

# Next Generation Carbon Capture Technology

Case Study: Mobile Demonstration Plant  
Work Package 4

Department for Business, Energy & Industrial Strategy

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## Table of Contents

Executive Summary .....	6
1. Nomenclature .....	7
2. Introduction .....	8
2.1 The project.....	8
2.2 Case study objectives.....	8
2.3 Review of existing state of the art for CCS facilities .....	8
2.4 Case study terms of reference.....	9
2.5 Risks targeted by the Pre-Deployment Verification Unit .....	10
2.6 Proposed scale for de-risking project.....	10
2.6.1 Maximum size.....	11
2.6.2 Minimum size.....	11
2.6.3 Intermediate size .....	11
2.6.4 Size selection recommendations .....	11
3. De-risking Plant Concept .....	12
3.1 Process description .....	12
3.1.1 Flue gas pre-treatment .....	12
3.1.2 Flue gas absorption .....	12
3.1.3 Rich amine regeneration.....	13
3.1.4 CO <sub>2</sub> compression and export.....	13
3.1.5 Lean amine cooling .....	14
3.1.6 Amine reclaiming .....	14
3.1.7 Boiler plant.....	14
3.1.8 Drains .....	15
3.2 Technology description (optional components).....	17
3.2.1 Flue gas pre-treatment .....	17
4. Budget .....	19
4.1 Capital costs .....	19
4.2 Operating costs .....	19
5. Project Schedule.....	20
6. Next Steps in Development .....	21
6.1 Future Project Requirements.....	21
6.2 Value Proposition.....	21
6.3 Related Research & Development Works .....	22
7. Conclusions .....	23
8. References .....	24
8.1 Project References.....	24
Appendix A Outline Specification.....	25
Appendix B – De-Risking Research and Development.....	26

## Figures

Figure 1 – Proposed Process BFD (Ref. 12).....	16
Figure 2 – Flue gas pre-treatment package outline.....	17

## Tables

Table 1 – Constructed CCS Facilities at Pilot and Full-Scale.....	8
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Table 2. Risk Table .....	10
Table 3. Estimated EPC cost for PDVU and other projects .....	19
Table 4. Preliminary project key milestone schedule.....	20
Table 5. Description of activities to be completed in next steps of development.....	21

## Executive Summary

AECOM has been appointed by BEIS to conduct a review of next generation carbon capture technologies and the potential application of these technologies to different industrial, waste and power sites. The outputs of the review are intended to inform government decisions relating to the provision of innovation support funding for carbon capture, and future policy around CCUS deployment.

This document was prepared as part of this review and presents a reference case study for a carbon capture demonstration plant for BEIS to use in assessment of next-generation demonstrator plants seeking BEIS funding.

The objective of the case study was to develop a concept design for a nominal 100 tonnes per day of CO<sub>2</sub> captured in an Energy from Waste application.

The case study comprises a demonstration plant, using solvent-based technology to operate extended test campaigns (e.g. on the order of 10,000 hours) at representative facilities and therefore predict reclaimer, waste stream, contaminant and make-up rates.

The initial terms of reference for the carbon capture demonstration plant were to develop a concept design for a nominal 100 tonnes per day of CO<sub>2</sub> captured in an Energy from Waste application. Such a plant would be significant in size (0.3 to 0.5 hectare), likely be a fixed installation with a project budget in excess of £10million.

As a result, the case study was expanded to consider the potential of a smaller unit that could be delivered under £10 million and suitable to be moved after a test campaign had been completed from one site to another. The final selection of the proposed plant size will be a compromise between cost, mobility, scale-up, as well as feasibility of integration with the host site and feasibility for continued operation beyond the initial site or configuration.

The table below summarises the results of the case study:

Plant	CO <sub>2</sub> captured	Base cost (£ <sub>2021</sub> )	Accuracy
PDVU, 0.4m stripper basis	9 tpd	£4,000,000	-50% / +100%
PDVU, Intermediate	20 tpd	£7,000,000	-50% / +100%
Original basis	100 tpd	£20,000,000	-50% / +100%

The evaluation of existing test facilities presented in this document indicates a niche exists within the carbon capture development industry for a long-term de-risking facility. In response to the large number of projects likely to seek simultaneous deployment and results from demonstration plants, it is likely that multiple units would be required to be deployed within a short period of time. Therefore, this report indicates a preliminary preference towards smaller mobile units of the 5-9tpd scale for the PDVU. The benefits of a smaller demonstration unit scale are summarised as:

- Lower capital cost (reduced government or company funding required)
- Quicker deployment, owing to easier integration within existing sites (lower power and cooling demand)
- Smaller footprint required
- Mobile, allowing units to be reused on multiple sites once test campaigns are complete
- Lower operating costs

The case study has been completed for a carbon capture demonstration plant with a nominal capture capacity of 9 tonnes per day of CO<sub>2</sub> captured in an Energy from Waste application. The PDVU could be alternatively implemented with minor modifications to process CCGT flue gas and nominally capture up to 5 tonnes per day. At the proposed 5-9 tonnes per day scale, the PDVU would meet the key objectives for de-risking various applications and technologies simultaneously by deploying multiple units.

The case study has been based on solvent-based capture technology and has provided outline budget information as approximately £4 million and an outline schedule of approximately 20 months from beginning of FEED through to operation.

While the original purpose of the demonstration plant has been outlined as primarily de-risking carbon capture deployment, the plant can also potentially be used for investigating site-specific optimisations.

# 1. Nomenclature

The following nomenclature has been used within this report:

Acronym	Description
CATO	CO <sub>2</sub> Afvang, Transport en Opslag (CO <sub>2</sub> capture, transport and storage)
CCU	Carbon Capture Utilisation
CEPCI	Chemical Engineering Plant Cost Index
CO <sub>2</sub>	Carbon Dioxide
DCC	Direct Contact Cooler
DeSO <sub>x</sub>	Desulphurisation
EfW	Energy from Waste
IPS	Intermediate Pressure Steam
LPS	Low Pressure Steam
MEA	Monoethanolamine
MHI	Mitsubishi Heavy Industries
N <sub>2</sub>	Nitrogen
NAOH	Sodium Hydroxide
NCCC	National Carbon Capture Centre
NO <sub>x</sub>	Nitrogen Oxides (NO <sub>2</sub> , NO <sub>3</sub> )
PACT	Pilot-scale Advanced Capture Technology
PCC	Post Combustion Capture
PDVU	Pre-Deployment Verification Unit
RAM	Reliability, Availability and Maintainability
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SO <sub>x</sub>	Sulphur Oxides (SO <sub>2</sub> , SO <sub>3</sub> )
TCM	Technology Centre Mongstad
TEG	Triethylene Glycol
Tonnes	1000 kilograms
tpd	Metric tonnes-per-day

## 2. Introduction

### 2.1 The project

AECOM has been appointed by BEIS to conduct a review of next generation carbon capture technologies and a techno-economic analysis of selected options to benchmark them against a base case of current state of the art amine solvent technology. The review will consider the potential application of carbon capture technology to different industrial, waste and power sites. The outputs of the assignment are intended to inform government decisions relating to the provision of innovation support funding for carbon capture, and future policy around CCUS deployment. AECOM are working with Professor Jon Gibbins of the University of Sheffield who has been a director of the UK CCS Research Centre since 2012.

The study commenced in August 2021 and will be completed in April 2022. The main deliverables are:

- A report on next-generation carbon capture technologies, focussing on technologies with the potential to be deployed in the order of 1,000 tonnes per day scale by 2030.
- An industry workshop to gather feedback on barriers and opportunities relating to the development of carbon capture projects, which will inform an updated report.
- A case study of a mobile carbon capture de-risking project (**this report**).
- A techno-economic methodology and benchmarking report.
- A techno-economic analysis of carbon capture technology options considering different technologies and different industries.
- A second industry workshop to present the findings of the study and allow carbon capture technology providers to present their technologies.

The review does not cover the transportation and storage of CO<sub>2</sub>, direct air capture technologies, hydrogen production, biochar technologies or certain other technologies, discussed in detail in the Work Package 2 report.

### 2.2 Case study objectives

This report outlines a reference case study for a carbon capture demonstration plant for BEIS to use in assessment of next-generation demonstrator plants seeking BEIS funding.

The objective of the case study was to develop a concept design for a nominal 100 tonnes per day of CO<sub>2</sub> captured in an Energy from Waste application.

The demonstration plant is to use a solvent-based technology to operate extended test campaigns (e.g. on the order of 10,000 hours) at representative facilities and therefore predict reclaimer, waste stream, contaminant and make-up rates.

### 2.3 Review of existing state of the art for CCS facilities

Multiple test facilities already exist for proving solvent performance, generally at or below the 100tpd scale, see Table 1 for a non-exhaustive summary, as well as brief commentary on scale and reclaiming at each facility.

**Table 1 – Constructed CCS Facilities at Pilot and Full-Scale**

Name	Scale	Approximate Production (tpd)	Comments
TCM	Pilot	80	Verify process performance e.g. energy consumption. CHP or refinery flue gas. Reclaimer normally in batch use
NCCC	Pilot	10	Processing coal flue gas feedstock, Reclaimer normally in batch use
PACT	Pilot	1	Determine solvent energy requirements and CO <sub>2</sub> removal performance, no reclaimer
CATO	Pilot	6	Determine flue gas compatibility, scale-up (closed)



Name	Scale	Approximate Production (tpd)	Comments
Aker Mobile Test Unit	Pilot	1	Mobile plant testing a variety of flue gases, reclaiming is believed to occur, but this information has not been reported in public domain sources
Boundary Dam	Full	~3,000	Full scale plant for reference, processing slipstream from coal power plant flue gas stack with capture CO <sub>2</sub> used for enhanced oil recovery
Petra Nova	Full	4,000	Full scale plant for reference, processing slipstream from coal power plant flue gas stack with capture CO <sub>2</sub> used for enhanced oil recovery. Reclaiming with success was reported

Note from Table 1 above that monitoring of solvent health and testing with intentional integration of reclaiming into the core process is generally less well developed than, for example, the testing of solvent performance metrics such as energy consumption. The majority of test facilities (with the exception of the Aker Mobile Test Unit also referred to as Just Test) are fixed and therefore are generally limited in the types of flue gases available for testing.

Therefore, a gap has been identified for a facility such as the PDVU for long-term testing of capture plant directly on candidate flue gases by sites wishing to explore carbon capture as a potential technique for meeting their climate change obligations.

## 2.4 Case study terms of reference

The initial terms of reference for the carbon capture demonstration plant were to develop a concept design for a nominal 100 tonnes per day of CO<sub>2</sub> captured in an Energy from Waste application. Such a plant would be significant in size (0.3 to 0.5 hectare), likely be a fixed installation with a project budget in excess of £10million.

As a result, the case study was expanded to consider the potential of a smaller unit that could be delivered under £10 million and suitable to be moved after a test campaign had been completed from one site to another.

The mobile de-risking concept – referred to as the Pre-Deployment Verification Unit (PDVU) in this report – has commonality with pilot plants in the mature water desalination industry, which are regularly used to de-risk and verify plant performance prior to investment. The desalination industry includes recent examples such as the Masdar Ghantoot pilot programme which was completed in 2017 [1]. The Ghantoot programme objectives included (among others) extended operation in-situ to explore cost reduction and technology verification prior to provide valuable feedback into Masdar's design process for future desalination plants.

The PDVU will have the following key objectives:

- Intentionally mobile construction, with fabrication to enable containerised transportation to the first site and reuse for future de-risking and/or research and development programmes once the test campaign is complete
- Solvent-agnostic generic design with flexibility to undertake minor modifications for site-specific criteria such as:
  - Alternative aqueous solvent formulations including proprietary mixes as well as open-art mixes such as 35wt% monoethanolamine (MEA)
  - Ready access to modify columns or connect other proprietary equipment such as mist eliminators and flow distributors
  - Testing of a variety of flue gas pre-treatment strategies, including bypass of pre-treatment and processing of raw flue gas within the capture unit.
  - Testing of a variety of reclaiming strategies, with flexibility to modify the thermal reclaimer unit according to individual site and solvent licensor specifications. The reclaiming strategies will be based on those intended for the full-scale plant.

The plant design balances the capability to accommodate a range of site-specific conditions and requirements for the industrial sectors with the specification that would be achieved for a site and sector specific design. This

compromise is recognised and accepted as the rationale of the plant is to de-risk technologies rather than optimise solutions.

## 2.5 Risks targeted by the Pre-Deployment Verification Unit

The PDVU unit concept has been developed for use by sites wishing to obtain key process data regarding long-term solvent performance in realistic conditions for representative flue gas. It is intended that the data from the extended test run would be used to address a variety of process risks, which have been summarised in Table 2 below. The risks have been categorised into three overall categories:

- Critical risks which may cause plant shutdown as well as wider industry impacts
- Medium risks which may harm the plant operation such as uptime or additional unexpected operating expenditure
- Marginal benefits which comprise items that may identify cost reduction opportunities or other optimisations through de-risking

**Table 2. Risk Table**

Risk category	Risk description	Cause without de-risking	Effect with de-risking on real site flue gas
Critical risks	Sites shut down, T&S network under-utilised, potential for UK Government taking T&S capacity risk	Long-term onset of hazardous atmospheric emissions to air or water	Identify mitigation measures (e.g. post-treatment, alternative operating mode or change solvent mix) with long-term de-risking. Full scale plant includes any necessary means to maintain compliance through full operating life.
		Project uneconomic - unable to recover running costs, or fails to meet BEIS DPA/ICC/other business model criteria	Identify full process OPEX and validate operating performance. FID of full-scale plant can take into consideration long-term OPEX for own flue gas.
Medium risks	Exceed environmental permit conditions	Process upsets causing outages in excess of annual emissions limits	Identify any low RAM and modify full-scale design where appropriate
	Excessive waste disposal costs	Hazardous waste classification of process waste e.g. Cr from corrosion of stainless, hazardous degradation products	Identify long term waste chemical composition and formation rate
	Barriers to deployment of CCUS	Risk of not obtaining permit, slow technology maturation, non-optimal technology choices due to lack of test data to demonstrate BAT.	Demonstrate long-term emissions performance at small scale prior to FID, test variety of advanced technologies and solvents as pilot for full-scale plant.
Marginal benefits	Potential for cost reduction	Equipment/packing/materials over specified in conservative design	Identify cost reduction options for full scale plant
	Potential for waste classification as 'non-hazardous'	Solvent waste likely to be pre-emptively assumed to be hazardous leading to high potential disposal costs	Verify presence/absence of hazardous components in solvent waste
	Potential for higher capture efficiencies	Challenges of transient and residual emissions during off-design performance become more significant barriers to future projects being willing to commit to further elevating reference capture efficiencies	Potential to enable higher threshold levels to be set for future plant by directly testing off-design performance modes and means for maintaining high capture efficiencies during off-design performance (such as buffering start-up emissions)

## 2.6 Proposed scale for de-risking project

Setting the scale of the PDVU has a variety of impacts on cost, schedule, feasibility of mobility as well as other secondary effects which would require consideration.

## 2.6.1 Maximum size

At the largest end of the spectrum, 100tpd was used as the top boundary for the possible size of the PDVU. 100tpd is comparable to a large test facility such as TCM (80-100tpd depending on flue gas) or some full-scale plant such as the Tata Chemicals (approximately 120tpd). Note that neither TCM nor the Tata Chemicals plant have any provision for mobility, however, this category of plant represents the state-of-the-art for scale-up testing and/or full-scale application for some industrial sites.

## 2.6.2 Minimum size

Generally, it is accepted by the main packing vendors that the minimum threshold size for valid scaling of packing performance is driven by a minimum column diameter of approximately 0.4m. Below the threshold size, packing performance prediction may be unreliable, due to unpredictable effects on the mass transfer performance. Therefore, 0.4m has been used as the minimum threshold for the size of the PDVU stripper column, with an estimated capture capacity of up to 5tpd when operating with CCGT flue gas and 9tpd with EfW flue gas.

## 2.6.3 Intermediate size

An intermediate scale of approximately 20tpd represents a compromise between the two extremes as a more cost-effective option with potential for mobility. Initial process design that has been undertaken as part of this work package indicates that the majority of equipment to be used if 20tpd were selected would be industry-standard size and types with minimal bespoke equipment design. Industry standard equipment would be required for an efficient overall project capital cost.

## 2.6.4 Size selection recommendations

The final selection of the proposed plant size will be a compromise between cost, mobility, scale-up, as well as feasibility of integration with the host site and feasibility for continued operation beyond the initial site or configuration. The decision regarding the final size of the PDVU will require consultation with the owners of individual sites that may be willing to host the PDVU for de-risking their full-scale deployment. For example:

- If scale-up and minimising the gap between PDVU scale and full-scale remains by far the most significant driver, then the maximum scale plant may be preferable. However, although some efficiencies could likely be reached through standardisation of the design, it is unlikely that a large number of PDVU units would be deployed due to the high cost associated with a plant on the order of TCM in capacity.
- If a compromise for a practical, flexible generic design is recognised, then approaching approximately 20tpd for the scale of the facility would represent a more cost-effective option for a mobile unit that may be retained following the completion of its test duration and redeployed at another facility.
- If the primary concern remains de-risking of projects with operation for long periods of time on real-world flue gas then the 5-9tpd scale will likely be sufficient.

The evaluation of existing test facilities presented in Section 2.3 indicates a niche exists within the carbon capture development industry for a long-term de-risking facility. In response to the large number of projects likely to seek simultaneous deployment and results from PDVU, it is likely that multiple units would be required to be deployed within a short period of time. Therefore, this report indicates a preliminary preference towards the 5-9tpd scale for the PDVU. This preference has been discussed and verified at the Advisory Board meeting in January 2022.

## 3. De-risking Plant Concept

### 3.1 Process description

The following process description applies to a process using monoethanolamine (MEA) at 35 wt.% and therefore if a different solvent was deemed preferable the temperatures and pressures stated would have to be adjusted.

A Block Flow Diagram (BFD) of the process is provided in Figure 1.

#### 3.1.1 Flue gas pre-treatment

Flue gas from the interface with the host emitter enters the pre-treatment package (which is bypassed in the initial configuration to test solvent degradation rate without pre-treatment in order to establish a baseline for comparison), into a blower through ducting at around 60-120°C (see Section 3.2.1 for potential pre-treatment options). This blower is used to overcome the pressure losses that occur whilst the flue gas travels from the host emitter, however it also causes a rise in the temperature of the flue gas by approximately 10°C. The flue gas is sent via ducting into the Direct Contact Cooler (DCC), which quenches the flue gas temperature to the desired value of approximately 40-45°C for absorption.

The quench to lower the flue gas temperature in the DCC is provided by wash water cooling spray which also reduces SO<sub>x</sub> and NO<sub>x</sub> concentrations in the flue gas further from Pre-treatment levels before it enters the amine absorber. This coolant flow is provided by the DCC Circulation Pump which pumps water from the sump of the DCC, through the DCC Circulating Water Cooler which uses fin-fan cooling to reduce the water temperature before the cooled water is returned to the top liquid distributor in the DCC.

The quench water condenses some of the combustion-generated water vapour present in the flue gas from the host emitter site, which accumulates in the DCC and is then removed allowing it to be reused elsewhere in the process. This water (along with contaminants dissolved in the flue gas) is removed via a slip-stream from the DCC Circulation Pump and is then sent to either:

- Make-up to the amine reclaimer package (without intermediate treatment)
- Process water storage tank for reuse and make-up to the solvent loop. However, for processes where the DCC water is expected to be contaminated with high levels of impurities, an intermediate polishing unit may be fitted as an optional package upstream of the process water storage tank.

Flue gas cooling via the DCC is presented as the minimum level of pre-treatment for the flue gas prior to capture. Alternative options for further pre-treatment in addition to temperature control are considered in Section 3.2.1.

#### 3.1.2 Flue gas absorption

After being quenched to the correct temperature, flue gas enters the first carbon dioxide (CO<sub>2</sub>) absorber column at the lowest section of packing. Semi-lean amine solution from the intercooler enters the column at the top of the packing at approximately 40°C and counter-currently contacts the flue gas which is travelling upwards. This results in the absorption of CO<sub>2</sub> into the liquid phase as a temporary salt product via the acid-base reaction between dissolved CO<sub>2</sub> and MEA. Amine rich in the CO<sub>2</sub> drops into the absorber sump whilst treated flue gas rises and exits the column where it then enters the sump of the second absorber column. The second absorption column provides further contact between the partially treated flue gas travelling upwards; and lean solvent supplied to the top of the packed section which travels downwards and collects in the second absorption column sump. The second absorption column sump gathers the semi-lean solvent which is pumped through the intercooler into the top section of the first absorption column. Following the second absorption column, flue gas enters the wash column. Note that CCGT flue gas may not require intercooling, in which case the intercooler would be either manually bypassed or not fitted for a CCGT application.

The wash column contains two wash beds for recovery of contaminants from the treated flue gas, comprising:

- A single water wash bed which circulates water to cool the flue gas that enters from the amine absorption column, condensing volatile compounds within the flue gas. Excess overflow from this wash bed is returned to the main solvent circulation loop by a section comprising of a Wash Stage Pump, which pumps through to a Wash Cooler, bleeding excess into the solvent line to storage, with the remainder recycled to the top of the water wash stage. The primary function of this section is to minimise solvent wastage by returning the volatile solvent to the circulation loop.

- A second wash bed circulating with concentrated sulphuric acid to capture contaminants such as ammonia from the treated flue gas to ensure air emissions controls are met. Ammonia (and any residual solvent not previously recovered by the water wash bed stage) is neutralised by this sulphuric acid solution with excess solution removed for off-site disposal via an Acid Drain Drum. Fresh sulphuric acid is supplied to the suction line of the Acid Wash Pump, which circulates the acid wash from the acid wash draw tray through the Acid Wash Cooler before finally entering the liquid distributor at the top of the acid wash section.

Prior to being discharged to the atmosphere, the flue gas is passed through a mist eliminator device to recover any mist or droplets from the flue gas. Following the mist eliminator, the flue gas enters the stack and emissions monitoring equipment for discharge to atmosphere.

### 3.1.3 Rich amine regeneration

Rich amine from the sump of the first absorber column is pumped by the Rich Amine Pump through the Lean/Rich Amine Cross-Exchanger, with the rich amine heated to approximately 110-120°C. This heated rich amine is then injected into the packed section of the CO<sub>2</sub> Stripper Column where it is stripped by rising steam and CO<sub>2</sub> vapour. At high temperatures, the amine-CO<sub>2</sub> salt formed in the absorber becomes unstable, releasing CO<sub>2</sub> as a vapour which is freely stripped by the rising vapour stream.

The stripped amine runs down the packed section and into the sump of the regenerator. The amine is then drawn from the sump into the CO<sub>2</sub> Stripper Column Reboiler where saturated Low Pressure Steam (LPS) supplies the heat, condensing within the tubes and transferring heat into the solvent side to maintain a temperature in the range of 125-130°C. Boiling amine solution is returned to the stripper and a hot amine stream is also drawn from the sump.

The overheads steam from the regenerator is partially condensed and cooled to 25-40°C in the CO<sub>2</sub> Stripper Condenser to recover water vapour into the CO<sub>2</sub> Reflux Drum. Any condensed water is returned as a washing reflux to remove amine carried into the top section of the Stripper Column by the CO<sub>2</sub> Stripper Reflux Pump while vapour from the separator (mainly consisting of CO<sub>2</sub> saturated with water vapour) is sent to the compression package. A pressure control valve in the overhead line maintains a stripper pressure of approximately 1-1.5 barg.

The CO<sub>2</sub> Reflux Drum is also provided with a purge line to remove occasional build-up of volatile components from the stripper overhead line where they may reduce full column capacity if allowed to accumulate. This purge would be used intermittently and discharge into a Reflux Drain Drum for offsite treatment.

### 3.1.4 CO<sub>2</sub> compression and export

The wet CO<sub>2</sub> product vapour is sent to a Suction Knock-Out Drum to recover any condensed water droplets and allow a second layer of protection against solvent carry-over after the Reflux Drum. Any recovered liquid is returned to the Stripper Column by the Knock-Out Water Pump. The Suction Knock-Out Drum also receives:

- Recovered liquid from the Compressor Package Stages
- Recycled gas from the Molsieve Dehydration Package

After the Suction Knock-Out Drum, the CO<sub>2</sub> product enters the Compression Unit where it is compressed in several stages whilst liquid from the Inter-Stage Knock-Out Drums is returned to the Stripper Column.

Following compression, the CO<sub>2</sub> product is sent to the De-Oxygenation Package which uses hydrogen gas to reduce oxygen content to below 10ppmw. The De-Oxygenation Package is supplied with LPS to preheat the CO<sub>2</sub> product to approximately 130°C for the catalytic oxygenation reaction.

Following de-oxygenation, the CO<sub>2</sub> product enters the Molsieve Dehydration Package where molsieve drying is used to reduce water content to below 50ppmv. Any water recovered during bed regeneration is returned in the recycle to the Stripper Column. It has been assumed that regeneration heat would be supplied from an electric heater for the proposed configuration.

Finally, the conditioned CO<sub>2</sub> is liquified in the CO<sub>2</sub> liquefaction stage by Joule-Thomson flash, with liquid product CO<sub>2</sub> collected in an insulated drum for sampling and measurement of any impurities.

Where the objective of the PDVU is to analyse a capture technology's suitability for a flue gas stream in early project development, rather than to capture CO<sub>2</sub> there is an opportunity to reduce both initial investment costs

and operating costs of the PDVU by not including the compression and export components. In this configuration the captured CO<sub>2</sub> would be released to atmosphere.

### 3.1.5 Lean amine cooling

Hot lean amine is drawn from the regenerator sump of the Stripper Column by the Lean Amine Booster Pump before being pumped through the Lean-Rich Cross-Exchanger, where the lean amine stream is cooled to 50°C. After passing through the Cross-Exchanger, the lean amine is cooled further to approximately 40°C by the Lean Amine Trim Cooler before entering the Solvent Storage Tank which is used for process surge volume. If the plant is shut down for extended outage, lean amine should be drained to this Solvent Storage Tank which is to be sized to allow storage of the full solvent inventory.

From the Solvent Storage Tank, lean amine is pumped by the Lean Amine Circulation Pump to the second absorber column to begin the process of CO<sub>2</sub> capture again.

### 3.1.6 Amine reclaiming

The purpose of the Amine Reclaimer Package is to remove solvent degradation products and other contaminants from the solvent circulation. The Amine Reclaimer Package in the proposed configuration has been based on a semi-continuous concept comprising continuous processing of a slip stream of the hot lean amine from the reboiler product line, recovering some reversibly degraded solvent, as well as concentrating residual impurities into a sludge for intermittent removal. The Reclaimer Package is operated at atmospheric pressure using Intermediate Pressure Steam (IPS) extraction from the cold reheat for two operations:

- To boil the slip stream in an atmospheric reclaimer reboiler still, breaking the heat-stable salt degradation products present to recover water and solvent as a vapour stream. The vapour is driven back into the sump of the main CO<sub>2</sub> Stripper Column with a steam ejector.
- To raise IP-level motive steam to drive the steam ejector. The motive steam is generated within the reclaimer package by boiling the discharge water (untreated) from the DCC in a heat exchanger using the extracted IPS to provide heat. The extracted IPS condensate is mixed with the reclaimer reboiler steam condensate and sent to condensate cooling. This means that no water mass is consumed from the steam cycle by the reclaimer package as the DCC effluent provides the mass for the motive force used to drive the ejector.

Periodically, the build-up of heat-stable salts, degradation products, metals and other dense contaminants are removed from the reclaimer package for off-site disposal in batches.

Note that the process and philosophy for concentrating and removing the residue will be site-specific and solvent-specific to allow alternative packages to be tested. The proposed concept for the PDVU would be sympathetic to a variety of reclaiming strategies by either minor modification or replacement of the default Amine Reclaimer Package for individual projects as part of a comprehensive solvent health management philosophy. For the purposes of setting the default configuration, it has been assumed that a single-stage reclaimer (operating at either atmospheric pressure or partial vacuum) will be used initially for robust operation with MEA solvent as the default configuration.

### 3.1.7 Boiler plant

To ensure mobility, steam for the process will be supplied using an on-site packaged boiler plant as opposed to depending on connections from the host facility. Should heat be available from the host facility at a preferential cost, the boiler plant could be superseded by an interface for extraction of steam and return of condensate between the PDVU and the host facility.

LPS supplied at a temperature of approximately 140-150°C and a pressure of up to 3.5 barg. Saturated LPS enthalpy is used in the amine reboiler and the De-Oxygenation Package Pre-Heater.

IPS for the CCS plant is raised at two different conditions for varying parts of the process which are:

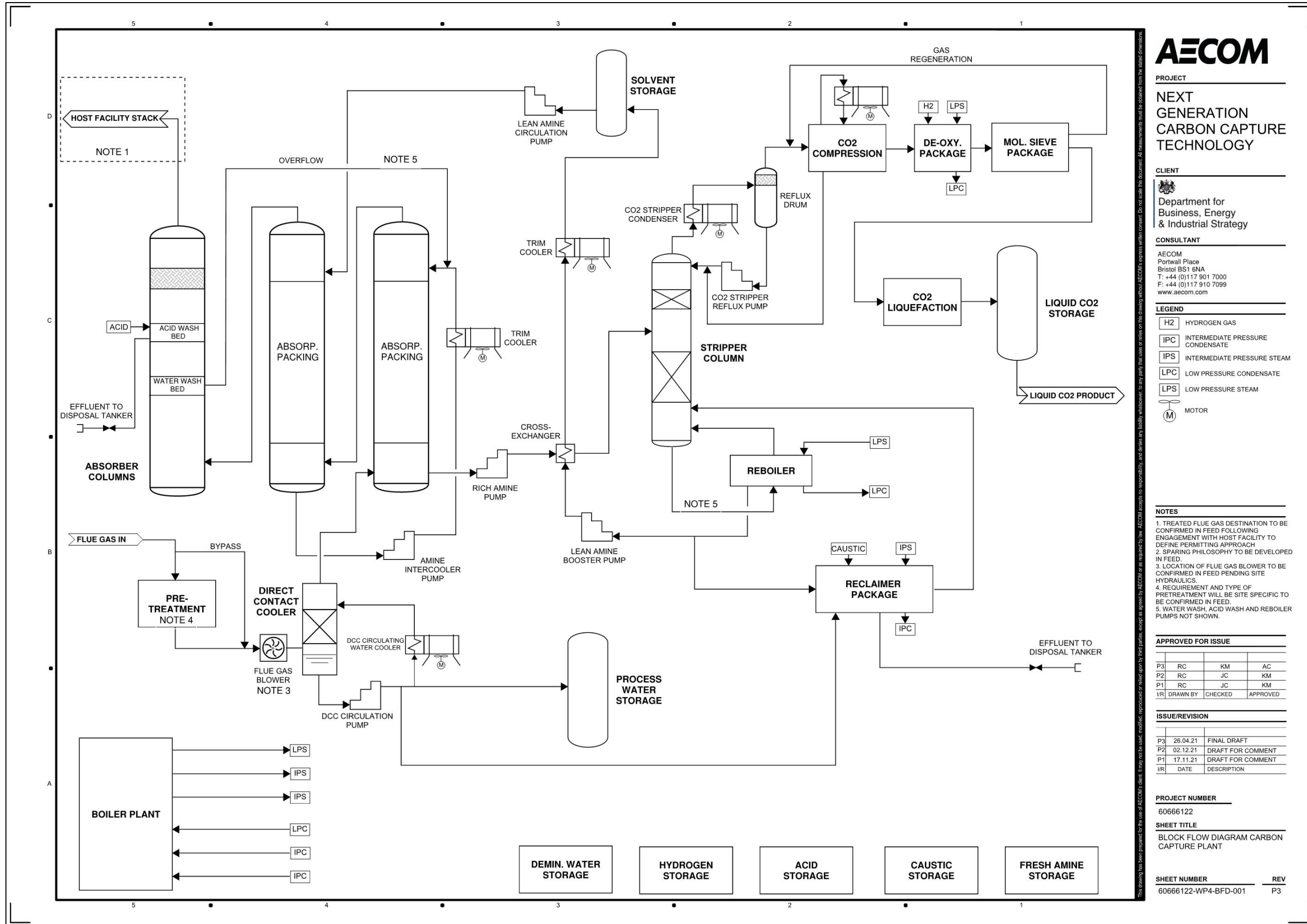
- 25 barg for the TEG Dehydration Package and the Reclaimer Package Ejector Heater
- 10 barg for the Amine Reclaimer Package

IPC will be collected and flashed to provide LPS in an intermediate flash drum, offsetting some LPS requirement. Saturated LPC will be mixed in a collection drum operating at atmospheric pressure. The mixed condensate stream is then returned via the Condensate Return Pump which sends the condensate to the packaged boiler plant.

### 3.1.8 Drains

The closed drain systems will comprise separate closed drain vessels:

- An Acid Drain Drum, equipped with a vacuum truck connection and backup pump for trucks without a vacuum pump. Acid wash effluent would be collected by road trucks for off-site disposal or reuse. This Acid Drain Drum accepts the combined acid wash effluent streams from:
  - CO<sub>2</sub> Absorber acid wash bleed (continuous)
  - DCC Produced Water Contactor ammonia absorption section (continuous)
- An Amine Closed Drain Drum equipped with a vacuum truck connection and backup pump for trucks without a vacuum pump. This drum is used to store residual amine drains if these are deemed not suitable for recycle into the Lean Amine Storage Tank. No continuous amine drainage is planned in normal operation.
- A Reflux Drain Drum equipped with a vacuum truck connection and backup pump for trucks without a vacuum pump. This drum is provided as an intermediate hold-up storage of reflux purge effluent from the stripper reflux line. Effluent from the Reflux Drain Drum is to be removed for off-site disposal.



**PROJECT**  
**NEXT GENERATION CARBON CAPTURE TECHNOLOGY**

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**LEGEND**

H2	HYDROGEN GAS
IPC	INTERMEDIATE PRESSURE CONDENSATE
IPS	INTERMEDIATE PRESSURE STEAM
LPC	LOW PRESSURE CONDENSATE
LPS	LOW PRESSURE STEAM
(M)	MOTOR

- NOTES**
1. TREATED FLUE GAS DESTINATION TO BE CONFIRMED IN FEED FOLLOWING ENGAGEMENT WITH HOST FACILITY TO DEFINE PERMITTING APPROACH
  2. SPARING PHILOSOPHY TO BE DEVELOPED IN FEED.
  3. LOCATION OF FLUE GAS BLOWER TO BE CONFIRMED IN FEED PENDING SITE HYDRAULICS
  4. REQUIREMENT AND TYPE OF PRE-TREATMENT WILL BE SITE SPECIFIC TO BE CONFIRMED IN FEED.
  5. WATER WASH, ACID WASH AND REBOILER PUMPS NOT SHOWN.

**APPROVED FOR ISSUE**

P3	RC	KM	AC
P2	RC	JC	KM
P1	RC	JC	KM
IR	DRAWN BY	CHECKED	APPROVED

**ISSUE/REVISION**

P3	26.04.21	FINAL DRAFT
P2	02.12.21	DRAFT FOR COMMENT
P1	17.11.21	DRAFT FOR COMMENT
IR	DATE	DESCRIPTION

**PROJECT NUMBER**  
 60666122

**SHEET TITLE**  
 BLOCK FLOW DIAGRAM CARBON CAPTURE PLANT

**SHEET NUMBER**      **REV**  
 60666122-WP4-BFD-001      P3

Figure 1 – Proposed Process BFD (Ref. 12)



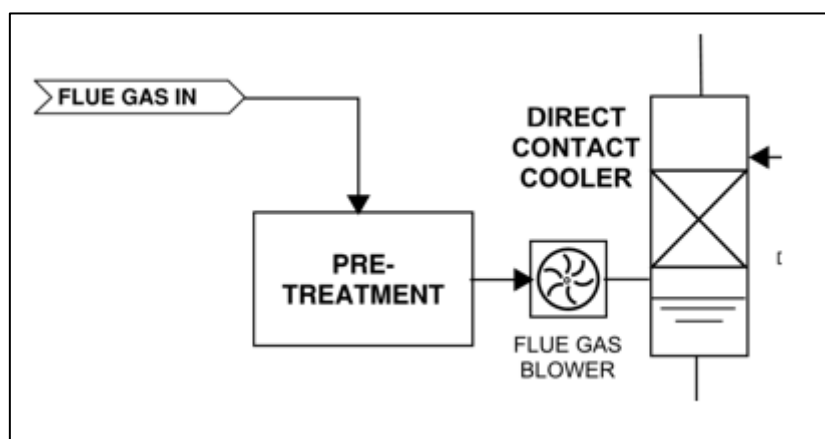
## 3.2 Technology description (optional components)

The technology chosen for the proposed process shown in Figure 1 was selected with the aim of de-risking prior to deployment of full-scale carbon capture projects. Achieving long term test data on the proposed flue gas will be key to forecasting solvent make-up rate, reclaiming rate, waste production and other factors affecting solvent health, and therefore project operating costs beyond initial operation once some solvent degradation has taken place.

### 3.2.1 Flue gas pre-treatment

Dedicated pre-treatment for Post-Combustion Capture (PCC) may be required as amine-based solvents that are typically used for PCC are well documented as susceptible to chemical degradation in the presence of contaminants such as NO<sub>x</sub> and SO<sub>x</sub> present in the raw flue gas stream [2] [3]. The level and type of contamination will drive selection of the pre-treatment technology (if any), in combination with the solvent stability to the particular contaminant to avoid performance losses and increased operating costs [4].

This process will assess the benefit of additional flue gas pre-treatment as a package, as shown in Figure 2, to determine the potential mitigation of long-term degradation effects on the solvent used. Interface conditions will be clearly defined to enable effective design of the pre-treatment package, with appropriate flexibility in flue gas blower design to accommodate a variety of methods.



**Figure 2 – Flue gas pre-treatment package outline**

Depending on the process fuel being combusted the types of harmful contaminants in the flue gas may vary as shown below:

- Natural gas combustion: NO<sub>x</sub>, SO<sub>x</sub>
- Coal/biomass combustion: NO<sub>x</sub>, SO<sub>x</sub> and other acids, particulates such as transition metals

The level of contaminants present in flue gases also varies by sector in line with sector-specific environmental guidance. For this reason, several different methods and stages of pre-treatment for flue gas exist and have seen various levels of deployment, reinforcing the requirement for flexibility of the PDVU concept to enable a variety of pre-treatment options. Individual plants may wish to test some or all the potential pre-treatment stages listed below which include:

- **Particulate Removal**

A common method of removing particulates from a flue gas stream is using an Electrostatic Precipitator (ESP). This removes particles by charging them either positively or negatively before they pass collector plates with the opposite charge which attract the particles, removing them from the flue gas stream. The ESP can either be wet or dry, with dry the more common type. This refers to the method with which the particles are collected, either by mechanical vibration (dry) or with a water wash (wet). This method has a typical collection efficiency of >99% [5].

### - **Catalytic Reduction of NO<sub>x</sub>**

NO<sub>x</sub> are typically formed during combustion of fuels, with the most common methods of removal being Selective Catalytic Reduction (SCR) or Selective Non-Catalytic Reduction (SNCR) [6].

SCR is the most commonly used method for reducing NO<sub>x</sub> in power generation systems post-combustion. Typically, an aqueous ammonia reagent (19-29% ammonia) is injected into the exhaust stream of the power generation facility containing the flue gas as a reducing agent in the presence of a catalyst (usually containing a mixture of tungsten, titanium and vanadium [7]). This causes a reaction, producing nitrogen (N<sub>2</sub>), water and small quantities of CO<sub>2</sub>. This method is the most suitable if large-scale reduction is required with reduction values of up to 90% or potentially greater possible.

SNCR has also been commonly used in power plants using coal or biomass as well as EfW facilities. SNCR follows a similar procedure to SCR of injecting aqueous ammonia into the flue gas producing N<sub>2</sub> and water vapour, however no catalyst is used. To compensate for this reduced rate of reaction, high temperatures (870°C to 1150°C) are required. This method saves on the cost of expensive catalysts but is not suitable for processes where high rates of reduction are required with typical rates only ranging from 30-70%.

### - **Desulphurisation (DeSO<sub>x</sub>)**

Flue gas produced from coal typically contains large amount of SO<sub>x</sub> making desulphurisation a crucial part of the pre-treatment process for CCS plants retrofitted to these coal plants. These can either be wet, dry or semi-dry depending on the flue gas and the available space. This is a common requirement for EfW plants.

A dry scrubbing process can be as simple as injecting hydrated lime which is fluidised in air into the exhaust ducting where it will neutralise the vast majority of SO<sub>x</sub> (>95%) present. The calcium based acidic products formed are then captured on bag filters as solids, with excess lime being recycled.

Semi-dry scrubbing requires lime mixed with water which is sprayed from the top of a chamber containing hot flue gas. The water present in the spray evaporates, cooling the flue gas with the SO<sub>x</sub> contaminants then dissolving and reacting with the lime present. After all the water present has evaporated, the solid reaction products along with any unreacted lime are carried by the flue gas from the scrubber to a dust collector (typically a bag filter) for collection. A typical rate of SO<sub>x</sub> removal of >95% is achieved with this approach.

A typical wet-scrubbing process involves feeding the polluted flue gas to the sump of a stripper column and the caustic (typically lime) is sprayed from the top of the scrubber. As the gas rises, the SO<sub>x</sub> within the flue gas is almost entirely absorbed by the lime spray (>95%), before precipitating as calcium sulphate. A limestone DeSO<sub>x</sub> process has been tested and proven to be effective at removing Sox from a coal-based power station at pilot-plant scale at Ferrybridge Power Plant by ERG [8]. If desired, the slurry can also be recirculated and injected with oxygen, forming gypsum which can be sold as a by-product [9].

## 4. Budget

### 4.1 Capital costs

An approximate capital budget required for the PDVU has been calculated based on total anticipated equipment and construction costs. Publicly available information on other similar project data has been scaled to estimate the cost of the major items in the budget. The purpose of this task was to provide BEIS with a value regarding the budget likely to be necessary to develop such a de-risking plant on a generic open-art basis.

This cost estimation has focused on an estimate of the EPC cost and does not include additional expected costs such as tax, insurance, land lease or acquisition. Assumptions have been made regarding typical engineering, procurement and indirect costs associated with the cost build-up. Costs have been presented in £<sub>2021</sub> with escalation estimated using the CEPCI. No attempt has been made to reconcile impacts on costs due to recent disruptive events such as Brexit or the Covid-19 pandemic.

The costs have been estimated consistent with an AACE Class 5 level methodology, generally used for project screening and early feasibility studies. An overview of the calculated EPC cost for the PDVU at a range of sizes – (as well as comparison against other recent project data) is presented in Table 3 below.

**Table 3. Estimated EPC cost for PDVU and other projects**

Plant	Base cost (£ <sub>2021</sub> )	Accuracy	Source
PDVU, 0.4m stripper basis	£4,000,000	-50% / +100%	Scaled from previous project data, capacity up to 5tpd for CCGT flue gas or up to 9tpd EfW flue gas. Assuming only one flue gas archetype
PDVU, 20tpd basis	£7,000,000	-50% / +100%	Scaled from previous project data, assuming EfW application and only one flue gas archetype
PDVU, 100tpd basis	£20,000,000	-50% / +100%	Scaled from previous project data
TATA Chemicals, ~120tpd	£16,700,000	N/A	<a href="https://www.geos.ed.ac.uk/sccs/project-info/2703">https://www.geos.ed.ac.uk/sccs/project-info/2703</a>

### 4.2 Operating costs

Indicative operating data for the process has been provided in Appendix A, at the 0.4m stripper basis scale. Further OPEX evaluation would be undertaken in FEED.

## 5. Project Schedule

This section provides an indicative, high-level schedule for the development of a 9 tonnes per day carbon capture demonstration plant. All activity duration times given are estimates and will be dependent on-site specific challenges, technology selected, additional site-specific pre-treatment of the flue gas (if required), as well as the modularisation approach which will be determined in FEED.

A draft project schedule is presented in Table 4, and assumes the design is based upon a single generic configuration, using open art design and non-proprietary solvents. Additional time prior to FID would be required for a design that utilised licensor proprietary solvents or alternative technologies due to additional commercial and non-disclosure arrangements required.

The fabrication phase is predominantly led by the lead time for procurement of major plant items such as:

- Packed columns (assumed to be subcontracted as a package to a packing vendor)
- Heat exchangers
- Compressor package

**Table 4. Preliminary project key milestone schedule**

Step	Month in relation to Final Investment Decision
Development studies	(-4)
FEED kick-off	(-3)
Final Investment Decision and award of EPC	0
Procurement of major items complete	3
Fabrication of all modules complete	11
Site installation complete	12
Site commissioning complete	13

## 6. Next Steps in Development

### 6.1 Future Project Requirements

Other than the items considered in this report, there are a number of other project requirements that must be completed as part of the development of a demonstration plant. These activities, listed in Table 5, were considered out of scope for this report but are essential stages in the progression of the project.

**Table 5. Description of activities to be completed in next steps of development.**

Activity	Description
Project Objectives	Refine specific purpose of demonstration plant, including any potential research and innovation objectives.
Site Location	Identify a suitable host sites for the first PDVU with feasible supply of flue gas, utilities and desire to de-risk project. Outline strategy for sharing test data with any other project partners.
FEED-phase funding	Establish funding for FEED
FEED	Undertake FEED-level engineering design to produce layouts, equipment specifications, philosophies, developed cost estimates and other associated deliverables to enable EPC for the PDVU by a competent fabrication contractor. Undertake Reliability, Availability and Maintainability (RAM) studies to support development of overall Sparing Philosophy and ensure RAM for the PDVU is consistent with the host site.
Contract strategy	Determine contracting strategies for the EPC and operational phases

This is not an extensive list and there will likely be many more activities to be completed prior to the commencement of the project. In addition to this, the tasks completed as part of this report can be developed further as the project progresses so that more detail may be added.

### 6.2 Value Proposition

The following key items have been identified as a value proposition from deployment of the PDVU:

- Through long-term testing in situ, solvent health and degradation can be monitored allowing solvent lifespans to be predicted using real flue gases.
- Providing a flexible configuration that is easily adaptable to different flue gases and configurations, e.g. ready-built configuration allowing for testing delayed regeneration duty through solvent storage methods.
- Preliminary identification of recommended downtime for cleaning as well as direct, intentional on-the-run testing of reclaiming as part of the core facility.
- Offering the flexibility to test a variety of pre-treatment options, including the impact of processing raw untreated flue gas versus treated flue gas.
- Providing ownership of the data generated by sites, as the equipment ownership will be independent from the developers of the equipment.

The main stakeholders to benefit from deployment of the PDVU would be the Government (through funding) and the site operators themselves, although the priorities of the key items to each stakeholder would vary, as discussed below:

- **Government and the public**

The Government has invested in carbon capture development and is likely to continue to do so in future. The success of the industrial clusters and the wider decarbonisation programme will depend on deployment of robust technologies with well-understood, reliable and cost-effective performance in the long term. Therefore, there is clearly a benefit to the Government in ensuring that projects have an appropriate de-risking strategy in place, whether that be with the PDVU or some alternative means.

Further, at time of writing, the draft business models for carbon capture would see a Contract-for-Difference payment to operators of the Transmission & Storage system in the event of a shortfall of transmitted CO<sub>2</sub> for

sequestration in circumstances outside the operator's control. Such an event may be the long-term shutdown of a key emitter in the event of inaccurate solvent performance prediction. Therefore, there is a direct financial incentive from the Government to minimise the risk of incurring such a scenario by ensuring appropriate de-risking measures have been taken by sites wishing to engage with clusters.

- **Operating sites**

Operating sites would be able to develop and optimise reclaiming strategies and identify waste production rates for their proposed solvent mix operating on their own flue gas mixture (or a selected equivalent facility in the case of a new-build). Further, operators would be able to identify any savings that may be possible in the design of their facilities. Through ownership of their test data, the site operators would be able to identify and trial any potential savings in the design of the full scale facility such as alternative operating strategies.

### **6.3 Related Research & Development Works**

Separate work undertaken by the University of Sheffield that is relevant to the subject of the PDVU concept and de-risking commercial projects in general has been included within Appendix B.

## 7. Conclusions

Deployment of carbon capture at scale by 2030 in the UK is likely to benefit from de-risking to establish long term performance data with certainty beyond the short-term data that is currently available. The Pre-Deployment Verification Unit (PDVU) has been proposed as a benchmark to fill the niche for long-term testing and verification of solvent health parameters on real-world flue gases.

The scale of the PDVU will be subject to confirmation with the project Advisory Board and individual sites, with an indicative preference for a plant on the order of 5-9tpd of CO<sub>2</sub> capture post-combustion from gas or waste, respectively. The preference has been made based on the likely requirement for construction of multiple plants which would overlap in deployment and therefore strong incentive to maintain costs to a minimum while still maintaining representative packing performance.

Outline EPC costs have been calculated consistent with Class 5 estimating methodology for the purpose of preliminary project screening. These costs have been estimated as a range of approximately £2 million - £8 million (accuracy of -50% / +100% with central figure £<sub>20214</sub> million) and an indicative outline for a project schedule of approximately 20 months from beginning of FEED through to operation. However, this schedule is largely driven by the expectation that procurement of major equipment for the first unit may require 6 months. It is likely that streamlining in the procurement of further units would allow some efficiencies in the programme and cost to be made.

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### 8.1 Project References

12. 60666122-WP4-BFD-001 Rev B PDVU Block Flow Diagram.pdf



## Appendix A Outline Specification

## **Appendix B – De-Risking Research and Development**

[aecom.com](http://aecom.com)