Nanoporous materials for CO_2 capture

Baker Hughes effort for a better future

Dr. Elkid COBANI

23/09/2024

We take energy forward—making it safer, cleaner, and more efficient for people and the planet

120+
countries

~58,000
employees

$25.5B
revenue 2023

199
HSE Perfect Days in 2023

$658M
in research and development

>2,000
patents granted

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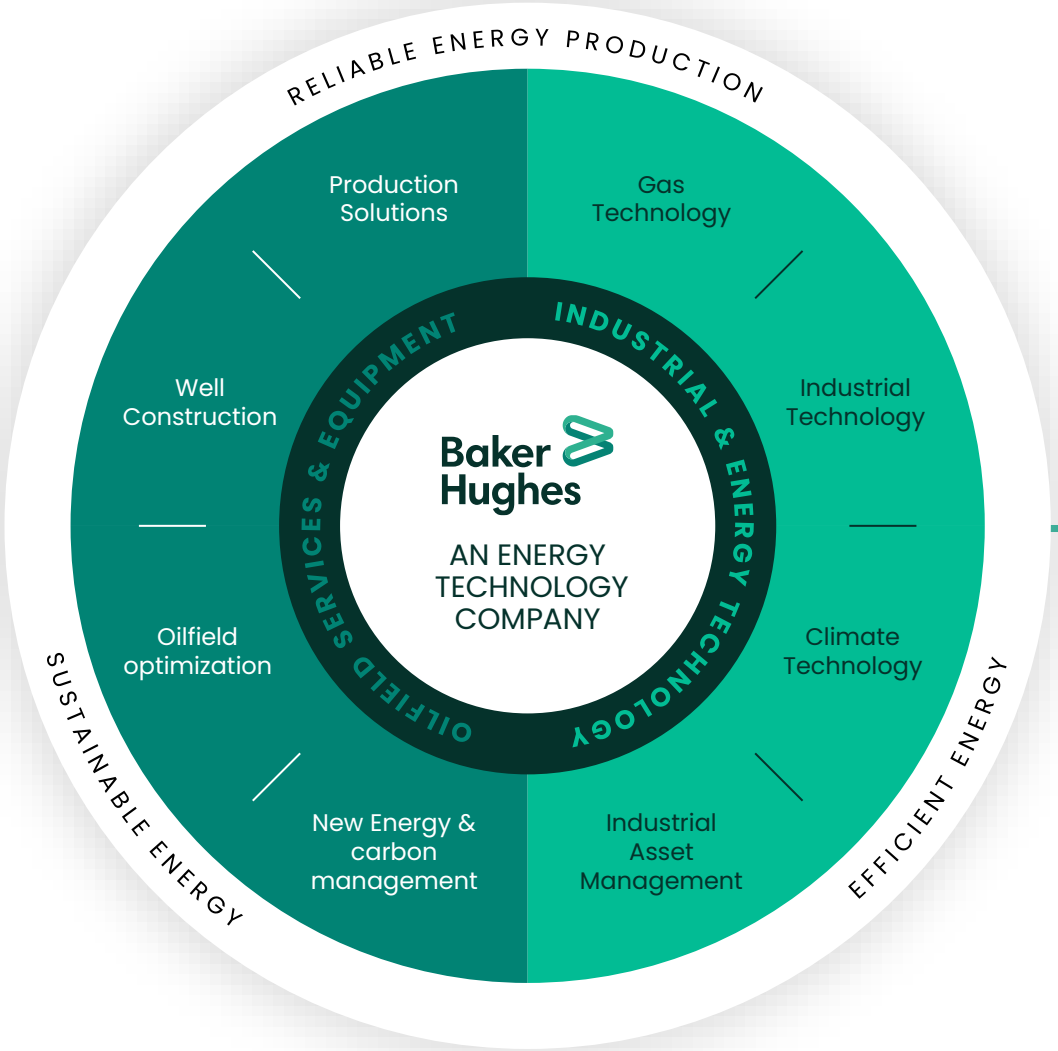
Our business segments

We deploy solutions to the world's greatest energy challenges



Global energy security

Climate change

Industrial efficiency and productivity

Executing the IET strategy across three time horizons

Horizon 1
Through 2025

Transform our business and simplifying the way we work.

Optimizing and integrating recent acquisitions.

Leveraging world-class capabilities to progress digital & new energy tech

Horizon 2
Mid to late 2020s

Rising investment in infrastructure, energy efficiency & electrification. New energy starts to scale - adoption of incubated technologies. Focus on continuously improving margin & return profile

Horizon 3
2030 and beyond

Decarbonization becomes all encompassing - significant new energy orders growth and high proportion of recurring revenues from services & digital businesses

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Technology Areas of interest

- H2 Value Chain

- Waste Energy Recovery

- Energy Storage

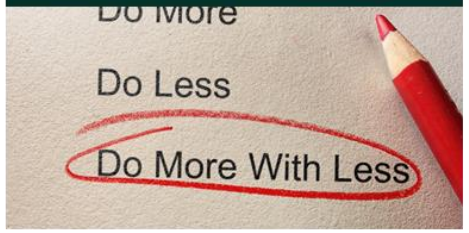
Clean integrated power

Hard to abate sectors

CCUS

SMART GRIDS

Efficiency



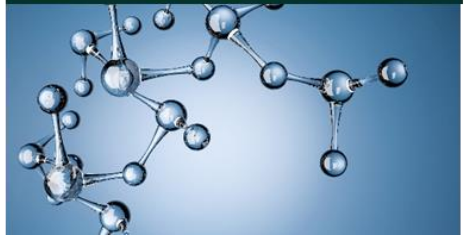
Energy storage platforms and auxiliaries

Emissions monitoring and abatement

Factory of the Future

Artificial Intelligence & Digital

Process Engineering Technologies



Hydrogen value chain engineering technologies

Advanced chemistries and chemical process technologies

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Investing for growth today and tomorrow

$2.1B of strategic acquisitions and investments

CARBON CAPTURE, UTILIZATION, AND STORAGE

Modular Carbon Capture technology
Nov 2020

Exclusive license for mixed-salt capture
Mar 2021

Bio-methanation and synthetic natural gas technology investment
Jun 2021

Next-gen Direct Air Capture technology
Apr 2022

Polaris carbon storage project in Norway
Mar 2021

Industrial process equipment and technologies to eliminate GHG emissions
Feb 2022

CCS hub for Norwegian Industrial Cluster
Jun 2021

Project developer that utilizes CO_2 and H_2 to produce eFuels
March 2023

HYDROGEN

Methane pyrolysis technology to produce turquoise H2
Nov 2021

Early-stage hydrogen technologies
Dec 2021

Hydrogen compression and turbines for multiple projects
Jun 2021

Hydrogen infrastructure investment platform Anchor Investor
Apr 2021

Clean power solutions

Clean integrated power and hydrogen solutions
May 2021

Technology development & global deployment of zero-emission power plants
Feb 2022

DIGITAL

Reliability and industrial asset management solutions
Feb 2021

OILFIELD SERVICES & EQUIPMENT

Well intervention services & downhole technology
Mar 2022

Advanced artificial lift and electrical submersible pumps technology
Jul 2022

GAS & INDUSTRIAL

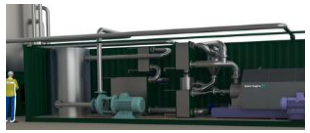
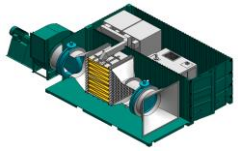
Inspection solutions for critical infrastructure
Mar 2022

Electrification equipment, generators, and motors
Aug 2022

GEOTHERMAL

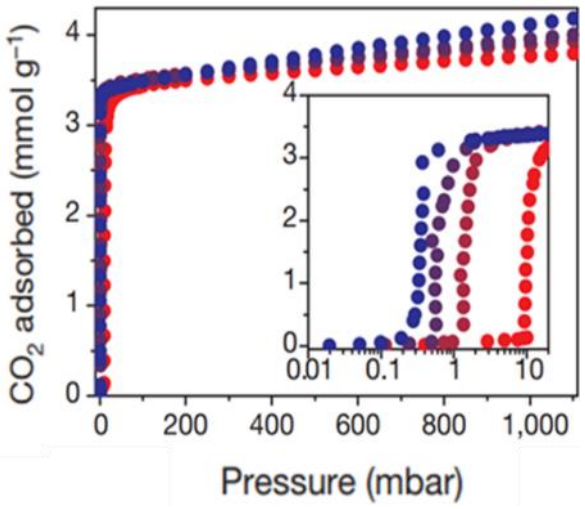
Closed loop geothermal technology
Mar 2022

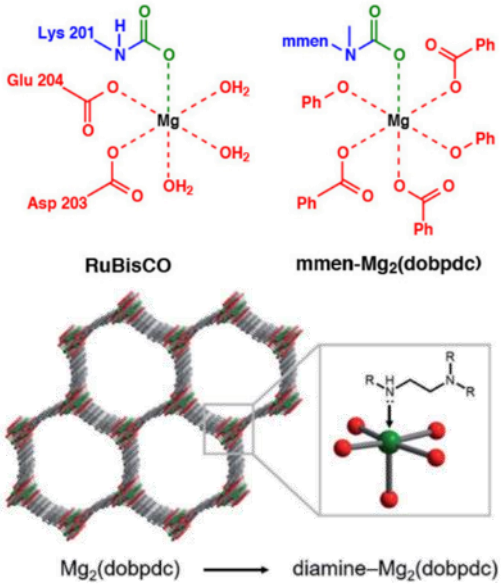
CO_2 capture technologies

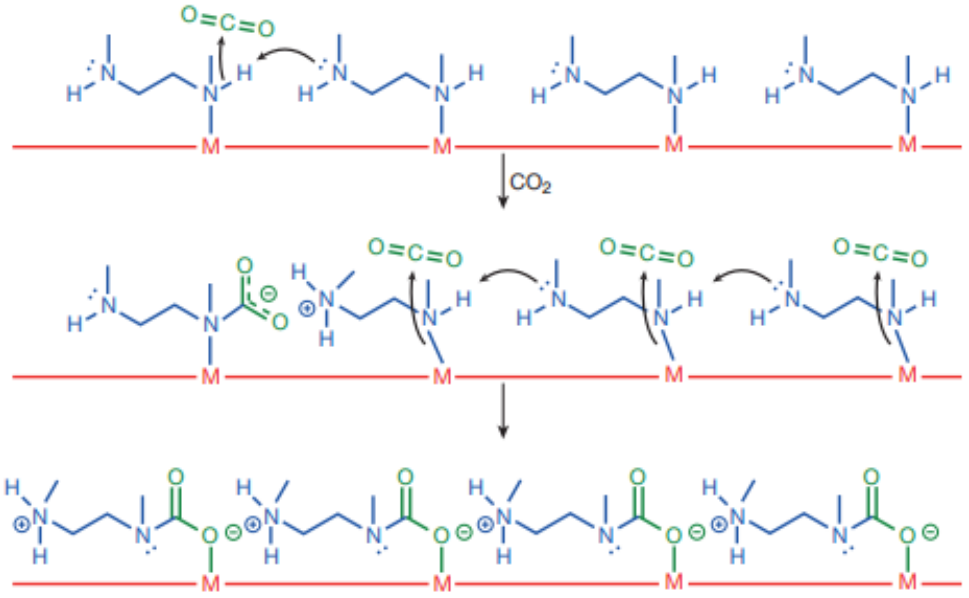
Technology		Readiness level	Key features
Chilled Ammonia Process (CAP) Solvent: ammonia-based		1 2 3 4 5 6 7 8 9 *Validated at TCM (80ktpy)*	Releasing CO_2 at high pressure: • Reducing compression needs • Allows for direct liquefaction Sustainable solvent: • Widely available/commodity • No thermal and oxidative degradation • Environmentally friendly effluents Controllable emissions to atmosphere and tolerant to flue-gas contaminants (NOx, O_2, etc.)
Mixed Salt Process (MSP) Solvent: potassium-based with ammonia		1 2 3 4 5 6 7 8 9 *TRL6 on-going at UIUC (10tpd)*	
Industrial Climate Solutions (ICS) Pulsing froth gas-liquid contactor Compact size with no moving parts		1 2 3 4 5 6 7 8 9	More efficient mass-transfer: • Reduced column diameter • Reduced bed depth Versatile for challenging applications: • Pre- or Post-combustion capture • Self-cleaning for high-solids processes • Capture/scrubbing or 2- or 3-phase reactors
Compact Carbon Capture (CCC) Solvent agnostic (tested with MEA) Rotating beds to intensify mass-transfer		1 2 3 4 5 6 7 8 9 *TRL7 on-going*	More efficient mass-transfer: • Shorter absorber columns • Compact regeneration system Modular and scalable configuration: • Reduction in footpint & height • Retrofittable for brownfield applications
Mosaic Metal Organic Frameworks for DAC		1 2 3 4 5 6 7 8 9	• The extra step to meet 1.5°C • Adsorbent w/ higher efficiency & lower costs • Unique performance achieved thru a proprietary “cooperative binding” process

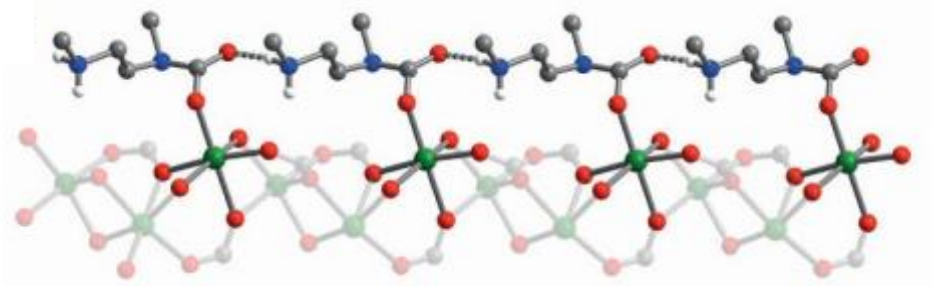
Diamine Functionalised MOFs

- Diamine functionalised MOFs display exceptional CO_2 adsorption performance.
- Diamine MOFs contain a CO_2 binding site which acts as a functional model to the CO_2 binding site in the RuBisCo enzyme.
- The high density of CO_2 binding sites combined with the unique CO_2 adsorption mechanism gives way to S-shaped adsorption isotherms which enabled exceptional trace CO_2 adsorption.



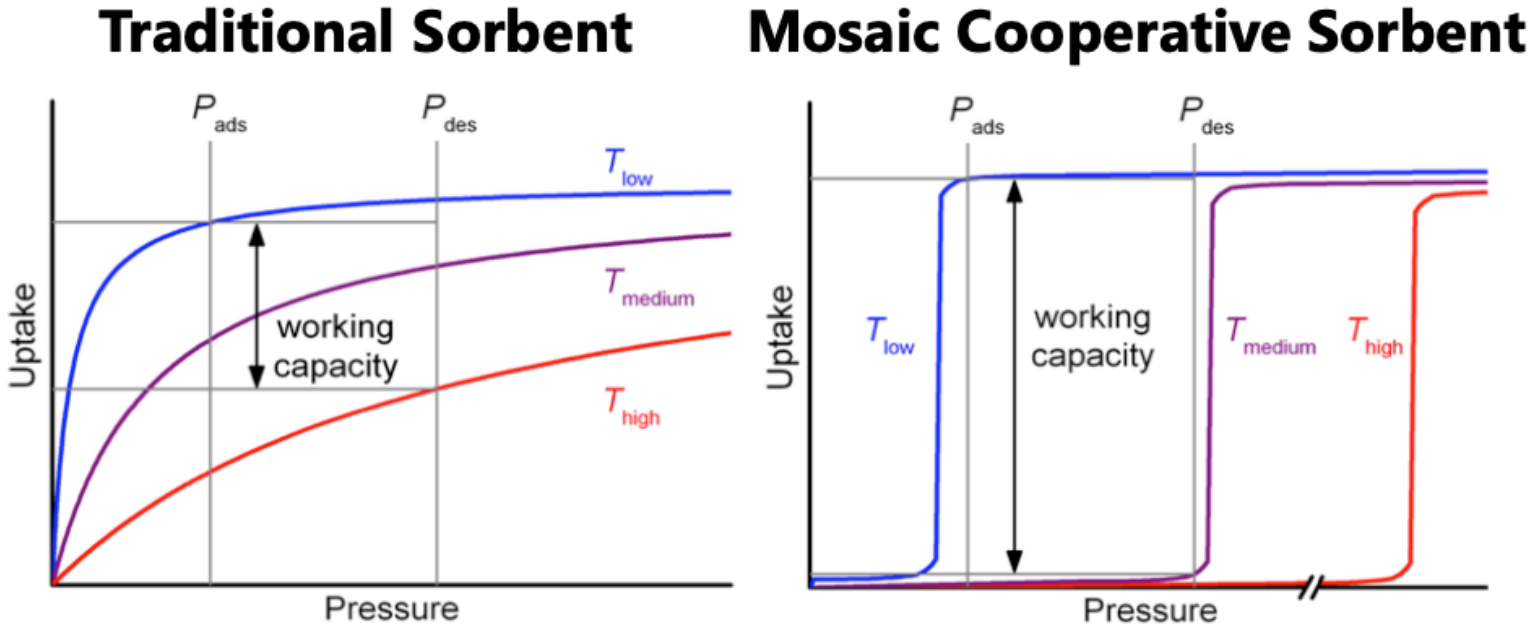






1) McDonald, T. *et al. Nature* 519, 303–308 (**2015**).

Critical Discovery | Cooperative Adsorption



- Working capacity of cooperative sorbents is significantly greater than traditional sorbents because lean loading of CO_2 is nearly zero
- For temperature-swing adsorption process, reduced regeneration temperature reduces OpEx and increases sorbent lifetime

CO_2 Direct Air Capture (DAC)

- Mosaic DAC systems will utilize **highly optimized CO_2 contactors** to maximize CO_2 capture
- Incorporating waste heat and renewable energy provide options for **offsetting overall energy intensity**

Mosaic DAC – Development Roadmap

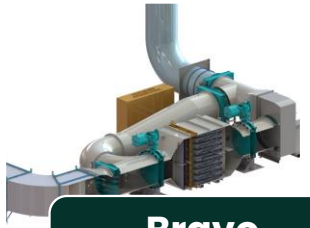
- Validating materials and process at increasing scales and levels of integration

Lab Scale

<0.1 TPY

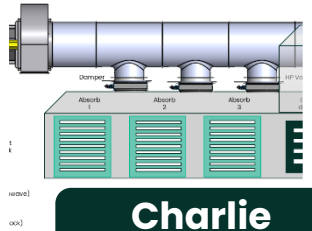
Alpha

1 TPY



Bravo

125 TPY



Charlie

1,000 TPY

Commercial

10k TPY

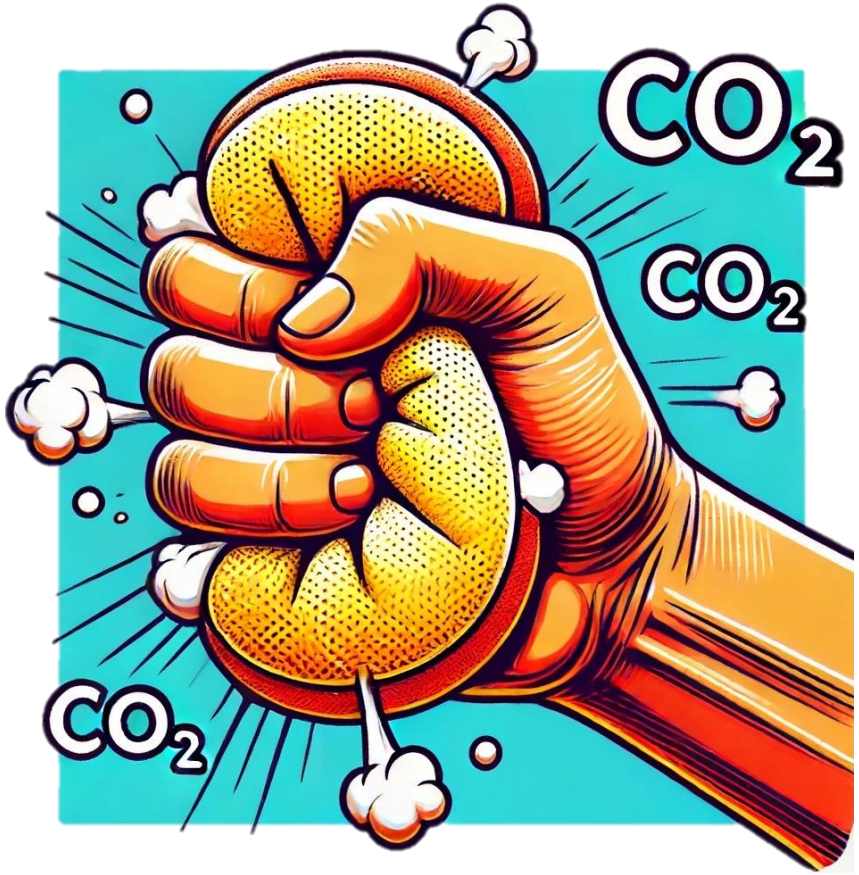
Duration	2016-24	2022-25	2022-25	2024-26	2026+
TRL Scale	1-3	3-4	4-5	6-7	8-9
MOF Production	100 g/week	3 kg/week	1 T/yr	10 T/yr	100 T/yr
Key Validation Points	Chemistry & Material Manufacturing	Material-Process Integration	Contactor Design & Process Controls Material MFG'd at 1 T Scale	Multi-contactor Module	Multi-Module Integration

Bravo DAC Device in Houston

Need for research

One of the most **energy-intensive** part of the process is the **desorption** phase.

What can we do to make it less energetic?



The CO2 release phase in MOF-based adsorbers is the most energy-intensive process. This is because a significant amount of thermal energy is required to break the stable bond formed between CO2 and the amine MOF groups. This process is analogous to squeezing a sponge to expel water; it requires altering the entire structure to release water.

Is there a more efficient method to selectively disrupt only the stable CO2 without affecting the rest of the material? This would be similar to using a pair of tweezers to precisely remove CO2 from a sponge.

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CCUS – playing across the value chain

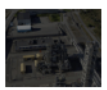
Unique combination of sub-surface to surface capabilities

TECHNOLOGIES & SOLUTIONS

Capture, transport, and utilization

Post-combustion capture

inorganic Solvent-based



CAP

MSP

Process Intensification

ICS

COMPACT CARBON CAPTURE

Transport

Compressors & Pumps

Liquefaction & conditioning

Nonmetal /Flexible Pipes

DAC

mosaic

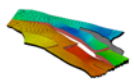
Utilization

Electrochaea

(Biomethanation)

Storage products and services

JewelSuite™ *Sub-surface Eng.*



PermaSet™ *Well Integrity cementing*

SureVIEW™ *Well monitoring*

MMV *Well monitoring*

Additional services and solutions

Integrate & Collaborate

Eng system integration

S2S Integration

Integrated Project Exc.

Sub-surface Evaluation

Digital Platform & Syn. Simulation

Consulting

io consulting

Project strategic evaluation

Gaffney Cline

Carbon Mkts analysis

PARTNERSHIPS

Research & Technology players to accelerate technology maturation and expand footprint

Project developers with new tech. chains and business models: e.g. HIF e-fuel production

Service providers covering value chain gaps: Carbon Collectors – liquid CO_2 offshore shipping

HIF

CARBON COLLECTORS

CarbonWatch™ autonomous CO_2 monitoring

KEY PROJECTS & PILOTS

Pilots

Demo plants (CCC,MSP → TRL 6/7, Mosaic → TRL 5)

Mobile testing unit (CAP, MSP, ICS)

MMV CarbonWatch™ ongoing pilot

Image by courtesy of Technology Centre Mongstad

Commercial awards (recent)

- **Capture - CAP** (US-Project FEED, #1)
- **Compression** – liquefaction (NL,#1), capture/re-injection (MY, #1), FPSO (BR, #3), blue NH3 prod.(US, #2)
- **Offshore Well Construction** (NO#1, AU #1) and **onshore storage** for NH3/H2 sites (US, #2)
- Involved in 46% of projects requesting Class VI **permits**
- 10+ **test wells** in NAM, 20+ **reservoir/MMV** studies, **permitting** support for storage globally

number of projects

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Note. MMV = Measurement, monitoring and verification, CAP = chilled ammonia process, MSP = mixed salt process,