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Advanced CO_2 /CH_4 Separation Technologies for Kazakhstan: Environmental Performance, ESG Assessment and Research Opportunities

Biomethane, Gas Processing and CO_2 Utilisation Pathways: Technology Assessment, Sustainability and Scientific Cooperation

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Abstract

Separating carbon dioxide (CO_2) from methane (CH_4) can enable gas upgrading and recovery, but separation alone does not prevent methane emissions. Net climate benefits depend on the baseline, recovered methane use, measured process losses and full lifecycle emissions. The same separation step turns raw biogas into grid-quality biomethane, removes CO_2 from high-CO_2 and sour natural gas, and recovers a concentrated CO_2 stream that can be used or stored. This paper assesses CO_2/CH_4 separation technologies through an Environmental, Social and Governance (ESG) lens, using Kazakhstan as the case study.

Kazakhstan's NDC 3.0 reports 349.22 Mt CO_2e of net greenhouse gas emissions in 2023; the energy sector accounted for 278.5 Mt CO_2e. Inventory figures must be compared using consistent coverage and accounting boundaries. Methane accounts for about 16% of national emissions. Waste-sector emissions grew by 73% between 1990 and 2023, the fastest growth of any sector. The country has committed to carbon neutrality by 2060, joined the Global Methane Pledge in 2023, and in its 2025 NDC 3.0 pledged a 42% cut in fugitive methane in the energy and waste sectors by 2035.

We review established upgrading technologies (water scrubbing, chemical absorption, pressure swing adsorption, cryogenics) and polymeric hollow-fibre membranes, which are commercially deployed in biogas upgrading. We then examine next-generation materials, including polymers of intrinsic microporosity, mixed-matrix membranes and metal-organic frameworks. A transparent ESG scoring framework is applied to five pathways in Kazakhstan: agricultural biomethane, landfill gas, wastewater sludge gas, high-CO_2 and associated gas processing, and CO_2 utilisation.

In the illustrative ESG screening, agricultural biomethane receives the highest indicative score (3.75 of 5), reflecting potential environmental and social co-benefits. Governance receives relatively weak scores across several pathways, owing to the absence of biomethane standards, certification and a meaningful carbon price; Kazakhstan's ETS price has been about US$1 per tonne. A worked example shows that methane slip of 1% erases roughly 10% of a plant's fossil-displacement benefit over 100 years, and about three times more over 20 years. The paper closes with a phased 2027–2035 roadmap and recommendations for policymakers, operators, academia and international partners.

Keywords: CO_2/CH_4 separation; biogas upgrading; biomethane; membrane gas separation; methane slip; ESG assessment; Kazakhstan; Central Asia; Global Methane Pledge; carbon neutrality 2060

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Table of Contents

Key Findings at a Glance 4
Chapter 1 — Introduction 5
Chapter 2 — Kazakhstan's Methane and CO_2 Challenge 6
Chapter 3 — CO_2/CH_4 Separation Technologies 9
Chapter 4 — ESG Assessment Methodology 13
Chapter 5 — Application Pathways in Kazakhstan 16
Chapter 6 — ESG Assessment Results 19
Chapter 7 — International Lessons and Finance 22
Chapter 8 — Barriers and Enablers in Kazakhstan 23
Chapter 9 — Recommendations and Roadmap 2027–2035 25
Chapter 10 — Conclusions and Future Research 28
References 29
Annex A — Glossary 31
Annex B — Adjacent Technologies 32
Annex C — Scoring Sheet and Robustness Check 32
Annex D — Worked Example Assumptions 32
Annex E — Data Notes 33
Annex F — Illustrative ESG Scoring Protocol 33
Annex G — Gas-Separation Test and MRV Data Sheet 33
About EEESEF 34

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Key Findings at a Glance

1. **Methane is Kazakhstan's fastest climate lever. It makes up about 16% of national emissions. Each tonne avoided delivers roughly 27–30 times the 100-year warming benefit of a tonne of CO_2.**
2. **Waste and agriculture are the untapped methane sources. Waste emissions rose 73% between 1990 and 2023. Livestock is the largest single methane source, while only three biogas power plants operated nationally at the end of 2025.**
3. **The separation step decides the climate result. Upgrading technologies differ by an order of magnitude in methane slip, from below 0.1% for amine scrubbing to above 1% for some water scrubbers and PSA units. Slip must be measured, not assumed.**
4. **Membranes suit Kazakhstan's distributed resource. Modular hollow-fibre systems generally avoid the regeneration heat required by chemical absorption, but need electricity and may require chemical or adsorptive pretreatment for contaminants; their economic suitability at farm scale is site-dependent. They are already used in commercial biomethane upgrading plants.**
5. **Next-generation materials are moving from laboratory to field. Ultra-permeable polymers now exceed the long-standing permeability–selectivity limit for CO_2/CH_4. Plasticisation, ageing and cold-climate performance must be proven under Kazakh conditions before scale-up.**
6. **Governance is a significant deployment constraint. Kazakhstan's ETS carbon price has been about US$1 per tonne, domestic gas has been sold below cost, and the 2025 biogas power auction attracted no valid bids. No national biomethane standard or certificate system yet exists.**
7. **In our illustrative ESG screening, agricultural biomethane receives the highest indicative score (3.75 of 5), followed by wastewater sludge gas (3.50) and landfill gas (3.40).**
8. **A phased roadmap can unlock the sector by 2035.** It runs from standards and MRV (2027–2028), through pilots and market rules (2029–2031), to commercial scale and Article 6 carbon finance (2032–2035).

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Chapter 1 — Introduction

1.1 Why CO_2/CH_4 Separation Matters

Methane is the second most important greenhouse gas after CO_2. It has contributed nearly a third of the warming observed since pre-industrial times. Under the IPCC Sixth Assessment Report, one tonne of fossil methane has a 100-year global warming potential (GWP100) of 29.8 t CO_2e, and biogenic methane 27.0 t CO_2e. Over 20 years the effect is roughly 80 times that of CO_2. Because methane leaves the atmosphere in about 12 years, cutting it slows warming within a generation.

The energy sector alone emitted around 145 Mt of methane in 2024, more than 35% of human-caused methane. Agriculture and waste account for most of the rest. Many of these sources produce gas mixtures in which methane sits alongside large volumes of CO_2. Raw biogas typically holds 35–85% methane and 10–65% CO_2 plus inert gases. That CO_2 lowers the heating value of biogas to 20–25 MJ/m³, against 35–40 MJ/m³ for upgraded biomethane.

Separating the two gases is therefore the step that turns a waste stream into a fuel. It also yields a concentrated CO_2 stream that can be used or stored. The International Energy Agency (IEA) estimates that sustainable feedstocks could supply nearly 1 trillion m³ of biogas per year, about a quarter of today's global gas demand. Current production remains far below this estimated sustainable potential; the scale of the gap depends on the resource and methodology considered.

1.2 Scope, Objectives and Research Questions

The principal technical scope is CO_2/CH_4 separation, with complementary discussion of upstream methane capture, pretreatment and downstream CO_2 management. Capture of CO_2 from power-plant and cement flue gas separates CO_2 from nitrogen, which is different chemistry; it is treated only briefly in Annex B. The paper asks four questions:

1. Where in Kazakhstan's economy does CO_2/CH_4 separation offer the greatest climate and development benefit?
2. How do current and next-generation separation technologies compare on performance, cost drivers and suitability for Kazakh conditions?
3. How do the main application pathways perform when assessed on environmental, social and governance criteria?
4. Which policies, institutions and partnerships would allow Kazakhstan to deploy these technologies at scale by 2035?

1.3 Methodology, Data Sources and Limitations

The study combines a structured literature review with policy analysis and a multi-criteria ESG assessment. Sources include Kazakhstan's UNFCCC submissions (National Inventory Documents, NDC 3.0 and the 2060 Strategy), IEA and IEA Bioenergy Task 37 publications, peer-reviewed materials science and national statistics and market reporting.

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The ESG assessment uses the framework set out in Chapter 4. Scores are the author's structured judgement, informed by the cited evidence. They are indicative and intended to guide prioritisation, not to replace project-level due diligence.

Three limitations apply. First, national inventory releases and NDC reporting can differ in reporting year and accounting scope; the 2026 National Inventory Document should be consulted for the most recent inventory series, while the 2025 NDC figures cited here refer to 2023. Second, site-specific data on biogas composition and methane slip in Kazakhstan are scarce, so European performance data are used as indicative comparators. Third, independent verification of methane data remains limited, as discussed in Chapter 2.

1.4 Structure of the Paper

Chapter 2 sets out Kazakhstan's emissions and policy context. Chapter 3 reviews the technologies. Chapter 4 defines the ESG method, and Chapters 5 and 6 apply it to five pathways. Chapter 7 draws international lessons, Chapter 8 analyses barriers, Chapter 9 gives recommendations and a roadmap, and Chapter 10 concludes.

Chapter 2 — Kazakhstan's Methane and CO_2 Challenge

2.1 Emissions Profile

Kazakhstan is a major greenhouse-gas emitter in Central Asia. Its 2025 NDC reports 349.22 $MtCO_2e$ of net national emissions in 2023, and energy-sector emissions of 278.5 $MtCO_2e$. The latter is reported as 70.8% on the NDC's sector-accounting basis; it should not be recalculated as a percentage of net emissions because the accounting denominators differ [4].

Carbon dioxide dominates Kazakhstan's greenhouse-gas inventory, while methane emissions from energy, agriculture and waste create important near-term mitigation opportunities. Gas-by-gas shares should be compared only when the reporting year, GWP convention and treatment of land use are consistent [4].

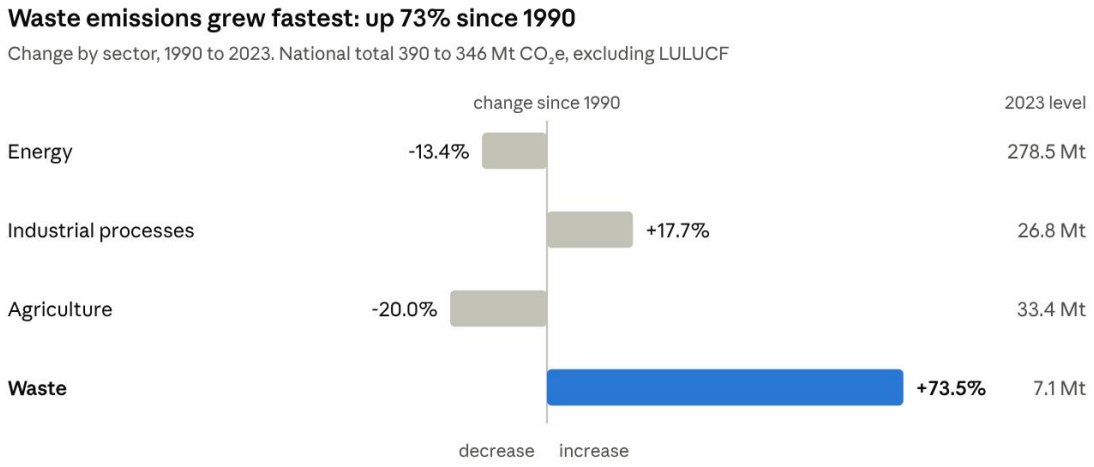


Figure 1. Kazakhstan greenhouse-gas emissions: illustrative presentation; consult the official NDC and national inventory for consistent sector and net-emissions accounting [4].

Kazakhstan's NDC reports that 2023 agricultural emissions were 33.4 $MtCO_2e$, industrial-process and product-use emissions 26.7 $MtCO_2e$, and waste-sector emissions 7.1 $MtCO_2e$. These figures are presented as sector totals from the official NDC and should not be combined with net emissions to derive new percentages [4].

2.2 Methane: Where It Comes From

IEA estimates attribute Kazakhstan's methane to livestock (38%), oil (24%), coal (13%), waste (10%) and natural gas (8%). Nearly half comes from biogenic sources (Figure 2). Biogas systems can capture landfill and wastewater methane and the manure-management share of livestock methane. They cannot capture enteric methane released by animals' digestion, which is the larger part of livestock emissions.

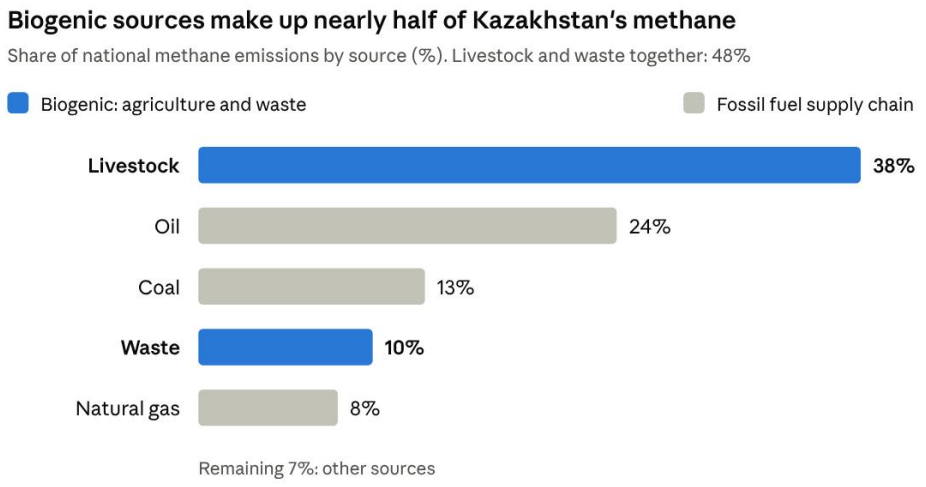


Figure 2. Source: IEA estimates as reported by Yessekina et al. (2024)

Fossil methane remains a major target. Flaring and venting made up about 21% of fugitive emissions in 2023, and venting has overtaken flaring since 1990. Routine flaring has been banned since 2004, yet World Bank satellite data suggest total flaring rose about 13% between 2016 and 2024. The IEA found that over half of oil and gas methane in Kazakhstan and its neighbours could be cut at no net cost using known technologies. Full mitigation in Kazakhstan's oil and gas sector is estimated to need at least US$1.4 billion of spending through 2030.

Data quality is itself a governance issue. Kazakhstan has not reported flaring data to the World Bank's Zero Routine Flaring initiative since 2018. Its four largest oil and gas operators have joined the Oil and Gas Methane Partnership 2.0 (OGMP 2.0), but their reports are not yet public.

2.3 Policy Framework

Carbon Neutrality Strategy 2060. Approved by Presidential Decree No. 121 of 2 February 2023, the Strategy is Kazakhstan's long-term low-emission development strategy under the Paris Agreement. It commits to decarbonising the oil and gas sector through leak reduction and Best Available Techniques (BAT), without phasing out production. An implementing Action Plan was approved on 1 September 2026 and includes methane-reduction offset projects.

Nationally Determined Contributions. The 2023 NDC set an unconditional 15% cut and a conditional 25% cut by 2030, against 1990. NDC 3.0, submitted in November 2025, raises the unconditional target to 17% below 1990 by 2035, with up to 25% conditional on international support. It also targets a 42% reduction in fugitive methane in the energy and waste sectors by 2035. It promises a methane legislative framework, a National Methane Emissions Database and a National Methane Emissions Reduction Programme.

Environmental Code (2021) and subsoil law. The Code requires BAT at major facilities and classifies oil and gas installations as Category I, with automated emissions monitoring. Article 146 of the 2017 Subsoil Law prohibits routine flaring, except in emergencies or where "technologically inevitable".

Emissions Trading System (KazETS). Launched in 2013, KazETS was the first ETS in Central Asia. It covers more than 200 companies and about half of national emissions. Its cap covers CO_2 only, allowances are allocated free by benchmarking, and domestic offsets are accepted without limit. The resulting price of about US$1 per tonne compares with roughly US$90 in the EU ETS in 2023. Analysts estimate at least US$20 per tonne is needed to drive low-carbon investment.

International commitments. Kazakhstan joined the Global Methane Pledge at COP28 in December 2023, committing to a collective 30% methane cut by 2030 from 2020 levels. It signed a Joint Crediting Mechanism agreement with Japan under Article 6.2 of the Paris Agreement in October 2023. In 2025 it agreed with the Global Methane Hub to create a National Methane Action Plan and a National Methane Office.

2.4 What This Means for Separation Technology

Three demand signals emerge. First, the methane targets in NDC 3.0 require capture of methane from waste and, by extension, agriculture, where upgrading to biomethane turns abatement into revenue. Second, processing of high-CO_2 and associated gas must expand to cut flaring and venting. Third, rising disclosure and MRV expectations mean that any technology deployed must deliver measured, verifiable methane outcomes, not assumed ones.

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2.5 Interpretation and Evidence Boundaries

Reported national inventories, IEA modelled estimates and facility observations use different boundaries and should not be combined without reconciliation. Statements about the absence of a national biomethane standard mean that no comprehensive dedicated framework was identified in the sources reviewed, not that no relevant gas-quality or safety rules exist. Project selection requires current legal confirmation.

Chapter 3 — CO_2/CH_4 Separation Technologies

3.1 The Gas Streams

Three families of gas mixtures matter for Kazakhstan. Biogas from anaerobic digestion of manure, food waste or sewage sludge contains 35–85% methane and 10–65% CO_2, plus hydrogen sulphide (H_2S, up to about 5,000 ppm), water, ammonia and siloxanes. Landfill gas has a similar composition but is usually leaner in methane and contains nitrogen and oxygen drawn in by the gas-collection system. High-CO_2 and sour natural gas is common in Kazakhstan's Caspian fields; reservoir fluids at Kashagan, for example, contain about 15% H_2S and 4% CO_2.

The same physical task, removing CO_2 from methane, applies in all three cases. The scale, contaminants and pressures differ greatly, which determines which technology fits.

3.2 Established Upgrading Technologies

Established biogas-upgrading approaches include water scrubbing, amine or other solvent absorption, pressure-swing adsorption and commercial polymeric membrane separation. Cryogenic routes are also used in specific applications, but their energy demand and operational requirements must be assessed separately. Technology market shares vary by geography, year and counting method and are not used here as comparative performance evidence [5, 6].

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Table 1. Comparison of commercial CO_2/CH_4 separation technologies

Technology	Separation principle	Methane-loss considerations	Energy and utilities	Fit for Kazakhstan
Water scrubbing	Physical absorption of CO_2 in pressurised water	Reported losses vary by design and off-gas treatment	Electricity for compression and pumping; continuous water make-up	Water demand is a constraint in arid regions
Amine (chemical) scrubbing	Chemical absorption; solvent regenerated by heat	Low losses achievable; verify site-specific data	Electricity and regeneration heat; site-specific values required	Suits larger plants with waste heat; oxygen degrades the solvent
Pressure swing adsorption	CO_2 adsorbed on activated carbon or zeolites under pressure	Off-gas may contain methane; treatment matters	Electricity for compression and cycling; pretreatment may be needed	Mature; off-gas usually needs treatment
Membrane separation	Selective permeation through polymer hollow fibres	Recovery depends on stages, recycle and operating conditions	Compression electricity; drying and contaminant removal may add utilities	Modular and scalable to farm size; cold-climate behaviour to verify
Cryogenic separation	CO_2 condensed or frozen out at low temperature	Depends on configuration	High electricity demand; can yield liquid CO_2 and bio-LNG	Suits large plants targeting LNG or liquid CO_2

No technology is best on every criterion. Amine absorption can achieve low methane losses but requires solvent management and regeneration heat; membrane and PSA systems depend on compression, electricity and pretreatment. Comparisons of energy demand, methane recovery, purity and costs must use equivalent feed composition, product specifications, system boundaries and operating conditions [5, 6].

3.3 How Membrane Separation Works

Polymeric membranes separate gases by the solution-diffusion mechanism. CO_2 dissolves into the polymer and diffuses through it faster than methane, so it passes to the low-pressure side as permeate. Methane stays on the high-pressure side as retentate. Two properties define a membrane: permeability (how fast CO_2 passes) and selectivity (how much faster CO_2 passes than methane).

Industrial membranes are spun as hollow fibres thinner than a hair and bundled by the thousand into cartridges. This gives a very large separation area per unit volume. The first

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commercial polymeric gas-separation plant was built in 1979 for natural gas, and polymers from the 1980s and 1990s still make up 80–90% of the membrane industry.

A single membrane stage may struggle to achieve both high purity and high methane recovery under typical operating constraints. Plants therefore use two or three stages with recycle (Figure 3). Membrane type, cartridge dimensions and operating conditions together set the methane slip.

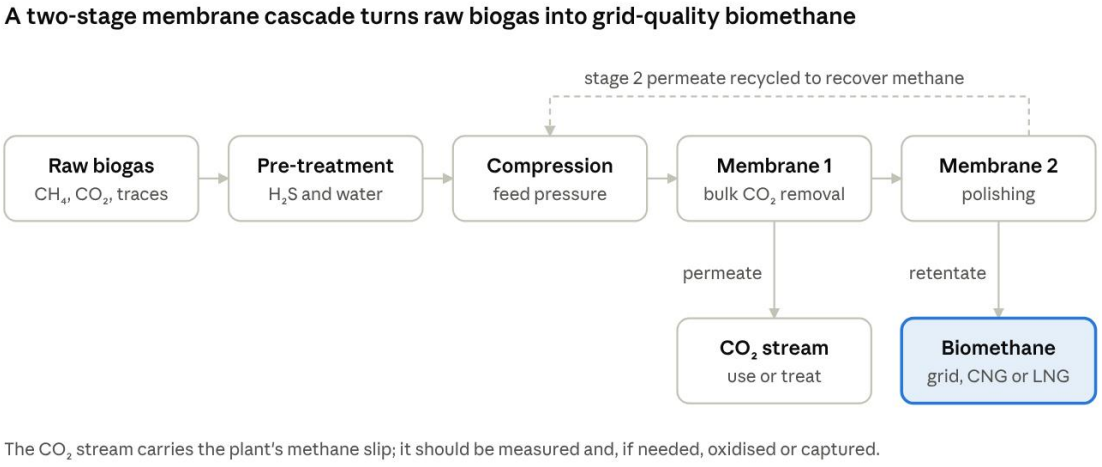


Figure 3. Generic two-stage membrane upgrading configuration with permeate recycle. Original conceptual schematic prepared for this White Paper; not a detailed engineering design.

3.4 Performance Limits

Polymer membranes exhibit a well-established permeability–selectivity trade-off, described by the Robeson upper-bound framework. The upper bound is a comparison of material properties, not a guarantee of industrial module performance [7]. Three practical issues also matter:

- **Plasticisation. At high CO_2 partial pressure, CO_2 swells glassy polymers, raising methane permeability and lowering selectivity.**
- **Physical ageing. High free-volume polymers slowly densify, losing permeability over months.**
- **Contaminants. H_2S, water, siloxanes and volatile organics degrade membranes unless removed in pre-treatment.**

These factors influence module life, replacement costs and methane recovery. Advanced PIM, MOF and mixed-matrix membranes remain research or development candidates unless industrial-scale operating evidence is supplied. Pure-gas laboratory selectivity, mixed-gas testing, module results and long-term field performance must be reported separately [7].

3.5 Next-Generation Materials

Materials science is pushing past the 2008 upper bound. A series of benzotriptycene-based polymers of intrinsic microporosity (PIMs) combined ultra-high CO_2 permeability with high selectivity, prompting a proposed redefinition of the CO_2/CH_4 and CO_2/N_2 upper bounds. Thermally rearranged (TR) polymers have demonstrated promising laboratory permeability and selectivity, but reported values vary with polymer chemistry, conditioning and test conditions and cannot be treated as module-level performance guarantees.

Mixed-matrix membranes (MMMs) disperse porous fillers in a polymer. Fillers include metal-organic frameworks (MOFs), covalent organic frameworks and two-dimensional materials such as MXenes. MOF-based sorbents and MMMs can also remove trace impurities (H_2S, ammonia, siloxanes, moisture) as well as separate CO_2. Some MMMs target small digesters that operate at very low pressure, where conventional upgrading is uneconomic.

Two further directions matter for durability and circularity. On-site regeneration aims to restore membrane performance after ageing, plasticisation or contamination. Low-temperature solid sorbents target difficult or dilute CO_2 separations. Both remain at early commercial or pilot stage, and claims should be judged on independent, long-duration field data.

3.6 Technology Readiness and Fit for Kazakhstan

Water scrubbing, amine scrubbing, PSA and established polymeric membrane systems have commercial deployment (generally TRL 9 for the established process configurations). Cryogenic upgrading is commercially deployed in selected applications, but readiness and economics depend on the specific configuration. PIMs, TR polymers and MOF-based MMMs are mostly at laboratory or pilot stage (around TRL 4–6, by the authors' assessment).

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Four Kazakh conditions should guide selection. The continental climate imposes large seasonal temperature swings that affect digesters and membranes alike. Water is scarce in many regions, which penalises water scrubbing. Feedstock is dispersed across thousands of farms, which favours modular units. And engineering skills for gas processing are concentrated in the oil and gas sector, which suggests a role for technical training (Chapter 8).

3.7 Comparative Technology Evaluation Protocol

Future comparisons should report feed composition (CH_4, CO_2, H_2S, N_2, O_2, moisture and siloxanes), temperature, pressure, membrane area, stage configuration, pretreatment, electricity and heat demand, methane recovery, product purity, CO_2-stream quality, uptime and maintenance. Membrane separation itself may avoid solvent regeneration, but integrated pretreatment and polishing may require chemicals or thermal processes.

3.8 Emerging Materials: Evidence and Commercial Readiness

High permeability or selectivity reported on pure-gas laboratory tests is not sufficient evidence of industrial readiness. Independent testing should examine mixed-gas performance, high CO_2 partial pressures, plasticisation, ageing, contaminants, freeze–thaw exposure, regeneration effectiveness and membrane/module lifetime. TRL ranges are indicative rather than supplier certifications.

3.9 Research Hypotheses for Kazakhstan

H1: modular multistage membranes can achieve high methane recovery with acceptable energy use on distributed farm biogas. H2: pretreatment and hybrid configurations can reduce performance losses on oxygen- and nitrogen-bearing landfill gas. H3: material and module performance over winter operation differs materially from short laboratory tests. These are hypotheses requiring measured validation, not established outcomes.

Chapter 4 — ESG Assessment Methodology

4.1 Purpose and Scope

The framework asks one question of each pathway: does it cut emissions measurably, fairly and credibly? It assesses pathways, meaning a combination of feedstock, separation technology and end use, rather than individual products or companies. The unit of analysis is a typical project in Kazakhstan's current conditions.

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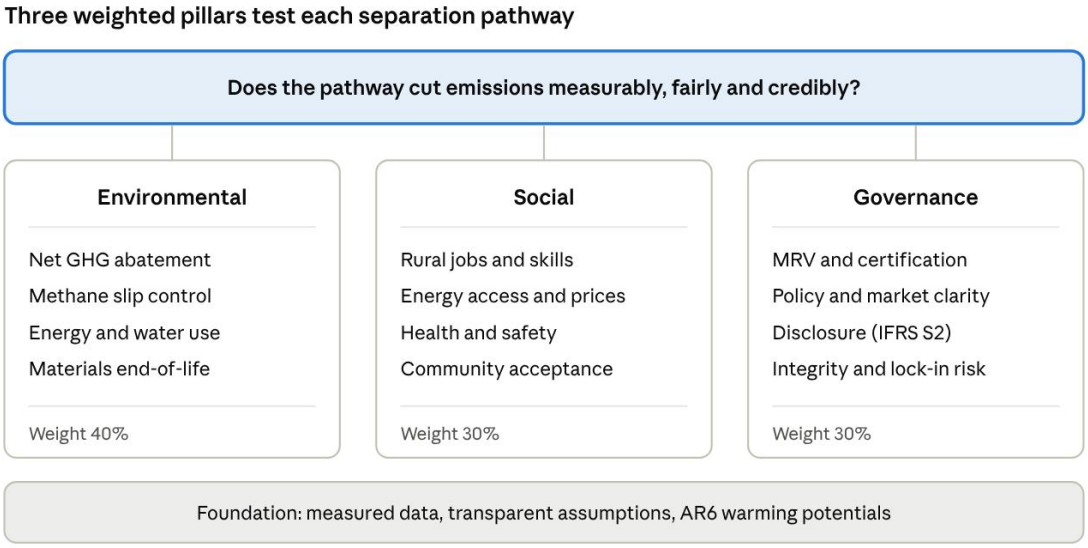


Figure 4. EEESEF ESG assessment framework for CO_2/CH_4 separation pathways. Prepared by the authors

4.2 Indicators

Twelve indicators sit under three pillars (Table 2). Each is scored from 1 (poor) to 5 (strong) against the descriptors shown.

Pillar	Indicator	What a score of 5 means	What a score of 1 means
Environmental	Net GHG abatement	Large, additional cut in CO_2e over the life cycle, including avoided methane	Small or uncertain net benefit
Environmental	Methane slip control	Measured slip below 0.5%, with off-gas treatment where needed	Slip unmeasured or above 1%
Environmental	Energy and water use	Low specific energy; no process water or heat	High energy, heat or water demand
Environmental	Materials end-of-life	Long-life modules, regeneration or recycling route	Short life; no end-of-life plan
Social	Rural jobs and skills	Permanent local jobs and transferable skills	Few or temporary jobs
Social	Energy access and prices	Improves local supply or lowers costs	No local benefit or raises prices

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Social	Health and safety	Reduces odour, air pollution or H_2S exposure	Introduces new hazards
Social	Community acceptance	Strong local support and benefit sharing	Opposition or land-use conflict
Governance	MRV and certification	Independent measurement and certified product	No standard or verification route
Governance	Policy and market clarity	Stable, bankable revenue mechanism	No revenue mechanism or unstable rules
Governance	Disclosure	Reportable under IFRS S2 and OGMP 2.0 where relevant	Not disclosed
Governance	Integrity and lock-in	No risk of prolonging fossil use; no double counting	High lock-in or double-counting risk

Table 2. ESG indicators and scoring descriptors

4.3 Scoring and Weighting

Indicator scores are averaged within each pillar. Pillar scores are then weighted: environmental 40%, social 30% and governance 30%. The environmental pillar carries the most weight because climate abatement is the primary purpose of the technology. Social and governance pillars carry equal weight because, in Kazakhstan's context, weak governance is as likely to block delivery as weak technology.

Scores are expert judgements by the authors, anchored on the evidence cited in Chapters 2, 3 and 5. As a robustness check, results were also compared using equal weights (one third each); the ranking of the top three pathways did not change (Annex C).

4.4 Alignment with International Frameworks

The framework is built to be compatible with the main standards that investors and regulators in Kazakhstan now apply:

- **IFRS S2 Climate-related Disclosures, issued by the International Sustainability Standards Board in June 2023. Kazakhstan's Ministry of Finance is implementing a roadmap for phased adoption of IFRS S1 and S2 in 2027–2028.**
- **IPCC AR6 warming potentials, which distinguish fossil methane (GWP100 29.8) from biogenic methane (27.0). Projects should state which values they use.**
- **OGMP 2.0, the measurement-based reporting standard joined by Kazakhstan's largest oil and gas operators.**
- **The Sustainable Development Goals**, chiefly SDG 7 (clean energy), SDG 8 (decent work), SDG 12 (responsible production) and SDG 13 (climate action).

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4.5 Scoring Transparency and Uncertainty

The five pathway scores are indicative expert judgements, not measured facility ESG ratings. The original pillar-level scoring is retained for traceability in Annex C; an expanded provisional indicator-level reconstruction is provided in Annex F and must be independently validated before the numerical ranking is used for investment or certification. Equal-weight checks alone do not test score uncertainty. A ±0.5-point indicator sensitivity, alternative pillar weights and uncertainty intervals are recommended. Governance indicators describe institutional readiness, not verified compliance of any operator.

4.6 Comparability of Pathways

Agricultural, landfill, wastewater and associated-gas pathways describe feedstock-to-product systems. CO_2 utilisation is a downstream option applicable to multiple pathways, and therefore is presented for context but excluded from the principal like-for-like gas-source ranking. Its historical score is retained separately in Annex C for transparency.

Chapter 5 — Application Pathways in Kazakhstan

Four gas-source pathways are compared, while separated CO_2 utilisation is discussed as a complementary downstream option. The original five-pathway scores are preserved as historical indicative results. Four use biogenic or fossil gas streams that already exist in Kazakhstan; the fifth uses the CO_2 that separation produces. Table 3 summarises them before each is discussed.

Table 3. Pathway summary

Pathway	Feedstock	Typical scale	Likely technology	Main benefit	Main risk
A. Agricultural biomethane	Cattle, dairy and poultry manure; crop residues	Farm to cluster	Membranes; PSA	Avoided manure methane; rural fuel and fertiliser	Leakage along the biogas chain
B. Landfill gas upgrading	Municipal solid waste in landfills	City landfill	Hybrid membrane systems with N_2/O_2 control	Captures fast-growing waste methane	Variable gas quality; air ingress
C. Wastewater sludge gas	Sewage sludge, co-digested food waste	City treatment plant	Membranes; amine where heat is available	Uses existing digesters and utility governance	Small volumes per site
D. High-CO_2 and	CO_2-rich and sour gas from	Very large	Amine; membranes	Less flaring and venting;	Fossil lock-in

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Pathway	Feedstock	Typical scale	Likely technology	Main benefit	Main risk
associated gas	oil and gas fields		for bulk CO_2 removal	more domestic gas	
E. CO_2 utilisation	Biogenic CO_2 from upgrading	Plant-linked	Liquefaction and purification	Value from a by-product	Short-lived storage; weak additionality

5.1 Pathway A: Agricultural Biomethane

Kazakhstan has a large and growing livestock sector. In October 2025 it held about 8.4 million cattle, 20 million sheep, 4.4 million horses, 0.5 million pigs and 48 million poultry. Studies confirm a large biogas potential from manure, while noting that the sharply continental climate affects digestion and requires heated, insulated digesters.

Not all of this manure is collectable. Much of the sheep and horse herd grazes on open pasture. The realistic feedstock is concentrated at dairy farms, cattle feedlots and poultry farms, where manure is already collected and stored. Uncovered manure storage is itself a methane source, so digestion delivers a double benefit: it avoids storage emissions and displaces fossil fuel.

The sector is small. At the end of 2025, only three of Kazakhstan's 162 renewable power plants used biogas. Earlier auctions awarded biogas projects of 2.4–4.8 MW at about 32 tenge per kWh, but the 2025 auction for 20 MW of bioenergy was declared invalid. Today's support schemes reward electricity only. Upgrading to biomethane would open other markets: injection into the expanding gas grid, compressed biomethane for farm machinery and trucks, and heat for rural settlements.

Digestate, the residue of digestion, is a valuable fertiliser. The IEA estimates that, if waste-based biogas potential were fully used, digestate could meet about 15% of projected EU fertiliser needs by 2050. For Kazakhstan's grain belt, this is an important co-benefit.

The principal environmental risk is leakage. European measurements found methane losses of 0.1–2.4% during feedstock handling, 0–12% during biogas production and 0.2–10% during upgrading. Without leak detection and slip control, a poorly run plant can lose much of its climate benefit.

5.2 Pathways B and C: Landfill Gas and Wastewater Sludge Gas

Kazakhstan generates 4.2–4.8 million tonnes of municipal solid waste a year, peaking at 4.8 Mt in 2024. About 48 Mt has accumulated in landfills. Of roughly 3,000 operating landfills, only about 20% meet environmental standards, and Astana's landfills have been reported as 98% full. Officially reported recycling reached 25.8% in 2024, though only a small fraction became usable secondary material.

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This explains the 73% growth in waste-sector emissions since 1990 (Figure 1). It also creates an opportunity: organic waste already in landfills will keep producing methane for decades, whatever future waste policy achieves. Landfill gas capture with upgrading turns that liability into fuel. The government is meanwhile backing waste-to-energy incineration, including a 2,000-tonne-per-day, 60 MW plant under construction in Almaty. Incineration and landfill gas capture are complementary: one treats new waste, the other addresses the legacy stock.

Landfill gas is harder to upgrade than farm biogas. Air drawn in by the collection system adds nitrogen and oxygen, which membranes separate poorly from methane. Practical schemes therefore combine careful well-field management with hybrid upgrading, or use the gas for local power and heat where upgrading is uneconomic.

Wastewater treatment plants offer simpler conditions. Sewage sludge digesters produce steady, relatively clean biogas under municipal utility management. The Global Methane Initiative has assessed methane capture at two representative Kazakh treatment plants. A Japanese feasibility study proposed co-digesting Astana's sewage sludge with separately collected organic waste for power generation. Co-digestion increases gas output and links waste and water policy.

5.3 Pathway D: High-CO_2, Sour and Associated Gas

Kazakhstan's giant Caspian fields produce associated gas rich in H_2S and CO_2. At Kashagan, reservoir fluids hold about 15% H_2S and 4% CO_2, and much of the gas is reinjected to maintain pressure. QazaqGaz and a Chinese engineering partner are developing a 2.5 bcm per year plant to process Kashagan's sour associated gas into marketable gas.

Domestic demand for gas is rising with the national gasification programme. Wholesale prices have been below production cost: in 2025 QazaqGaz reported an average wholesale price of 22,037 tenge per 1,000 m^3 against a cost of 33,742 tenge. The government raised prices by about a third in 2025 and planned a further 33% rise from July 2026 to attract investment.

In this pathway, membranes typically serve as a bulk CO_2 removal stage ahead of, or alongside, amine units. Their role in sour service is narrower, because H_2S must still be removed to very low levels. The ESG case is mixed. Processing gas that would otherwise be flared or vented cuts methane and black carbon, and additional domestic gas can replace coal in city heating. But it also extends fossil supply and can lock in infrastructure. This pathway therefore scores lower on integrity than the biogenic pathways.

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5.4 Pathway E: Using the Separated CO_2

Every biomethane plant also produces a CO_2 stream. After polishing, biogenic CO_2 can serve greenhouses, beverage carbonation, dry ice, water treatment, algae cultivation, mineralisation into building materials, or synthetic methane when combined with green hydrogen.

The ESG value of these uses depends on permanence and substitution. Greenhouse or beverage use returns the CO_2 to the atmosphere within days or months. It delivers a climate benefit only if it displaces CO_2 that would otherwise be produced from fossil sources. Mineralisation stores CO_2 for centuries. Use of CO_2 for enhanced oil recovery stores part of it underground but also increases oil production, so it is excluded from this assessment's positive scenarios. Kazakhstan has not yet mapped its geological storage capacity in detail, which is a research priority (Chapter 10).

5.5 Downstream CO_2 Management: Separate Assessment

The separated CO_2 stream requires its own mass balance, impurity specification, compression and transport assessment, lifecycle boundary and evidence of displacement or durable storage. Short-lived uses must not be described as permanent sequestration. CO_2 utilisation should be assessed as an optional downstream module, not ranked as a fifth comparable gas-source pathway.

Chapter 6 — ESG Assessment Results

6.1 Pathway Scores

An illustrative expert-screening exercise assigns agricultural biomethane 3.75/5, wastewater sludge gas 3.50/5, landfill gas upgrading 3.40/5 and high-CO_2/associated-gas processing 3.15/5 under the stated base weights. These are scenario judgments, not measured environmental outcomes or statistically validated rankings. CO_2 utilisation (3.00/5) is downstream of separation and is not directly comparable with the four source pathways.

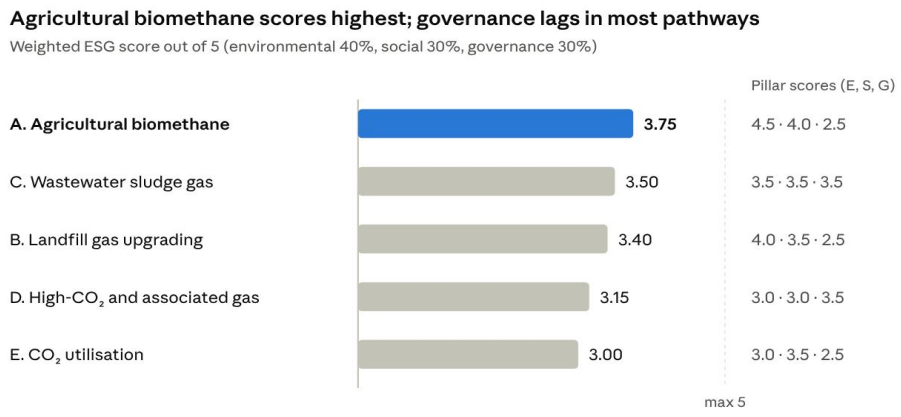


Figure 5. EEESEF illustrative ESG screening scores; not independently measured or validated.

Three patterns stand out.

1. **Biogenic methane recovery may provide substantial climate benefits where the project captures methane that would otherwise escape and controls losses across the entire chain. The magnitude depends on the counterfactual, upgrading emissions, energy source and methane slip; it cannot be inferred from the gas-separation technology alone [1, 3].**
2. **Governance scores are particularly sensitive to assumptions about monitoring, regulation, certificates and operator capability. These screening judgments require project-specific evidence before they can be used to rank investments or institutions.**
3. **Wastewater sludge gas may offer a practical municipal pilot pathway where digesters and utility governance already exist; site-level feedstock volume, gas quality and measurement capability must be established before making a comparative risk claim.**

6.2 Worked Example: Why Methane Slip Matters

Consider an illustrative agricultural plant processing 500 Nm^3/h of biogas at 55% methane for 8,000 hours per year. This contains 2.2 million Nm^3 of methane annually. Assuming complete combustion and equal displaced fossil-methane energy, the gross combustion-only displacement is approximately 4,340 t of fossil CO_2 per year (Annex D).

If methane escapes through upgrading off-gas, part of that gross displacement is offset. Table 4 shows illustrative losses at four slip rates, using IPCC AR6 GWP100 of 27.0 for non-fossil methane and an approximately 80-fold 20-year methane factor. Slip is assumed to be a percentage of methane entering the upgrader [1].

Table 4. Share of fossil-displacement benefit lost to methane slip (illustrative plant)

Methane slip	Methane lost (t/yr)	Lost benefit, 100-year basis	Lost benefit, 20-year basis
0.1%	1.6	43 t CO_2e (1%)	126 t CO_2e (3%)
0.5%	7.9	213 t CO_2e (5%)	631 t CO_2e (15%)
1.0%	15.8	426 t CO_2e (10%)	1,262 t CO_2e (29%)
2.0%	31.5	852 t CO_2e (20%)	2,523 t CO_2e (58%)

This calculation is an illustrative fossil-combustion displacement comparison, not a lifecycle greenhouse-gas balance. It excludes avoided manure-storage emissions, electricity and heat, gas collection, upgrading, transport, digestate and upstream methane leakage. The example shows how methane slip can materially offset gross combustion-displacement benefits, particularly over a 20-year horizon; it does not quantify the project's net climate benefit [1, 3].

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6.2.1 Boundaries of the Illustrative Calculation

The 500 Nm³/h example compares methane-slip warming impacts with a gross benchmark of 4,340 t fossil CO_2 from combustion of the same nominal methane volume. It is not a complete project LCA: recovered methane is lower as slip rises, and process electricity, upstream leakage, manure baseline, digestate effects and end-use efficiency are excluded. For a slip fraction s, delivered methane is approximately 2.2 million × (1−s) Nm³/year, before other losses. Consequently net avoided emissions should be modelled as displaced fossil emissions from delivered methane plus avoided baseline methane minus project emissions and methane slip, using a consistent GWP horizon.

6.2.2 Measurement and Sensitivity Requirements

A project study should vary feed methane content, annual operating hours, electricity emissions factor, methane slip and feedstock baseline. Report both GWP100 and GWP20 without mixing horizons in one total; distinguish biogenic and fossil methane factors and document the selected IPCC edition. For the original illustrative table, 27.0 and approximately 80 are retained as the stated assumptions rather than presented as universally mandatory factors.

6.3 Risk Assessment

Seven ESG risks were identified (Figure 6). Three fall into the act-now quadrant: low gas and carbon prices (R1), the lack of a biomethane standard and certificate system (R2), and methane slip and leakage (R3). Fossil lock-in (R4) and supply-chain concentration (R7) need contingency planning. Membrane performance in cold or contaminated feed (R5) and operator skills (R6) can be managed at project level through testing and training.

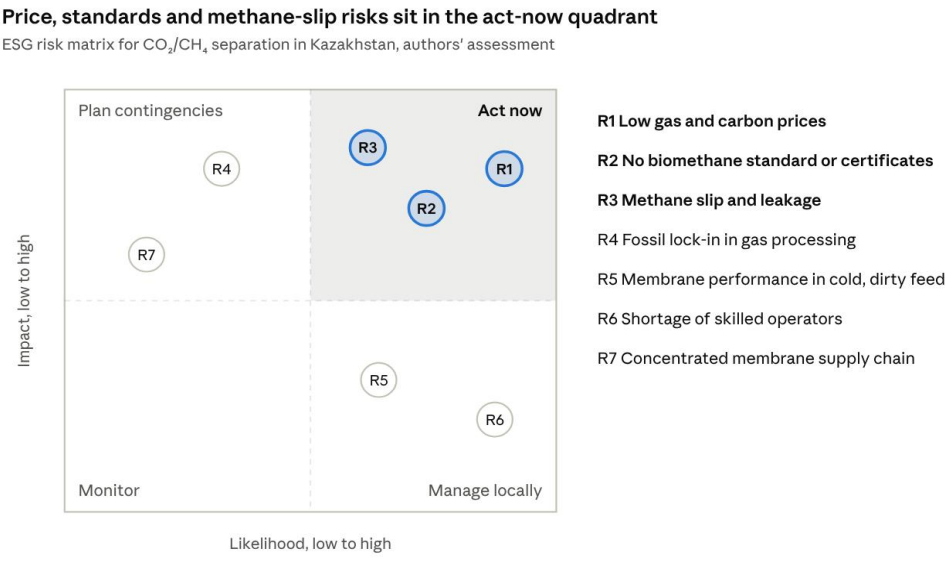


Figure 6. ESG risk matrix, authors' assessment; positions indicate zones, not precise probabilities

Chapter 7 — International Lessons and Finance

7.1 The European Union: Targets, Rules and Certificates

The EU shows how policy can scale biomethane quickly. Its REPowerEU plan of 2022 set a target of 35 bcm of biomethane per year by 2030, and a public-private Biomethane Industrial Partnership was launched in September 2022 to deliver it. Europe's operating biomethane plants rose from 483 in 2018 to 1,678 in 2025. Installed biomethane capacity reached about 7 bcm per year in early 2025.

The pace has differed sharply by country. France overtook Germany as Europe's leading biomethane producer and now has about three times as many plants, while the UK and Germany have nearly stagnated, largely because of regulatory uncertainty. The lesson for Kazakhstan is that stable grid-injection rules and long-term revenue mechanisms matter more than headline targets.

Europe also shows the importance of methane-leak control. The leakage ranges cited in Chapter 5 come from European plants. Industry bodies have responded with certification schemes for anaerobic digestion and calls for global regulatory standards. Kazakhstan can adopt such standards from the start rather than retrofitting them.

7.2 The EU Carbon Border Adjustment Mechanism

The EU's Carbon Border Adjustment Mechanism (CBAM) entered its definitive, financially binding phase on 1 January 2026. It covers imports of iron and steel, aluminium, cement, fertilisers, hydrogen and electricity. Kazakhstan's metal exporters must now document the embedded emissions of their products.

CBAM creates an indirect incentive for CO_2/CH_4 separation. Biomethane or low-carbon hydrogen used as process fuel can lower embedded emissions in covered products. Credible MRV of methane, which Kazakhstan is building for the Global Methane Pledge, is the same capability exporters need for CBAM reporting.

7.3 China: Scale, Manufacturing and Partnership

China has the largest number of biogas plants among IEA Bioenergy Task 37 countries, with more than 100,000 installations. It has also set a biomethane target of 20 bcm by 2030. China is a major manufacturing base for membrane materials, cartridges and upgrading equipment, and Chinese companies are already active in Kazakhstan's gas processing and waste-to-energy sectors.

This offers Kazakhstan access to cost-competitive equipment and engineering. It also creates a supply-chain concentration risk (R7 in Figure 6). A balanced approach would combine Chinese manufacturing with European and international standards, independent testing in Kazakhstan, and local assembly and maintenance capacity.

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7.4 Finance Mechanisms

The IEA estimates that a carbon price of about US$50 per tonne would make roughly 280 bcm of manure-based biomethane competitive with natural gas worldwide. More than 50 new policies supporting biogases have been introduced globally since 2020. For Kazakhstan, five finance channels are relevant:

1. **Domestic carbon pricing. KazETS accepts domestic offsets without limit, and the 2026 Action Plan provides for methane-reduction offset projects. Offsets will drive investment only if the ETS price rises well above today's level of about US$1 per tonne.**
2. **Article 6 of the Paris Agreement. Kazakhstan's Joint Crediting Mechanism with Japan allows emission reductions to be credited and partly transferred under Article 6.2. Methane abatement projects with measured outcomes are well suited to such cooperation, provided corresponding adjustments avoid double counting.**
3. **Development finance. The EBRD supports Kazakhstan's programme on fugitive methane and carbon intensity, including leak detection and a national methane database. Full oil and gas methane mitigation needs at least US$1.4 billion through 2030.**
4. **Green finance and disclosure. Kazakhstan adopted a green taxonomy in 2021 that can be used to finance projects such as biogas plants. Phased adoption of IFRS S1 and S2 from 2027–2028 will make climate-related risks and opportunities more visible to lenders.**
5. **Gas price reform. Planned increases in wholesale gas prices improve the case for biomethane and for processing associated gas.**

7.5 Lessons for Kazakhstan

Table 5. International lessons and their application

Lesson	Evidence	Application in Kazakhstan
Stable rules beat ambitious targets	National deployment depends strongly on policy design and implementation	Adopt a long-term biomethane support mechanism with grid-injection rules
Measure methane, do not assume it	Methane leakage varies materially with site design and operations	Make slip and leak monitoring a licensing condition
Certificates create markets	EU guarantees-of-origin systems link producers and buyers	Create a national biomethane certificate registry compatible with EU systems
Carbon price drives economics	Economic viability depends on feedstock, avoided methane, policy and financing	Tighten KazETS and introduce auctioning and a price floor

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Lesson	Evidence	Application in Kazakhstan
	assumptions	
Diversify supply chains	Concentrated manufacturing creates dependency	Combine imports with local testing, assembly and service capacity

Chapter 8 — Barriers and Enablers in Kazakhstan

The technology is ready; the market around it is not. Kazakhstan's barriers are mostly economic and institutional, while its enablers are recent policy commitments that have yet to be translated into project-level rules.

8.1 Barriers

Table 6. Main barriers to CO_2/CH_4 separation projects

Category	Barrier	Evidence
Economic	Domestic gas sold below production cost	Gas-price and project-cost assumptions require site-specific, dated quotations
Economic	Carbon price too low to reward abatement	Carbon-price signals and allowance rules require current official verification
Economic	Support rewards electricity, not gas	Bioenergy auction and tariff eligibility must be verified for the project year
Technical	Harsh continental climate	Large seasonal temperature range affects digestion and equipment
Technical	Dispersed feedstock, much of it on open pasture	Large herds but limited collectable manure
Technical	Water scarcity in many regions	Penalises water-intensive upgrading options
Institutional	No biomethane quality standard, grid-injection rules or certificate registry	No national framework identified in published policy
Institutional	Methane legislation and database still being built	Official policy commitments need implementation plans and verifiable monitoring
Institutional	Gaps in emissions transparency	Operator-level emissions and flaring transparency varies; independent MRV is needed
Human capital	Gas-processing skills	Limited operating reference sites and local

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Category	Barrier	Evidence
	concentrated in the oil and gas sector	maintenance capacity

Two of these barriers interact. Below-cost gas makes any substitute look expensive, and a near-zero carbon price provides no compensating reward. Together they explain why biogas has stayed marginal despite a large resource. Both are now changing: gas prices are rising by about a third per year, and reform of KazETS, including auctioning and a price floor, is under discussion.

Civic space matters for governance too. Methane commitments depend on independent verification of emissions data. Civil-society organisations report growing restrictions on access to information and public participation in Kazakhstan. Transparent, publicly accessible methane data would strengthen the credibility of the country's commitments with investors and partners.

8.2 Enablers

1. **Clear national targets. NDC 3.0's 42% fugitive-methane target, the 2060 Strategy and its 2026 Action Plan give a policy anchor for the whole sector.**
2. **International partnerships. The Global Methane Pledge, the U.S.–Kazakhstan methane statement, the Global Methane Hub agreement and the JCM with Japan bring technical support and finance.**
3. **Gas price reform. Moving gas prices towards cost recovery improves the competitiveness of biomethane and associated-gas processing.**
4. **Expanding gas grid.** Gasification extends the network that biomethane can be injected into.
5. **Disclosure reform. IFRS S1 and S2 adoption from 2027–2028 and the green taxonomy create demand for measurable low-carbon projects.**
6. **Research and education base. Kazakh universities already study biogas potential and landfill gas systems. Technical and vocational education can supply operators for a new industry.**

Chapter 9 — Recommendations and Roadmap 2027–2035

The recommendations follow from the assessment: fix governance first, prove performance in Kazakh conditions, then scale. They are grouped by actor, and sequenced in the roadmap in Section 9.6.

9.1 For Policymakers

1. **Adopt a national biomethane quality standard and grid-injection rules** by 2028, aligned with European standards to keep export and certificate options open.
2. **Create a revenue mechanism for biomethane, not only biogas power.** Options include a feed-in premium or contract for difference for injected biomethane and bio-CNG, or opening renewable auctions to gas.

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3. **Make methane measurement a licensing condition.** Upgrading plants should report measured methane slip and treat off-gas where slip exceeds an agreed limit. Leak detection and repair should apply across the biogas chain.
4. **Establish a biomethane certificate registry** that records production, prevents double counting and is interoperable with EU guarantee-of-origin systems.
5. **Strengthen KazETS through partial auctioning, a carbon price floor and coverage of methane, as recommended by the Astana International Financial Centre.**
6. **Publish methane and flaring data, resume reporting to the World Bank's Zero Routine Flaring initiative, and make the National Methane Emissions Database public.**

9.2 For Industry and Operators

1. Specify guaranteed methane slip and methane recovery in procurement, verified by independent testing.
2. Test separation equipment on real local gas over at least one full winter before scale-up.
3. Combine membranes with other technologies where the gas demands it, for example hybrid systems for landfill gas with nitrogen and oxygen.
4. Publish OGMP 2.0 methane reports and include separation projects in IFRS S2 disclosures.
5. Treat digestate quality and use as part of project design, not an afterthought.

9.3 For Academia and Research Institutions

1. Create an open national test platform for separation materials and modules, operating on real biogas and landfill gas in cold-climate conditions.
2. Map collectable feedstock by region, distinguishing housed from pasture-based livestock.
3. Assess geological CO_2 storage capacity and CO_2 utilisation markets in Kazakhstan.
4. Develop life-cycle assessment methods for biomethane in Kazakh conditions, including leakage.
5. Build curricula and technical and vocational education programmes for biogas and gas-separation operators.

9.3.1 Proposed Collaborative Research Programme

EEESEF proposes a non-commercial, technology-neutral programme with interested universities and research institutes. Workstream A: advanced polymer, PIM, mixed-matrix and sorbent materials; outputs include comparable mixed-gas permeability, selectivity and durability data. Workstream B: pilot-scale testing on representative farm, wastewater and landfill gases; outputs include methane recovery, CO_2 purity, energy intensity and uptime. Workstream C: independent methane monitoring and lifecycle assessment; outputs include measurement protocols, uncertainty budgets and transparent environmental baselines. Workstream D: separated CO_2 purification, utilisation and storage-screening; outputs include product specifications and comparative lifecycle cases.

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9.3.2 Research Protocol, Deliverables and Participation

Each proposed study should begin with a written research question, sample provenance, safety and ethics review, instrument calibration plan, operating envelope, quality-assurance method, independent replication where practical, and a publication/data-sharing agreement. Candidate deliverables are an open protocol, anonymised datasets where permitted, a technical research note, student training and a jointly reviewed public report. EEESEF may coordinate dialogue and disseminate non-confidential results; laboratories and partners retain responsibility for their own equipment, safety and resources.

9.3.3 Independence, Intellectual Property and Funding

Publicly available scientific concepts may be reviewed independently; proprietary formulations, performance data, confidential samples and vendor equipment require separate permission and arrangements. Participation does not imply endorsement, certification, a funded pilot or an obligation to provide free laboratory services. Any intellectual-property, publication, confidentiality or financing conditions should be documented separately before work begins.

9.4 For International Partners and Funders

1. Support Article 6 methodologies for biomethane and landfill gas that reward measured, not modelled, methane reductions.
2. Provide blended finance and grants for first-of-a-kind pilots, where risk is highest.
3. Transfer standards and certification practice from the EU, and support independent testing of imported equipment.
4. Help diversify supply chains through local assembly and service partnerships.

9.5 The Role of EEESEF

As a non-commercial foundation, EEESEF can act as a neutral convenor between government, universities, operators and international partners. It can help develop open testing protocols, publish independent data, support education and training, and track progress against this roadmap. It does not endorse or represent any technology supplier.

9.6 Roadmap

The roadmap has three phases separated by two gates (Figure 7). Moving to the next phase depends on meeting the gate criteria, not on the calendar alone.

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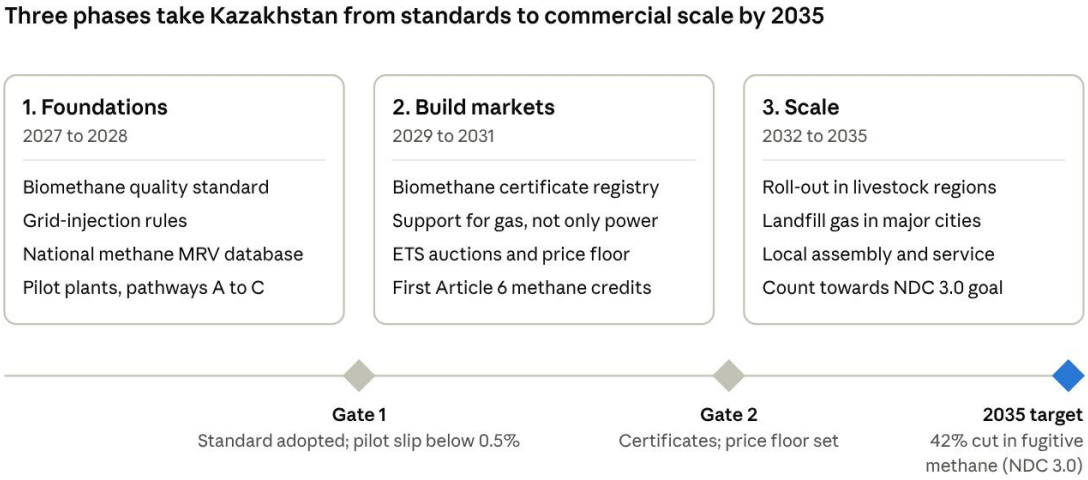


Figure 7. Proposed roadmap for CO_2/CH_4 separation in Kazakhstan, 2027–2035. Phases not to scale; 2035 target from NDC 3.0

The 0.5% slip criterion at Gate 1 is a proposed benchmark, consistent with the performance range of well-designed membrane and amine systems. Gate 2 requires a functioning certificate market and a carbon price floor, so that Phase 3 investment rests on bankable revenue.

9.7 Practical Cooperation Sequence

Stage 1 (scoping): identify a university laboratory, feedstock partner and test question; review safety, gas composition and available instruments. Stage 2 (bench testing): compare commercial reference technology and candidate materials on reproducible mixed-gas protocols. Stage 3 (pilot design): establish measurement points, operating limits, risk controls, permitting and an independent evaluation plan. Stage 4 (publication): report measured performance, uncertainties, failures and reproducibility without implying technology endorsement. Advancement depends on evidence and partner resources, not the calendar alone.

Chapter 10 — Conclusions and Future Research

10.1 Summary of Findings

CO_2/CH_4 separation is a mature, versatile technology family that sits at the centre of Kazakhstan's methane challenge. It converts manure, landfill and sewage gas into a renewable substitute for natural gas. It cleans CO_2-rich fossil gas that would otherwise be flared or vented. And it produces a concentrated CO_2 stream with potential uses.

Kazakhstan has the resource, the targets and growing international support. Its 2025 NDC 3.0 commits to a 42% cut in fugitive methane by 2035, waste emissions are rising fast, and biogenic sources make up nearly half of national methane. Yet only three biogas power plants operated at the end of 2025.

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The ESG assessment shows why. Environmental and social performance is strong, especially for agricultural biomethane. Governance is weak: there is no biomethane standard or certificate system, the carbon price is about US$1 per tonne, and gas has been sold below cost. The technology choice also matters: the worked example shows that methane slip can erase between 1% and 58% of a plant's fossil-displacement benefit, depending on slip rate and time horizon.

The central conclusion is that governance reform is a major national enabling condition, alongside site-specific technical feasibility, feedstock availability and verified lifecycle performance. With a standard, a certificate registry, a bankable revenue mechanism and measured methane outcomes, Kazakhstan can build a biomethane and methane-abatement industry by 2035 that serves its climate commitments, rural economy and energy security together.

10.2 Open Research Questions

1. How do current and next-generation membranes perform on real Kazakh biogas and landfill gas over a full continental winter?
2. What is the collectable, not theoretical, manure and organic waste potential by region?
3. What are measured methane leakage and slip rates at Kazakhstan's existing biogas and landfill sites?
4. What is the levelised cost of biomethane in Kazakhstan, and at what gas and carbon prices does it reach parity?
5. What geological CO_2 storage capacity exists in the Caspian and other basins, and which CO_2 utilisation markets are viable?
6. How can benefit-sharing models increase community acceptance of landfill gas and agricultural biogas projects?

EEESEF invites universities, operators and public institutions in Kazakhstan, Central Asia and Europe to collaborate on these questions through open, non-commercial research.

10.3 Proposed Research Outputs and Next Steps

Near-term academic outputs could include a Kazakhstan gas-stream specification dataset, comparative membrane-testing protocol, winter-operability study, methane-slip MRV guide and open lifecycle boundary template. These are proposals, not existing EEESEF facilities or commitments. The foundation invites non-commercial scientific discussions with universities, environmental institutes and qualified technical partners; commercial implementation and proprietary technology remain outside the remit of this publication.

10.4 Interpretation of the Findings

The gas-source pathway ranking should be interpreted as a preliminary prioritisation exercise. Site-specific data could reverse the order, especially where recoverable manure, landfill gas quality, wastewater digestion infrastructure or associated-gas treatment conditions differ. Policy, technical performance and lifecycle outcomes must be evaluated together.

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Annexes

Annex A — Glossary

Term	Meaning
Anaerobic digestion	Breakdown of organic matter by microbes without oxygen, producing biogas and digestate
Biogas	Raw gas from digestion or landfills, mainly methane and CO_2
Biomethane	Biogas upgraded to natural-gas quality by removing CO_2 and impurities
Digestate	Nutrient-rich residue of digestion, usable as fertiliser
GWP100 / GWP20	Warming effect of a gas relative to CO_2 over 100 or 20 years
Hollow fibre	Thin, hair-like tubular membrane bundled into cartridges
KazETS	Kazakhstan's national emissions trading system
Methane slip	Methane lost in the CO_2-rich off-gas of an upgrading unit, as a share of methane processed
MMM	Mixed-matrix membrane: a polymer containing dispersed porous fillers
MOF	Metal-organic framework: a crystalline porous material built from metal nodes and organic linkers
MRV	Measurement, reporting and verification
OGMP 2.0	Oil and Gas Methane Partnership 2.0, a measurement-based methane reporting framework
Permeate / retentate	The gas that passes through a membrane / the gas that stays on the feed side
PIM	Polymer of intrinsic microporosity
PSA	Pressure swing adsorption
TRL	Technology readiness level, from 1 (basic principles) to 9 (proven in operation)

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Annex B — Adjacent Technologies: CO_2 Capture from Flue Gas

Capturing CO_2 from coal power, cement or metallurgical flue gas separates CO_2 from nitrogen at near-atmospheric pressure and low CO_2 concentration. This is chemically and economically different from CO_2/CH_4 separation, which is why it falls outside the scope of this paper. Many of the same materials are relevant, however. The 2008 Robeson analysis added an upper bound for CO_2/N_2, and ultra-permeable PIMs have been proposed to redefine it. For Kazakhstan, where coal supplies about half of energy consumption and steel and aluminium exports now face CBAM, flue-gas capture deserves its own dedicated assessment.

Annex C — Scoring Sheet and Robustness Check

The following values are illustrative screening judgments under alternative weights, not empirical estimates. Because underlying indicator evidence and uncertainty distributions are not available, unchanged rankings under two weighting schemes should not be interpreted as proof of robustness. CO_2 utilisation is shown for context only and should be assessed separately.

Pathway	Equal-weight score	Rank, base weights	Rank, equal weights	Main reasons for scores
A. Agricultural biomethane	3.67	1	1	Double climate benefit; rural jobs and fertiliser; no standards or gas tariff
C. Wastewater sludge gas	3.50	2	2	Existing digesters; utility governance; small volumes
B. Landfill gas upgrading	3.33	3	3	Fast-growing waste methane; air ingress; weak landfill regulation
D. High-CO_2 and associated gas	3.17	4	4	Cuts flaring and venting; OGMP 2.0 reporting; fossil lock-in
E. CO_2 utilisation	3.00	5	5	Adds value to by-product; short-lived storage; additionality unclear

Annex D — Worked Example Assumptions

- Biogas flow 500 Nm^3/h at 55% methane; 8,000 operating hours a year, giving 2.2 million Nm^3 of methane a year.
- Methane density 0.717 kg/Nm^3 at 0°C and 1 atm.
- Combustion of 1 Nm^3 of methane releases $0.717 \times 44/16 = 1.97$ kg CO_2, so 2.2 million Nm^3 displaces about 4,340 t of fossil CO_2 a year.
- Biogenic methane GWP100 = 27.0; GWP20 taken as about 80.
- Avoided emissions from manure storage, digestate effects, electricity demand, gas handling, transport and construction are excluded. Their combined effect cannot be assumed to be conservative or beneficial without a full lifecycle inventory.

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- Upgrading electricity and other process emissions are excluded; they depend on technology and the grid mix.

Annex E — Data Notes

- Kazakhstan submitted a National Inventory Document in April 2026. This paper distinguishes the 2023 figures cited from the 2025 NDC from later inventory reporting; any comparison between releases should account for differences in covered years, methods and accounting boundaries.
- Estimates of energy-sector methane differ between sources. One review cites an IEA estimate of 3.7 Mt of methane from the energy sector, about 74% of national methane, while the national inventory attributes about half of methane to energy. This paper uses inventory data where available and states the source in each case.
- The 2023 NDC update set the 2030 targets; NDC 3.0 sets the 2035 targets.
- Kazakhstan's sustainability disclosure roadmap for IFRS S1 and S2 was prepared with UNDP and EU support.

Annex F — Illustrative Indicator-Level ESG Scoring Protocol

For each of the four gas-source pathways, a future assessment sheet must list the twelve Chapter 4 indicators in order, an integer or half-point score, documentary evidence, a short rationale, an uncertainty rating and reviewer identity. The illustrative pillar scores are not accompanied by a complete documented set of twelve underlying indicator judgments; therefore, their precise indicator-level allocations cannot be independently reconstructed. Until those allocations are supplied and independently checked, the 3.75/3.50/3.40/3.15 scores are illustrative only; CO_2 utilisation (3.00) is retained as a separate downstream historical score. Recalculate weighted scores as 0.40 × mean(E1–E4) + 0.30 × mean(S1–S4) + 0.30 × mean(G1–G4). Test equal weights, environmental weights of 30–50%, and plausible ±0.5 changes in each indicator. Publish ranges and any rank reversals.

Annex G — Proposed Gas-Separation Test and MRV Data Sheet

Record site ID; sample dates; feed source; CH_4/CO_2/H_2S/N_2/O_2/moisture and trace impurities; standard-volume reference conditions; feed/product/off-gas flows; temperature and pressure; pretreatment and stage/recycle design; electrical and thermal energy; operating hours; gas analyser calibration; methane recovery and measured methane slip; CO_2 product quality; shutdowns; maintenance; safety events; baseline assumptions; uncertainty intervals; and chain of custody. Report process performance separately from full lifecycle emissions. No numerical performance guarantee is made in this proposed protocol.

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Sign-Off and Closing Block

APPROVAL FOR PUBLICATION

This White Paper has been reviewed and approved for publication by the Euro-Eurasia Environmental Science & Education Foundation (EEESEF).

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