WHITE PAPER

Promethean Particles®

TURNING WASTE INTO RENEWABLE FUEL

THE TRANSFORMATIVE ROLE OF METAL – ORGANIC FRAMEWORKS (MOFS) IN ENABLING THE NEXT GENERATION OF BIOGAS UPGRADING SYSTEMS

April 2026

CONTENTS

> **"The age of fossil fuel is coming to an end. The rise of renewable energy is irreversible."**
>
> **António Guterres**[1]
> UN Secretary-General

EXECUTIVE SUMMARY

The Fossil Fuel Challenge and Climate Imperative

Achieving net zero requires a fundamental reduction in carbon dioxide (CO_2) emissions across global energy systems, including those reliant on fossil fuel derived natural gas.

Traditionally viewed as a “cleaner” bridge fuel, natural gas still contributes significantly to climate change, not only through the release of carbon dioxide from its combustion, but also through the unintended release of methane (the primary component of natural gas) into the atmosphere.

One alternative to natural gas is biomethane, a sustainable methane gas derived from upgrading biogas (a mixture of methane, carbon dioxide and trace impurities) produced through the anaerobic digestion of organic waste. When coupled with carbon capture, the production of biomethane from biogas offers a pathway to maintain energy services while reducing net greenhouse gas emissions and improving energy security.

Among the emerging technologies for biogas upgrading and carbon capture, metal-organic frameworks (MOFs) stand out. These highly porous materials are ideal for both separating and storing carbon dioxide from biogas.

Once seen as a futuristic concept, high-quality MOFs are now commercially viable at an industrial scale due to the breakthrough in manufacturing processes developed by Promethean Particles.

TURNING ORGANIC WASTE INTO RENEWABLE FUEL

Upgrading biogas to produce biomethane by the removal and capture of carbon dioxide represents a vital step in both decarbonising the energy sector and achieving net zero.

Biogas - Generating Energy from Waste

Anaerobic digestion (AD) is a proven, scalable biotechnology that converts organic waste into biogas. In an oxygen-free digester tank, bacteria breakdown materials such as agricultural residues, livestock manure, food waste, and wastewater sludge. This process yields biogas, a mixture of methane (CH_4), carbon dioxide and trace impurities along with a nutrient rich digestate that can be used as fertilizer. AD effectively harnesses the same decay processes that occur in landfills or manure pits, but in a controlled environment that enables gas capture. If left unmanaged, decomposing organic waste generates methane that would escape to the atmosphere. Methane is a greenhouse gas with 28 – 36 times the warming impact of CO_2 over 100 years[2]. By contrast, when that methane is captured and used as fuel, the net climate impact is far lower. Around the world, there are over 130,000[3] active AD facilities, from small farm-based digesters to large municipal or industrial plants.

Today, the majority of biogas produced through AD is used as a low-quality fuel source for heating and energy generation. However, the potential of upgrading biogas to produce biomethane to provide an alternative to fossil-derived natural gas, and of capturing the separated carbon dioxide, is beginning to be more widely recognised and incorporated into net zero planning. For example, the European Commission has identified biomethane as "a sustainable alternative to fossil gas[4]" that can play a significant role in achieving clean energy objectives and reducing dependence on imported natural gas. In the global shift toward renewables, biomethane is emerging as a promising solution to decarbonise gas use without requiring new infrastructure, since it is fully compatible with current gas pipelines and appliances.

Biomethane - A Renewable Natural Gas

While raw biogas can be used as a fuel source, its full potential is only realised when it is upgraded to high purity biomethane (also known as renewable natural gas, RNG). Upgrading refers to removing the non-methane components, primarily carbon dioxide, and impurities like hydrogen sulfide (H_2S), moisture, and siloxanes, to produce a gas that meets the quality standards of pipeline natural gas or vehicle fuel. This step is essential because pipeline operators and engine manufacturers require fuel gas with a high methane content and minimal corrosive or harmful impurities.

Typically, pipeline-grade biomethane must have a methane concentration of 95-99%[5], with carbon dioxide reduced to only 1-2%. By contrast, untreated biogas can contain 35-45% carbon dioxide[6]. This has far too low an energy content and can damage equipment due to acidic gases and moisture.

Biomethane is virtually indistinguishable from conventional natural gas and can be injected into existing gas distribution grids, stored and transported just like fossil derived gas, or compressed/liquefied for use as vehicle fuel[7]. This means consumers can use biomethane for cooking, heating, electricity generation, or transportation without any changes to appliances or engines, enabling a seamless transition to a greener gas supply.

Carbon Dixode - Separation and Storage

Upgrading biogas to biomethane requires efficient separation of carbon dioxide and other impurities, which can be technically and economically challenging. In 2018, only 10% of Europe's biogas was upgraded to biomethane[8], but interest in both upgrading biogas and capturing the separated carbon dioxide is growing.

In the report "*The World's Cheapest Cleaner - Why Carbon Capture From Biogas Upgrading Makes Sense*" Chris Hulme, the chair of the Anaerobic Digestion and Bioresources Association (ADBA), commented that "*one of the most compelling benefits of the biogas to biomethane process* …" is that "… *the biogas process can capture carbon dioxide more cheaply and more assuredly than any other technology.*[9]" The report highlighted that capturing carbon dioxide from biogas upgrading could meet up to 25% of the UK government's projected need for greenhouse gas reduction to offset hard to abate sectors by 2050[9].

Looking ahead

Over the past decades, several commercially proven technologies have been developed to refine biogas into biomethane, including membrane separation, different adsorbents, water scrubbing, and chemical scrubbing. Each technology has its own operational considerations, benefits and limitations which we explore further in the next section.

As demand for biogas upgrading to produce high-purity biomethane and the capturing of the separated carbon dioxide increases, MOFs are expected to become a leading technology enabling the transition to a low-carbon energy economy.

BIOGAS UPGRADING FAST FACTS:

1 RAPID CLIMATE CHANGE IMPACT

Methane accounts for ~30% of today's global warming[10]. Cutting methane emissions is one of the fastest ways to slow near term temperature rise.

United Nations Environment Programme (UNEP)

2 AVOIDS WASTE METHANE RELEASE

Unmanaged organic waste is a major source of methane. Managing this waste through capturing and upgrading biogas prevents emissions while turning waste into renewable energy.[11]

Intergovernmental Panel on Climate Change (IPCC)

3 REPLACEMENT FOR FOSSIL GAS

Biomethane can be injected into existing gas grids and used in vehicles and industry without infrastructure changes.[12]

International Energy Agency (IEA)

4 ENERGY SECURITY DRIVER

The EU targets 35 billion m^3 of biomethane per year by 2030 to cut reliance on imported fossil gas and strengthen domestic energy supply.[13]

European Commission (REPowerEU)

5 CO_2 CAPTURE OPPORTUNITY

Upgrading concentrates CO_2 into a usable stream, enabling carbon utilisation or storage alongside renewable energy production.[14]

(IRENA)

POLICY HIGHLIGHT

The EU's REPowerEU plan[15] (2022) identifies biomethane as a sustainable alternative to fossil fuel derived natural gas. Biomethane is viewed as a renewable and dispatchable energy source that can be stored, distributed and used according to demand within the existing infrastructure and gas appliances.

The REPowerEU plan highlights a clear need to scale-up the production and use of biogas and biomethane to reach 35 billion cubic metres per year by 2030. The plan states that increasing the production and use of biomethane can play a significant role towards achieving the EU's clean energy objectives, diversifying the EU's gas supplies, reducing the exposure of consumers to volatile natural gas prices and helping to address the climate crisis.

The plans highlights that achieving such growth will depend on deploying effective biogas upgrading technologies at scale, and on advancing new solutions to make the upgrading process more efficient and affordable.

BIOGAS UPGRADING TECHNOLOGIES

Several commercial technologies have been developed to efficiently separate carbon dioxide from raw biogas and yield a stream of biomethane that can serve as a direct substitute for fossil natural gas, and carbon dioxide which can be reused or sequestered.

Metal-organic Frameworks

MOFs are advanced, highly porous materials designed for selective gas separation and are increasingly being explored to improve the efficiency and economics of biogas upgrading. Their key advantage over traditional adsorbents, such as activated carbon or zeolites, is tunability. By adjusting the metal, ligand, and pore chemistry, MOFs can be tailored for high carbon dioxide selectivity and reduced methane slip, delivering high-purity biomethane from a smaller, more energy-efficient upgrading unit.

MOF-based systems combine the best features of amine scrubbing and conventional Pressure Swing Adsorption (PSA) systems to separate and capture carbon dioxide. Their fast adsorption and desorption kinetics enable quicker carbon dioxide capture, while requiring less energy to release it than other adsorbents. With industrial-scale manufacturing now available, MOFs are becoming a leading option for the next generation of biogas upgrading systems.

ADVANTAGES

- ✓ Low energy intensity
- ✓ Lower capital costs
- ✓ Modular and scalable
- ✓ Does not require chemical solvents
- ✓ Enables selective capture of CO_2 with reduced methane slip

DISADVANTAGES

- ✗ Limited number of systems in use
- ✗ Unproven long-term durability

Membrane Separation

In biogas upgrading systems using selective, semi-permeable polymer membranes, gas separation occurs by a solution-diffusion mechanism, where gases dissolve into the polymer and permeate at different rates under a pressure gradient. Selectivity arises from differences in gas solubility and diffusivity, so carbon dioxide passes through the membrane more readily than methane. By using multiple membrane stages, high-purity biomethane with minimal methane slip can be produced on one side, while carbon dioxide-rich gas is vented or collected on the other.

Membrane system performance can be tuned through membrane choice and module design. They usually operate at elevated pressure, so significant compression energy is required. Gas pre-treatment, including drying and H_2S removal, is often needed to prevent membrane damage. The technology is valued for mechanical simplicity and fast start/stop operation.

ADVANTAGES

- ✓ Compact and modular units
- ✓ Quick startup and shutdown
- ✓ No moving parts

DISADVANTAGES

- ✗ Requires multiple stages to achieve high purity & recovery
- ✗ Membranes degrade and need replacement
- ✗ Requires significant compression energy, particularly for multi-stage systems

Chemical Scrubbing (e.g. amines)

Biogas is contacted with a chemical solvent that reacts selectively with carbon dioxide. The most common approach is amine scrubbing, where an aqueous amine solution (e.g., monoethanolamine, MEA) chemically binds to carbon dioxide from the gas stream. The carbon dioxide rich solvent is then heated in a stripping column to release concentrated carbon dioxide and regenerate the amine solution for reuse.

Chemical absorption can achieve very high carbon dioxide removal efficiency and deliver pipeline-quality biomethane. It is proven at scale in natural gas processing and post-combustion carbon capture, and adapted systems are used for biogas upgrading.

The main trade-off is complexity and energy demand. Regeneration requires significant heat, increasing operating costs. As a result, amine systems are typically best suited to larger installations where high purity and throughput justify the added energy use and equipment complexity.

ADVANTAGES

- ✓ Can achieve high methane purity
- ✓ Removes H_2S and other acidic gases
- ✓ Proven technology

DISADVANTAGES

- ✗ Significant thermal energy required
- ✗ Solvent degradation creates ongoing costs and waste handling requirements
- ✗ Complicated system

Water Scrubbing

Water scrubbing is a physical absorption process that uses water as a solvent to selectively dissolve carbon dioxide and hydrogen sulphide from biogas. Because carbon dioxide is more soluble in water than methane, pressurised biogas is fed into a packed column where it contacts a downward flow of water. Carbon dioxide (and much of the H_2S) transfers into the liquid phase, leaving a methane-enriched gas stream at the outlet.

This approach is relatively simple and environmentally friendly because it uses water rather than chemical reagents. It is widely implemented worldwide and is often preferred for small to medium-scale projects due to lower capital cost and straightforward operation.

The carbon dioxide rich water can be depressurised or regenerated in a desorption column to release the absorbed gases, allowing the water to be recycled and reducing overall water consumption.

ADVANTAGES

- ✓ Can achieve high methane purity
- ✓ Simple process
- ✓ No hazardous chemicals needed
- ✓ Removes some impurities as well

DISADVANTAGES

- ✗ High water usage
- ✗ Biofouling in recirculated water
- ✗ Biomethane requires drying
- ✗ Introduces oxygen into biomethane

Traditional Adsorbents

Solid porous adsorbents such as zeolites and activated carbon are used in pressure swing adsorption (PSA) systems to remove carbon dioxide from biogas.

Under pressure, these materials act as molecular sieves, preferentially adsorbing carbon dioxide and other impurities, while methane, which adsorbs less strongly, passes through. The system is then depressurised, or placed under vacuum, to desorb the carbon dioxide and regenerate the adsorbent. Multiple adsorption vessels operate in sequence, enabling continuous separation.

PSA systems based on conventional adsorbents are a proven and widely used technology, capable of producing methane purities above 95%. Their modularity and chemical-free operation make them attractive, particularly at small- to medium-scale. However, they do require electrical energy for compression and, where used, vacuum regeneration.

ADVANTAGES

- ✓ Low maintenance
- ✓ Proven technology
- ✓ Scalable
- ✓ Removes some impurities

DISADVANTAGES

- ✗ Does not achieve as high purity methane as other technologies
- ✗ Some methane is lost
- ✗ Sensitive to moisture
- ✗ Complex system

Cryogenic separation

Cryogenic (low temperature) upgrading cools and compresses biogas until carbon dioxide liquefies while methane remains gaseous. This works because carbon dioxide changes phase at much higher temperatures than methane (dry ice forms at about –78.5°C at 1 atm, while methane liquefies at about –161.5°C). In practice, the process uses multi-stage refrigeration with heat exchangers and expansion turbines to reach the required temperatures and separate carbon dioxide from the gas stream.

Cryogenic systems can deliver very high purity biomethane and produce liquid carbon dioxide that can be captured for industrial use or sequestration. However, these systems are energy-intensive and usually only economically viable at larger scales.

As a result, cryogenic upgrading is less common than other routes but remains attractive for niche applications where liquid biomethane or CO_2 is specifically desired.

ADVANTAGES

- ✓ Can achieve high methane purity
- ✓ Produces liquified biomethane for transportation fuel usage
- ✓ Does not require chemical solvents

DISADVANTAGES

- ✗ Energy intensive
- ✗ Complex system
- ✗ High maintenance costs

ABOUT METAL-ORGANIC FRAMEWORKS

MOFs represent a cutting-edge class of sorbent materials. Their fast adsorption and desorption kinetics makes them one of the most promising materials for carbon dioxide capture and storage in biogas upgrading systems.

A new class of incredible materials

MOFs are a relatively new family of compounds which were first discovered in 1965 as by-product from other chemical processes. They first came to prominence in mid 1990s, with academic interest ramping in the mid-2000s.

The first permanently porous metal-organic framework was discovered by Omar Yaghi et al. in 1999[12] when the term metal-organic framework was also coined[13]. More than 100,000 MOFs have been recorded in the Cambridge Structural Database[14] (CSD) as of 2025, although very few have been made at any industrially significant scale — until now.

What makes a MOF special?

MOFs are highly porous, crystalline frameworks comprised of metal ions and organic linkers (ligands). They exhibit a ‘cage’ like structure, which can be a two or three-dimensional lattice, which has an incredibly high surface area that acts as a ‘sieve’ to selectively trap (adsorb) specific molecules (adsorbate). The trapped adsorbate can then be released (desorbed) to regenerate the MOF and this cycle can be repeated many times.

A MOF’s surface area can be 10 to 100 times that of other ‘high surface area’ materials like activated carbons and zeolites. The choice of metal ion and organic linker is also almost limitless, allowing for the tuning of the MOFs’ pore size and volume for different applications.

Key attributes of MOFs:

- Incredibly high surface areas
- Tunable selectivity
- Low energy of desorption
- High thermal and chemical stability
- Recyclability

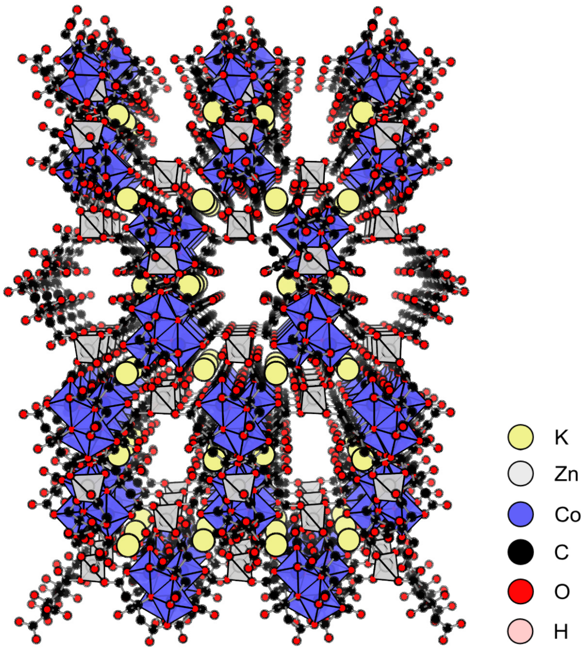


Figure 1. The structure of ProMOF® 9100

Figure 1 shows the structure of ProMOF® 9100 which contains metal nodes of cobalt and zinc, preferentially occupying specific sites in the framework of octahedral and tetrahedral geometry respectively. Potassium ions are also a structural feature of this framework, and the active site for carbon capture.

DID YOU KNOW?

7,839 m^2/g

The highest reported surface area[4] for a MOF is 7,839m^2/g[16]. That’s equal to the average size of an entire football pitch.

(Angewandte Chemie International)

Evaluating MOFs for Biogas Upgrading

The carbon dioxide adsorption behavior of a MOF and its suitability for biogas upgrading, can be assessed by passing a known composition of methane and carbon dioxide gas through a column containing MOF and measuring the composition of the outlet gas.

Figure 2 shows the results for an experiment with ProMOF® 9100 in which a gas mixture of methane (60%) and carbon dioxide (40%) was passed through a column packed with MOF and the composition of the gas at the column's outlet was measured. Before testing, the MOF was activated to remove water and any residual gases from its pores.

At the start of the test, carbon dioxide is preferentially adsorbed by the MOF, while methane is only weakly adsorbed. Methane is then rapidly displaced by carbon dioxide, causing a temporary rise in methane at the outlet above its inlet concentration. This roll-up effect shows that the MOF has a strong preference for carbon dioxide over methane. As the test progresses the MOF starts to become saturated and carbon dioxide begins to appear at the column outlet. This is shown in Figure 1 by c/c_0 for carbon dioxide starting to increase. This is known as 'breakthrough' and indicates that the MOF's adsorption capacity is being approached.

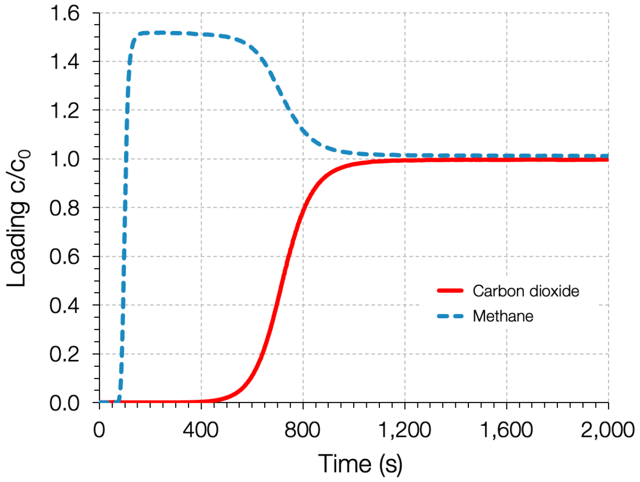
In practice, MOF-based biogas upgrading systems use multiple adsorption columns. When breakthrough occurs in one column, the inlet gas flow is switched to another column containing activated MOF so adsorption can continue without interruption. The saturated column can then be regenerated for reuse.

Not all MOFs are the Same

The ability of a MOF to adsorb carbon dioxide across a range of partial pressures at constant temperature can be evaluated by measuring its carbon dioxide uptake isotherm. This allows the uptake capacity of different MOFs to be compared and helps identify the material best suited to a specific application.

Figure 3 compares the carbon dioxide uptake

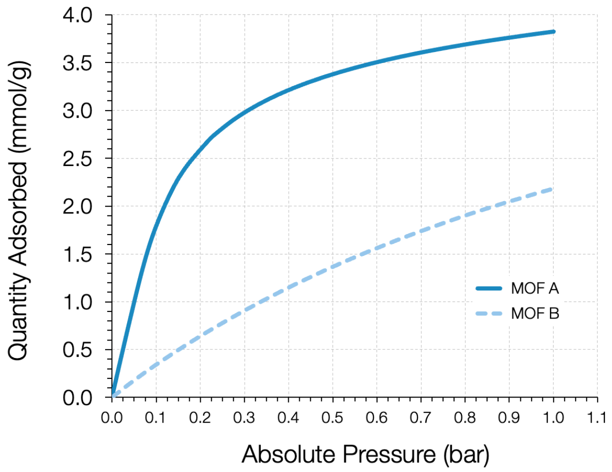
Figure 2. Competitive Adsorption of CH_4 and CO_2 (60:40) in Dry Conditions



The graph shown in Figure 2 plots the ratio of outlet to inlet concentration (c/c_0) for carbon dioxide (solid red line) and methane (dotted blue line).

A value of 1 indicates that the composition of gas at the outlet is the same as the inlet meaning the component is no longer being retained by the MOF. A value for c/c_0 of 0 indicates that the component is fully adsorbed by the MOF bed and does not appear at the outlet.

Figure 3. Comparison of CO_2 isotherms for two MOFs



isotherms of two different MOFs at 25°C.

MOF A (dark blue solid line) adsorbs a greater quantity of carbon dioxide than MOF B across the full pressure range from 0 to 1 bar. MOF A also shows higher carbon dioxide uptake at low partial pressures than MOF B, indicating a stronger affinity for CO_2. While both MOFs are capable of adsorbing carbon dioxide, MOF A would be the better candidate for a biogas upgrading system because of its higher carbon dioxide affinity at low partial pressures and higher overall uptake capacity.

MOF Selection and Shape

MOFs are typically produced as fine crystalline powders, yet most industrial processes require them to be converted into shaped forms such as pellets, granules or pills. This shaping, or forming, step is critical because it has a direct influence on how the MOF performs in an application. The final form of the MOF affects its mechanical strength, handling, pressure drop, packing density, and the rate at which gases or vapours can move into and out of the structure.

Shaping must be carefully controlled, and is a key part of translating the intrinsic properties of a MOF powder into reliable, efficient performance in an industrial system. Shaping also reduces the health and safety considerations associated with powder handling at scale.

There are many factors which can impact the selection of a particular MOF for a biogas upgrading carbon capture application. These include:

- the rate of adsorption and desorption
- the pressure range over which adsorption takes place
- the total working capacity
- the regeneration conditions

This makes the selection, tuning, and shape of a specific MOF for an application critical to maximise its effectiveness in a system.

Promethean Particles' carbon capture test rig

ABOUT PROMETHEAN PARTICLES

Promethean Particles is a world-leading specialist in the industrial-scale production of high-quality, cost-effective metal-organic frameworks.

Founded in 2007 as a spin-out from the University of Nottingham, UK, we operate the world's largest MOF manufacturing plant at our Nottingham site.

Our proprietary and patented continuous flow manufacturing process enables the industrial scale production of high-quality, cost-effective MOFs.

Over the past decade, we have evolved into a global leader, delivering advanced MOF solutions for a diverse range of gas storage and separation applications including carbon capture, biogas upgrading and atmospheric water harvesting.

Our team of research chemists and process engineers bring deep expertise in the application of MOFs in biogas upgrading systems.

Contact us to discuss how you can take advantage of the remarkable properties of MOFs to enable more energy efficient biogas upgrading.

GLOSSARY

Absorption	The process by which atoms, ions, or molecules penetrate into the bulk of a solid or liquid material, becoming uniformly distributed throughout its volume. Unlike adsorption, absorption is a bulk phenomenon rather than limited to the surface
Adsorbate	The substance that accumulates on the surface of an adsorbent.
Adsorbent	A solid material that has the ability to attract and hold molecules (such as gases, liquids, or dissolved substances) on its surface through the process of adsorption.
Adsorption	The process by which atoms, ions, or molecules (adsorbate) from a gas, liquid, or dissolved solid accumulate on the surface of a solid or liquid material (adsorbent), forming a film or layer. Unlike absorption, adsorption is a surface phenomenon.
Anaerobic digestion (AD)	A biological process in which microorganisms break down organic matter in the absence of oxygen, producing biogas and digestate.
BET surface area	The specific surface area of a porous material, determined using the Brunauer–Emmett–Teller (BET) method, which applies gas adsorption isotherms to calculate the surface accessible to adsorbates. BET surface area is a key metric for characterizing porosity and adsorption capacity of MOFs.
Biogas	The raw gas produced from anaerobic digestion. It is mainly composed of methane (CH_4) and carbon dioxide (CO_2), with smaller amounts of water vapour, hydrogen sulfide and trace gases.
Biogas upgrading	The process of removing CO_2 and other unwanted components from raw biogas to increase methane concentration and produce biomethane.
Biogenic CO_2	Carbon dioxide originating from recently living biomass rather than fossil sources.
Biomethane	A purified form of biogas with methane content typically around 95–100%, making it broadly interchangeable with fossil natural gas for grid injection, transport fuel or industrial use.
Breakthrough	In adsorption-based upgrading, the point at which the target gas being removed, often CO_2, begins to appear at the outlet because the adsorbent is becoming saturated.
CCS	The capture of CO_2 followed by permanent geological storage. For biomethane plants, captured biogenic CO_2 may be stored to help generate negative-emissions outcomes.
CH_4 (methane)	The main energy-bearing component of biogas and the principal constituent desired in biomethane. Its concentration is increased during upgrading.
CO_2 polishing	A final clean-up step used after bulk CO_2 removal to achieve the methane purity needed for grid injection or vehicle fuel standards.

Compression	Raising gas pressure to support upgrading, storage, transport or grid injection. Many upgrading systems depend on compression as part of normal process operation.
Contaminants	Undesirable gas components in raw biogas, such as hydrogen sulfide (H_2S), water vapour, ammonia, siloxanes, oxygen or particulates, that must be removed to protect equipment and meet end-use specifications.
Digestate	The nutrient-rich residual material left after anaerobic digestion. It is typically used as a biofertiliser or soil improver, depending on regulation and quality.
Feedstock	The organic material fed into the digester, such as manure, food waste, sewage sludge, crop residues or industrial organic waste. Feedstock choice strongly affects gas yield and composition.
Grid injection	Supplying biomethane into the natural gas network after it has been upgraded and conditioned to meet gas quality requirements.
H_2S (hydrogen sulfide)	A toxic and corrosive sulfur-containing contaminant commonly present in biogas. It must usually be removed before upgrading or end use.
Isotherm	Graphs that describe the relationship between the amount of gas adsorbed by a porous material and the pressure of that gas at a constant temperature. Adsorption isotherms are used to evaluate pore size distribution, surface area, and adsorption capacity.
Landfill gas (LFG)	A methane-containing gas generated by decomposition of waste in landfills. It is different from AD biogas but can also be upgraded to renewable natural gas in some systems.
MOF	Metal-organic framework
Methane slip	Methane lost in the off-gas or waste stream during upgrading. Minimising methane slip is important because it reduces product yield and methane is a potent greenhouse gas.
Off-gas	The gas stream rejected from the upgrading process, usually rich in CO_2 and potentially containing traces of methane, depending on the technology used.
Pressure swing adsorption (PSA)	A gas separation process that uses adsorbent materials and cyclic pressure changes to separate CO_2 from methane.
Renewable natural gas (RNG)	The term commonly used in the United States for upgraded biogas that can substitute for fossil natural gas. In Europe, the equivalent term is usually biomethane.
Siloxanes	Silicon-containing trace contaminants often found in some waste-derived biogas streams, especially sewage sludge and landfill gas. They can form abrasive deposits during combustion and are typically removed during gas cleaning.
Vacuum swing adsorption (VSA)	A variation of PSA that adds a vacuum step to improve regeneration of the adsorbent and often improve separation

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