HUMBERZERO

TECHNOLOGY SELECTION REPORT

VPI-Immingham and Phillips 66

Humber Zero Project
Immingham, UK

April 2022

wood.

CONTENTS

PREFACE

"Achieving Net Zero is essential if the UK is to play its part in addressing the global climate emergency, and Humber Zero is an opportunity to advance this.

Humber Zero is a combined set of decarbonisation projects that aim to lower greenhouse gas emissions from the world-scale industrial complex at Immingham, comprising the 1.2 GW Combined Heat and Power plant, operated by VPI Immingham LLP ("VPI-I"), and the adjacent Humber Refinery, operated by Phillips 66 Limited ("Phillips 66").

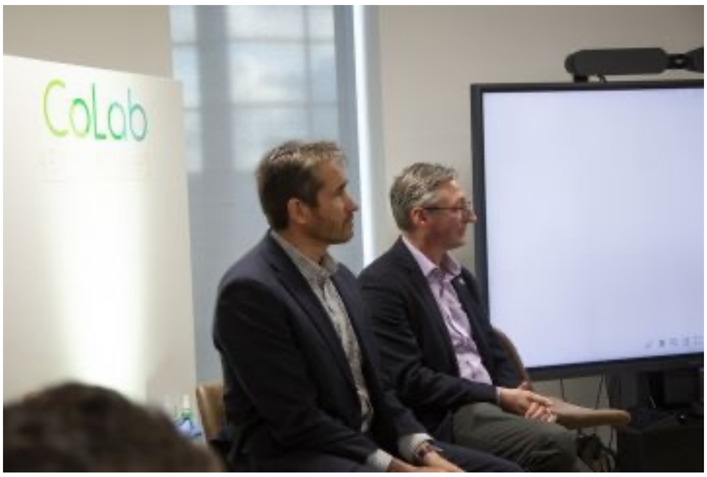
Humber Zero's initial phase focuses on the post-combustion carbon capture and storage (CCS) components of the decarbonisation strategy required to achieve UK's net zero target by 2050, while remaining competitive in an increasingly lower carbon world.

In addition to the benefits to climate change, Humber Zero will safeguard and provide thousands of highly skilled and high value jobs, as well as deliver the necessary infrastructure to support continued economic growth for the region.

Jonathan Briggs, Project Director for Humber Zero

CCS is not a new concept, however implementing it at an industrial scale in the UK is, so collaboration between government and private enterprise is required for success.

This document summarises the carbon capture technology selection lessons learnt, and by sharing this information publicly, we hope it will assist other projects to realise their decarbonisation ambitions more easily."



Jonathan Briggs, Project Director for Humber Zero and Chris Gilbert, Technical Director for Phillips 66 Humber Refinery attending COP26.

Jonathan Briggs, Project Director for Humber Zero, Suzanne Ferguson, Carbon Capture Lead Consultant at Wood, Chris Gilbert, Technical Director for Phillips 66 Humber Refinery and Dan Carter, Vice President, Decarbonisation & New Energies at Wood at COP26.

PREFACE

"The Humber Zero project participants provide the energy, fuels and products used by society. The demand for energy is expected to increase and this will require industries, such as the Humber Zero participants, to lower the carbon intensity of its products in order to meet Net Zero. The power and refining sectors have a track record of adapting to environmental legislation, and therefore have the knowledge and expertise to evolve for the energy transition.

Traditional industries such as combined heat and power plants and refineries are still expected to play a role in the future. Decarbonised electricity from VPI's gas-fired generation can provide grid balancing when renewable sources, such as offshore wind, are at reduced output. Phillips 66 is developing the 'Refinery of the Future' to produce lower carbon products. The refinery is leading the UK in the production of lower carbon fuels, processing waste streams such as used cooking oil in place of fossil hydrocarbons and is the first in the country to produce sustainable aviation fuel. Furthermore, the Humber Refinery is the only European producer of synthetic graphite, a vital component in the manufacture of electric vehicle batteries. Humber Zero can therefore be an integral part of the energy transition.

VPI-I and the Humber Refinery are an integrated complex, part of the Immingham Industrial Hub located on the South Bank of the Humber Estuary. The Humber region has the largest industrial emissions in the UK. Furthermore, Immingham is located at the junction of two proposed CO_2 pipelines to the sequestration fields in the North Sea. Humber Zero affords an ideal location to deploy carbon capture and storage at industrial scale, not only creating and safeguarding jobs, but establishing a UK centre of excellence.

Chris Gilbert, Technical Manager for Phillips 66 Humber Refinery

This technology selection review is an excellent marker on industry's decarbonization journey. The intent of the study is to inform and broaden the knowledge base for carbon capture technologies, building on previous experience in the power generation sector and leveraging for a first of a kind at-scale application in a refinery process unit. Humber Zero would like to thank Wood and the technology licensors for their contribution and collaboration on this report."

EXECUTIVE SUMMARY

Humber Zero aims to decarbonise the world-scale Immingham industrial hub, which is situated in the Humber region, and will capture up to 8 million tonnes of CO_2 per annum (MTPA) by 2030. The Immingham industrial hub represents the UK's single greatest opportunity for industrial decarbonisation, with several critical industries sited within a small geographical area.

The Humber Zero project participants, VPI Immingham and Phillips 66, operate facilities at Immingham that are central to the ongoing development of the region. VPI Immingham's Combined Heat and Power Plant supplies electricity and steam to the Phillips 66 Humber Refinery and nearby industry, as well as electricity to the grid. The Humber Refinery manufactures fuels and products that are essential to the energy transition, such as lower carbon liquid fuels and sustainable aviation fuel and advanced road fuels. It is also the only European producer of graphite coke, a key component in the global electric vehicle battery market.

In 2021, match funding was awarded by UK Research & Innovation (UKRI) to develop conceptual and Front-End Engineering Design (FEED) for deployment of the initial Humber Zero projects. These projects target carbon capture starting in 2026, with a capture rate of 3.8 MTPA from 2027. This will be achieved by post-combustion carbon capture of 0.5 MTPA of CO_2 from emissions from the Humber Refinery's Fluid Catalytic Cracker (FCC) unit and 3.3 MTPA of CO_2 from emissions from VPI-I's auxiliary boilers and gas turbines.

Post-combustion carbon capture technology typically involves use of an amine solvent to strip CO_2 from the flue gas stream, with regeneration of the CO_2 rich amine solvent to produce a CO_2 stream for compression and transportation via a pipeline for storage in the North Sea. The transportation and storage is not included in the technology selection.

The purpose of this document is to summarise the knowledge and key learnings from the Humber Zero project's post-combustion carbon capture technology selection process, which was conducted through a structured process comprising of:

· Identification of comprehensive lists, representing the potential technology providers

· Expression of interest engagements and capability questionnaires to reduce the "long lists" to "short lists", which were manageable for tendering

· Competitive tendering

· Compilation of technical and commercial bid evaluation criteria

· Separate technical and commercial bid evaluations

· Negotiation of commercial issues, terms and conditions, followed by contract award

Key lessons learned through this process are summarised below and discussed in more detail through this report.

KEY LESSONS LEARNED

Accurately assess and **characterise** the flue gas

Shortlist suitable CO_2 capture technologies based on **applicability** and **readiness**

Technology claims must be substantiated by **performance guarantees**

Consider **layout** to minimise duct lengths

Establish **pre-treatment** requirements

Carry out comprehensive **normalisation** of technology proposals

Consider availability of **pilot plant testing** or access to test facilities

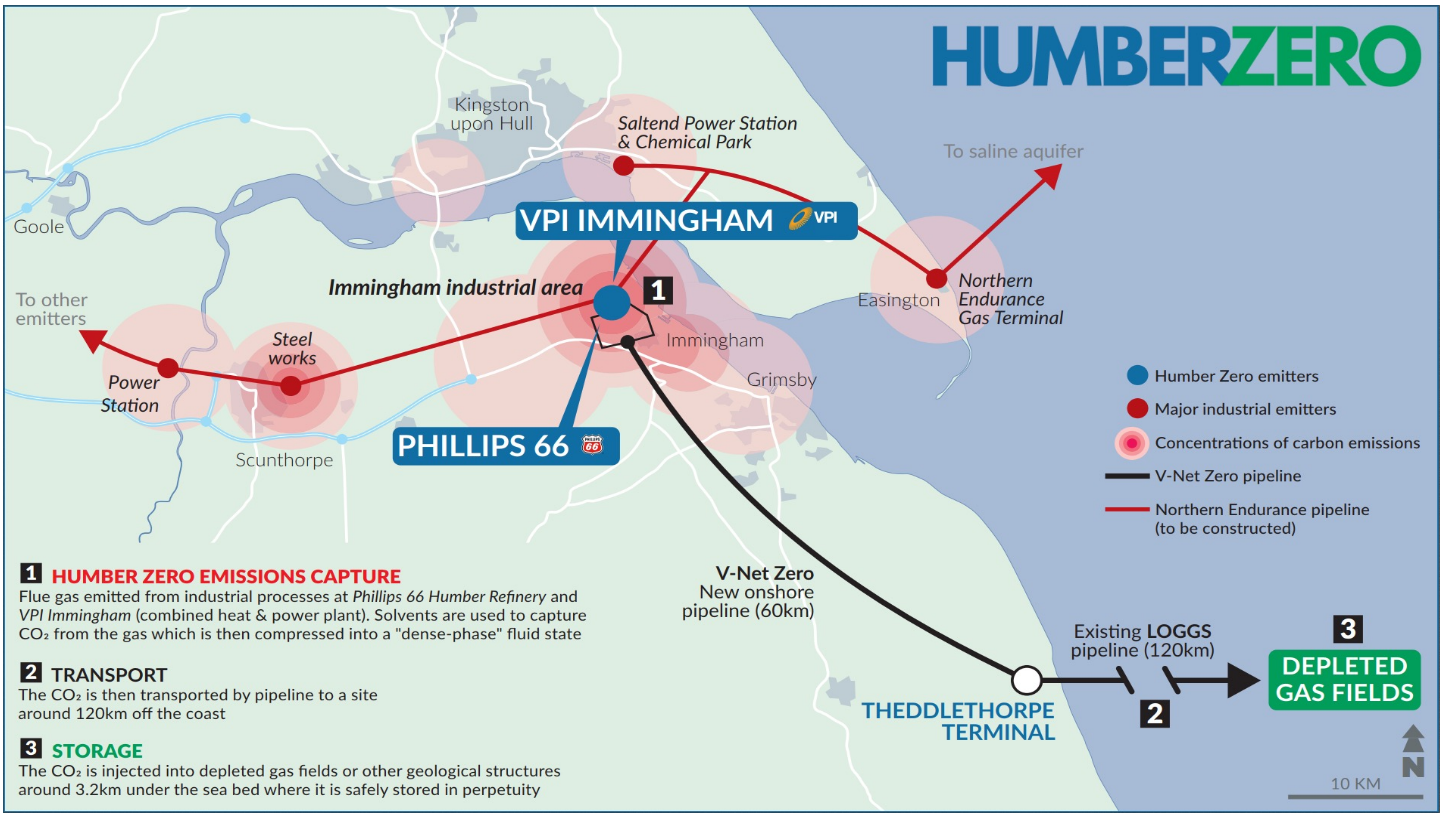
Maximise reliability and **energy efficiency** where possible

PURPOSE

The purpose of this document is to record and transfer knowledge and key learnings from the technology selection process of the Humber Zero project.

The document focuses on the initial concept development through to completion of pre-FEED, with a focus on the CO_2 technology selection for three types of flue gas including refinery Fluidised Catalytic Cracker (FCC) flue gas, Combined Cycle Gas Turbine (CCGT) flue gas and Auxiliary Boiler flue gas.

OVERVIEW



Humber Zero is a combined set of decarbonisation projects that aim to decarbonise the world-scale industrial complex at Immingham, UK, comprising VPI-I's 1.2 GW Combined Heat and Power (CHP) plant and the adjacent world-scale Phillips 66 Humber Refinery (HR).

The Humber region has the largest CO_2 emissions of the UK industrial clusters and aims to be the world's first net zero industrial cluster by 2040. The region benefits from proximity to the depleted oil and gas reservoirs and saline aquifers in the North Sea for storage of CO_2, and has two pipeline and storage networks under development – the East Coast Cluster and Harbour Energy's V Net Zero pipeline and storage option.

Immingham is strategically located close to the planned pipeline routes for both of the networks under development and has a number of emitters located within close proximity, making it the ideal location for the development of carbon capture and storage (CCS).

1.1 - PROJECT OVERVIEW

The decarbonisation roadmap being developed for the Humber envisages that Immingham will become a carbon capture and hydrogen hub, providing cost effective decarbonised energy supply and storage opportunities to industry. Humber Zero will provide a platform for demonstrating critical deep decarbonisation technologies on an industrial and commercial scale. Through deployment of the full decarbonisation roadmap, the Humber Zero projects can capture up to 8 MTPA of carbon dioxide (CO_2) emissions by 2030, via a combination of technology pathways.

Humber Zero's first phase focuses on the initial post-combustion carbon capture components of this strategy. This phase will aim to deliver 3.8 MTPA of abated CO_2 emissions via a post-combustion carbon capture (PCC) retrofit to two gas turbines and two auxiliary boilers at VPI-I CHP (3.3 MTPA) together with a PCC retrofit to the Fluidised Catalytic Cracker (FCC) at the Phillips 66 Humber Refinery (0.5 MTPA)

The project has selected technology providers for the PCC processes and connected these with the owners' sites and utility systems. The resulting design includes the necessary CO_2 treatment, conditioning and compression for export into a regional dense phase CO_2 Transport & Storage system.

The project is investing an initial £25-million, including match funding through the UK Research & Innovation (UKRI) Industrial Strategy Challenge Fund (ISCF), in developing technology to capture and safely deliver the CO_2 into the transportation and storage network. This would significantly reduce greenhouse gas emissions whilst safeguarding 20,000 local jobs with opportunities to create 200 new, highly skilled professions.

1.2 - PROJECT PARTICIPANTS

PHILLIPS 66 | HUMBER REFINERY

The Humber Refinery has operated more than 50 years and supplies around 20% of the UK's liquid fuel demand.

The refinery is one of the most sophisticated and energy efficient in Europe and is recognised by the Department for Transport (DfT) as leading within the UK on the production of lower carbon liquid fuels such as Sustainable Aviation Fuel and advanced biofuels., which are made from the processing of waste oils. The Humber Refinery is the only European producer of graphite coke, an essential component of electric vehicle batteries.

VPI Immingham

VPI-Immingham (VPI-I) is a Combined Heat and Power (CHP) plant near Immingham, on the South Bank of the River Humber in the UK.

VPI-I (owned by Vitol - global energy and commodities company that trades and distributes energy around the world using its logistics and infrastructure network), is one of the largest CHP plants in Europe, capable of generating 1.2 GW and up to 930 tonnes of steam per hour, which is used by neighbouring refineries.

VPI-I also supplies electricity to the National Grid.

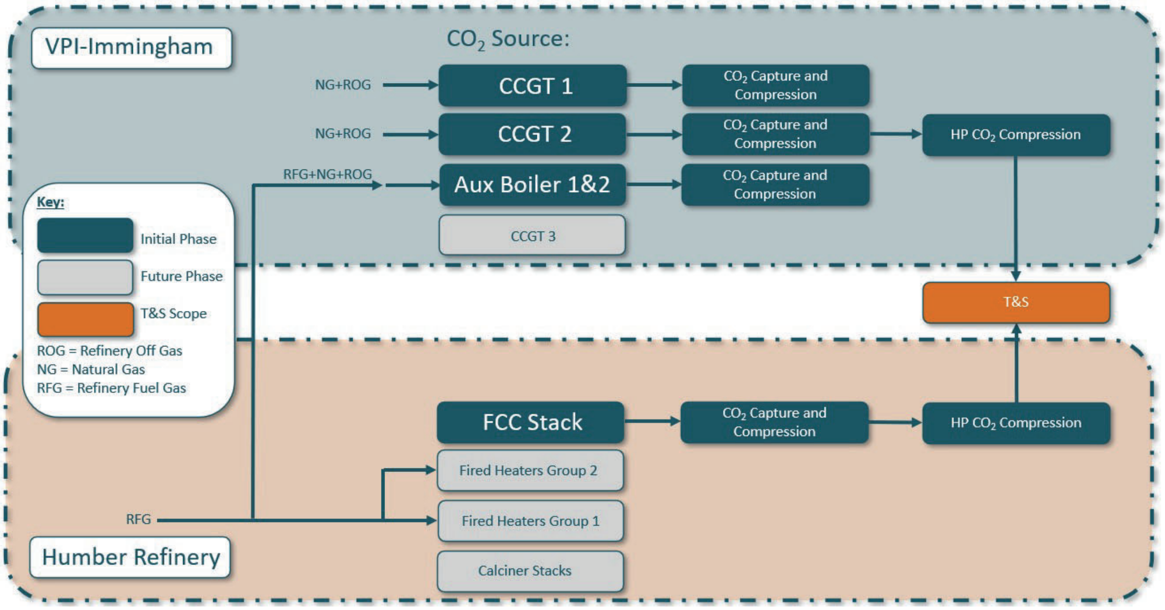
Project Structure

Humber Zero is being developed as a programme of projects led and executed by the respective industrial partners and coordinated by a Joint Project Management Team (JPMT).

Common parts of the project were supported by Wood through early concept / Pre-FEED studies and as the Integration Project Management Contactor (IPMC).

1.3 - PROJECT SCOPE

The initial phase of the Humber Zero project will deliver 3.8 MTPA of abated CO_2 emissions from existing industrial facilities. This first phase develops the facilities for the initial post-combustion CO_2 capture plants where government co-funding has been awarded, as shown below:



Once captured, CO_2 can be safely transported by pipeline and permanently stored in geological formations such as saline aquifers and depleted oil and gas fields.

The most well-established CO_2 capture technologies use solvents to selectively remove CO_2 from gas mixtures. The solvent is then regenerated via heating, to release pure CO_2, and reused within the process in a continuous loop.

Background to CCS

Carbon capture technologies have been used in industry for decades to obtain CO_2 for further use, for example in the food and beverage industry or for enhanced oil recovery, or because the CO_2 must be removed from a process stream.

CO_2 capture has also been used specifically for climate change mitigation in the oil and gas industry since the mid-1990s, when the first large scale project was implemented in Norway, at the Sleipner platform in the North Sea. In the US, earlier application of CO_2 capture have been used for Enhanced Oil Recovery.

There are now 27 industrial CCS projects in operation globally, capturing and storing 37 MTPA of CO_2, with a further 4 under construction and over 100 in engineering design.

Definitions

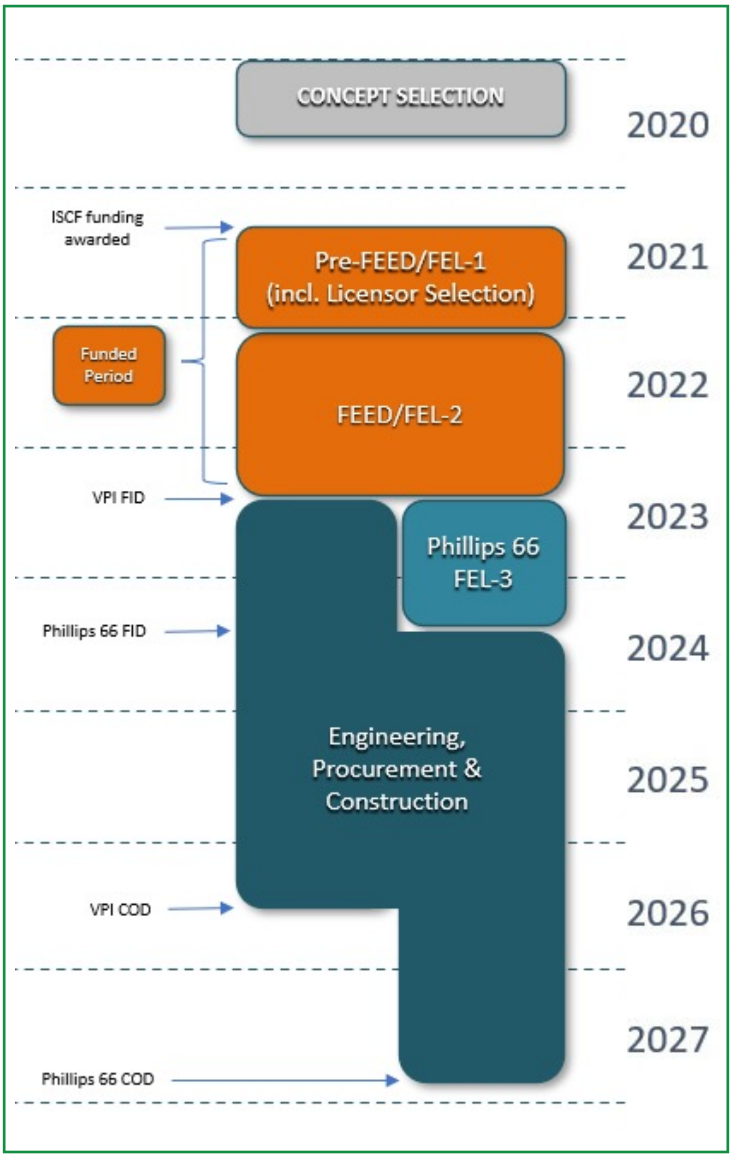
Carbon capture and storage (CCS) is the capture of carbon dioxide (CO_2), which would otherwise have been emitted to atmosphere, and its permanent storage.

Post-combustion carbon capture involves treatment of the flue gas after combustion has taken place, and occurs at near ambient conditions.

1.4 - TARGET TIMELINE

Key Activities During Pre-FEED/ FEL-1

- Conducting initial safety reviews and siting studies
- Reviewing of key utility and energy requirements
- Commencing ecological surveys, appointing environmental contractor and establishing planning and permitting strategy
- Establishing the basis of design, including the need for pre-treatment of flue gases to remove contaminants prior to the PCC plant. This is especially important for the HR FCC flue gas stream.
- **Review and selection of carbon capture technology, appointment of licensors – activity covered by this report.**



Key Activities During Pre-FEED/ FEL-2 will include

- Carrying out Environmental Impact Assessment and submitting planning and permitting applications
- Maturing the engineering design and update the cost estimate to aid FID
- Prepare a FEED Package and scope of work for EPC tendering

Notes

Phillips 66 has a FEL-3 stage prior to taking FID and moving into EPC.

East Coast Cluster CO_2 transport and storage system scheduled to be available at Humber Zero from Q4 2027.

SECTION 2.0

TECHNOLOGY SELECTION

The post-combustion capture projects for Humber Zero included characterisation of flue gas and identifying pre-treatment facilities.

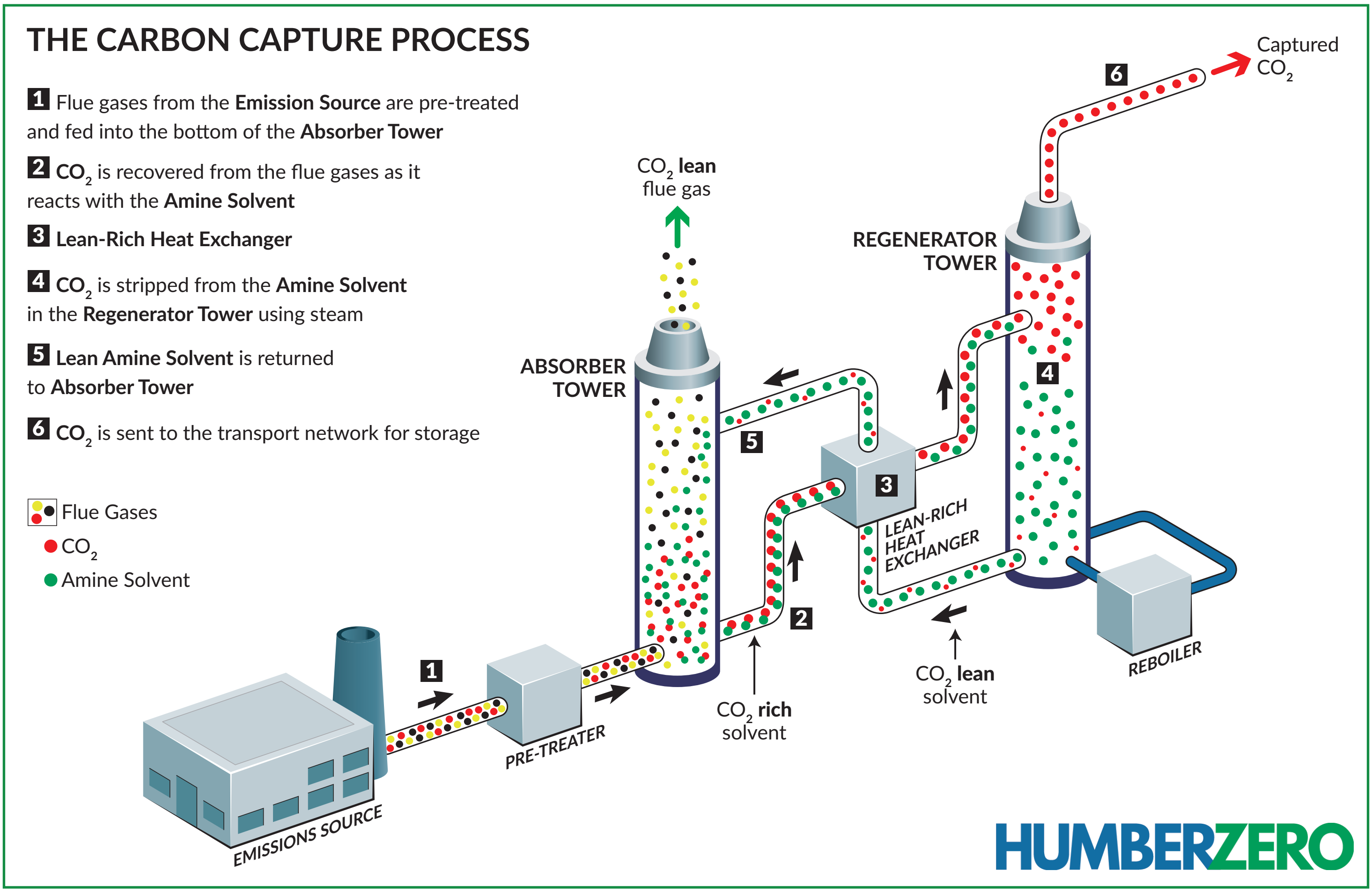
This section outlines the path taken from the concept design basis to the post-combustion carbon capture technology selection for flue gases from:

- Combined Cycle Gas Turbines (CCGTs)
- Auxiliary Boilers
- Fluid Catalytic Cracker (FCC)

2.1 - TECHNOLOGY OVERVIEW

The following section gives an overview of a PCC technology employing an amine solvent-based process to remove CO_2 from the flue gas in an absorber tower, with subsequent capture of CO_2 from a regeneration tower.

One of the key requirements of the carbon capture unit is to achieve a minimum recovery efficiency of 95% of the CO_2 in the flue gases from the CCGTs, auxiliary boilers and FCC.



The main process steps within a typical amine solvent-based carbon capture process are:

- Gas pre-treatment including flue gas blower and cooler
- CO_2 absorption with water washing
- Solvent regeneration

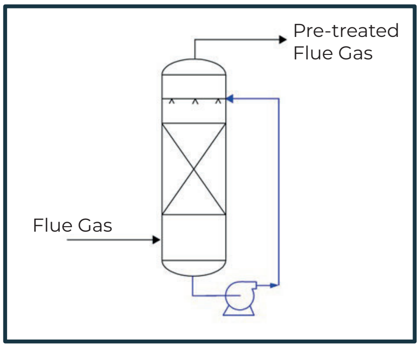
Additional facilities include:

- Fresh solvent storage and make-up
- Solvent reclaiming
- Effluent treatment
- CO_2 compression, dehydration and metering for export

These elements are detailed in the following pages.

Gas Pre-Treatment

The flue gas feed to the PCC unit is hot and contains contaminants such as dust, SOx and NOx. The hot flue gas needs to be adequately cooled before reaching the CO_2 absorber in order to achieve high recoveries in the CO2 absorber and mitigate solvent degradation.



The pre-treatment technology choice depends on the level of contaminants in the flue gas.

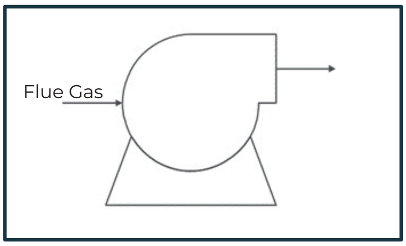
Flue gases from VPI-I's CCGTs and aux-boilers do not require additional pre-treatment other than quenching in a direct contact cooler. However, the flue gas from the Humber Refinery FCC contains contaminants that are above acceptable levels for the carbon capture plant and licensors will stipulate additional equipment such as a wet gas scrubber and/or a wet electrostatic precipitator, in order to minimise solvent degradation and generation of aerosols.

The cooling achieved by direct contact can condense much of the combustion water present in the flue gas and also removes many contaminants such as dust and SOx. To facilitate this, additional equipment for caustic dosing and solids handling may be required.

The condensed water from the flue gas is purged continuously and sent to effluent treatment or re-used, if suitable as cooling water make-up.

Flue Gas Blower

Typically, post-combustion flue gas streams are near atmospheric pressure and a flue gas blower is required to provide the motive force to overcome the pressure drop across the pre-treatment section and the CO2 absorber.



If sufficient pressure is available from the emissions source, then a blower may not be required. This would eliminate a major rotating equipment item which reduces power consumption and improves overall reliability.

Key Learning Points

Flue Gas Characterisation

It is important to understand the gas composition and particulates /contaminants levels. This is particularly important with respect to FCC PCC unit applications, which have additional and variable contaminant levels.

Pre-treatment

A full understanding of the flue gas will allow selection of a robust pre-treatment solution in co-ordination with the PCC unit licensor.

Reliability

The flue gas blower is one of the largest power consumers. It is also a potential source of unreliability that could cause periodic disruption to the operation of the capture plant. Therefore, it is prudent to consider flue gas tie-in points that either:

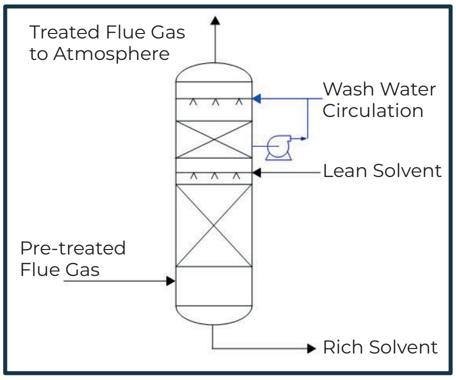
- Negate the need for a blower; or
- Reduce the size and power demand of the blower and reduce the variability and severity of the process conditions by locating it downstream of the pre-treatment cooling section to reduce volumetric flow.

Fan size will be smaller if the blower is located within the cool gas stream downstream of the pre-treatment section.

However, this is ultimately governed by the arrangement and construction of other parts of the PCC unit, and it may not be practical to install the blower downstream of pre-treatment.

CO_2 Absorption

Typically, the CO_2 absorber is a cylindrical steel column, with rectangular concrete columns used for higher flue gas flowrates. The column normally contains structured packing with CO_2 absorption section at the bottom and water wash sections at the top.



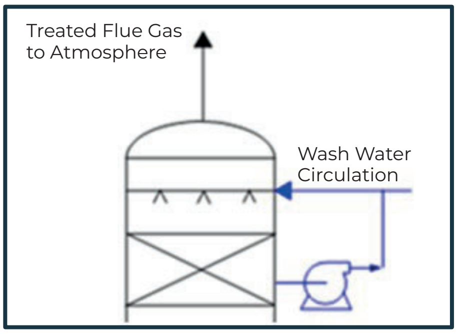
The cooled flue gas is introduced into the bottom of the column and contacted with solvent fed from the top of the absorption section. CO_2 in the flue gas is absorbed by the solvent.

The CO_2 rich solvent is sent to the regenerator column.

The temperature rise resulting from the exothermic reactions within the CO_2 absorber reduces the lean solvent absorption efficiency and increases amine degradation rate. Therefore, the semi-rich solvent at the bottom of the CO_2 absorber is often drawn off, cooled and pumped around.

Wash Water

To minimise solvent losses and emissions to atmosphere, one or more water wash sections are employed in the CO_2 absorber. The flue gas, now with the CO_2 mostly removed, flows upward into the water wash section, which comprises a circulation of wash water and can incorporate a cooling system to cool the flue gas it contacts, removing heat of absorption, and washing out any entrained solvent.



Solvent loss from the top of the wash section is minimised by a demister. The treated flue gas is emitted to atmosphere from the top of the absorber.

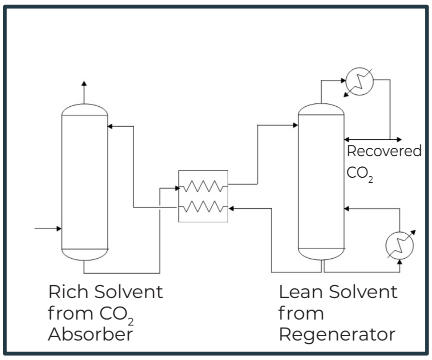
Key Learning Points

Site integration & constructability

Incorporating PCC to an existing facility will require routing of significant volumes of low-pressure gas via large ducting, therefore a review should be carried out on available plot space local to the emissions point in order to optimise layout and minimise the distance of ducting. Longer ducting adds cost and presents a greater challenge to the constructability of the plant.

Solvent Regeneration, Storage & Make-Up

The rich solvent from the bottom of the CO_2 absorber is pre-heated, against hot lean solvent circulation, in the lean / rich solvent heat exchanger before going to the top of the regenerator. The regenerator is a cylindrical column with structured packing, which increases the gas/liquid distribution. Low-pressure steam is supplied to the regenerator reboiler which heats the solvent to high temperature, stripping out CO_2. After regeneration, the lean solvent is recycled back to the CO_2 absorber via the lean / rich heat exchanger.



Energy efficiency is improved around the bottom of the regenerator by implementing additional heat integration or, in some cases, novel proprietary techniques.

The CO_2 product with water vapour at the overhead of the regenerator is cooled by the regenerator reflux cooling system consisting of the regenerator reflux cooler, reflux drum and reflux pump. The steam condensate from the regenerator reboiler is recovered and returned to the steam condensate system. The recovered CO_2 product is sent to the CO_2 capture unit battery limits for further treatment and compression. The unit includes a solvent drainage and make up system, comprising a solvent storage tank, solvent sump, solvent sump pumps and filter.

During maintenance and inspections, the solvent storage and makeup systems are used for draining solvent from process equipment. At the cold draining conditions, it is not expected that the solvent will oxidise, and therefore, nitrogen blanketing is not required.

Solvent Reclaiming

The primary purpose of reclaiming is to remove soluble solvent degradation products such as heat stable salts, dissolved metals, and suspended solids accumulated in the solvent. Different technologies are employed to achieve this such as thermally vaporising the solvent to leave the contaminants or by proprietary filtration methods.

The waste is removed as slurry into a tank for periodic truck disposal and recovered water and solvent are returned to the main circulation.

Effluent Treatment

To minimise the load on the existing treatment facilities, water from the quencher/ WGS system, which is loaded with dust and other contaminants, must first be treated.

The wastewater and solids handling are therefore integral to the flue gas pre-treatment system, and may comprise of mixing tanks, clarifiers, filters and filter cake bins / conveyors, aeration tanks and blowers, sumps and ancillaries.

The separated solids would be sent for offsite disposal by truck, and the water can be sent to the wastewater treatment system.

2.2 - DESIGN BASIS

VPI-I and Phillips 66 flue gas specifications are as follows:

VPI-I		Phillips 66
Combined Cycle Gas Turbine Flue Gas	**Auxiliary Boilers Flue Gas**	**FCC Flue Gas (incl. FCC Fired Heaters)**
• CO_2 capture flow - 1.4MPTA (above limits of many demonstrated PCC unit capacities)	• CO_2 capture flow rate - 0.5MPTA (within demonstrated PCC unit capacity)	• CO_2 capture flow rate - 0.5MPTA (within the demonstrated PCC unit capacity)
• Low pressure, close to atmospheric	• Low pressure, close to atmospheric	• Slight pressure; blower not required
• Low CO_2 concentration (5vol%)	• Moderate CO_2 concentration (10vol%)	• Moderate to high CO_2 concentration (15vol%)
• High O_2 content (10vol%)	• Moderate O_2 content (2vol%)	• Moderate O_2 content (1vol%)
• No solid particulates, lower in SOx and NOx	• No solid particulates, lower in SOx and NOx	• Large variance in solid particulates due to intermittent process operations, higher SOx and NOx
• Moderate temperature (100°C)	• Moderate temperature (125°C)	• High temperature (300°C), waste heat recovery exchanger required upstream of pre-treatment

As demonstrated above, flue gas characterisations can vary significantly and influence the degree of pre-treatment required and heat recovery available upstream of a PCC unit.

Key Learning Points

A robust pre-treatment selection for flue gas emissions containing impurities is a key component in the operation of a PCC unit, particularly when considering the impact any impurities (e.g. dust/particulates, SOx, NOx, ammonia, oxygen etc.) can have on the performance and life cycle of the carbon capture process solvent.

In high temperature flue gas PCC applications, heat integration via a waste heat exchanger to generate steam can assist in reducing OPEX from the PCC unit steam demands.

2.3 - CARBON CAPTURE TECHNOLOGIES

Available Technology

The Humber Zero team carried out a review of the available carbon capture technologies, to determine which technologies would be suitable for consideration in application to the Humber Zero project. This review was carried out at an appropriate time during the pre-FEED phase to help inform the Technology Selection process, and narrow down technologies for more detailed consideration going forwards.

The review considered the specific needs of the industrial participants and applications for Humber Zero, and therefore is not intended to be a broadly applicable evaluation of the available technologies, but a case-specific suitability assessment. Proven technology readiness and scalability in similar applications was a key consideration in the review, as well as economic viability for the application.

Technology		Feasibility
Solvent Based Technology	Open-art MEA or CESAR	Technology is feasible and there are available designs but none deployed at scale to date. Open art offerings were compared against proprietary technologies during licensor evaluation.
	Proprietary amine based solvents	Technology demonstrated commercially in various comparable capacities. However, FCC PCC unit application are limited to test settings. Consequently attention has been paid to other applications requiring gas clean up such as coal power generation.
	Non-amine based solvents	Technology performance has not been proven at scale at the time of review or only capable of operating in a more concentrated CO_2 emission streams.
Alternative Technology	Membrane Solid Adsorption	Technology performance has not been proven at scale at the time of review or only capable of operating in a more concentrated CO_2 emission streams.
	Fuel Cells	Technology limited and requires high CO_2 flue gas concentration
	Phase Change	No credible process flow scheme developed yet

The technology review carried out by the Humber Zero pre-FEED team found that the only post combustion carbon capture technology proven at a comparable commercial scale to achieve the Humber Zero project's carbon capture target at the time of the review is the proprietary amine based solvent CO_2 capture process. The Humber Zero team are keen to keep the development of the technologies under review for potential future applications of carbon capture that could be deployed by the project participants.

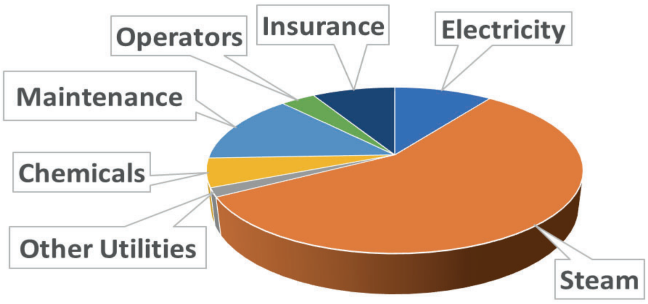
Key Learning Points

Technology Readiness

The maturity of the available CO_2 technologies is an important factor for consideration, as use of unproven or novel technology will require qualification. The qualification of a new technology will add risk to the project and requires significant time and resources during project development. Technology qualification is typically completed using a recognised industry standard to ensure all relevant aspects are reviewed and results are presented in a structured and transparent manner.

2.4 - ENERGY INPUT

Amine solvent-based CO_2 capture technologies are inherently energy intensive with most of the operating cost allocated to steam and power consumption. The pie chart shows an indicative distribution of operating costs.



Power

Some of the largest power consumers, excluding pre-treatment and post-treatment compression, are the cooling system and flue gas blower.

The process has a large cooling duty to achieve high CO_2 absorption efficiency in the CO_2 absorber and mitigate solvent degradation.

The cooling system can be direct air cooling, evaporative water cooling or a hybrid of the two, dependent on the availability of cooling media and plot space. The large duty requirement is reflected in the resultant infrastructure and large power demands for air cooler fan motors or cooling water pumps.

Steam

The largest steam consumer in the capture process is the solvent regeneration column reboiler within the CO_2 recovery section. The solvent reclamation/polishing section also consumes a significant portion of the unit LP steam. Combined, these two processes make up most of the process heat duty and therefore steam consumption.

Licensors provide heat integration and other proprietary techniques to recover heat from the bottom of the regenerator column, thereby reducing the LP steam demand and improving overall energy efficiency.

Key Learning Points

Energy Intensity

Post-combustion carbon capture is an energy intensive process requiring significant levels of steam and power. steam is used for heating (within the solvent regenerator) and power is used for process cooling (airfins, cooling water pumps or both).

The Humber Zero PCCs have a readily available heating medium through the steam from the VPI-I CHP. This supply is more energy efficient than sources of steam usually used in industrial CCS and will significantly reduce in carbon intensity through the implementation of carbon capture. However, projects without access to this type of heat source may have to realise the extra capital and operating costs for the additional heat input which may impact their economic viability.

Cooling Medium

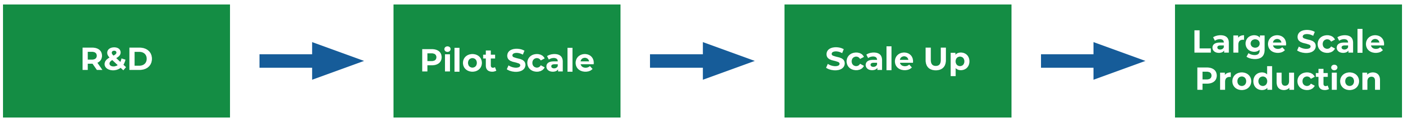
Due to the significant process cooling requirements and resultant airfin cooler footprint, cooling towers may be considered to optimise plot plan. This should be weighed against the fact that evaporative cooling requires a large amount of make-up water which is a valuable resource, and additional water consumption may be restricted.

2.5 - SCALE UP

Scale-up is an important consideration when reviewing carbon capture technology. Licensor's references, particularly operating plants and the track-record availability of the PCC units is key to determining the risk associated with the technology.

The capacities of the Phillips 66 PCC unit and VPI-I Auxiliary Boiler PCC unit were both found to be well within the demonstrated capacity of commercially operating units. Therefore, scale up of the technology is considered less of a concern for the Humber Zero projects.

For the VPI-I CCGT application, CO_2 content of the flue gas source was low relative to the total flue gas throughput. As a result, although the CO_2 capacity (based on the amount recovered) was within proven limits the total flue gas volumes exceeded current scale. Licensors therefore had to provide evidence based on experience and lessons learned on similar projects that they were able to manage the risks of scale-up.



Some licensors scale up using a "building block" methodology, expanding capacity offering by increasing the number of cells, whereas others simply increase the size of process equipment. The credibility and constructability of both methods should be reviewed when considering a PCC unit design.

Furthermore, it is worth noting that, based on cost and constructability, there exists a design break point above 1 MTPA of CO_2, where some licensors may switch from conventional circular type quench or CO_2 absorber column to a square / rectangular design. This should also be reviewed for impact on available plot space and for potential site constructability issues.

Key Learning Points

Scale Up

Scale up of the licensor technology based on demonstrated applications is an important factor to consider.

Options and willingness to use a pilot plant or access to testing facilities could be of benefit to provide assurances and allow for review of the technology in practice for the specific flue gas.

2.6 - LICENSOR QUALIFICATION

A Humber Zero licensor qualification process was completed to shortlist viable technology providers capable of delivering the project requirements utilising the following key criteria:

- Technology to be commercially available to support design phases through to start up in mid-2020s
- Previous experience providing a design package / process data to support design phase
- Licensor has previously delivered a design at a similar throughput
- Technology deployed in operating or demonstration plants at > 50kTPA scale
- Track record as a provider of gas treating units under license
- Licensor has faced adverse issues related to reliability and be able to bring forward lessons learned
- Willingness to participate and provide information to project, including supporting knowledge transfer

The licensors identified within the shortlist qualification process were invited to bid for the VPI-I and Phillips 66 Humber Zero project scopes, separately.

Permitting and Regulatory

A Post-combustion Carbon Capture plant is likely to require a planning and permit application to the relevant authorities, such as the Local Authority and/or Environment Agency. Use of the solvent could result in emissions, such as amine and amine degradation products, that will require detailed Environmental Impact Assessment as part of these applications.

Key Learning Points

Technology Review

Each proprietary solvent will have its own advantages and disadvantages.

Licensor solvent technology is continuously improving and with each iteration a licensor’s solvent performance is likely to improve.

2.7 - LICENSOR EVALUATION

Licensors submitted proposals, which were evaluated for the following criteria:

Criteria	Aspects Evaluated	
Health, Safety, Environment, Quality	HSEQ Management Systems	HSE & Quality Management Systems & Standards
	Equality, Diversity and Inclusion	Equality Diversity & Inclusion Policy
	Process Safety	Intrinsic Safety Hazardous Inventories & Operations
	Hazardous Inventories & Operations	Solids, liquid & gaseous emissions (inc. NOx, SOx, CO, NH_3, degradation products & particulates)
Technology	Energy Efficiency	Utility consumptions (inc. steam & power)
	CO_2 Recovery	Maximum guaranteed % CO_2 recovery
	Logistics	Logistic methods for solids and liquid handling vs operational impact
	Design Features	Unique system design features Energy saving features Novel design items Erosion & corrosion
	Availability	Expected availability and plant reliability
	Operability	Simplicity / difficulty of process operation Ramp up / start up rates / turndown constraints
	Plot Area	Proposed licensor plant footprint
	Process Guarantees	Compliance with project process guarantees
Execution	RFP / Clarifications Responses	Bid compliance and responsiveness to clarifications requests
	Execution Compliance	Compliance to the project philosophies, standards and adherence to scope of work
	Number of LLI & Proprietary Items	Assessment of proprietary and log lead times and expected delivery times
	Organisation	Capability to manage project workload
	Engineering / Technical Assistance	Willingness to support the project and provide operational assistance
Economics	Levelised Cost of CO_2 Abatement (LCOA)	LCOA is calculated for each licensor using a simple project economic model, which takes into account CAPEX and OPEX
Project / Technical Risks	Technical Barriers	Limitations and uncertainties of the licensor process technologies
	Availability Track Records	Performance and availability of the units in any similar services
	Total References	Licensor number of process installations
	Scale-up Factor	Any scale up from previous / existing demonstrated plants reviewed

Key Learning Points

Performance Guarantees

The ability of a proprietary technology provider to issue and back up performance with guarantees is an important factor in PCC projects.

The guarantees will differ between licensors and should be agreed as early as possible within the project.

2.7 - LICENSOR EVALUATION

Each of the submitted licensor's bids were assessed and evaluated for completeness, quality, technical and economic performance for the VPI-I and Phillips 66 project scope.

Furthermore, each licensor bid was subject to a rigorous normalisation review undertaken to ensure all submitted bids were evaluated and costed on a consistent and fair basis.

Examples of project licensor normalisation includes:

Normalisation Examples	Description
Blower location, sizing & sparing	Licensors flue gas blower locations differed across the FCC Flue Gas PCC unit bids. A normalisation activity was completed, with licensor input via clarifications, to review and relocate the blowers in a consistent position downstream of the pre-treatment stage for a consistent comparison.
Equipment count	Each licensor's equipment list contained different equipment count. Any large variations in licensor equipment count were reviewed, and accounted for via: • Licensor's itemised equipment list format • Packaged equipment and • Equipment specification to the Licensor's process configuration
Design margin	Licensor equipment list design margins varied between bids. All equipment design data was normalised to include the appropriate design margin as per the project process engineering design guidelines.
Wastewater & solids handling	PCC unit licensors have differing approaches to handling particulates and containments within the flue gas feed stream, based on the proprietary nature of their respective technologies. It is important to identify the approach taken and the impact on the PCC unit CAPEX and OPEX costs. As particulates are identified as being continuously present within the Phillips 66 FCC flue gas, an effluent treatment and solids handling facility was foreseen to be required regardless of the selected licensor configuration. Therefore, equipment associated with wastewater treatment and solids handling was normalised and included across all Phillips 66 licensor bids.

Key Learning Points

Normalisation

Equipment list normalisation must be carried out rigorously to ensure all the licensor proposals are brought up to a level and consistent basis. Some major areas to focus on include:

- Design margins
- Equipment sparing
- Unit scope gaps such as missing steam condensate, wastewater and solids handling facilities
- Uncalled for features, such as providing flue gas re heaters when dispersion is not an issue
- Common tanks and pumps shared between trains

SECTION 3.0

LESSONS LEARNED SUMMARY

3.1 - LESSONS LEARNED

The Humber Zero projects offer a unique opportunity to capture learnings to inform and assist in the development of future carbon capture projects. Key learnings identified during the licensor selection activities, carried out in Pre-FEED/FEL-1 stage of the project, are summarised in this report.

Subject	Key Learning Points
Design Basis	A robust **pre-treatment** selection for flue gas emissions containing impurities is a key component in the operation of a PCC unit, particularly when considering the impact any impurities (e.g. dust / particulates, SOx, NOx, ammonia, oxygen etc.) can have on the performance and life cycle of the carbon capture process solvent.
	In high temperature flue gas PCC applications, heat integration via a waste heat exchanger to generate steam can assist in reducing OPEX from the PCC unit steam demands.
Technology Overview	**Flue Gas Characterisation** - It is important to understand the gas composition and particulates / contaminants levels. This is particularly important with respect to FCC PCC unit applications, which have additional and variable contaminant levels.
	Pre-treatment - A full understanding of the flue gas will allow selection of a robust pre-treatment solution in co-ordination with the PCC unit licensor.
	Reliability - The flue gas blower is one of the largest power consumers. It is also a potential source of unreliability that could cause periodic disruption to the operation of the capture plant. Therefore, it is prudent to consider flue gas tie-in points that either negate the need for a blower or reduce the size and power demand of the blower and reduce the variability and severity of the process conditions by locating it downstream of the pre-treatment cooling section to reduce volumetric flow.
Available Technology	**Technology Readiness** – The maturity of the available CO_2 technologies is an important factor for consideration, as use of unproven or novel technology will require qualification. The qualification of a new technology will add risk to the project and requires significant time and resources during project development. Technology qualification is typically completed using a recognised industry standard to ensure all relevant aspects are reviewed and results are presented in a structured and transparent manner.
Energy Input	**Energy Intensity** - Post-combustion carbon capture is an energy intensive process requiring significant levels of LP steam and power. LP steam is used for heating (within the solvent regenerator) and power is used for process cooling (airfins, cooling water pumps or both). The Humber Zero PCCs have a readily available heating medium through LP steam from the VPI-I CHP. This supply is highly energy efficient and will significantly reduce in carbon intensity through the implementation of carbon capture. However, projects without this facility may have to realise the extra capital and operating costs for the additional heat input which may impact their economic viability.
	Cooling Medium - Due to the significant process cooling requirements and resultant airfin cooler footprint, evaporative cooling may be considered to optimise plot plan. This should be weighed against the fact that evaporative cooling requires a large amount of make-up water which is a valuable resource, and additional water consumption may be restricted.

3.1 - LESSONS LEARNED

Subject	Key Learning Points
Scale Up	**Scale up** of the licensor technology based on demonstrated applications is an important factor to consider. Options and willingness to use a pilot plant or access to testing facilities could be of benefit to provide assurances and allow for review of the technology in practice for the specific flue gas.
Licensor Qualification	**Technology review** - Each proprietary solvent will have its own advantages and disadvantages. Licensor solvent technology is continuously improving and with each iteration a licensor's solvent performance is likely to improve.
Licensor Evaluation	**Performance Guarantees** - The ability of a proprietary technology provider to issue and back up performance with guarantees is an important factor in PCC projects. The number of guarantees available will differ between licensors and should be agreed as early as possible within the project.
	Normalisation - Equipment list normalisation must be carried out rigorously to ensure all the licensor proposals are brought up to a level and consistent basis. Some major areas to focus on include design margins, equipment sparing, unit scope gaps such as missing steam condensate, wastewater and solids handling facilities, additional features, such as providing flue gas re-heaters, common tanks and pumps shared between trains.

A robust process was established at the start of pre-FEED/FEL-1, including a technology shortlisting exercise before technology providers were solicited for submitting proposals for the CO_2 capture units. Licensor evaluation procedures and tools were developed, covering everything from technical query clarifications, criteria weightings, equipment list normalisation, CAPEX estimation and economic modelling basis.

The lessons learned from this process are applicable across a broad range of sectors seeking to decarbonise through the application of post combustion carbon capture.

This rigorous licensor evaluation process enabled selection and appointment of licensors for both VPI Immingham and Humber Refinery scopes setting the projects up for success as the Humber Zero programme moves into FEED/FEL-2 and beyond.

SECTION 4.0

ABBREVIATIONS

4.1 - ABBREVIATIONS

CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture & Storage
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
EPC	Engineering, Procurement & Construction
FCC	Fluidised Catalytic Cracker
FEED	Front End Engineering Design
FEL-1/2/3	Front End Loading 1/2/3
FID	Final Investment Decision
HR	Humber Refinery
HP	High Pressure
HRSG	Heat Recovery Steam Generator
IPMC	Integration Project Management Contractor
ISCF	Industrial Strategy Challenge Fund
LP	Low Pressure
MP	Medium Pressure
MTPA	Million Tonnes per Anum
MW	Mega Watt
PCC	Post-Combustion Carbon Capture
Pre-FEED	Pre-Front End Engineering Design
T&S	Transport and Storage (CO_2 pipeline system)
UKRI	United Kingdom Research & Innovation