Promethean Particles®

Life Cycle and Technoeconomic Assessment

CCUS Innovation 2.0

Key Knowledge Deliverable 5.1

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Key Knowledge Deliverable Cover Sheet

This Key Knowledge Deliverable (KKD) has been produced by Promethean Particles Ltd. as part of the Department for Energy Security and Net Zero £1bn Net Zero Innovation Portfolio (NZIP) - CCUS Innovation 2.0 programme. The document is reflective of the status of the project at the time of writing. The material presented could have been subject to change as the project matured. These documents should not be considered a full representation of the final project.

Description of KKD D5.1 – CAPEX Technoeconomic Analysis (TEA)

This report provides a capital expenditure (CapEx) analysis of the MONET post-combustion carbon capture system (PC-CCS) pilot plant that is to be installed at an operational power station, and also includes an operational expenditure (OpEx) analysis for the MOF to be used during the trials.

The model uses the Hand Method to analyse the CapEx costs, and provides results in annualised costs, and provisional levelised cost of capture (LCOC). The baseline model has allowed the annualised cost to be calculated for both the PC-CCS and the MOF, as well as the LCOC for both the PC-CCS and the MOF.

Physical and financial variable scenarios were considered as part of the analysis. The physical variables which influence the CapEx analysis included the production quantity of MOF, which had a small impact. Plant life for the CapEx analysis was set to 25 years as this is the standard for TEAs but is in reality only 2 years for the demonstration nature of the MONET system. Finally, the carbon capture potential of the MOF was found to make a significant impact on the LCOC up to 500 tonnes per annum, after which the impact diminished as the LCOC levelled out, indicating for the CapEx analysis, that there is an optimal carbon capture level, beyond which there are diminishing reductions in costs. The financial variables of ISBL and OSBL impacted the LCOC but not as dramatically as carbon capture potential, whilst hurdle rates could have significant impacts on the full OpEx analysis, which will be conducted and presented in deliverable 5.2.

There is significant data uncertainty regarding the carbon capture potential, as no pilot scale MOF-based PC-CCS has been tested to date. Therefore, the data in this study should become higher quality and have reduced in uncertainty for the OpEx analysis, as this data will be collected from the pilot scale rig.

KKDs to be released in full:

D6.4 - Marketing Material Creation

D6.5 - Conference Presentations and Trade-Show Exhibitions

KKDs to be released after redaction:

D3.2 - Control and Safety System Manufacturing

D3.4 - Build of Capture Rig

D4.1 - Installation of Capture Rig

D4.3 - Rig Operation and Decommissioning

D5.1 - CAPEX Technoeconomic Analysis (TEA)

D5.2 - OPEX TEA

D5.3 - Life Cycle Analysis (LCA)

D6.6 - Stakeholder Analysis

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Introduction

The University of Nottingham is conducting a technoeconomic analysis (TEA) of Promethean's metal-organic framework (MOF) production and the MONET pilot scale carbon capture plant, which will be operated at an operational power station in the UK. The methodology and capital expenditure (CapEx) analysis is provided in this report.

This is the first study of its kind to model the CapEx of MOF production at the pilot-scale, and the first study to model MOF carbon capture at the pilot scale using real data from a power station. The study forms part of deliverable 5.1 (CapEx TEA) of WP5 (Life Cycle and Technoeconomic Assessment) for the MONET project. The aim of this deliverable is to provide a CapEx analysis of the initial costs of the MOF and pilot scale carbon capture plant based on costs for the equipment costs for producing the MOF and construction of the post-combustion carbon capture system. This report audience is Promethean Particles and aims to benchmark the cost of capture carbon using MOFs against competitor technologies such as amines.

CapEx Model

This CapEx TEA has been developed by the University of Nottingham using a TEA model developed by Dr Sarah Rodgers[1-3] and cost data provided by Promethean Particles on the MOF production costs and capital costs for the MONET post-combustion carbon capture rig. The steps in conducting the CapEx TEA are shown in Figure 1.

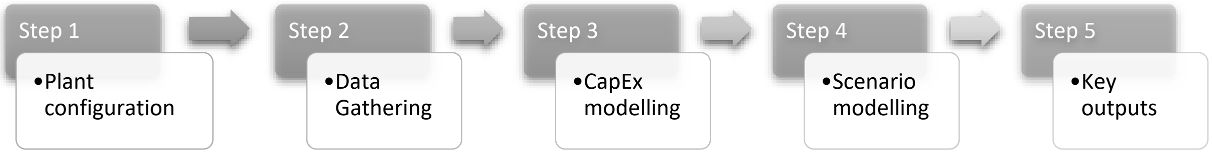

Figure 1. CapEx analysis steps

The study is limited by the fact it is based on pilot-scale data rather than full-scale manufacturing data. Thus, the CapEx costs are based on pilot-scale production, not an optimised full-scale production of MOF. Furthermore, Promethean Particles are MOF manufacturers, not carbon capture system manufacturers. Whilst a demonstrator plant has been produced as part of this project, this is not the business objective of Promethean Particles, and thus the costs for future carbon capture systems would vary based on the design of the system. Whilst this is the largest known MOF-based CCS demonstrator to date, it is not full scale, and thus future TEA will be required for the full-scale production of MOF and capture of CO2 for a true comparison with other full scale carbon capture technologies.

This report will include the following scenarios:

- Variation in carbon capture potential and MOF produced for PC-CCS.
- Variation in the Inside Battery Limits (ISBL) - this refers to all equipment items that directly impact the process. This includes all process operations, immediate feedstock and product storage, etc.
- Variation in the Outside Battery Limits (OSBL) - this refers to all equipment items that are solely related to the process operation, but are outside the actual requirements of immediate operation. This includes the majority of feedstock and product storage, any packaging and logistical operations, the control room etc.
- Plant life
- Discounted Rate of Return or hurdle rates

Scenarios such as the introduction of carbon prices and use of renewable energy will be explored in the OpEx analysis in D5.2.

Project Scope

This is the first CapEx analysis conducted of a pilot scale continuous flow MOF production system, and the application of MOFs in a PC-CCS. The CapEx is using real cost data provided by Promethean Particles for the analysis and the MOF production and PC-CCS is based on the actual set-up at Promethean Particles and the PC-CCS test site. An outline of the MOF production system and how it fits into the PC-CCS system is shown below. A production campaign volume of MOF has been produced for the PC-CCS. The PC-CCS assumes a portion of this volume is used during the trials. The model only includes the MOF production and PC-CCS. It does not include any downstream systems such as carbon storage and transport, or any upstream processes at DPS where the flue gas originates from.

Data Quality

In this study, an uncertainty rating for each assumption in the model has been allocated by assessing the quality of the data source and the impact of the assumption on the model outputs. Table 1 provides the definitions for the quality and impact ratings used, and Table 2 shows how these translate into uncertainty ratings for the assumptions made.

Table 1: 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	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.

	decreases. A wide confidence interval (eg ±50%) would have a low quality rating.	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 2: 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

CapEx Modelling

CapEx modelling normally only considers the capital (fixed capital/working/manufacturing or non-manufacturing) investments of a project [4], but this model is complicated due to the combination of the MOF production and PC-CCS. Thus, the PC-CCS part, which only includes equipment installed costs, is limited to the total plant costs (TPC). The MOF production CapEx is covered in a separate MOF production analysis which includes some operational expenditure (OpEx) elements such as labour and electricity costs. The fixed capital investment (FCI) was calculated using the Hand Method for calculating the CapEx costs for the PC-CCS [5]. The assumptions of the model are outlined in Table 3. The data used in this CapEx model is confidential.

Table 3: Fixed capital cost model assumptions

Economic Parameters	Value	Data Quality	Model Impact	Uncertainty
Cost basis year	2024	High	Low	Low
OSBL	25% of ISBL	High	Low	Low
Commissioning Cost	5% of ISBL	High	Low	Low
Fixed Capital Investment (FCI)	ISBL + OSBL + Commissioning	High	Low	Low

Working Capital	10% of ISBL + OSBL	High	Low	Low
Total Capital Investment (TCI)	FCI + Working Capital	High	Low	Low
Location Factor	1 (Data Given for UK Location)	High	Low	Low
Contingency Cost	10%	High	Low	Low
Working Capital	10%	High	Low	Low
Discounted Rate of Return (r)	8%	Medium	Medium	High
Corporation Tax	25%	High	Low	Low
Linear depreciation	10 years	High	Low	Low
Annual inflation	2%	High	Low	Low
Plant Life (n)	25 years	Medium	Medium	High
Carbon Capture per annum (t CO2)	500	Low	High	Very High

The ISBL fixed capital cost of a plant is given as a function of the total purchased equipment cost based on the following equation:

$$ISBL = F\left(\sum C_e\right)$$

Where F are installation factors which vary by equipment category (Table 4) and Ce is the total cost of all major equipment items. In general, larger plant equipment has a smaller factor.

Table 4: Values of the Hand Factors (F) for different equipment categories [6]

Equipment Type	Hand Factor (F)
Compressors	2.5
Distillation columns	4.0
Fired heaters	2.0
Heat exchangers	3.5
Instruments	4.0
Miscellaneous equipment	2.5
Pressure vessels/tanks	4.0
Pumps	4.0

PC-CCS CapEx Model

The capital costs for the main equipment for the PC-CCS system are provided in Table 5. These figures were used in a CapEx model based on the Hand Method to provide the annualised Capital Cost for the PC-CCS. In this model, the Total Capital (CapEx cost) is calculated from the ISBL capital, OSBL capital, contingency cost and working capital. The Annualised cost is then calculated from the following equations:

$$Annualised\ CapEx = \frac{CapEx}{Annualised\ Facor}$$

$$Annualised\ Factor = \sum_{i=1}^{n} \left[\frac{1}{(1+r)^{n}}\right]$$

Where n represents the operational years or plant life and r is the discount rate for a 2 year construction period and 23 years of operation [4], the values for which are provided in Table 3.

Table 5: Capital costs for PCCS

Item	Cost	Installation Factor
Inlet flue gas blower	Redacted	4.0
Air cooled heat exchanger	Redacted	3.5
Knock out pot	Redacted	4.0
MOF adsorber vessel	Redacted	4.0

Vacuum pump	Redacted	4.0

MOF Production CapEx Model

In contrast to the PC-CCS CapEx model, which followed a standard CapEx modelling process, the MOF production requires elements of OpEx analysis to be included. This is due to the additional costs associated with producing the materials which are not required for the PC-CCS. This is not calculated as a continuous operation, but for a production campaign of MOF, only a portion of which will be used in the PC-CCS. The additional costs are associated with the labour (wage and salary), consumable costs and electricity used to create the MOF. The capital and operational costs for a production campaign of MOF are summarised in the table below. It should be noted that a production campaign of MOF was produced to ensure that there is enough material for the PC-CCS after drying, pelleting and any transportation losses. It is a nominal figure, not an optimised figure, and a full-scale production system will operate on minimal optimised losses. Averaged labour costs are assumed based on the average base salary for a UK plant operator [7]. Shift teams are assumed to be 4.8, with 2 members per shift. The hours of operation are assumed to be 8,000 hours. The total production cost is the sum of the operating labour, consumables cost, annualised CapEx and electricity costs. This is then inputted into an investment analysis model with a discounted rate of return, corporation tax, linear depreciation, annual inflation and plant life values as stated in Table 3. Based on this a CapEx cost per tonne of CO2 captured can be provided for the PC-CCS and MOF production, which can then be combined to give the total CapEx cost per tonne of CO2 captured within MONET.

Table 6: Capital and operational costs for a production campaign of MOF

Category	Cost
MOF	
Direct Costs (incl. equipment, consumables, utilities, staff, etc.)	Redacted
How many operators for each bit of kit (persons)	
Promethean: Reagent preparation	2
Promethean: MOF Production on CFS Rig	2
Promethean: MOF Washing	2
Life Time	

Assumed life of kit (pilot scale)	2 years
Labour time	
How long does it take to do each part (for labour and energy costs)	
Promethean: Reagent preparation	3 hours
Promethean: MOF Production on CFS Rig	6 hours
Promethean: MOF Washing	4 hours

Benchmarking of MOF CCS TEA

Industrial-scale MOF production is not yet a mature process. Most MOF production is conducted in batch processes, with high manufacturing costs. The MOF used in this project has been demonstrated by Promethean Particles as a suitable MOF for CO2 capture at ambient conditions [8]. Several TEAs have been done for MOFs for CCS, but often based on lab scale production methods for the MOFs [9]. Furthermore, these methods are small scale batch methods, not continuous flow process as used by Promethean Particles [10]. TEA for MOFs for CCS have been done for producing 1kg of MOF [9]. The production cost of UiO-66-NH2 has been found to be $14.2/kg to $17.5/kg of MOF for aqueous solution-based system and $56/kg to $117/kg of MOF for a solvothermal system. However, these are based on laboratory-scale productions, not continuous-flow pilot or full-scale systems. Furthermore, this is significantly lower than other studies which have shown a levelized cost for UiO-66-NH2 of approximately $6,498 per kilogram, which is comparable in cost to other archetypal MOFs offered in retail markets [11]. Table 7 shows a comparison of the production costs of different CO2 adsorbents developed by Loughran et al. [12]. To date, no production costs have been reported for the MOF utilised by Promethean Particles in this study (Table 8).

Table 7: Cost of MOF sorbents

MOF sorbent	Cost to produce	Batch or continuous	Scale	REF
MIL-120	$2916.5 /kg	Batch	Lab	[12]
MEA	$1140-2880 / mt	Continuous	Commercial	[13, 14]
Al-PMOF	$37,609.37 /100g	Batch	Lab	[12, 15]
CALF-20	$1,823.38/ 100g	Batch	Lab	[12, 16]
Co-MOF-74	$2,735.3 / 100g	Batch	Lab	[12, 17]
SGU-29	$26.33 / 100g	Batch	Lab	[12, 18]
MIL-91	£35,338.12 / 100g	Batch	Lab	[12, 19]
MIL-160	$4,828.67 / 100g	Batch	Lab	[12, 20]

The current standard post combustion carbon capture technology is a monoethanolamine (MEA) solvent-based post-combustion carbon capture system [21]. Studies have shown MEA to have a total cost of €2.60/t CO2 [22] and $3.75 /t CO2 [23]. Comparative TEA of MOFs and amines have been conducted, but are based on simulated data and not empirical plant data [9]. Studies have used the same system as amines for the comparison, which is not realistic of MOF-based CCS. Furthermore, the power plant is often included in the analysis, rather than considering the CCS plant as a stand-alone system which could be applied to any flue gas process containing CO2. A steam cycle has been assumed for the adsorption/desorption process, while project MONET is using a vacuum swing adsorption process. Several TEAs have been conducted for MOFs for CCS, but often based on laboratory-scale production methods for the MOFs [9].

Table 8: Comparative TEA CCS studies

CCS sorbent	Cost per tonne CO2 captured	Data used	Scale	REF
UTSA-16	\$113.3-\$146.9	Simulation of PC-CCS	N/A	[24]
UTSA-16	€104.9	Simulation of Vacuum Swing Adsorption for PC-CCS	N/A	[25]
MEA 30 wt.%	€74.36	Simulation in AspenPlus	N/A	[22]

Baseline CapEx Model

Based on the data provided for the capital costs of the project, the baseline capital costs are provided in Table 9 based on the baseline assumptions detailed in Table 3, 5 and 6. It is important to note that the LCOC presented in this report are based on CapEx values for the PC-CCS and OpEx for the MOF. Thus, these results will change for project task T5.2 which covers the OpEx analysis. The Levelized Cost of CO2 Capture (LCOC) is used as one of the key outputs of the study. LCOC has been shown to be a more suitable metric for decision-making compared to either heat consumption or exergy efficiency [13]. It is calculated using the following equation:

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

Where the Total discounted lifetime cost (£) is calculated using CapEx, OpEx and discount rate, and the total discounted lifetime CO2 captured (tCO2) is calculated using mass of CO2 captured and discount rate. In this CapEx analysis, the OpEx component of the PC-CCS has not been included but is included for the MOF production. The total LCOC is lower than that reported for other MOF PC-CCS studies (Table 8), and slightly higher than that of MEA. However, this analysis is a CapEx based analysis, and the full costs should be considered against the OpEx analysis in task T5.2.

Table 9: Baseline CapEx Model Costs

Item	Cost
PC-CCS Annualised CapEx	Redacted
MOF Annualised CapEx	Redacted
Annual MOF Production Cost	Redacted
MOF Production Cost per kg	Redacted
CO2 Captured	500 tonnes/yr
Total Capex Cost	**£389,692**
PC-CCS LCOC	Redacted
MOF LCOC	Redacted
Total LCOC	**£85/tCO2**

Scenario CapEx Models

Physical Variables

MOF Production

The current model is based on the production campaign volume of MOF, as this is the actual amount produced for this project. A portion of this volume was put into the design, which would reduce the total MOF production cost. This is a slight reduction on the cost presented in Table 7, but assuming the same carbon capture rate of 500t CO2, then the MOF LCOC would drop. This shows that the carbon capture rate needs to be adjusted to CO2/kg of MOF to ensure variations in production can be compared accurately. This data will be provided in the trial stage of this project and will improve the accuracy of the OpEx model.

Carbon Capture Potential

Carbon capture potential does not directly impact the CapEx of the PC-CCS. However, it will dictate how much MOF is required for the PC-CCS and thus is an important consideration in the economic viability of the system. This is the first pilot scale MOF demonstration plant, and the actual capture potential of MOFs in real systems is unknown. This is a significant uncertainty regarding this data which cannot be resolved during this project, as long-term trials at scale are required to determine the operational life and true carbon capture capacity of the MOFs. Figure 2 shows the influence of carbon capture rate of PC-CCS, MOF and total LCOC based on the CapEx analysis for the production campaign volume of MOF. It is clear that low carbon capture rates (<500t CO2) result in increased LCOCs, but there is a diminishing impact over 500t CO2, with little change over 750t CO2. This implies that increasing carbon capture rates does not provide a linear LCOC, and increasing carbon capture capacity rates does not result in linear reductions in costs, as LCOC levels out. It is important to note that the LCOC presented in this report are based on CapEx values for the PC-CCS and OpEx for the MOF. Thus, these results will change during work package task T5.2, which covers the OpEx analysis.

Plant Life

Technoeconomic analysis is normally used to assess an investment opportunity. Thus, plant life is normally set to 25 years for the analysis. However, this pilot scale demonstrator only has a plant life of 2 years. Decreasing the plant life to 2 years in the CapEx model increases the annualised costs for both the PC-CCS system and the MOF production cost.

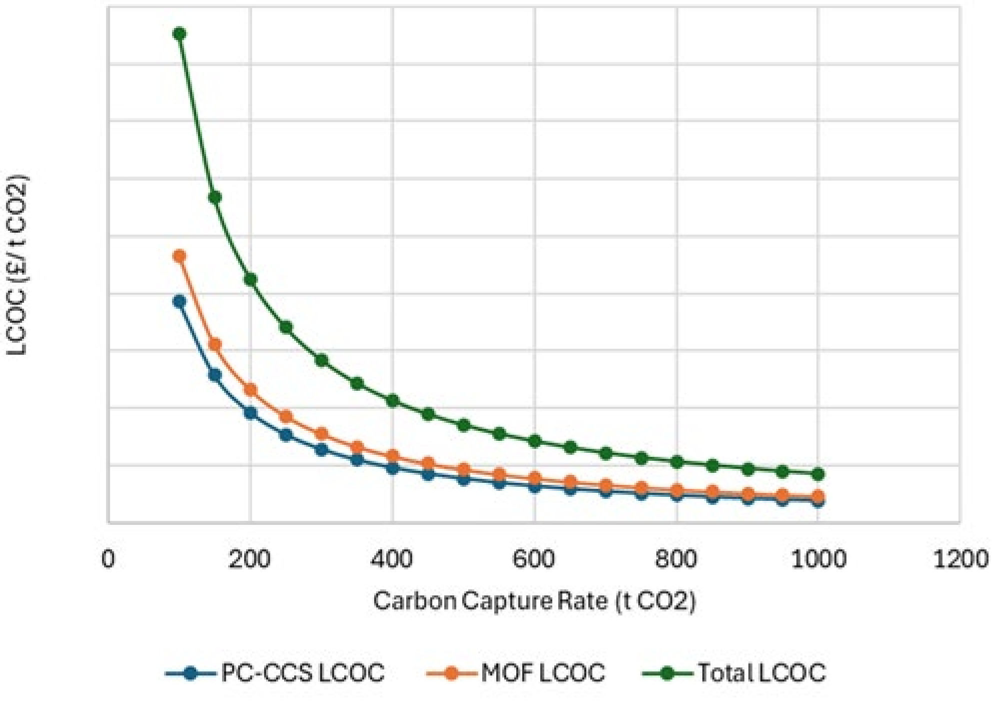

Figure 2. Influence of Carbon Capture rate on LCOC

Financial Variables

ISBL & OSBL

CapEx includes investment for the core plant, “inside battery limits” (ISBL), and investment for connection and infrastructure, “outside battery limits” (OSBL). Depending on whether the project is an expansion of an existing plant (brownfield) or a new plant (greenfield), civil and structural costs can vary greatly because most, if not all, of the support infrastructure may already be in place for a plant expansion project [26]. Two terms, Inside battery limits (ISBL) and Outside battery Limits (OSBL) have been used historically to distinguish the main processing area (ISBL) from the supporting infrastructure that is located apart from the processing units (OSBL). The ISBL and OSBL directly impact the annualised capital costs. Figure 8 shows the impact a ±20% variance of ISBL and OSBL has on the annualised PC-CCS costs. This further impacts the PC-CCS LCOC.

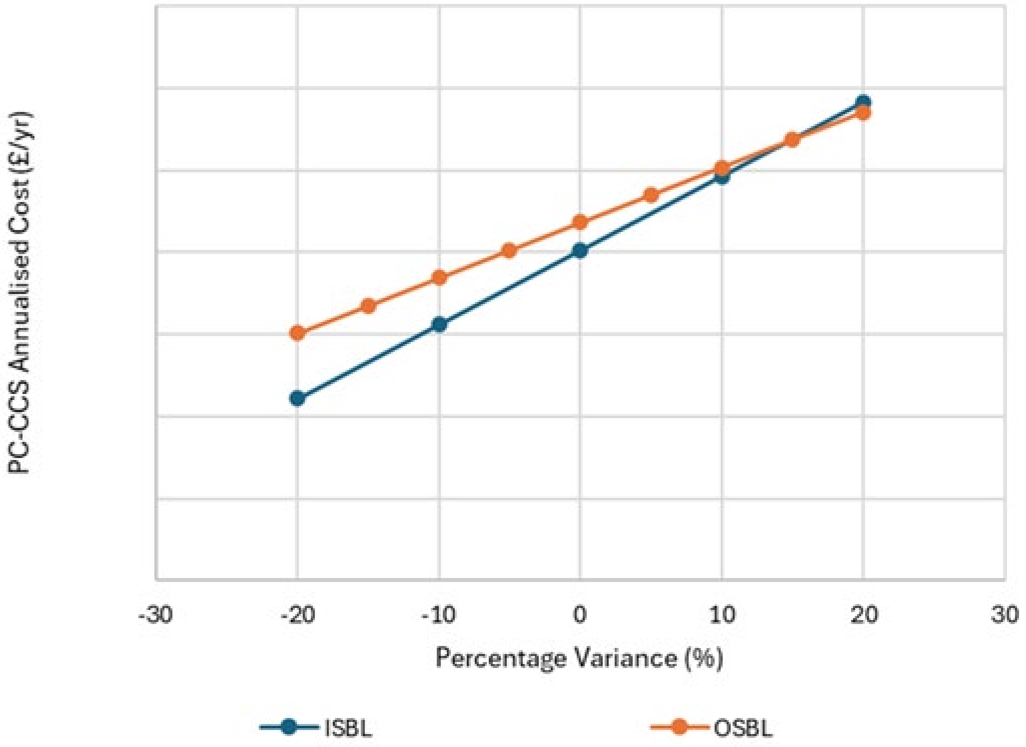

Figure 3. Impact of Varying ISBL and OSBL by ±20%

Discounted Rate of Return or hurdle rates

A hurdle rate, or discounted rate of return, is the lowest rate of return a project or investment must achieve before a manager or investor deems it acceptable. Riskier projects generally have higher hurdle rates than those with less risk. The current hurdle rates for Biomass CCS is 11.4% according to the UK Government [27]. However, the PC-CCS model is only a CapEx and a full OpEx is required to gain a full appreciation of the impact of hurdle rates. The impact of hurdle rates will be explored in more detail during the OpEx analysis.

Conclusions

This report provides an overall CapEx analysis of the PC-CCS pilot plant which is to be installed at a power station test facilities, which also includes a OpEx analysis of the MOF Production of a production campaign volume which is to be used during the trials. The model is split into two parts, a CapEx of the PC-CCS, and an OpEx of the MOF production. This is due to the additional costs associated with producing the materials which are not required for the PC-CCS.

The model uses the Hand Method to analyse the CapEx costs, and provides results in annualised costs, and provision LCOC.

The physical variables which influence the CapEx analysis included the production quantity of MOF, which had a small impact. Plant life for the CapEx analysis was set to 25 years as this is the standard for TEAs but is in reality only 2 years for the demonstration pilot scale rig. Finally, the carbon capture potential of the MOF was found to make a significant impact on the LCOC up to 500 tonnes per annum, after which the impact diminished as the LCOC levelled out, indicating for the CapEx analysis, that there is an optimal carbon capture level, beyond which there are diminishing reductions in costs. The financial variable of ISBL and OSBL impacted the LCOC but not as dramatically as carbon capture potential, whilst hurdle rates could have significant impacts on the full OpEx analysis, which will be conducted in work package task T5.2.

There is significant data uncertainty regarding the carbon capture potential, as no pilot scale MOF PC-CCS has been tested to date. Therefore, the certainty of the data in this study should become higher quality and reduced in uncertainty for the OpEx analysis, as this data will be collected from the pilot scale rig.

References

1. Rodgers, S., et al., Probabilistic commodity price projections for unbiased techno-economic analyses. Engineering Applications of Artificial Intelligence, 2023. 122.

2. Rodgers, S., et al., Reconciling the Sustainable Manufacturing of Commodity Chemicals with Feasible Technoeconomic Outcomes : Assessing the investment case for heat integrated aerobic gas fermentation. Johnson Matthey Technology Review, 2021. 65(3): p. 375-394.

3. Rodgers, S., et al., A surrogate model for the economic evaluation of renewable hydrogen production from biomass feedstocks via supercritical water gasification. International Journal of Hydrogen Energy, 2024. 49: p. 277-294.

4. Aromada, S.A., N.H. Eldrup, and L. Erik Øi, Capital cost estimation of CO2 capture plant using Enhanced Detailed Factor (EDF) method: Installation factors and plant construction characteristic factors. International Journal of Greenhouse Gas Control, 2021. 110.

5. El-Halwagi, M.M., Sustainable Design Through Process Integration : Fundamentals and Applications to Industrial Pollution Prevention, Resource Conservation, and Profitability Enhancement. 2 ed. 2017, Oxford, UNITED STATES: Elsevier.

6. Towler, G. and R. Sinnott, Chemical Engineering Design - Principles, Practice and Economics of Plant and Process Design (3rd Edition). Elsevier.

7. ERI Economic Research Institute, I. Salary Expert - plant operator. 2024 20 May 2024 20/05/2024]; Available from: https://www.salaryexpert.com/salary/job/plant-operator/united-kingdom.

8. Xiang, S., et al., Microporous metal-organic framework with potential for carbon dioxide capture at ambient conditions. Nature Communications, 2012. 3(1): p. 954.

9. Luo, H., et al., Comparison between conventional solvothermal and aqueous solution-based production of UiO-66-NH2: Life cycle assessment, techno-economic assessment, and implications for CO2 capture and storage. Journal of Environmental Chemical Engineering, 2021. 9(2): p. 105159.

10. Gimeno-Fabra, M., et al., Instant MOFs: continuous synthesis of metal-organic frameworks by rapid solvent mixing. Chem Commun (Camb), 2012. 48(86): p. 10642-4.

11. Wenger, S.R., et al., Green, One-Step Mechanochemical Synthesis and Techno-economic Analysis of UiO-66-NH2. ACS Applied Energy Materials, 2022. 6(18): p. 9074-9083.

12. Loughran, R.P., et al., CO2 capture from wet flue gas using a water-stable and cost-effective metal-organic framework. Cell Reports Physical Science, 2023. 4(7).

13. Julio, A.A.V., et al., Exergy and economic analysis of the trade-off for design of post-combustion CO2 capture plant by chemical absorption with MEA. Energy, 2023. 280.

14. INTRATEC. Monoethanolamine Prices | Historical and Current. 2024; Available from: https://www.intratec.us/chemical-markets/monoethanolamine-price#n.

15. Lu, C., et al., Comparative Study of CO2 Capture by Carbon Nanotubes, Activated Carbons, and Zeolites. Energy & Fuels, 2008. 22(5): p. 3050-3056.

16. Boyd, P.G., et al., Data-driven design of metal-organic frameworks for wet flue gas CO(2) capture. Nature, 2019. 576(7786): p. 253-256.

17. Gonçalves, D.V., R.Q. Snurr, and S.M.P. Lucena, Impact of H2O and CO2 on methane storage in metal–organic frameworks. Adsorption, 2019. 25(8): p. 1633-1642.

18. Wang, J., et al., Hydration Energetics of a Diamine-Appended Metal–Organic Framework Carbon Capture Sorbent. The Journal of Physical Chemistry C, 2020. 124(1): p. 398-403.

19. Datta, S.J., et al., CO2 capture from humid flue gases and humid atmosphere using a microporous coppersilicate. Science, 2015. 350(6258): p. 302-306.

20. Nandi, S., et al., Ultralow Parasitic Energy for Postcombustion CO(2) Capture Realized in a Nickel Isonicotinate Metal-Organic Framework with Excellent Moisture Stability. J Am Chem Soc, 2017. 139(5): p. 1734-1737.

21. AECOM, Next Generation Carbon Capture Technology: Technology Review, Work Package 2. 2022, Department for Business, Energy and Industrial Strategy.

22. Raynal, L., et al., From MEA to demixing solvents and future steps, a roadmap for lowering the cost of post-combustion carbon capture. Chemical Engineering Journal, 2011. 171(3): p. 742-752.

23. Panja, P., B. McPherson, and M. Deo, Techno-Economic Analysis of Amine-based CO2 Capture Technology: Hunter Plant Case Study. Carbon Capture Science & Technology, 2022. 3.

24. Peh, S.B., S. Farooq, and D. Zhao, Techno-economic analysis of MOF-based adsorption cycles for postcombustion CO2 capture from wet flue gas. Chemical Engineering Science, 2023. 268.

25. Subraveti, S.G., et al., Techno-economic assessment of optimised vacuum swing adsorption for post-combustion CO2 capture from steam-methane reformer flue gas. Separation and Purification Technology, 2021. 256.

26. Administration, U.E.I., Technical Economic Analysis Guide - DRAFT. 2015.

27. Economics, E., Cost of capital update for electricity generation, storage and DSR technologies. 2018.