The thinking behind the thesis

The Sorbent Question: How Metal-Organic Frameworks Reshape Gas Separation

Why the material at the heart of the separation unit, not the unit itself, determines where value accrues across carbon capture, biogas upgrading, and hydrogen purification.

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ABSTRACT

Across the earlier papers in this series, our investment thesis has held that value in the clean-fuels economy accrues not to the owner of any single capture technology but to the equipment companies that provide the purification, dehydration, compression, gas generation, and system integration that every project depends on. Those equipment companies are our investment targets; the sorbent producers upstream of them are their vendors, not ours. This paper stress-tests that thesis against the material that sits at the physical heart of solid-sorbent gas separation, the metal-organic framework (MOF), and it does so across the whole separation portfolio rather than direct air capture alone. The same adsorbent science that pulls CO_2 from air also drives biogas upgrading, hydrogen purification, and oxygen and nitrogen separation, so a shift in the sorbent reshapes the economics of an entire equipment business at once. Three developments make the timing pointed. First, MOF chemistry has crossed from laboratory curiosity into commercial manufacture, marked by the 2025 Nobel Prize in Chemistry for the development of MOFs and by the first multi-tonne industrial production of a capture-grade framework. Second, machine-learning-accelerated discovery has collapsed the search across millions of candidate structures from years to weeks, shifting advantage away from who discovers a sorbent toward who can deploy it. Third, Chinese innovation concentrates in the contactor, regeneration, and process engineering that surrounds the sorbent rather than in the sorbent molecule itself. We argue these developments reinforce, rather than undermine, the equipment thesis: the sorbent is becoming a purchasable commodity input, and durable margin migrates to the balance-of-plant and system integration that the equipment companies own, across every separation the portfolio serves. We map the landscape, quantify where MOF economics must still travel, and set out the sorbent-agnostic procurement posture that makes those equipment companies attractive investments.

Keywords: metal-organic frameworks; solid sorbents; gas separation; pressure swing adsorption; biogas upgrading; hydrogen purification; direct air capture; sorbent-agnostic integration

1. The Sorbent Question

The papers before this one argued that captured carbon is worth more as a feedstock than as a buried liability, that green methanol is the storable liquid linking capture to aviation-grade fuel, that direct air capture must still travel a demanding cost curve to become bankable, and that sustainable aviation fuel is the demand engine pulling the whole chain forward. At each link our conclusion was the same: the durable position for patient capital is to invest in the equipment companies that supply the enabling systems, the purification, compression, gas handling, and integration that every project needs, rather than to build the plants or bet on a single technology. A word on terms is useful here, because two distinct roles are easy to conflate. The equipment companies are our investment targets. The sorbent producers, the chemicals majors and specialist manufacturers that make the adsorbent material, are vendors to those equipment companies, not to the family office. This paper opens the box on the equipment and examines the one component that most determines a separation system's energy use, footprint, and cost: the sorbent itself, and in particular the engineered crystalline materials known as metal-organic frameworks.

A metal-organic framework is a porous crystalline solid built from metal nodes connected by organic linker molecules, forming a repeating scaffold riddled with internal channels. The internal surface area is extraordinary, with a single gram of a good framework presenting hundreds to thousands of square metres, and, decisively, the chemistry of the pores can be tuned to prefer one gas molecule over another. That tunability is why MOFs matter well beyond carbon capture. The same principle that separates CO_2 from air also separates CO_2 from methane in biogas upgrading, hydrogen from reformate and purge streams, and oxygen from nitrogen in air separation. These are the core separations of a gas-technology equipment business, and they rest on a shared adsorbent science. A change in the sorbent is therefore not a niche event confined to one product line; it reshapes the economics of the whole portfolio at once.

For an investor, the question is not whether MOFs are scientifically elegant, which they plainly are, but where in the value chain the advantage they confer actually accrues, and whether that location is one the equipment companies we back can occupy. This paper answers by establishing what has genuinely changed in MOF development, locating those changes against the equipment thesis across the full separation portfolio, disciplining the enthusiasm with the economics that remain unresolved, and translating the analysis into a procurement posture.

2. What Has Actually Changed

2.1 From Laboratory to Multi-Tonne Manufacture

The single most consequential development is that a capture-grade MOF is now manufactured at industrial scale. CALF-20, a zinc-based framework originally developed at the University of Calgary, is produced commercially by BASF and used by the technology firm Svante, which reports the first multi-tonne production of a MOF sorbent for carbon capture. The framework captures a high fraction of CO_2 from industrial gas streams, resists the water vapour and acidic contaminants that degrade many rival materials, and regenerates with low-pressure steam. The significance is not the specific chemistry but the precedent: MOFs have crossed from bespoke laboratory batches into a purchasable industrial commodity, coated onto structured adsorbent filters by continuous processes. The scientific establishment has ratified the field's arrival, with the 2025 Nobel Prize in Chemistry awarded to Kitagawa, Robson, and Yaghi for the development of MOFs, and with CALF-

20 cited as the benchmark example for industrial carbon capture. For an investor weighing a multi-year commitment, that maturity reduces the technology risk of building a position around solid-sorbent separation.

2.2 Discovery Has Been Compressed by Machine Learning

The number of conceivable MOF structures is effectively unbounded: well over a hundred thousand have been synthesised and millions more are computationally plausible. Historically, screening this space for a material that separates a target gas selectively under realistic conditions was the rate-limiting step, requiring years of trial synthesis. That constraint has broken. Machine-learning models trained to quantum-chemical accuracy now simulate gas behaviour inside candidate frameworks quickly enough to screen very large libraries in a fraction of the former time, and open datasets have grown to tens of millions of computed structures. The practical effect is a strategically important inversion. When discovery was hard, advantage sat with whoever held the winning molecule. When discovery is cheap and commoditising, advantage migrates downstream to manufacturing, formulation into usable pellets or laminates, contactor engineering, and system integration, precisely the terrain the equipment companies occupy and this series has argued patient capital should back.

2.3 Chinese Innovation Sits Around the Sorbent, Not in It

Patent analysis of recent years places Chinese institutions at a majority of direct-air-capture filings, with leading universities concentrating on electrothermal regeneration and modular contactor design, while Western filings cluster around advanced sorbent chemistries. The domestic adsorbent research ecosystem confirms this orientation across the wider portfolio: Jilin University leads fundamental zeolite discovery, Zhejiang University pairs green synthesis routes with applied MOF-versus-zeolite separation data, and Tianjin University specialises in the pressure-swing-adsorption process design and bed optimisation that governs hydrogen purification. This is a geographic division of labour weighted toward the engineering that surrounds the sorbent, how to heat it, how to package it, how to cycle it, rather than toward proprietary molecules. For a gas-technology equipment company, the domestic ecosystem is oriented toward exactly the integration and balance-of-plant layer where it competes, while the sorbent itself is increasingly available on an open market from external producers.

TABLE 1

Sorbent Classes for Gas Separation: Comparative Profile

Sorbent Class	Typical Use	Regeneration	Maturity / Cost Signal
Zeolite (e.g. 13X)	Biogas CO_2/CH_4; H_2 PSA; O_2/N_2	Pressure or thermal swing	Mature commodity; low cost
Solid amine	CO_2 capture (flue, air)	~80–120 °C thermal / steam	Widely piloted; ~$5–20/kg
MOF (e.g. CALF-20)	CO_2 capture; selective separations	Low (~60–100 °C); steam	First multi-tonne output; ~$50–200/kg

Note. Ranges are order-of-magnitude figures from 2025–2026 public sources, indicative rather than procurement quotations. MOF cost is the principal remaining gap versus incumbent adsorbents; lower regeneration energy is the principal offsetting advantage. Zeolites remain the workhorse of biogas and hydrogen PSA today.

3. Reading the Change Against the Equipment Thesis

The instinctive worry is that a breakthrough sorbent could disintermediate the equipment company, that whoever owns the material owns the value, and so undermine the investment case. The evidence points the other way, for three connected reasons, and the logic holds across every separation the portfolio serves.

First, the sorbent is becoming a commodity input rather than a proprietary moat. When a framework is manufactured by a global chemicals producer, sold on an arm's-length basis, and shadowed by a rapidly expanding field of computationally discovered alternatives, its ability to command monopoly rents erodes. The equipment company does not need to win the sorbent race; it needs to buy the winning sorbent and integrate it well. A commoditising input upstream of the equipment company's position is favourable, not threatening, because it lowers the cost of the one component that company would otherwise have to license or invent, whether that sorbent goes into a carbon-capture contactor, a biogas upgrader, or a hydrogen PSA skid. For the family office, a cheaper input to its investment target improves that target's margins.

Second, the value-critical difficulties are downstream of the molecule. A high-performing powder is not a working plant. Turning a framework into a unit requires shaping it into attrition-resistant pellets or coated laminates, engineering a contactor or adsorption bed that moves large gas volumes across it at low pressure drop, designing a regeneration or cycle that releases the target gas without degrading the material, and then drying, compressing, and conditioning the product to specification. Every one of those steps is a purification, gas-handling, or system-integration problem, the equipment company's core competence, and none is solved by the sorbent chemistry alone. This is as true for hydrogen recovery from a synthesis-loop purge as it is for CO_2 from air.

Third, the surrounding ecosystem is aligned with the integration layer. With innovation concentrated in regeneration and contactor engineering, and with captured or separated gas treated as a feedstock rather than an end in itself, the party that connects a separation module to the next process step captures the recurring margin. This is the crux of the distinction for the family office: the sorbent producer sells a material once, at commodity margins, whereas the equipment company earns across the installed base and its service life. We invest in the second, not the first.

TABLE 2

Where Sorbent Advances Land in the Value Chain

Value-Chain Layer	Effect of Recent Sorbent Advances	Who Captures It
Sorbent molecule	Discovery cheapened by AI; supply commoditising	Chemicals majors; open market
Formulation / shaping	Roll-to-roll and pelletisation now industrial	Specialist manufacturers
Contactor & regeneration	Focus of Chinese patent activity	Equipment integrators
Gas conditioning	Unchanged necessity; higher-purity demand	The equipment company
Integration to next process	Where recurring margin concentrates	The equipment company

Note. The series thesis holds under the sorbent transition: recent advances cheapen an input the equipment company buys and intensify demand in the layers that company owns, across carbon capture, biogas upgrading, and hydrogen purification alike.

4. Where the Economics Must Still Travel

Enthusiasm should be disciplined by the numbers. Three gaps remain between MOF promise and MOF bankability, and an equipment company, and the family office underwriting it, must account for each rather than assume it away.

1. **Sorbent cost.** MOF synthesis today runs on the order of $50 to $200 per kilogram against roughly $5 to $20 per kilogram for solid amines, and far less for the zeolites that dominate biogas and hydrogen PSA. Because a single plant can require tonnes of sorbent, this gap is material. It is narrowing as production scales and as cheaper linkers and single-step syntheses mature, but a procurement model must price sorbent replacement over the plant's life, not just at first fill.
2. **Cycle durability.** A sorbent's economics depend on how many separation cycles it survives before capacity fades. CALF-20's resistance to steam and acidic contaminants over thousands of hours is precisely why it commercialised first; less robust frameworks with higher headline capacity may lose on lifetime cost. Qualification must weight durability over peak uptake, the same discipline that governs zeolite selection in existing PSA systems.

3. **System energy, not sorbent energy.** The headline MOF advantage is low regeneration temperature, but a separation system as a whole still consumes energy across fans or compressors, heat, and conditioning. In direct air capture specifically, the whole system still runs on the order of 1.5 to 2.5 megawatt-hours per tonne of CO_2 and delivered cost remains in the $400 to $600 per tonne range in 2026. A better sorbent improves one term in that equation; it does not by itself deliver the step-change in cost, consistent with the cost-curve argument of the third paper.

The implication is that an equipment company should treat sorbent selection as an optimisation over lifetime system cost, weighing capacity, durability, regeneration energy, and replacement price together, rather than chasing the highest laboratory capacity. That is an integrator's judgement, it is defensible precisely because it is hard to make well, and the ability to make it is part of what makes such a company a durable investment.

5. A Sorbent-Agnostic Posture

The recommendation continues the technology-agnostic position established across the series, now specified for the sorbent layer. The equipment companies we back should neither bet on a single framework nor attempt to develop proprietary sorbent chemistry in competition with chemicals majors and national laboratories. They should build the capability to qualify, procure, and integrate whichever sorbent wins on lifetime system economics, across every separation the portfolio serves. The principles that follow guide which such companies we invest in:

- **We back companies that qualify, not invent.** We favour equipment companies that build an internal protocol ranking candidate sorbents on delivered cost per tonne under real operating conditions, weighting durability and regeneration energy over peak capacity. That protocol is itself a defensible asset, and its presence is a marker of an attractive investment target.
- **We back companies that keep multiple vendor relationships.** We prefer equipment companies that source across commercial MOF producers, domestic zeolite makers, and amine developers, preserving the option to switch as prices and performance move, and avoiding single-sorbent lock-in exactly as the series has counselled avoiding single-technology lock-in.
- **We back companies that invest ahead in the layers they own.** We favour equipment companies that direct their own capital toward higher-purity drying and compression, contactor and cycle integration, and the tie-in to the next process step, the layers where sorbent advances raise, rather than erode, the value of their position, and which are common across carbon capture, biogas, and hydrogen.

- **We back companies that follow the research frontier selectively.** We favour equipment companies that maintain light-touch tracking of the leading domestic groups in regeneration, contactor design, and PSA optimisation, and of the commercial manufacturers that translate academic work into industrial product on a multi-year lag.

Taken together, these principles convert the sorbent transition from a perceived threat into a confirmation of the thesis. The material at the heart of the separation unit is becoming cheaper, better understood, and more openly available, while the difficulty, and therefore the margin, moves into integration, where the equipment companies we back already stand. This holds across carbon capture, biogas upgrading, and hydrogen purification alike, which is why a change in the sorbent strengthens rather than weakens the case for investing in the equipment layer.

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