PrometheanParticles™

# BEYOND $CO_2$ UPTAKE Determining the Industrial Viability of MOFs for Carbon Capture and Storage (CCS)

Scalable | Cost-effective | Energy-efficient

Microsoft Teams Webinar
3rd 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 metal-organic 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**
- Click here 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 $CO_2$
- 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**

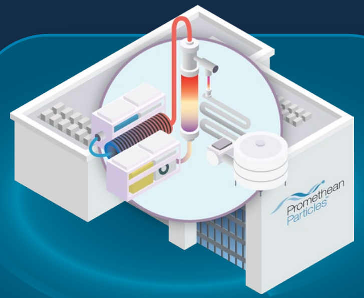
A necessity to meet global decarbonisation targets

**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**

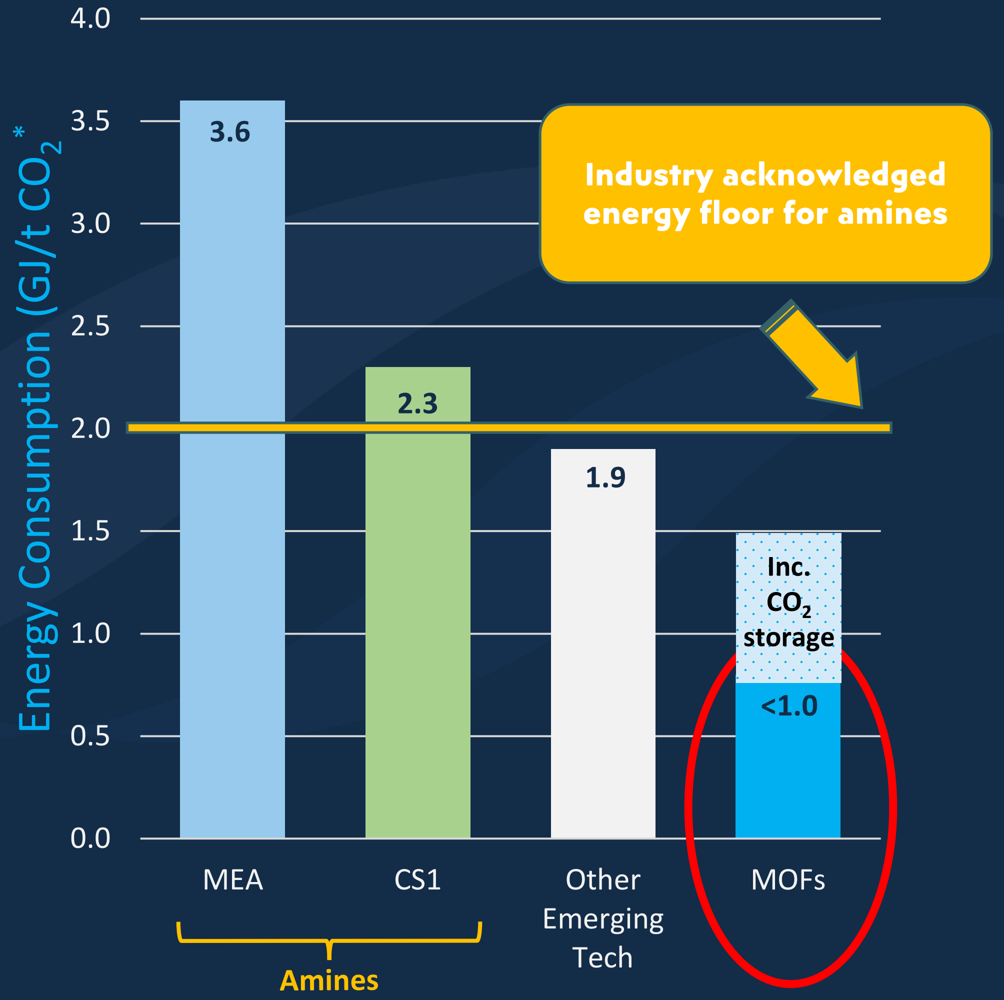
Overcomes historical barriers, uniquely enabling industrial scale, cost-effective MOFs

# 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

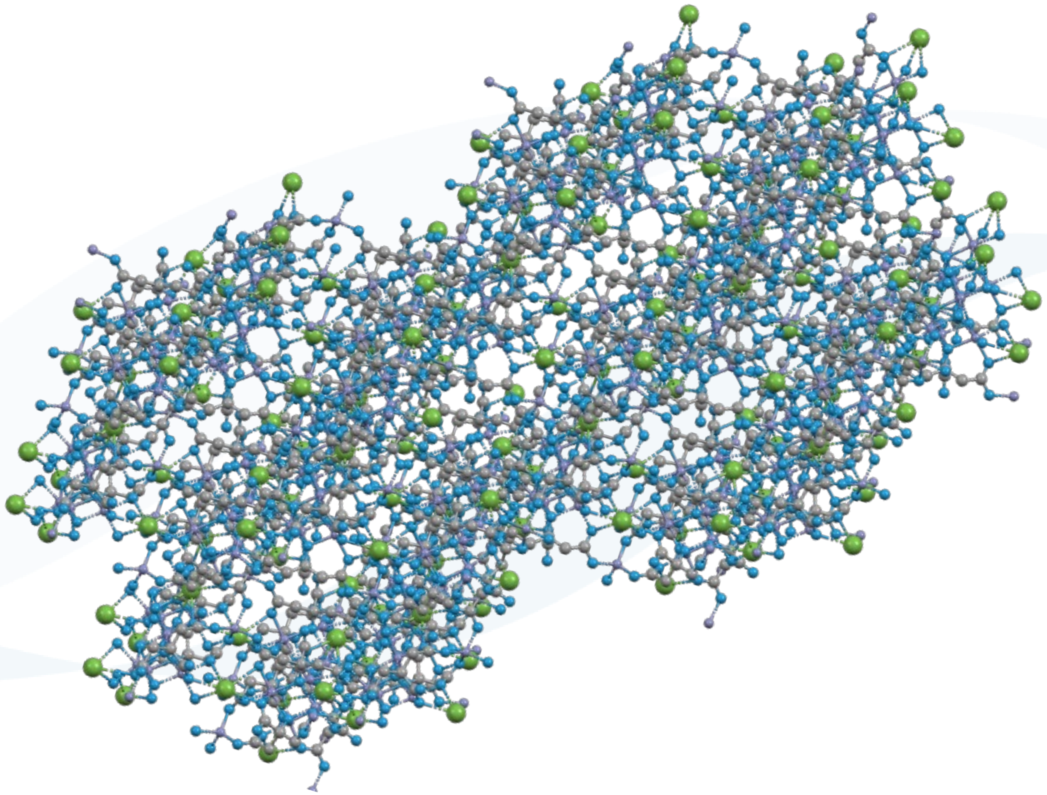
MOFs are starting-out with a huge energy-efficiency advantage over incumbent and emerging technologies

* Internal data + literature

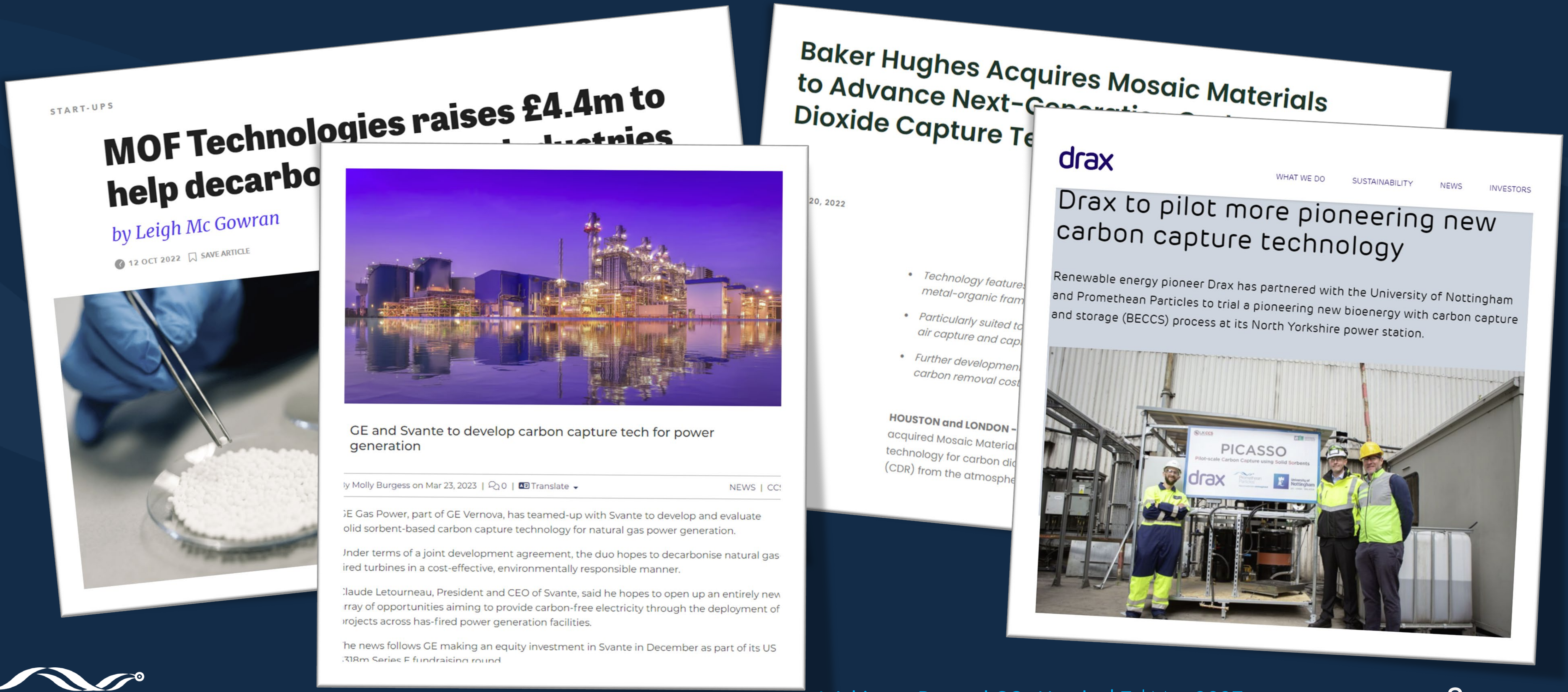


# Metal-organic Frameworks

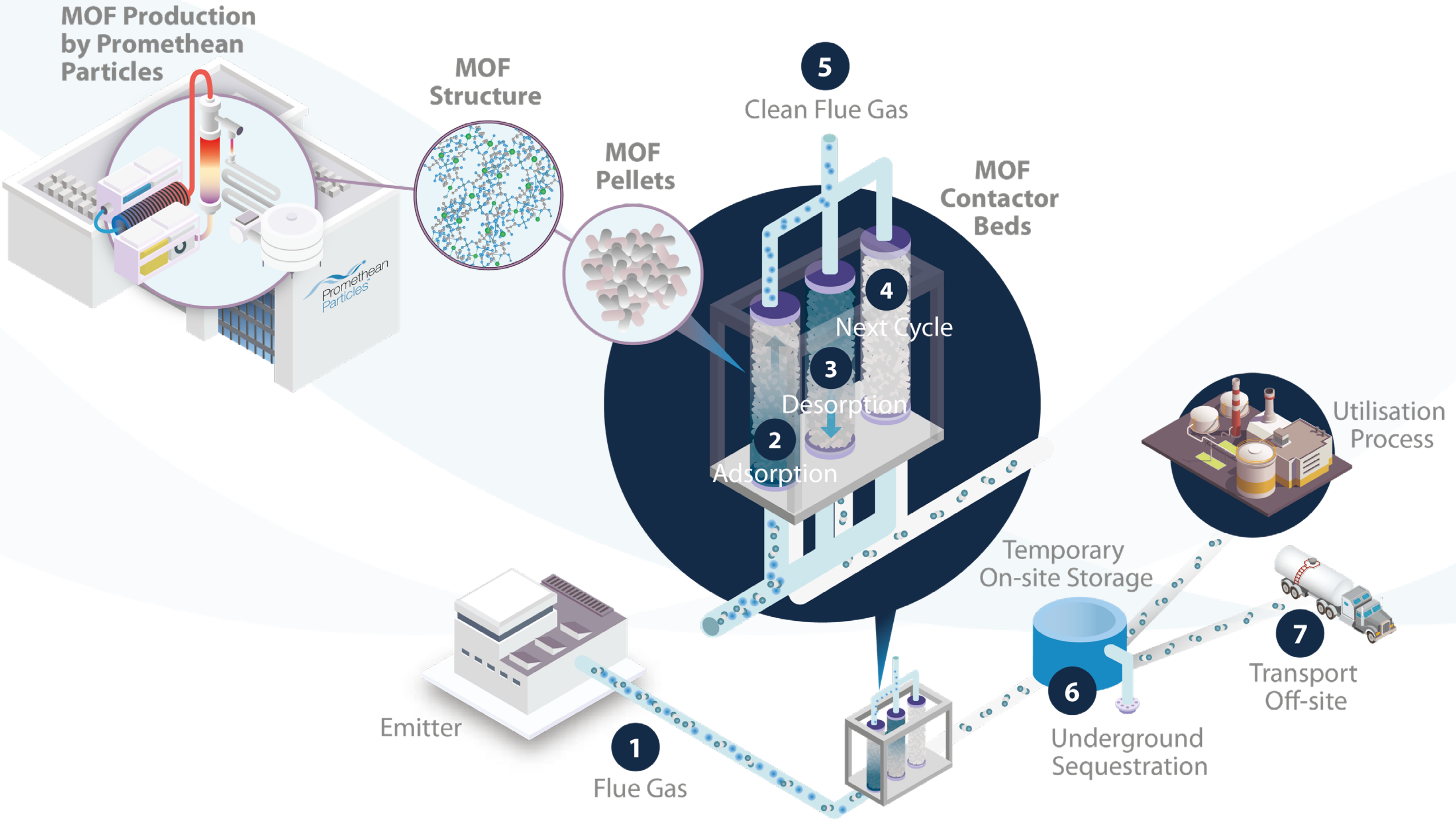
- MOFs are highly porous, structured materials
- “Sieves” that selectively trap $CO_2$
- Highest known $CO_2$ uptake capacities
- Desorption energies a fraction of those of amine solvents
- High thermal and chemical stabilities, tuneable selectivity, and recyclable
- Industrial adoption constrained due to a perceived lack of scale and exorbitant costs and pricing



# MOF-based CCS on the Rise



# MOF-based Carbon Capture



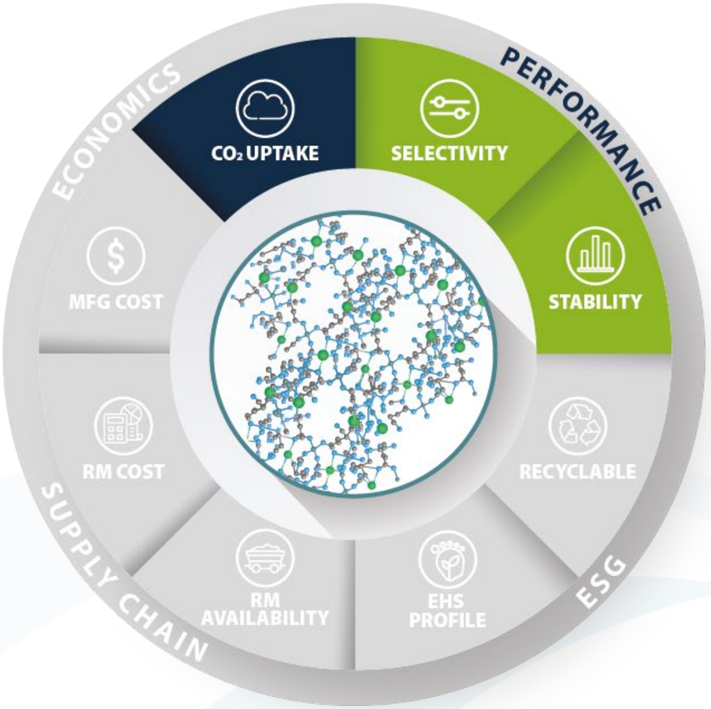

1. Flue gas continually flows to the MOF-based CCS system
2. $CO_2$-rich flue gas enters a column of MOF pellets which capture the $CO_2$
3. Once saturated, a bed goes into a regeneration/desorption mode
4. After desorption, bed is ready for the next cycle
5. "Clean" flue gas stripped of $CO_2$ is released 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

# Industrially Viable MOFs

Scale viability is imperative to tackle global $CO_2$ emissions

# Determining Viability: 8-Factor Model

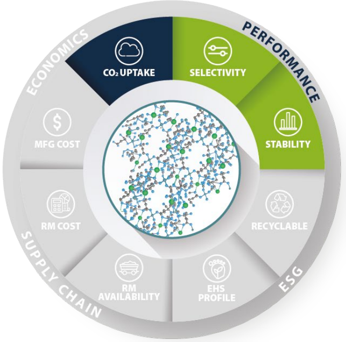
- How to select optimal MOF(s) from 100,000 different chemistries reported to date?
- Various requirements can be broadly grouped into 8 different *factors*, under 4 **thematic pillars**
  - Strong interconnection between *factors* and **pillars**, e.g., *Raw Material Costs* has implications on the **Economics**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




# **Performance** Pillar

## Performance factors determining industrial viability

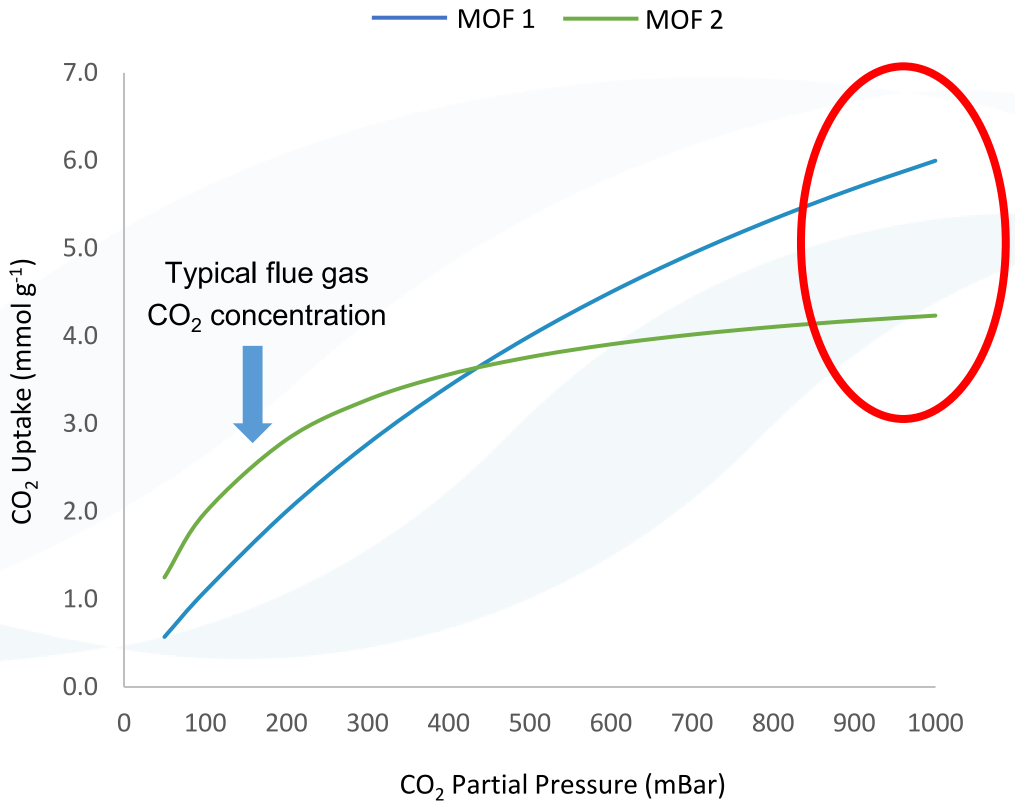
# Performance




*$CO_2$ Uptake*

- Uptake rate is typically fast across all MOFs, while uptake capacity is the differentiator

- If comparing $CO_2$ uptake capacity between MOFs, consider data at <u>pressures</u>, <u>temperatures</u> and <u>$CO_2$ concentration</u> relevant to the application

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# Performance

*Selectivity for $CO_2$*

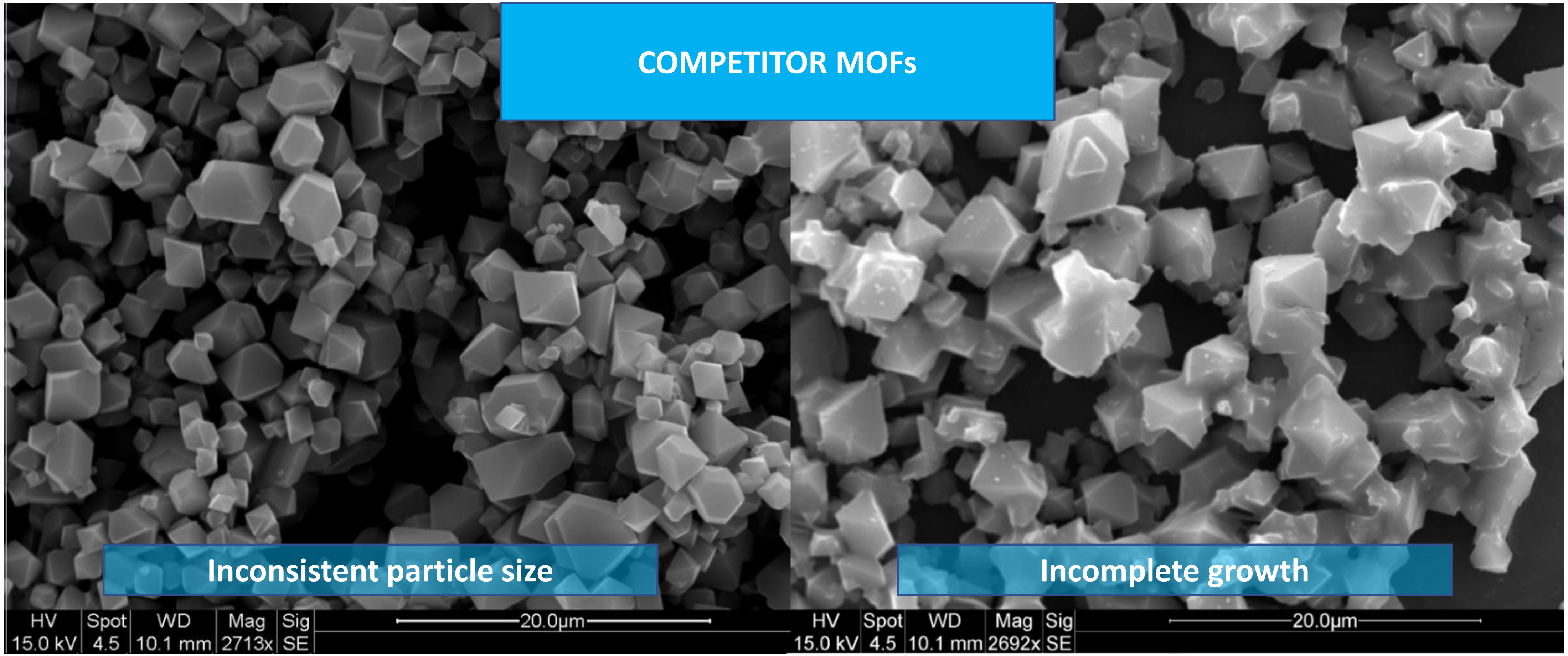
- A MOF's ability to adsorb $CO_2$ over other components in the gas stream
- Higher *Selectivity* means more available capacity for *uptake*, and likely better *Stability*
- IAST predicts *Selectivity*, but is difficult to measure in practice
    - Promethean's in-house Breakthrough Analyser simulates 'real-world' adsorption measurements

# Performance

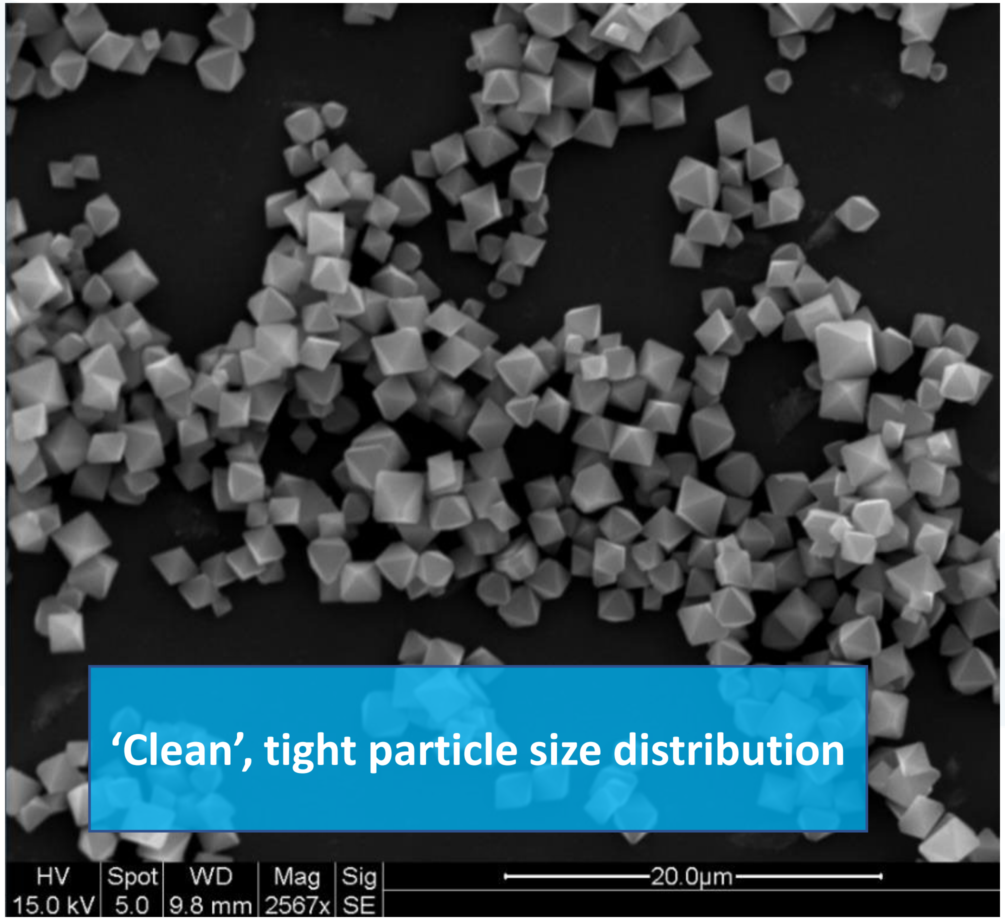

*Stability*

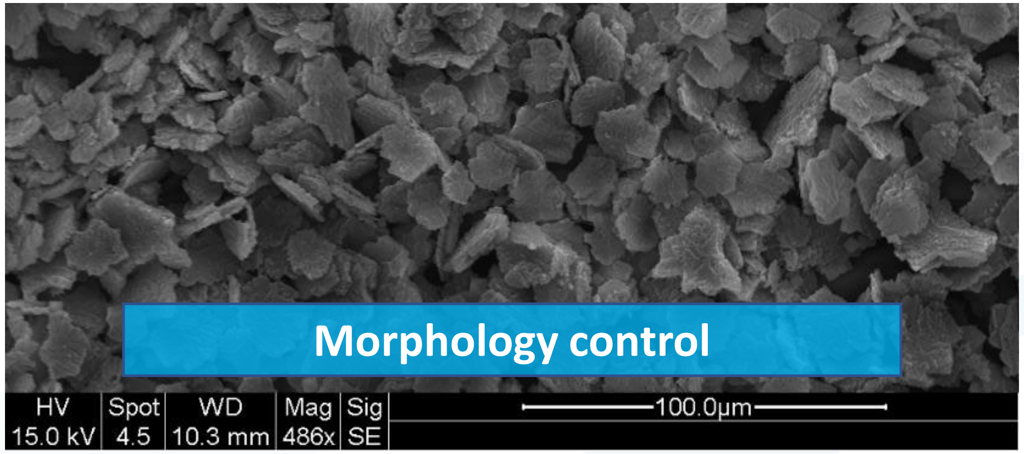
- MOFs generally more robust than incumbent liquid amine sorbents, but a spectrum of stability exists between MOFs
- MOF should be chemically and mechanically robust to withstand temperature/ pressure fluctuations of regeneration cycles
  - 2–3-year useful lifetime to be economically viable
- Poor *Selectivity* 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

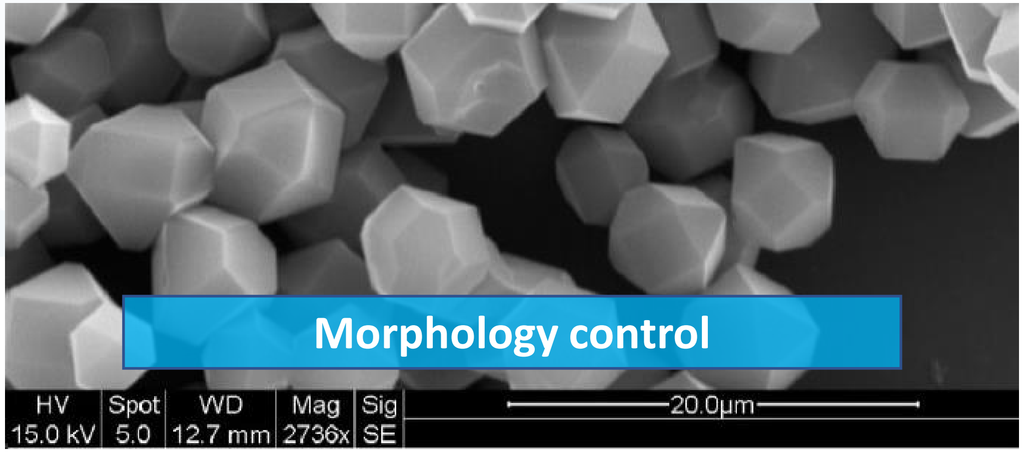
# MOFs are not Created Equally

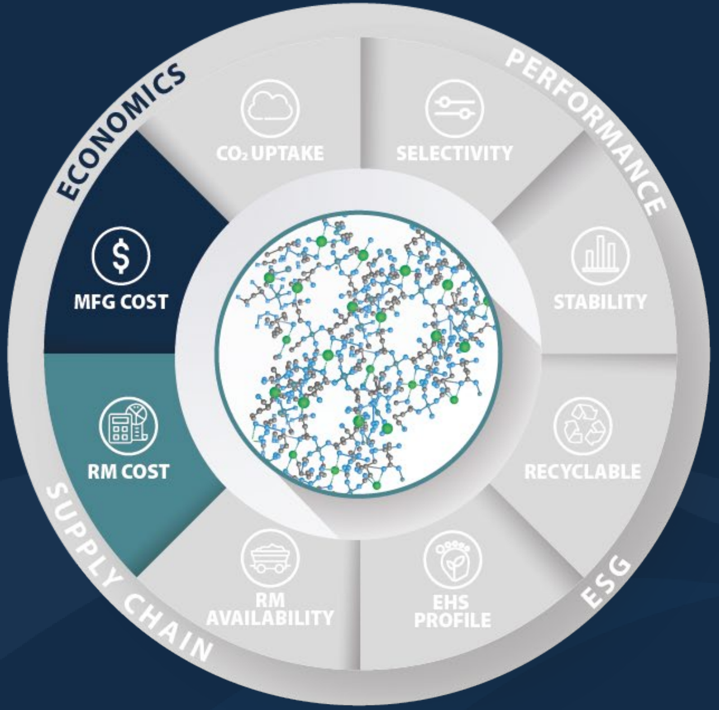


# Promethean MOFs



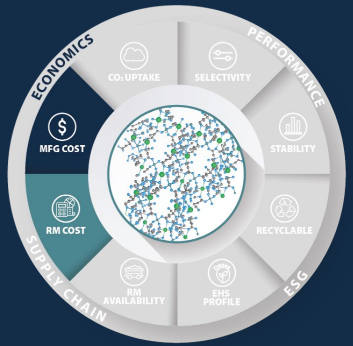






# **Economics** Pillar

Cost significantly influences the commercial viability of MOFs

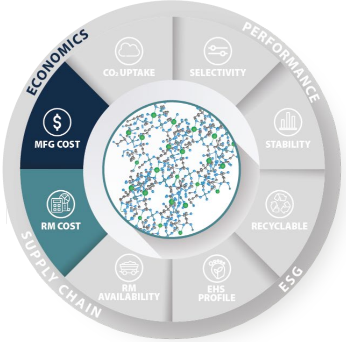
# Economics

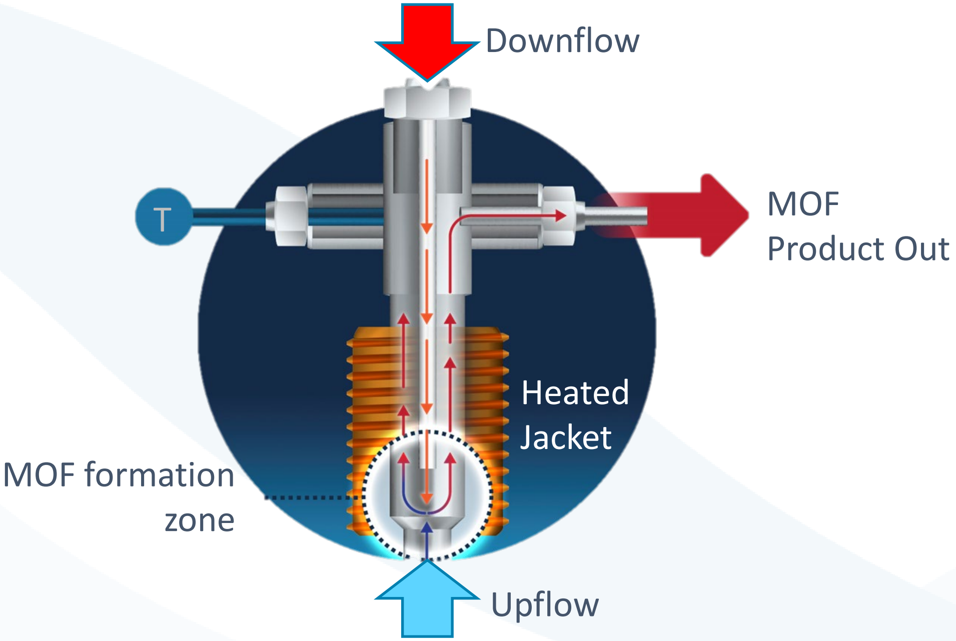



*Manufacturing Cost*

- 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

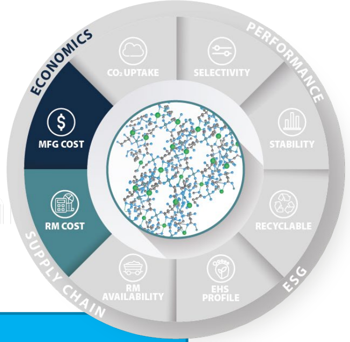



Our proprietary continuous flow synthesis process overcomes historical MOF manufacturing scale and cost constraints

- 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




Largest of its kind continuous-flow MOF manufacturing facility

~1,000 tonne/year capacity

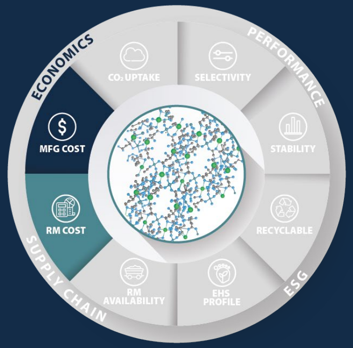
~250X nearest competitor*

Additional 10X increase enabled by new reactor design

Low unit cost of MOFs at industrial scale facilitates commercial viability

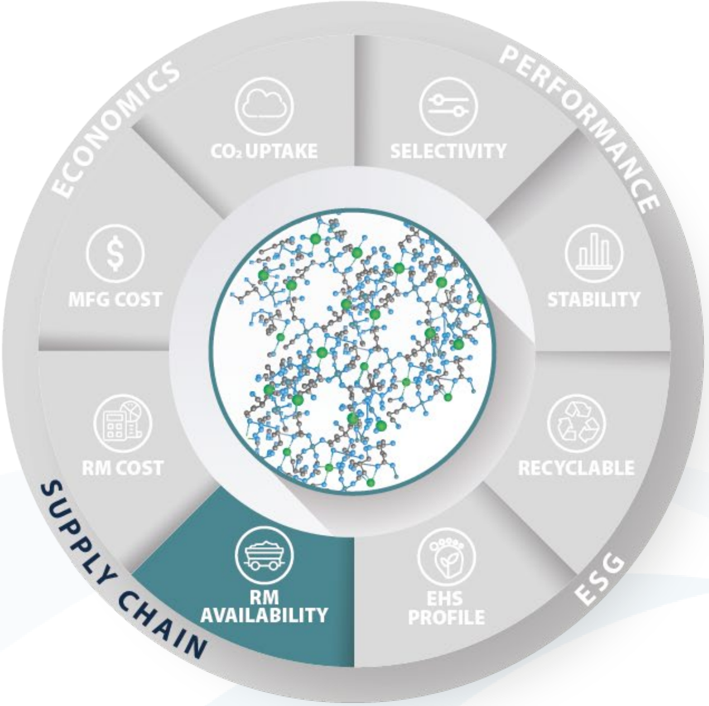
*Based on Promethean estimations from published talks, papers, etc.

# Economics




*Raw Material Costs*

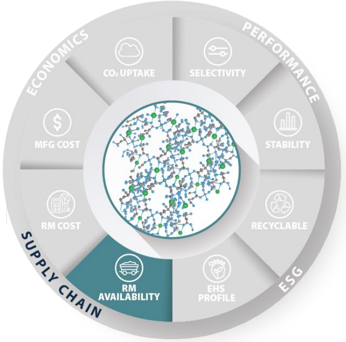
- The largest cost component for cost-effective manufacturing processes
- Typical MOF raw materials: metal salt, organic ligand (linker), and solvent
- Reports of MOFs produced from precious metals and/or niche ligands; unlikely to be cost viable for industrial application
- Material development programs 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

# Supply Chain - RM Availability



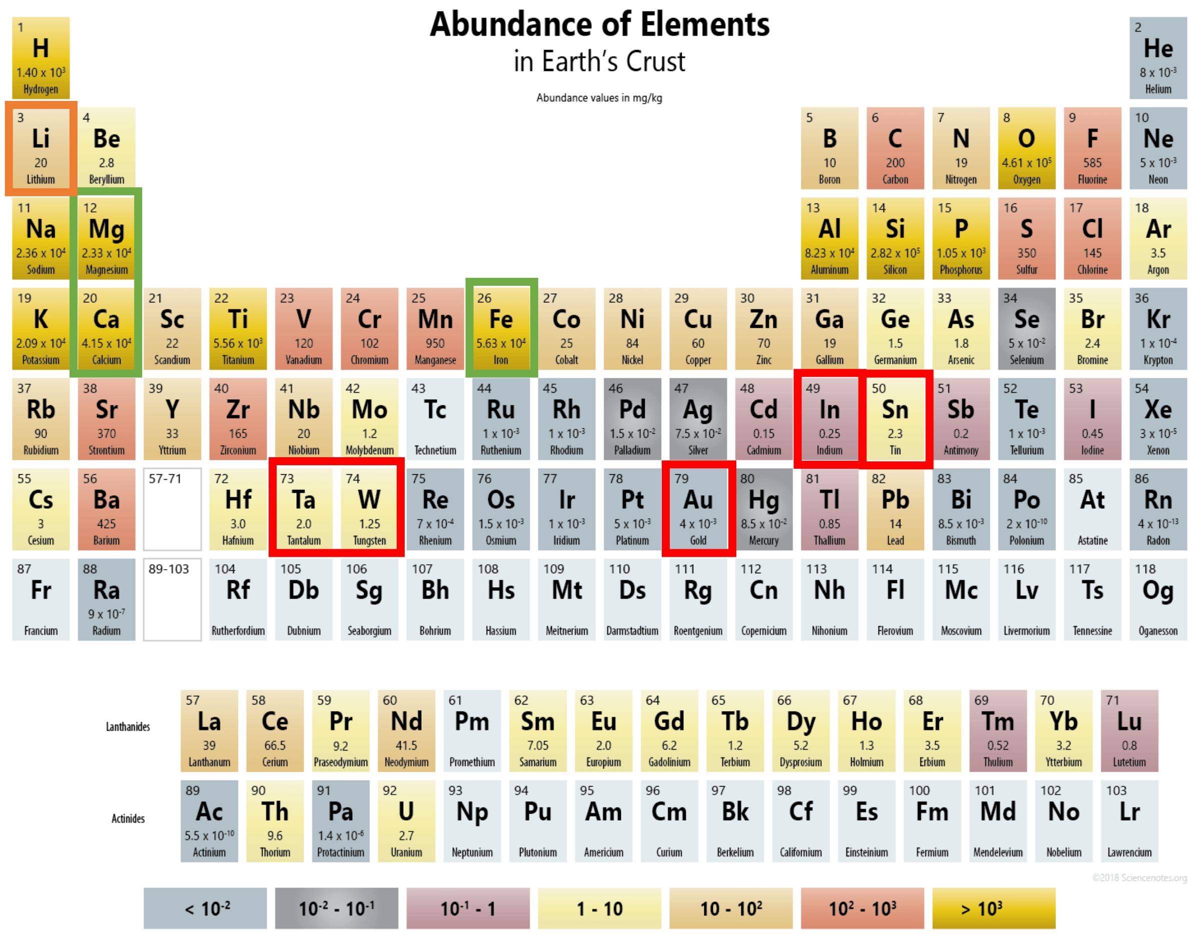
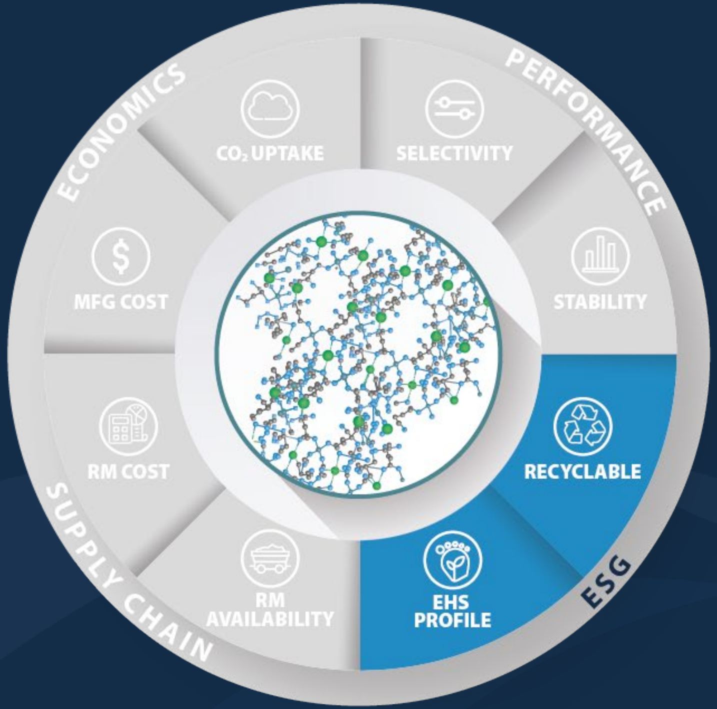



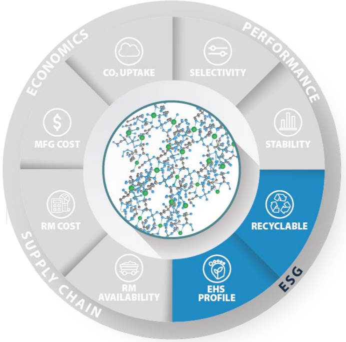

Image source: https://sciencenotes.org/abundance-of-elements-in-earths-crust-periodic-table-and-list




# Environmental, Social and Governance (ESG) Pillar

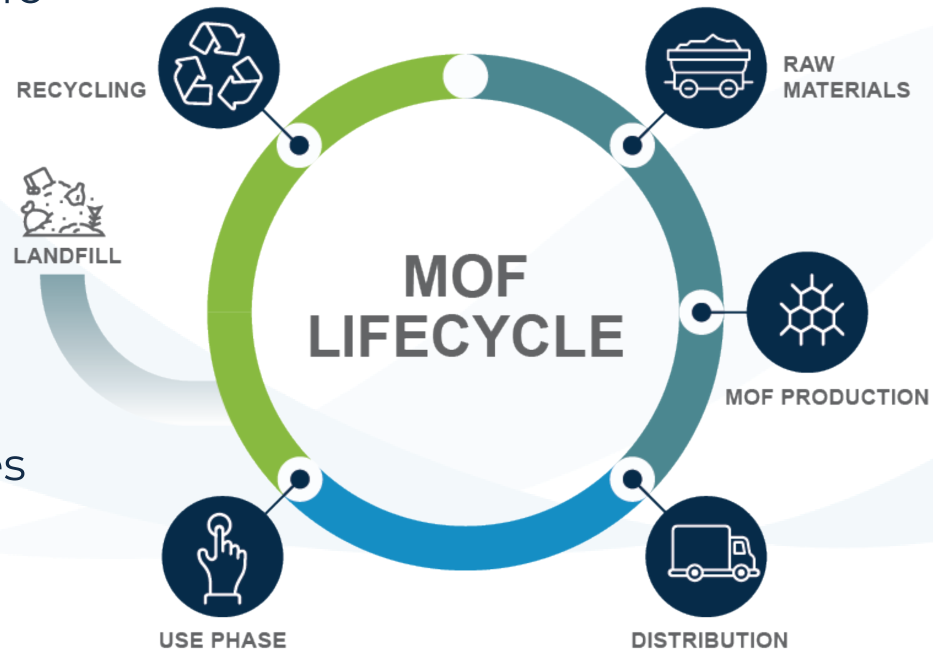
EHS, Pollution Reduction, and Corporate Social Responsibility

# 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

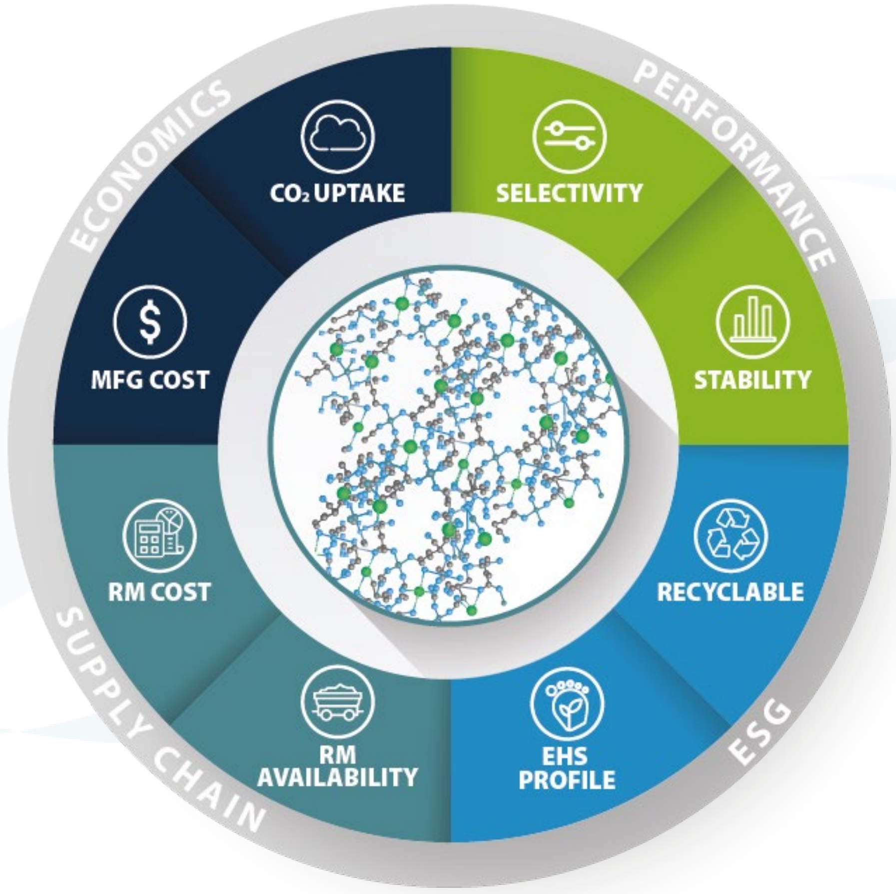



*EHS Profile*

- 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

- 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



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# Q&A

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