Conference Presentations and Trade-Show Exhibitions

CCUS Innovation 2.0

Key Knowledge Deliverable 6.5

May 2025

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 D6.5 - Conference Presentations and Trade-Show Exhibitions

Within WP6 (Commercialisation, Exploitation, Dissemination), Task 6.2 (Dissemination Activities) aims to promote the scope, aims and achievements of the MONET project. While the technical work packages (WPs 1-4) focus on developing the technology, WP6 targets the communication of project activities to external stakeholders, thereby increasing their likelihood of successfully exploitation and commercialisation beyond the project duration. This deliverable report lists conferences and trade-show exhibitions attended, where knowledge associated with Project MONET was disseminated. Attached as an annex are copies of posters, presentations, and publicly published material captured within this deliverable.

As part of the work in T6.2, this deliverable report D6.5 (Conference Presentations and Trade-Show Exhibitions) contains a summary of the key results and conclusions of the project disseminated through conference presentations and trade-show exhibitions. Final output will be a variety of materials released into the wider domain.

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

Contents

Events Attended

1. EuroMOF2023, Granada, Spain – 24th – 27th September 2023 – Dr Scott Priest (Promethean Particles)
2. PorMat 2024, Liverpool, UK – 4th-5th June 2024 – Dr Leah Matsinha Poster Presentation(Promethean Particles)
3. PorMat 2024, Liverpool, UK – 4th-5th June 2024 – Rebecca Ryder Matsinha Poster Presentation (Promethean Particles)
4. MOF2024, Singapore – 15th-19th July 2024 – Dr Paul Kirkman Oral Presentation (Promethean Particles)
5. MOF2024, Singapore – 15th-19th July 2024 – Dr Selina Ambrose Presentation (Promethean Particles)

For each event attended, an associated supporting document is available. See the Annex list below.

Attached Documents Annex List

Annex 1 - D6.5 Scott Priest EuroMOF2023 Poster Presentation

Annex 2 - D6.5 Leah Matsinha PorMat 2024 Poster Presentation

Annex 3 - D6.5 Rebecca Ryder PorMat 2024 Poster Presentation

Annex 4 - D6.5 Paul Kirkman MOF2024 Oral Presentation Slides

Annex 5 - D6.5 Selina Ambrose MOF2024 Oral Presentation Slides

Annex 1 - D6.5 Scott Priest EuroMOF2023 Poster Presentation

PrometheanParticles™

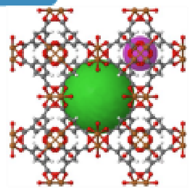
SCALE-UP OF A CONTINUOUS, ROOM-TEMPERATURE SYNTHESIS OF HKUST-1 AND DEMONSTRATION IN A CARBON CAPTURE AND STORAGE (CCS) APPLICATION

__Scott Priest__, Venus So, Rebecca Ryder, Paul Kirkman and Selina Ambrose
Promethean Particles Ltd.
Email: Scott.Priest@proparticles.co.uk

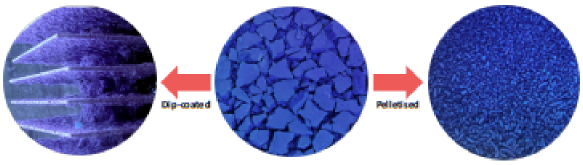
HKUST-1 for CCS

- Formula unit = $Cu_3(BTC)_2$
- **Open-metal sites** within the pores act as **CO_2 adsorption sites**

Exceptional CO_2/N_2 **selectivity**
High CO_2 **adsorption capacity**
Relatively **inexpensive** precursors
Relatively low **regeneration temperatures**



HKUST-1 Shaping



Retained performance after shaping
Robust pellets

Batch Synthesis

__Typical solvothermal methods__
50 – 100 °C
Ambient pressure
Several hours

HKUST-1
BET SA: ~1,600 $m^2\ g^{-1}$
Yield: 50-90 %

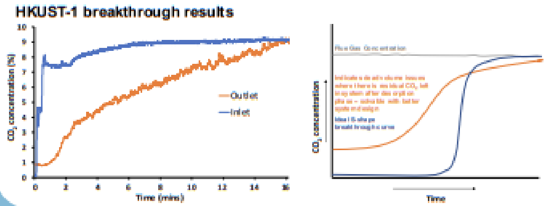
Difficult to **scale-up**
Batch-to-batch **variability**
Wide particle size distribution

PICASSO CCS Project

Pilot Scale Carbon Capture using Solid Sorbents (PICASSO) outline
- CCS project at DRAX incubation site
- Real flue gas from DRAX's Biomass based power generation on-site
- Temperature swing adsorption
- Tens of kg scale MOF for CCS
- MOF casted heat-fins for heat transfer

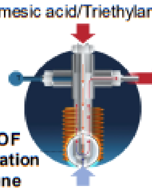
PICASSO outcomes
- Selective CO_2 adsorption demonstrated at scale
- Temperature swing not ideal due to low thermal conductivity of MOFs
- Low void space required to get correct "S" curve of breakthrough

HKUST-1 breakthrough results

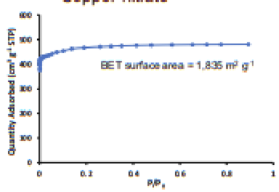


Continuous Flow Manufacturing

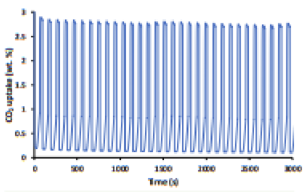
__Promethean's proprietary counter-current reactor[1,2]__



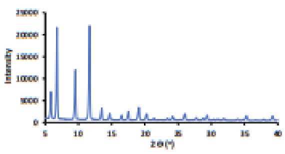
Millisecond reaction time
Excellent **scale-up reproducibility**
Instantaneous and homogeneous mixing



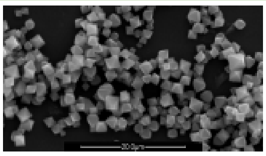
High surface area



Stable humid air cycling in 15% CO_2



High crystallinity



Narrow particle size distribution

MONET CCS Project

MOF-based Negative Emissions Technology (MONET) outline
- Follow-on CCS project from PICASSO at the DRAX incubation site
- CCS trial for 2024
- 100 kg of selected MOF to be used in a fully-automated prototype carbon capture unit
- Pressure swing adsorption
- MOFs pelleted for robustness and packing density with minimal pressure-drop
- The MONET project is funded by the Department for Energy Security and Net Zero as part of Call 2 of its CCUS Innovation 2.0 competition

Department for Energy Security & Net Zero

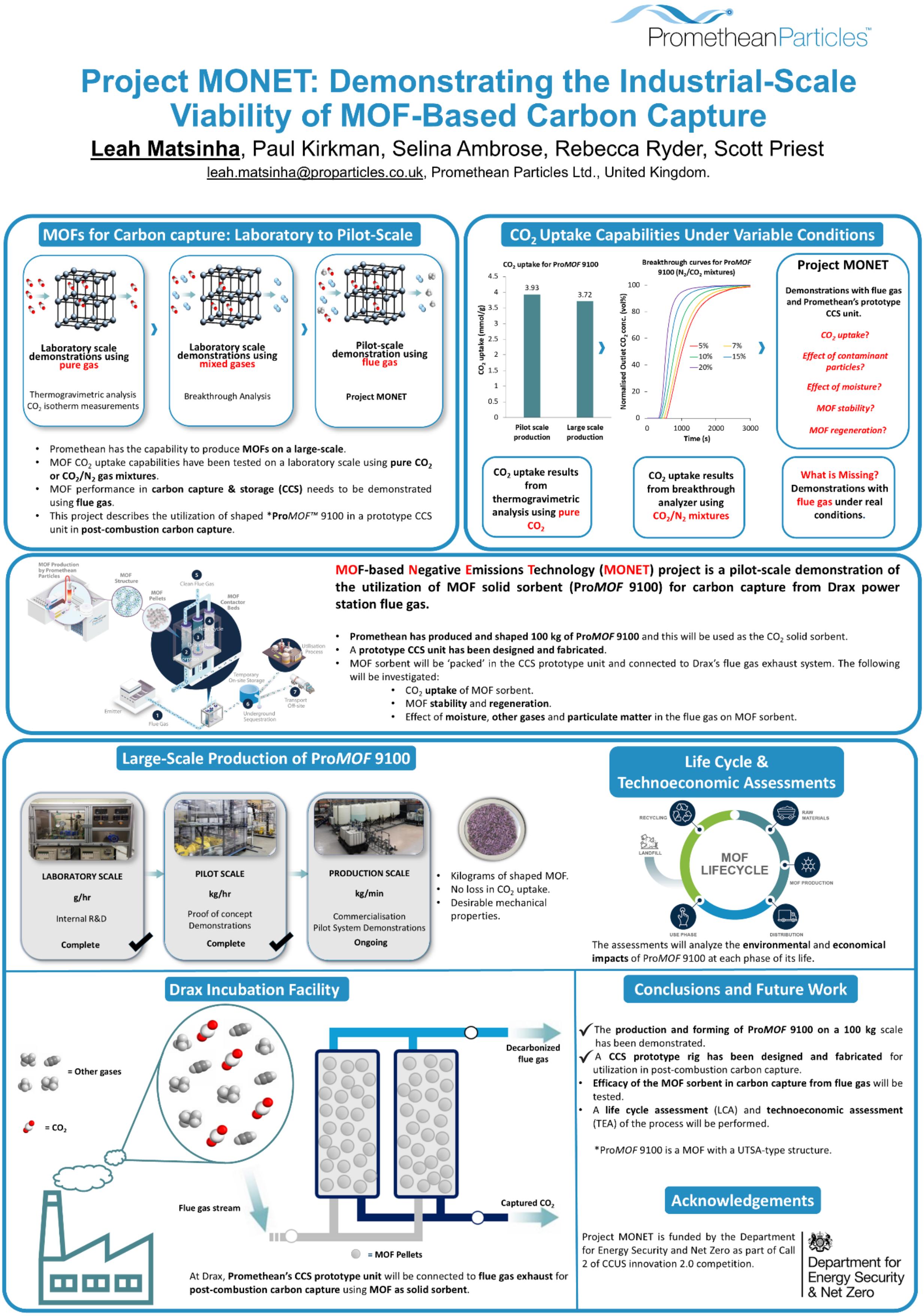
Real flue gas
100 kg of MOF for **CCS**
Pressure swing adsorption

Conclusions and Future Work

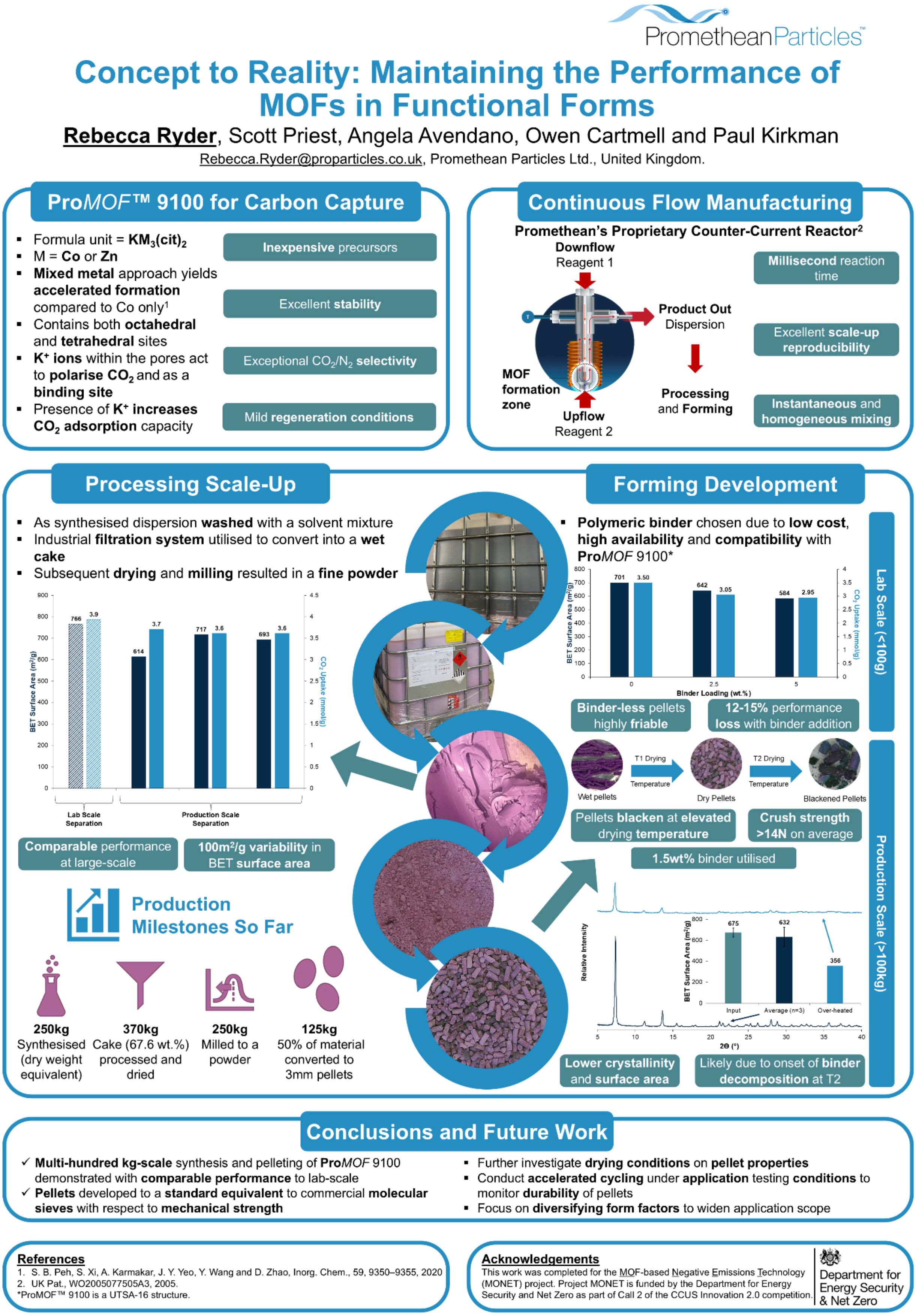
- ✓ High quality **HKUST-1** can be synthesised at **room temperature** in **continuous flow**
- ✓ **Successfully scaled up to 25 kg production**
- ✓ **Shaped without reduction in performance**
- ✓ Used in an industrial scale trial CCS demonstration rig (PICASSO Project)
- Future scale-up to 100 kg CCS unit (MONET Project)

__References__
1. M. Gimeno-Fabra, A. S. Munn, L. A. Steven, T. C. Drage, D. M. Grant, R. J. Kashtiban, J. Sloan, E. Lester and R. I. Walton, *Chem. Commun.*, 2012, **48**, 10642-10644.
2. *UK Pat.*, WO2005077505A3, 2005.

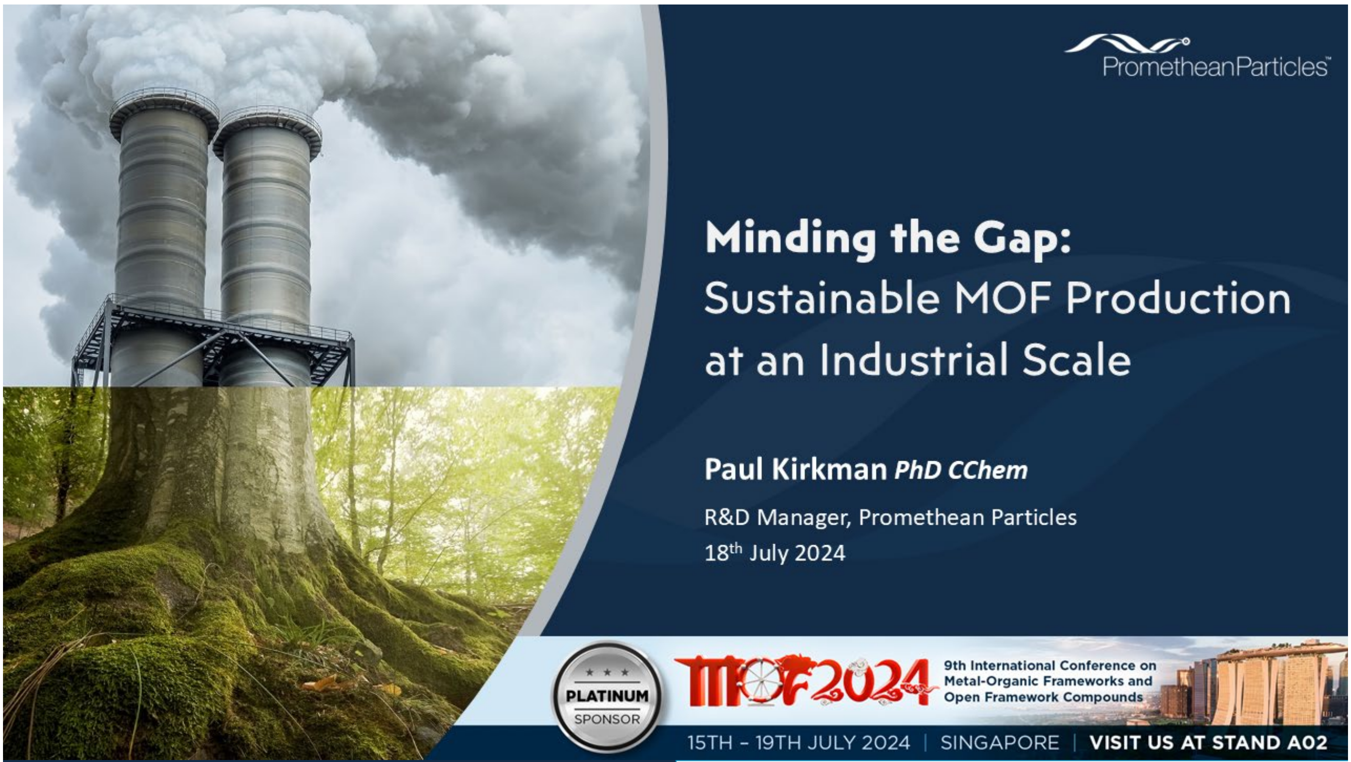
Annex 2 - D6.5 Leah Matsinha PorMat 2024 Poster Presentation



Annex 3 - D6.5 Rebecca Ryder PorMat 2024 Poster Presentation



Annex 4 - D6.5 Paul Kirkman MOF2024 Oral Presentation




PrometheanParticles™
Industrial Scale
Largest of its kind continuous-flow MOF manufacturing facility
~1,000 tonne/year reactor capacity
Additional 10X increase enabled by new reactor design
Large scale directly impacts cost-effective production
MOF 2024 – 18th July 2024, Singapore
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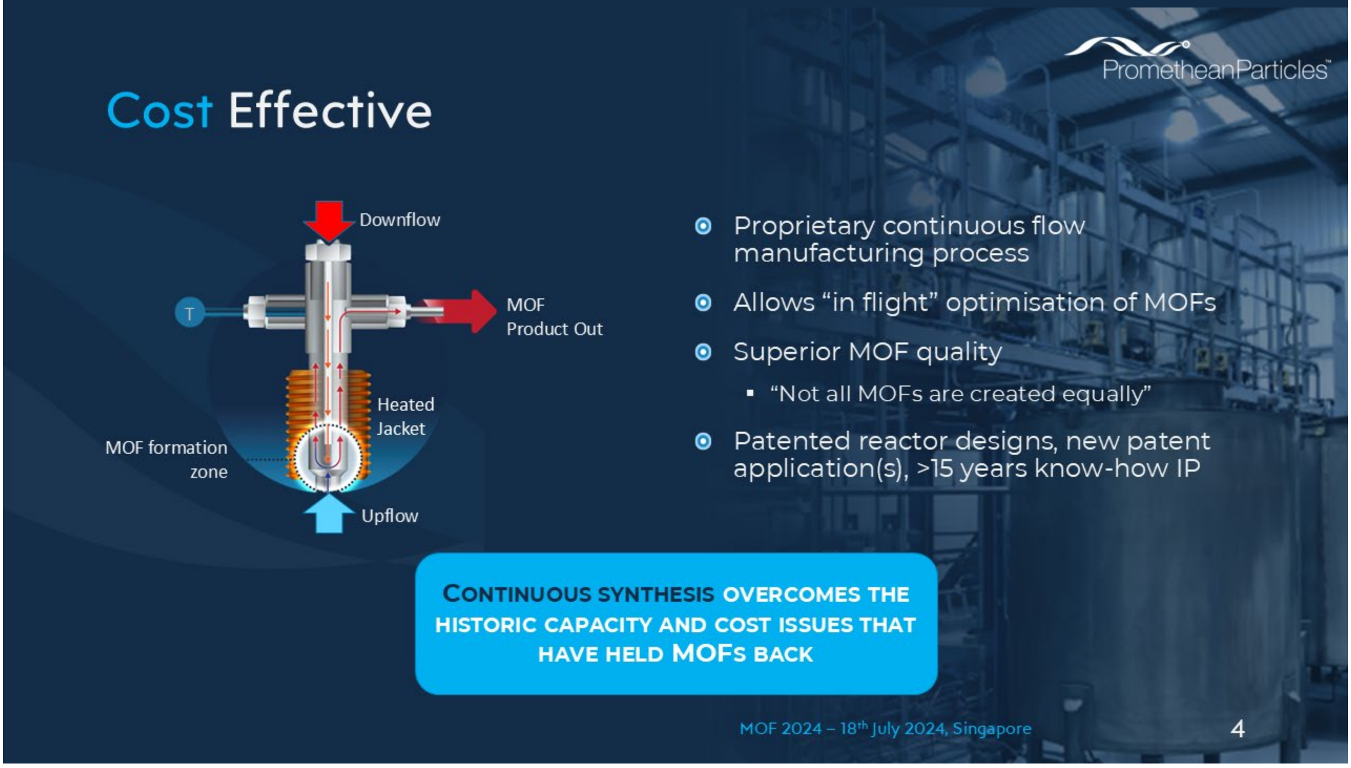
PrometheanParticles™
Cost Effective
Downflow
T
MOF Product Out
Heated Jacket
MOF formation zone
Upflow
Proprietary continuous flow manufacturing process
Allows "in flight" optimisation of MOFs
Superior MOF quality
"Not all MOFs are created equally"
Patented reactor designs, new patent application(s), >15 years know-how IP
CONTINUOUS SYNTHESIS OVERCOMES THE HISTORIC CAPACITY AND COST ISSUES THAT HAVE HELD MOFS BACK
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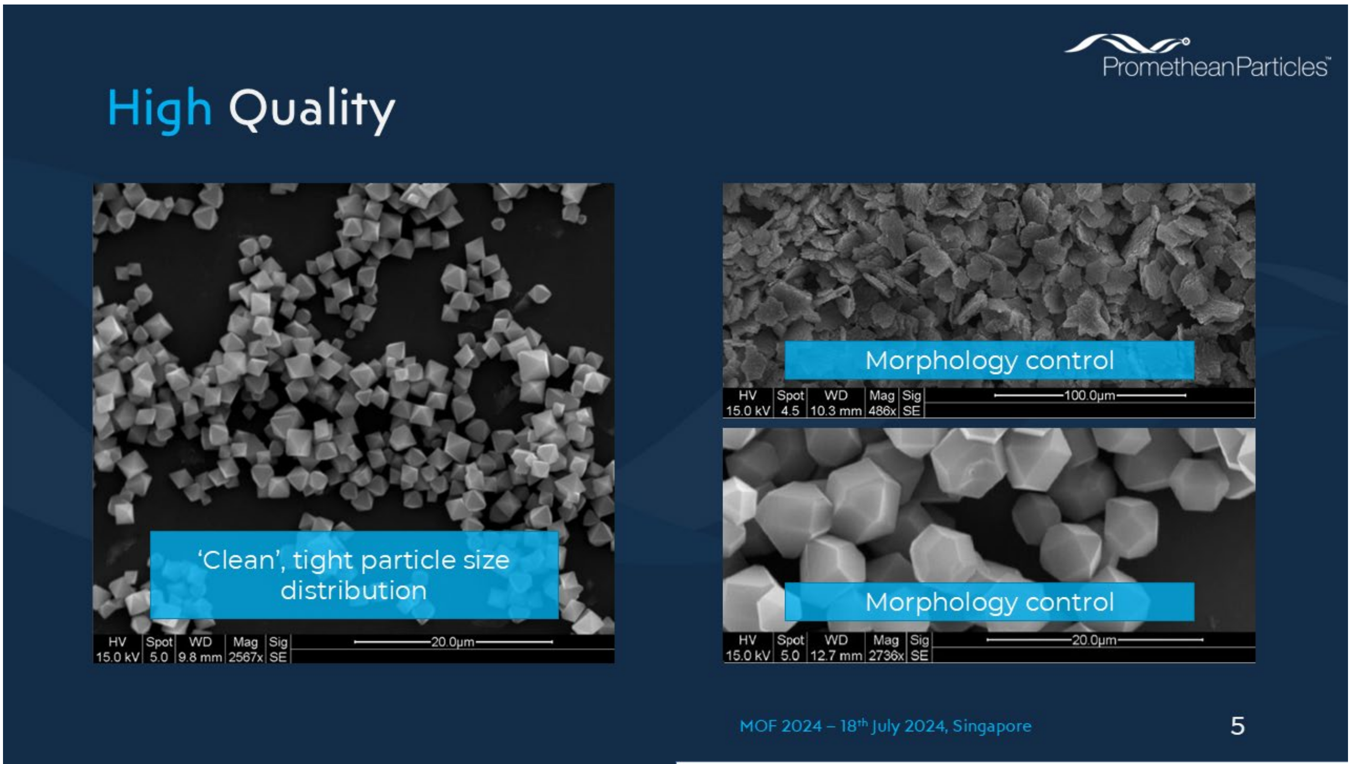
4


PrometheanParticles
High Quality
'Clean', tight particle size distribution
HV 15.0 kV Spot 5.0 WD 9.8 mm Mag 2567x Sig SE 20.0µm
Morphology control
HV 15.0 kV Spot 4.5 WD 10.3 mm Mag 486x Sig SE 100.0µm
Morphology control
HV 15.0 kV Spot 5.0 WD 12.7 mm Mag 2736x Sig SE 20.0µm
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Promethean's Mission
To unleash the game-changing potential of MOFs in the fight against climate change through our proprietary continuous-flow manufacturing processes
PrometheanParticles
KPI
Uptake Capacity
MIND THE GAP

PrometheanParticles™

Determining Viability: Our Approach

- Approximately 100,000 different MOF chemistries reported to date
  - How do we select an optimal MOF(s) for a given application?
- Various considerations can be broadly grouped into 8 different *factors*
- These factors can be summarized under 4 **thematic pillars**
  - **Performance**
  - **Economics**
  - **Supply Chain**
  - **ESG**

Promethean Whitepaper (May 2023)
Beyond CO_2 Capture: Determining the Industrial Viability of Metal-organic Frameworks (MOFs) for Carbon Capture and Storage (CCS) Applications

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Demonstrated Scale-Up

LAB/BENCH SCALE

g/day

Internal R&D
Client R&D

PILOT SCALE

kg/day

Application Development
PoC System Demonstrations

PRODUCTION SCALE

kg/min

Commercialisation
Large-Scale Field Trials
Pilot System Demonstrations

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Demonstrations of Scale

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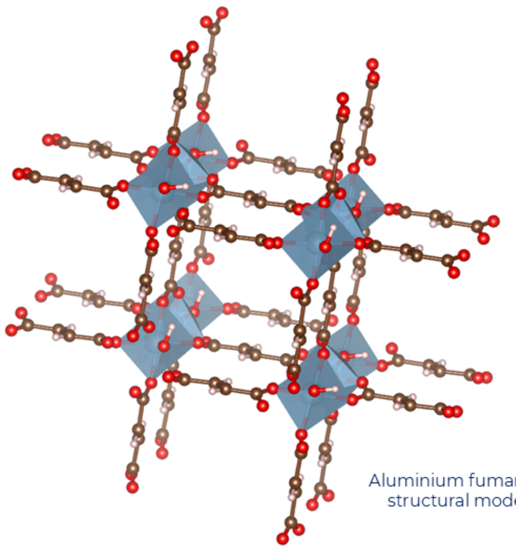
Case Study 1

Material: Aluminium fumarate

- **4-tonne commercial order**
- **Defined Structure**
  - Rigid structural analogue of MIL-53(Al)-BDC
  - Aluminium cation, fumaric acid linker
  - Hydrothermal synthesis reported
- **Key Properties**
  - Moisture stable and thermally resistant
  - Surface area >1,000 $m^2\ g^{-1}$
- **Application Interest**
  - Water harvesting
  - Gas capture and storage



Aluminium fumarate structural model

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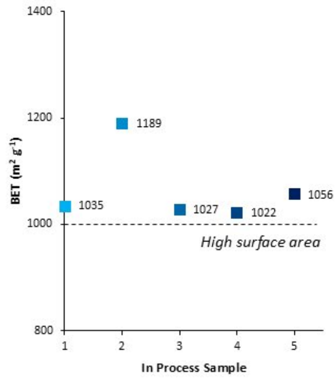
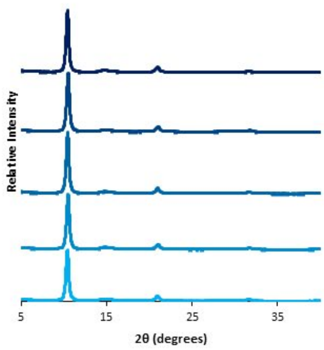
Case Study 1: AlFu





High Quality & Consistent

Industrial Scale

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Case Study 2

Material: MUF-16

- **Collaboration with MOF Inventor**
- **Defined Structure**
  - Range of cations (Co, Ni, Mn)
  - 5-aminoisophthalic acid linker
  - Solvent based synthesis route
- **Key Properties**
  - Thermally stable (beyond 330 °C)
  - Remains stable in the presence of steam
- **Application Interest**
  - Gas capture
    - Selectivity for CO_2 over hydrocarbons
    - Biogas upgrading

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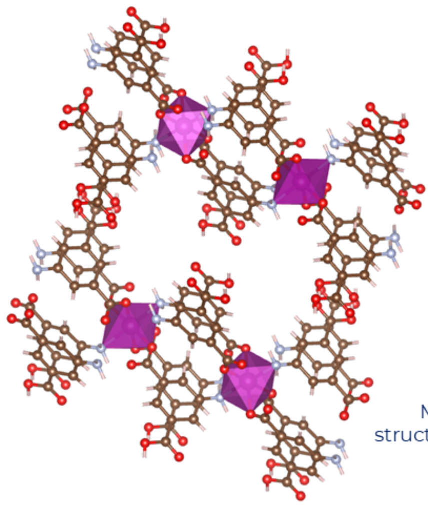

MUF-16 structural model

Qazvini, O.T., Babarao, R. & Telfer, S.G *Nat Commun* **12**, 197 (2021)

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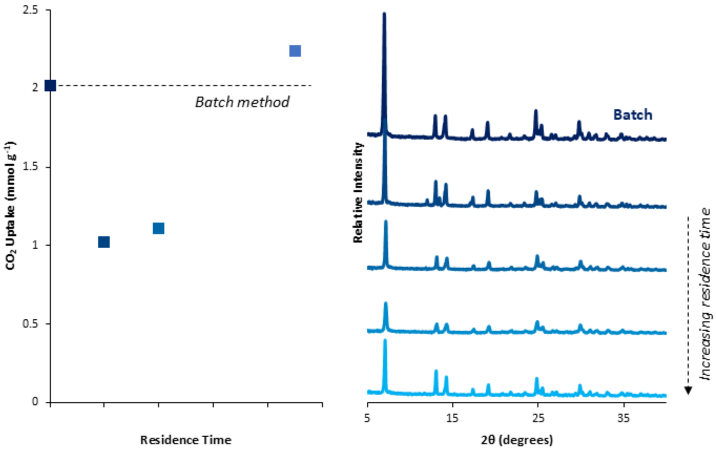
Case Study 2: MUF-16



High Quality & Consistent

Cost Effective

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Summary

- Promethean's proprietary reactor technology enables **industrial scale**, **high quality**, **cost-effective** MOF production
- By taking a **holistic approach to MOF viability**, we're on a mission to unleash the performance of MOFs in industrial applications
  - This holistic approach ensures we **Mind the Gap** when evaluating viability
- We collaborate with MOF inventors to develop **scalable production methodologies** for novel MOFs
- We have already demonstrated **MOF production** at the **tonne-scale** through our synthetic approach

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PrometheanParticles
Thank You for Attending!
Visit our exhibition booth **A02**
Follow our LinkedIn page and website for more information and recruitment updates
Download our white paper discussing the industrial viability of MOFs for CCS
BEYOND CO2 UPTAKE
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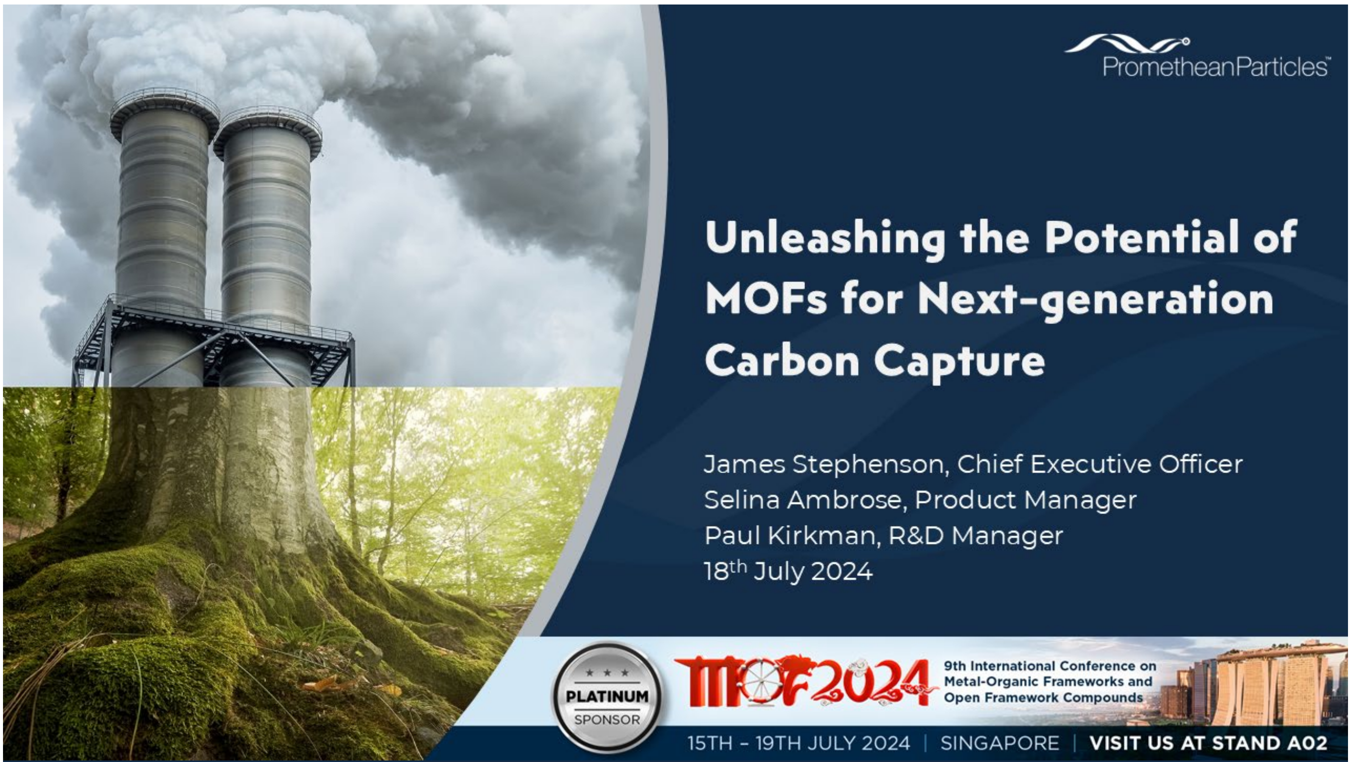
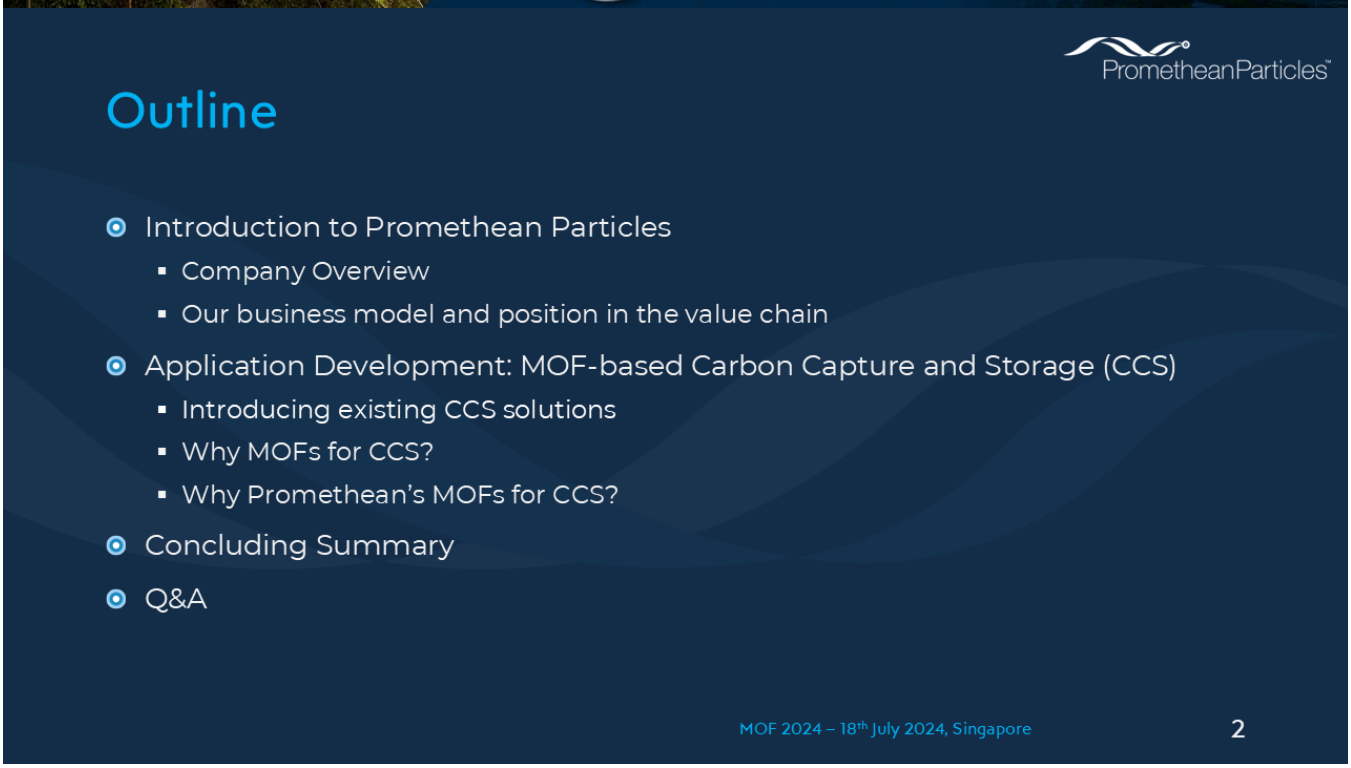
Annex 5 - D6.5 Selina Ambrose MOF2024 Oral Presentation





PrometheanParticles™

Company Overview

- Promethean Particles is an industrial-scale manufacturer of high quality and cost-effective MOFs
- Focused on development of MOFs to aid the energy transition
  - Carbon capture
  - Water harvesting
  - Gas storage
- Existing patents & know-how on reactor designs and MOF processing at scale
- Ownership and operation of the world's largest manufacturing plant of its kind
- Based in Nottingham, UK with manufacturing and R&D facilities

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Promethean's Mission

To unleash the **game-changing potential of MOFs** in the fight against climate change through our proprietary continuous-flow manufacturing processes

PrometheanParticles™

Industrial Scale | **High Quality** | **Cost Effective**

Promethean's Proprietary Reactor Technology

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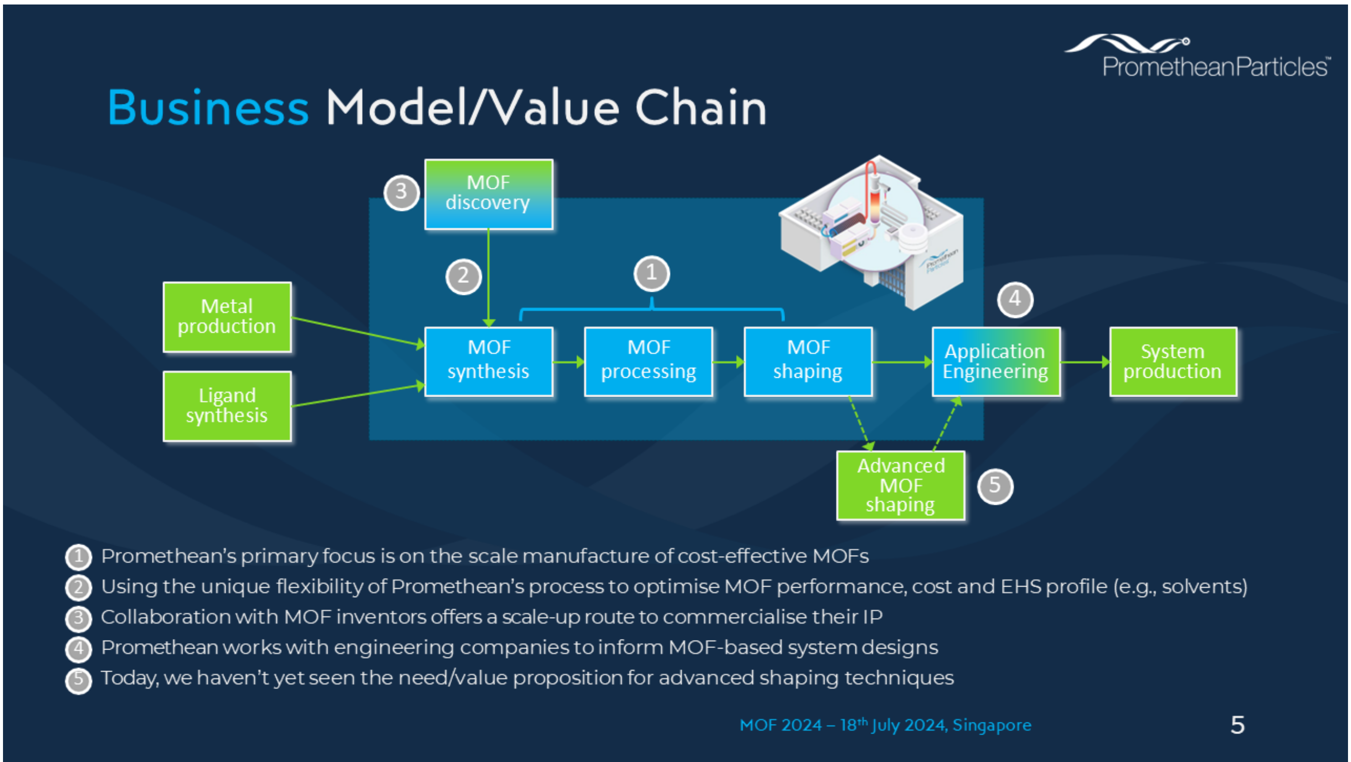
PrometheanParticles™
Business Model/Value Chain
MOF discovery
Metal production
Ligand synthesis
MOF synthesis
MOF processing
MOF shaping
Application Engineering
System production
Advanced MOF shaping
1 Promethean's primary focus is on the scale manufacture of cost-effective MOFs
2 Using the unique flexibility of Promethean's process to optimise MOF performance, cost and EHS profile (e.g., solvents)
3 Collaboration with MOF inventors offers a scale-up route to commercialise their IP
4 Promethean works with engineering companies to inform MOF-based system designs
5 Today, we haven't yet seen the need/value proposition for advanced shaping techniques
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More on Promethean's MOF Production Later….
UNLOCK THE POTENTIAL OF YOUR MOF
Join us for an industry forum session on 18th July at MOF2024
PLATINUM SPONSOR
MOF2024
15TH - 19TH JULY 2024 | SINGAPORE | STAND A02
Presented by:
Dr. Paul Kirkman
R&D manager, Promethean Particles
Industry Forum session: Today at 16:15 Room 329
Paul's talk will focus on Promethean's manufacturing capabilities and case studies of MOF scale-up and commercialisation
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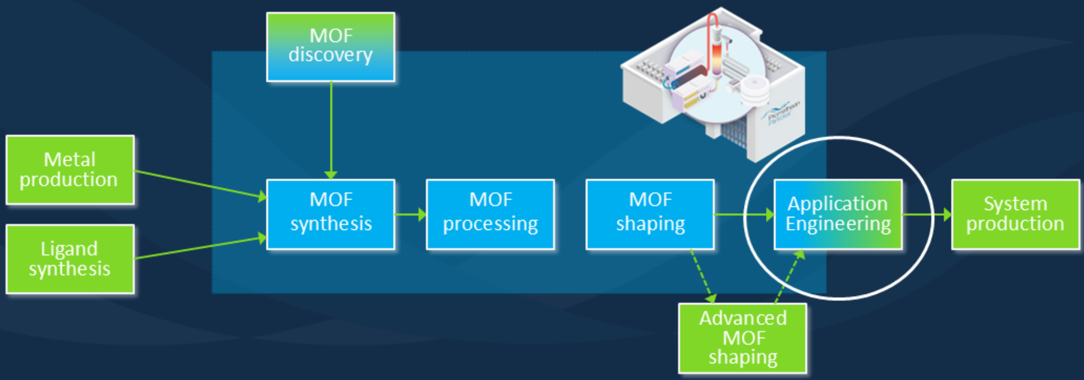
Business Model/Value Chain



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Application Development

Carbon Capture and Storage (CCS)

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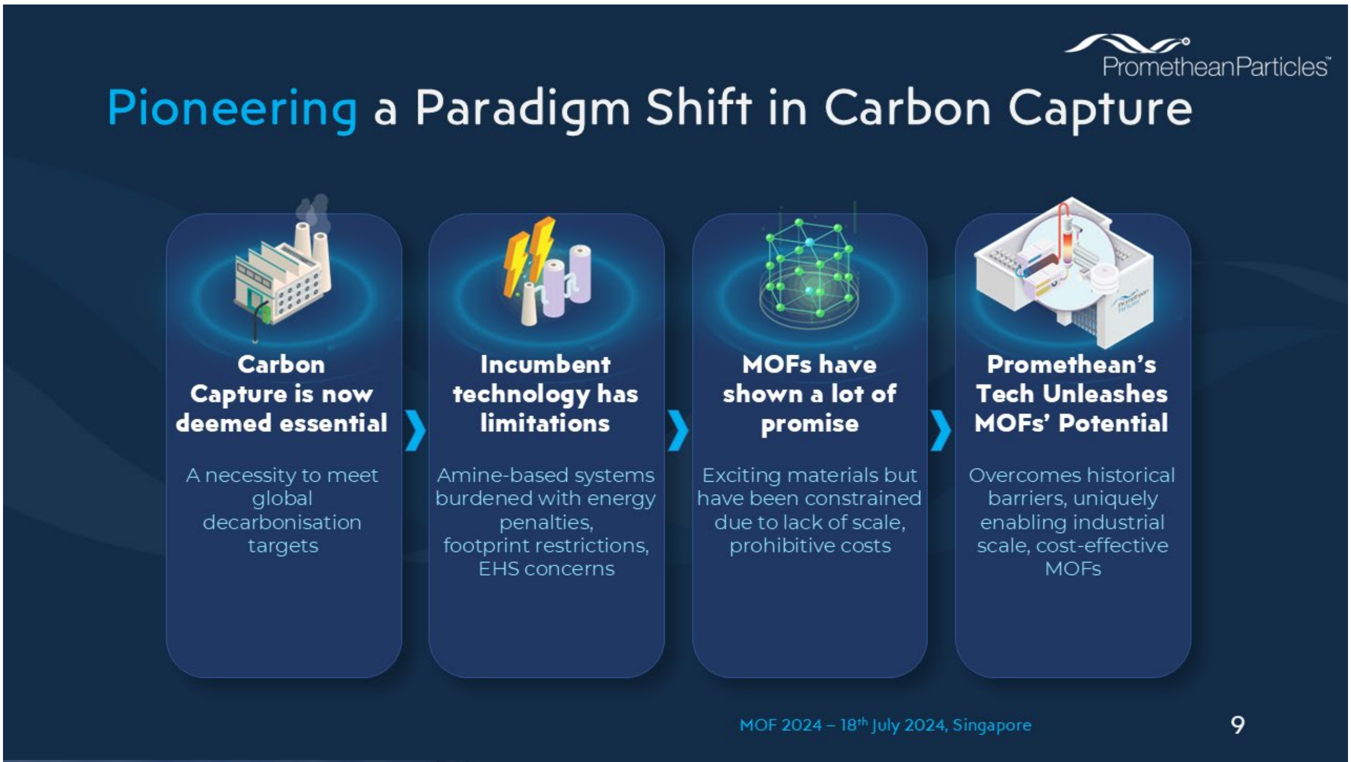
PrometheanParticles
Pioneering a Paradigm Shift in Carbon Capture
Carbon Capture is now deemed essential
A necessity to meet global decarbonisation targets
Incumbent technology has limitations
Amine-based systems burdened with energy penalties, footprint restrictions, EHS concerns
MOFs have shown a lot of promise
Exciting materials but have been constrained due to lack of scale, prohibitive costs
Promethean's Tech Unleashes MOFs' Potential
Overcomes historical barriers, uniquely enabling industrial scale, cost-effective MOFs
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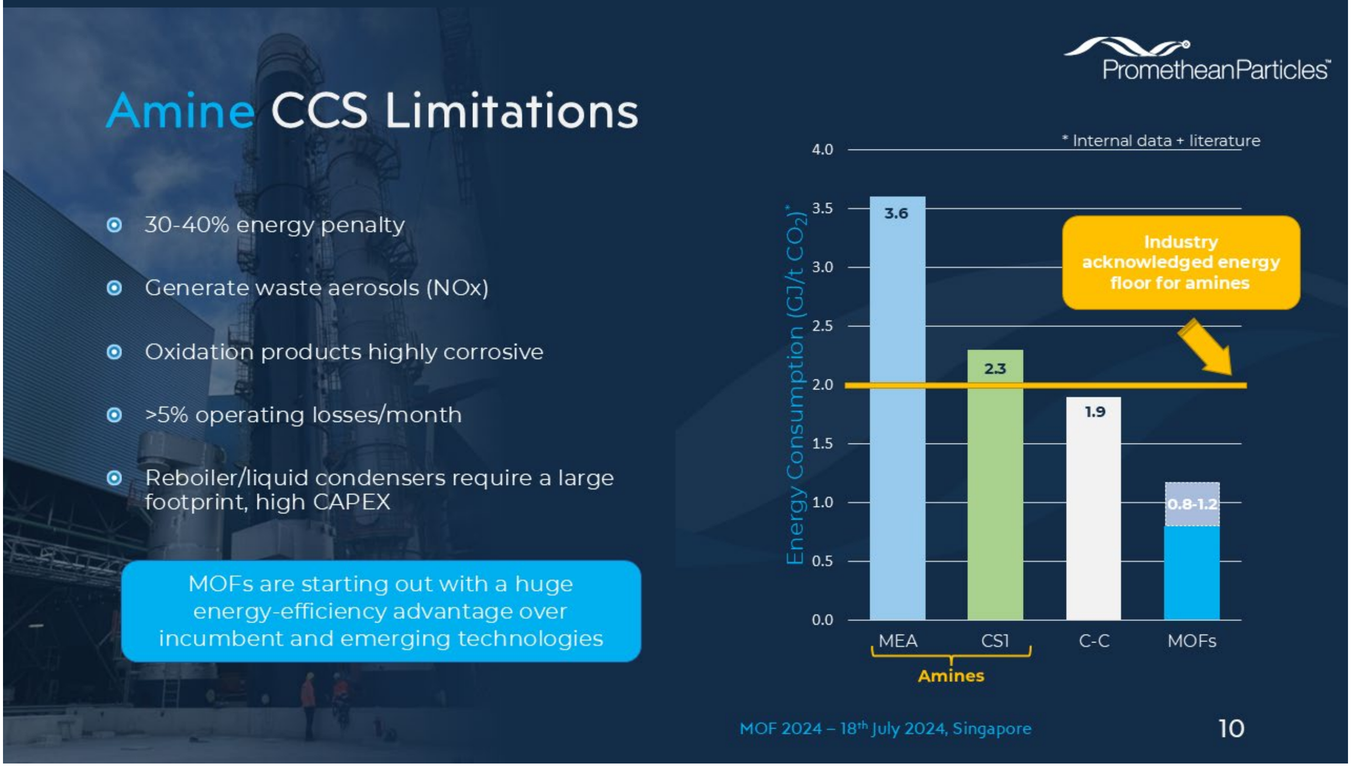
PrometheanParticles
Amine CCS Limitations
30-40% energy penalty
Generate waste aerosols (NOx)
Oxidation products highly corrosive
>5% operating losses/month
Reboiler/liquid condensers require a large footprint, high CAPEX
MOFs are starting out with a huge energy-efficiency advantage over incumbent and emerging technologies
* Internal data + literature
Energy Consumption (GJ/t CO_2)*
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
3.6
2.3
1.9
0.8-1.2
Industry acknowledged energy floor for amines
MEA
CS1
C-C
MOFs
Amines
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Why MOFs for CCS?

Hypothesis: MOF-based CCS is more viable than incumbent amines

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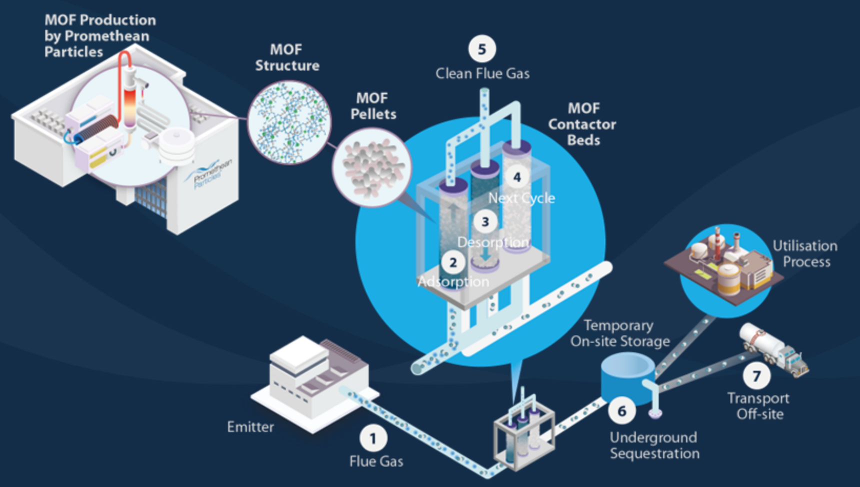
MOF-based Carbon Capture



1. Flue gas continually flows to the MOF-based CCS system
2. CO_2-rich flue gas enters a column of MOF pellets which capture the CO_2
3. Once saturated, a bed goes into a regeneration/desorption mode
4. After desorption, bed is ready for the next cycle
5. "Clean" flue gas stripped of CO_2 is released into the atmosphere
6. Stripped CO_2 is sent to temporary on-site compression & storage
7. CO_2 can then be transported off-site, further used, or sequestered

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Validating the Hypothesis

- Approached by an Oil & Gas Major to conduct a proof-of-concept **desktop feasibility study to compare MOF-based CCS vs. incumbent amine technology**
- Study based on flue gas parameters provided by the customer:
  - CO_2 Concentration: 25-30 mol%
  - Water content: >20 mol%
  - Flow rate: >2,000,000 kg/hr
- Promethean worked with an experienced engineering company in the O&G field to conduct the feasibility study, and calculate for both technologies:
  - CapEx & OpEx
  - Energy Penalty
  - CO_2 Capture Cost
- Models based on literature reports and lab test data obtained on Promethean's MOF products

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Feasibility Study – Assumptions

- Amines typically have a 90% capture rate compared to 95% for MOFs
- Monoethanolamine (MEA) used for comparison as the most studied amine
- MOF price (at the scale required for this study) = £30/kg
- 10-minute cycling time for CO_2 adsorption/desorption
- MOF can be cycled 100,000 times before replacement is necessary

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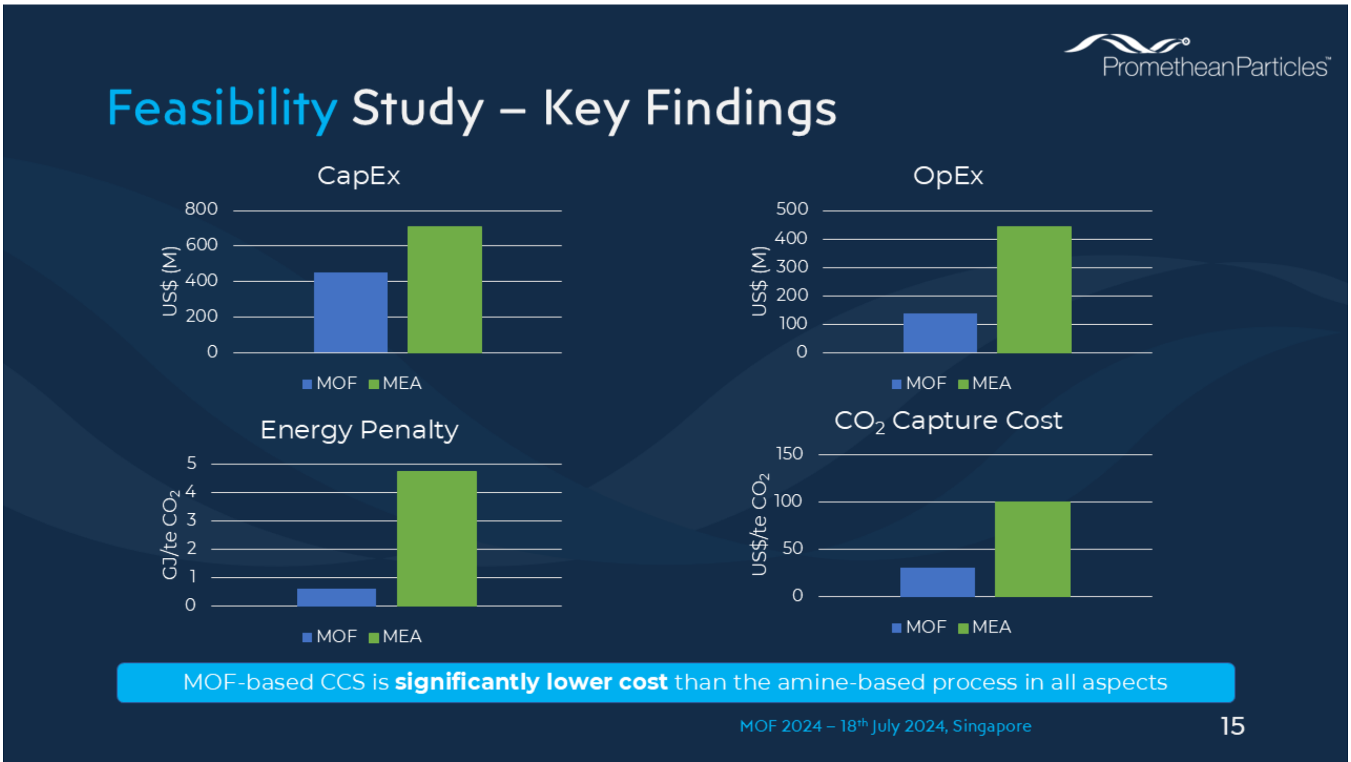
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Feasibility Study – Key Findings
CapEx
US$ (M)
800
600
400
200
0
MOF MEA
OpEx
US$ (M)
500
400
300
200
100
0
MOF MEA
Energy Penalty
GJ/te CO2
5
4
3
2
1
0
MOF MEA
CO2 Capture Cost
US$/te CO2
150
100
50
0
MOF MEA
MOF-based CCS is significantly lower cost than the amine-based process in all aspects
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Demonstrating MOF-based CCS
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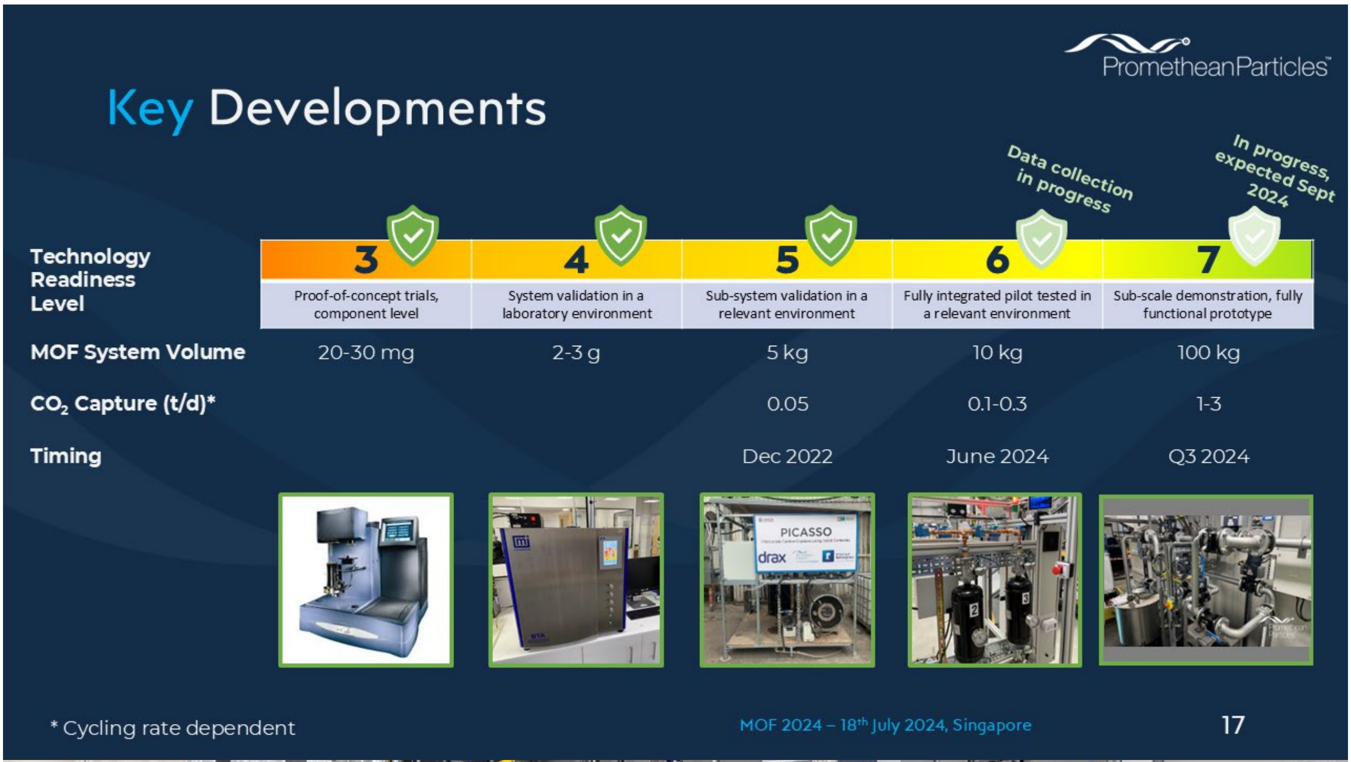
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Key Developments
Data collection in progress
In progress, expected Sept 2024
Technology Readiness Level
3
Proof-of-concept trials, component level
4
System validation in a laboratory environment
5
Sub-system validation in a relevant environment
6
Fully integrated pilot tested in a relevant environment
7
Sub-scale demonstration, fully functional prototype
MOF System Volume
20-30 mg
2-3 g
5 kg
10 kg
100 kg
CO_2 Capture (t/d)*
0.05
0.1-0.3
1-3
Timing
Dec 2022
June 2024
Q3 2024
PICASSO
drax
* Cycling rate dependent
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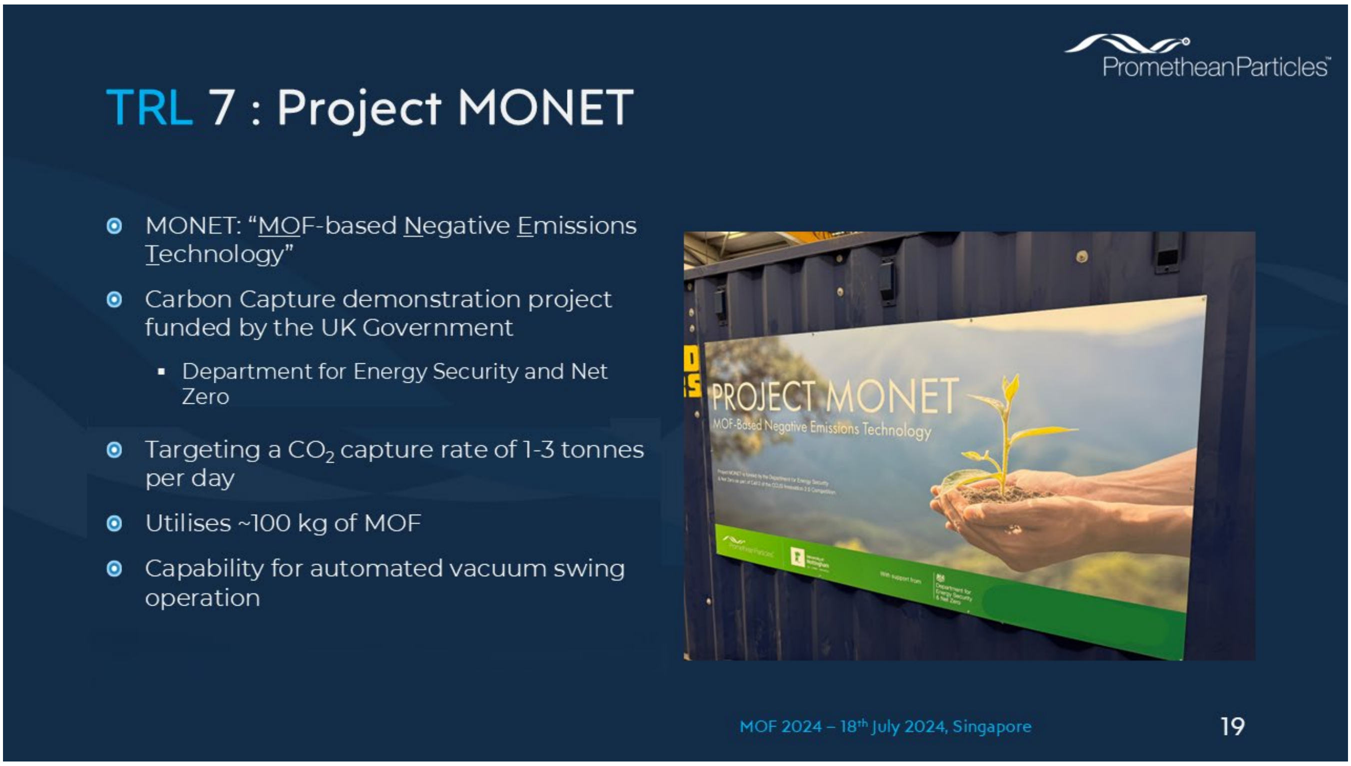
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TRL 7 : Project MONET
MONET: "MOF-based Negative Emissions Technology"
Carbon Capture demonstration project funded by the UK Government
Department for Energy Security and Net Zero
Targeting a CO2 capture rate of 1-3 tonnes per day
Utilises ~100 kg of MOF
Capability for automated vacuum swing operation
PROJECT MONET
MOF-Based Negative Emissions Technology
MOF 2024 – 18th July 2024, Singapore
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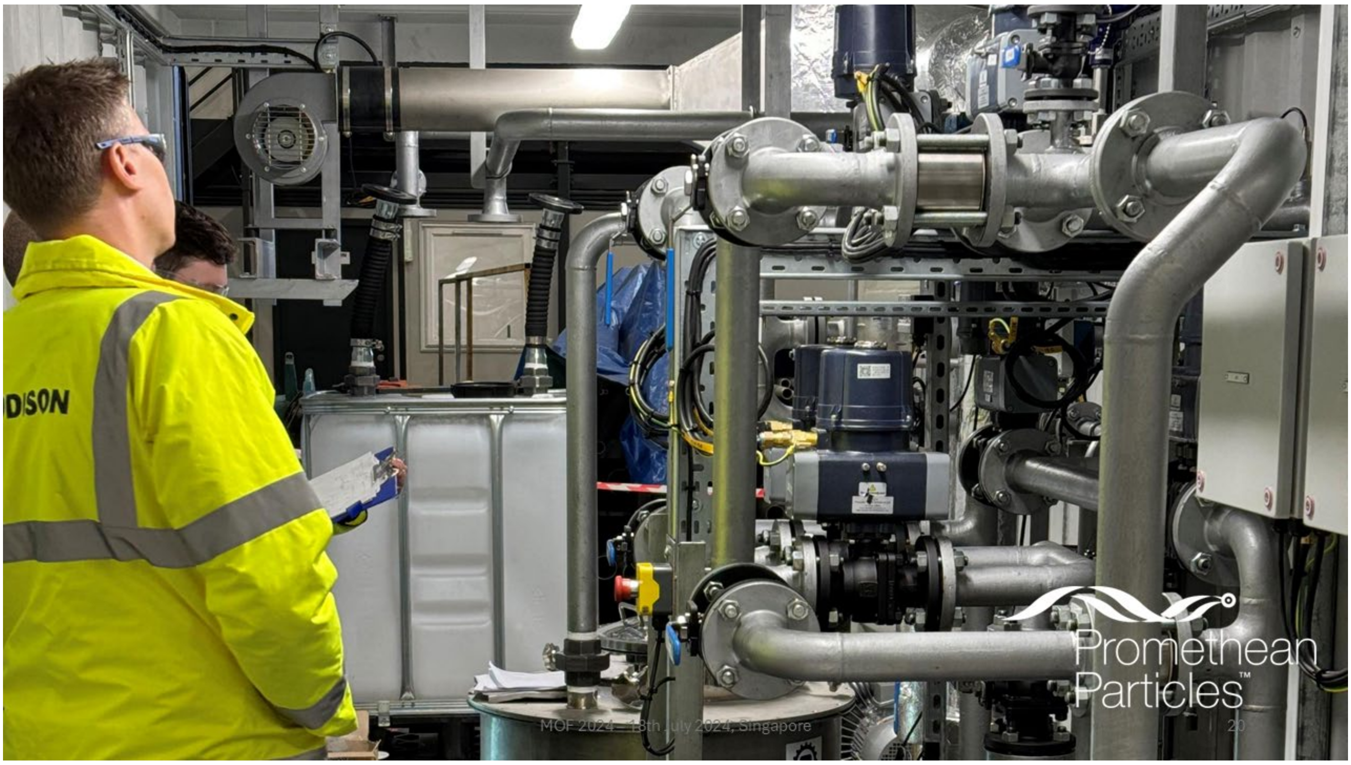
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Summary

- Promethean is a leading provider of industrial-scale, high-quality and cost-effective MOFs
  - Focus on MOFs for applications that tackle climate change
  - Promethean offer scale-up services to help MOF developers commercialise IP
- As MOFs are an emerging technology, application development is required to commercialise MOFs
- Application development:
  - Desktop study shows the significant cost and energy benefits of MOF-based CCS
    - >85% reduction in energy penalty and ~70 % reduction in CO_2 capture cost
  - MOF-based CCS demonstration projects underway using real-world flue gas
    - Project MONET will demonstrate a capture rate up to 3 te/day CO_2

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Thank You for Attending!

- Visit our exhibition booth **A02**
- Attend Paul's talk today in the industry forum
  - 16:15, Room 329
- Follow our LinkedIn page and website for more information and recruitment updates
- Download our white paper discussing the industrial viability of MOFs for CCS:

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If you need a version of this document in a more accessible format, please email enquiries@energysecurity.gov.uk Please tell us what format you need. It will help us if you say what assistive technology you use.