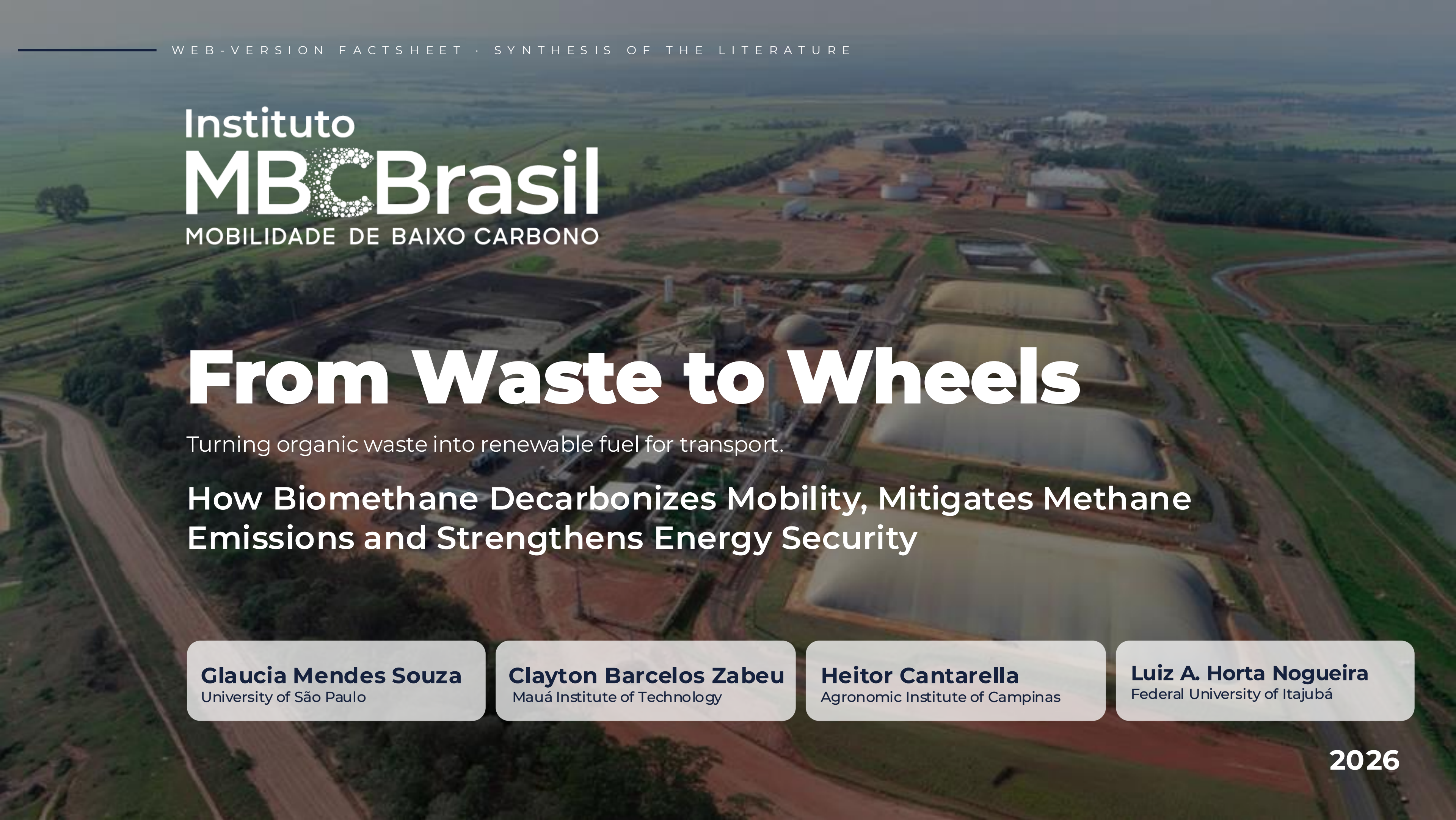
WEB-VERSION FACTSHEET · SYNTHESIS OF THE LITERATURE



Instituto MBCBrasil
MOBILIDADE DE BAIXO CARBONO

From Waste to Wheels

Turning organic waste into renewable fuel for transport.

How Biomethane Decarbonizes Mobility, Mitigates Methane Emissions and Strengthens Energy Security

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ABOUT THIS FACTSHEET

A synthesis of the scientific and industry literature on biomethane as a fuel for decarbonizing heavy-duty transport and delivering broader environmental and socio-economic benefits.

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WHAT IS INSIDE

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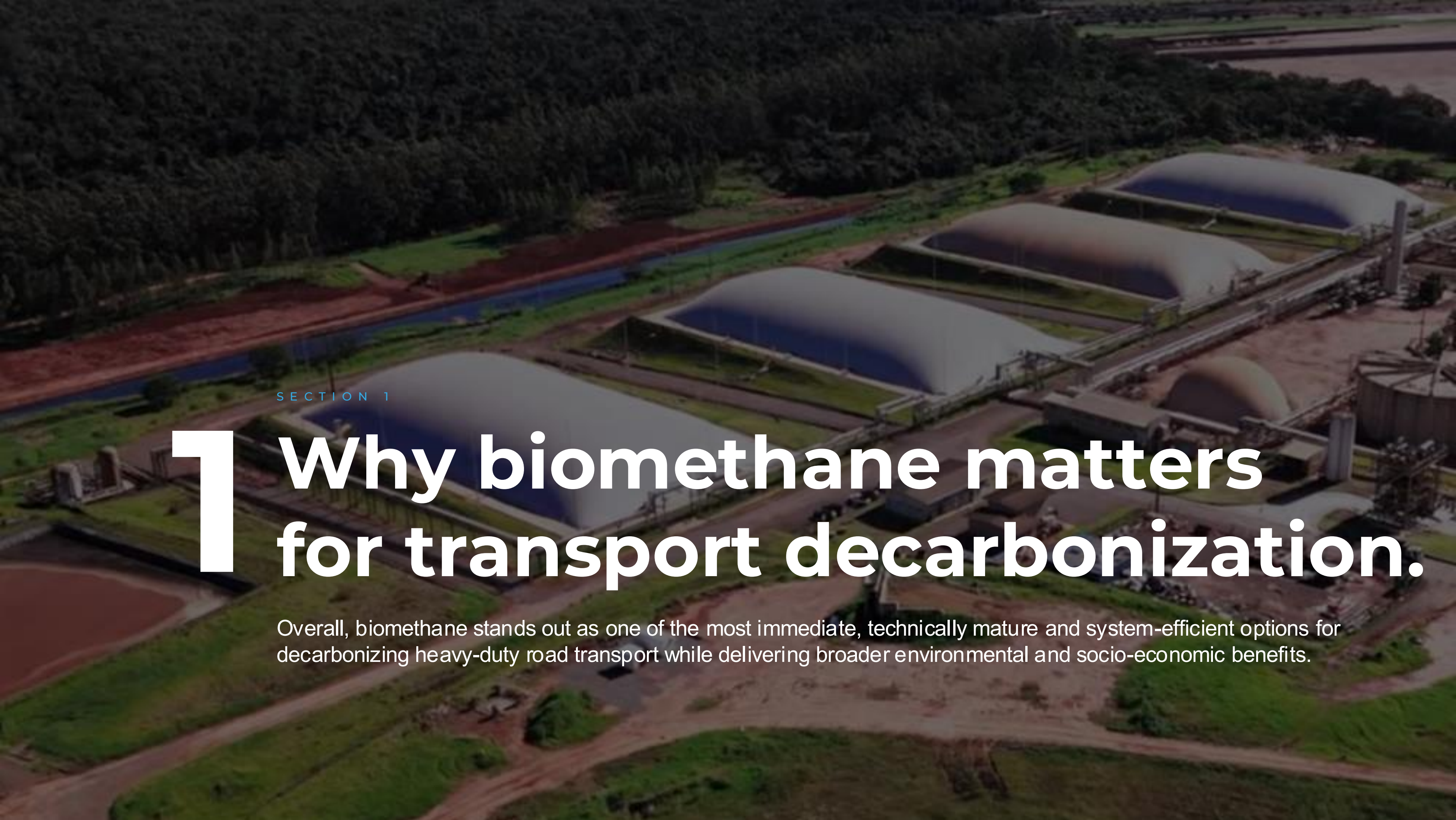


SECTION 1

1 Why biomethane matters for transport decarbonization.

Overall, biomethane stands out as one of the most immediate, technically mature and system-efficient options for decarbonizing heavy-duty road transport while delivering broader environmental and socio-economic benefits.

One fuel, ten reasons it matters

01. Immediate compatibility, substantial GHG emissions reduction and systemic

Biomethane, also called Renewable Natural Gas (RNG), Bio Compressed Natural Gas (bio-CNG) and Bio Liquified Natural Gas (bio-LNG), matters for transport decarbonization because it combines three attributes rarely found in a single solution: immediate compatibility with commercially available gas vehicle technologies and infrastructure (1); substantial lifecycle greenhouse gas reductions—particularly when produced from wastes and residues (2,3); and broader system value through methane abatement, waste management, nutrient recycling, and energy security (4,5).

02. Faster, cheaper decarbonization

Its strongest role is as a targeted, high-impact solution for heavy-duty, long-distance, and captive fleet applications where electrification is slower, costlier, or operationally constrained (1,6). Biomethane aligns well with the operational realities of heavy transport. Liquefied biomethane provides high energy density suitable for long-haul freight, while compressed biomethane can serve shorter-range applications. These fuels can be used in existing vehicle technologies and partially leverage current gas infrastructure, enabling faster deployment compared to solutions that require entirely new systems (7,8).

03. Huge potential

IEA Bioenergy's report on the global prospects for biogases, highlighted "its huge untapped potential and scope for growth across advanced and emerging market and developing economies." It also recognizes "a growing recognition that biogases can provide broad, system-wide benefits when effectively integrated into the energy system. These include helping to sustain a circular economy while supporting energy security, economic and environmental goals."(4)

04. Energy Sovereignty

Recent geopolitical crises—including the war in Ukraine and the conflict involving Iran—have reinforced that energy security is inseparable from national security. In this context, biomethane is increasingly recognized as a strategic asset: a domestically produced, decentralized fuel that reduces dependence on volatile fossil fuel imports while enhancing system resilience and price stability.

05. Energy security

Energy security is now a primary driver of energy transition policies — not just climate. The IEA explicitly states that energy security is now a key driver of biogas/biomethane deployment. Biomethane is being framed as a "strategic sovereignty" fuel. Biomethane is a domestic, controllable, non-geopolitical energy product. Security experts explicitly link biomethane to resilience: local production reduces vulnerability to supply disruption; decentralized systems improve energy system robustness under conflict conditions. Biomethane contributes to the three dimensions of energy security: supply independence, price stability and system resilience. It is sourced domestically from waste, it is not tied to global oil/gas markets and it is produced in a decentralized manner.

06. A solution for the hard-to-abate

Biomethane addresses one of the hardest parts of the transport transition: cutting emissions in applications where electrification is not always the fastest or easiest solution, especially heavy-duty road freight, long-distance haulage and bus fleets. The literature consistently shows that biomethane is not a marginal option for these segments. It is a practical low-carbon fuel for trucks and buses, already compatible with commercially available gas vehicle technologies and with existing natural gas supply chains in compressed or liquefied form (1,7).

07. Deep cuts

Its strategic value comes first from climate performance. Studies show that biomethane used in heavy vehicles can deliver major well-to-wheel greenhouse gas reductions relative to diesel, typically around 45% (manure) to 75% (food waste) (2), and through several routes including biomethane gasification (43-67%) (9). In some cases, when avoided methane emissions from waste management are credited, biomethane pathways can even become net-negative on a lifecycle basis (10). This advantage is strongest when biomethane is produced from wastes and residues such as manure, food waste, sewage sludge and municipal solid waste. The decarbonization benefit comes not only from replacing diesel at the tailpipe, but from improving the entire upstream system, integrating waste management and energy production in a circular model (11,12). However, biomethane performance depends on factors such as feedstock type, methane leakage control, and supply chain efficiency. Effective policy frameworks, infrastructure development and sustainability governance are essential to ensure robust climate benefits (12).

08. Healthier

In addition to climate benefits, biomethane contributes to improved air quality. Studies indicate reductions in NOx and particulate emissions compared to diesel, along with potential trade-offs in other pollutants depending on engine configuration (13). These co-benefits strengthen its role as a near-term solution for both climate and public health goals.

09. Circular

From a systems perspective, biomethane offers a strategic pathway that connects energy, agriculture and waste sectors. It enables circular use of resources, reduces methane emissions from unmanaged waste, and contributes to energy security by diversifying fuel supply with locally available resources (14). Biomethane is not only an energy vector; it is a product of a broader biogas system that delivers waste treatment, biofertilizer, CO_2 recovery, methane abatement, fuel and it is also a Platform Chemical (15).

10. Global

Biomethane is already produced in around 40 countries worldwide and used as a transport fuel in nearly 30 markets, with commercial-scale deployment in more than a dozen countries — primarily in Europe but rapidly expanding in the Americas and Asia. Mature deployment (core markets): ~10–12 countries (1) with significant use in fleets (Sweden -benchmark case, Germany, Italy, France, Netherlands, Denmark, Finland, Switzerland, UK, Norway). Emerging/early-stage use: ~15–20 countries where biomethane is used in pilot fleets, municipal buses, freight corridors; Brazil (rapid growth linked to sugarcane and waste), USA (4) (RNG in trucks, especially California), China and India (policy-driven expansion), Spain, Austria, Belgium, Ireland. (4,16–21).

	STATE OF PRODUCTION AND USE	MAIN MOTIVATIONS / DISTINCTIVE PRACTICES	MAIN FEEDSTOCKS	FULL REFERENCES
BRAZIL	Expanding biomethane sector linked to transport, grid injection and industrial decarbonization. More than 755 biogas plants reported and growing biomethane production capacity.	Integration with sugar-energy sector; use in trucks, industry and agricultural machinery; linkage with RenovaBio and Future Fuel Law.	Sugarcane vinasse, filter cake, livestock manure, MSW, sewage sludge, agro-industrial residues.	(22,23)
CANADA	Strong landfill gas and wastewater biogas sector with growing RNG market.	Methane mitigation strategy linked to landfill gas capture and agricultural AD.	Landfill gas, wastewater sludge, source-separated organics, dairy manure.	(22,24)
CHINA	One of the world's largest biogas systems with ~40 million household digesters and >100,000 non-household plants. Biomethane sector still emerging.	Rural energy access, manure management, pollution control and renewable gas development.	Livestock manure, crop residues, rural organic waste, industrial residues.	(22,25)
DENMARK	Highly integrated centralized biogas system with extensive grid injection.	Circular-economy model connecting farms, biomethane, biofertilizer and CO_2 recovery.	Manure, agricultural residues, straw, catch crops.	(22)

	STATE OF PRODUCTION AND USE	MAIN MOTIVATIONS / DISTINCTIVE PRACTICES	MAIN FEEDSTOCKS	FULL REFERENCES
FINLAND	Moderate biogas scale with strong transport orientation for biomethane.	Heavy-duty transport decarbonization, nutrient cycling, regional energy security.	Bio-waste, WWTP sludge, landfill gas, manure.	(1,22)
FRANCE	Rapidly growing agricultural biomethane sector with major grid injection expansion.	Farm diversification, intermediate crops, nutrient recycling and climate policy.	Manure, intermediate crops, agricultural residues, bio-waste.	(22,24)
GERMANY	Europe's largest biogas producer with >10,000 plants and ~87 TWh/year biogas production.	Long-standing feed-in tariff system and agricultural biogas model.	Energy crops, manure, agricultural residues, wastewater sludge.	(22)
IRELAND	Emerging biomethane market focused on agricultural feedstocks.	Rural development, farm income diversification and transport decarbonization.	Grass silage, slurry, manure, food-processing residues.	(22)
NORWAY	Significant transport biomethane use, especially from waste streams.	Decarbonization of transport and management of fish-processing and food waste.	Food waste, fish-processing sludge, sewage sludge, manure.	(22,24)

	STATE OF PRODUCTION AND USE	MAIN MOTIVATIONS / DISTINCTIVE PRACTICES	MAIN FEEDSTOCKS	FULL REFERENCES
SWEDEN	One of the strongest transport biomethane systems globally; major use in buses and vehicles.	Urban air-quality improvement, transport decarbonization and waste valorization.	Bio-waste, sewage sludge, industrial residues, agricultural substrates.	(15,22)
SWITZERLAND	Extensive wastewater biogas adoption and strong digestate quality systems.	Wastewater treatment, sanitation and nutrient recovery.	Wastewater sludge, agricultural residues, bio-waste.	(22,24)
UNITED KINGDOM	Mature AD market with agricultural and food-waste focus.	Methane reduction, renewable energy and rural economic development.	Food waste, manure, agricultural residues, sewage sludge.	(22,25)
UNITED STATES	Largest global biomethane producer; California dominant in RNG vehicle fuel use.	RNG credits, transport fuel markets and landfill methane capture.	Landfill gas, manure, wastewater sludge, organic waste.	(26,27)
ITALY	Second-largest European biogas market with strong biomethane transport focus.	NGV integration and municipal solid waste utilization.	Municipal solid waste, agricultural substrates.	(28)

Sustainable Development

In South America, studies indicate that biomethane remains largely underdeveloped in most countries, primarily due to fragmented efforts, inadequate infrastructure, and a lack of targeted public policies, but production is increasing (23). Biomethane is prone to contribute to several SDGs in developing economies.

STATE OF PRODUCTION AND USE	MAIN MOTIVATIONS / DISTINCTIVE PRACTICES	MAIN FEEDSTOCKS	FULL REFERENCES
INDIA			
One of the world's major biogas producers after EU, China and US.	Rural energy access, residential gas use and growing transport gas market.	Agricultural residues, manure, municipal organic waste.	(27)
ARGENTINA			
Early-stage biomethane sector with strong agricultural potential.	Agro-industrial waste utilization and decentralized rural energy systems.	Livestock waste, agro-industrial residues, urban organic waste.	(23)
BOLIVIA			
Biomethane development constrained by low waste-management infrastructure and strong fossil gas presence.	Opportunity associated with municipal organic waste and agricultural residues.	Organic solid waste, agricultural residues, livestock residues.	(23)

	STATE OF PRODUCTION AND USE	MAIN MOTIVATIONS / DISTINCTIVE PRACTICES	MAIN FEEDSTOCKS	FULL REFERENCES
🇨🇱	**CHILE** Existing biogas experience provides a platform for biomethane expansion.	Renewable-energy diversification and waste valorization.	Wastewater sludge, municipal organic waste.	(23)
🇨🇴	**COLOMBIA** One of the countries with regulation allowing biomethane injection into natural gas networks.	Integration of renewable gas into existing gas infrastructure.	Agricultural residues, wastewater sludge, municipal waste.	(23)
🇪🇨	**ECUADOR** Renewable-energy tariff framework exists but with limited effect on current biomethane growth.	Waste treatment and renewable diversification potential.	Agricultural residues, municipal organic waste.	(23)
🇵🇾	**PARAGUAY** Very low recycling and reuse rates currently limit biomethane deployment despite strong agricultural base.	Opportunity to connect waste management and energy production.	Agricultural residues, municipal organic waste.	(23)
🇵🇪	**PERU** Large opportunity from urban organic waste and agriculture, but low implementation so far.	Waste-management modernization and renewable-energy diversification.	Municipal organic waste, agricultural residues.	(23)

STATE OF PRODUCTION AND USE	MAIN MOTIVATIONS / DISTINCTIVE PRACTICES	MAIN FEEDSTOCKS	FULL REFERENCES
URUGUAY			
Limited deployment despite agricultural potential; only a few facilities produce electricity from biogas.	Industrial methane recovery and waste-management opportunity.	Industrial methane streams, livestock residues.	(23)
VENEZUELA			
Large fossil natural gas availability reduces biomethane competitiveness.	Waste regulation and methane management identified as important gaps.	Municipal waste, wastewater, industrial methane streams.	(23)

An evolving solution for many societal problems

Biomethane evolved from sanitation-driven biogas to grid-quality renewable gas, then to CNG bus fuel, then to bio-LNG for heavy freight, and is now entering a strategic phase as a circular-economy fuel for hard-to-electrify transport, industry and energy security. The most important transport chapters are Sweden's bus/fleet model, Italy's transport-centered biomethane market, California's RNG vehicle-fuel market, and the emerging Brazilian sugarcane/agroindustrial biomethane pathway.

PERIOD	LANDMARK CHAPTER	WHAT CHANGED	TRANSPORT RELEVANCE
1859–1895	First engineered anaerobic digestion	First AD plant reported in Bombay, India; by 1895, biogas from sewage treatment was used for street lighting in Exeter, UK (29).	No transport yet; sanitation + lighting.
1900s–1930s	Sewage gas and municipal digesters	AD became linked to wastewater treatment and municipal waste management.	Natural gas vehicle applications began in the 1930s, but not yet biomethane-centered.
1940s–1970s	Rural biogas expansion	China, India and parts of Europe expanded small-scale digesters for cooking, heat and farm energy.	Still mostly stationary energy.
1970s–1980s	Oil crises and environmental regulation	Biogas gained attention as a domestic energy and waste-management option.	Natural gas vehicles attracted renewed interest due to pollution and energy-security concerns.
1980s–1990s	Upgrading technology matures	Water scrubbing, PSA, chemical/physical absorption and later membranes enabled biogas upgrading to natural-gas quality.	Biomethane became technically usable in CNG vehicles and gas grids.

PERIOD	LANDMARK CHAPTER	WHAT CHANGED	TRANSPORT RELEVANCE
1980s–1990s	Upgrading technology matures	Water scrubbing, PSA, chemical/physical absorption and later membranes enabled biogas upgrading to natural-gas quality.	Biomethane became technically usable in CNG vehicles and gas grids.
1990s–2000s	Sweden, Switzerland, Germany lead transport deployment	Biomethane moved from waste/energy plants into buses, municipal fleets and gas grids. IRENA identifies Sweden, Switzerland and Germany as early transport leaders.	Sweden became the iconic case: upgraded biogas used extensively as vehicle fuel, especially buses and captive fleets.
2000s	Grid injection and virtual biomethane markets	Biomethane could be injected into gas grids and allocated contractually to transport, heat or industry.	This solved the “plant not near fleet” problem.
2010s	Commercialization phase	By 2016, Germany, Sweden, Switzerland, the UK and the US were the largest producers of biogas as vehicle fuel; around **500 plants** upgraded biogas to natural-gas quality, producing about **50 PJ/year**.	Biomethane became a real transport fuel, not just a pilot option.
	Heavy-duty focus emerges	Liquefied biomethane/bio-LNG became relevant because it has higher energy density than compressed biomethane and is better suited for long-distance trucks.	Bio-LNG opened the long-haul freight chapter.
2017–2020	New transport pilots outside Europe	Examples included Vaasa, Finland biogas buses and Kolkata, India biogas bus pilots using organic/human/animal waste.	Demonstrated municipal circular-economy transport models.

PERIOD	LANDMARK CHAPTER	WHAT CHANGED	TRANSPORT RELEVANCE
2018–2023	Policy-driven scale-up	Italy introduced support for biomethane in transport in 2018; nearly all Italian biomethane is now used in transport, and Italy has Europe's largest NGV fleet with a high biomethane share.	Italy became the strongest example of biomethane as mainstream transport energy.
2020s	RNG boom in the United States	US renewable natural gas expanded rapidly, especially from landfills, wastewater and manure. As of 2023, the US had about **470 AD projects producing RNG** (30).	California became a flagship case: **97% of natural gas vehicle fuel was RNG in 2023** (31).
2010s	Biomethane becomes a strategic gas	IEA reports biomethane is growing about **20% per year**, but still only around **10 bcme globally**, about **0.2% of natural gas demand** (27).	Transport competes with industry, heat, grid gas and green ammonia uses.
2024–2025	Europe scales industrially	Europe reached **1,678 biomethane plants by June 2025**, up from 1,548 in 2024 (32).	France, Italy and Denmark show different pathways: transport fleets, grid injection, and industrial gas substitution.
2024–2030 outlook	Brazil and emerging markets enter the scale-up phase	Brazil's Fuel of the Future Law starts in 2026 with a 1% GHG-reduction target for gas producers/importers, rising gradually to 10%; final demand is expected mainly from industry and transport.	Strong potential for trucks, farm machinery, sugarcane logistics and diesel displacement.

The Case of Germany

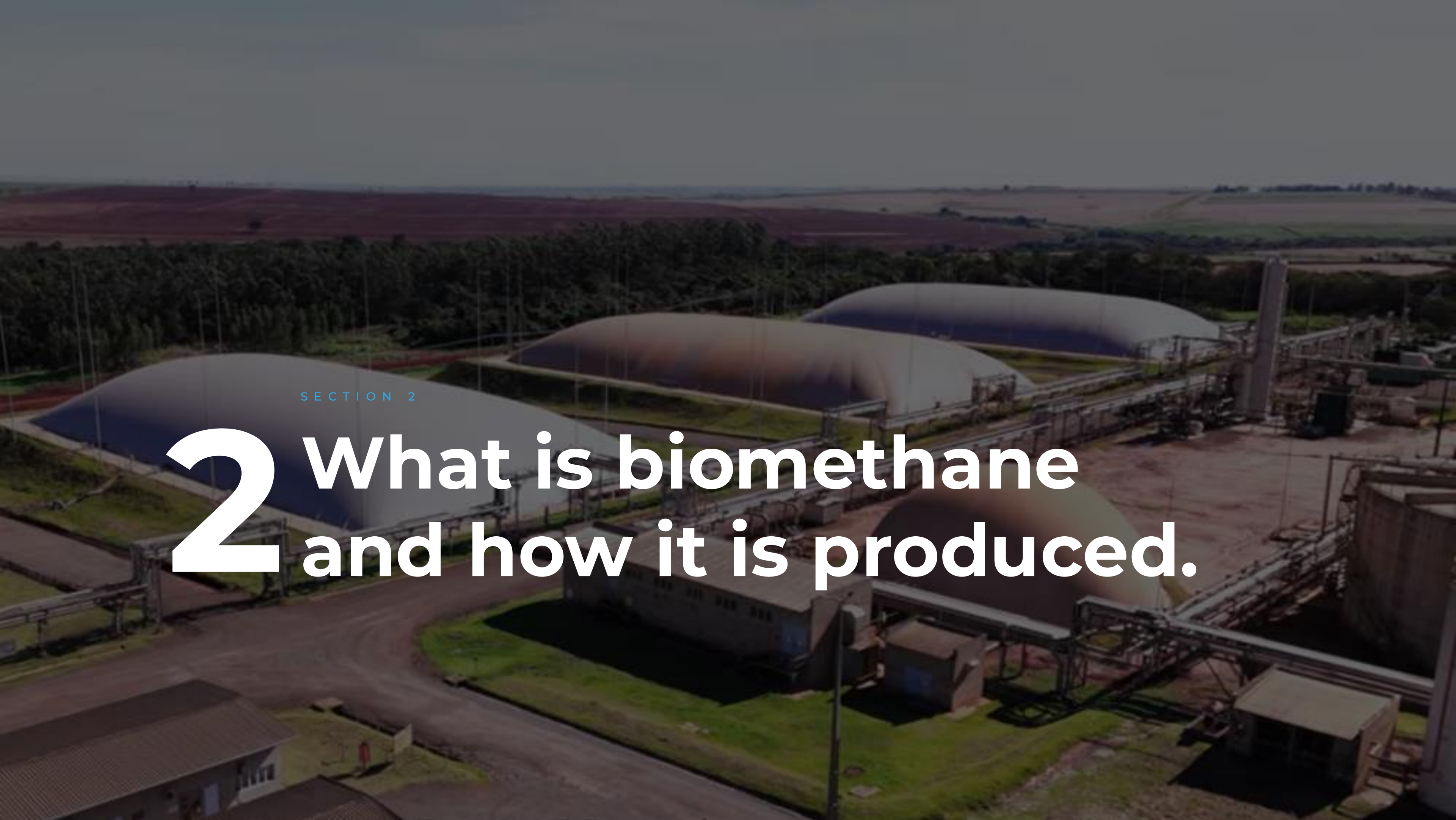
Biogas, produced by anaerobic biodigestion, is not a new thing. In the 1980s there was a push in many countries to use organic residues of various sources to generate biogas as a fuel with multiple uses. The most common target residue was animal waste, in many cases also to take care of foul odors.

Energy prices were also an issue at that time. In most countries the biogas initiatives faded away with time.

But Germany is an interesting case. Biogas production was incentivized for the same reasons: get rid of bad odors as animal husbandry was a widespread farming activity; farms were usually close to villages and small towns. The Government stimulated the construction of biodigesters by guaranteeing a market for the biogas, as biomethane could be inserted into the natural gas network. In addition, the biomethane has many market possibilities, from local heating to electricity. This caused Germany to lead the development of the biogas industry in Europe and the world. There was an enormous increase in biogas in the last two decades in Europe, but, especially in Germany.

Many new businesses started around this subject, mainly by small and medium companies, that developed technologies for the whole biogas industry chain – perfecting biodigesters, providing parts and services, biomethane purification (separating CO2, water and gases containing S), small-scale electric generation adapted to small biogas facilities, among other things. Thanks to the government push, a whole new industry was created in Germany.

In 2017, nearly 9,500 of the around 13,400 European biogas plants were in Germany. They processed municipal and industrial biowaste, manure, other agricultural residues, as well as energy crops. When also counting plants based on landfill and sewage gas, the number amounts to a total of 17,783 European biogas plants. There are local and international associations dealing with biogas, such as the German Biogas Association, the Indian Biogas Association, the International Solid Waste Association, the World Biogas Association (33–36). Therefore, the example of Germany in building a biogas/biomethane industry, can be replicated elsewhere, where the opportunities to produce and use biomethane are many.



SECTION 2

2 What is biomethane and how it is produced.

What is Biomethane and How it is Produced

WASTE ENERGY

Societies all over the world generate huge amountes of organic wastes such as animal residues and manures, crop residues, organic industrial residues of food processing, sewage sludege, and other urban residues. When inadequately disposed of, for instance, in landfills, such organic material represents a liability because they not only take space around cities, but also can generate methane, an important greenhouse gas that goes off into the atmosphere, and leachates that contaminate groundwater. All this has adverse environmental and social effects. On the other hand, if the organic wastes are anaerobically decomposed in biodigesters, they result in a usuful biofuel – biogas/biomethane (33,34).

BIOGAS COMPOSITION

Biogas

Biogas is the product of the biodigestion of organic waste and consists of a mixture of methane (CH_4), CO_2, and water. Biogas from agricultural waste typically contains, by volume, CH_4 (55–70%) and CO_2 (25–40%), in addition to smaller amounts of moisture, hydrogen sulfide (H_2S, 0.5–1%), and ammonia (NH_3, <0.01). The composition may vary depending on the feedstock used in the biodigester (33,37).

Biomethane production

Biogas can be used directly to produce electricity or heat for industrial applications. However, to produce biomethane it is necessary a further step or upgrading, in which CO2, water and smal amounts of other gases and of sulfur compounds are removed (37).

UPGRADING · FIVE TECHNOLOGIES

Five upgrading technologies dominate the global market:

WATER SCRUBBING
a mature and widely deployed technology based on preferential CO_2 absorption in water.

PRESSURE SWING ADSORPTION (PSA)
uses selective adsorption materials to separate CO_2 from methane under alternating pressure cycles.

CHEMICAL SCRUBBING AMINE SYSTEMS
achieves very high methane purity and low methane slip through selective chemical absorption.

MEMBRANE SEPARATION
currently one of the fastest-growing technologies due to modularity, lower energy consumption, scalability, and high methane recovery.

CRYOGENIC SEPARATION
removes CO_2 through cooling and condensation, offering the additional advantage of producing liquefied biomethane (LBM/Bio-LNG) and high-purity biogenic CO_2 streams. Today, membrane systems, PSA, water scrubbing, and chemical absorption represent the dominant commercial solutions worldwide.

Sources Ref (33); Refs (34–45)

Several next-generation technologies are under development or early commercial deployment:

- Biological methanation, where renewable hydrogen reacts with biogenic CO_2 to produce additional methane.
- Catalytic methanation (Power-to-Gas), integrating biomethane production with renewable electricity systems.
- Electrochemical CO_2 separation technologies.
- Hybrid upgrading systems combining membranes, PSA, and cryogenic processes.
- Advanced carbon capture and utilization pathways producing renewable methanol, hydrogen, ammonia, and synthetic fuels from biomethane-derived carbon streams.

These innovations are transforming biomethane facilities into integrated circular biorefineries capable of simultaneously producing renewable gas, biofertilizers, biogenic CO_2, hydrogen, e-fuels, and renewable chemicals.

There is no universally superior upgrading technology. The choice depends on plant size, feedstock composition, methane recovery requirements, availability of water and heat, desired product (grid injection vs Bio-CNG vs Bio-LNG), operating costs, and local conditions.

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TECHNOLOGY	SEPARATION PRINCIPLE	MAIN ADVANTAGES	MAIN LIMITATIONS	BEST APPLICATIONS
Water Scrubbing	CO_2 dissolves preferentially in water	Mature, reliable, no chemicals required, relatively simple operation	High water demand, pumping energy, less attractive in water-scarce regions	Small-to-medium plants; regions with abundant water
Chemical Scrubbing (amines)	Chemical absorption of CO_2	Very high methane purity (>99%), high CH_4 recovery, suitable for low-CH_4 biogas	Requires heat for solvent regeneration, higher CAPEX and OPEX, solvent degradation	Large plants; high-purity gas requirements
Pressure Swing Adsorption (PSA)	Selective adsorption of CO_2 under pressure	No water or chemicals, modular design, mature technology	Some methane slip, multiple compression/decompression cycles increase energy demand	Medium-sized plants; decentralized applications
Membrane Separation	Different permeabilities of CH_4 and CO_2 through membranes	Compact footprint, modular, low operational complexity, increasingly cost-competitive	Methane losses if poorly designed, multiple stages often required for high purity	Fast-growing option for small-to-large facilities
Cryogenic Separation	Cooling and liquefaction of CO_2 and/or CH_4	Produces liquefied biomethane (Bio-LNG), recovers high-purity CO_2, very high methane recovery	High electricity demand, more complex process, higher investment costs	Large facilities producing Bio-LNG
Biological Upgrading	Methanogenic microorganisms convert CO_2 + H_2 into CH_4	Direct CO_2 utilization, integration with green hydrogen, increases methane yield	Still emerging, slower kinetics, biological process control challenges	Power-to-Gas systems and future integrated biorefineries

Sources Refs (38- 49)

Over the last decade, membranes have become one of the fastest-growing upgrading technologies because they offer: modular expansion, relatively low maintenance, no solvent handling, low water consumption, compact installation footprint. For biomethane plants below roughly 500–1000 Nm^3 biogas h^{-1}, membranes are increasingly competitive with PSA and water scrubbing.

PSA remains attractive because it requires neither water nor chemicals, adsorbent materials have long lifetimes and operation is relatively straightforward. However, PSA generally exhibits slightly higher methane losses than optimized membrane or amine systems.

Chemical absorption becomes attractive at larger scales because methane recovery can exceed 99%, biomethane purity is extremely high and gas quality fluctuations have less impact on performance. The tradeoff is the need for thermal energy to regenerate the solvent. Cryogenic upgrading attracting attention when the target is Bio-LNG.

Road freight and maritime transport increasingly require liquefied fuel.

Cryogenic upgrading can produce liquefied biomethane directly, recover food-grade biogenic CO_2 and minimize methane losses. This makes cryogenic systems particularly attractive for large manure, landfill, and waste-to-fuel projects serving heavy-duty transport.

The scientific literature increasingly identifies three R&D trends: integration with green hydrogen, carbon utilization instead of carbon removal and the development of biomethane biorefineries. Instead of removing the CO_2, green hydrogen can convert it into additional methane. This can increase methane yields by roughly 50–70%, depending on the original biogas composition.

For carbon utilization instead of carbon removal, rather than venting or selling CO_2, future plants may use biogenic CO_2 for renewable methanol, e-fuels, green chemicals, algae production and in greenhouse applications. Future biorefineries facilities will likely produce simultaneously biomethane, biogenic CO_2, digestate fertilizers, renewable hydrogen, renewable ammonia, renewable methanol.
This is increasingly viewed as the long-term direction for maximizing both economic value and greenhouse gas mitigation.

Biomethane use

Biomethane is mostly CH4, that blends nicely with natural gas, widely used globally as a source of energy and in the chemical industry (35). Biomethane is a ready-to-use biofuel. It can be fed into vehicles (buses, trucks, farming machines, cars). Purified biomethane can be uploaded into natural gas pipelines and replace natural gas in its innumerous uses. Biogas or biomethane may also generate electricity. CH4 is a versatile molecule, which may be used as building blocks in the chemical industry. (33,35,36,50–52).

BIOMETHANE / METHANE PLATFORM	MAIN CONVERSION ROUTE	FOSSIL-BASED PRODUCT REPLACED	TECHNOLOGY READINESS	KEY INSIGHT / RELEVANCE
Biomethane → Steam Methane Reforming (SMR) → H_2	Steam reforming of CH_4	Fossil hydrogen (“grey hydrogen”) from natural gas	Commercial / High	Most direct industrial substitution route. Existing SMR infrastructure can operate with biomethane with minimal adaptation. (53)
Biomethane → H_2 → Haber–Bosch	Renewable ammonia and urea	Fossil ammonia and nitrogen fertilizers	Commercial / High	One of the strongest industrial decarbonization opportunities for Brazil, especially integrated with sugarcane and ethanol industries. (3)
Biogas/Biomethane → Syngas (SMR, ATR, POX) → Methanol	Syngas production followed by methanol synthesis	Fossil methanol	Medium–High	Biomethane can act as renewable carbon feedstock for methanol production. Particularly attractive when coupled with captured biogenic CO_2. (54)
Biogas + CO_2 → Dry Reforming → Syngas	Dry reforming of methane with CO_2	Fossil syngas for fuels and chemicals	Medium	Enables simultaneous utilization of CH_4 and biogenic CO_2 from upgrading streams. Produces syngas suitable for methanol, DME, and Fischer–Tropsch fuels. (5)

BIOMETHANE / METHANE PLATFORM	MAIN CONVERSION ROUTE	FOSSIL-BASED PRODUCT REPLACED	TECHNOLOGY READINESS	KEY INSIGHT / RELEVANCE
Biomethane + Green H_2 → Methanation	Catalytic or biological methanation	Fossil natural gas	Medium	Upgrades CO_2 streams into additional methane ("e-methane" or synthetic methane), improving carbon utilization efficiency. (54)
Biomethane / Syngas → Fischer–Tropsch Fuels	FT synthesis	Diesel, jet fuel, marine fuels	Medium	Potential route for renewable hydrocarbons and SAF production from renewable methane platforms. (54)
Biomethane / Syngas → Dimethyl Ether (DME)	Syngas conversion	LPG/diesel substitute	Medium	DME is a promising low-emission fuel for heavy-duty and marine sectors. (56)
Biomethane → Industrial Heat and Steam	Direct combustion	Fossil natural gas in industry	Commercial / High	Immediate decarbonization option for food, beverage, pulp, and chemical industries. (5)
Biogas Upgrading → Biogenic CO_2 Recovery	CO_2 purification and liquefaction	Fossil CO_2 used in industry	Commercial / Emerging	Captured CO_2 can be used in beverages, chemicals, methanol synthesis, Power-to-Gas, and greenhouses. (57)
Digestate from AD Systems	Nutrient recovery and fertilizer use	Synthetic fertilizers	Commercial / High	Digestate closes nutrient loops and is central to circular biorefinery concepts. (24)
Anaerobic Digestion Biorefineries	Integrated production of biomethane, CO_2, digestate, chemicals and energy	Multiple fossil-based products simultaneously	Emerging / Expanding	Integrated biorefineries maximize resource efficiency and improve economics through coproduct valorization. (58)
Industrial AD + Biomethane Integration	Food, beverage, slaughterhouse and distillery integration	Fossil energy and waste disposal systems	Commercial / Expanding	Strong opportunity for agro-industrial symbiosis and circular carbon systems. (56)

Types of Biodigesters

Biogas/biomethane is generated by anaerobic digestion in biodigesters of different types, sizes, and models. They have in common the creation of an anerobic environment in which organic material is decomposed. Anaerobic biodigestion undergoes several steps, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis, each carried out by different microorganisms (37). Therefore, depending on the type and amount of organic waste to be processed a biodigester is recommended. Small equipment may be used in farms and facilities that use animal manure, whereas large lagoons may be used employed in vinasse processing. Lagoon-type biodigesters have the disadvantage of poor mixing of the feedstock as well as poor control of the biodigestion reactions. Vertical biodigesters are preferred when the conditions of biodigestion must be best monitored. Brazil has many companies that provide equipment and services for biodigesters (8,59).

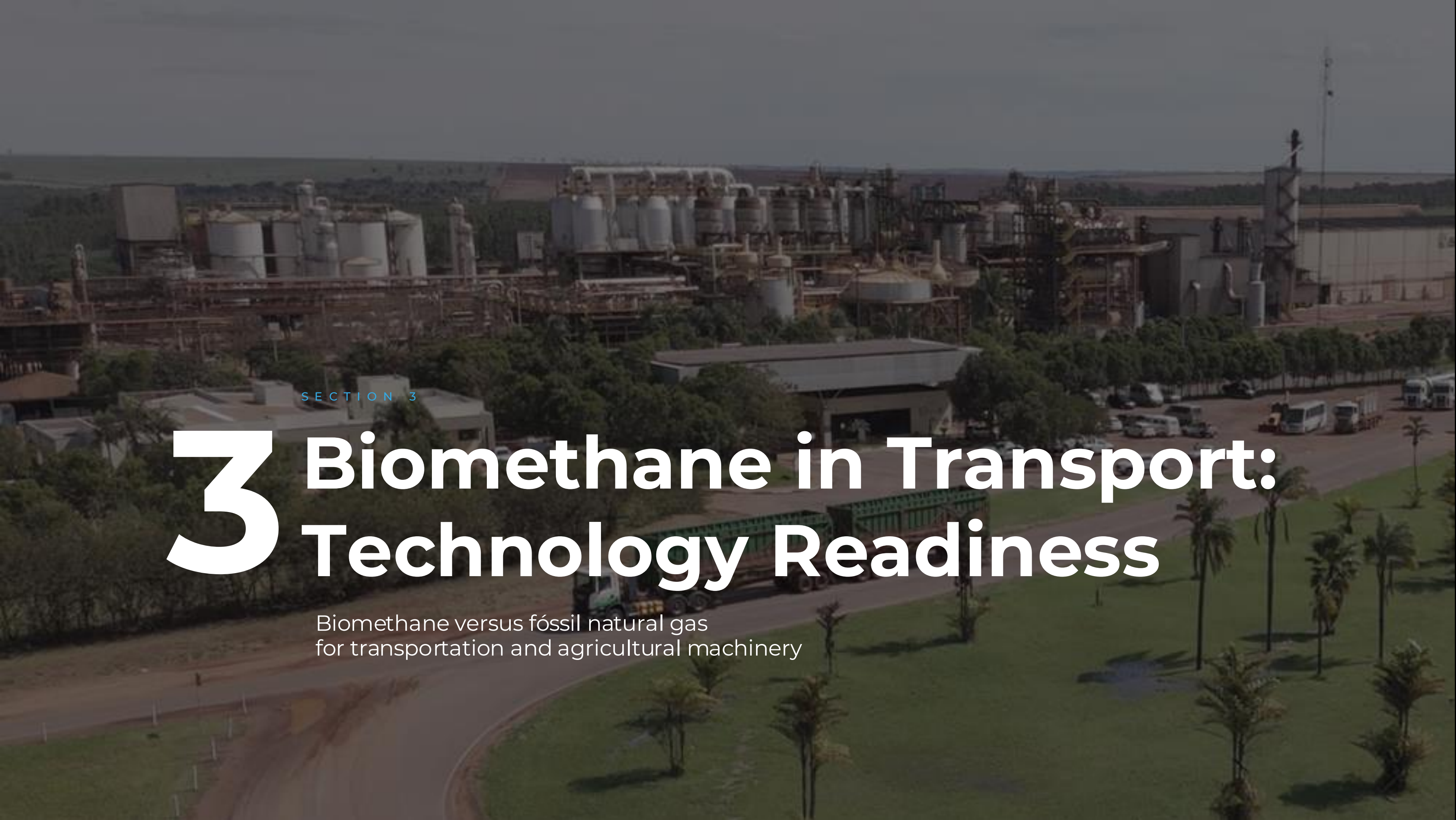
Upgrading

Anaerobic digestion combined with biogas upgrading is the dominant route to produce biomethane. The technology is mature and is used in many countries (60,61). Other routes include:

Gasification plus syngas methanation, the so-called syngas road), in which dry or semi-dry biowaste is gasified to syngas, followed by cleaning, methanation and upgrading (62). It offers high energy efficiency and carbon utilization, but its complexity and cost reduce its adoption (62).

Power-to-gas/biological methanation which requires the use of electrolytic H2 plus CO2 from biogas anaerobic digestion (63,64). The high cost of electrolytic H2 makes this route less competitive with the dominant biodigesters (63,65).

Sources Refs (1), (2), (28), (32), (91–94)



SECTION 3

3 Biomethane in Transport: Technology Readiness

Biomethane versus fóssil natural gas
for transportation and agricultural machinery

Potential use as a diesel substitute.

According to Righi et al., the transport sector is responsible for ~ 23% of global GHG emissions, and out of this fraction on-road (cars, heavy-freight trucks, light commercial vehicles, buses, and 2-wheelers) is the dominant source, corresponding to 77% of transport emissions (66).

During 2019 in the United States, heavy trucks consumed a quarter of the energy used in U.S. transportation, producing a similar share of the sector's greenhouse gas (GHG) emissions and accounting for roughly half of the current emissions of nitrogen oxides (NOx) and soot or particulate matter (PM) from highway vehicles (67).

The transport segment is among the ones presenting challenges in decarbonization due to the moving nature of fuel consumption and distributed GHG generation across the chain. Besides these facts, the cargo transportation sector faces a huge challenge of decarbonization using electricity and/or hydrogen due to energy storage and refueling/recharging limitations and availability (68).

In this sense, the use of biomethane is a fast track cheaper decarbonization option. Biomethane also is a very attractive alternative for replacing diesel in the agricultural sector. Assandri et al. also emphasize that half of CO2eqv generated in the agricultural segment is due to the utilization of fossil fuels in tractors and machinery.

In their study, based on mean annual available agricultural wastes over the last seven years (2015–2021) in the Piedmont region, the annual potential biomethane energy is 3.8 times higher than the energy requirements for the regional tractors' fleet (69).

Hannukainen & Åman show the potential of biomethane/biogas utilization in farming energy consumption, where some projects have demonstrated the ability of farms to cut direct energy costs by replacing all or part of machinery fossil fuel with their own produced RNG (Palopuro Agroecological Symbiosis case), with and additional side-effect of reducing demand for fossil fertilizers by utilization of digestate (70).

Kivekäs & Lajunen compared battery electric, fuel cell, hydrogen ICE, and biofuel tractors and concluded that the lowest CO2 eqv emissions were achieved by the biogas version, for which the biomethane was produced from wet manure, with WTW emissions of the biogas tractor were negative because of the high amount of emissions credit provided due to the prevention of anaerobic decomposition of the manure (71).

Drop-in

Biomethane, also called Renewable Natural Gas, RNG, Bio CNG when compressed, or Bio LNG when liquefied, is widely recognized as a "drop-in" renewable substitute for fossil natural gas in light- and heavy-duty transport because it can be used in existing infrastructure and engines without major technical modifications (72–75).

It can be produced from different sources, as food and household waste, agricultural residues, manure, sewage sludge, industrial organic waste, wastewater (76).

Usually produced by anaerobic digestion of such organic material, a biogas composed mainly of CH_4 and CO_2 is produced. Subsequently gas upgrading (e.g., membranes, water scrubbing, PSA) leads to the generation of biomethane (typically >95% CH_4), while fossil natural gas consists of methane mixed with heavier hydrocarbons.

Comparison of Key Specifications

The technical requirements for biomethane as a vehicle fuel in Europe are primarily defined by the European standard EN 16723-2, the primary European regulation for gas quality when used as automotive fuel. It covers natural gas (Group L and H), biomethane, and their blends, whether in compressed (CNG) or liquefied (LNG) form (75,77)..

It also ensures that a driver can refuel with 100% fossil CNG one day and 100% Bio-CNG the next without the engine control unit (ECU) needing a manual recalibration. This is achieved by keeping the Wobbe Index and Density within a range that the ECU can compensate for using its "Lambda" (Oxygen) sensor feedback.

This standard also adds to EN 16726 (which focus on grid injection) specific protections for automotive components. The main differences found between NG and biomethane are shown below:

FEATURE	BIOMETHANE (UPGRADED)	FOSSIL NATURAL GAS (CNG/LNG)
Methane CH_4	90% – 98%+ (75,78)	80% – 95% (typical pipeline variation)
Non-Methane Alkanes	Near zero (78,79)	3% – 15% (Ethane, Propane, Butane)
CO_2 Content	< 2% (after upgrading)	< 3% (industry standard)
Methane Number	High (~130-140) (78,79)	Lower (~70-90) (due to C_{2+} content)
Energy Density	Slightly lower volumetric density	Higher due to heavier hydrocarbons
Primary Risks	Siloxanes, Terpenes, Ammonia	Sulfur, Mercury, Helium

The presence of volatile organic compounds (VOC) in the biogas, especially from landfill or sewage sources, is a major concern. The siloxanes (volatile organosilicon compounds found in small but operationally important concentrations in landfill biogas), if not properly removed during upgrading to biomethane, decompose into silica microparticulates (SiO2) during combustion.

These form abrasive, glass-like deposits on cylinder heads, spark plugs, and oxygen sensors. This crystalline silica has similar physical and chemical properties to glass and may cause abrasion on engine surfaces and subject sensitive engine parts to elevated temperatures due to its thermal insulating properties. Furthermore, it acts as an electrical insulator, hindering spark plug function and resulting in serious damage and the formation of deposits on various engine components including spark plugs, pistons, cylinder heads and the exhaust after treatment systems. These deposits also collect in engine oil and can lead to the severe deactivation of downstream catalyst monoliths (77,80).

Recent studies indicate that biomethane can contain high concentrations of terpenes, depending on the feedstock (e.g., food waste) and the upgrading method. These compounds can potentially mask the odorants (like tetrahydrothiophene) added for safety, making leak detection more difficult if purification is insufficient (77).

The Methane Number serves as a measure of the fuel's resistance to "knocking" in spark-ignition engines. Because biomethane is nearly pure methane, it possesses a superior Methane Number compared to fossil natural gas, which contains heavier alkanes that lower this value. This high stability often allows biomethane to exceed the quality of fossil gas in terms of combustion characteristics (79).

In terms of energy content, as biomethane is a "leaner" gas (lacking heavier hydrocarbons ethane (C2H6), propane (C3H8), and butane (C4H10), its energy density is generally lower than that of "rich" fossil natural gas (81), as it can be observed in table below (82). A truck engine running on biomethane might require a slightly higher injection volume to achieve the same power output as it would with a rich fossil gas (23). In terms of volumetric energy density, a normal cubic meter of natural gas and biomethane roughly corresponds to a liter of pure diesel fuel.

FUEL TYPE	LHV MASS-BASED	LHV VOLUME-BASED	DENSITY	COMPOSITION DETAIL
Pure Methane CH_4	50.0 MJ/kg	35.8 MJ/Nm^3	0.716 kg/Nm^3	Theoretical baseline
Biomethane	47 – 49 MJ/kg	34 – 36 MJ/Nm^3	0.723 - 0.735 kg/Nm^3	~95-98% CH_4
Fossil natural gas	45 – 52 MJ/kg	37 – 41 MJ/Nm^3	0.788 - 0.822 kg/Nm^3	Contains C_{2+} content & alkanes
Regular diesel (without biodiesel)	42.8 – 43.2 MJ/kg	35.0 – 36.8 MJ/L	0.818 - 0.852 kg/L	HC blends

Standard Reference Grades

For truck testing and certification, the industry often uses reference gases defined by the EN 16723-2 standard (77):

- G20 (High Methane): 34.02 MJ/m3 (LHV)
- G25 (Low Methane/High Nitrogen): 29.30 MJ/m3 (LHV)
- Biomethane: Typically aligns with the G20 standard but with fewer heavy alkanes (83)

Technology availability

Passenger car vehicles, heavy-duty trucks, gensets are already available for biomethane utilization in Europe, Brazil, United States and China. Major heavy-duty vehicle manufacturers have CNG/LNG trucks available for commercialization today (84–89).

Agricultural machinery companies have already launched some models based on liquified gas and some prototypes using compressed gas (90), with same power and torque of their similar diesel versions (91–93).

In terms of engine technologies available for use of NG or biomethane, currently there are four alternatives for utilization of biomethane in heavy diesel vehicles:

- dual-fuel (diesel + gas);
- spark ignition lean burn (gas only);
- spark ignition stoichiometric (gas only);
- HPDI (high pressure direct injection (diesel + gas).

The most employed technologies today are the spark ignition stoichiometric and dual-fuel (89).

For the spark-ignition stoichiometric version, trucks employ a usual three-way catalyst as main aftertreatment system, for simultaneous reduction of NO and NO2 and oxidation of unburned hydrocarbons THC and carbon monoxide CO, with no need of a filter for particulate matter. Engine operates close to lambda=1 condition, where the catalyst presents its highest conversion efficiency for all 3 gases. One notable benefit of this technology in substitution of regular diesel combustion is the virtual absence of particular matter.

For the dual-fuel version, which uses a small "pilot" injection of diesel to ignite the methane-air mixture, engines typically employ a Methane Oxidation Catalyst (MOC) or a specialized Diesel Oxidation Catalyst (DOC), because special attention has to be paid to methane slip – a phenomena where some biomethane escapes from engine combustion chamber. Regular DOCs are not efficient in converting methane into CO2 and H2O. Regular selective catalyst reduction (SCR) strategies are used to reduce nitrogen oxides in these engines due to overall lean operation. And here, as there is diesel being combusted and generating particulate matter, a diesel particulate filter is necessary.

Benefits of utilization of natural gas and biomethane in transportation

In terms of fuel consumption and performance, a vehicle powered by fossil natural gas presents same behaviour when powered by biomethane (94), as the main composition of both fuels are very similar.

In Brazil, Resolution ANP #886 of 29 Sept 2022 establishes the specification and rules for approval & quality control of biomethane from landfills and sewage treatment plants intended for vehicular use and residential, industrial and commercial facilities (95) and Resolution ANP #906 of 18 Nov 2022 specifies biomethane from agrosilvopastoral and commercial organic products and waste, intended for vehicular use and residential and commercial installations (96), in a way that biomethane meeting these specifications can be injected into natural gas pipelines in the country.

In Europe, in order to be used for grid application or for transport, biomethane needs to meet quality specifications: the European standard EN 16723-1 for injection into the gas grid; EN 16723-2 listing the quality specifications for use in road transport (97). In several countries, LNG is already being used as an alternative to diesel fuel in long haul operations.

Modelling and tests indicate NG trucks emit from 10% to 20% less CO_2e than diesel; when fueled with biomethane the equivalent carbon emissions can be reduced 92%, with several studies indicating >70% reductions vs. diesel on a lifecycle basis (76,89,98).

In Europe, the REPowerEU Plan of 18 May 2022 remarks the clear need to scale-up biomethane by 2030. As a renewable and dispatchable energy source, increasing the production and use of biomethane also helps to address the climate crisis. The EU's biomethane production, either as biogas or its upgraded version, needs to reach 35 billion cubic meters (bcm) per year by 2030 and the estimated investment need for the period amounts to €37 billion. the CO2 standards (99). Regulation (EU) 2024/1610, Recital 17 & Art.15 for HDVs foresees and should implement as soon as possible the recognition of CO2 neutral fuels such as biomethane to decarbonize the HDV sector (100).

In terms of total cost of ownership for vehicles operating with biomethane, a technical report issued by a Brazilian consortium and coordinated by FIESP in 2025 about the biomethane in Sao Paulo state shows that, for heavy vehicles, TCO with biomethane can be in the range of -30 to + 25% compared to TCO for diesel fuel, depending on the spread of the biomethane costs along the regions considered (101).

Benefits of utilization of natural gas and biomethane in transportation

There are studies by Hoffelner et al (102) suggesting that LNG is the energy carrier that may offer low cost compared to diesel and electric versions, but still emitting more CO2 compared to electrified version. Another study by Rajalehto & Helo showed a comparable TCO between a long-haul truck operating with diesel and biomethane, even without tax incentives (103). Pääkkönen et al. mentioned that, in Finland, the fuel costs in 2019 were in the range of biomethane 81–190 €/MWh for biomethane and 152 €/MWh) for diesel, which helped to bring the TCO levels to comparable ones (104).

In general terms, biomethane presents WTW emissions significantly lower than diesel fuel and it can deliver very high lifecycle greenhouse gas (GHG) reductions compared with diesel or petrol. Madhusudhanan et al. reported a reduction from 91.87 to 16.87 gCO2 eqv/MJ , corresponding to a reduction of equivalent carbon emissions with biomethane long-haul trucks being more than 70% compared to diesel (76).

According to Han et al. report from Argonne National Laboratory, all biomethane pathways show significantly less fossil fuel consumption and GHG emissions than conventional fossil NG and gasoline. GHG emission reductions of 81–91% on a per-MJ basis are estimated for AD-based renewable CNG relative to petroleum gasoline, depending on reactor types. Similarly, GHG emission reductions for AD-based renewable LNG relative to petroleum diesel on a per-MJ basis are estimated to be 86–94% (105).

*Not considering the effects of oil prices in the international market due to Iran -Israel-USA conflicts

Fuel Transportation, storage and refueling stations

Biomethane can benefit from the availability of natural gas pipelines. Injecting biomethane into existing natural gas pipelines - often referred to as "grid injection" - is widely considered the most efficient way to scale up its use. Because biomethane is chemically identical to fossil natural gas, since it meets the pipeline gas quality standards, it can utilize existing infrastructure without risking "stranded assets" or requiring pipeline modifications (106). In the United States, the gas pipelines cover more than 4.8 million km and, in 2022, transported more de 800,000,000 cubic meters, from what 40% was employed for electric power generation, 32% for industrial utilization, 14% for residential usage, 10% for commercial and 4% for transportation (107). And Europe counts on more than 260,000 km of installed pipelines (106), with Italy only with a well spread gas infrastructure/grid of more than 32,000 km and numerous connections to other transnational grids (97).

Companies in different countries already accept biomethane for grid injection. Some examples of United States pipeline operators already accepting biomethane are shown in the table below (108).

COMPANY NAME AND WEBSITE	STATE(S) WHERE RNG IS INJECTED	FEEDSTOCK(S)[1]
Enterprise Pipeline	Texas	LF
Equitrans Midstream	Pennsylvania	LF
Four-S Oil Company	Texas	LF
Fremont Department of Utilities Gas Distribution	Nebraska	WW
General Gas Pipeline, LLC	Tennessee	LF
Great Lakes Gas Transmission Company	Michigan	LF

LF - Landfill Gas, **WW** - Wastewater/Water, **OW** - Organic Waste digester

COMPANY NAME AND WEBSITE	STATE(S) WHERE RNG IS INJECTED	FEEDSTOCK(S)[1]
Gulf South Pipeline	Louisiana, Texas	LF
Hawaii Gas Transmission and Distribution	Hawaii	WW
Houston Pipe Line Company	Texas	LF
Kinder Morgan	Arizona, Mississippi, Oklahoma, Texas	LF, WW
Memphis Light, Gas and Water (MLGW)	Tennessee	LF
Metropolitan Utilities District of Omaha	Nebraska	LF
Montana-Dakota Utilities Co.	Montana	LF
Mountaineer Gas Company	West Virginia	LF
National Fuel Gas	Pennsylvania	LF
National Gas & Oil Cooperative	Ohio	WW
National Grid	New York	LF, WW
Northern Indiana Public Service Company (NIPSCO)	Indiana	Ag
Northern Natural Gas	Kansas, Nebraska, Wisconsin	Ag, WW
NW Natural	Oregon	WW
Pacific Gas and Electric Company (PG&E)	California	Ag
Panhandle Eastern Pipe Line Company	Kansas	LF
Peoples Natural Gas	Pennsylvania	LF

LF - Landfill Gas, **WW** - Wastewater/Water, **OW** - Organic Waste digester

COMPANY NAME AND WEBSITE	STATE(S) WHERE RNG IS INJECTED	FEEDSTOCK(S)[1]
Philadelphia Gas Works	National	LF
Piedmont Natural Gas Company, Inc.	North Carolina	Ag
Puget Sound Energy	Washington	LF, WW
Southern California Gas Company (SoCalGas)	California	Ag, OW, WW
Southern Company Gas	Georgia	LF
Southern Company Gas (Atlanta Gas Light Company)	Georgia	LF
Southern Star Central Gas Pipeline	Kansas, Oklahoma	LF
Summit Utilities, Inc.	Maine	Ag
Texas Gas Transmission LLC	Kentucky	LF
UGI Utilities	Pennsylvania	LF
Utica Gas Services (subsidiary of Williams Gas Pipeline)	Ohio	LF
Vectren Energy Delivery	Ohio	LF
Vermont Gas	Iowa, Quebec, Vermont	Ag, LF, WW
Williams Gas Pipeline	Washington	LF
Wisconsin Public Service Corporation	Wisconsin	OW
Xcel Energy	Colorado	WW
XTO Energy	Oklahoma	LF

LF - Landfill Gas, **WW** - Wastewater/Water, **OW** - Organic Waste digester

The possibility of having the biomethane injected into the grid is a way to begin replacing the fossil fuel gradually, not only in the transportation sector but also in all other segments which consume gas as a fuel.

Biomethane can reach supply via existing grid infrastructure, as mentioned above, but it can also be produced and transported in compressed or liquid form as bio-CNG and bio-LNG respectively.

This occurs typically in regions where the gas grid is too far away (106). The “virtual pipeline” concept refers to a logistics system used to transport natural gas or biomethane (typically compressed or liquefied) to areas where a physical pipeline infrastructure is either non-existent, too expensive to build, or technically unfeasible. Instead of traditional underground steel pipes, the "pipeline" is formed by a fleet of vehicles—such as trucks, trains, or barges—that continuously move gas from a supply point to the end user (109). Bhatt et al. concluded that RNG transport by pipeline was found to have the lowest carbon intensity (CI) score over medium to long distances due to the high energy efficiency of the transmission network. Compressed natural gas (CNG) tube trailers had the lowest carbon intensity (3.2gCO2e/MJ) over shorter distances (up to 250 miles) due to minimal static emissions, but their limited payload capacity leads to higher delivery emissions (1.56gCO2e/MJ per 100miles) over distances above 250miles. As a result, liquid natural gas (LNG) trailer transport, despite having higher static emissions (10.2 gCO2e/MJ), becomes more favorable over longer distances (above 650 miles) due to its superior delivery efficiency. These findings suggest that while CNG transport is advantageous for short hauls, pipeline transmission remains the most efficient option, with LNG trailers only becoming competitive over long distances (over 900 miles) (73).

Today, as the biomethane sector is transitioning to a more industrialized model, the sources of competitive advantage are shifting. Scale, operational excellence, and integrated capabilities are becoming critical differentiators. In the transportation segment, the biomethane has been used mainly by fuel producers, like agriculture & sugar-energy and municipal waste treatment sectors: companies with direct access to organic residues (animal manure, agricultural waste, or vinasse) are the most frequent users, because logistics fleets use biomethane processed directly from wastes material and utilizes a closed-loop system where the trucks are fueled by the very waste they collected (110).

On-board gas reservoirs for heavy duty trucks

Natural gas or biomethane present a very low energy density compared to liquid fuel. Both fuels must be compressed or liquefied to achieve the volumetric energy density required for its use as a transport fuel. While the volumetric energy density of LNG is in the range of still approximately 40 % lower than the volumetric energy density of diesel, it is significantly higher than that of compressed natural gas (CNG), making LNG a suitable fuel for long-haul transportation (111,112).

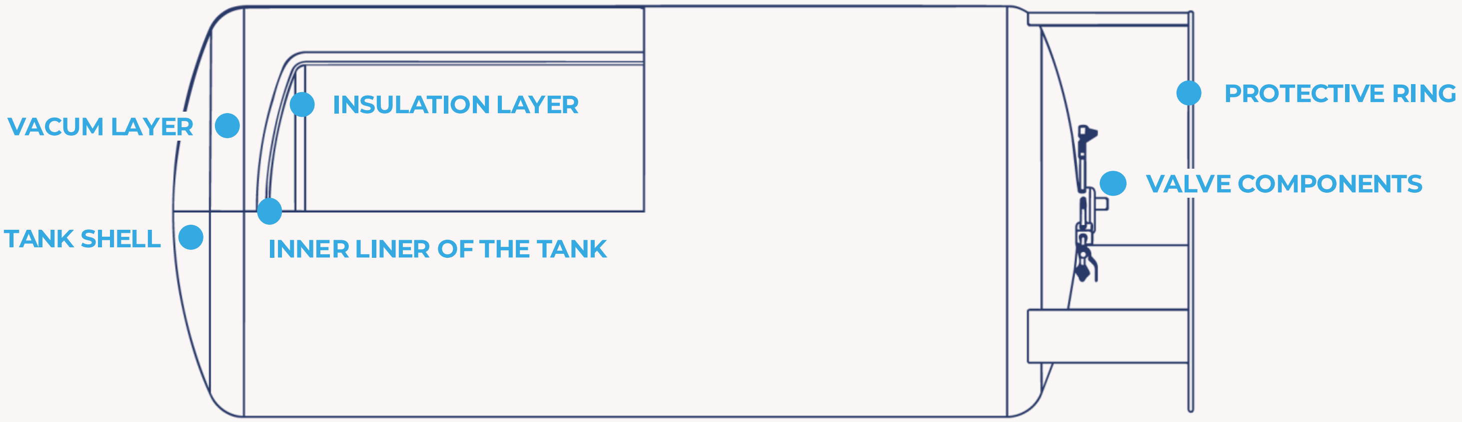
For compressed natural gas / biomethane truck versions, vehicles are usually equipped with high-pressure reservoirs. Cylinders for natural gas/biomethane, depending on the materials and configuration, are classified into 4 types, shown in the table:

TYPE 01	full metal, steel or aluminum	**~1,0kg/l**
TYPE 02	metal liner with hoop wrapped fiber reinforced plastic	**~0.75 kg/l**
TYPE 03	metal liner fully wrapped fiber reinforced plastic	**~0.4 kg/l**
TYPE 04	Plastic liner fully wrapped with fiber reinforced plastic	**~0,25-0,35 kg/l**

ISO 11439:2013 specifies minimum requirements for refillable gas cylinders intended only for the on-board storage of high pressure compressed natural gas as a fuel for automotive vehicles to which the cylinders are to be fixed (113). This standard is also applied in the Mercosur region.

CNG or compressed biomethane vehicle´s range can vary from 300 to 700 km, depending on the number of high-pressure cylinders present in the vehicle, which can reach a total of 16 cylinders with a total capacity of 406 Nm^3 at 220 bar maximum pressure as an example (114,115).

For liquified natural gas / biomethane truck versions, vehicles are usually equipped with cryogenic, vacuum-insulated fuel tanks, 2 x 540 L each – total 1080L, at pressures around 10 bar, where LNG is stored at temperatures of -125 °C to -160 °C (89,116). The Figure below shows schematically the structure of a cryogenic tank for truck application (112). ISO 12991:2012 standard specifies the requirements of a tank for LNG on-board storage (117).



A typical installation for a HDD truck comprises 2 cryogenic tanks. Due to higher energy density of fuel in liquid state, LNG truck´s range can be increased up to 1200 - 1700 km (84,115).

When LNG internal pressure reaches 16 bar, and no fuel consumption is present (engine off), the vaporized portion of LNG should be vented, which should be avoided as much as possible due to high warming potential of methane. According to Regulation 110 of the United Nations Economic Commission for Europe (118), vehicle LNG tanks must have a design hold time of at least 5 days after being filled using the highest temperature and pressure allowed by the tank's design. However, there are instances over the lifetime of an LNG truck where the 5-day holding time limit may be exceeded. These include vehicle manufacturing, transport from the factory to the dealer, second-stage manufacturing (i.e., bodybuilders), maintenance, unexpected disruptions in logistic operations, and the vehicle's end of life.

Main Components of a CNG / Biomethane Refueling Station

A standard Compressed Natural Gas (CNG) refueling station is a specialized, equipment-heavy facility engineered to handle high pressures (typically escalating from municipal pipeline pressures up to 200–250 bar). Because the system deals entirely with gaseous compression, the components are capital-intensive and subject to strict safety standards (119,120). EN/ISO 16923:2026 (121) “Natural gas fueling stations – CNG stations for fueling vehicles" standard covers the design, construction, operation, inspection and maintenance of stations fueling CNG vehicles, including equipment, safety and control devices. This European standard also applies to portions of a refueling station where natural gas is in a gaseous state and dispensing CNG derived from liquefied natural gas (L-CNG) according to EN ISO 16924. It also applies to biomethane, upgraded coal-bed methane (CBM) and gas supplies coming from LNG vaporization (on-site or off-site). The elements of the standard EN ISO 16923 ensuring the interoperability of the CNG refueling stations and the vehicles should apply to CNG refueling points.

A typical Fast-Fill station (designed to fill heavy-duty trucks or cars at a speed comparable to a diesel pump) consists of five core equipment blocks (122).

[Gas Pipeline] ➔ [1. Gas Dryer] ➔ [2. Compressor] ➔ [3. Priority Panel] ➔ [4. Storage Cascades] ➔ [5. Dispenser]

A. In Gas let & Dehydration (Dryer) System

- **Function:** Raw natural gas drawn from the utility pipeline contains moisture. The gas dryer uses desiccant beds to strip out water vapor before compression.

- **Why it's critical:** If water is not removed, it will freeze inside the truck's fuel lines and high-pressure valves when the gas undergoes a rapid pressure drop during dispensing (122).

B. The CNG Compressor Block

- **Function:** The "heart" of the station. It takes low-pressure or medium-pressure utility gas and compresses it through multiple mechanical stages up to 250 bar.

- **Why it's critical:** It dictates the refueling capacity (throughput) of the station. These are large electrical loads that usually require dedicated utility transformers (480V three-phase service) (120).

C. Priority Panel & Control Logic

- **Function:** An automated valve routing matrix that dynamically directs the compressed gas.

- **Why it's critical:** It determines whether the gas coming out of the compressor goes directly into an arriving vehicle, or into the high, medium, or low-pressure storage buffers to optimize filling efficiency (122).

D. High-Pressure Storage Cascades

- **Function:** A bank of thick-walled steel or composite cylinders designed to store gas at roughly 275 bar.

- **Why it's critical:** For fast-fill truck operations, the compressor alone cannot pump gas fast enough. The cascade acts as a battery, dumping pre-compressed gas into the vehicle quickly using differential pressure (120).

E. Dispensers and Metering Systems

- **Function:** The customer-facing fuel pump. They feature specialized heavy-duty breakaway nozzles, integrated mass-flow meters (Coriolis meters), and temperature compensation loops.

- **Why it's critical:** Gas expands as temperatures change; the dispenser calculates the true mass delivered rather than just volume (119).

Typical Installation and Capital Costs (CAPEX) of a CNG refueling station.

The financial scope shifts dramatically depending on whether the station is built for a private fleet that can fill slowly overnight (Time-Fill) or a high-throughput public transport hub (Fast-Fill) (120).

Breakdown by Component and Project Phase

COMPONENT / COST LINE	TYPICAL RANGE (USD)	KEY VARIABLE
Compressor block	$150k – $500k	Motor horsepower, flow rate, staging
Storage cascades	$50k – $150k	Number of cylinders, volume capacity
Gas dehydration (dryer)	$20k – $50k	Inlet moisture levels and flow rate
Dispensers (per unit)	$30k – $60k	Dual vs single hose, payment integration
Priority panel & automation	$15k – $40k	Control complexity, valve actuators
Civil works & electrical	$50k – $150k	Foundations, 480 V transformer tie-in
Engineering & permitting	$20k – $60k	Zoning, environmental clearances

Totals: private depot / time-fill $400k–800k (omits heavy cascades and priority panels — trucks fill directly over 6–8 h); public fast-fill $1.0–1.8M H_2-ready" future-proofing adds 10–20% and may qualify for green finance.

Overall Station Cost Summaries

Private Depot / Time-Fill Station: $400,000 – $800,000
(Saves money by omitting heavy storage cascades and priority panels; trucks fill directly from small compressors over 6–8 hours) (119,120).

Public/Commercial Fast-Fill Station: $1,000,000 – $1,800,000
(Requires the complete high-capacity system to match the user experience of a standard truck stop) (120).

“H2-Ready” Future-Proofing
Some investors are now requesting ”H2-Ready” stations that can be converted to handle hydrogen blending in the future. This adds 10-20% to initial equipment costs but may qualify for green financing.

Sources Ch.3 (commercial maturity)

Main Components of an LNG Refueling Station

While a CNG station relies on mechanical compressors to compress pipeline gas, an LNG station handles a cryogenic liquid stored at approximately -162°C. Because LNG is highly dense, these stations do not need heavy compressor blocks unless they double as L-CNG stations (facilities that pump liquid LNG and then vaporize it to fill conventional CNG vehicles). EN/ISO 16924:2026 – "Natural gas fuelling stations — Liquefied natural gas (LNG) stations for fuelling road vehicles" (123) specifies requirements for the design, construction, operation, maintenance and inspection of stations for fuelling liquefied natural gas (LNG) to vehicles, including equipment, safety and control devices

A standard commercial LNG/L-CNG fast-fill station consists of five core cryogenic modules (124):

[Cryogenic Tanker] ➔ [1. Insulated Storage Tank] ➔ [2. Cryogenic Pumps] ➔ [3. Saturation System] ➔ [4. Dispenser] (➔ Optional: [5. High-Pressure Vaporizer for L-CNG])

A. Cryogenic LNG Storage Tank

- Function: A massive, double-walled, vacuum-insulated stainless steel tank designed to keep the liquid at super-cooled temperatures (-162°C) without external refrigeration.
- Technical Context: These tanks use "boil-off gas" (BOG) management systems to capture any liquid that vaporizes due to ambient heat leakages, venting or recycling it back into the loop to avoid fuel loss.

B. Submerged Cryogenic Liquid Pumps

- Function: Pumps the liquid LNG directly out of the storage tank toward the fuel dispensers.
- Technical Context: Unlike standard fuel pumps, these units operate fully submerged inside a cryogenic sump or column to prevent thermal shock and vapor locks.

C. Saturation System (Conditioning Loop)

- Function: Warms the LNG slightly (up to roughly -130°C) before it enters the vehicle.
- Why it's critical: Heavy-duty truck engines (such as those from Scania or Volvo) require the fuel to be at a specific "saturation pressure" (usually 6 to 10 bar) to feed properly into the engine injection systems. The conditioning loop loops a portion of the cold liquid through an air-heated heat exchanger to build up vapor pressure inside the tank.

Main Components of an LNG Refueling Station

D. Cryogenic Dispensers and Nozzles

- Function: The dual-hose fuel pump (one hose for delivering liquid, one for balancing tank vapor pressure).
- Why it's critical: It requires specialized insulated breakaway nozzles. Operators must wear cryogenic gloves and face shields during use because skin contact with spilled LNG causes immediate frostbite.

E. High-Pressure Pump & Ambient Vaporizers (L-CNG Module Only)

- Function: An optional but highly common add-on. A cryogenic high-pressure pump forces liquid LNG through ambient air vaporizers, converting the liquid instantly into compressed gas at 200–250 bar (125).
- Why it's critical: This allows the station to sell both LNG (for long-haul trucks) and CNG (for delivery vans or passenger cars) from a single liquid storage source, improving station profitability.
- Typical Installation and Capital Costs (CAPEX)

Because of the specialized metallurgy, heavy insulation, and strict safety clearance zones required for cryogenic liquids, LNG stations have higher baseline capital expenditures than simple CNG setups.

Cost Breakdown by Component and Project Phase

Based on field data collected from European deployment networks like the LNG Blue Corridors project and North American logistics analyses, the costs break down as follows (124):

COMPONENT / COST LINE ITEM	TYPICAL COST RANGE (USD)	KEY VARIABLES
Cryogenic Storage Tank (approx. 40-80 m³)	$180,000 – $350,000	Tank capacity, vertical vs. horizontal orientation
Cryogenic Liquid Pumps & Sump	$70,000 – $140,000	Flow rate, single vs. redundant multi-pump setups
Conditioning / Saturation Skid	$40,000 – $80,000	Dynamic pressure regulation valves, size
Dispensers (per unit)	$45,000 – $75,000	Liquid-only vs. dual LNG/L-CNG configurations
Civil Works, Insulation & Piping	$150,000 – $300,000	Double-walled vacuum piping, boil-off gas handling
Electrical, Safety Loops & Automation	$110,000 – $160,000	Hazardous lighting, sub-stations, leak sensors
Engineering, Zoning & Permitting	$40,000 – $100,000	High cryogenic safety clearances, blast walls

Overall Station Cost Summaries

Pure LNG Station (Liquid only)
$550,000 – $800,000 (€500,000 – €600,000 equivalent) (125). These are tailored specifically for dedicated fleet depots operating long-haul heavy trucks (124).

Combined LNG + L-CNG Station
$1,000,000 – $1,500,000 (€850,000 – €1,250,000 equivalent), occasionally peaking up to $2,000,000 depending on the scale of the high-pressure vaporization loops (124).

Despite the higher CAPEX, this layout provides a faster return on investment because it captures both the local compressed and liquid natural gas markets simultaneously and can also use the boil-off gas from LNG storage and compress it into CNG reservoirs, reducing the fugitive methane parcels.

Total Cost of Ownership (TCO) in Heavy-Duty Transport

Heavy-duty transport remains one of the most promising applications for biomethane. To evaluate its economic feasibility, the most used parameter is the Total Cost of Ownership (TCO), a financial estimate designed to uncover the direct and indirect costs of a product or asset over its entire lifespan. It goes beyond the initial purchase price to include maintenance, operation, training, and disposal.

Biomethane can be used as Bio-CNG or Bio-LNG in existing natural-gas vehicle technologies, providing substantial greenhouse-gas reductions while utilising established infrastructure.

ILLUSTRATIVE BRAZILIAN FREIGHT STUDIES INDICATE:

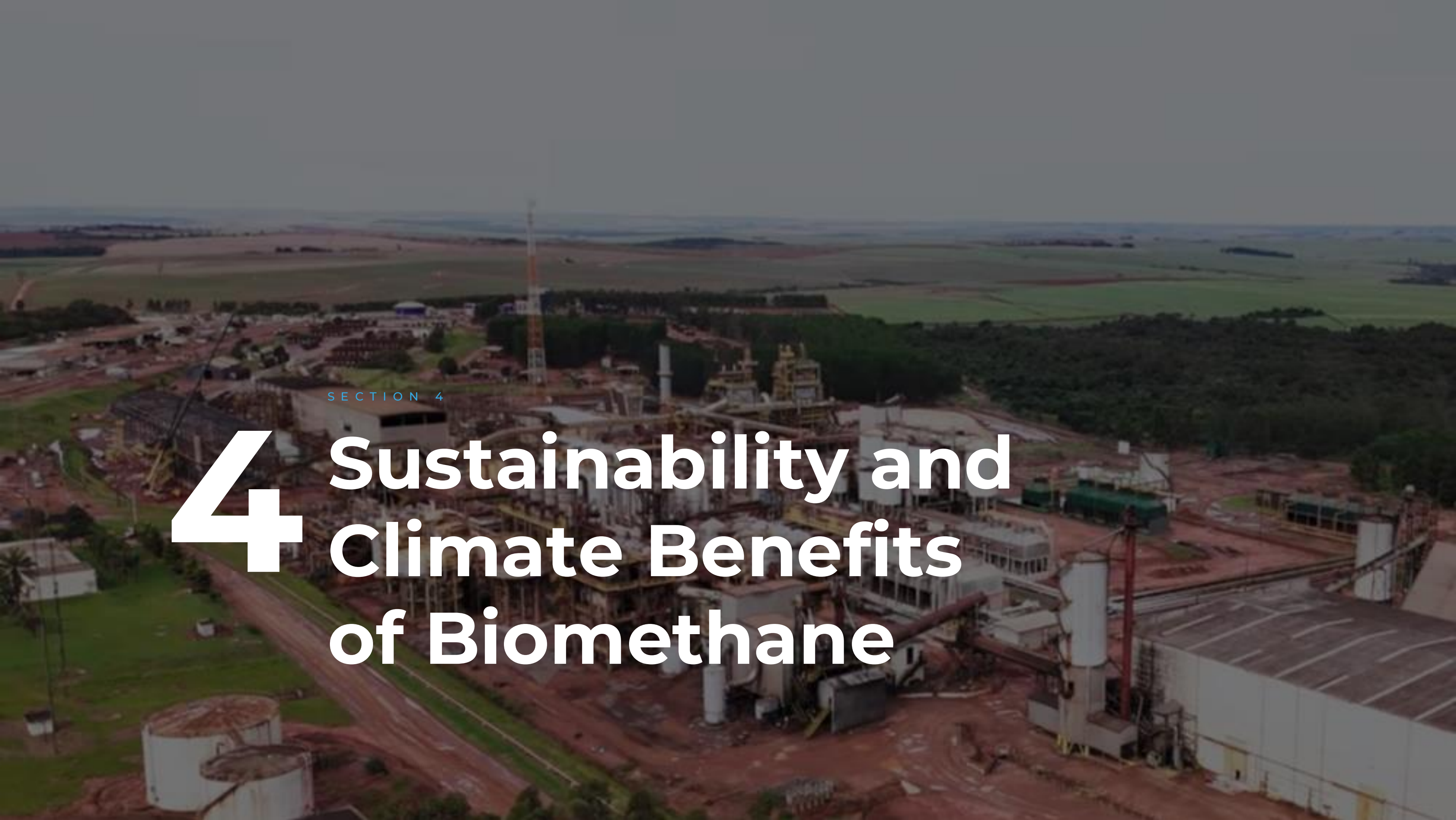
FUEL	TCO (US$/km)
LNG	1.59
CNG/Biomethane	1.73
Diesel	1.87

Additional considerations

All OEMs must comply with emission limits when new vehicles are produced and sold. In Europe, EURO 6 for light-duty vehicles and EURO VI for heavy-duty vehicles determine the limits of CO, NOx, THC, PM, PN among other restrictions today (126). In Brazil, the Air Pollution Control Program by Motor Vehicles - PROCONVE – also determines the emission limits, and for heavy duty vehicles its current phase P8 is somehow similar to EURO VI.

However, only some countries / regions also specify how the retrofitted vehicles should comply with emission limits. For instance, there are specific regulations for retrofitting trucks from diesel to CNG/LNG in Europe - UN ECE Regulation n° 115, imposing that the retrofitted vehicle shall comply with the limit values according to the type-approval of the original vehicle(s) including the deterioration factors applied during the type-approval of the original vehicle (118). In Brazil, retrofitted vehicles are not subjected to emission tests, but only need to show compatibility/conformity to high pressure storage systems (127,128).

Mainly due to the potential issue of methane slip in converted engines, it is mandatory that specific legislation should be put in place for retrofitting activities.



SECTION 4

4 Sustainability and Climate Benefits of Biomethane

Key determinants of sustainability

Well-to-wheel (WTW) climate performance varies sharply by feedstock, counterfactual waste management, methane leakage, electricity used for upgrading/liquefaction, and whether the LCA credits digestate substitution and avoided methane emissions from manure or waste.

Factor: Feedstock (waste/manure vs crops)
Effect on GHG & Sustainability: Waste & manure generally give much larger GHG savings, sometimes net-negative; crop-based can be weaker or even problematic (2,10,129)

Factor: Methane leakage (AD, upgrading, fueling)
Effect on GHG & Sustainability: If total leakage exceeds ~3–6%, biomethane can lose its advantage and may be worse than diesel on a well-to-tank basis (12,129–131)

Factor: System boundaries & co-products
Effect on GHG & sustainability: Crediting avoided methane from waste and mineral fertilizer substitution greatly improves results (2,10,129,132)

Factor: Electricity mix for upgrading/liquefaction
Effect on GHG & Sustainability: Low-carbon power is critical; carbon-intensive grids shrink or negate GHG benefits ((2,14,129,133)

Lifecycle GHG emissions reduction

01. There is a solid base showing that diverting **vinasse** into biogas through anaerobic digestion pathways can improve the environmental profile of sugarcane biorefineries and displace fossil energy. Biomethane from wastes and residues can deliver very large WTW GHG reductions, and in some cases net-negative emissions; **crop-based** biomethane is much less robust (134–137).

02. **Manure/slurry** anaerobic digestionsis the best-performing pathway in the literature.

A major JEC/European Commission pathway cited in the IEA Bioenergy transport report gives about −67 g CO2e/MJ WTW for biomethane from manure when avoided methane from conventional manure storage is credited. The same IEA report also notes that biomethane from a manure + food waste mix was calculated at 0.6 g CO2e/MJ WTW under system expansion. Some authors give a much less favorable central case of ~30 g CO2e/MJ for manure biomethane but their study (range -44 to +72 g CO2e/MJ) is considering high upstream methane leakage which could erode performance (138). Manure pathways are extremely sensitive to the assumed baseline for manure storage and fugitive CH4.

03. Biomethane derived from **waste and municipal biowaste** (OFMSW) shows consistently strong emissions reduction.

For heavy-duty transport, Gustafsson and Svensson found that liquefied biomethane (LBM) from food waste can cut climate impact by 50–75% relative to diesel, depending on electricity mix and assumptions. They also report that if digestate replaces mineral fertilizer, the climate impact can drop below zero. IRENA's broader technology brief is consistent with this direction, reporting 60–80% GHG reductions for biogas/biomethane vehicle fuel versus fossil fuels, with better outcomes for wastes and residues than for energy crops. A 68–98% lower impact for MSW collection/transport is observed when trucks use biomethane instead of diesel (139) . Garbage trucks on compressed biomethane show 55–75% lower GHG vs compressed natural gas (140). In specific cases ~70–85% CO_2 reductions vs diesel in bus/urban mobility trials were observed (141, 142).

Lifecycle GHG emissions reduction

04. Sewage sludge/wastewater sludge show favorable, but methodology-sensitive cuts.

The ICCT's EU white paper gives a central case of 69 g CO2e/MJ for wastewater sludge biomethane, but explicitly notes that JEC estimates for this pathway are higher because JEC does not apply the same avoided-emissions logic used in the GREET-based ICCT model for that pathway. JEC's comparator cited in the ICCT paper is 20 g CO2e/MJ. So sludge-based biomethane is still often favorable, but one must specify the methodology.

05. Landfill gas is considered to contribute good, but usually not as strong as manure, reductions. The ICCT central case for landfill-gas-derived biomethane is -30 g CO2e/MJ. The same study says landfill gas can deliver significant carbon reductions relative to fossil fuel comparators, but it also notes that much landfill gas is already committed to heat/power in Europe, which limits incremental transport deployment.

06. Extensive scientific literature address the climate impact of biomethane/biogas-based methane as a vehicle fuel (compressed or liquefied) in road transport, especially heavy-duty.

These papers together provide the main scientific evidence base for biomethane use in land transport, especially heavy duty trucks and buses, including environmental performance (GHG, some PM/NOx related categories), techno economic feasibility, infrastructure, and engine level pollutant behaviour.

FOCUS	MAIN CONTRIBUTION (TRANSPORT & EMISSIONS)	CITATIONS
LBM vs LNG vs diesel in heavy trucks	Well-to-wheel LCA of liquefied biomethane (LBM), LNG and diesel for HDVs; LBM from manure or food waste cuts climate impact 45–75% vs diesel; previous work cited shows biomethane trucks among the lowest-impact bus fuels and LBM superior in most impact categories vs diesel	(2)
Bio-methane via gasification in HD engines (EU)	WtW comparison of bio-CNG/bio-LNG from biomass gasification vs CNG, LNG, diesel in HD engines; 60–67% GHG reduction vs diesel (spark-ignition), 43–47% (dual-fuel), 64% (HPDI); compatible with existing CNG/LNG supply chains	(9)
Biomethane potential in HDV fleet (Finland)	Scenario analysis: up to ~50% of Finnish heavy-duty road transport could be biomethane-fuelled by 2030; ~50% CO_2 reduction vs diesel; discusses dual-fuel and spark-ignition gas trucks and infrastructure needs	(1)
Net-negative HDV emissions via biomethane upcycling	Regional assessment for South-East England: liquid biomethane trucks give ~75% lifecycle GHG reduction vs diesel; when avoided methane emissions are credited, net-negative CO_2e (up to 246% reduction vs diesel) becomes possible	(10)
Biomethane for freight via catalytic methanation	LCA of biomethane production (upgrading vs catalytic methanation) for truck fuel from pig manure; use-phase assumed emission-neutral → total freight emissions 0.03–0.07 kg CO_2-eq/t·km vs 0.17–0.19 for diesel	(14)
Environmental & economic assessment: biomethane injection and HGVs	Consequential LCA of biomethane plants serving natural-gas HGVs and residential heating; biomethane in HGVs significantly reduces global warming, fine PM formation and acidification vs diesel; stresses methane-leakage thresholds and grid constraints	(12)
Environmental impact of biomethane end-uses	LCA comparing biomethane in heavy-duty vehicles, light-duty vehicles and cooking; replacing diesel in HDVs is beneficial in all impact categories (acidification, eutrophication, photochemical oxidation, climate change); combustion dominates impacts	(11)

FOCUS	MAIN CONTRIBUTION (TRANSPORT & EMISSIONS)	CITATIONS
Biogas-based vehicle fuels overview (CBG & LBG)	Review of compressed biomethane (CBG) and liquefied biomethane (LBG) as vehicle fuels; concludes they are the only biogas-derived fuels commercially used in transport, with strongest short-term potential, including for heavy freight	(143)
LBM corridor in São Paulo freight sector	Spatial-economic design of a liquefied biomethane heavy-duty freight corridor using sugarcane vinasse and MSW; LBM found cost-competitive vs diesel, able to replace up to ~50% of regional diesel use, with associated GHG reductions	(8)
Local ecosystem HD truck analysis (UK)	Shows conversion of HD trucks from diesel to biomethane enables rapid GHG reduction with modest conversion costs, complementing battery-electric trucks depending on grid conditions	(10)
Dual-fuel CI engine with biomethane	Experimental CI engine tests with dual fuels: diesel–methane and HVO–“biogas/biomethane” (60% CH_4/40% CO_2 blend); dual fuels cut NOx by 67–82% and smoke by 23–39%, at the cost of higher CO/HC and lower efficiency; illustrates combustion/NOx–PM trade-offs	(13)

Lifecycle GHG emissions reduction

07. On a well-to-wheel basis, biomethane from wastes and residues—especially manure, food waste, sewage sludge and landfill gas—can reduce transport GHG emissions dramatically relative to diesel and natural gas, and in some manure-based systems can even deliver net-negative emissions when avoided methane emissions and nutrient recycling are properly credited. Biomethane produced from **agricultural residues/catch crops** is described as a strong reducer of emissions. The IEA Bioenergy Task 37 report (18) concludes that biomethane from manure, residues, waste and catch crops has low GHG emissions compared with other renewable fuels, and specifically notes that cover/intermediary crops can exceed 100% GHG reduction relative to fossil fuels when soil carbon gains are counted. On the other side ICCT (138) reported **that silage maize** biomethane can be worse for the climate than fossil fuels once land-use change is included, and Noussan et al. likewise show a strong reduction in benefits when crop-related credits and penalties are applied in Italy (3).

08. For heavy-duty road transport specifically, two current papers are especially useful. Gustafsson and Svensson (2) show that replacing diesel with LBM can materially reduce climate impact in truck applications, with the result strongly influenced by feedstock and electricity mix.

Noussan et al. conclude that, depending on feedstock mix and application, 1 bcm of biomethane can save 2.33–4.37 MtCO2e, and their truck-specific scenario work shows the highest per-unit savings generally in trucks and shipping, not light-duty cars.

09. Manure biomethane: contributes around −67 g CO2e/MJ WTW in JEC-style cases with avoided manure-storage methane credited; -30 g CO2e/MJ in the ICCT central case without such favorable assumptions. Wastewater sludge biomethane: about −69 to 20 g CO2e/MJ, depending mainly on methodology and crediting approach. Landfill gas biomethane: about -30 g CO2e/MJ in the ICCT central case. Food-waste biomethane / LBM for trucks: 50–75% lower climate impact than diesel; potentially below zero if digestate fertilizer substitution is credited. General waste/residue pathways: typically 60–80% lower GHG emissions than fossil transport fuels in broad technology assessments. Crop-based maize/silage pathways: can be much worse than residue pathways and may even be worse than fossil fuels if land-use change is included.

Air quality improvements (NOx and particulate reduction)

01. Biomethane often reduces **particulate matter** (Keogh et al., 2024; Ferreira et al., 2019; De Almeida Roque et al., 2025; Gustafsson & Svensson, 2020; Bidart et al., 2022).Trade-offs: some LCAs report higher eutrophication and photochemical oxidant formation compared with diesel or CNG, depending on plant design and emissions control (11,12,14,144).

02. In India, the government has encouraged adoption of CNG as a transport fuel in the country, to improve air quality. India has one of the world's largest markets for CNG in transport, with around 7.7 million CNG-fuelled vehicles on the road. In 2023, 7.6 bcme of CNG was consumed in road transport, a near 40% increase from 2021 (IEA, 2025c).

03. A life cycle and dispersion modelling study of a biogas plant compared two options: (1) on-site biogas combustion in a CHP unit and (2) upgrading to biomethane for grid injection or transport fuel. Local NOx and PM impacts from biogas combustion were non-negligible; adopting biomethane instead of local biogas combustion could partly or totally avoid these NOx and PM plumes, while delivering similar CO_2-equivalent reductions if methane slip is controlled (145).

04. A short review of biogas environmental impacts concludes that biomethane used as a gasoil substitute is expected to improve urban air quality, because emission factors for PM, VOCs and PAHs from methane are up to 10-fold lower than from liquid fossil fuels (146). This review also notes that upgrading to biomethane generally improves air quality, but stresses that methane slip can erode climate benefits (146).

05. A broader review of biogas/biomethane similarly states that biomethane use as an alternative to gasoil improves local air quality with respect to NOx and PM, and that biogas upgrading for vehicle fuel yields optimal benefits in photochemical oxidant formation and related impact categories (146).

06. At the end-use level, evidence from gas-fuelled vehicles supports lower local pollutants compared with conventional diesel: Real-world measurements on a biogas-fuelled city bus with a three-way catalyst note that gas buses are a cost-effective way to reduce local pollutants including NOx and PM compared with diesel buses, while biomethane provides ~80% well-to-wheels GHG savings relative to diesel (147). Even in an aging bus where the catalyst had partly deactivated, the study treats biomethane as environmentally preferable provided after-treatment is maintained (147).

Air quality improvements (NOx and particulate reduction)

07. A life cycle assessment of different biomethane end-uses (cooking, light- and heavy-duty transport) compared to LPG, gasoline and diesel found that replacing diesel with biomethane in heavy-duty vehicles was beneficial across all impact categories (acidification, eutrophication, photochemical oxidation, climate change). While these categories are not identical to tailpipe NOx and PM, the contribution analysis shows that fuel combustion dominates these impacts, implying lower NOx/PM-related burdens when diesel is displaced by biomethane (11).

08. A global assessment of biomethane replacing fossil natural gas focuses mainly on GHGs but confirms that displacing fossil gas with biomethane substantially reduces net system emissions, conditional on low methane leakage (148). When biomethane is used in existing gas infrastructure, local combustion-related PM is intrinsically low because methane combustion is essentially soot-free, in contrast to oil-based fuels (146).

09. After-treatment performance matters: Aging catalysts on gas vehicles can diminish NOx benefits if not monitored and maintained (147).

10. Methane slip is critical for climate, less for local AQ: High slip (e.g., 4%) can negate GHG benefits, while low slip (~0.05%) preserves strong climate advantages (145,146). Local NOx/PM gains remain, but overall sustainability is affected.

11. Across plant-scale, regional and review studies, there is consistent evidence that using biomethane to replace diesel/gasoil, locally combusted biogas, and residential solid biomass leads to substantial reductions in particulate emissions and generally lower NOx, provided modern low-NOx combustion technology and effective exhaust after-treatment are used and methane slip is minimized (11,145–147,149,150).

Noise reduction in urban transport

01. Urban traffic noise typically ranges 50–90 dB from combustion engines and is a major health concern (151,152). At various loads, higher methane share reduced combustion sound pressure levels, with maximum around 95 dB, lower than diesel-only operation at all loads (153).

02 An analysis of Swedish city buses modeled noise during acceleration for biogas, diesel, and electric buses on an urban route (154). Starting from 60 dBA for diesel at façades, replacing diesel by electric buses reduced noise-related societal costs by ~1.0 SEK/km, while biogas increased noise-related costs by ~1.1 SEK/km vs diesel (154).

03. Evidence specific to biomethane buses vs diesel buses in real urban noise is very limited. One engine study suggests biomethane substitution can lower combustion noise, but a bus system study indicates biogas buses may be slightly noisier than diesel during acceleration, while electric buses are clearly quieter. For substantial noise reduction in urban transport, current research points more strongly to electrification than to switching from diesel to biomethane alone.

Waste management and landfill diversion

01. Landfills are a major human-made source of methane, a powerful greenhouse gas. Research quantifies how much methane landfills emit and shows that capturing and using landfill gas can substantially cut climate impacts while producing energy.

02. Landfills are among the largest anthropogenic methane sources, contributing about 10–18% of global humanmade methane and a few percent of total greenhouse gases (155–158).

03. Methane's warming effect is ~28–32 times CO_2 over 100 years and ~84 times over 20 years, so cutting landfill methane strongly reduces near-term warming (156,157).

04. Studies in the US, Indonesia, India, Thailand, and Cambodia all report large landfill methane outputs, often >10^4– 10^5 Mg/year at individual sites, with many landfills lacking gas recovery systems (159–164).

05. Remote sensing in the US finds significant point-source emissions at most large landfills and highlights active "work faces" as dominant, often under-controlled, sources (155,165–167).

06. Anaerobic digestion of organic MSW diverts waste from landfills and produces biomethane plus digestate, improving MSW management and reducing methane leaks from dumps (168,169).

07. Global MSW landfilling is estimated at ~75 billion Nm^3 CH_4/year; <10% captured (158,164).

08. Early gas recovery and reduction of biodegradable waste are identified as the most effective landfill methane mitigation measures globally (157,167,170).

09. Flaring captured CH_4 can cut landfill GHG emissions by ≥55%. Using captured CH_4 for electricity can mitigate ≥83% of emissions, avoiding 52–63 kg CO_2-eq per ton of waste (162).

10. Life-cycle studies find that active gas collection plus power generation can reduce landfill GHG impacts by ~40–45% relative to unmanaged landfilling, by destroying methane and displacing fossil electricity (Lee et al., 2017; Scheutz et al., 2023). Up to 79% lower global warming potential of waste biomethane in transportation than using the same waste for electricity/heat only (168).

Nutrient recycling and biofertilizer production

01. Biomethane systems contribute to closing nutrient loops, reducing dependence on synthetic fertilizers, and improving soil health—especially when based on manure, agricultural residues, and organic waste streams (14,15).

02. Digestate from Anaerobic Digestion (AD) of manures, food waste, and other organics is rich in nitrogen (N), phosphorus (P), potassium (K), sulfur, micronutrients, and organic matter, and can be used directly as fertilizer or soil conditioner (171–174).

03. Reviews highlight digestate as a core product of biogas plants, not a waste, with demonstrated yield increases, higher N uptake, and P recovery when used on crops (172,174). Digestate-based products (liquid, solid, pellets, organomineral fertilizers) can act as slow-release fertilizers and help diversify farm income (175–177).

04. Several analyses published by the European Biogas Association (EBA) (178–180) following the Russia–Ukraine energy crisis highlighted the strategic role of anaerobic digestion (AD) and biomethane systems in strengthening agricultural resilience under conditions of fertilizer and energy market disruption. The reports showed that the sharp increase in natural gas prices translated directly into unprecedented increases in synthetic ammonia fertilizer prices across Europe, substantially increasing production costs for farmers.

Between 2021 and 2022, nitrogen fertilizer prices in Europe increased by more than 140–150% in some markets, while natural gas prices temporarily increased more than fivefold relative to pre-crisis averages. Under these conditions, digestate from AD systems gained strategic economic value as a substitute for mineral fertilizers, helping reduce dependence on imported fossil-based nitrogen fertilizers while recycling nutrients locally. EBA assessments indicated that digestate can replace substantial portions of mineral fertilizers, particularly nitrogen (N), phosphorus (P), and potassium (K), reducing fertilizer purchasing costs by hundreds of euros per hectare depending on crop type and fertilizer intensity. In several European agricultural systems, digestate substitution was estimated to reduce mineral fertilizer demand by 20–40%, while also lowering exposure to fertilizer market volatility. EBA also emphasized that farms operating AD and biomethane systems were less economically vulnerable during the energy crisis because they combined lower fertilizer expenditures with additional revenues from electricity, biomethane, heat, CO_2 utilization, and organic waste treatment services. The combined effect improved farm cash flow stability and increased resilience against input price shocks. As a result, biomethane systems contributed not only to renewable energy generation and methane mitigation, but also to rural economic resilience, energy security, circular nutrient management, and stabilization of agricultural production costs during the European energy crisis.

Water pollution reduction from improved waste management

01. Improved handling of organic wastes via anaerobic digestion can simultaneously generate biomethane and reduce pollution loads that would otherwise contaminate water bodies. The link is clearest where waste streams (manure, sewage sludge, food and aquaculture wastes) are diverted from uncontrolled discharge or landfills into controlled biogas systems.

02. Wastewater treatment removes pollutants and pathogens while producing biomethane and nutrient-rich manure, reducing pressure on natural water sources and supporting sustainable agriculture (181).

03. Sewage sludge from wastewater treatment plants is identified as a key feedstock for biomethane within a circular economy, reducing disposal needs and environmental impact (182).

04. A GIS-based regional model shows how directing sludge to biogas plants can enhance bioenergy production while minimizing environmental impact, including pollution from sludge disposal (182).

05. A farm-scale dairy biogas/composting facility with solid–liquid separation and AD reports not only biogas production but explicit "environmental quality improvement through odor control and water pollution reduction," fertilizer recovery, and water recycling (reusing treated overflow for barn cleaning) (183).

06. In aquaculture, anaerobic digestion of fish solids produces methane-rich biogas; the authors highlight mitigation of environmental impacts of waste streams via onsite treatment and valorization (184).

07. Reviews of biogas/biomethane emphasize AD of agricultural, animal, industrial, food wastes and sewage sludge as an efficient solution to waste treatment, embedded in circular-economy and green-economy frameworks (185–187).

08. Food-waste-to-biomethane pathways are presented as an "appreciable solution" to food waste management, avoiding uncontrolled disposal that causes air, water, and soil pollution (188).

09. Biohythane schemes (combined biohydrogen + biomethane from organic wastes, including OFMSW and sludge) are framed as both clean energy generation and improved waste management for challenging streams (189).

WASTE STREAM	VALORIZATION ROUTE	MAIN CO-BENEFITS BEYOND ENERGY	CITATIONS
Municipal / industrial wastewater	AD in WWTPs → biogas/biomethane	Clean water supply, lower pressure on natural sources	(181,182,186,187)
Sewage sludge	Co-digestion in biogas plants	Reduced sludge disposal, lower environmental impact	(182,187)
Food waste	AD to biomethane	Less uncontrolled dumping, reduced air/water/soil pollution	(169,188)
Livestock manure / dairy waste	Farm-scale AD + composting	Odor and water pollution reduction, fertilizer recovery	(183,186)
Aquaculture solids	AD to biomethane	Onsite treatment, reduced waste stream impacts	(184)

Socio-economic benefits

01. Valorizing digestate can enhance the economic viability and sustainability of rural biogas production, making the business model more robust. In Indonesia, by replacing synthetic fertilisers purchased from foreign agrochemical companies with digestate, farmers in the country have reduced their synthetic fertiliser consumption by more than 30% the year following the installation of the biodigesters. In addition, respondents reported enhanced plant resistance to drought or disease.

02. Biomethane/biogas expansion can generate measurable rural employment, income, and fiscal benefits. In Denmark (190), expanding biogas production using 10% of available manure resources would create 342 permanent jobs, generate €20.8 million/year in additional income, and €6.3 million/year in tax revenue, with a theoretical potential of up to 3,420 jobs at full resource utilization.

03. At the household level, biogas systems can generate direct monetary savings and broader economic benefits. In Nepal (191), a typical household biogas plant yields around NRs 9,000/year in direct savings, with total monetized benefits estimated to be 35–43% higher when indirect effects (e.g., time savings, health, fertilizer substitution) are included.

04. Public perception studies show that biomethane systems can translate into perceived economic value at the consumer level. In Rome (192,193), respondents indicated a willingness to pay an 11.2% premium for biomethane-derived energy services and expected 18.7% reductions in waste-related taxation, reflecting anticipated redistribution of local economic gains.

05. System-level optimization studies in Brazil (194) indicate that biomethane production from livestock waste can be more economically attractive than electricity generation, supporting decentralized rural infrastructure and improving regional economic performance, particularly when integrated into local value chains.

06. At the macro level, bioenergy expansion (including biomethane) is associated with substantial economic benefits. In Australia (195), biomethane projections indicate up to 26,200 new jobs and approximately AUD 10 billion/year in additional GDP, alongside improvements in fuel security.

07. Multiple studies find positive or potentially positive NPV/IRR for biomethane plants supplying transport, often with gate fees or moderate subsidies (196–202).

08. Benefits include fuel diversification and energy security, especially using MSW, manure and agriresidues that have few alternative uses (141,198,203–205).

09. Projects create jobs and local value along the waste–to–fuel chain (collection, digestion, upgrading, fuelling) (200,202,204).

Food security and biofuels

Evidence does not support a simple claim that biofuels "contribute" or "do not contribute" to food security. Crop-based biofuels may compete for land and water, raising prices and sometimes lowering food availability, especially where staple crops are diverted. However, where biofuels are linked to environmental improvements, agroforestry, co-product use as feed, and inclusive value chains, they can support food production and household food security. Outcomes depend strongly on land-use policy, and broader economic conditions. There is no correlation of a feedstock being edible, non-edible or both and food insecurity. When studies describe that biofuels have been associated to increased food prices they are most oftenly derived from modeling studies or the effects were observed in High Development index countries.

REFERENCE	TYPE OF STUDY	MAIN FINDINGS ON BIOFUELS AND FOOD SECURITY	COMPLETE REFERENCE
The effect of biofuel crops cultivation on food prices stability and food security-A Review	Literature review	Finds no correlation of feedstock being edible or non-edible and food security. Concludes that the relationship between biofuels and food security is context dependent rather than universally negative. First-generation biofuels may increase food prices through competition for land, water, and crops, but impacts vary according to policy design, productivity gains, and feedstock choice.	(206)
Biofuels versus food production: Does biofuels production increase food prices?	Economic analysis/review	Finds that biofuels contributed to food price increases during the 2007–2008 food crisis, but were not the sole or dominant factor. Oil prices, speculation, weather, and rising meat demand also played major roles.	(207)
The Effects of Biofuels on Food Security in Selected Countries	Cross-country econometric analysis	Reports heterogeneous effects across countries. In some countries biofuels negatively affected food affordability, while elsewhere increased agricultural investment and rural income offset these effects.	(208)

REFERENCE	TYPE OF STUDY	MAIN FINDINGS ON BIOFUELS AND FOOD SECURITY	COMPLETE REFERENCE
Biofuels and food security: evidence from Indonesia and Mexico	Empirical country case study	Finds no universal food-versus-fuel outcome. Biofuels generated rural employment and income benefits in some contexts while increasing food-price vulnerability in others.	(209)
The distribution of food security impacts of biofuels, a Ghana case study	Distributional case study	Shows that food-security impacts are unevenly distributed. Some rural households benefited through jobs and income, while others experienced reduced land access and higher food expenditures.	(210)
Challenges in Agricultural Land Allocation: Biofuel Versus Food Production in Brazil	Brazilian land-use analysis	Finds that Brazil differs from simplistic food-versus-fuel narratives because sugarcane expansion has largely occurred on pasturelands rather than directly replacing staple crops.	(211)
Local food security impacts of biofuel crop production in southern Africa	Multi-country field study	Finds mixed outcomes across Southern Africa. Benefits included employment and infrastructure, while negative impacts occurred where land rights were weak.	(212)
Biofuels and food security	Review article	Reviews global evidence and concludes that first-generation biofuels can create food-security risks, but impacts differ strongly among countries and policy frameworks.	(213)
Food Security in the Context of Liquid Biofuels Production	Review/policy analysis	Finds both risks and opportunities. Risks include land and commodity price pressure, while benefits include diversification of farm income and rural development.	(214)
The effects of biofuels on food security: A system dynamics approach for the Colombian case	System dynamics modelling	Shows that biofuel expansion can simultaneously stimulate rural development and increase food-price risks depending on productivity and land-use efficiency.	(215)

REFERENCE	TYPE OF STUDY	MAIN FINDINGS ON BIOFUELS AND FOOD SECURITY	COMPLETE REFERENCE
Biofuels and Their Co-Products as Livestock Feed: Global Economic and Environmental Implications	Review article	Shows that biofuel co-products such as DDGS substantially offset feed-market competition and improve land-use efficiency.	(216)
Bioenergy from agroforestry can lead to improved food security, climate change, soil quality, and rural development	Agroforestry review	Finds that agroforestry-based bioenergy systems can improve food security, diversify farm income, and enhance soil fertility and climate resilience.	(217)
Biofuels, environmental sustainability, and food security: A review of 51 countries	Cross-country review	Finds no universally consistent relationship between biofuel expansion and food insecurity across 51 countries. Outcomes depend on governance and agricultural productivity.	(218)
The impact of biofuels on food security	Econometric analysis	Finds that biofuel production may negatively affect food security in countries with weak agricultural systems, but may improve food access where rural income increases.	(219)
Population Growth, Biofuel Production and Food Security	Macro-level analysis	Argues that future food-security pressures are driven by the interaction of population growth, climate change, and resource limitations rather than biofuels alone.	(220)
Growing Biofuel Production in the Context of Food Security	Policy/economic analysis	Concludes that sustainable feedstocks, productivity improvements, and advanced biofuels are critical to minimizing risks to food systems while supporting decarbonization.	(221)

Other environmental dimensions

Lifecycle assessments indicate that biomethane can also reduce impacts related to acidification and eutrophication, particularly when integrated with improved nutrient management and digestate use (15,222,223).

Several system-level and review studies explicitly address local air pollutants when biogas is upgraded to biomethane and used in place of diesel/gasoil or other fossil fuels.

TRANSITION PATHWAY	NOX IMPACT	PM / POLLUTANTS IMPACT	EVIDENCE / KEY FINDINGS	REFS.
Biogas CHP → biomethane for grid/transport	Local NOx largely avoided; regional NOx lower if used in low-NOx engines	Local PM from stack avoided; vehicle use of biomethane essentially soot-free vs liquid fuels	Dispersion modelling shows CHP stack emissions; shifting to biomethane end-use avoids or significantly reduces NOx and PM exposure near plant locations	(145,146)
Diesel/gasoil → biomethane in heavy-duty vehicles	Lower NOx per unit service in modern gas engines with after-treatment	Strong reduction in PM, VOCs, and PAHs (up to ~10× lower than liquid fuels)	LCA and review studies show combustion stage dominates air quality impacts; gas buses and trucks identified as low-pollution alternatives	(11,146,147)
Residential biomass → biomethane (gas boilers / network)	Expected decrease in NO_2 compared with many biomass combustion systems	Large reduction in PM2.5 compared to wood and other solid biomass appliances	Health-impact and policy analyses identify biomethane substitution as a high-leverage strategy in regions dominated by residential biomass use	(146,149,150)

SECTION 5

5 Economic and System Value

Fossil substitution along methane mitigation, environmental protection, social benefits and economic resilience

Biomethane is frequently assessed through a narrow energy-market perspective, where its competitiveness is measured primarily against fossil natural gas, diesel, or electricity. While such comparisons remain relevant, they capture only a fraction of the value generated by biomethane systems. Unlike fossil fuels, biomethane is produced from organic residues and waste streams, generating multiple environmental, economic and social benefits simultaneously. Consequently, its contribution to sustainable development extends far beyond the energy content of the fuel itself.

This broader perspective is increasingly recognised by international organisations. According to the International Energy Agency (224), sustainable global biogas and biomethane production could approach one trillion cubic metres annually, equivalent to approximately one-quarter of current global natural-gas demand. Yet only a small fraction of this potential is currently exploited. Furthermore, the benefits of biomethane extend well beyond fuel substitution, encompassing methane mitigation, waste management, nutrient recycling, renewable carbon production and enhanced energy security.

Recent assessments by the International Energy Agency, the Food and Agriculture Organization of the United Nations (FAO), the Global Bioenergy Partnership (GBEP) and the European Biogas Association emphasise that successful biomethane projects frequently derive a substantial portion of their economic viability from co-products and environmental services. Waste treatment, digestate valorisation, renewable carbon dioxide, avoided greenhouse-gas emissions and compliance with environmental regulations often contribute significantly to project profitability.

From this perspective, biomethane should be viewed not merely as a renewable fuel, but as an integrated circular-bioeconomy platform capable of generating multiple value streams simultaneously.

Biomethane within the circular bioeconomy

The circular bioeconomy seeks to maximise resource efficiency by keeping biological materials, nutrients and carbon within productive cycles for as long as possible. Biomethane production is one of the clearest examples of this concept in practice.

Feedstocks suitable for biomethane production include livestock manure, municipal organic waste, sewage sludge, agricultural residues, food-processing waste and agro-industrial by-products. In conventional waste-management systems, many of these materials generate methane emissions through uncontrolled decomposition or impose significant disposal costs. Through anaerobic digestion and upgrading, however, they become valuable resources capable of producing renewable energy, biofertilisers and renewable carbon dioxide.

Unlike fossil fuels, which release geological carbon into the atmosphere, biomethane utilises contemporary biological carbon already circulating within ecosystems. As a result, biomethane contributes to carbon circularity while simultaneously reducing methane emissions from waste streams.

The circularity of biomethane systems extends beyond carbon. Nutrients originally contained in feedstocks remain largely available within the digestate, enabling their return to agricultural soils. Upgrading processes also generate concentrated streams of biogenic carbon dioxide suitable for industrial applications. These characteristics distinguish biomethane from many renewable-energy technologies and explain its growing prominence within circular-economy and climate policies. (224–226).

Organic Residues → Anaerobic Digestion → Biogas → Upgrading → Biomethane

CO-PRODUCTS AND SERVICES:

- DIGESTATE → BIOFERTILISER
- BIOGENIC CO_2 → INDUSTRIAL APPLICATIONS
- METHANE MITIGATION
- WASTE TREATMENT
- CARBON CREDITS

Multiple Value Streams

RENEWABLE FUEL PRODUCTION

The primary output of upgrading biogas is biomethane, a renewable gaseous fuel that can be fully compatible with natural-gas infrastructure and end-use technologies. Once upgraded, biomethane may be injected into gas grids, compressed as Bio-CNG for transport, liquefied as Bio-LNG for long-distance freight and maritime applications, or utilised in industrial processes.

Its compatibility with existing infrastructure significantly reduces transition costs and facilitates rapid market deployment.

WASTE MANAGEMENT SERVICES

One of the most important but often overlooked contributions of biomethane projects is the provision of waste-management services. The GBEP regional assessment concluded that waste treatment, sanitation improvements, reduced soil and water contamination, and methane-emission reductions are among the principal factors supporting the success of biogas and biomethane projects across Africa, Asia and Latin America (225). In many cases, avoided waste-disposal costs constitute a substantial component of project revenues.

DIGESTATE AND NUTRIENT CIRCULARITY

Digestate is increasingly recognised as a valuable agricultural product rather than a waste stream. Hurst and Allwood (2026) emphasise that anaerobic digestion should be viewed as a combined energy and nutrient-recovery system.

Digestate contains significant quantities of nitrogen, phosphorus, potassium and organic matter. It can partially replace synthetic fertilisers, improve soil quality and contribute to nutrient circularity. This characteristic is particularly important in countries dependent on fertiliser imports, where nutrient recovery can improve agricultural resilience and reduce exposure to international market volatility.

Multiple Value Streams

RENEWABLE CARBON DIOXIDE

Biogas upgrading removes carbon dioxide from raw biogas to increase methane concentration. Traditionally regarded as a waste stream, biogenic CO_2 is increasingly becoming a valuable commodity.

Potential applications include:

- food and beverage industries;
- greenhouse cultivation;
- renewable methanol production;
- sustainable aviation fuel pathways;
- synthetic fuels and RFNBOs.

As markets for renewable carbon products expand, biogenic CO_2 is expected to become an increasingly important revenue stream.

ENVIRONMENTAL ATTRIBUTES AND CARBON MARKETS

Biomethane projects may generate revenues through carbon credits, renewable-gas certificates, guarantees of origin and low-carbon fuel standards.

As carbon markets expand and sustainability certification becomes more widespread, these environmental attributes are expected to play an increasingly important role in project economics.

Monetisation of System Benefits

Conventional fuel-market comparisons frequently underestimate the economic value of biomethane because they focus exclusively on fuel revenues. In reality, biomethane projects generate multiple products and environmental services that contribute significantly to overall project economics.

Recent international studies indicate that these additional value streams may collectively represent between 20% and 60% of total project revenues in mature biomethane markets.

ILLUSTRATIVE MONETISATION OF BIOMETHANE SYSTEM BENEFITS

VALUE STREAM	TYPICAL VALUE (USD/GJ)	COMMENTS
Renewable fuel	8–18	Depends on gas and diesel prices
Waste treatment services	1–6	Landfill diversion and manure management
Digestate / Biofertilizer	0.5–4	Dependent on fertiliser markets
Carbon credits	1–8	Strongly dependent on carbon price
Renewable CO_2	0.5–5	Emerging market
Guarantees of Origin	0.5–3	Common in Europe
Energy-security value*	Difficult to monetise	Strategic value

*Energy-security benefits are generally captured through reduced imports and improved resilience rather than direct project revenues. Sources: Adapted from (17,224,226,227).

The table demonstrates that the value of non-fuel revenue streams can be substantial. In projects based on livestock manure, municipal waste or landfill gas, the combined value of waste treatment, nutrient recovery and environmental credits may rival or even exceed revenues from biomethane sales alone.

Climate and Environmental Value

The climate value of biomethane extends beyond fossil-fuel substitution. One of its most important contributions arises from methane capture. Methane possesses a significantly higher warming potential than carbon dioxide over short and medium time horizons. Consequently, capturing methane from organic waste streams generates substantial climate benefits.

Several lifecycle assessments have demonstrated that biomethane pathways can achieve greenhouse-gas reductions exceeding 80% relative to fossil natural gas, while some manure-based systems may achieve net-negative emissions when avoided methane releases are fully considered (224, 228, 229).

Additional environmental benefits include:

- reduced odours;
- improved sanitation;
- reduced groundwater contamination;
- lower landfill dependence;
- improved nutrient management.

MAIN ENVIRONMENTAL BENEFITS OF BIOMETHANE SYSTEMS

BENEFIT	MECHANISM
Climate mitigation	Methane capture and fossil-fuel substitution
Waste reduction	Diversion of organic residues
Water protection	Improved waste treatment
Air quality	Reduced uncontrolled decomposition
Nutrient recycling	Recovery of N, P and K
Resource efficiency	Circular utilisation of residues

Sources Adapted from (224 – 226)

Energy Security and Strategic Value

Recent geopolitical disruptions have highlighted the vulnerability of many countries to fluctuations in fossil-fuel markets. Energy security has therefore re-emerged as a central objective of energy policy.

Biomethane contributes to energy security through several mechanisms:

- utilization of domestic resources;
- reduced dependence on imported fuels;
- distributed production systems;
- compatibility with existing gas infrastructure;
- diversification of energy supply.

The IEA identifies energy security as one of the principal drivers behind the rapid expansion of biomethane policies introduced worldwide since 2020. For emerging economies, biomethane offers a unique opportunity to simultaneously strengthen energy sovereignty, improve waste management and support climate objectives.

Digitalisation and Optimisation of Biomethane Systems

Digital technologies are becoming increasingly important in the biomethane sector.

Recent GBEP dialogues between European and Chinese experts highlighted growing applications of:

- artificial intelligence;
- digital traceability systems;
- emissions monitoring;
- precision nutrient management;
- smart fertigation technologies.

Large-scale Chinese facilities are increasingly using AI to optimise anaerobic-digestion processes, logistics and service chains. Digital tools also improve digestate traceability and environmental reporting, supporting compliance with increasingly demanding sustainability requirements.

Income Composition of a Typical Biomethane Project

When waste-treatment revenues, carbon credits, digestate valorisation and renewable CO_2 sales are included, biomethane frequently becomes considerably more attractive than suggested by fuel-price comparisons alone. (17,224–226).

Finally, it is worth considering the potential opportunity costs of stationary biomethane projects. Indeed, using biogas directly, for example in drying systems or electricity generation, can represent more economically viable alternatives.

INCOME COMPOSITION OF A TYPICAL BIOMETHANE PROJECT

FUEL SALES (40–70%)	CARBON CREDITS (5–20%)
WASTE TREATMENT (10–20%)	RENEWABLE CO_2 (0–10%)
DIGESTATE / BIOFERTILISERS (5–15%)	CERTIFICATES / GUARANTEES OF ORIGIN (0–10%)

The economic value of biomethane extends far beyond its role as a renewable substitute for natural gas. Biomethane projects simultaneously provide renewable energy, waste-management services, nutrient recovery, renewable carbon dioxide, methane mitigation and energy-security benefits.

This multiplicity of value streams explains why biomethane is increasingly recognised as one of the most versatile technologies available for supporting the transition towards low-carbon energy systems. Rather than being viewed solely as a fuel, biomethane should be understood as an integrated circular-bioeconomy platform capable of generating economic, environmental and social value simultaneously.

As governments seek solutions aligned with the objectives of COP30, COP31 and broader sustainable-development agendas, biomethane stands out as a technology capable of connecting climate mitigation, circular-economy principles, agricultural sustainability and energy security within a single integrated framework.

SECTION 6

6 Brazil: a strategic opportunity

Biogas/Biomethane potential in Brazil

In Brazil, ABIOGAS congregate innumerous companies and institutions of biogas/biomethane (230,231). Having the right public policies, the biogas/biomethane production in Brazil may expand rapidly, both counting on local technology or by using the expertise of other countries. As wastes are the main feedstock for anaerobic digestion, the potential is enormous, in Brazil and worldwide, since it is estimated that each person generates approximately 1 kg of wastes per day. In addition to the urban centers, farming operations also produce organic waste, such as animal manures, crop residues, and other organic materials that can be converted into biogas. There are several texts examining the potential of biogas/biomethane in Brazil. The prospects are very encouraging (37,50–52,59,232–240). As a large producer of food, both vegetal and animal, the Brazilian agroindustrial sector generates plenty of organic residues that can be transformed into biogas/biomethane. The potential of biomethane in the State of São Paulo alone varies from 8.5 to 15.5 billion Nm3 per year, considering different sources of feedstock (36). These are huge figures, considering that each Nm3 of biomethane has energy equivalent to 1 L of diesel oil.

Sewage biomethane

Most of the sewage sludges generated in Brazilian cities go to landfills, a costly and environmentally unsound solution. The sewage sludge may have better uses, as for instance, to produce organic fertilizers by mixing it with city clippings through aerobic composting. An interesting example is that of Campinas. Campinas is a 1.2 million people city in the State of São Paulo, Brazil. In 2020 a co-project of the municipal government and Agronomic Institute of Campinas (Government of the State of São Paulo), started to produce approximately 80 t/day of compost made of the sewage sludge and rough vegetal materials collected in the city. The compost is an organic fertilizer approved to general use in agriculture by the Ministry of Agriculture. An investment of approximately 2 million US$ was needed to prepare the composting site, purchase machinery, and obtain the necessary operating licenses. The investments were paid for in less than one year since the city government used to spend US$ 2,000 monthly on transporting and landfill costs. This project can be adopted by many cities because it is economically feasible and environmentally sound. Now, the project is contemplating a new step: producing biogas by anaerobic biogestion of the sewage sludge. This will also avoid the foul odor of moving sewage sludge in urban areas. In addition to the valuable biofuel, the digestate will go back to aerobic composting and continue to generate organic fertilizers.

Author's personal information as member of IAC's directory.

Biogas/biomethane from crop/agricultural wastes and animal manures

Biogas/biomethane from crop/agricultural wastes and animal manures have the potential to generate useful bioenergy and organic fertilizers in farms all over Brazil. Small or medium-size biodigesters are available to be installed and operated locally; proper financing and public policies are needed to support this activity. Food industries of different sizes operating all over Brazil generate organic wastes the industry must deal with, resulting in a sometimes-costly liability. There are several schemes by which residues are passed on at low or even negative cost to other companies which use them for composting in aerobic processes or producing biogas by anaerobic biodigestion. This is an opportunity for creating many new businesses. Therefore, multiple opportunities arise from the food industry to promote a circular economy and produce fertilizer and/or bioenergy in a decentralized way. It creates also a market for biodigester and other equipment, and services, promoting new jobs. There are many companies in Brazil with the capability to provide equipment and services (236).

Biogas/Biomethane from landfills

Landfills all over Brazil are the destination of most of the urban and industrial wastes, including organic material from households, sewage sludges. Landfills take valuable space near urban centers, cause pollution both as greenhouse gases emission and leachates that contaminate groundwater and are costly to maintain.

Many landfills are actually Dumpsters with minimum control; approximately 40% of the urban solid wastes in Brazil are disposed of in inadequate ways (237). A Federal Legislation of 2010 establishes rules for the landfills and timelines for their deactivation (238). However, many small municipalities have had difficulties complying with the legislation because of the high investment needed and the implementation of the legislation has been postponed several times.

It is estimated that each person generates 384 kg of urban solid waste, amounting to 81.6 million tons per year in Brazil, although in the large urban areas in the Southeast Brazil the figures are even larger (237). Landfills emit large volumes of methane, given the high load of organic matter and anaerobic conditions that usually prevail. Fortunately, many landfills, especially those around large cities, have been passed on to the administration of private companies, which may invest in extracting CH_4.

Biogas generated by the anaerobic transformation of organic loads in landfills can then be collected. Usually, vertical and horizontal pipes are drilled into the landfill mass to draw gases (CH_4, CO_2, water vapor, and other gases) out of the pipes, directing them into a network of interconnected ducts.

The biogas undergoes processes of cooling, filtration, and the removal of moisture and impurities. The treated gas is combusted to destroy the methane, used as fuel in generator engines to produce electricity, or refined to produce biomethane (a natural gas substitute).

Currently, the State of São Paulo has 15 biogas plants operating or others are being implemented in landfills in the State of São Paulo (36). Recently, the largest biogas/biomethane unit was inaugurated in Paulínia, State of São Paulo, with a nominal capacity of 225 thousand Nm^3/day (239). Statistics and developments on all sorts of residues, including those or landfills, are collected and organized periodically by ABREMA, the Brazilian Association of Residues and Environment (241), an organization that congregate dozens of associated companies that offer equipment and services for biogas/biomethane operations and other destinations of societies' residues.

Biogas/biomethane from the ethanol sector

One interesting example of a promissing souce of biomethane is the sugarcane and ethanol industry. Currently, Brazil has 345 sugar mills in operation, of which almost 92% are in the Center-South region. The potential of biogas for the sugarcane sector is estimated at 41.4 billion m3 per year in the sugar-energy sector. However, less than 2% of this is achieved so far (37).

Feedstock for biogas/biomethane of the ethanol industry

Vinasse: in the 2024-25 season, approximately 680 million tons of sugarcane were processed, generating 94 million tons of sugar and 38 billion liters of ethanol (230). The vast volume of vinasse generated (~380 billion L) is recycled in the sugarcane fields. In addition to vinasse from first generation sugarcane, other types of vinasse exist nowadays, such as corn ethanol vinasse and second-generation vinasses (from lignocellulosic materials).

Vinasses are spread to sugarcane fields recycling mainly K, in which vinasses are rich, but other nutrients are also present in this fluid byproduct. Vinasses also supply organic matter which has a relevant role in improving soils. However, vinasse has a relatively low organic C concentration, varying from 23 to 52 kg organic matter per cubic meter of vinasse, depending on whether vinasse is generated from molasses, sugarcane juice, or mixed mash (231). Therefore, the methane yield of the biodigestion of pure vinasse is low. But there are other organic materials around the ethanol plants that can be used, such as filter cake, harvest residues and others.

Vinasses, combined or not with other residues of the ethanol industry (filter cake, harvest residues), can be used to produce biogas/biomethane. Several authors showed the potential and advantages of using vinasses to produce bioenergy (50–52). Biomethane from vinasse can generate a new source of income to the sugarcane industry in addition to carbon credits as CBIOs. There are 60 sugar mills in the State of São Paulo within 20 km or less of a natural gas pipeline, meaning that with relatively small investments, the biomethane of the ethanol industry can be blended with natural gas and be used by industry or biofuel in urban areas making use of an already existing infrastructure (50).

Biodigestion is a biological process in which microorganisms transform, under anaerobic conditions, organic materials into biogas. Therefore, depending on the material fed into the biodigester, the reacting medium pH, nutrient content, and other conditions must be adjusted (33).

Types of biodigester used for vinasse biogas

The least expensive biodigesters are large horizontal lagoons covered with an impermeable canopy to hold the gases produced during biodigestion. However, lagoons have disadvantages such as lack of mixing of vinasse and/or other organic feedstock, decreasing biogas yields. Anaerobic biodigestion is performed by microbial processes in a cascade of biochemical reactions which includes hydrolysis, acidogenesis, acetogenesis, and methanogenesis, each step carried out by different groups of microorganisms (37). Large horizontal lagoons hardly guarantee the optimum conditions for anaerobic biodigestion, implying in a biogas production with low efficiency.

Biogas/biomethane projects are already operational in Usina Cocal (Narandiba), Raízen in Guariba, and São Martinho, in Pradópolis, all in the State of São Paulo. Four other projects were in implementation stages, as of 2024 (36). Similar projects are being installed in sugar-ethanol companies in other states, as is the case of Adecoagro, in Mato Grosso do Sul (232).

More recent projects of biogas/biomethane are starting to make use of vertical biodigesters, equipped with capabilities to mix the feedstock, monitor pH and temperature and the biogas yields. This is the case with Usina Cocal, in Narandiba, SP (www.cocal.com.br), A host of companies in Brazil can make vertical biodigesters or other equipment for biomethane projects from vinasse (233).

Digestate as fertilizer

The current use of vinasses as a fluid fertilizer returned to sugarcane fields is not compromised as only part of the C contained in vinasse is converted into biogas. In addition, after biodigestion, most of the nutrients in vinasse are preserved and can be directed to fields as fertilizer both as a liquid effluent or as digestate (37).

Fertilizer of low carbon footprint from vinasse biomethane

Biomethane can also be employed to produce renewable energy fertilizers based on green ammonia. Yara Fertilizers, one of the largest fertilizers companies worldwide, has an ongoing project to produce green ammonia and green ammonium nitrate in a plant operating in Cubatão, SP (234). The feedstock is vinasse biomethane to replace fossil natural gas, the main component of ammonia synthesis (37). Biomethane may be fed by sugar mills into gas pipelines that cross the state of São Paulo and collected in the fertilizer plant in Cubatão. Ethanol producers can have a double benefit in this business model. In addition to the extra income with biomethane, ethanol plants using green fertilizers in the fields will be able to obtain extra CBIOs because nitrogen fertilizers are responsible for a sizeable proportion of the biofuel C footprint (235).

Despite the large potential of vinasse biomethane, Yara so far has under contract only a small fraction of the biomethane needed to run the fertilizer plant in Cubatão. Biomethane costs and payment for the pipeline's infrastructure are issues that require further attention before the green ammonia plant can run only with renewable energy. However, the prospects are encouraging.

Laws and Regulations

Given the prospects for biogas/biomethane in Brazil, several national and regional legislations and initiatives have emerged to stimulate its production. In fact, proper legislation and regulatory frameworks are as important as money incentives for the takeoff of this nascent industry (230,231,242,243). One important legislation issued by the Brazilian Government is the so-called Fuel of the Future (Combustível do Futuro, in Portuguese) - Law 14,993 from October 2024 (231). It creates a program to reduce the CO2 emissions from the transport sector in Brazil. Biogas and biomethane are relevant parts of the legislation. The law establishes, for instance, that, starting in January 2026, companies that operate with natural gas must mix and insert 1% of biomethane in the grid, a proportion that will increase with time as the biomethane production evolves in Brazil. This legislation creates a clear market for biomethane in the country and will certainly stimulate initiatives to produce this renewable energy.

"Fuel of the Future": Law 14.993/2024

Proper legislation is as important as money incentives for this nascent industry. The law creates a clear market for biomethane and stimulates production.

Transport decarbonization
Beyond gas blending, the law establishes a program to reduces CO2 emissions specifically from Brazil's transport sector.

Guarantee of origin
A tradable CGOB certificate decouples biomethane's environmental green value from the physical gas molecule.

Twin markets
The certificate splits demand into a compulsory mandate for gas suppliers and a voluntary corporate/ESG market.

Premium product
The scheme adds a purely financial revenue line, turning biomethane into a premium product that speeds plant payback.

Biomethane production units in Brazil (representative selection)

Biogas/biomethane projects are already operational in Usina Cocal (Narandiba), Raízen in Guariba, and São Martinho, in Pradópolis, all in the State of São Paulo. Four other projects were in implementation stages, as of 2024 (36). Similar projects are being installed in sugar-ethanol companies in other states, as is the case of Adecoagro, in Mato Grosso do Sul (232). More recent projects of biogas/biomethane are starting to make use of vertical biodigesters, equipped with capabilities to mix the feedstock, monitor pH and temperature and the biogas yields. This is the case with Usina Cocal, in Narandiba, SP (www.cocal.com.br), A host of companies in Brazil can make vertical biodigesters or other equipment for biomethane projects from vinasse (233). Several projects have been announced recently to produce biogas/biomethane (237,244,245).

One interesting initiative is that of Goiás. The local government has announced that the bus flit that operates in Goiania, the capital city of the state, will run on biomethane from waste, to stimulate this activity in that region. Bus and engine makers are committed to producing vehicles that will use this biofuel (246). Makers of trucks and heavy farming machinery are also adapting and testing engines to run on biomethane. This is important because biomethane produced in rural areas may have a direct use, reducing logistical costs and taxes.

PROJECT / PLANT	LOCATION	BIOMASS / ORIGIN	OWNERS/OPERATORS	PRODUCTION (NM³/DAY)	START OF OPERATION
GNR Fortaleza	Caucaia (CE)	Landfill	Environmental Canopy + MDC Energy	~100,000	2018
GNR Two Arcos	São Pedro da Aldeia (RJ)	Landfill	MDC Energy + partners	~60,000	2017
Cocal – Narandiba	Narandiba (SP)	Vinasse + filter cake	Cocal Responsible Energy	~50,000	2020
Cocal – Paraguaçu Paulista	Paraguaçu Paulista (SP)	Vinasse + sugarcane waste	Cocal Responsible Energy	~30,000–40,000	2022
FS Bioenergy	Lucas do Rio Verde (MT)	Corn ethanol residues	FS	~20,000–30,000 (estimated)	2023
GNR Paulínia	Paulínia (SP)	Landfill	OneBio (Edge+Orizon)	up to 225,000	2026
H2A Bioenergia / Copercampos	Campos Novos (SC)	Pig manure	H2A + Copercampos	~16,000	2026

Sources (247)

SECTION 7

7 Biomethane potential in emerging markets

Introduction

As the global energy transition accelerates, increasing attention is being directed towards solutions capable of simultaneously addressing climate change, energy security, waste management and sustainable development. While advanced economies have largely focused on decarbonising existing energy systems, many emerging economies face the dual challenge of expanding access to affordable energy while reducing greenhouse-gas emissions. In this context, biomethane has emerged as one of the few renewable energy options capable of delivering multiple benefits simultaneously.

The strategic relevance of biomethane for emerging markets derives from a fundamental characteristic: these countries often possess abundant organic resources but relatively limited waste-management infrastructure. Rapid urbanisation, expanding agricultural production, increasing livestock populations and growing agro-industrial sectors generate large quantities of organic residues that frequently remain underutilised. When improperly managed, these residues become significant sources of methane emissions, water contamination and local environmental degradation. However, when converted into biogas and subsequently upgraded to biomethane, these same residues become valuable sources of renewable energy, biofertilisers and renewable carbon dioxide.

According to the International Energy Agency (IEA 2025), sustainable global biogas and biomethane production could approach one trillion cubic metres annually, equivalent to approximately one quarter of current global natural gas demand. Yet only a small fraction of this potential is currently exploited. The largest untapped opportunities are concentrated precisely in regions where agricultural production, livestock activities and urban growth are expanding most rapidly, including Latin America, Sub-Saharan Africa, South Asia and Southeast Asia.

For emerging economies, biomethane should therefore be viewed not merely as a renewable fuel but as an integrated development solution capable of supporting climate objectives, energy diversification, circular-economy strategies and rural development simultaneously.

Global Feedstock Availability and Untapped Potential

One of the most compelling arguments for biomethane deployment in emerging economies is the abundance of available feedstocks.

Unlike many renewable-energy technologies that depend on specific geographical conditions, biomethane can be produced from a wide variety of organic residues, including:

- animal manure;
- crop residues;
- agro-industrial by-products;
- municipal organic waste;
- landfill gas;
- sewage sludge;
- food-processing residues.

The availability of these resources is closely linked to economic development and population growth. As emerging economies expand their agricultural production and urban populations, the volume of organic residues generated also increases.

The IEA's latest global geospatial assessment demonstrates that the technically sustainable resource base is significantly larger than current production levels. Most available biomass streams remain unexploited, particularly in developing regions where collection systems, upgrading facilities and supportive regulatory frameworks are still emerging (IEA 2025).

Importantly, many of these feedstocks are already generating methane emissions through uncontrolled decomposition. Biomethane production therefore captures an existing emission source rather than competing for additional land resources. This characteristic distinguishes biomethane from some first-generation biofuel pathways and strengthens its sustainability credentials.

Principal Biomethane Feedstocks in Emerging Economies

FEEDSTOCK CATEGORY	TYPICAL SOURCES	MAIN REGIONS
Animal manure	Dairy, cattle, swine and poultry production	Brazil, India, China, Argentina
Agricultural residues	Sugarcane, rice, maize, cassava	Brazil, India, Thailand, Indonesia
Municipal organic waste	Urban food waste and markets	India, China, Indonesia
Agro-industrial residues	Distilleries, food processing, slaughterhouses	Latin America, Southeast Asia
Landfill gas and sludge	Urban solid waste disposal sites	Major metropolitan regions
Wastewater sludge	Municipal sanitation systems	Emerging urban centres

Sources Adapted from IEA (2025), FAO (2026), and GBEP (2020).

Climate Benefits and Methane Mitigation

Methane has become an increasingly important focus of international climate policy. Although carbon dioxide remains the dominant greenhouse gas in cumulative emissions terms, methane possesses a significantly higher warming effect over shorter time horizons.

The Global Methane Pledge, launched during COP26, has reinforced international recognition that methane mitigation represents one of the fastest available pathways for slowing near-term climate change. Biomethane projects contribute directly to this objective by capturing methane that would otherwise be released from landfills, livestock manure, wastewater systems and organic waste streams.

For emerging economies, this climate benefit is particularly relevant because waste-management infrastructure frequently lags behind urban growth. As a result, uncontrolled emissions from organic residues often constitute a significant component of national greenhouse-gas inventories.

Biomethane systems therefore provide a dual climate benefit:

- avoidance of methane emissions from waste decomposition;
- displacement of fossil fuels through renewable energy production.

Several lifecycle assessments have demonstrated that biomethane pathways can achieve greenhouse-gas reductions exceeding 80% relative to fossil natural gas. In specific circumstances, particularly when livestock manure is utilised as feedstock, net-negative emissions may be achieved because avoided methane emissions exceed emissions generated throughout the production chain.

Consequently, biomethane represents one of the few renewable fuels capable of contributing simultaneously to methane-abatement strategies and long-term decarbonization objectives.

Biomethane and Sustainable Urban Development

Rapid urbanisation represents one of the defining trends of the twenty-first century. By 2050, nearly 70% of the global population is expected to reside in urban areas, with much of this growth occurring in Asia, Africa and Latin America.

Urban expansion creates substantial challenges related to waste management, sanitation and energy supply. Municipal solid waste generation is increasing rapidly in many developing countries, while landfill capacity and waste-treatment infrastructure frequently struggle to keep pace.

Biomethane offers a practical solution to this challenge by transforming urban organic waste into valuable resources.

The city of Surat, India, provides an illustrative example. Supported through initiatives documented by FAO, a bio-CNG facility processes approximately 50 tonnes of organic market waste per day, producing renewable transport fuel and biofertilisers while avoiding an estimated 7,500 tonnes of greenhouse-gas emissions annually. The project demonstrates how waste-management systems can be integrated with renewable-energy production and circular-economy principles.

Similar opportunities exist in major metropolitan areas across Brazil, Indonesia, Thailand, Mexico, Colombia and numerous African cities. As urban populations continue to expand, municipal organic waste is likely to become an increasingly important feedstock source for biomethane production.

Agricultural Development and Rural Opportunities

While urban residues offer substantial opportunities, agriculture remains the largest source of biomethane feedstocks globally.

Emerging economies account for a significant share of global agricultural production and livestock populations. Consequently, they also generate large quantities of agricultural residues and manure suitable for anaerobic digestion.

Biomethane production can contribute to rural development in several ways:

- diversification of farm revenues;
- reduction of waste-management costs;
- improved nutrient recycling;
- local energy production;
- job creation in rural regions;
- reduced dependence on imported fuels and fertilisers.

The digestate produced through anaerobic digestion represents an additional economic opportunity. Rather than being treated as a waste stream, digestate can be utilised as a biofertiliser containing valuable nutrients and organic matter. This characteristic is particularly important in countries dependent on imported fertilisers, where nutrient recovery can improve both agricultural resilience and national trade balances.

Recent research has increasingly emphasised that biomethane plants should be viewed as integrated bioresource centres rather than solely energy-production facilities. Their economic viability frequently depends upon the combined value of energy, nutrient recovery, waste treatment and environmental services.

Regional Perspectives

LATIN AMERICA

Latin America possesses some of the world's most favourable conditions for biomethane development. Large agricultural sectors, extensive livestock production and expanding urban populations generate substantial feedstock availability.

Brazil has emerged as one of the leading biomethane markets in the developing world, driven by residues from sugarcane processing, livestock production and municipal waste management. Argentina, Colombia and Mexico also possess significant technical potential.

The region's experience demonstrates the importance of integrating biomethane within broader bioeconomy and transport-decarbonisation strategies.

ASIA

Asia contains the largest concentration of biogas installations globally. China alone has deployed millions of household digesters and continues to expand large-scale biogas and biomethane systems.

Recent developments have increasingly focused on upgrading biogas to biomethane, facilitating gas-grid injection and transport applications. Technological innovation has also advanced rapidly, including digital monitoring systems, artificial intelligence applications and nutrient-management tools.

India has become another important growth market. Bio-CNG initiatives linked to municipal waste, livestock residues and agricultural feedstocks are increasingly integrated within national programmes focused on waste management, clean mobility and rural development.

AFRICA

Although current biomethane deployment remains relatively limited, Africa may possess some of the largest long-term opportunities.

The continent combines abundant agricultural residues, growing urban populations and substantial unmet energy demand. Studies conducted by FAO, UNDP and GBEP indicate that biogas and biomethane systems could simultaneously improve energy access, reduce environmental degradation and strengthen climate resilience.

The principal challenges remain access to finance, technical capacity and supportive regulatory frameworks. However, growing international interest in climate finance and methane mitigation may create favourable conditions for accelerated deployment.

International Cooperation and Knowledge Exchange

The expansion of biomethane in emerging markets increasingly depends upon international cooperation. Recent initiatives coordinated by the Global Bioenergy Partnership (GBEP), FAO, UNDP and the International Energy Agency have highlighted the importance of knowledge exchange between regions. Experiences from Europe, China, India and Latin America demonstrate that successful biomethane development requires not only technology but also regulatory frameworks, certification systems, operator training and market design (248).

The 2026 GBEP dialogue between European and Chinese experts identified several priority areas for cooperation, including:

- biomethane upgrading technologies;
- digestate management;
- carbon-accounting methodologies;
- guarantees of origin;
- sustainability certification;
- operator training;
- digitalisation and artificial intelligence.

Particularly relevant for emerging economies is the transfer of practical operational knowledge. Capacity-building programmes can accelerate deployment while reducing project risks and improving long-term performance. South-South cooperation may also become increasingly important. Countries such as Brazil, India and China possess practical experience in adapting biomethane technologies to developing-country conditions and can provide valuable lessons for other emerging markets.

Conclusions

Biomethane possesses exceptional potential in emerging economies due to the convergence of three factors: abundant organic feedstocks, growing energy demand and increasing pressure to improve waste-management systems.

Unlike many renewable-energy technologies that address a single challenge, biomethane simultaneously contributes to climate mitigation, methane reduction, renewable fuel production, nutrient recycling, waste management and rural development. This multifunctionality makes it particularly attractive for countries seeking integrated solutions aligned with sustainable-development objectives.

The technical resource base available in emerging economies remains vastly underutilised. According to recent international assessments, current production represents only a small fraction of the sustainable global potential. Unlocking this opportunity will require investments in infrastructure, regulatory frameworks, financing mechanisms and capacity building.

As COP30 in Brazil and COP31 continue to emphasize methane mitigation, circular economy approaches and just energy transitions, biomethane is increasingly positioned as a strategic technology capable of delivering tangible climate and development benefits simultaneously. For many emerging economies, it may represent one of the most practical and scalable pathways towards a low-carbon and resource-efficient future.

SECTION 8

8 Policy enablers

Policy Enablers

Because biomethane faces a structural production cost disadvantage relative to conventional fossil natural gas and diesel – at least in some current scenarios – its deployment is fundamentally dependent on robust, cohesive public policy frameworks. In parallel, fossil fuels subsidy reforms are also an effective way to increase the competitiveness of biofuels and reduce the consumption of diesel fuel (249). The primary policy enablers facilitating the replacement of diesel with biomethane for truck fleets across four key categories are addressed in the following topics: fuel blend mandates, sectoral renewable energy targets, physical infrastructure deployment, and market-based financial or tax incentives.

FUEL BLEND MANDATES

01. EUROPEAN UNION (EU) MEMBER STATES

- The EU RED III obligates fuel suppliers to include minimum renewable energy shares in transport, with advanced fuels counting double. Under the evolution of the European Union's regulatory framework, the primary mechanism driving blending requirements has shifted from volume-based quotas to greenhouse gas intensity reduction obligations (251).

- **The Netherlands & Germany:** fuel suppliers are legally obligated to achieve an incremental percentage reduction in the lifecycle GHG intensity of their total distributed fuel volume. Because biomethane derived from agricultural residues and organic waste possesses an exceptionally low - or even negative - carbon intensity profile, it serves as a highly efficient tool for suppliers to fulfill these compliance quotas compared to lower-performing first-generation liquid biofuels (75).

- **Germany:** instead of a simple volumetric blending mandate, Germany utilizes a GHG Reduction Quota (Treibhausgasminderungsquote). Fuel suppliers are legally mandated to reduce the carbon footprint of the fuels they sell by a specific percentage each year (252).

- **Sweden:** historically, Sweden relied on sweeping tax exemptions to incentivize biomethane utilization. However, to align with European statutory models, Sweden implemented a “Reduction Obligation” system (“Reduktionsplikt”). This regulatory mechanism mandates that fuel distributors continuously lower the carbon footprint of their products, generating a stable domestic market for high-blend biomethane and bio-LNG within commercial trucking fleets (253).

- **France:** utilizes a blend of strict feedstock regulations and supply-side obligations to drive rapid biomethane adoption. Enacted through its Climate and Resilience Law, France utilizes a Biogas Production Certificate (BPC) system. This scheme obligates natural gas suppliers to purchase BPCs for unsubsidised biogas based on the total volume of natural gas they supply to the market. To ensure high net climate benefits and protect food chains, France enforces a strict statutory limit dictating that no more than 15% of food or energy crops can be utilized as feedstock for biogas/biomethane production. Production must rely heavily on agricultural residues and cover crops.

- **Portugal:** implementation of volumetric substitution/injection obligations for grid operators, with so called Biomethane Action Plan 2024-2040 (PAB 2024-2040) created by Federal Resolution n° 41/2024 (254). Portuguese ordinance expects substitution of 18 % of natural gas by biomethane until 2040, taking 2030 as a reference.

- **Italy:** unlike some nations that focus primarily on household heating, Italy has structurally aligned its biomethane framework with its vast gas-powered transportation infrastructure and large agricultural footprint: the support scheme for biomethane is fully financed by transport fuel suppliers as part of their biofuel blending obligations. Companies releasing fossil diesel and gasoline into the Italian market are legally mandated to include a specific, rising percentage of renewable biofuels (including biomethane) in their annual fuel mix. And instead of taxpayers funding biomethane via direct government subsidies, the entire support scheme is funded by these obligated fuel suppliers. They must purchase Biomethane Certificates (CIC) from producers to prove they met their legal blending quotas.

02. UNITED STATES

In the United Stares there are both federal and state mandates that require or strongly incentivize the blending and procurement of biomethane, more commonly referred to as Renewable Natural Gas (RNG), into the United States energy grid and transportation system.

The regulatory landscape is generally split into two types of mechanisms:
Transportation Sector Blending Mandates: strict volumetric or carbon-intensity mandates requiring fuel providers to blend RNG into the vehicle fuel supply.
Thermal/Utility Procurement Mandates: state-level mandates requiring gas utilities to procure a specific percentage of RNG for their pipeline infrastructure to serve homes and businesses (similar to Renewable Portfolio Standards for electricity).

Federal Mandate: The Renewable Fuel Standard (RFS)

Administered by the U.S. Environmental Protection Agency (EPA), the Renewable Fuel Standard (RFS) is the foundational federal mandate driving biomethane blending in the transportation sector. Renewable Identification Numbers (RIN) are essentially the "currency" of the RFS program in the United States which are related to the GHG reduction targets. The program mandates that petroleum refiners and fuel importers ("obligated parties") blend minimum volumes of renewable fuels into the national transportation fuel supply every year. RFS defines RNG qualifies under the strict Cellulosic Biofuel (D3) RIN category (more than 95% of biomethane today in US) or Advanced Biofuel (D5) RIN category (less than 5% of biomethane produced) (250,255).
Through the principle of commercial displacement, RNG producers can inject biomethane into a commercial natural gas pipeline anywhere in the contiguous United States. As long as an equivalent physical volume of gas is withdrawn as Compressed Natural Gas (CNG) or Liquefied Natural Gas (LNG) for transportation use somewhere on the grid.

State-Level Mandates (Low Carbon Fuel Standards)

While structurally operating as market-based credit programs rather than flat volumetric blending requirements, these state mandates function as de facto blending requirements by penalizing high-carbon fossil fuels. Some examples are given below:

California Low Carbon Fuel Standard (LCFS)

The LCFS mandates a progressive reduction in the overall carbon intensity of the state's transportation fuel mix. The California Air Resources Board sets carbon intensity targets and assigns carbon intensity scores to transportation fuels sold in the state, but is not directly involved in private transactions in the LCFS credit market. Companies that sell conventional fuels earn deficits, while those that sell low-carbon alternatives—including biorefineries, biomethane producers, and electric vehicle charging aggregators—earn credits based on the carbon intensity scores assigned by the board.

Because RNG derived from organic waste (like dairy manure) traps methane that would otherwise escape into the atmosphere, it receives highly favorable, negative carbon-intensity scores. This has forced massive infrastructure blending, making virtually all bio-CNG dispensed in California transportation systems come from RNG (250). LCSF is administered by the California Air Resources Board (CARB) under the authority of the Global Warming Solutions Act of 2006 (Assembly Bill 32) and subsequent extensions (256).

California: Senate Bill 1440 (Biomethane Procurement)

In 2018, the California Public Utilities Commission (CPUC) implemented a strict procurement mandate requiring the state's investor-owned natural gas utilities (like SoCalGas and PG&E) to collectively procure annually biomethane volumes. In 2022, CPUC established short- and medium-term goals for 2025 and 2030 as 17.6 and 72.8 billion cubic feet of biomethane respectively. This targets roughly 12.3% of the state's baseline core residential/commercial gas consumption.(257), which was codified in California Public Utilities Code § 2840, formally implemented via CPUC Decision (D.) 22-02-025.

Oregon: Senate Bill 844 & Senate Bill 98

SB 98 established a voluntary framework that quickly transitioned into an active regulatory mechanism, setting goals for large natural gas utilities to replace conventional fossil gas with RNG. The targets scale up aggressively, aiming for up to 15% RNG blending in the utility pipeline mix by 2030. Oregon Senate Bill 98 (2019) was codified in Oregon Revised Statutes (ORS) § 757.390 through § 757.398.

Nevada: Senate Bill 154

SB 154 requires public natural gas utilities to offer customers the option to blend RNG into their service and explicitly directs utilities to actively procure biomethane. It mandates that a portion of the utility's total gas supply must come from renewable sources, provided it meets cost-effectiveness thresholds set by the Public Utilities Commission of Nevada (PUCN). Nevada Senate Bill 154 (2019), amending Nevada Revised Statutes (NRS) Chapter 704.
Mandates create structural demand that de-risks investments.

03. BRAZIL

Brazil maintains one of the longest-running and most highly integrated bioenergy frameworks in the global transport sector. Under Federal Law 13,576/2017 (the National Biofuels Policy, or "RenovaBio"), the country establishes legal mandates utilizing a market-wide supply structure (258).

The National Council of Energy Policy (CNPE) published the Resolution #4 April 4th 2026 (259) the GHG reduction target for the natural gas for 2026. It defines a reduction goal of 0.5% in GHG emissions, to be accomplished by importers and producers of natural gas by means of introduction of biomethane in its consumption or by acquisition of biomethane guarantee of origin certificate (CGOB), as determined by Federal Law 14,993/2024 – called Fuel of the Future Law (231). According to this law, GHG reduction due to biomethane introduction is mandatory and increased yearly up to 10%.

The CGOBs are the official traceability certificate backed by the volume of biomethane produced and marketed by the biofuel producer, with its renewable content, issued by a certifying agent of origin accredited by the National Petroleum and Biofuels Agency (ANP), which attests to the characteristics of the production process and which must include, at least, the origin of the input for biomethane production and the location of production, in addition to other items provided for in regulations.

Its main innovative feature is the concept of decoupling: the CGOB makes it possible to separate the environmental attribute (the green value) from the physical molecule of the gas. This means that the producer can inject the biomethane into the pipeline network and sell the physical gas to a local customer, while the environmental certificate (CGOB) can be sold independently to a company in another region of the country that wants to decarbonize its operation.

THE CGOB ECOSYSTEM WAS STRUCTURED AT THREE LEGAL LEVELS:

The Legal Basis: established by the Fuel of the Future Law (Law No. 14,993/2024) (231), which created the National Program for the Decarbonization of Natural Gas Producers and Importers.

The Regulation: Detailed by Decree No. 12,614/2025 (260) and operationalized by National Agency of Petroleum, Natural Gas and Biofuels (ANP) through Resolutions No. 995/2026 and No. 996/2026 (261,262).

Inspection and Issuance: The ANP acts as a central regulatory body. The issuance of certificates at the tip is done by Certifying Agents of Origin (ACOs) - independent entities accredited by the agency to audit and seal the volume produced.

SUMMARY OF CGOB RULES

PARAMETER	RULE
Unity	1 CGOB = 100 m^3 of biomethane effectively injected into the grid or sold.
Expiration date	18 months after issue date.
Traceability	Registered on auditable digital platforms (using technologies such as blockchain) to ensure transparent inventory and prevent double counting.
Coexistence with CBIO	Certified producers under RenovaBio rule can issue CGOB and CBIO at the same invoice, provided that the CBIO link is specified in the CGOB registration for full regulatory transparency.

CGOB MARKETS • THE CGOB MARKET CAN BE SPLIT INTO TWO MAJOR FRONTS:

The Compulsory Market (Biomethane Mandate): producers and importers of **fossil natural gas** have mandatory annual targets for reducing greenhouse gas (GHG) emissions. To meet these goals individualized by the ANP, they must acquire CGOBs to prove the insertion of renewable equivalents in the matrix.

The Voluntary Market (Corporate/ESG): industries, carriers, and multinationals that use fossil fuels (natural gas, diesel, CNG) buy CGOB to neutralize their Scope 1 or Scope 2 emissions. It is highly accepted in global sustainability inventories such as the GHG Protocol.

Strategic Benefits

For Biogas/Biomethane Producers: creates a new line of purely financial revenue and transforms biomethane into a premium product, accelerating the return on investment (ROI) of new plants.

For the Natural Gas Sector: ensures legal certainty and predictability of demand in the coming years due to the fulfillment of mandatory targets.

For Buyers (ESG): it allows you to decarbonize operations immediately, without the need to make heavy investments or modify the physical infrastructure for gas flaring and logistics.

Quebec's Renewable Natural Gas Blending Mandate in Canada requires natural gas distributors to reach **10% biomethane in networks by 2030**.

India's CBG Blending Obligation mandates biomethane blending starting at **1% in 2025/26, rising to 5% by 2028/29** for CNG and piped natural gas.

Infrastructure deployment

For biomethane to serve as a viable alternative to diesel in heavy-duty long-haul trucking, a synchronized distribution infrastructure is required. Because long-haul trucks demand high energy density to maintain operational range, policy enablers must actively support the deployment of both Compressed Natural Gas (CNG) stations for regional logistics and Liquefied Natural Gas (LNG) refueling networks for cross-border freight. The IEA emphasizes that while approximately 60% of Europe biomethane potential lies within 20 km of existing gas transmission pipelines, in China this value falls to 50 % and in South America it drops to only 10% of biomethane potential, making grid connections an important aspect for the distribution and location of refueling stations (224).

Grid interconnection costs represent a major barrier. Policy mechanisms to address this should include:

- **Cost-sharing programs:** California's biomethane interconnector monetary incentive program reimburses up to 50% of interconnection costs (capped at $80 million total funding), with half the funding sourced from cap-and-trade auction proceeds;
- **Government pipeline construction support:** India's 2024 scheme assumes up to 50% of pipeline infrastructure costs for compressed biogas injection into city gas distribution networks, covering pipelines up to 75 km from eligible plants;
- **Legal obligations for grid connection assessment:** France (Law 2018-938), Sweden (Natural Gas Act), and the Czech Republic (Energy Act 458/2000) mandate that gas grid operators must assess and facilitate biomethane injection requests, removing regulatory discretion that might block projects.

Given that heavy-duty vehicles often operate on return-to-base or corridor patterns, infrastructure deployment should prioritize freight hubs, ports, and logistics centers. The U.S. MHDV National Plan emphasizes that port infrastructure planning must jointly consider demands from maritime, rail, and off-road cargo handling equipment alongside trucking, to identify coordinated least-cost solutions for electricity, hydrogen, and biofuel supply (263).

European Union infrastructure directives

The physical deployment of gaseous fuel infrastructure across Europe was initially guided by the "Alternative Fuels Infrastructure Directive (AFID - 2014/94/EU)", which mandated that Member States establish national policy frameworks to deploy public refueling networks for methane-powered vehicles (264).

To eliminate geographical disparities and ensure cross-border freight corridors, the EU upgraded this framework to the "Alternative Fuels Infrastructure Regulation (AFIR)". AFIR establishes legally binding, distance-based targets for alternative fuel infrastructure along the Trans-European Transport Network (TEN-T) core and comprehensive corridors. For heavy-duty vehicles utilizing liquefied gas, this ensures a reliable density of refueling points across Europe, allowing fleet operators to invest in bio-LNG trucks with absolute certainty of fuel availability (265).

Furthermore, because biomethane can function as a direct "drop-in" fuel chemically identical to fossil natural gas, it fully utilizes this expanding infrastructure without requiring dedicated, isolated supply pipelines or alternative dispenser networks.

GRID INJECTION POLICIES AND THE UNION DATABASE

A major infrastructure enabler in Europe is the regulatory support for direct injection of upgraded biomethane into national and pan-European gas transmission grids.

Mass Balance Tracking: regulators utilize a mass balance system, enabling a truck fleet in one region to purchase the environmental attributes of biomethane injected into the grid thousands of kilometers away. In the European biomethane market, mass balance tracking is the mandatory regulatory chain-of-custody framework used to verify that biomethane injected into the natural gas grid retains its sustainability and green attributes from production all the way to the final consumer (267). Because the European gas grid blends gases of different origins into one physical stream, it is impossible to track individual molecules of biomethane. The mass balance system solves this by creating a digital connection between the physical volumes injected and the sustainability data attached to them, ensuring that the clean energy attributes are legally matched to what is withdrawn down the line (266).

- The Union Database for gaseous and liquid fuels (UDB): to guarantee the cross-border tracking of these physical flows and mitigate the risk of double-counting, the European Commission implemented the Union Database. This digital infrastructure registry traces the sustainability documentation of every unit of biomethane from the point of production to its final point of consumption at a transport refueling pump, providing the transparency required by corporate logistics compliance structures. By tracking batches of fuels and raw materials from their origin through the supply chain, the database ensures that consignments are counted toward renewable energy quotas only once (268).

The rollout of the Union Database represents a massive structural shift for European renewable gas markets:

- A Pre-requisite for Compliance Markets: for biomethane to be eligible under high-stakes compliance markets - such as the FuelEU Maritime Regulation or the EU Emissions Trading System (EU ETS), its lifecycle must be verified and logged inside the UDB.

- By standardizing proof of sustainability, the UDB enables a highly flexible, market-driven, pan-European trade network. This framework is essential for the EU's larger goals, such as the REPowerEU target, which aims to scale up sustainable biomethane production. A study by CE Delft recommended closely monitoring **Swedish and Italian models**, where transport-sector biomethane strategies are integrated into broader natural gas infrastructure planning, creating "level playing fields" between biofuels and biomethane through unified infrastructure standards (269).

UNITED STATES

For long-haul trucking, liquefied biomethane (bio-LNG) infrastructure is critical due to energy density requirements. The U.S. Department of Energy's Corridor Strategy targets completing Phase I by 2027, deploying refueling infrastructure at regional freight hubs to support ZE-MHDV adoption. The Alternative Fuel Refueling Property Tax Credit (IRC Sec. 30C) provides up to 30% or $100,000 per qualifying refueling equipment item, though implementation guidance remains pending for some categories.

BRAZIL AND SOUTH AMERICA

Lightweight CNG Types III & IV cylinders suitable for HDVs are not available in Brazil. Homologation/certification of these tanks in Brazil is expensive, and certification done abroad is not accepted in Brazil. Current regulation also require foreign CNG manufacturers to undergo complete recertification at every 3 yrs. This fact has a double effect: reduces the introduction of lightweight cylinders presence in the country and increases the total cost of ownership of trucks fueled by biomethane (270). Besides this, the absence of regulations for LNG trucks, tanks, fuel connectors/receptacles and fuel stations (including Liquid-to-CNG stations [L-CNG]) prevent the use of the LNG option (270). Today LNG users are mainly those who have private stations (LNG terminals for regasification, for instance). LNG boil-off is still a question to be addressed.

Gas pipelines in Brazil are still concentrated close to the shore. Higher penetration of natural gas/biomethane trucks will require refueling stations not only on the coast, but also on the country side (271).

A variety of private and semi-public fueling station options and strategies will be available to serve a growing HDV market: on-site at fleets (mobile and stationary); shared fueling stations exclusively for multiple heavy-duty fleets in urban centers; truck stations along 'Blue Corridors' (271). Some options are:

- Compression stations – refueling CNG stations close to pipelines;
- Mother-daughter stations or virtual pipelines – refueling CNG stations regasifying LNG brought by LNG trucks and compressing CNG;
- Portable LNG stations (use truck-supplied LNG) – to provide gas to fleet operators for small / private fleets.

*The use of mass balance has been challenged by several Europe Member States, particularly the Netherlands, which has introduced a requirement for physical segregation imported biomethane (bio-LNG/CNG), justifying its position by raising several concerns regarding the application of mass balance to imported LNG, in particular. Chief among these is the integrity of renewable claims and the risk of "administrative greening" (266).

Tax and Credit Incentives & Carbon Pricing

Financial viability is the ultimate determinant for fleet operators considering transitioning away from diesel powertrains. Public policy employs a combination of fiscal instruments, including direct tax exemptions, carbon pricing mechanisms, and tradeable environmental credit markets, to close the price gap between biomethane and fossil diesel. The higher cost of biomethane compared to CNG and/or diesel means it is unlikely to penetrate this market without further public support (224).

Brazil’s RenovaBio Program and the CBIO Mechanism

- Brazil’s “RenovaBio” policy represents an innovative, market-driven decarbonization credit structure that does not rely on direct government subsidies or state capital allocation. The entire program operates as an open environmental asset market integrated into national climate finance systems.

- The Decarbonization Credit (CBIO): one Decarbonization Credit (CBIO) is a financial asset traded openly on the B3 stock exchange and over-the-counter markets, representing exactly one metric tonne of avoided CO2 equivalent emissions.
- The RenovaCalc Lifecyle Assessment: to generate CBIOs, a biomethane producer must undergo third-party certification using a standardized lifecycle greenhouse gas accounting tool called RenovaCalc. This calculation evaluates the entire emissions pathway "from well to wheel" (including feedstock collection, anaerobic digestion, gas upgrading, and final distribution).

- The Environmental Efficiency Advantage: the difference between the certified biomethane producer's carbon intensity and that of the fossil diesel it replaces establishes the producer’s “Energy-Environmental Efficiency Score”. Because biomethane derived from organic waste residues features the lowest carbon footprint score among certified domestic biofuels, biomethane plants generate a high volume of CBIOs per cubic meter of gas produced. This provides an autonomous revenue stream that significantly offsets capital expenditure and production costs.

- Land-Use Protections: to maintain high environmental integrity, biomass produced on agricultural lands deforested after December 2018 is strictly barred from participating in the program, preventing indirect land-use expansion.

European Carbon Pricing: ETS2 and Eurovignette

In Europe, the economic competitiveness of biomethane for heavy-duty commercial transport is heavily reinforced by comprehensive carbon pricing structures.

The ETS2 Framework: starting in 2027, the European Union's Emissions Trading System is expanded via a separate emissions cap-and-trade mechanism (known as ETS2) that explicitly covers commercial road transport and the built environment. By imposing a direct carbon cost on wholesalers of fossil diesel, ETS2 increases the pump price of conventional petroleum fuels, structurally enhancing the economic competitiveness of zero-rated renewable fuels like biomethane.

The Eurovignette Directive: road infrastructure pricing across European highway networks increasingly relies on the revised Eurovignette Directive. This policy mandates that national road tolling systems vary their infrastructure charges based on the certified CO_2 emissions performance of the heavy-duty vehicle. Trucks running on certified bio-LNG or bio-CNG qualify for significant toll reductions (often exceeding 50% to 75% compared to standard Euro VI diesel vehicles), which dramatically alters the Total Cost of Ownership (TCO) calculation for logistics operators.

National Subsidies and Financial Frameworks

- The Netherlands and Germany: both countries have historically deployed temporary, targeted operational support mechanisms, such as exemptions from heavy vehicle road tolls (e.g., the German “Maut” exemption for natural gas trucks) and capital expenditure grants for transport operators purchasing dedicated gaseous-fueled trucks.

- Brazil (BNDES Credit Lines): complementing market-driven CBIO revenues, the Brazilian National Economic and Social Development Bank (BNDES) provides structured capital via specialized credit facilities. The most critical of these is the “Fundo Clima” (Climate Fund), which offers low-interest, long-term financing lines designed specifically to fund corporate decarbonization initiatives, industrial biogas collection infrastructure, and the acquisition of biomethane-powered truck fleets.

Carbon Intensity-Based Credit Markets

The most effective pricing mechanisms for biomethane operate through carbon intensity (CI) reduction credits rather than simple volumetric subsidies. California's Low Carbon Fuel Standard (LCFS) establishes a declining annual CI benchmark for transportation fuels; fuels performing below the benchmark generate tradable credits, while deficit generators must purchase them. For biomethane produced from dairy manure, LCFS credits have provided incentives equivalent to approximately $45/MMBtu, while landfill gas biomethane receives roughly $4.00–$4.25/MMBtu (depending on methane avoidance accounting). The U.S. Renewable Fuel Standard (RFS) complements this through Renewable Identification Numbers (RINs), where cellulosic biofuel (D3) RINs for waste-derived biomethane meeting 60% lifecycle GHG reduction have historically provided effective incentives around $23.32/MMBtu (at 2016 price levels).

In the European context, the EU Renewable Energy Directive (RED II/III) establishes sustainability thresholds: biomethane used in transport must achieve at least 65% GHG emissions savings versus the fossil comparator (94 g CO_2eq/MJ), with a maximum allowed emissions intensity of 33 g CO_2eq/MJ. The directive awards double counting for advanced biofuels (including certain waste-derived biomethane), effectively increasing the value of each unit of biomethane toward national renewable transport targets.

Fuel Price Parity Mechanisms

Sweden's Law 1994:1776 established full tax exemption for biomethane used as automotive fuel, combined with high fossil fuel taxes, creating one of the most successful heavy-duty biomethane markets globally. Similarly, Italy's Biomethane Decree (2018/2022) provides transport-specific certificates averaging 375 €/MWh for biomethane directed to transport use, with additional premiums for compression/liquefaction infrastructure.

Federal Production and Investment Tax Credits

In the United States, the Inflation Reduction Act (IRA) of 2022 established technology-neutral investment tax credits (48E) and production tax credits for clean fuel projects. The Alternative Fuel Tax Credit (AFTC) provides $0.50/gallon-equivalent at the dispenser for natural gas and RNG used as transportation fuel, while the Renewable Natural Gas Incentive Act of 2023 introduced a $1.00/gallon credit specifically for biomethane used in heavy-duty vehicles. These are end-user focused incentives that directly reduce fleet fueling costs and improve ROI per vehicle.

Technology-Specific Feed-in Tariffs and Premiums

Feed-in tariffs (FiTs) remain the dominant support mechanism in mature biomethane markets. Germany's Renewable Energy Sources Act (EEG) – updated in 2021 and 2025 – shifted from fixed tariffs to tender-based systems with flexible operations, including specific tenders for biomethane-to-transport pathways. The UK closed its FiT scheme but maintains the Renewable Heat Incentive and Renewable Transport Fuels Obligation (RTFO), which mandates fuel suppliers to include renewable content, with biomethane counting toward obligations.

Italy's Biomethane Decree provides capital contributions plus 15-year FiTs for biomethane plants, with transport-sector destinations receiving higher tariff values than heat/power applications.

Carbon Credit Markets and Tradable Instruments

Beyond compliance markets, voluntary carbon credits can support project finance. The IMO's emerging GHG pricing mechanism for shipping could be adapted for heavy-duty road transport, creating a sectoral carbon price that would make biomethane competitive if set sufficiently high.

Vehicle Purchase Incentives

For fleet operators, direct vehicle incentives reduce the capital cost barrier of natural gas vehicles (which typically carry a premium over diesel). California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) provides point-of-sale vouchers, while federal programs like the Clean Heavy-Duty Vehicles Grant Program ($1 billion) and iMHZEV Program support early adoption. Repealing the 12% Federal Excise Tax (FET) on heavy-duty gaseous-fueled trucks (as advocated by industry groups) would remove a discriminatory cost premium on cleaner technology purchases.

Synthesis: Recommended Policy Package for Heavy-Duty Biomethane Table

POLICY ELEMENT	RECOMMENDED INSTRUMENT	AUTHORITY REFERENCE
Carbon Pricing	CI-based credit trading (LCFS-style) + methane avoidance credits for manure/waste feedstocks	IEA (2025); CARB LCFS; EU RED III
Fuel Pricing	Tax parity/exemption for biomethane vs. diesel; technology-neutral production tax credits	Sweden Law 1994:1776; IRA 48E/45X; AFTC
Infrastructure	Cost-shared grid injection (50% public funding); mandated grid operator connection obligations; freight hub refueling corridors	California interconnector program; India pipeline scheme; U.S. MHDV Corridor Strategy
Waste Integration	Mandatory organic waste separation (2024+); manure management regulations limiting raw application; digestate valorization support	EU Waste Framework Directive; EU Nitrates Directive; GOBAR-Dhan
Credits/Incentives	Feed-in tariffs differentiated by feedstock and end-use; blending mandates with double-counting for advanced/waste-derived; vehicle purchase vouchers	Italy Biomethane Decree; EU RED III; HVIP; Quebec RNG Mandate

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