



BEYOND CO<sub>2</sub> UPTAKE Determining the Industrial Viability of MOFs for Carbon Capture and Storage (CCS)

Scalable | Cost-effective | Energy-efficient

Microsoft Teams Webinar 3<sup>rd</sup> May 2023



### **Company** Overview

- Founded 2007, spin-out from University of Nottingham
- Historically positioned as a broad-based nanomaterial technology platform
- Strategic pivot in 2021 towards metalorganic frameworks, focused on carbon capture applications
- World's largest continuous, metal-organic framework manufacturing plant
- Existing patent & know-how portfolio, patent pending applications
- Venture-capital backed with a mix of private and institutional investors



### White Paper Release



- Webinar supports our white paper, published April 2023
- Aim to guide MOF developers and assist designers of MOF-based CCS systems
  - Accelerate the development and commercial deployment of MOF-based carbon capture
- <u>Click here</u> to download the white paper





# **Executive** Summary



Even a MOF with a record-breaking  $CO_2$  uptake value may not be industrially viable, if:

- It's not sufficiently *selective* for CO<sub>2</sub>
- It's not stable and durable enough during use
- We can't source enough of the raw materials
- The raw materials are too expensive
- Complex manufacturing steps are required, reducing capacity and excessively increasing cost
- It presents manufacturing and/or EHS risks that can't be mitigated



### **Pioneering** a Paradigm Shift



Carbon Capture is now deemed essential

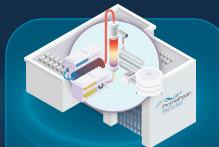
A necessity to meet global decarbonisation targets



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

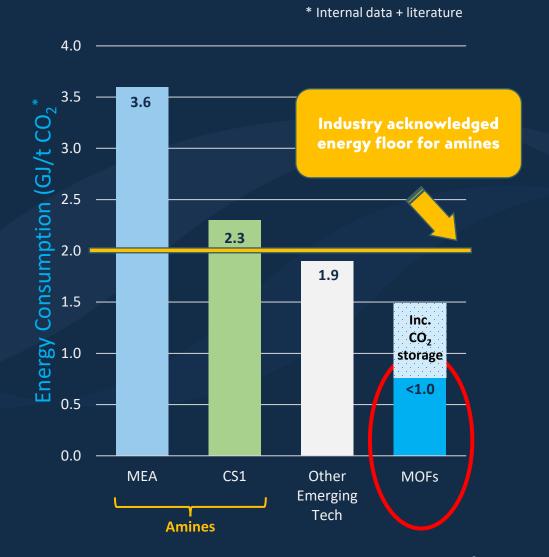




### **Amine CCS Limitations**

- 30-40% energy penalty
- Generate waste aerosols (NOx)
- Oxidation products highly corrosive
- >5% operating losses/month
- Reboiler/liquid condensers require large footprint, high CAPEX

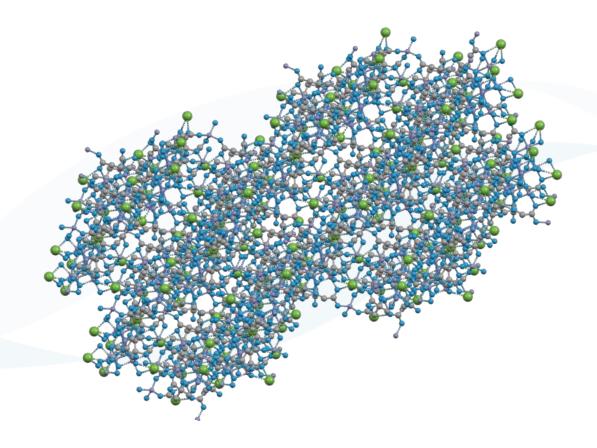
MOFs are starting-out with a huge energy-efficiency advantage over incumbent and emerging technologies



## Metal-organic Frameworks



- MOFs are highly porous, structured materials
- "Sieves" that selectively trap CO<sub>2</sub>
- Highest known CO<sub>2</sub> uptake capacities
- Desorption energies a fraction of those of amine solvents
- High thermal and chemical stabilities, tuneable selectivity, and recyclable
- Industrial adoption constrained due to a perceived lack of scale and exorbitant costs and pricing





### MOF-based CCS on the Rise

MOF Technologies raises £4.4m to START-UPS help decarbo by Leigh Mc Gowran 🕜 12 OCT 2022 🗍 SAVE ARTICLE



Promethean Particles"



GE and Svante to develop carbon capture tech for power generation

ly Molly Burgess on Mar 23, 2023 | 🖓 0 | 📧 Translate 🗸 NEWS | CC!

E Gas Power, part of GE Vernova, has teamed-up with Svante to develop and evaluate olid sorbent-based carbon capture technology for natural gas power generation.

Inder terms of a joint development agreement, the duo hopes to decarbonise natural gasired turbines in a cost-effective, environmentally responsible manner.

laude Letourneau, President and CEO of Svante, said he hopes to open up an entirely new rray of opportunities aiming to provide carbon-free electricity through the deployment of rojects across has-fired power generation facilities.

he news follows GE making an equity investment in Svante in December as part of its US 318m Series E fundraising round

#### Baker Hughes Acquires Mosaic Materials to Advance Next-Concernition Dioxide Capture Te

#### drax

#### INVESTORS Drax to pilot more pioneering new carbon capture technology

WHAT WE DO

SUSTAINABILITY

NEWS

 Technology feature. metal-organic fram

20, 2022

- Particularly suited to air capture and cap
- Further developmen carbon removal cost

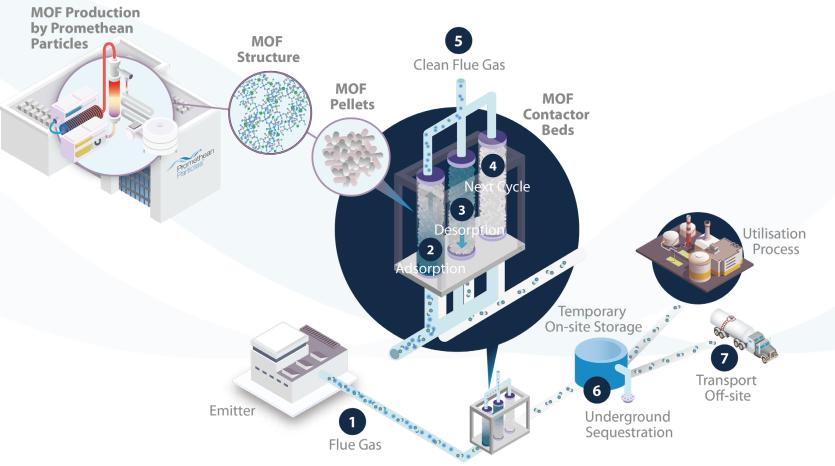
HOUSTON and LONDON acquired Mosaic Materia technology for carbon dir (CDR) from the atmosphe

Renewable energy pioneer Drax has partnered with the University of Nottingham and Promethean Particles to trial a pioneering new bioenergy with carbon capture and storage (BECCS) process at its North Yorkshire power station.

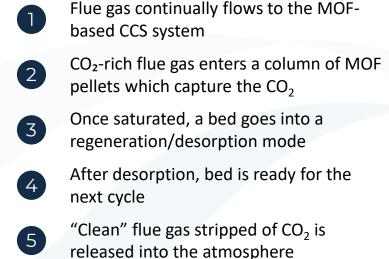
#### Webinar - Beyond CO<sub>2</sub> Uptake | 3<sup>rd</sup> May 2023



## **MOF-based** Carbon Capture







- Stripped CO<sub>2</sub> is sent to temporary on-site compression & storage
- 7

6

 $CO_2$  can then be transported off-site, further used, or sequestered



# Industrially Viable MOFs

Scale viability is imperative to tackle global CO<sub>2</sub> emissions



### **Determining** Viability: 8-Factor Model

- How to select optimal MOF(s) from 100,000 different chemistries reported to date?
- Various requirements can be broadly grouped into 8 different *factors*, under 4 thematic pillars
  - Strong interconnection between factors and pillars, e.g., Raw Material Costs has implications on the Economics and Supply Chain pillars







# **Performance** Pillar

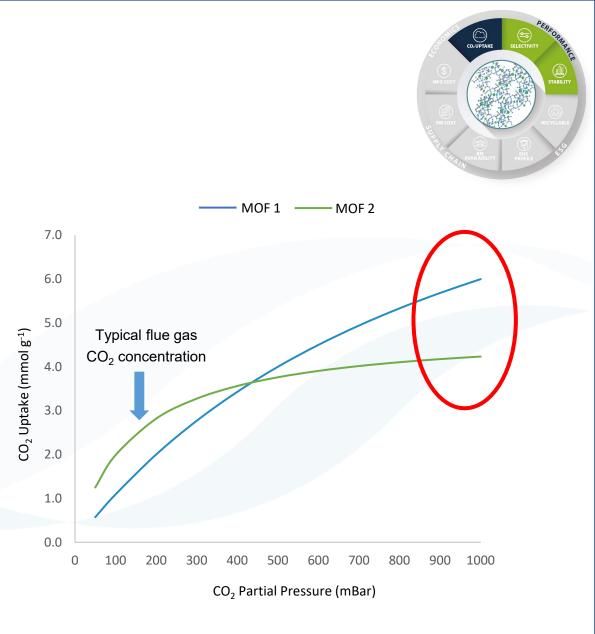
Performance factors determining industrial viability



## Performance

#### CO<sub>2</sub> Uptake

- Uptake rate is typically fast across all MOFs, while uptake capacity is the differentiator
- If comparing CO<sub>2</sub> uptake capacity between MOFs, consider data at <u>pressures</u>, <u>temperatures</u> and <u>CO<sub>2</sub></u> <u>concentration</u> relevant to the application





## Performance



- A MOF's ability to adsorb CO<sub>2</sub> over other components in the gas stream
- Higher Selectivity means more available capacity for *uptake*, and likely better *Stability*
- IAST predicts *Selectivity*, but is difficult to measure in practice
  - Promethean's in-house Breakthrough Analyser simulates 'real-world' adsorption measurements





## Performance



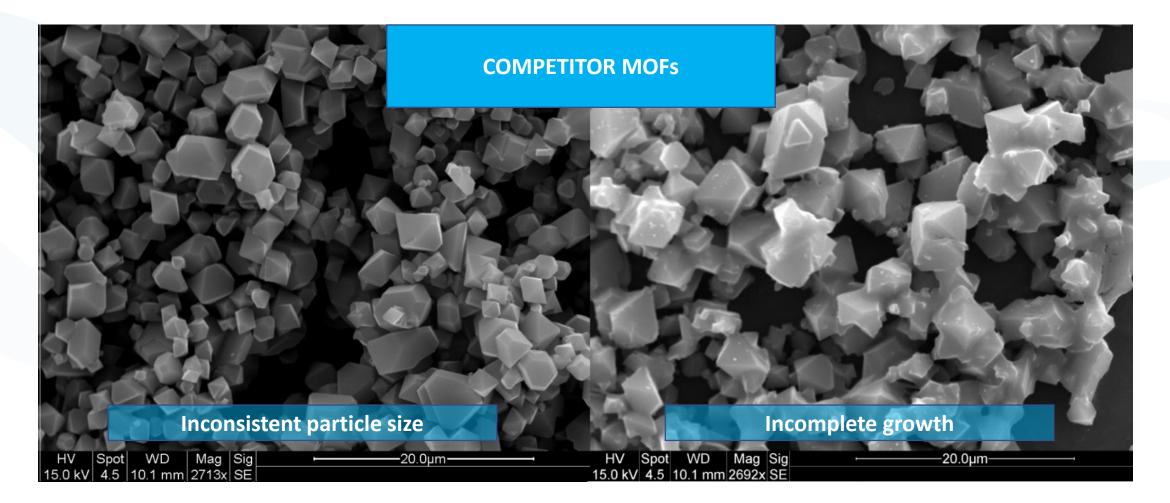
#### Stability

- MOFs generally more robust than incumbent liquid amine sorbents, but a spectrum of stability exists between MOFs
- MOF should be chemically and mechanically robust to withstand temperature/ pressure fluctuations of regeneration cycles
  - 2–3-year useful lifetime to be economically viable
- Poor *Selectivity* can lead to pore blockage by contaminants
- Degradation means replacement with fresh sorbent to maintain system operation
- Stability affects overall system OPEX and **Economics** pillar



### **MOFs** are not Created Equally

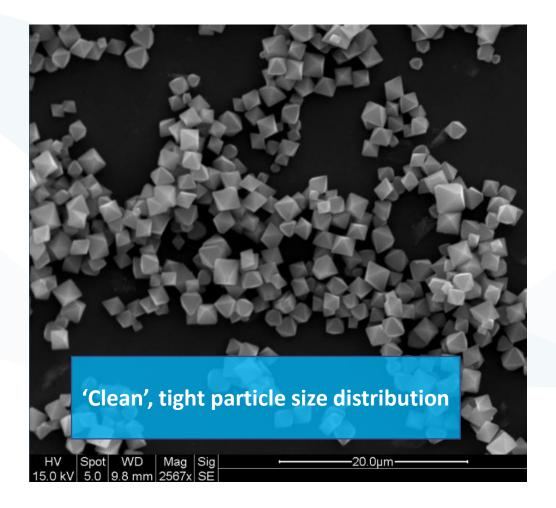






### **Promethean MOFs**













# **Economics** Pillar

Cost significantly influences the commercial viability of MOFs



### Economics



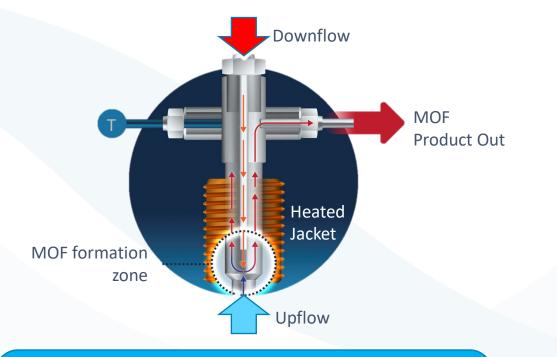
Manufacturing Cost

- Different manufacturing methods carry a range in costs, particularly at industrial scale
- Environmental, Health and Safety (EHS) Profile of manufacturing process also affects its cost
  - Equipment to mitigate risks and deliver safe and reliable processes can increase costs
- To date, most MOF syntheses is via batch solvothermal routes which can be costly and difficult to scale up
- Promethean offer service for the batch-to-continuous flow 'translation' of MOF production...



# **Continuous** Flow Manufacturing





Our proprietary continuous flow synthesis process overcomes historical MOF manufacturing scale and cost constraints

- Proprietary continuous flow manufacturing process
- Allows "in flight" optimisation of MOFs
- Superior MOF quality
- Patented reactor designs, new patent application(s), >15 years know-how IP
- Feasibility Study service offered for custom development of scalable manufacturing for specific MOFs



### **Unprecedented Scale**





\*Based on Promethean estimations from published talks, papers, etc.

Largest of its kind continuous-flow MOF manufacturing facility

~1,000 tonne/year capacity

~250X nearest competitor\*

Additional 10X increase enabled by new reactor design

Low unit cost of MOFs at industrial scale facilitates commercial viability



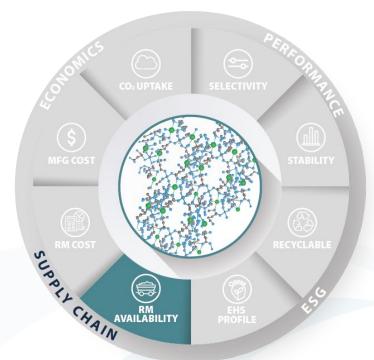
### **Economics**



Raw Material Costs

- The largest cost component for cost-effective manufacturing processes
- Typical MOF raw materials: metal salt, organic ligand (linker), and solvent
- Reports of MOFs produced from precious metals and/or niche ligands; unlikely to be cost viable for industrial application
- Material development programs can decrease Raw Material Costs, e.g., full or partial substitution of metal, ligand or solvent while maintaining sufficient performance
  - Success of such substitution approach may vary depending on the route of synthesis used
  - Technoeconomic Analysis can be a useful tool to compare options and direct R&D activities





# Supply Chain Pillar

Vital factors to move lab synthesis to industrial-scale manufacture



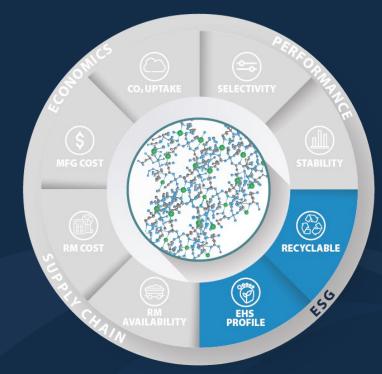
Webinar - Beyond CO<sub>2</sub> Uptake | 3<sup>rd</sup> May 2023

# Supply Chain - RM Availability

1 <b>H</b> 1.40 x 10 <sup>3</sup> Hydrogen						Ab	<b>und</b> a in	i Earth	<b>of E</b> n's Cru	ıst	nts						2 <b>He</b> 8 x 10 <sup>-3</sup> Helium
3 Li 20 Lithium	4 Be 2.8 Beryllium									2		5 <b>B</b> 10 Boron	6 C 200 Carbon	7 <b>N</b> 19 Nitrogen	8 <b>0</b> 4.61 x 10 <sup>0</sup> 0xygen	9 <b>F</b> 585 Fluorine	10 <b>Ne</b> 5 x 10 <sup>-3</sup> Neon
11 <b>Na</b> 2.36 x 10 <sup>4</sup> Sodium	12 <b>Mg</b> 2.33 x 10 <sup>4</sup> Magnesium											13 <b>Al</b> 8.23 x 10 <sup>4</sup> Aluminum	14 <b>Si</b> 2.82 x 10 <sup>5</sup> Silicon	15 <b>P</b> 1.05 x 10 <sup>3</sup> Phosphorus	16 <b>S</b> 350 Sulfur	17 Cl 145 Chlorine	18 Ar 3.5 Argon
19 <b>K</b> 2.09 x 10 <sup>4</sup> Potassium	20 <b>Ca</b> 4.15 x 10 <sup>4</sup> Cakium	21 Sc 22 Scandium	22 <b>Ti</b> 5.56 x 10 <sup>3</sup> Titanium	23 V 120 Vanadium	24 <b>Cr</b> 102 Chromium	25 Mn 950 Manganese	26 <b>Fe</b> 5.63 x 10 <sup>4</sup> Iron	27 Co 25 Cobalt	28 <b>Ni</b> 84 Nickel	29 Cu 60 Copper	30 <b>Zn</b> 70 Zinc	31 Ga 19 Gallium	32 Ge 1.5 Germanium	33 As 1.8 Arsenic	34 <b>Se</b> 5 x 10 <sup>-2</sup> Selenium	35 Br 2.4 Bromine	36 <b>Kr</b> 1 x 10-4 Krypton
37 <b>Rb</b> 90 Rubidium	38 Sr 370 Strontium	39 <b>Y</b> 33 Yttrium	40 <b>Zr</b> 165 Zirconium	41 <b>Nb</b> 20 Niobium	42 Mo 1.2 Molybdenum	43 Tc Technetium	44 <b>Ru</b> 1 x 10 <sup>-3</sup> Ruthenium	45 <b>Rh</b> 1 x 10 <sup>-3</sup> Rhodium	46 <b>Pd</b> 1.5 x 10 <sup>-2</sup> Palladium	47 <b>Ag</b> 7.5 x 10 <sup>-2</sup> Silver	48 <b>Cd</b> 0.15 Cadmium	49 In 0.25 Indium	50 <b>Sn</b> 2.3 Tin	51 Sb 0.2 Antimony	52 <b>Te</b> 1 x 10 <sup>.3</sup> Tellurium	53 0.45 Iodine	54 <b>Xe</b> 3 x 10 <sup>-5</sup> Xenon
55 Cs 3 Cesium	56 Ba 425 Barium	57-71	72 Hf 3.0 Hafnium	73 <b>Ta</b> 2.0 Tantalum	74 W 1.25 Tungsten	75 <b>Re</b> 7 x 10 <sup>-4</sup> Rhenium	76 <b>Os</b> 1.5 x 10 <sup>-3</sup> Osmium	77 <b>Ir</b> 1 x 10 <sup>-3</sup> Iridium	78 <b>Pt</b> 5 x 10 <sup>-3</sup> Platinum	79 <b>Au</b> 4 x 10 <sup>-3</sup> Gold	80 <b>Hg</b> 8.5 x 10 <sup>-2</sup> Mercury	81 <b>TI</b> 0.85 Thallium	82 <b>Pb</b> 14 Lead	83 <b>Bi</b> 8.5 x 10 <sup>-3</sup> Bismuth	84 <b>Po</b> 2 x 10 <sup>-10</sup> Polonium	85 At Astatine	86 <b>Rn</b> 4 x 10 <sup>-13</sup> Radon
87 <b>Fr</b> Francium	88 <b>Ra</b> 9 x 10 <sup>-7</sup> Radium	89-103	104 <b>Rf</b> Rutherfordium	105 Db Dubnium	106 <b>Sg</b> Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 <b>Ds</b> Darmstadtium	111 <b>Rg</b> Roentgenium	112 Cn Copernicium	113 <b>Nh</b> Nihonium	114 <b>Fl</b> Flerovium	Moscovium	116 Lv Livermorium	117 <b>Ts</b> Tennessine	118 Og Oganesson
	Lanthanic				-	Nd P		im I	Eu (	Gd	Tb	Dy I	Но		īm 🛛	Yb	Lu
	Actinide	Lan 89 ss 5.5	thanum (e 90 Ac T x 10 <sup>-10</sup>	rium Prasee 91 <b>Fh F</b> 9.6 1.4	Adymium Neo 92 Pa x 10 <sup>-6</sup>	93 U 2.7	nethium Sar Np F	Pu A	nopium Ga	dolinium 1 97 Cm	98 Bk	sprosium H S Cf	olmium E Es F	bium 10 m N	1 /Id	No 10	0.8 Lutetium D3 Lr
		_	10 <sup>-2</sup>	-	- 10 <sup>-1</sup>		<sup>1</sup> - 1		- 10		- 10 <sup>2</sup>		- 10 <sup>3</sup>	> 1			8 Sciencenotes.org

Image source: https://sciencenotes.org/abundance-of-elements-in-earths-crust-periodic-table-and-list





# Environmental, Social and Governance (ESG) Pillar

EHS, Pollution Reduction, and Corporate Social Responsibility

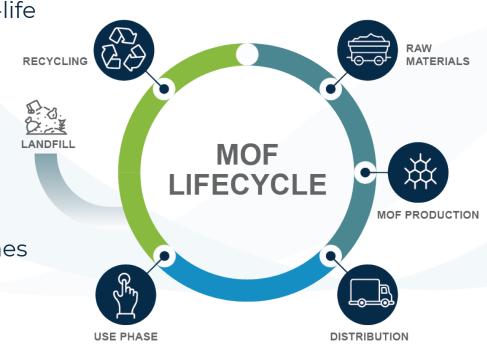


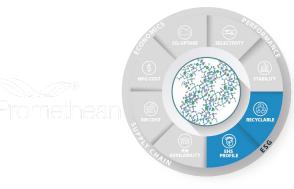
Webinar - Beyond CO<sub>2</sub> Uptake | 3<sup>rd</sup> May 2023

### ESG

#### Recyclability

- Importance of end-of-life fate as scale increases
- Recycling MOFs allows 'cradle-to-cradle' lifecycle assessment
- Better recycling potential for MOFs than incumbent amines





#### EHS Profile

 Solid sorbents offer advantages for safe transport, handling and use

 Promethean has improved the EHS profile of Production for a range of MOFs

> Solutions exist to manage and mitigate risks of hazardous chemicals

 More work needed to establish Safety Data Sheet (SDS) info for all MOFs



# **Concluding** Remarks

Promethean Particles

- Achieving industrially viable MOFs for CCS can be a complex field to navigate
- Our 8-factor model summarises requirements
- Factors are interconnected and vary in weighting
- There are existing MOF candidates which meet viability requirements, and more are emerging!
- Contact us if you are developing CCS systems and looking to use MOFs



### Contact Us



Promethean offers products and services to accelerate the industrial application of MOFs:

- MOF materials: multi-kg scale from our existing portfolio for development/testing
- Feasibility studies: contract development to translate batch-to-continuous production of specific (proprietary) MOFs
- Analytical services: Breakthrough Analyser to simulate custom gas composition and assess MOF performance

Dr Selina Ambrose	Product Market Manager	selina.ambrose@proparticles.co.uk
Dr Jack Turner	CCS Application Development Manager	jack.turner@proparticles.co.uk
James Stephenson	Chief Executive Officer	james.Stephenson@proparticles.co.uk







Unleashing the potential of MOFs for the benefit of the **Planet** and its **People** 



29