Next Generation Carbon Capture Technology

Technoeconomic Methodology Report
Work Package 5

Department for Business, Energy and Industrial Strategy

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Quality information

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Executive Summary

AECOM has been appointed by the Department for Business, Energy and Industrial Strategy (BEIS) to conduct a review of next generation carbon capture technologies and their application in the power, waste and industrial sectors. As part of this review, a technoeconomic analysis of selected technology options has been conducted. The next generation carbon capture configurations analysed have been benchmarked against scenarios using current state of the art amine solvent technology. The purpose of the technoeconomic analysis is to allow comparisons to be made between different carbon capture technologies when used in different applications.

This document describes the methodology and assumptions used in the technoeconomic analysis and benchmarking exercise conducted. A separate report provides details of the benchmark technology configurations against which the next generation technologies have been compared.

The principal steps within the methodology are:

- Defining plant configurations
- Data gathering
- Modelling of scenarios
- Summarising key outputs
- Highlighting principal assumptions and uncertainties.

Key outputs from the technoeconomic analysis include the levelised cost of CO_2 capture (LCOC), the impact on product cost and comments on the key opportunities, challenges and uncertainties for each scenario.

The LCOC is based on the whole life capex and opex for each technology assessed, assuming a 25-year operating life. For the purposes of this study, to compare capture technologies, a cost of zero (£/tonne) for exporting CO_2 to the transport and storage infrastructure has been assumed. If carbon capture plants are developed there will be costs associated with exporting captured CO_2 via transport and storage infrastructure, but these will be site specific and are outside the scope of this study.

The cost of emitting residual CO_2 that is not captured due to the limitations of the technology is not included as an operating cost in the LCOC calculation, as the LCOC relates only to the capture process. However, where operators are charged for CO_2 emissions these residual emissions costs will be paid for by the host process plant. Therefore, the cost of residual emissions is included in the impact on product cost calculation. A scenario with a lower capture level will pay a higher price for residual emissions to the atmosphere.

Understanding the assumptions and quality of data used as an input to any technoeconomic analysis provides a better understanding of the output. A summary of common assumptions and associated uncertainties has been provided. This summary gives an indication of where the important areas of uncertainty lie. Further commentary on uncertainty is provided in the write-up of each scenario.

Data and assumptions used in the technoeconomic modelling have been gathered from a variety of sources. Where possible, publicly available information has been used from journals, academic studies and third-party publications. In addition, an extensive consultation exercise was conducted involving technology providers to obtain as much information for the study as possible.

When studying emerging technologies there are unavoidably performance data that do not exist. For example, the long-term maintenance costs of an item of equipment that has never operated for a long time. These data can significantly impact the results of the analysis. Where information is absent or appears unreliable, engineering judgement has been used to inform assumptions as necessary to complete the assignment.

Our understanding of the limitations of the data has been used to inform the commentary provided on the uncertainty associated with the scenarios investigated. Understanding the strengths and weaknesses of the data available is essential in relation to interpreting the results from any study that compares emerging technologies.

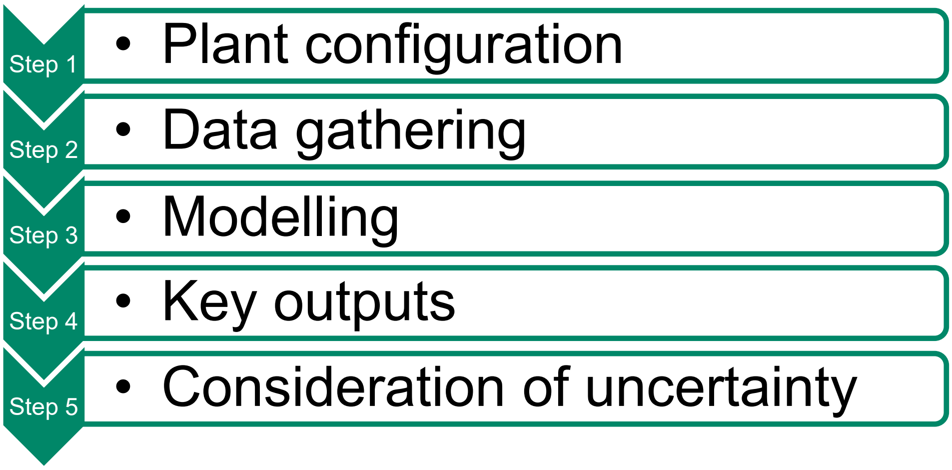
1. Introduction

AECOM has been appointed by the Department for Business, Energy and Industrial Strategy (BEIS) to conduct a review of next generation carbon capture technologies and their application in the power, waste and industrial sectors.

The methodology for completing benchmarking and the technoeconomic assessment of next generation carbon capture technologies is described herein. This document forms part of the supporting documentation for the models provided including descriptions of structure and details of data and assumptions used. Development of the methodology and benchmark scenarios constituted work package (WP) 5 of the study. Technoeconomic analysis of the selected next generation scenarios was conducted in WP 6.

Figure 1 shows the main steps in completing the technoeconomic analysis. These steps have been carried out for each of the benchmark scenarios and then subsequently for the next generation technology scenarios.

Figure 1. Technoeconomic analysis steps



The proposed benchmark carbon capture technology is Monoethanolamine (MEA) solvent-based post-combustion carbon capture. Benchmark scenarios based on this technology have been assessed for the following applications:

1. A utility scale gas-fired power plant
2. An energy from waste (EfW) plant
3. A cement manufacturing facility.

These industries were selected for the purposes of benchmarking as they are considered essential applications for carbon capture technology in the future as part of the transition to Net Zero. Furthermore, these industries cover a range of flue gas conditions that are broadly comparable to flue gases from other industries. This allows the results obtained to be of use to a wider range of industrial emitters. The benchmark scenarios are further described in a separate benchmarking report that contains information on interfaces with the main process plant, details of plant configurations and the results from the models created for the benchmarks.

The next generation carbon capture technology scenarios to be investigated are listed in Section 2. These scenarios all apply to the same emission sources as the benchmarks, but with alternative carbon capture technologies.

The assumptions and parameters that have been used to inform the development of the plant configurations and the technoeconomic models are explained in this report. The technoeconomic models created calculate technical and economic performance parameters for the scenarios investigated. The final outputs for each scenario are LCOC, an indication of the impact on product cost and comments on the key opportunities, challenges and uncertainties.

2. Plant Configurations

Plant configurations have been developed for the industries and capture technologies identified in Table 1. The carbon capture technologies selected for analysis are intended to represent a range of technology concepts. Where a specific technology provider has been identified for a technology concept, this is intended to provide a representative example of the technology type. The technology provider selection is based principally on availability of process and performance data at an appropriate scale, and willingness of the technology provider to participate in the study. For many of the concepts, alternative suppliers that offer technology based on a similar concept are available.

The main purpose of the technoeconomic analysis is to compare different carbon capture technology concepts in different industries. Due to the stage of development and developing nature of many the technologies, the final performance results calculated in this analysis may not reflect the actual performance that would be obtained by implementing projects using the selected technologies. Comments on the uncertainties associated with the scenarios have been provided.

Where possible, the capacity of the base process plant and carbon capture plant is the same for the next generation scenarios as the benchmark scenario for the industry concerned. Where information is not available at the same capacity, a plant scale within the same order of magnitude is adopted so that, in deriving LCOC, the economies of scale are broadly consistent and hence the cost per tonne of CO_2 captured is comparable.

The utility scale gas fired power generation scenarios are assumed to be constructed in association with new build gas fired power plants. For the EfW and cement manufacture scenarios it is assumed the carbon capture plants will be retrofitted to existing facilities.

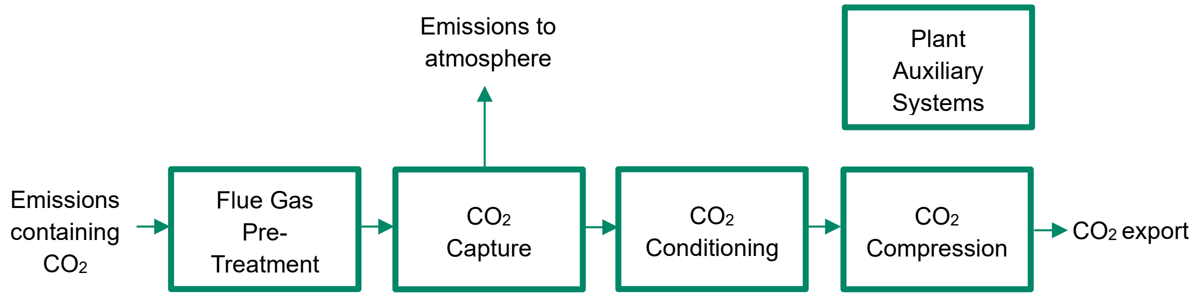
Table 1. Technoeconomic analysis options

Industry	Scenario Label
Utility Scale Gas Fired Power Generation	
Combined cycle gas turbine (CCGT) with post combustion carbon capture using MEA solvent. Plant capacity of approximately 910 MW gross electrical output, 6500 tpd of CO_2 captured.	Benchmark - Gas
CCGT with post combustion carbon capture using an improved amine solvent process.	Advanced Amine - Gas
CCGT with post combustion carbon capture using a non-amine solvent (CO2 Capsol).	Hot Potassium Carbonate - Gas
Energy from Waste (EfW)	
Post combustion carbon capture using MEA solvent. Plant capacity of approximately 350 ktpa of municipal waste, 1000 tpd of CO_2 captured.	Benchmark – EfW
Post combustion carbon capture using an improved amine solvent process.	Advanced Amine – EfW
Post combustion carbon capture using a non-amine solvent (CO2 Capsol).	Hot Potassium Carbonate - EfW
Post combustion carbon capture using a non-amine solvent (C-Capture).	Non-Amine Solvent – EfW
Post combustion carbon capture using a solid sorbent (Svante).	Solid Sorbent - EfW
Post combustion carbon capture using a molten carbonate fuel cell as a powered membrane (FuelCell Energy).	MCFC - EfW
Post combustion carbon capture using a Polaris polymeric membrane	Polymeric Membrane - EfW
Cement Manufacture	
Post combustion carbon capture using MEA solvent. Plant capacity of approximately 1 mtpa clinker, with 2500 tpd of CO_2 captured.	Benchmark - Cement
CO_2 captured from calcination using the LEILAC direct separation reactor process. CO_2 from fuel used to operate the cement works and the LEILAC process is not captured.	LEILAC - Cement
Post combustion carbon capture using a molten carbonate fuel cell as a powered membrane (FuelCell Energy).	MCFC - Cement
Partial oxyfuel cement production.	Partial oxyfuel - Cement

2.1 Technology Description

For each scenario a process block diagram has been developed showing the main process blocks and the interface between the CO_2 emissions source and the carbon capture plant. For post combustion processes the carbon capture plant generally consists of flue gas pre-treatment to treat the incoming emission stream to the required specification for the CO_2 capture process, the CO_2 capture process, CO_2 conditioning and CO_2 compression. This is illustrated in Figure 2.

Figure 2. Generic block diagram for post combustion carbon capture



For each scenario, an overview of the process, all inputs and outputs and a description of the interface with existing process equipment have been provided. For configurations that involve fundamental alterations to the process, these alterations have been included in the technology description. Such processes include the LEILAC process for cement manufacture.

2.2 Demonstration Status and Development

The current demonstration status of each technology has been described. Comments have been provided on existing reference plants and changes to the application of the technology compared to previous projects. The development status of each technology impacts information availability on the process and the level of uncertainty associated with the results obtained for each scenario.

Further commentary has been provided in relation to the future development of each technology including scale-up requirements, areas of uncertainty, further innovation requirements and approaches to overcoming barriers to implementation. Where technology readiness levels, (TRLs) are referenced in this assignment, the National Energy Technology Laboratory definitions are used, as detailed in Table 2 [1].

Table 2. Simplified definitions of TRL

Category	Technology Readiness Level	Description
Demonstration	9	Normal commercial service
	8	Commercial demonstration, full scale deployment in final form
	7	Sub-scale demonstration, fully functional prototype
Development	6	Fully integrated pilot tested in a relevant environment
	5	Sub-system validation in a relevant environment
	4	System validation in a laboratory environment
Research	3	Proof-of-concept tests, component level
	2	Formulation of the application
	1	Basic principles, observed, initial concept

2.3 Safety and Environmental Hazards

High level comments have been provided on any new or unique hazards created by the carbon capture equipment or alterations to the main process required to accommodate the plant. These comments are intended to provide information on any unique hazards that relate to the plant configurations under investigation. Comprehensive hazard identification studies have not been conducted for the benchmarks or the scenarios analysed.

2.4 Maintenance

The nature and extent of maintenance required will impact the viability of any technology. For many of the technologies investigated there is uncertainty associated with maintenance requirements due to the limited scale and operational track record of the reference plants. Similarly, if a technology is being used in a different application, such as processing an emission stream with different characteristics, then maintenance requirements may be altered.

Maintenance requirements are described for key items of equipment in each of the benchmarks and additional scenarios analysed. Descriptions include highlighting key areas of uncertainty relating to the maintenance of the equipment.

2.5 Data Gathering

Following the development of scenario configurations, a data gathering exercise was conducted to inform the technoeconomic modelling. Section 7 contains a description of the data gathering process undertaken and a summary of assumptions made.

3. Modelling

A separate model has been created using Microsoft Excel for each benchmark and each next-generation technology scenario. Key outputs from the models are LCOC (£/tonne) and impact on product cost of adding carbon capture. Further detail on the key outputs is contained in Section 6.

3.1 Model Setup Assumptions

Table 3 provides details of key assumptions relating to the set-up of the models.

Table 3. Model setup parameters

Parameter	Value	Comment
Currency	Pound Sterling (£, GBP)	Costs provided in other currencies have been converted to GBP using the average annual exchange rates for the relevant year, as published by the Bank of England.
Cost basis year	2025	The cost basis year is the first year of construction of the plant. 2025 has been selected for the purposes of the modelling to allow cost data from a variety of sources to be presented on a common basis. It is not intended to represent a realistic construction start date for the scenarios presented.
Discount rate	7.8%	Based on previous studies conducted for BEIS.
Equipment design life	25 years	The design life is assumed to be the period between completion of commissioning and final shut-down of operations. This includes periods of major outages and process overhauls.
Capture level	95%	This capture level has been assumed for all scenarios unless stated otherwise. For some technology configurations the maximum capture level achievable is lower than 95%.
Availability	85%	This figure has been selected to account for potential reduced plant availability during the early years of operation and reduced availability during years with major outages. Plant availability is critical to project economics. Comments have been provided relating to the availability uncertainty associated with the different scenarios being analysed.

3.2 Model Interfaces

The points at which the capture plant models interface with the main process plant, external infrastructure or the environment are presented in Figure 3. Definitions for the terms used are provided in Table 4.

Figure 3. Schematic diagram of model interfaces

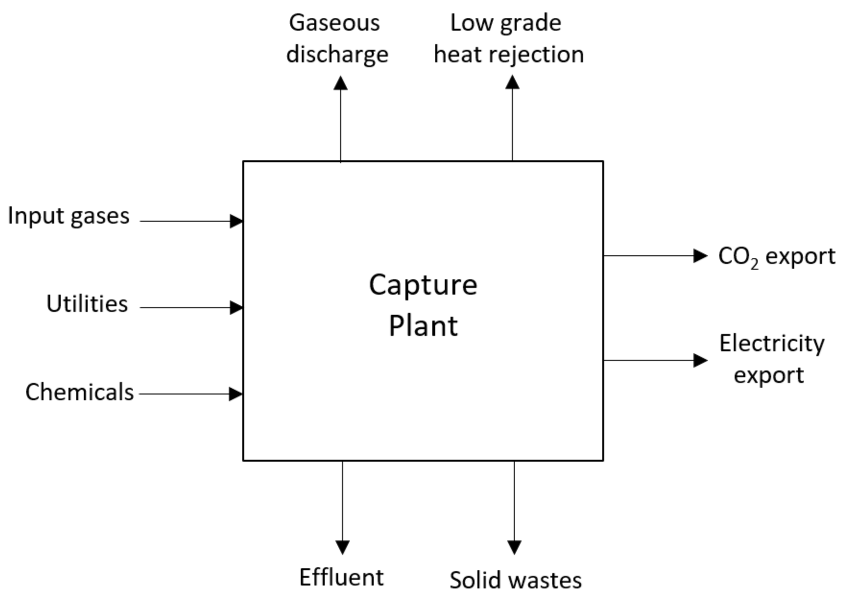


Table 4. Definition of interface points

Label	Description
Input gases	Exhaust gases from the power, waste or other industrial processes are the input gases to the carbon capture plants. It is assumed that input gases are received in a condition that the main process plant would normally treat them to for discharge to atmosphere. The interface point is a connection to a discharge stack associated with the main process plant.
Utilities	Utilities include electricity, steam, natural gas, town's water, demineralised water, instrument air and nitrogen. The interface point is the on-site metering point for all utilities.
Chemicals and consumables	Chemicals and consumables may include solvents, sorbents, membranes and reagents that are critical to the operation of the processes. The interface points are the chemical delivery points prior to on-site storage.
Gaseous discharges	Gaseous discharges from the sites will generally comprise of the input gases following the removal of most of the CO_2. There may also be gaseous emissions from process vents or the combustion of natural gas. Any equipment required to remove traces of solvent, solvent degradation products or other compounds from the gaseous discharges is included as appropriate to meet assumed emissions limits. The interface point for gaseous discharge is the discharge point from the onsite stack.
CO_2 export	The interface point is the point of discharge into a CO_2 transportation pipeline. For gas fired power generation scenarios it has been assumed that CO_2 is exported at a pressure of 100 barg on the basis that CO_2 will be exported to an export pressure pipeline. For EfW and cement scenarios, that are of a smaller scale, CO_2 is exported at a pressure of 27.5 barg, representing export to a gathering network. The proposed specification of the export CO_2 is provided in Table 6 below.
Electricity export	Some capture technologies (fuel cells) will export electricity. In these scenarios the interface point will be the export meter from the capture plant.
Liquid effluent	All equipment, infrastructure, chemicals, and consumables required for treating aqueous effluents to a suitable standard for discharge to a third-party wastewater treatment works is assumed to be included in the plant. The interface point is the discharge point to public sewer. Where disposal of degraded solvent, or other liquid effluent requiring specialist treatment, is required the interface point is the transfer point to road tankers.
Solid waste	For solid residues and wastes that require off-site disposal, the plant is assumed to include the equipment and infrastructure up to the point of discharge from on-site storage.
Low grade heat rejection	Low grade heat is discharged to atmosphere for the purposes of process cooling. It is assumed that no heat is exported to other processes or district heating networks from the capture plants.

3.2.1 Input Gas Composition

In most cases the input gas stream is flue gas produced from the industrial process relevant to each scenario. In some cases, a process adjustment may be made to the core process that allows a more concentrated stream of CO_2 to be produced. For example, when the LEILAC process is used in cement manufacture. In such cases, a second flue gas stream may also be produced that may require to be processed by the carbon capture system. How the two input gas streams are treated is described in the description of the individual scenario.

The composition of the input gas streams will vary between different industries and different individual processing sites. For example, the fuel used in a cement works will influence the composition of the flue gases generated. For the purposes of this study, the compositions in Table 5 have been assumed as representative input gas compositions for the three benchmark scenarios (refer to Section 1 above). In all cases, these gas compositions are assumed to be downstream of any flue gas treatment processes that would typically be provided on the base process site to meet air emissions standards.

Table 5. Composition of input gases for benchmark scenarios

Parameter	Units	Gas fired Power Plant	EfW Plant	Cement Works
Carbon dioxide, CO_2	mol %	5	12	18
Nitrogen, N_2	mol %	74	61	55
Oxygen, O_2	mol %	10	8	8
Water, H_2O	mol%	10	18	18
Argon, Ar	mol %	1	1	1
Carbon monoxide, CO	mol % / mg/Nm^3	0.01 mol %	0 mol %	1500 mg/Nm^3
Sulphur oxides, SO_x	mg/Nm^3	0	20	25
Nitrogen oxides, NO_x	mg/Nm^3	45	150	250
Ammonia	mg/Nm^3	4	5	0
Particulates	mg/Nm^3	0	3	10
HCl	mg/Nm^3	0	5	10
HF	mg/Nm^3	0	0.5	2
Heavy metals	mg/Nm^3	0	0.35	0.45

In all cases in Table 5, concentrations of contaminants are quoted at a temperature of 273 K and pressure of 101.3 kPa. In line with the conventions used in the Industrial Emissions Directive, contaminant concentrations in gas turbine flue gas are quoted at 15% O_2, contaminant concentrations in EfW flue gas are quoted at 11% O_2 and contaminant concentrations in flue gas from solid fuel fired cement works are quoted at 6% O_2.

3.2.2 CO_2 Export Specification

Table 6 contains details of the CO_2 export specification assumption that was used for all scenarios. This specification is from Appendix 3 of the BEIS CCUS Innovation 2.0: Call 1 Guidance [2]. For gas fired power generation scenarios it has been assumed that CO_2 is exported at a pressure of 100 barg on the basis that CO_2 will be exported to an export pressure pipeline. For EfW and cement scenarios, that are of a smaller scale, CO_2 is exported at a pressure of 27.5 barg, representing export to a gathering network.

Table 6. CO_2 Specification

Parameter	Units	Value
Temperature	°C	25-30
Pressure	barg	27.5 / 100
Carbon dioxide, CO_2	mol %	> 96
Total non-condensable gases	mol %	< 4
Total methane & other hydrocarbons	mol %	< 2
Hydrogen, H_2	ppmv	5000 - 7500
Carbon monoxide, CO	ppmv	1000 - 2000
Water, H_2O	ppmv	30 - 50
Oxygen, O_2	ppmv	10 - 100
Hydrogen sulphide, H_2S	ppmv	5 - 200
Sulphur oxides, SO_x	ppmv	10 - 50
Nitrogen oxides, NO_x	ppmv	10 - 50
Amines	ppmv	2 - 10
Ammonia	ppmv	10 - 50
Aldehydes	ppmv	≤ 20
Glycol	ppmv	≤ 10
Mercury	mg/m^3	≤ 0.03
Total Cadmium & Thallium	mg/m^3	≤ 0.03

The scenarios modelled in the analysis are intended to be representative of plants that would be capable of meeting the CO_2 specification above. However, the process modelling conducted did not consider the generation of, and management of, all minor contaminants detailed above. This would be undertaken during the detailed design of equipment.

4. Capital Cost

4.1 Basis of Capital Cost Estimating

The capital cost (CAPEX) derived for the scenarios includes all costs required to provide a complete and functioning project.

It was assumed that the projects are delivered using a competitively tendered lump sum engineering, procurement, and construction (EPC) contract. The cost for the EPC contract was estimated using the methodology described in subsection 4.2, then costs for additional elements required to deliver each project were determined based on typical percentages of the EPC cost. Additional elements of the capital cost include land purchase, engineering consultancy, planning and regulatory requirements, developers' costs, start-up and commissioning costs, utility connections and plant integrations and contingency.

The uncertainty associated with capital cost estimates is affected by the maturity of the technology being analysed, the availability of costing data and the technical complexity of the scenario. Where scenarios have notable uncertainties associated with them relating to capital cost these have been commented on in the individual scenario descriptions. Such uncertainties may include large scale-up factors relative to existing equipment, or reliance on components with limited track record.

All capital costs have been assumed to be expended over a three-year period prior to the commencement of operation. Annual capital spends over years one, two and three of the construction and commissioning period, as percentages of the total capital spend, have been assumed to be 20%, 40% and 40% respectively.

4.2 EPC Contract Cost Estimation

An EPC contracting arrangement allows a commissioned and tested plant to be purchased with some level of guarantee on price, performance and delivery schedule being provided by the contractor. In this study it is assumed that the EPC contract covers all facilities located at the site including the main process, connection of utilities to the interface points, storage, civil infrastructure, and administration facilities.

The estimate of EPC contract cost has been built up from a number of discrete process blocks, consistent with those used in the process model. These blocks generally include:

- Flue gas pre-treatment
- Carbon capture equipment
- CO_2 conditioning
- CO_2 compression
- Other auxiliary equipment. This includes items such as water treatment, waste-water treatment, process cooling, fire detection and suppression, control, chemical and fuel handling, chemical storage, metering, and electrical equipment.

Costs for each of the main process blocks have been derived based on applying appropriate scaling factors to publicly available information, through engagement with technology providers and from internal AECOM cost data. Estimates have been developed using costing methodologies consistent with a Class IV cost estimate as defined by the American Association of Cost Engineers (AACE).

For civil costs, no cost allowance has been made for unusual or onerous ground conditions, such as poor bearing capacity, contaminated land or major site preparation or enabling works.

The cost of first-fill chemicals, catalysts and other consumables are captured within the allowance made for commissioning and start-up costs, as described below.

4.3 Land Requirements

It is assumed that all land required for the facilities being modelled is purchased rather than leased. This includes the area occupied by all processing facilities, ancillary equipment, storage, buildings, and necessary infrastructure up to and including the interface points.

The location of the scenarios to be modelled is not fixed. However, for the purposes of determining a land cost, the cost of industrial land in the Northeast of England has been assumed. Information from the Ministry of Housing Communities & Local Government gives a cost range of £135,000 to £250,000 per hectare [3]. Taking an average value and correcting to a 2025 basis gives a cost of £21/m^2.

4.4 Engineering Consultancy

Engineering services costs (fees paid to third party consultants) incurred through the conceptual design, pre-front end engineering design (pre-FEED) and FEED stages of project development typically range between 0.5% and 3% [4]. For this study, consultancy costs have been assumed to be 1% of the EPC cost.

4.5 Planning and Regulatory Requirements

This includes the costs incurred in obtaining all necessary planning and permitting consents for the development. A value of 2% of EPC cost has been assumed.

4.6 Developer's Costs

This covers the Development company's internal costs to develop the project from concept through to start-up. It includes costs associated with direct-hire personnel, taxes and insurances. It is assumed that all projects will be balance sheet financed and no additional finance costs are incurred. A development on a greenfield site in a moderately industrial area, with a supportive local council and other stakeholders has been assumed. As with previous benchmarking studies conducted for BEIS [5], this aspect of capital cost is assumed to be 7% of the EPC cost.

4.7 Start-up and Commissioning Costs

These costs are incurred in the months prior to the commencement of normal operation. They cover having a trained operation and maintenance team on the facility during the commissioning and start-up process and the consumables that are used during the period. There is also a requirement for spares and consumables to be held on-site to enable maintenance activities. Commissioning services are typically 3.5% of the investment cost of a process plant but can reach 25% for a technically challenging process [4]. Of this, typically 70% is for labour costs and 30% is for consumables. As all scenarios being investigated involve the use of emerging technologies with a limited number of operational examples, a start-up and commissioning cost assumption of 5% of EPC cost has been assumed.

4.8 Utility Connection and Plant Integration

Connections to utilities for each scenario may include connection to the gas network, electricity network, CO_2 transport infrastructure, water, wastewater, and telecommunications services. The cost of utility connections is highly site specific due to factors including the capacity of the connections required, the proximity to suitable infrastructure and details of the terrain between the plant and utility connection points.

Some of the utility requirements of the capture plants are met by connecting to the main process plant rather than an external network. This may increase, or decrease, the utility requirements of the main process plant. The ability of existing connections to accommodate any increase in capacity requirements is highly site specific.

In addition to utility connection requirements, there are integration costs associated with connection of the carbon capture plant to the main process plant. These costs arise from factors such as connecting the flue gas stream of the existing plant to the new carbon capture unit.

For the purposes of the technoeconomic modelling, an overall allowance of 1% of EPC cost has been allowed for utility connection and plant integration costs.

4.9 Contingency

A contingency of 10% of the total capital cost has been added to each scenario. Commentary has been provided on any significant uncertainties relating to the capital cost estimations for each scenario.

5. Operating Cost

Operating cost (OPEX) consists of both fixed and variable components. Fixed costs are incurred regardless of plant operational hours and load; variable costs vary with operational hours and load. In this analysis, fixed and variable costs include the following sub-components.

Fixed Operating Costs:

- Labour
- Administration and other overheads
- Scheduled maintenance

Variable Operating Costs:

- Utilities
- Chemicals and consumables
- Waste disposal
- Subsidiary revenues

A contingency cost of 10% of the total OPEX has been added to each scenario.

5.1 Fixed Operating Costs

5.1.1 Labour

Labour costs cover the full cost of employment of operational staff and include salary, national insurance, income tax, pension contributions, medical insurance, and other in-house company benefits. Staff costs for different grades of staff has been based on data available from the Office for National Statistics.

Operational labour is dependent on the staff numbers required to operate the plant. Staffing requirements have been developed on a case-by-case basis considering the equipment installed, process complexity and scale. Requirements for different types of staff including senior management, shift leaders, shift operators, maintenance staff, technical support, and day workers have been estimated for each scenario.

Each facility is assumed to have high levels of control and automation, as would be expected on a large new build processing plant in the UK. In most scenarios the capture plants are built adjacent to a waste, power, or industrial processing site. While the carbon capture plant is treated as a separate entity, and has its own dedicated staff, the ability for limited sharing of operational staff between the sites has been considered in relation to determining staffing requirements.

5.1.2 Administration and Other Overheads

Administration and other overhead costs include services not directly involved in the operation of the plant, such as management, insurance, business rates, taxes, rental and annual licence or permit charges. These services vary significantly between companies and processes.

These costs are typically assessed as a component of the EPC contract cost and can vary between 1% and 5% [6] depending on the size of the process and its complexity. All scenarios being analysed in this study are large scale process plants. In some cases, there may be scope for sharing costs and services with the main process plant. A figure of 1.5% of total capital cost is assumed in all scenarios.

5.1.3 Maintenance

Maintenance costs cover routine servicing, cleaning, repairs, planned minor outages and major overhauls over the lifetime of the plant. Maintenance activities will be conducted by internal teams with service contracts to external contractors or technology providers where appropriate.

There are fixed and variable elements to maintenance costs at any process plant. Fixed costs are incurred regardless of the operational hours or load of the plant, for example repairs and maintenance of site buildings. Variable costs are dependent on operational hours and load, an example being repairs required due to wear on an item of mechanical equipment.

All scenarios in this technoeconomic analysis are assumed to operate at full load with high operational availability. A single figure has been used to cover both fixed and variable maintenance. The assessment has assumed maintenance costs as a function of total capital cost.

The ability to operate reliably without incurring excessive maintenance costs is fundamental to the viability of any process plant. Many of the technologies being analysed have a limited track record in the applications proposed and / or have only been tested at a smaller scale. In these cases, there are gaps in the data available relating to the long-term maintenance cost of the equipment and this is a source of uncertainty. Comments have been provided relating to the uncertainty associated with the maintenance assumptions made for each scenario.

5.2 Variable Operating Costs

5.2.1 Utilities and CO_2

Utility costs are determined by multiplying the consumption rate of each utility by the unit cost in any given year of the model. For electricity, gas, and residual CO_2 emissions, cost predictions are based on data from BEIS publications, adjusted to a 2025 cost basis using the deflator index provided in the BEIS Green Book Supplementary Guidance. The data used and data sources are presented in Table 7. Electricity, Gas, Steam and CO_2 costs, presented on a 2025 basis.

Table 7. Electricity, Gas, Steam and CO_2 costs, presented on a 2025 basis

Year	Electricity Market Price (£/kWh)	Electricity Wholesale (£/kWh)	Gas (£/kWh)	Steam Gas Power Generation (£/kWh)	Steam EfW (£/kWh)	Steam Cement (£/kWh)	Residual CO_2 emissions (£/ton)
2025	0.135	0.064	0.028	0.015	0.032	0.064	275
2026	0.136	0.063	0.029	0.015	0.032	0.063	279
2027	0.135	0.065	0.030	0.016	0.033	0.065	283
2028	0.132	0.064	0.030	0.015	0.032	0.064	287
2029	0.131	0.065	0.031	0.016	0.033	0.065	292
2030	0.132	0.065	0.031	0.016	0.033	0.065	297
2031	0.129	0.067	0.031	0.016	0.033	0.067	301
2032	0.127	0.066	0.032	0.016	0.033	0.066	306
2033	0.125	0.067	0.032	0.016	0.034	0.067	310
2034	0.123	0.067	0.033	0.016	0.034	0.067	315
2035	0.122	0.068	0.033	0.016	0.034	0.068	320
2036	0.122	0.069	0.033	0.016	0.034	0.069	325
2037	0.122	0.069	0.033	0.016	0.034	0.069	330
2038	0.124	0.069	0.033	0.016	0.034	0.069	335
2039	0.124	0.068	0.033	0.016	0.034	0.068	340
2040	0.123	0.069	0.033	0.016	0.034	0.069	345
2041	0.123	0.069	0.033	0.016	0.034	0.069	350
2042	0.123	0.069	0.033	0.016	0.034	0.069	355
2043	0.123	0.069	0.033	0.016	0.034	0.069	361
2044	0.123	0.069	0.033	0.016	0.034	0.069	366

2045	0.123	0.069	0.033	0.016	0.034	0.069	372
2046	0.123	0.069	0.033	0.016	0.034	0.069	377
2047	0.123	0.069	0.033	0.016	0.034	0.069	383
2048	0.123	0.069	0.033	0.016	0.034	0.069	389
2049	0.123	0.069	0.033	0.016	0.034	0.069	394
2050	0.123	0.069	0.033	0.016	0.034	0.069	400
2051	0.123	0.069	0.033	0.016	0.034	0.069	400
2052	0.123	0.069	0.033	0.016	0.034	0.069	400
Data source	BEIS Green Book supplementary Guidance, central, industrial [7].	BEIS 2019 Updated Energy and Emissions Projections, Annex M, central estimates [8].	BEIS Green Book supplementary Guidance, central, industrial [7].	See text below	See text below	See text below	BEIS Green Book supplementary Guidance, central, industrial [7].

Electricity

The unit cost for supply of electrical power to the carbon capture plants will vary between sites. At sites where electricity is not generated by either the main process plant (power plants or EfW) or the carbon capture plant (fuel cells), the market price is used.

In the case of gas fired power generation, EfW or carbon capture plants that generate electricity, it is assumed that the electricity to operate the carbon capture plant is treated as a parasitic load rather than purchased from the grid. The unit cost of electricity in these cases is lower, as there are no grid operation charges, environmental levies or generator profit margin included in the price. In these scenarios, the wholesale electricity price is used as it represents the opportunity cost from reduced electrical export.

There are different ways in which electricity can be purchased and sold. For companies developing capture projects, the cost of electricity purchase and lost revenue from reduced electricity sales will be site specific and dependent on the sales and purchase contract arrangements as well as market prices.

Thermal Energy - Steam

Where required by the capture process, it is assumed that thermal energy is supplied to the capture plants using steam, although other media could also be suitable. The unit cost and availability of steam is industry and site specific and will depend on how much steam is required and how the steam is obtained. For carbon capture plants being developed at industrial sites, provision of the required thermal energy will be a key part of the conceptual design process.

Steam cost assumptions used for the different industry sectors included in the analysis are stated in the benchmark scenario write-ups.

Residual CO_2 Emissions

The potential costs of residual CO_2 emissions are based on BEIS Green Book 2021 central carbon values . Use of these forecast values is not intended to presume a future UKETS price or arrangement, but are adopted solely for the purpose of demonstrating what trade-off UK-based sites might have to make when transitioning their sites to a net zero business environment.

The cost of emitting residual CO_2 that is not captured due to the limitations of the technology is not included as an operating cost in the LCOC calculation, as the LCOC relates only to the capture process. However, where operators are charged for CO_2 emissions these residual emissions costs will be paid for by the host process plant. Therefore, the cost of residual emissions is included in the impact on product cost calculation. A scenario with a lower capture level will pay a higher price for residual emissions to the atmosphere.

If the cost of residual carbon emissions increases during the lifetime of a carbon capture plant as anticipated, this may create an incentive to minimise residual emissions and / or deploy supplementary technologies to capture emissions not captured by the main plant assessed in this study.

CO_2 Transport and Storage

If carbon capture plants are developed, there will be costs associated with operating the CO_2 transport and storage infrastructure. For the purposes of this study, to compare capture technologies, a cost of zero (£/tonne) for exporting CO_2 to the transport and storage infrastructure has been assumed.

Cooling

In all scenarios, it is assumed that cooling is provided by rejection of heat to atmosphere using dry-air-blast cooling systems. Electricity consumption for the fans powering these units is included in the overall electrical consumption of the plant. Therefore, there is no separate utility cost for the provision of process cooling.

Water

Table 8 contains unit costs for water used by the plants.

Table 8. Water costs

Item	Unit Cost (2021)	Cost Estimate (2025)	Source
Town's water	£0.25/m^3	£0.26/m^3	Typical costs from personal communication with Northumbrian Water Ltd and adjusted to 2025 [9]
Demineralised water	£0.50/m^3	£0.53/m^3	Towler, G. Sinnott, R. K. 2013, Chemical Engineering Design – Principles, Practice and Economics of Plant and Process Design, 2nd Edition [10]

5.2.2 Chemicals and Consumables

For many of the carbon capture plants there is a cost associated with ongoing replacement of chemicals or consumables. This may include solvents, sorbents, or membrane units. Information on the degradation rates and costs for these chemicals and consumables has been reported on a case-by-case basis based on publicly available information and information from suppliers.

The degradation rates of these chemicals and consumables may be a key parameter in relation to the cost of operating the technologies being analysed. However, degradation rates will vary depending on the quality of the input gases and, in some cases, may be unknown if long term test data is unavailable. Where data is unavailable, professional judgements have been made and the associated uncertainty commented on accordingly.

For other chemicals and consumables used in the scenarios, estimates of annual usage have been multiplied by unit costs based on current market rates.

5.2.3 Waste Disposal

Unit costs for the disposal of wastes are detailed in Table 9 below. The value quoted for hazardous waste includes £96.70 in landfill tax (value from 1 April 2021).

Table 9. Waste disposal costs

Landfill Component	Typical Range	Assumed Value (2021)	Assumed Value 2025
Hazardous Waste	£137 - £177/tonne	£157/tonne	£166/tonne [11]
Wastewater			£1.26/m^3 [10]

Trade effluent disposal costs vary depending on composition and service provider. A value based on prices charged to United Utilities customers for average strength trade effluent has been used and adjusted for inflation.

For all solvent based carbon capture systems, degraded solvent has been treated as hazardous waste. The cost of disposal of this material will be dependent on its composition.

Subject to the limitations of the equipment installed, the composition of the degraded solvent, and the permitting restrictions at the site, it may be possible for some EfW or cement sites to dispose of degraded solvents into the furnace in the main process plant, rather than exporting it for treatment elsewhere. If this were possible, waste disposal costs would reduce at these sites.

5.2.4 Subsidiary Revenues

There is limited scope for generating subsidiary revenues for most of the scenarios considered in the study. Where electricity is generated from a gas power plant or EfW plant this is not counted as a subsidiary revenue because it is outside of the capture plant system boundary. In some cases, specifically fuel cell technology, electricity is generated as a result of the carbon capture process. Where revenue is generated from the sale of this electricity this has been included as a negative operating cost when calculating OPEX in the relevant scenarios.

Gate fees from processing of waste in the EfW scenarios has not been included in the technoeconomic analyses as the EfW plant is outside the boundary of the carbon capture plants being analysed. Similarly, revenue from the sale of manufactured product is not considered in relation to the technoeconomic analyses.

6. Analysis Outputs

The key outputs for each scenario analysed are the LCOC, an indication of the impact on product cost of adding carbon capture and comments on the key uncertainties associated with the figures obtained. These outputs allow comparisons to be drawn between the benchmark scenarios and the scenarios based on next-generation technologies.

6.1 Levelised Cost of CO_2 Capture (LCOC)

LCOC is calculated using Equation 1.

Equation 1. LCOC

$$\mathrm{LCOC}\ (£/tCO_2) = \frac{Total\ discounted\ lifetime\ cost\ (£)}{Total\ discounted\ lifetime\ CO_2\ captured(tCO_2)}$$

Total discounted lifetime cost (£)	Calculated using CAPEX, OPEX and discount rate
Total discounted lifetime CO_2 captured (tCO_2)	Calculated using mass of CO_2 captured and discount rate

Equation 1 is like the equations used for calculating levelised cost of energy (LCOE) or other products (LCOX). As with any LCOX calculation, it is critical that the underlying assumptions are understood when interpreting or using results obtained. Care must be taken when comparing LCOX results taken from different studies as the use of different assumptions may create flawed comparisons.

6.2 Impact on Product Cost

The impact on product cost associated with adding carbon capture for each scenario has been estimated, based on Equation 2.

Equation 2. Product cost with CO_2 abatement

$$\begin{aligned} &Product\ cost\ with\ CO_2\ capture\ (£/unit) \\ &\quad = Base\ cost\ (£/unit) + LCOC\ (£/tCO_2) \times \left(\frac{CO_2\ captured\ (tCO_2)}{Product\ produced\ (Unit)}\right) \\ &\quad + Levelised\ cost\ of\ residual\ CO_2\ emissions\ \ (£/tCO_2) \times \left(\frac{CO_2\ Emitted(tCO_2)}{Product\ produced\ (Unit)}\right) \end{aligned}$$

Base cost (£/unit)	Representative market unit cost for the product when produced without carbon capture.
LCOC (£/tCO_2)	Calculated using Equation 1.
CO_2 captured (tCO_2)	The mass of CO_2 captured by the capture plant.
Levelised cost of residual CO_2 emissions (£/tCO_2)	Discounted cost of whole life residual emissions based on annual emissions and forecast carbon price per year
Product produced	Number of units of product produced in abated operation.

6.3 Key Uncertainties

For each benchmark and next generation scenario analysed, commentary has been provided on the key uncertainties that specifically relate to the benchmark or scenario assessed. This commentary is intended to identify key areas of uncertainty relating to the results obtained. Areas of focus for this commentary include uncertainties relating to the technology, sector specific issues or environmental issues.

Each scenario has then been given an overall uncertainty rating of *medium*, *high* or *very high*. These ratings are based on an overall professional opinion on the uncertainties associated with the scenario, noting that some assumptions have a greater potential to impact the results obtained.

These scenario-specific uncertainties should be considered in conjunction with the common uncertainties and assumptions that relate to all scenarios along with an understanding of the assumptions used in the analysis and the wider opportunities and barriers to the deployment of carbon capture technology, as described in the WP 2 report.

7. Summary of Data and Assumptions

Understanding and appropriate use of the outputs from the technoeconomic analysis is dependent on an understanding of the assumptions and quality of input data used in the analysis. The following summary of assumptions and associated uncertainties is intended to provide clarity on the evidence base used for the analyses and an indication of where the important areas of uncertainty lie.

Data and assumptions used in the technoeconomic modelling have been gathered from a variety of sources. Where possible, publicly available information has been used from journals, academic studies and third-party publications. In addition, an extensive consultation exercise was conducted involving technology providers to obtain as much information for the study as possible.

When studying emerging technologies, there are unavoidably performance data that do not exist. For example, the long-term maintenance costs of an item of equipment that has never operated for a long time. These data can significantly impact the results of the analysis. Where information is absent or appears unreliable, engineering judgement has been used to inform assumptions as necessary to complete the assignment.

Our understanding of the limitations of the data has been used to inform the commentary provided on the uncertainty associated with the scenarios investigated. Understanding the strengths and weaknesses of the data available is essential in relation to interpreting the results from any study that compares emerging technologies.

7.1 Definitions

In this assignment an uncertainty rating for each assumption in the models has been allocated by assessing the quality of the data source and the impact of the assumption on the model outputs. Table 10 provides definitions for the quality and impact ratings used.

Table 11 shows how these translate into uncertainty ratings for the assumptions made.

Where quality and / or impact ratings are listed as variable between scenarios, further information relating to the parameter has been provided in the write-ups of the individual scenarios. Consideration has been given to the BEIS Quality Assurance requirements during the gathering of data and presentation of assumptions.

Table 10. Quality and impact rating definitions

Rating	Definition	Grade	Explanation
Quality Rating	This assesses the certainty and/or robustness of a data source. If the data is manipulated or transformed in some way, the quality decreases. A wide confidence interval (eg ±50%) would have a low quality rating.	High	The value is based on real data and transformations are minimal or robust. The data is current and there is a narrow confidence interval.
		Medium	Value is based on limited data, but reasoning is robust. There has been significant manipulation to the data and the confidence interval is wide.
		Low	There is either no data source or an unreliable data source has been used. Quality rating may also be low if a robust data source is used but the data is likely to change significantly over the model period.
Impact Rating	This assesses the sensitivity of the model outputs to variations in inputs. Rating should reflect the relative change in output when input value is changed.	Low	A change in input value has negligible impact on model outputs.
		Medium	A change in input value has some impact on model outputs.
		High	A change in input value has significant impact on model outputs and could affect decision making.
Uncertainty Rating	This assesses which assumptions need to be highlighted.	Low	Assumption has low impact and source is of good quality. Very little can be done to improve.
		Medium	Assumption has medium impact on model outputs. Changes would affect results but not significantly.
		High	Assumption has high impact on model outputs. Changes have the potential to affect results significantly.
		Very High	Assumption has a very high impact on model outputs. Changes are likely to affect results significantly.

Table 11. Summary of uncertainty ratings based on impact and quality rating

Uncertainty Rating		**Impact Rating**		
		Low	**Medium**	**High**
Quality Rating	**High**	Low	Medium	High
	Medium	Low	High	Very High
	Low	Medium	Very High	Very High

7.2 Model Setup Assumptions

Table 12 provides details of model set-up assumptions.

Table 12. Model setup assumptions

Modelling Assumption	Value	Data Quality	Model Impact	Uncertainty	Comment
Cost basis year	2025	High	Low	Low	The cost basis year selected has a limited impact on comparative model outputs.
Discount rate	7.8%	High	Medium	Medium	When model outputs are used for the intended purpose of comparing carbon capture technologies, the discount rate has a limited impact on results, although the selected discount rate may impact the comparison with other study work or alternative decarbonisation options.
Design life	25 years	High	Low	Low	Plant design life has a limited impact on model outputs.
Capture level	95%	High	Low	Low	The capture level has been selected for the purposes of comparing the technologies. Any scenario that will not meet this capture level has been highlighted.
Plant availability	85%	Variable	Variable	High Potential	The ability of plants to work reliably is fundamental to project economics. This study relates to emerging technologies with limited demonstrated operation. Comments have been provided on the relative availability uncertainty of different technologies.
Input gas composition	See Table 5	Variable	Variable	High Potential	For many industries there could be considerable variation in input gas composition depending on the fuels used.
CO_2 export specification	See Table 6	High	Medium	Medium Potential	Changes to CO_2 export pressure and composition requirements could impact capture costs.

7.3 Capital Cost Assumptions

Table 13 provides details of capital cost assumptions used in the modelling.

Table 13. Capital cost assumptions

Modelling Assumption	Value	Data Quality	Model Impact	Uncertainty	Comment
Construction Period	3 years	High	Low	Low	Based on experience of constructing process plants of similar scale and complexity.
EPC Contract	Calculated for each scenario	Medium	Medium	High	There is unavoidable uncertainty associated with estimating construction costs for emerging technologies.
Land Purchase [3]	£21.34/m^2	Medium	Low	Low	Land costs will vary depending on location. However, for technology comparison land cost has a limited impact.
Consultancy [4]	1% of EPC Cost	Medium	Low	Low	Consultancy costs vary between projects but the overall impact on results is limited.
Planning and other regulatory	2% of EPC Cost	Medium	Low	Low	Planning and regulatory costs vary between projects and can make projects unviable. However, for technology comparison the overall impact on results is limited.
Developer's costs [5]	7% of EPC Cost	Medium	Low	Low	Developer's costs vary between projects but the overall impact on results is limited.
Start-up and commissioning [4]	5% of EPC Cost	Medium	Medium	High	Start-up and commissioning cost is a significant uncertainty for emerging technologies. Comments have been provided on the relative uncertainty of different technologies.
Utility connection	1% of EPC Cost	Medium	Low	Low	Utility connection costs vary between projects and can make projects unviable. For the purposes of technology comparison, the overall impact on results is limited.
Developer Contingency	10% of total capital	Medium	Low	Low	Contingency levels assumed by developers will vary between projects but the overall impact on results is limited.

7.4 Operating Cost Assumptions

Table 14 provides details of operating cost assumptions used in the modelling.

Table 14. Operating cost assumptions

Modelling Assumption	Value	Data Quality	Model Impact	Uncertainty	Comment
Fixed Operating Costs					
Labour cost	From staffing costs and numbers	Medium	Low	Low	Values for each role are based on Office for National Statistics values for average employee earnings in the UK and amended to 2025. Quality is medium due to uncertainty in staffing numbers required.
Administration and other overheads [6]	1.5% of EPC Cost	Medium	Low	Low	Overall impact on technology comparison results is limited.
Maintenance	2.5%	Variable	Variable	High Potential	There is unavoidable uncertainty associated with estimating maintenance costs for emerging technologies.
Variable Operating Costs					
Electricity Unit Cost [7] [8].	See Table 7. Electricity, Gas, Steam and CO2 costs, presented on a 2025 basis	High	Variable	High Potential	Values taken from BEIS publications. The impact, and therefore uncertainty, of this assumption varies depending on the electricity consumption of each scenario. Where power is generated by the base process plant (EfW or gas) electricity cost for the capture plant is parasitic, and hence is based on the opportunity cost of lost revenue from sale of electricity.
Electricity consumption	Variable between scenarios	Variable	Variable	High Potential	The uncertainty associated with consumption figures varies between scenarios. Some reliance has been placed on supplier data, with sense checks conducted as appropriate.
Steam price	Variable between scenarios	Variable	Variable	High Potential	Steam cost is industry and site specific and has a high impact on the results obtained for many of the scenarios.
Steam consumption	Variable between scenarios	Variable	Variable	High Potential	The uncertainty associated with consumption figures varies between scenarios. Some reliance has been placed on supplier data, with sense checks conducted as appropriate.
Emission of CO_2 to atmosphere [7]	See Table 7. Electricity, Gas, Steam and CO2 costs, presented on a 2025 basis	Low	Variable	High Potential	Values taken from BEIS publication. The cost of emitting CO_2 to the atmosphere will impact all scenarios. The impact of an increased cost of emitting CO_2 to the atmosphere will be greatest on projects with the lowest capture levels.
Primary consumables (solvents, sorbents, membranes)	Variable between scenarios	Variable	Variable	High Potential	The cost and consumption rate of key consumables is uncertain in some technologies and has a potentially high impact on project economics.
Natural gas [7]	See Table 7. Electricity, Gas, Steam and CO2 costs, presented on a 2025 basis	High	Medium	Medium	Values taken from BEIS publications. Few of the scenarios directly use natural gas. However, fluctuations in gas cost could impact project economics by impacting the market price of products.
Natural gas consumption	Variable between scenarios	Variable	Variable	Medium Potential	Most of the scenarios do not directly use natural gas.
Town's water [9]	£26/m^3	High	Low	Low	Unlikely to be a key operating cost for the scenarios investigated.
Demineralised water [10]	£52/m^3	High	Low	Low	Unlikely to be a key operating cost for the scenarios investigated.

Wastewater [10]	£1.26/m^3	High	Low	Low	Unlikely to be a key operating cost for the scenarios investigated.
Hazardous waste [11]	£166/t	Medium	Low	Low	Unlikely to be a key operating cost for the scenarios investigated.
Secondary consumables (eg acid or caustic)	Variable	Medium	Low	Low	Unlikely to be a key operating cost for the scenarios investigated.

8. References

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[11] Tolvik Consulting Ltd., *Personal comunication,* 2020.

[12] E. &. I. S. Department for Business, “Updated Short-Term Traded Carbon Values,” 2018.

[13] E. &. I. S. Department of Business, “Updated Short-Term Traded Carbon Values,” 2018.

9. Abbreviations

AACE	Association for the Advancement of Cost Engineering
BEIS	Department for Business, Energy & Industrial Strategy
CAPEX	Capital Expenditure
CCUS	Carbon Capture, Utilisation & Storage
CO_2	Carbon Dioxide
EfW	Energy from Waste
EPC	Engineering, Procurement & Construction
FEED	Front End Engineering Design
GBP	Pound Sterling
LCOC	Levelised Cost of CO_2 Capture
LCOE	Levelised Cost of Electricity
LCOX	Levelised Cost of Other Products
LEILAC	Low Emissions Intensity Lime and Cement
LNG	Liquified Natural Gas
OPEX	Operating Expenditure
QA	Quality Assurance
TRL	Technology Readiness Level
WP	Work Package

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