply. The Stanlow site is an ideal location for the first project, with significant rollout potential to refineries in the UK and around the world. The most significant risk to successful implementation of this project is the global market environment not evolving sufficiently to reduce demand for heavy fuel and other oil products.

2 Overview

2.1 Introduction

Refining of oils will remain an important, but declining piece of our energy mix, as the UK moves towards being a low carbon economy by 2050. Throughout this transition, there will be an ongoing requirement to meet demand for those refinery products with longer term decarbonisation pathways, such as jet fuel for aviation and petrochemical feedstocks. However, as low-carbon alternatives are deployed to replace today's technologies, such as petrol and diesel for cars, refineries will have a growing number of unavoidable "distressed" by-products, which, without alternative options, will be incinerated for energy or exported. This situation potentially offers a promising transitional opportunity to produce cost-competitive, low carbon hydrogen from these low value products – abating emissions and reinforcing the growing hydrogen economy.

A project partnership, led by Essar Oil (UK) Limited and supported by Progressive Energy Limited, has undertaken a feasibility study to decarbonise these low value, high carbon fossil fuel products through conversion to hydrogen via gasification with carbon capture. This study also considered the complex integration with the operating refinery and the flexibility required to decarbonise an ever-changing slate of feedstocks to respond to the country's reducing demand for fossil-derived product.

The feasibility study has engaged subject matter experts and technology licensors to explore various combinations of technologies and process configurations to establish the optimal process for Stanlow Refinery, to produce highly cost competitive export grade hydrogen. The study explored the feasibility for the technology as part of the Mersey corridor and wider North West region, including capturing substantially over 95% of CO_2 for permanent storage in Liverpool Bay utilising the proposed HyNet project disposal infrastructure.

Whilst Stanlow has been used as an exemplar, the solution proposed can be applied to any refinery in the UK and has considerable potential for other refineries abroad.

Phase 2 is proposed to demonstrate a potential solution to a technical issue that has been identified which could be seen as a limitation to the deployment of the plant design. To maximise the effectiveness of this solution, this proposed demonstration is supported by two stages of small-scale testing. The first is "bench-scale" at Aston University, followed by a larger demonstration at Cranfield. This will enable a design for an industrial scale to be developed through pre-FEED design stage. This demonstration work will set the basis for a future phase with the ultimate aim of constructing an industrial scale facility as a replicable model for other refineries nationwide.

2.2 Objectives

The objective of the project is to define a route that allows refineries to transition towards 'net zero', simultaneous with:

- Continuing to service existing petrochemical market pending substitution with sustainable alternatives at commercial scale
- Producing hydrogen at pipeline quality from un-utilised carboniferous feedstock
- Optimise the process to capture over 97% of any CO_2 produced within the process, and at pipeline/storage quality
- Optimising thermal efficiency by integration with the refinery where appropriate.

The study will also identify the financial circumstances which would make the necessary investment a commercially attractive proposition.

The project commenced with an examination of available technologies and identification of the best in terms of function, commercial availability at scale, and input material flexibility (given that this is likely to change significantly over time). Entrained flow gasification has been used in refineries since the 1980's to produce diverse chemicals, including ammonia, methanol, and oxo-chemicals from the high sulphur heavy oils and petroleum coke at the end of the refinery process, for which there is no, or a very limited market. It has also been used to supply hydrogen rich syngas to some refineries. Some 58 refineries worldwide have used gasifiers to dispose of unsalable end products, thus the core technology is proven: it is available from diverse licensors.

Downstream gas processing (particulate removal, shifting, acid gas removal) is also proven technology, albeit often in a different context: here it will be a matter of technology transfer.

However, none of the existing applications have been required simultaneously to:

- Account for and minimise all emissions of process CO_2
- Capture CO_2 and process it to a defined pipeline specification
- Export the hydrogen to a pipeline specification suitable for a public network

Building on the proven elements of this technology, an innovative solution has been proposed for the Stanlow refinery (acting as a model for other UK refineries) in which:

- The high purity hydrogen (meeting pipeline specification) is to be exported to form a low-carbon substitute natural gas fuel for industry and in homes (rather than consumed within the refinery), thus fitting into the hydrogen chain which will already be functioning in the area as a result of the HyNet project.
- Unreacted carbon from the feedstock is recycled within the process and removed as CO_2 in the CO_2 export stream, then sent to storage, making the plant almost zero-carbon emissions. This entailed optimising the design for carbon capture.
- The gasifier has been designed beneficially to utilise not just those materials for which there is limited market today, but to anticipate future distress products into the future, as existing carbon-intensive markets diminish towards net zero (and are replaced with hydrogen produced on the refinery)
- All of the captured CO_2 stream will be conditioned to a standard suitable for transport and storage

These objectives can be met with a new flows scheme using established process elements to ensure deliverability.

2.3 Process

The first steps in the study were to identify the preferred processes and licensors/vendors for major equipment items and to establish a Basis of Design. A 'high level' flows scheme was derived: essentially this is a sequence of chemical processing steps, coupled with a preliminary mass balance. A series of refinements were then introduced, starting with the gasifier (POX plant).

Having exchanged Confidentiality Agreements, aimed at protecting proprietary and commercially sensitive information, licensors/vendors were contacted, provided with the feedstock (Resid feed) composition and requested to model their equipment around the criteria listed in the Objectives (section 2.2). The output they provided was passed to the licensors/vendors of the shift, who were asked to do the same. This process was repeated until all of the major components had been covered.

The licensors/vendors also provided estimates for the CAPEX for their equipment (delivered, installed, commissioned) to class 5 level[1], which is appropriate for a project at this stage of development.

A full Heat and Mass Balance was produced, which also provided power demands for the electric motors for compressors and pumps. The detailed flow scheme and the results of the modelling are described in section 3.

2.4 Phase 2

It has been stated that the major process units are all proven technology. In considering how to minimise the carbon footprint, a second-order process was identified in which traditional methods of disposing of the gasifier soot was no longer appropriate. A novel method of addressing this was identified and is being proposed as a Phase 2 project, because until it has been demonstrated at reasonable scale, it cannot be considered as 'bankable'. This work is described in section 4.

2.5 Financial modelling

A financial model was also developed for this project using the CAPEX provided by the licensors/vendors, and the cost of hydrogen produced was analysed against a number of feedstock costs, determined by some possible future scenarios. This model and the conclusions are described in Section 6.

3 Modelling results and conclusions

3.1 Model Development

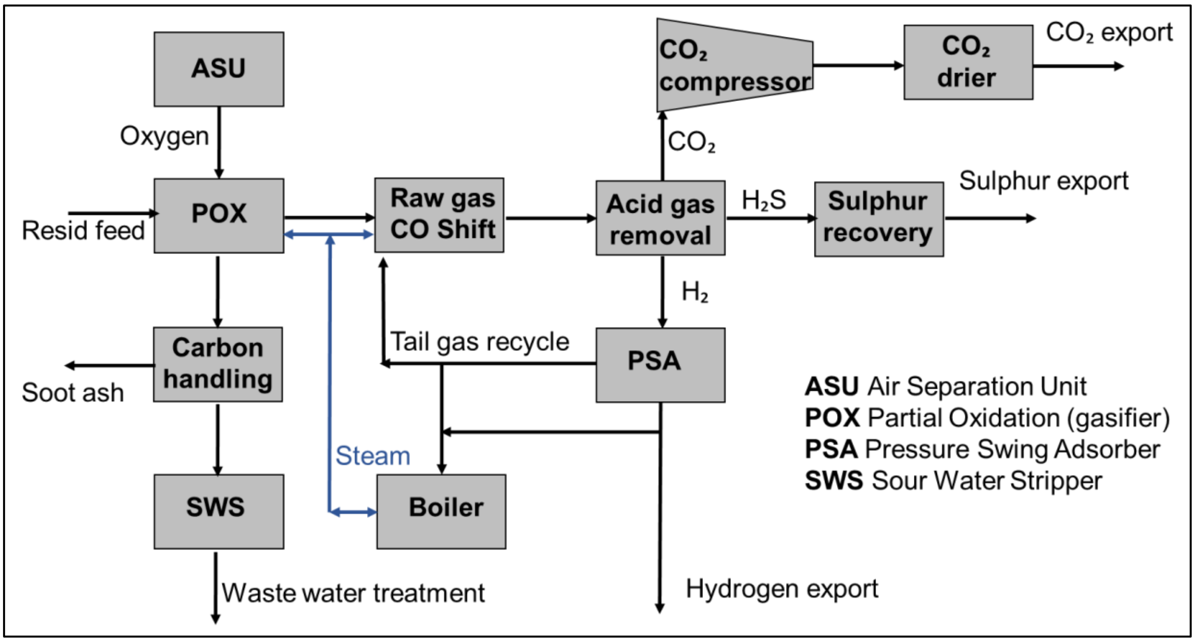
An initial model was made linking each of the individual process units in the overall plant, treating each as a black box using generic data. This was used to generate data to communicate to technology licensors enabling them to run their detailed models. In parallel with the licensors work a model of the plant, Progressive Energy's modelling group developed detailed models of the individual process units. These models were linked to portray the whole process plant and this complete model was then reviewed and adjusted in accordance with the licensor feedback to generate the final results.

3.2 Model Results

The block flow diagram of the plant as modelled is shown in Figure 3-1. The model was used to develop a heat and mass balance over the plant. It was also used to generate utility requirements, which included estimates for the air separation unit.

Figure 3-1: Developed flowscheme

[1] AACE International Recommended Practice No. 18R-97 "Cost estimate classification system – as applied in Engineering, Procurement and Construction for the Process Industries. TCM Framework: 7.3 – Cost Estimating and Budgeting



3.2.1 Process streams

The main feed and product streams are shown in Table 3 1 and Table 3 2.

The gasifier produces 1 tonne/hour of Soot ash containing ash and carbon, the disposal of which is the subject of the Phase 2 proposal.

The plant actually produces 167,248 Nm³/h pure hydrogen (1502), but 16,221 Nm³/h is used internally as fuel for the boiler leaving 151,027 Nm³/h as export product (1505).

3.2.2 Utilities

The overall electrical requirement is 65 MW, including 33 MW for oxygen production and 21 MW for CO_2 compression. Some 14 MW is produced internally from medium and low-pressure steam, leaving a net consumption of 51MW.

Table 3-1: Liquid and solid streams

Stream		Gasifier feed		Sulphur	
Stream no.		1101		1605	
Phase		Liquid		Liquid	
Component		**kg/h**	**wt%**	**kg/h**	**wt%**
	Carbon	56095	89.8		
	Hydrogen	5490	8.8		
	Sulphur	682	1.1	682	100
	Nitrogen	195	0.3		
	Oxygen	0	0		
	Ash	38	0.1		
	Water	0	0		
Total mass flow (kg/h)		62500		682	100
Pressure	barg	5		6	
Temperature	ºC	60		135	
LHV	MJ/kg	39.68			
LHV	MWth	688.96			

3.2.3 Effluents

Continuous effluent streams from the plant are:

- Soot ash (filter cake), treatment of which is the subject of the Phase 2 investigation (see section 4).
- Approximately 50 m³/h waste water pre-treated to a quality suitable for final treatment in a typical refinery waste water treatment plant. Investigation whether capacity exists in the existing facility or new capacity must be built would be the subject of a site-specific value engineering exercise.

Table 3-2: Gaseous streams

Stream		Pure hydrogen		Hydrogen export		CO_2 export		Flue gas	
Stream no.		1502		1505		2082		1803	
Phase		Vapour		Vapour		Vapour		Vapour	
Component		kmol/h	mol%	kmol/h	mol%	kmol/h	mol %	kmol/ h	mol%
	CO_2	0	0	0	0	0	0	57.14	1.6
	CO	0	0	0	0	0	95.6	0	0
	H_2	7462	100	6738	100	23.5	0.49	0	0
	CH_4	0	0	0	0	2.12	0.04	0	0
	N_2	0	0	0	0	184.5	3.84	2238	65.4
	Ar	0	0	0	0	1.05	0.02	44.2	1.24
	H_2S	0	0	0	0	0	0	0	0
	COS	0	0	0	0	0	0	0	0
	SO_2	0	0	0	0	0	0	0	0
	NH_3	0	0	0	0	0	0	0	0
	HCN	0	0	0	0	0	0	0	0
	O_2	0	0	0	0	0	0	57.23	1.6
	H_2O	0	0	0	0	0	0	1076	30.1
Molar flow	kmol/h	7462		6738		4809		3573	
Mass flow	te/h	150.4		13584		207.6		91	
Pressure	barg	49.00		49.00		39.00		1.00	
Temperature	ºC	30		30		44		90	
Vol. Flow	kNm^3/h	167.2		151		108		80,1	
Molar Mass	kg/kmol	2.02		2.02		43.17		25.47	
LHV	MJ/kg	241.8		241.8		1.66		0	
LHV	MWth	501		453		2		0	
Density	kg/m^3	3.92		3.92		63.86		0.84	

4 Description of the demonstration project

4.1 Introduction

The gasification plant (POX in Figure 3-1) rejects the ash from within the Resid feed (mainly inorganic silicates and oxides with metals such as vanadium, nickel and iron) as Soot ash, together with a small amount of unreacted carbon. The traditional combustion disposal mechanisms for gasifier soot residues are incompatible with a “net zero” future and landfill is not an option for the raw soot material in the UK. The presence of Vanadium in the Soot ash presents additional problems for combustion options.

At project inception it was realised that it would be necessary to provide an alternative solution whereby the unreacted carbon is recycled within the process or removed (as CO_2) and exported to storage. Existing options, those used at refineries on mainland Europe and in USA, were re-examined and found to be inappropriate for a 'net zero' future, thus an innovative solution is required.

There may well be commercial solutions to this problem for specific projects, such as combustion as part of a facility fitted with post combustion CO_2 capture, providing it can accommodate the residual elements and can be accommodated from a regulatory perspective. However, it was considered important to develop a net zero compatible solution within the fence-line, which addressed the carbon emissions.

Possible alternative methods were been considered, and gasification identified as being most appropriate. However, this is untried on this specific feedstock material.

Finding a solution to this that is consistent with 'net zero', thus enabling the hydrogen economy, is a key component in the whole system. The intention is to demonstrate a solution to two problems associated with combustion, the traditional method of disposing of Soot ash from oil gasifiers. These two problems are:

- Combustion of the carbon content produced CO_2: releasing this into the atmosphere is inconsistent with "net zero"
- Combustion oxidises the vanadium in the ash to V_2O_5 (vanadium pentoxide), which has a high melting point (700ºC). The V_2O_5 plates out on cooler surfaces (like boiler tubes) and is difficult to remove.

The proposed gasification solution addresses these as follows:

- Most of the carbon is only partially oxidised to CO, which can be utilised beneficially in the shift to release more hydrogen for sale: the carbon that becomes CO_2 can be captured in the Rectisol plant and exported.
- The vanadium is partially oxidised to V_2O_3, which has a melting point of about 1900ºC, so will remain in the ash. The potential exists to process the vanadium out of this (selling at around $30/kg).
- Some low-grade heat (e.g., for feedwater pre-heating) may be added into the main gasification plant or elsewhere on the refinery
- Eradicating an entire waste stream, bringing the whole plant closer to the "zero waste" criterion.

The objective of the demonstration is therefore to provide sufficient confidence to permit scale-up to an industrial-sized plant. Developing technology options is correctly perceived as having a high degree of risk. This has led to a proposed two-stage approach to Phase 2. The first stage comprises a series of bench-sized experiments from which critical parameters can be derived. Having gained a more detailed understanding of what would be required, the second stage is a demonstration at a size which would be of sufficient size to permit scale-up to a full-sized plant.

The first stage would utilise a small (1kg/hour) atmospheric pressure fluidised bed gasifier at Aston University, which can be modified to make it suitable for a series of tests. A number of modifications would be necessary including converting it from air- to oxygen-blown, and identifying the best method of feeding the Soot ash into the bed. Aston University will derive key parameters to assist in the design of the second stage, such as the optimum fluidising velocity to maintain bed fluidity and the oxygen flow to achieve maximum carbon burn-out. A report on the first stage demonstration will be prepared and published.

Having mapped the key parameters, Aston will pass the results to Cranfield University, building on the collaboration agreement that already exists between the two. Their somewhat larger gasifier will also need some modification to make it suitable for the proposed demonstration: this work will build upon the smaller-scale work at Aston.

This larger demonstration will be used to analyse the syngas composition and provide samples of V_2O_3-rich ash for examination and possible use by the Metals Extraction Industry. Cranfield have some novel technologies that could be applied to do this. Whilst the focus will be on vanadium, other metals present can be reported for their leachability and recovery potential.

Again, a report will be prepared and published on the second stage demonstration.

4.2 Process development

The intention of this Phase 2 project is to demonstrate those parts of the process described under Phase 1 that are new solutions to enable the supply of hydrogen from a reconfigured refinery to become cost-effective with a view to achieving the 'net zero' ambition.

To support a deliverable project, the experimental work developed in Stages 1 and 2 will be developed into an engineered flowscheme for the soot conversation process island. This will include development of a cost estimate for this part of the plant, which will also be used to refresh the overall financial assessment.

4.3 Counterfactual consideration

So that the gasification option can be weighed against an alternative, a counterfactual disposal mechanism will be considered. This would be co-combustion in a cement works to which CO_2 capture and storage has been retro-fitted (e.g., the Hanson Cement plant at Padeswood). Issues requiring attention include the possible effect of the metals within the Soot ash on the plant and product, metal oxide emissions to atmosphere and their dispersion characteristics, and the impact on the environmental consents under which the plant currently operates.

The counterfactual of disposal as a Hazardous Waste into landfill may also be considered, but this is not a sustainable route, and offers no benefit to any associated process (such as energy recovery from the carbon content or potential to sell the vanadium).

5 Development Plan

5.1 Demonstration phase

Cost estimates have been provided by the two universities involved with the Phase 2 work described in section 4): these are expected to be refined once agreement in principle has been given to the work. The overall Phase 2 programme includes input from Essar Oil ((UK), Progressive Energy and their subcontractors. Each of the two Universities, Aston and Cranfield have agreed to a programme and a plan of work which is expected to be completed within 24 months. The total expected cost is £1,616,647.

5.2 FEED for first project

On the basis that the demonstration project underpins a viable Soot ash disposal route (or that an alternative method to manage the ash that meets regulatory requirements, and does not adversely affect other parts of the process) the next stage would be to undertake Front End Engineering Design (FEED) for the resid gasification project. FEED for a plant of this scale would be expected to cost around £20Million. To undertake this, investors would need to be confident in the market for the hydrogen, the ability to access CO_2 transport and storage, and in the short-term/medium-term, the prospect of a support regime that would bridge the costs of production relative to the market value of the product.

It is not inconceivable that such a FEED could be undertaken in 2-3 years depending on the market development, potentially in 2025. A FEED programme would be expected to take a minimum of 12 months, and typically requiring around 18 months before being ready for a Financial Investment Decision (FID).

5.3 Execution and Operation of first project

Execution can only commence once an FID has been taken by the investors in the project. In the short term this is likely to depend on the policy regime under development by HM Government to support production of low carbon hydrogen[2]. This should be fully functioning to enable an investment decision following FEED, on a 2026-2027 timeline. It is likely that there will be some form of auction process in place, so the exact timing will depend on auction rounds. The HyNet CO_2 transmission and storage infrastructure with a capacity of up to 10 mtpa will already be operating by this time.

Based on the financial assessment, it would be expected that the project would require approximately £753m of investment, which, with project finance would require around £200m of equity. Construction for a project such as this is likely to be between 40-48 months, and so, on this basis, such a project would be operational at or by the end of this decade.

Operations would 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. This type of plant would have 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 provides a satisfactory return with an acceptable cost of low carbon hydrogen. Currently the low carbon support regime is expected to be 15 years.

5.4 Roll out of multiple projects

It would be expected that once the first project has entered FEED, it would be possible for further projects to start the development cycle. In the UK this would depend on the status of the CO_2 transport and storage infrastructure at the different refinery locations. On this time frame, it would be expected that all six would be making good progress towards either direct pipeline connection to storage (Stanlow, Humber, Lindsey) or the opportunity to establish a CO_2 shipping terminal for connection (Fawley, Pembroke, Grangemouth).

Therefore, there is the potential over the period 2025-2035 up to 6 UK projects could go through the process of FEED, construction and get into operation. This would represent an investment of around £5Billion.

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[2] https://www.gov.uk/government/publications/hydrogen-investor-roadmap-leading-the-way-to-net-zero

There is the prospect for wider roll out internationally at a scale of potentially 10 times this capacity. Given the UK's leading position on CCS, these would be expected to take place during the 2030's and 2040's, although some jurisdictions may deliver sooner.

6 Benefits and Barriers

This solution offers a number of significant benefits, primarily in transitioning essential refinery activities to reduce carbon emissions and underpin the low carbon market. These were assessed, grounded in an assessment of the levelised cost of production under a number of scenarios.

6.1 Capital cost estimation for a single plant

The Class 5 capital cost estimate for this project is £753m. As is normal for Class 5 estimates, this has been based on known costs and estimates from previously executed similar projects. These costs are adjusted to reflect different capacities of the different projects using industry recognised capacity correction factors. The costs have also been brought up to date to 2022 using published indices used for this purpose. Various process technology licensors have also been involved in providing high level proposals for their technologies. Some of these proposals have included budget cost information. This information has also been used to aid development of the estimate. The licensor information is also Class 5 based on their knowledge of previous projects incorporating their technologies.

The estimate is based on installation at a site such as Stanlow with appropriate allowances for utilities provision, Engineering, Procurement and Construction (EPC) services and owners' costs.

No forward escalation has been added to the capital cost estimate although it should be noted that cost escalation for projects in recent years has been very high (>10% per year).

6.2 Operational cost estimation

For projects at this level of definition, operating costs are normally estimated using a fixed typical percentage of capex, usually between 2% and 4%. Using the experience of the project team on previous projects, 3% of capital cost is deemed to be an appropriate representative level for operating cost. This cost does not include power or oxygen import costs which are handled separately.

Fuel is from both processes reject gas stream and parasitic use of the produced hydrogen and this is reflected in the overall heat and material balance used for the modelling.

From the experience of the project team, a cost of £20/Te has been assumed for transportation and storage of CO_2.

6.3 Feedstock and energy price assumptions

The forward price structure for the feed material is likely to evolve as the global trajectory in decarbonisation changes. The approach taken, uses two extreme scenarios, allows ongoing assessment of where this project sits in comparison to other potential sources of hydrogen such as blue hydrogen from natural gas or green hydrogen as that evolution occurs.

The first scenario represents the situation in which crude oil will remain strong, similar to 2022 markets and fuel oil will remain at a similar discount with potential for a small drop off at the end of the period. This scenario can be described as 'Low Global Decarbonisation'. In this scenario, demand within the marine sector for fuel oil remains strong and the crude price is supported by maintained demand for fossil fuels. This represents the 'most likely' scenario predicted by market analysts consulted for this project. It is certainly possible however that decarbonisation will progress faster, especially in the marine sector.

In this second 'High Global Decarbonisation' scenario, the price of fuel oil becomes detached from crude as the only potential destination remaining for it is in power generation. Crude Oil price will also fall significantly as global demand for refined products falls. The price of feedstock for this project then becomes linked to more closely linked coal on an energy basis. In this scenario, however coal is discounted more significantly than today relative to natural gas due to carbon offsetting. Coal price, and therefore refinery residual price, is equivalent to natural gas but offset by the cost to emit the carbon present in the feedstock.

6.4 Financial Modelling

The cost assumptions used for the financial modelling are summarised in Table 6-1.

Table 6-1: Cost Assumptions used for financial modelling

Commodity	Value	Unit
Electricity	55	MWh
Natural gas	25	MWh
Capture and storage of CO_2	20	tonne
OPEX	3	% of CAPEX
Feed material: Low decarbonisation scenario	57.2	£/MWh
Feed material: High decarbonisation scenario	14.3	£/MWh

Economic modelling of the refinery residual gasification process is intended to provide a levelised cost of hydrogen production that can then be compared against other production technologies. The model uses the standard approach adopted by BEIS for determining the levelised cost of hydrogen.

To capture the various sensitivities considered, the model is designed to provide a graphical output, showing levelized cost of hydrogen production relative to feedstock value scenarios and carbon cost. This can then be compared against the perceived value of hydrogen, taken as natural gas plus the value of avoided carbon. Results are shown in Figures 6-1 to6-4

A comparison of the first two cases (Figure 6-1 and Figure 6-2) shows, unsurprisingly, that in Case 1 – the cost of feedstock dominates the levelised cost of hydrogen. In Case 2, with significantly lower feedstock cost, the investment cost is a more significant factor.

Figure 6-1: Case 1, Low Global Decarbonisation – P50 Capex. Levelised cost of hydrogen £119/MWh

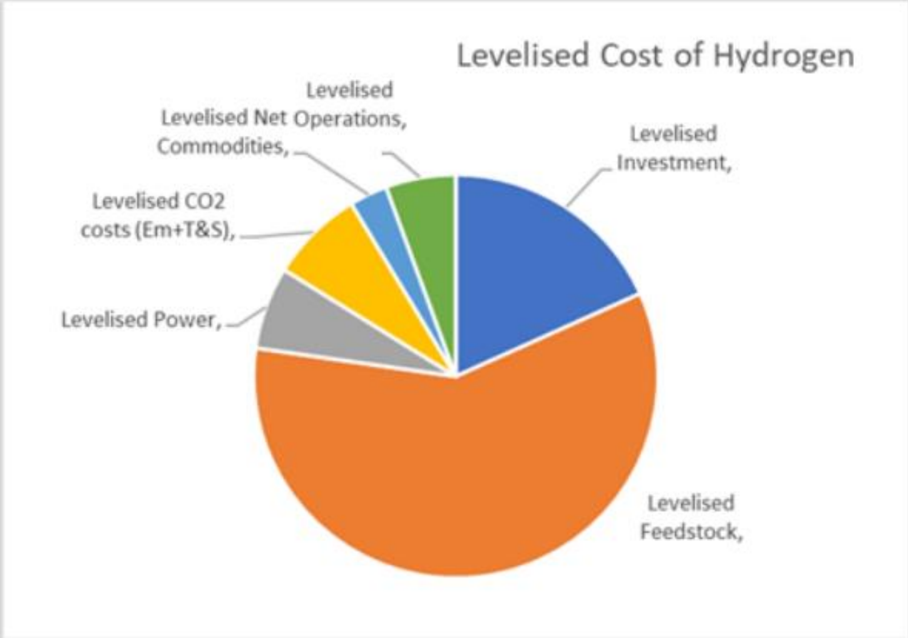
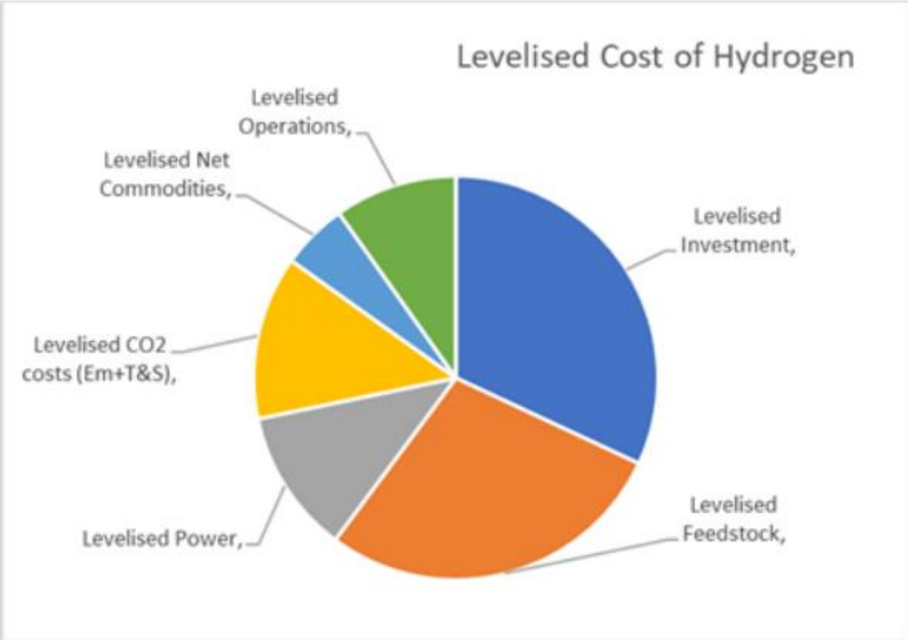


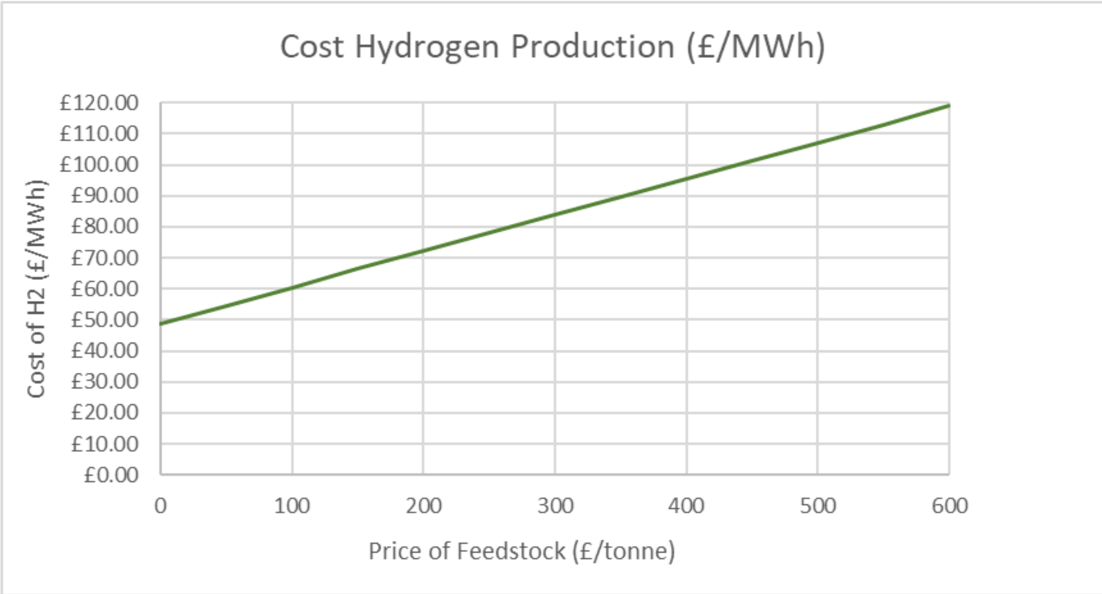
Figure 6-2: Case 2, High Global Decarbonisation – P50 Capex. Levelised cost of hydrogen - £68/MWh



Initial assessments suggest that any case in the Low Global Decarbonisation will not have a competitive levelised Cost of Hydrogen so no further sensitivities have been run in that scenario. Some sensitivities are run on the High Global Decarbonisation Case 2. Cases 3 and 4 are based on Case 2 and consider the effect of P90 Capex (P50+50%) and P10 Capex (P50-30%), giving levelised costs of £81/MWh and £60/MWh respectively.

The chart shown as Figure 6-3 shows the relative effect of feedstock price on the levelised cost of hydrogen from zero to £600/Te (£57/MWh). This shows that in the case where the feedstock is genuinely distressed and zero cost, then the cost of hydrogen production falls to £50/MWh

Figure 6-3: Effect of feedstock price on levelised cost of hydrogen



6.5 UK Energy Security and Diversity of Supply

There is also an energy security issue to be considered. As mentioned previously, currently all the residue streams from UK refineries of a type suitable for this project are either exported or used to bunker international shipping in the UK. Utilising this feedstock for CCS-enabled hydrogen production within the UK keeps the energy for consumption within the UK and adds to UK energy security, as it is largely independent of natural gas. It also adds an alternative source of energy supply.

The residual feedstock required for this project is traded globally and therefore the project is not reliant on the maintenance of current UK refining operations.

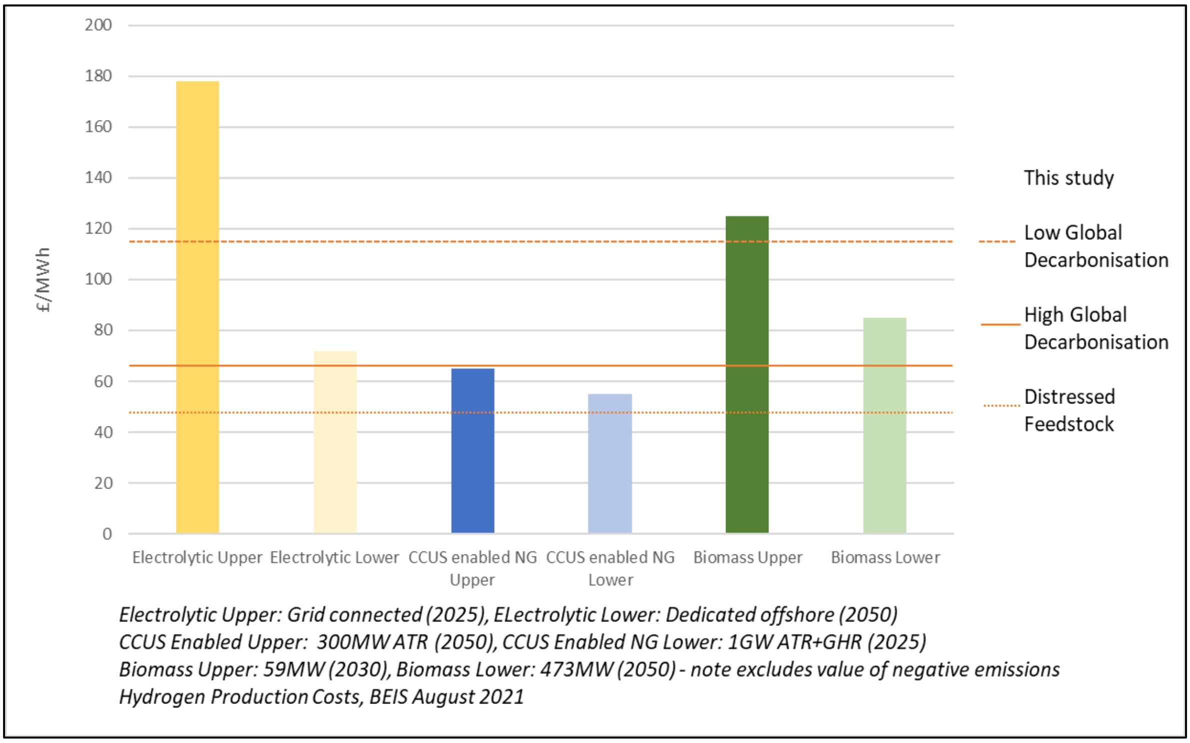
6.6 Comparison with alternative means of Hydrogen Production

Hydrogen can be manufactured by a variety of production methods, including from natural gas with CCUS, electrolytic production from low carbon electricity and from biomass. The costs of were assessed and reported by BEIS in supporting documentation to the Hydrogen Strategy[3]. The underlying energy assumptions were not dissimilar from those used in this work, and so provide a helpful comparison of cost. These are shown in Figure 6-4.

Figure 6-4 shows that there are a number of scenarios where this route of production is highly competitive with alternatives. These are all however in the 'High Global Decarbonisation' scenario for feedstock pricing. This scenario is not representative of current market conditions.

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

Figure 6-4: Comparison of the cost of hydrogen production



6.7 Hydrogen Purity

The plant design is based on the emerging hydrogen standard underpinning BEIS 100% work[4], and the developing industrial clusters. This equates to a hydrogen purity in excess of 98%.

6.8 Greenhouse gases mitigated

As described in Section 2.2, the objective is to demonstrate a CO_2 capture rate of >97%. Thus, for a typical plant of the size assessed here, this equates to 1.6mtpa captured, which would otherwise have been emitted to the atmosphere.

6.9 Low carbon hydrogen standard (LCHS)

This technology converts fossil products that are an inevitable part of the refining process. By capturing the CO_2, more than 97% of the carbon dioxide that would otherwise have been emitted is being stored.

6.10 Cost Escalation

The investment cost for the first project has been calculated at £753 million +50%/-30%. No escalation has been applied to this. The current geopolitical situation driven mainly by Covid-19 and the Russian invasion of Ukraine, has caused significant disruption to global supply chains, resulting in high inflation. The US publication ‘Chemical Engineering’ publishes a monthly set of plant cost indices (CEPCI). These are used by engineering professionals in the chemical process industries to compare and update real and estimated costs of investments in process projects such as gasification. Between April 2019 and April 2022, the CEPCI indices increased on average by around 35%. This means that installed cost of a project such as this is 35% more expensive in 2022 than it would have been in

[4] Hy4Heat (WP2) – Hydrogen Purity Standards, as referenced by IGEM

2019. The trajectory of these indices going forward is, of course, uncertain, but this does represent a significant cost risk to progression of projects of this type.

6.11 Other risks

Other risks are included in section 8, which describes the route to market. Aside from Feedstock risk, which is addressed above, the principal risk is that the necessary commercial drivers will not materialise as a result of a slow global change towards decarbonisation, and therefore support would be required if the UK Government wants to achieve ‘net zero’.

To make the project economically attractive for investment, the Low Carbon Hydrogen Business model would need to encompass this production route. The framework would need to reflect the true costs and benefits of this route for hydrogen production.

7 Rollout Potential

Once commercialised at one location such as the Stanlow refinery, the main considerations regarding rollout potential would be related to the suitability of the proposed locations and of the owner operator.

7.1 Availability of feedstock

Development of this project has been based on processing of feedstock from the existing Stanlow refinery. There is a logistical, and therefore a cost, advantage associated with processing feedstock produced on site, however this is not essential. The feedstock proposed from Stanlow (Heavy Cycle Oil and Slurry) are both residual products produced from the refining operation. The exact nature and quantities of these residual streams produced by refineries depends on the configuration of the individual refineries. The Stanlow refinery, for example, is configured with a Residue Fluidised Catalytic Cracker (RFCC). This means that all of the straight run (non-cracked) residue from crude oil distillation is fed to the RFCC and the resultant residual products from the refinery are all cracked and the total residue yield lower than the typical UK refinery configuration. 'These streams are either burned onsite to meet refinery energy needs or exported from the UK as either finished LSFO/HSFO or blending components for the same.

The global trading of these products means that it would be feasible to import appropriate feedstocks instead of or in addition to on-site produced feed. This will depend on availability of existing marine infrastructure for the importing which all refineries are likely to have. Importing would also facilitate development of a larger project not simply based on availability of feedstock from an existing site such as this one. Considering previously implemented residue gasification projects, it would be easy to envisage a plant five times the size of the one described here, if it could be fed by imported feedstock.

These considerations do not preclude rollout of this technology at non-refinery sites but it does make it potentially less commercially attractive.

7.2 Suitability of Site

Any implementation of the technology would represent a major industrial development. As such from a planning and permitting viewpoint, implementation on a site already permitted to undertake similar activities would be expected to require significantly fewer hurdles to be overcome.

Due to the processes employed and the associated inventories of Hazardous substances, the project would be classified as ‘Upper Tier’ under the Control of Major Accident Hazards

Regulations 2015 (COMAH) meaning it receives the highest regulation from the UK Safety regulator, the Health and Safety Executive (HSE). Implementation would be significantly easier at an establishment already operating as an upper tier COMAH establishment. Refineries are not the only upper tier establishments. Steelworks, oil terminals, gas plants, chemical manufacturing sites and many others also fit into this category. It would be a significant consideration in identifying suitable locations for rollout.

Given its associated emissions and inventories, a new plant would also require regulation and permitting by the Environment Agency under the Industrial Emissions Directive (IED). Although an EU directive, the UK government implemented legislation in the withdrawal act 2018 to ensure the directive was still applied in UK law. A new plant would be significantly easier to permit as a variation on a site already regulated under IED. Existing plants will tend to have already permitted discharges to air and water and the infrastructure for treating water.

7.3 Existing operations

The project has already considered integration and optimisation of the new development with the existing refinery infrastructure at Stanlow (see Figure 7-1). Generic optimisation opportunities with other refineries have also been identified.

Figure 7-1: Essar Oil (UK) Stanlow refinery

A process plant such as the gasifier and associated facilities, operated under the UK regulatory environment, requires a highly trained workforce to operate and maintain. These highly skilled workforces, along with the capability to train them already exist at the six UK refineries and albeit to a less applicable extent, at other UK industrial process sites. With the eventual degradation in demand for products from the remaining UK refineries and competition from more efficient refineries in the middle east, this will ultimately lead to partial or complete shutdown of some of the UK's refining capacity. An investment in a project such as this would allow redeployment of at least a part of those existing workforces in its development and ongoing operation.

7.4 Proximity to hydrogen distribution infrastructure

For the development to be commercially feasible, it would need to be in reasonably close proximity to a large demand for hydrogen. This could be one of the currently developing hydrogen clusters, potentially one or more local large industrial heat users or even a steel works evolving away from traditional blast furnace operation.

If hydrogen is to be injected into the natural gas national grid in any quantity, then proximity to an existing large gas feed-in point would suffice.

7.5 Connectivity to CO_2 storage infrastructure

A similar restriction applies to the accessibility to CO_2 transportation and storage capability. Again, proximity to one of the UK industrial clusters would provide this.

7.6 Out-turn Potential

All of the UK refineries, having their own marine terminals, could potentially be suitable locations for rollout of the technology using the criteria described. This would mostly depend on the last two factors (sections 7.4 and 7.5), proximity to a suitable market for hydrogen and access to CO_2 storage infrastructure. There is theoretical potential for gasification capacity to be built well in excess of the current production of suitable residue products from these UK refineries.

Assuming each site were to build a facility of the scale of the Stanlow project envisaged here, this equates to an installed capacity of around 3GW, providing a base load hydrogen production of around 25TWh. Together these projects would need to store around 10 million tonnes CO_2 per annum.

As described earlier however, there is potential for much larger installations, possibly in the order of 5 times the capacity of the currently-conceived Stanlow project. Installing this capacity at each of the UK refinery sites would demand a significant proportion of European residue production. This factor probably presents the limitation on rollout potential. The cause of the significant drop in Fuel Oil price which potentially makes this project economic also effects a reduction in total refining capacity, reducing the availability of feedstock. The same applies for potential to global roll out.

Although this project has considered just residue products as feedstock, gasification as a technology is applicable to a wide range of feedstocks including all hydrocarbons. As decarbonisation progresses and refining capacity reduces, crude price is likely to level out around a cost of production for the marginal barrel produced. This may also mean that crude rather than residue may become an economic feedstock for gasification.

7.7 Plant Delivery

The project can be delivered with a conventional EPC contractor model, using well proven contractual structures, delivered in a high skills region and supply chain assessed for delivery capacity.

7.8 Financing

The technology has been deliberately selected to use existing commercially developed process elements to form the novel flow scheme. This substantially reduces deployment risks. Based on a commercial FEED the project team is confident that a financeable project can be developed.

Financing will be dependent on a bankable support regime, which is being developed and will be in place in time for a financial investment decision on this project.

8 Route to market

The Route to Market requires three key elements: access to hydrogen off-takers, access to CO_2 infrastructure, and delivery of initial and follow-on projects. This assessment uses HyNet and a project at Stanlow as an exemplar or initial context for delivery, as a platform for the wider roll out discussed in Section 7.

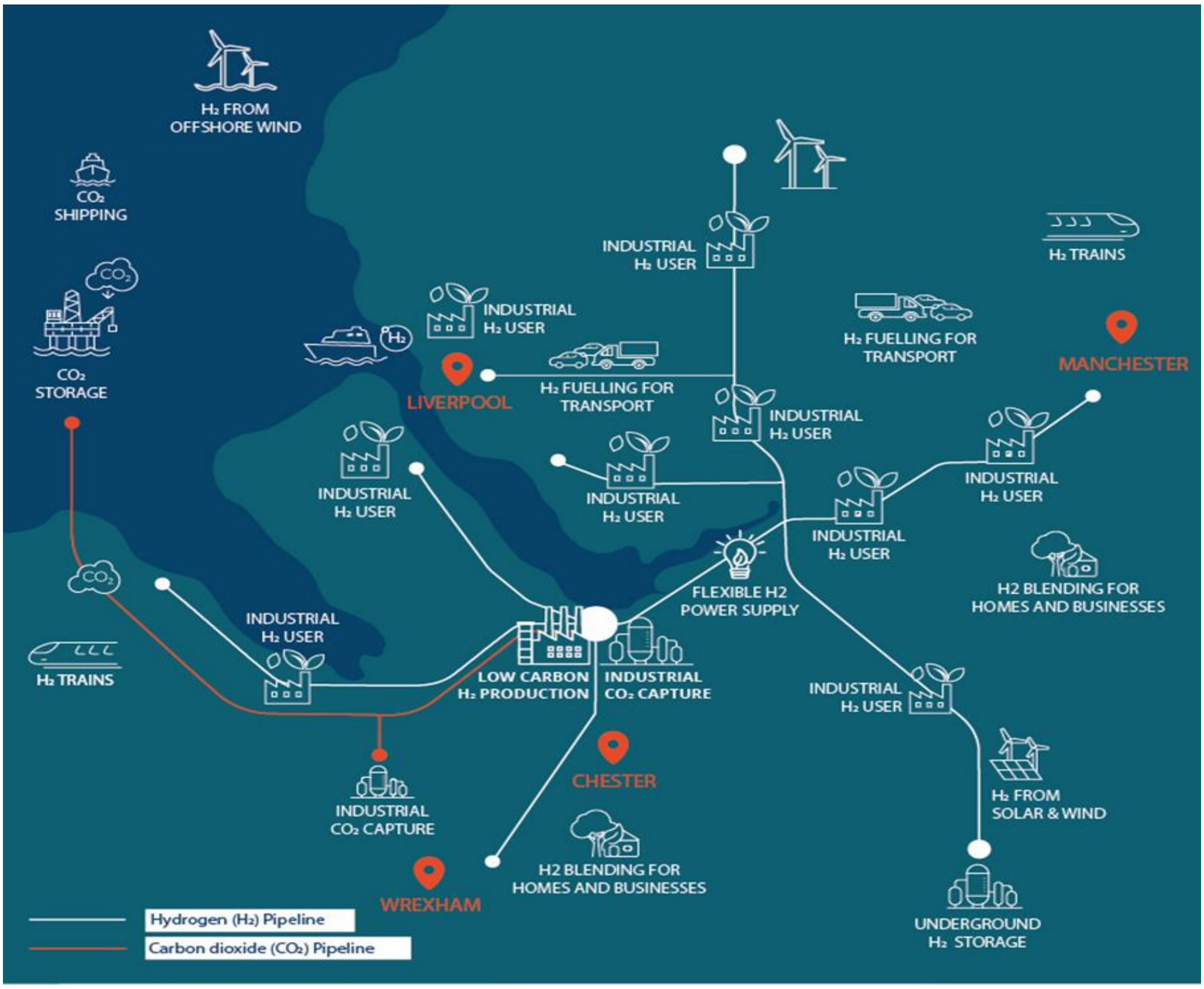
8.1 Hydrogen route to market

HyNet North West is made up of a series of 'links' in a chain of hydrogen production, hydrogen pipelines, hydrogen storage, CO_2 capture, CO_2 pipelines and CO_2 storage. It offers significant growth prospects for people and businesses in a range of sectors and would establish the region as a world leader in energy innovation.

A hydrogen-fuelled local economy will support ongoing growth for the region, while protecting and creating high-skilled career opportunities. HyNet North West will help maintain existing jobs and create a further 6,000 permanent jobs in the region, and many more during construction and across the wider UK. By kick-starting the hydrogen economy, HyNet will help support up to 75,000 jobs across the country by 2035.

Vertex Hydrogen is planning to build initially 1GW of low carbon hydrogen production capacity comprising two lines; 350MWth and a second at double the capacity. Both of these have successfully pass into the next phase of the Cluster sequencing process as of 12th August 2022[5] The hydrogen produced will be transported by pipeline and provided for industrial, transport, home and business use, as shown in Figure 8-1.

Figure 8-1 HyNet North West Infrastructure



[5] https://www.gov.uk/government/publications/cluster-sequencing-phase-2-eligible-projects-power-ccus-hydrogen-and-icc/cluster-sequencing-phase-2-shortlisted-projects-power-ccus-hydrogen-and-icc-august-2022

To meet this demand, even without grid conversion to hydrogen it is expected that over 30TWh of low carbon hydrogen will be required by 2030, equating to nearly 4GW of baseload production.

8.2 CO_2 transport and storage

CO_2 removal is through the low cost, low risk HyNet CO_2 infrastructure with transportation and storage capacity of up to 10MtCO_2/year, which is planned to have initial capacity on-stream as early as 2025. The HyNet infrastructure has a node point and AGI at Stanlow, which would make access to CO_2 export infrastructure easier. This transportation and storage system has a CO_2 purity specification to which this project has been designed.

8.3 Technology delivery

This is the subject of this feasibility report. The technology selected consists of various technology building blocks, each of which has been demonstrated at scale in commercial operation, but not in the configuration proposed, because, to meet the demands of 'net zero', it needs to be driven by maximising both hydrogen production and carbon capture rate, delivering the CO_2 to defined pipeline quality standards.

There is one technical element requiring further research, processing of the Soot ash produced from filtration of the coke slurry emanating from the gasification process. The existing routes for processing of this stream from gasifiers are likely to be closed off in future so a new solution will need to be developed. This solution is the focus of the Phase 2 plan for this project, described in section 4.

8.4 First Project Execution

8.4.1 Path to implementation

The next step would be to complete the Phase 2 work to bring the whole scope to a TRL ready for implementation. Once the commercial environment and price of available feedstock is sufficiently supportive to make the project commercially attractive a full Front End Engineering Design would be commissioned. The output of this would be sufficient to prepare a bankable report for financing the project.

8.4.2 Owner operator

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 developing the refining sector, whilst reducing the carbon intensity of existing operations. Progressive Energy has been undertaking project development of CCUS and low carbon hydrogen-based solutions since 1998. Together they have formed Vertex Hydrogen Ltd. to deliver low carbon hydrogen production projects on the site.

Essar, the owners and operators of the refinery, have already demonstrated a clear commitment towards embracing the requirements of 'net zero', by hosting the Vertex Hydrogen, project by initiating a low carbon CHP scheme to replace the oil-fired boilers, by planning to replace many of their fired heaters with low carbon alternatives and by commencing work to extract the CO_2 post-combustion from the CO boiler associated with their Fluidised Catalytic Cracking unit. Essar, as an experienced operator of similar large scale industrial processes would operate and maintain the new plant through augmentation of its existing organisation at Stanlow. A dedicated organisation would be populated by Essar to manage the execution of the project through to handover and operation.

8.5 EPC capability

Engineering Procurement and Construction companies are available worldwide with the capability to execute this project. Many of these are at least partly based in the UK. UK offices in general no longer carry the capacity to conduct detailed engineering work: this tends to be executed in offshore locations either offices of the same company or through partnership arrangements with other companies.

The availability and cost of these EPC services depends on global demand and therefore the number of large projects being built and operated globally. An important consideration is that the feedstock pricing environment which would make this project attractive would be as a result as a significant shift in the global energy supply position. This shift may itself be associated with major infrastructure project investment and therefore a high demand for EPC services.

8.6 Supply chain

There are two parts to the consideration for the supply chain and potential support for potential job creation and retention and economic growth. Project execution over a relatively short period would invest the capital cost (estimated at £753m). This would be followed by ongoing operations expenditure in the order of £25m/year.

Most major projects of this type executed in higher cost zones such as the USA or Western Europe would source much of the supply from lower cost areas such as India, China or South East Asia. This includes detailed engineering and procurement activities and supply of equipment and manufactured materials. To an extent it also includes construction. Rather than to ‘stick build’ in field locations in higher cost areas, the modern approach is to construct modules in lower cost locations and then install and connect these modules at the project location. This is a ‘modular construction’ approach.

It would be possible to source at least part of the required services, materials and equipment in the UK. Capability constraints and competition from other large projects would need to be considered as would the higher cost of such an approach which may affect the commercial attractiveness of the project.

In the pricing environment which would support investment in a project such as this, it is likely that at least some of the refining operation at the Stanlow site would change or fall away as low carbon markets develop. This project would be an ideal opportunity to redeploy the highly skilled workforce engaged in operating and maintaining those existing refining operations to project execution and ongoing operation and maintenance of the new plant.

9 Dissemination

This is an important topic to address, not only because it explores the question of the future of the UK oil refining industry, but importantly it offers a long-term transition from carbon to hydrogen and the move to ‘net zero’. It also contributes towards energy security in a world where established systems have come under considerable pressure.

Providing a future for the UK refining industry is important to the country’s economy: the oil and gas sector is directly responsible for nearly 40,000 jobs. It is estimated that in 2020 a total of almost 120,000 jobs were supported directly or indirectly by the UK upstream oil and gas industry with a further 60,000 jobs supported in the wider economy[6].

It is therefore essential that this work communicated effectively.

It needs to be appreciated that organisations who hold conferences, seminars, webinars and suchlike, plan the events months, if not years in advance. Therefore, opportunities to disseminate this work, for instance with a Professional institution or a Trade Body, need to be taken as they arrive.

Already some initial statements have been made concerning the intentions of the work in progress on this project. Without exception there is a general recognition of the need to reconfigure refineries to accommodate the energy transition away from carbon and towards hydrogen, yet continue to service those markets for which oil-based alternatives have yet to materialise (or materialise to an extent that means that the oil-based products can be replaced). The only concern would appear to be that nobody else has picked up on the topic, and so industry continues along a "business as usual" path. If anything, younger adults appear to be more aware of the situation than older people.

Examples of dissemination opportunities identified to date include:

- Science Council Climate Conference on September 29th speaking on "Meeting Energy Supply and Demand – the pathway to net zero[7]", where project is of particular relevance.
- Institution of Chemical Engineers, Clean Energy Special Interest Group (CESIG). A webinar on this topic is being planned for November 29th 2022.
- Essar, as a member of the UK Petroleum Industries Association (UKPIA), which includes all of the UK refiners will create the opportunity to present the project to the other members.
- UK Carbon Capture and Storage Association Technology Working Group meeting (date to be advised).
- The European Refining Technology Conference (World Refining Association), of which Essar is a member, planned for submission to the 2023 event.
- (Possibly) 10th International Freiberg Conference on IGCC & XtL Technologies, proposed for 17–20 September 2023 in Shanghai, China.

10 Conclusions

- The existing markets for oil-derived products produced by refineries will need to develop if 'net zero' ambitions are to be realised, and as the demand for hydrogen rises.
    - This move towards net-zero will modify the balance of products, reducing initially the market for heavy fuel oil for marine use, followed by reductions in the gasoline and diesel, while the market for aviation fuels is expected to remain at close to current levels for many years to come.
    - There is an increasing appetite for low carbon hydrogen in the UK and globally to deliver energy to industrials, power generators, for transport and potentially domestic homes with no emissions at the point of use.

[6] "Oil and gas in the UK", ETI, https://www.ukeiti.org/index.php/oil-gas

[7] https://sciencecouncil.org/climate-conference-the-uk-pathway-to-net-zero/

- A process has been developed which would be able to take a wide spectrum of feed materials and deliver low carbon hydrogen to pipeline standards.
    - The proposed core technology comprises building blocks of established commercial equipment to reduce deliverability risk, but configured in a unique manner designed to maximise the carbon captured - to over 98%, deliver CO_2 to a pipeline and storage quality, whilst maximising hydrogen yield.
    - The project uses Stanlow and its residual streams as an exemplar, but the technology is flexible and can be adapted to the requirements of any liquid refinery stream.
    - The acid gas removal unit is designed for pipeline quality CO_2, a requirement that deviates from existing units where only part of the CO_2 is recovered. The design enables full sulphur recovery and elimination of a CO_2 stream that is vented in conventional plants.
    - The overall result is the production of over 150,000 Nm3/h pipeline quality Low Carbon Hydrogen from 1500 t/d refinery residue with a capture rate of 98.5%.
- The study has established that there is, however, one aspect of the design which would benefit from further development in a net zero environment, as existing solutions would give rise to carbon emissions without additional post combustion capture. The process would be best deployed with a different route for the disposal of gasifier ash and soot from the ones utilised elsewhere in the world. A possible route has been identified which, although low risk, has yet to be demonstrated. Proposals to demonstrate this at sufficient scale to permit a full-size plant to be considered are developed as a Phase 2 project.
- The project economics are dominated by investment cost and cost of feedstock which together make up 60-80% of the levelised cost of hydrogen
- The levelised cost of hydrogen produced through this process depends on the alternative disposition for the residual feedstock and hence its value, and the cost to emit unabated CO_2.
    - Analyst opinion has been used to inform the basis used for modelling
    - The cases consider two extreme scenarios for feedstock pricing. The first, a Low Global Decarbonisation Scenario represents existing markets for residual products remaining strong. The second, a High Global Decarbonisation Scenario where decarbonisation of the marine transport industry has markedly reduced demand for such products. In this case. the alternative disposition for refinery residuals transitions to combustion fuel in power stations and is therefore priced equivalent to coal, with projection that coal discount relative to natural gas remains comparative to today

11 Glossary of Terms

AGI	Above Ground Installation, where pipelines are brought above ground to enable access for maintenance and on isolation valves
Basis of Design	A document that records the thought processes and assumptions behind major design decisions being made to meet the Owner's Project Requirements
BEIS	Department for Business, Energy & Industrial Strategy
Entrained Flow	An entrained-flow gasifier is one in which the fed and the oxidant (air or oxygen) and/or steam are fed into the top of the gasifier
EPC	A form of contract to Engineer, Procure and Construct a piece of plant or equipment
FEED	(Front End Engineering Design): Basic Engineering which is conducted after completion of Conceptual Design or Feasibility Study and as a precursor to FID and detailed design
FID	Final Investment Decision
Fluidising Velocity	The minimum velocity at which the drag force and the upward buoyant force due to an upward-directed fluid is balanced by the weight of the particles
Fluidised Catalytic Cracking unit	A conversion process used in petroleum refineries to convert the high-boiling point, high-molecular weight hydrocarbon fractions of petroleum (crude oils) into gasoline, olefinic gases, and other petroleum products.
Flowscheme	A sequence of processes or reactions within a system, often portrayed pictorially
HyNet	The UK's leading an low carbon and hydrogen energy project that will unlock a low carbon economy for the North West and North Wales
Oxo-chemicals	Generic name for intermediate and derivative chemical compounds which are characteristically used in chemical and manufacturing processes of paints, plasticisers, coatings, adhesives and lubricant additives.
Net Zero	A situation in which there is a balance between the amount of greenhouse gas (CO_2 being the current emphasis) produced and the amount removed from the atmosphere
Rectisol	A physical solvent gas treating process for acid gas removal using an organic solvent at low temperatures
Tail gas	Gases and vapours normally released into the atmosphere from an industrial process after all reaction and treatment has taken place.

Value engineering	A systematic, organised approach to providing necessary functions in a project at the lowest cost by promoting the substitution of materials and methods with less expensive alternatives, without sacrificing functionality.