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Methane Emissions Reduction Strategies for Safer and More Efficient Petroleum Production Operations

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Abstract
This paper develops an integrated measurement-to-mitigation architecture that links methane control with safety, reliability, and resource conservation. The study responds to the problem that methane losses arise from fugitive leaks, vents, pneumatic devices, tanks, compressors, incomplete combustion, maintenance activity, and abnormal operations. It uses an integrative conceptual review of scholarly and professional literature published to date. The framework organizes eight decision functions: source inventory development, measurement technology selection, emission quantification, risk and abatement ranking, repair and replacement planning, verification of reduction, data-quality assurance, management review. It applies those functions across well sites, gathering systems, processing facilities, compressor stations, storage assets, transmission and distribution interfaces. The analysis treats uncertainty, process safety, reliability, environmental performance, resource efficiency, economics, and organizational control as connected requirements. The proposed architecture links a system definition, evidence register, model assumptions, intervention portfolio, verification plan, and learning cycle. Its central proposition is that detect, quantify, prioritize, prevent, and verify methane reductions while protecting process safety and production continuity when decisions preserve traceability from measured conditions to selected actions and verified outcomes. The paper offers testable propositions, an implementation roadmap, asset-specific application protocols, and a research agenda. The framework supports case-study testing and quantitative extension without claiming universal performance before field validation.

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Keywords: methane-emission reduction, process engineering, reliability, process safety, risk management, asset integrity, environmental performance, decision framework

Introduction

Effective methane reduction joins measurement, maintenance, process control, flare performance, and reporting into one operating discipline. In the context of methane-emission reduction, methane losses arise from fugitive leaks, vents, pneumatic devices, tanks, compressors, incomplete combustion, maintenance activity, and abnormal operations. Local actions affect adjacent equipment, utilities, product quality, emissions, workforce exposure, and supply continuity. A defensible framework must therefore define both the physical process and the decision system through which evidence becomes action. Introduction is central to methane-emission reduction because methane losses arise from fugitive leaks, vents, pneumatic devices, tanks, compressors, incomplete combustion, maintenance activity, and abnormal operations. The analysis should define the industrial problem, explain its system consequences, and state the paper objectives. For compressor stations, the decision model must represent tank flashing, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Risk

and abatement ranking supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. National-level accounting confirms that even small fractional losses from compressor-station tank flashing can offset a large share of the climate benefit that switching from coal to gas is intended to deliver (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2012) (Eyetsemitan & Fadayomi, 2022; Nnabueze & Akokodaripon, 2021; Akomolafe & Agu, 2018) (Eyetsemitan *et al*., 2022; Oyeleye *et al*., 2022). (Omara *et al*., 2016; Peischl *et al*., 2016; Peischl *et al*., 2013)

Introduction is central to methane-emission reduction because methane losses arise from fugitive leaks, vents, pneumatic devices, tanks, compressors, incomplete combustion, maintenance activity, and abnormal operations. The analysis should define the industrial problem, explain its system consequences, and state the paper objectives. For storage assets, the decision model must represent malfunctioning flares, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Repair and replacement planning supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. Satellite-based nightfire detection of flare radiant heat provides an independent, facility-level check on reported flaring volumes and helps flag malfunctioning flares such as those affecting storage assets (Elvidge, Zhizhin, Baugh, Hsu, & Ghosh, 2016) (Obogo & Arumosoye, 2021) (Obogo *et al*., 2021; Arumosoye & Obriki, 2018). (Yacovitch *et al*., 2014; Zimmerle *et al*., 2015; Orise & Niniola, 2022)

Introduction is central to methane-emission reduction because methane losses arise from fugitive leaks, vents, pneumatic devices, tanks, compressors, incomplete combustion, maintenance activity, and abnormal operations. The analysis should define the industrial problem, explain its system consequences, and state the paper objectives. For transmission and distribution interfaces, the decision model must represent release during maintenance, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Verification of reduction supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. Pipeline safety management system standards formalize the governance expectations that apply when transmission and distribution interfaces experience planned or unplanned releases during maintenance (American Petroleum Institute, 2015). Independent atmospheric surveys of urban distribution networks similarly show that maintenance-related and leak-related releases from transmission and distribution interfaces can dominate local methane budgets even as system-wide emission rates decline over time (Lamb *et al*., 2015; McKain *et al*., 2015) (Adegbite & Ahmed, 2022; Arumosoye & Obriki, 2020) (Obogo *et al*., 2022; Obogo *et al*., 2020; Arumosoye & Obriki, 2020).

Theoretical Framework

Methane-control planning depends on traceable emission scenarios, measurement quality, control performance, and assigned responsibility (Kaplan & Garrick, 1981; Reason, 1997; Center for Chemical Process Safety, 2007; International Organization for Standardization, 2018). These four foundations anchor the conceptual framework developed in this paper. The quantitative definition of risk as a set of scenarios, likelihoods, and consequences supplies the vocabulary in which methane sources, detection limits, and downstream effects are compared across asset classes (Kaplan & Garrick, 1981). Organizational-accident theory explains why a locally acceptable condition, such as a single unrepaired leak or an impaired safeguard, can align with weaknesses elsewhere in the system to produce a larger loss, which is why the framework insists on traceability from measured conditions to verified outcomes rather than treating each decision in isolation (Reason, 1997). Risk-based process safety guidance translates that theory into an auditable management system of hazard identification, risk assessment, and continuous improvement, the same logic that structures the eight decision functions, comprising source inventory development, measurement technology selection, emission quantification, risk and abatement ranking, repair and replacement planning, verification of reduction, data-quality assurance, and management review, proposed here (Center for Chemical Process Safety, 2007). The international risk-management standard contributes the generic cycle of establishing context, assessing risk, treating risk, and monitoring and reviewing outcomes that this paper adapts into a measurement-to-mitigation architecture spanning well sites, gathering systems, processing facilities, compressor stations, storage assets, and transmission and distribution interfaces (International Organization for Standardization, 2018). Global technical-mitigation-potential assessments treat these interfaces as a single system whose abatement costs and opportunities must be evaluated together rather than asset class by asset class, a framing consistent with national inventory accounting compiled under the Greenhouse Gas Reporting Program (Höglund-Isaksson, 2012; U.S. Environmental Protection Agency, 2022) (Atta & Adenuga, 2020; Mbonu & Uzoka, 2022a; Anene & Clement, 2022) (Mbonu *et al*., 2022; Arumosoye & Obriki, 2021; Mbonu *et al*., 2018).

System Boundary and Functional Requirements is central to methane-emission reduction because methane losses arise from fugitive leaks, vents, pneumatic devices, tanks, compressors, incomplete combustion, maintenance activity, and abnormal operations. The analysis should identify physical, information, utility, organizational, and market interfaces. For compressor stations, the decision model must represent tank flashing, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Measurement technology selection supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently

precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. Framing compressor-station boundaries around asset-management principles clarifies how tank-flashing risk is owned, funded, and reviewed across the asset life cycle (International Organization for Standardization, 2014). Regional atmospheric studies of production and gathering infrastructure confirm that asset-management boundaries drawn around individual compressor stations can understate basin-level tank-flashing contributions unless aggregated with nearby sources (Barkley *et al*., 2017) (Adeyelu, 2021; Atakpa & Abetoh, 2022; Edivri & Oteri, 2022) (Ogbete *et al*., 2021; Adeyelu, 2021).

System Boundary and Functional Requirements is central to methane-emission reduction because methane losses arise from fugitive leaks, vents, pneumatic devices, tanks, compressors, incomplete combustion, maintenance activity, and abnormal operations. The analysis should identify physical, information, utility, organizational, and market interfaces. For storage assets, the decision model must represent malfunctioning flares, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Emission quantification supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. Interface definitions for storage assets should treat flare header capacity and reliability as a functional requirement, since national flaring inventories show that malfunctioning or under-sized flares remain a persistent source of avoidable loss (World Bank, 2021). Direct measurements of flare plumes in shale production regions confirm that combustion efficiency, not flare header capacity alone, governs how much of the vented stream at storage assets is actually destroyed (Gvakharia *et al*., 2017) (Michael & Ogunsola, 2021a).

System Boundary and Functional Requirements is central to methane-emission reduction because methane losses arise from fugitive leaks, vents, pneumatic devices, tanks, compressors, incomplete combustion, maintenance activity, and abnormal operations. The analysis should identify physical, information, utility, organizational, and market interfaces. For transmission and distribution interfaces, the decision model must represent release during maintenance, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Risk and abatement ranking supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. Quantitative risk analysis of shared-ditch pipeline corridors demonstrates that transmission and distribution interfaces require joint consideration of third-party damage and maintenance-related release scenarios when system boundaries are defined (Zhang, Qin, & Wang, 2019) (Ogbete & Ambali, 2021) (Aminu-Ibrahim *et al*., 2019; Aminu-Ibrahim *et al*., 2018).

Methodology

Conceptual Review Method is central to methane-emission reduction because methane losses arise from fugitive leaks, vents, pneumatic devices, tanks, compressors, incomplete combustion, maintenance activity, and abnormal operations. The analysis should describe source selection, cutoff control, thematic coding, and synthesis logic. For well sites, the decision model must represent undetected fugitive leakage, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Data-quality assurance supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. Direct measurement campaigns at well sites have shown that a small subset of components accounts for a disproportionate share of undetected fugitive leakage, a skewed distribution with direct implications for inventory design (Allen *et al*., 2013). Complementary synthesis work reconciling bottom-up component counts with top-down basin measurements reinforces the conclusion that well-site inventories built solely from component factors understate total loss (Allen, 2014) (Oyeleye & Fadayomi, 2022) (Eyetsemitan *et al*., 2020; Aneke & Adesemoye, 2019).

Conceptual Review Method is central to methane-emission reduction because methane losses arise from fugitive leaks, vents, pneumatic devices, tanks, compressors, incomplete combustion, maintenance activity, and abnormal operations. The analysis should describe source selection, cutoff control, thematic coding, and synthesis logic. For gathering systems, the decision model must represent high-bleed pneumatic operation, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Management review supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. Field measurements of pneumatic controllers indicate that high-bleed devices in gathering systems emit substantially more methane than manufacturer specifications suggest, supporting device replacement as a priority abatement option (Allen *et al*., 2015). Later work attributing atmospheric methane to specific anthropogenic source categories, and characterizing spatial and temporal variability in hydrocarbon source fingerprints across shale production regions, supports treating high-bleed pneumatic devices as a persistent rather than isolated source category (Allen, 2016; Allen, Cardoso-Saldana, & Kimura, 2017) (Okoruwa & Abolaji, 2020; Obogo & Obriki, 2020b) (Obogo *et al*., 2020).

Conceptual Review Method is central to methane-emission reduction because methane losses arise from fugitive leaks, vents, pneumatic devices, tanks, compressors, incomplete combustion, maintenance activity, and abnormal operations. The analysis should describe source selection, cutoff control, thematic coding, and synthesis logic. For processing facilities, the decision model must represent compressor seal

venting, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Source inventory development supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. Direct measurements at compressor stations show that seal venting and blowdown events can dominate facility-level methane emissions even when routine component leaks are well controlled (Subramanian *et al*., 2015). A companion measurement campaign at the same gathering and processing sites reached consistent conclusions using an independent sampling protocol, strengthening confidence that the result is not an artifact of a single measurement method (Mitchell *et al*., 2015) (Okonkwo & Mayo, 2019).

Findings and Discussion

The Proposed Framework

Well-site methane control ultimately rests on understanding why equipment fails, not just cataloguing that it does. Undetected fugitive leakage is the failure mode this review has to explain in mechanical terms: how it starts, where current detection methods reach their limits, what safeguards are already built in, how long a fix takes once the leak is found, and what the wider consequences are if it goes unnoticed. Repair and replacement planning records help build that explanation, but a maintenance log alone cannot certify that the underlying technical picture is sound. What is needed alongside it is a plain trail showing when each piece of data was gathered, under what operating mode, how much uncertainty it carries, which model version it fed into, and who is responsible for the conclusion drawn from it. Without that trail, a confident-sounding finding can rest on assumptions nobody actually tested, and once operations move on, there is no way to bring new field evidence back to revise the earlier judgment. Because corrosion-driven component failure is a recognized precursor to undetected fugitive leakage at well sites, corrosion-control practice is a governing mechanism that belongs inside the technology review rather than outside it (Ilodigwe & Adesemoye, 2019b; Atakpa & Abolaji, 2022; Dagodzo & Ahiaeke Patrick, 2022) (Dagodzo & Aliliele, 2022; Dagodzo & Ahiaeke, 2022).

High-bleed pneumatic operation is the specific failure this stage of the framework is built to explain for gathering systems, not fugitive leaks in general. That means tracing how the high-bleed condition develops, the sensitivity limits of the detection equipment on hand, the safeguards already engineered into the system, the time a repair crew needs to restore normal operation, and the effects that spread downstream if the condition persists. Verification-of-reduction figures are part of the case for how well the equipment is actually functioning, but one measurement round is rarely proof enough on its own. Instead, whoever performs the review has to note the date and origin of each reading, the operating mode at the time, the uncertainty in the measurement, the version of any model applied, and the person accountable for the result. That level of bookkeeping is what keeps an apparently clean reading from covering up assumptions that were never actually checked, and it is also what keeps the door open for a later field inspection to overturn or refine the earlier conclusion. Non-destructive testing and integrity-management practice for process equipment supply an independent check on the mechanical condition that governs whether high-bleed pneumatic devices and associated fittings continue to perform as designed.

At processing facilities, the technology-fundamentals question narrows to a specific mechanical failure: compressor seal venting. A useful review has to describe how seal venting begins, the blind spots in current detection, the safeguards that already exist, the recovery timeline once venting is caught, and what happens further along the process if it is not addressed quickly. Data-quality-assurance checks contribute evidence toward that description, but checking the data once is not the same as proving the underlying technical case is airtight. The missing piece is a documented history: where the input came from and when, what operating mode applied, how uncertain the number is, which model version processed it, and who signed off on the conclusion. That history is what stops a seemingly solid number from quietly resting on assumptions no one verified, and it is what lets a later shift in operating conditions actually change the technical conclusion instead of being noted somewhere and ignored. Weld-integrity evaluation methods developed for high-capacity infrastructure are directly transferable to compressor seal and casing welds, where undetected degradation is a recurring cause of seal venting (Atta & Adenuga, 2021).

Setting data and measurement requirements for well sites starts with a decision about which variables to track, what quality thresholds they must clear, how conflicting readings get reconciled, how uncertainty is stated, and how each number can be traced back to where it came from. Because undetected fugitive leakage is the failure this stage exists to catch, the plan needs to spell out how such a leak begins, the sensitivity limits of the detection method used, the safeguards already available, how quickly recovery is possible, and the effects further downstream if the leak persists. Emission-quantification totals contribute to the picture, though a single figure cannot on its own vouch for the technical soundness of the whole approach. The reviewer's task is to attach a record to every input, when and where it was measured, under what operating conditions, with what uncertainty, on which model version, and under whose accountability, so that an impressively precise-looking number cannot quietly rest on assumptions nobody checked, and so that field experience gathered later still has a way back into the decision instead of being logged and forgotten. Controlled-release testing of optical gas imaging cameras shows that detection sensitivity varies with wind speed, distance, and operator training, evidence that should inform how well-site measurement data are qualified (Ravikumar, Wang, & Brandt, 2017).

Gathering-system data requirements follow the same basic questions as elsewhere in the framework, which variables to track, what counts as acceptable quality, how discrepancies are resolved, how uncertainty is expressed, and how traceability is maintained, but here they are applied specifically to high-bleed pneumatic operation. The plan has to address how that condition develops, the limits of current detection, the safeguards already in place, the time needed to restore normal operation, and what happens downstream if the condition is left unresolved. Risk-and-abatement-ranking scores draw on this data, yet a ranking built from one dataset is not, by itself, evidence that the underlying numbers are technically sound. What is required in addition is a note of the source and date behind each figure, the operating mode,

the measurement uncertainty, the model version, and the person accountable for it, since that is what stops a confident-looking ranking from concealing assumptions that were never tested and what allows a later change in field conditions to actually revise the ranking rather than being recorded somewhere separate and ignored. Comparisons of airborne measurement campaigns with facility-level inventories in Alberta's gathering systems found that reported emission factors systematically understated observed methane loss (Johnson, Tyner, Conley, Schwietzke, & Zavala-Araiza, 2017) (International Organization for Standardization, 2015). Processing facilities pose their own version of the data-and-measurement question, still centered on which variables matter, what quality rules govern them, how discrepancies are reconciled, how uncertainty is captured, and how traceability is preserved, but applied here to compressor seal venting. The requirement is to represent how venting starts, the limits of what current detection can catch, the safeguards already engineered in, the time to recover once venting is found, and the effects that follow downstream. Repair-and-replacement-planning figures are useful supporting evidence, though no one dataset is enough by itself to demonstrate that the technical basis holds up. The reviewer's job is still to keep a record of the source and date of each input, the operating mode, the measurement uncertainty, the model version, and who is accountable, because that is what keeps a precise-seeming figure from resting on assumptions no one has actually confirmed, and what leaves room for field data gathered later to revise the picture instead of sitting untouched in a separate file. National measurement synthesis of gathering and processing facilities shows wide site-to-site variability in methane loss rates, underscoring why processing-facility data quality rules must capture operating mode rather than nameplate capacity alone (Marchese *et al*., 2015). The measurement protocols underlying that synthesis, published separately, document the tracer-release and mobile-sampling methods that make the site-to-site comparison possible (Roscioli *et al*., 2015) (Ilodigwe & Adesemoye, 2021).

A model is only as trustworthy as the separation it maintains between its assumptions, its calibration evidence, its sensitivity tests, and the limits at which it is considered acceptable, and for well sites that separation has to be organized around undetected fugitive leakage. The model needs to represent how such a leak initiates, the limits of the detection method assumed, the safeguards credited to the system, how quickly recovery is expected, and the effects the model assigns downstream. Source-inventory figures feed the calibration, but an inventory drawn from one source is not sufficient proof that the model's technical basis is sound. What has to travel alongside the model is a record of where each input came from and when, the operating mode, its uncertainty, the model version it was used in, and who is accountable for the result, since that record is what keeps a confident-looking model output from resting on assumptions no one actually tested, and it is what lets new field data correct the model later instead of the model staying fixed while the record sits elsewhere, unused. Efforts to close the gap between component-level inventories and top-down atmospheric measurements have shown that well-site emission factors used in many inventories understate actual loss, a finding directly relevant to model calibration (Rutherford *et al*., 2021). Earlier national-scale accounting of anthropogenic methane sources in the United States reached a similar conclusion using atmospheric inversion methods, supporting the case for calibrating well-site models against independent top-down evidence (Miller *et al*., 2013).

Validating a gathering-system model means testing whether its assumptions, calibration data, and sensitivity results actually hold up, rather than accepting the stated acceptance limits without question, and the failure mode that testing has to center on is high-bleed pneumatic operation. The model must represent how that operation begins, the limits of the detection technology assumed, the safeguards it credits, the expected recovery time, and the downstream effects it predicts. Measurement-technology-selection data feeds the calibration, but selecting one measurement method is not, on its own, evidence that the model is technically adequate. Alongside the model there still has to be a record of source and date, operating mode, measurement uncertainty, model version, and accountable owner for each input used, because that record is what prevents a plausible-looking model output from concealing assumptions that were never actually verified, and it is what keeps the model open to correction once new operating data arrives rather than closed off in a file no one revisits. Early aircraft-based mass-balance measurements over a gas-producing region found total methane emissions several times higher than bottom-up gathering-system inventories, motivating the verification step built into this framework (Karion *et al*., 2013). Follow-on aircraft-based campaigns over the Barnett Shale region and the Four Corners area likewise found total methane emissions exceeding bottom-up expectations, indicating that the discrepancy identified in gathering systems generalizes across basins (Karion *et al*., 2015; Kort *et al*., 2014) (Atakpa, 2021).

Compressor seal venting is the failure mode against which a processing-facility model's assumptions, calibration inputs, sensitivity results, and acceptance limits have to be checked. The model needs to capture how venting starts, what current detection is able to catch, the safeguards it assumes, the recovery time it expects, and the downstream effects it forecasts. Emission-quantification numbers support the calibration, but quantifying emissions once does not, by itself, establish that the model's technical foundation is reliable. What is still required is a documented trail, source and date, operating mode, measurement uncertainty, model version, accountable owner, for every input the model relies on, since that trail is what keeps a precise-seeming model result from disguising assumptions that were never actually tested, and it is what lets later field measurements revise the model instead of the model staying frozen while the evidence accumulates elsewhere. Reconciliation studies comparing top-down and bottom-up estimates for processing-facility methane attribute much of the discrepancy to a small population of high-emitting sites rather than to uniform underreporting (Zavala-Araiza *et al*., 2015). Isotope-based global accounting of fossil-fuel methane sources corroborates the conclusion that bottom-up processing-facility inventories have historically understated total emissions (Schwietzke *et al*., 2016).

Screening, Risk, and Assurance Considerations

Ranking sources, assets, technologies, and interventions is the point of the screening stage, and at compressor stations that ranking has to be organized around tank flashing as the failure case that matters most. The criteria need to reflect how flashing starts, the limits of the detection method in use, the safeguards already available, the time needed to bring it

under control, and the effects that follow downstream once it happens. Verification-of-reduction results feed into the ranking, but a single verification round does not, on its own, prove that the screening criteria rest on sound technical ground. What closes that gap is a record attached to each input: its source and date, the operating mode, the measurement uncertainty, the model version, and the person accountable for it. That record keeps a tidy-looking screening score from hiding assumptions no one has actually tested, and it means a later change in field conditions can still move a source up or down the ranking instead of the ranking staying fixed while new evidence piles up elsewhere. Classical process-hazard analysis of tank flashing and vapor release scenarios provides the consequence-severity inputs that a methane-focused screening criterion must still incorporate alongside emission volume (Mannan, 2012). Comparable lifecycle risk framing has been proposed for offshore produced water management, which similarly requires consequence severity to be paired with exposure frequency rather than assessed in isolation (Falegan & Aniebonam, 2022) (Obriki & Arumosoye, 2019) (Arumosoye & Obriki, 2022; Obriki & Arumosoye, 2019).

For storage assets, screening criteria have to be built around malfunctioning flares specifically, rather than treated as one item on a generic checklist. That means describing how a malfunction develops, the limits of the detection approach used, the safeguards already engineered in, the recovery time once the malfunction is identified, and the effects that follow if it is not caught quickly. Data-quality-assurance checks support the ranking, but running a quality check once does not, by itself, establish that the technical case behind the ranking is sound. The reviewer still needs to keep a record of source and date, operating mode, measurement uncertainty, model version, and accountable owner for every input feeding into the ranking, because that is what keeps a confident-sounding priority list from resting on assumptions nobody checked, and what allows new field evidence to change a storage asset's position in the ranking rather than the ranking staying static while the evidence sits unused elsewhere. Airborne imaging spectrometer surveys over a major gas-producing region found that a small number of point sources, including storage-related releases, accounted for a large share of total observed methane (Frankenberg *et al*., 2016). A subsequent satellite-based case study of a large uncontrolled release demonstrated that multisatellite imaging can independently quantify a storage-related point-source event of the same kind (Cusworth *et al*., 2021).

Transmission and distribution interfaces need a screening criterion built specifically around release during maintenance, since that is the scenario most likely to be missed by a generic ranking scheme. The criterion has to capture how such a release begins, the limits of what current detection can see, the safeguards already available, the time required to recover, and the effects that follow downstream. Management-review findings support the ranking, but one review cycle is not, by itself, proof that the ranking rests on sound technical ground. What is still needed is a record of source and date, operating mode, measurement uncertainty, model version, and accountable owner attached to every input used, since that is what keeps a seemingly precise ranking from concealing assumptions no one actually confirmed, and what leaves the ranking open to revision once later field experience becomes available, rather than fixed and filed away. Space-based imaging spectroscopy of a large storage-facility blowout demonstrated that remote sensing can quantify an extreme release from transmission and distribution interfaces in near real time, evidence summarized alongside the framework's decision stages in Table 1 (Thompson *et al*., 2016). Geostationary satellite concepts proposed for urban and industrial regions extend this real-time detection logic beyond dedicated methane missions (O'Brien *et al*., 2016).

Figure 1 uses an illustrative intervention portfolio to show the balance among detection, prioritization, repair, verification, and recurrence prevention. Table 1 instead defines the operational metrics used to measure detection performance, repair quality, recurrence, and abatement value.

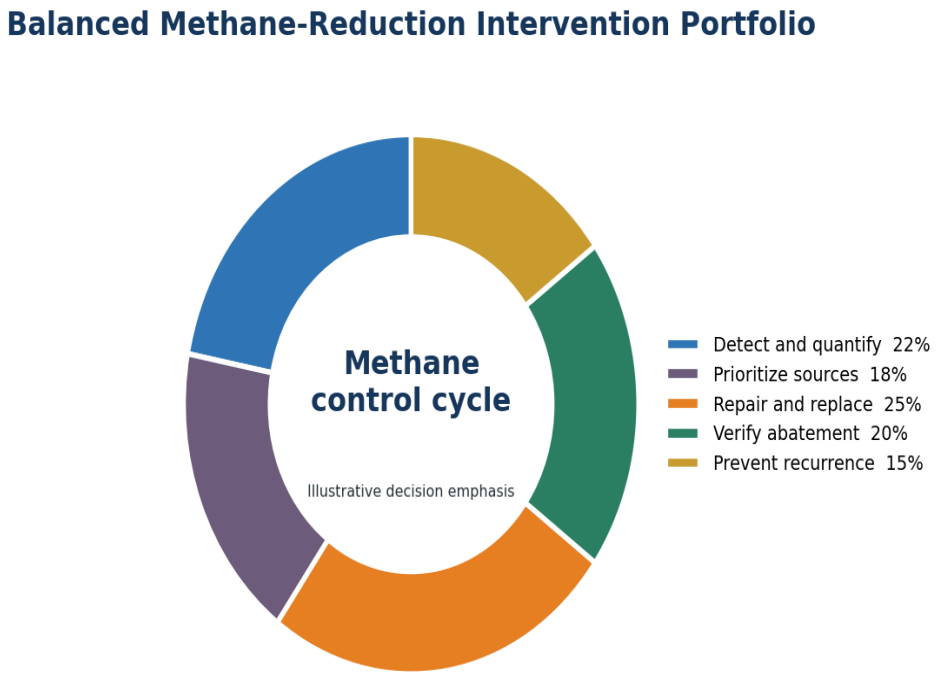


Fig 1: Illustrative decision emphasis across the methane-reduction intervention cycle.

Table 1: Operational Metrics for Evaluating Methane-Reduction Program Performance

Metric area	Recommended indicator	Interpretation	Operational response
Source prevalence	Sources per facility	Extent of the emission population	Set survey coverage
Emission magnitude	Mass rate by source class	Contribution of each source category	Prioritize high emitters
Intermittency	Active-emission frequency	Likelihood of missing episodic events	Adjust monitoring frequency
Detection performance	Probability of detection	Sensitivity at relevant release rates	Select monitoring methods
Repair speed	Median days to repair	Responsiveness after detection	Escalate delayed work
Repair quality	Post-repair verification rate	Evidence of effective closure	Repeat failed repairs
Recurrence	Repeat leaks by component	Persistence of underlying causes	Change equipment or practice
Cost effectiveness	Cost per tonne avoided	Economic efficiency of abatement	Allocate program funding

Tying loss scenarios to reliability, safety, emissions, and resource outcomes, for compressor stations, means tracing all four of those consequences back to tank flashing as the event that connects them. That requires setting out how flashing initiates, the limits of the detection method relied on, the safeguards already in the design, the time needed to recover once flashing occurs, and the effects that ripple downstream. Management-review findings support that analysis, but a review conducted once does not, on its own, confirm that the technical basis behind it is adequate. The reviewer still has to log the source and date of each input, the operating mode, the measurement uncertainty, the model version, and the accountable owner, because doing so keeps an apparently well-supported hazard conclusion from resting on assumptions that were never checked, and it means later operating data can still revise that conclusion instead of it being written down once and left alone. Synthesis of measurement studies across the natural gas supply chain concluded that total system leakage, including compressor-station losses, exceeded official inventory estimates, a gap with direct process-safety and reliability implications (Brandt *et al*., 2014). Later statistical work characterizing the extreme, heavy-tailed distribution of natural gas system leaks, together with basin-scale evidence that fugitive ethane accompanies unaccounted methane loss, situates compressor-station underreporting within a broader pattern (Brandt, Heath, & Cooley, 2016; Kort *et al*., 2016) (Arumosoye & Obriki, 2019) (Obogo *et al*., 2021).

Storage assets connect loss scenarios to reliability, safety, emissions, and resource outcomes through malfunctioning flares specifically, which is why this stage has to represent how such a malfunction starts, the limits of the detection method assumed, the safeguards already built into the system, the recovery time expected, and the effects that follow downstream. Source-inventory figures contribute to that picture, but building an inventory from a single source is not, by itself, sufficient to establish technical adequacy. What is still required is a record of source and date, operating mode, measurement uncertainty, model version, and accountable owner behind each input, since that record is what keeps a precise-looking conclusion from resting quietly on untested assumptions, and it is what allows field experience gathered afterward to correct the hazard picture instead of the analysis staying fixed while new evidence accumulates elsewhere. Life-cycle assessments of shale-gas systems show that upstream methane loss, including storage-related venting, can materially change the climate performance calculus used in resource-conservation decisions (Howarth, 2014). Sector-by-sector assessments of readily available mitigation measures reach a comparable conclusion, finding that near-term methane abatement, including at storage assets, delivers climate benefits on a materially faster timescale than carbon dioxide reductions alone (Ocko *et al*., 2021) (Obogo & Ozobu, 2021) (Obogo *et al*., 2021).

For transmission and distribution interfaces, release during maintenance is the event through which reliability, safety, emissions, and resource outcomes all have to be traced together, which means capturing how the release begins, the limits of the detection technology chosen, the safeguards already in place, the recovery time involved, and the downstream effects that result. Measurement-technology-selection evidence supports this analysis, but selecting one measurement approach does not, on its own, confirm that the technical basis is sound. The reviewer still records source and date, operating mode, measurement uncertainty, model version, and accountable owner for each input, because that record is what stops an apparently precise hazard finding from hiding weak assumptions, and it is what lets operating experience gathered later revise the finding instead of the finding staying fixed in a file no one returns to. Regional aircraft surveys over shale development found localized methane enhancements consistent with maintenance-related releases at transmission and distribution interfaces, supporting the inclusion of upset conditions in hazard identification (Caulton *et al*., 2014). Basin-level aircraft measurements over comparable shale gas production regions similarly attribute a meaningful share of total methane loss to upset and maintenance-related conditions rather than steady-state operation (Peischl *et al*., 2015) (Obogo & Ozobu, 2019) (Obogo *et al*., 2019; Obogo *et al*., 2019).

Turning design assumptions into working operating limits, for compressor stations, means setting those limits around tank flashing rather than around loss scenarios in general. The limits need to reflect how flashing initiates, the limits of the detection method used, the safeguards already credited, the recovery time expected, and the downstream effects assumed. Risk-and-abatement-ranking data supports where those limits are set, but a ranking exercise conducted once is not, by itself, proof that the underlying technical case is sound. What still has to accompany the limits is a record of source and date, operating mode, measurement uncertainty, model version, and accountable owner for each input, because that record keeps a confidently stated limit from resting on assumptions nobody checked, and it means the limit can be adjusted once real operating experience comes in rather than staying fixed while that experience sits filed elsewhere. Statistical analysis of leak-size distributions shows that methane releases, including tank-flashing events at compressor stations, follow a heavy-tailed pattern in which a small number of excursions dominate total loss (Brandt, Heath, & Cooley, 2016) (Abayomi *et al*., 2021).

Storage assets need daily operating limits and excursion-response rules built specifically around malfunctioning flares, since a generic set of limits will not catch that failure mode reliably. The limits have to reflect how the malfunction starts, the limits of available detection, the safeguards already

in place, how long recovery takes, and the effects that follow downstream. Repair-and-replacement-planning records inform where those limits should sit, but planning data alone does not establish that the underlying technical basis is adequate. What has to travel with the limits is a record of source and date, operating mode, measurement uncertainty, model version, and accountable owner, since that is what keeps a precise-sounding limit from concealing untested assumptions, and it is what allows later operating experience to move the limit rather than leaving it fixed while the evidence accumulates in a separate file. Satellite retrievals of atmospheric methane columns give operators an independent, facility-external signal for updating excursion thresholds at storage assets between scheduled inspections (Jacob *et al*., 2016). International coordination efforts launched around the same period formalize the expectation that such independent, facility-external signals be used to hold national reduction commitments accountable (Global Methane Pledge, 2021) (Eze & Akinleye, 2022b).

For transmission and distribution interfaces, the operating envelope has to be drawn around release during maintenance, which means addressing how such a release begins, the limits of detection technology, the safeguards already built in, the recovery time involved, and the downstream effects that follow. Verification-of-reduction data supports where the limits are set, but a single verification exercise does not, on its own, confirm that the technical basis is sound. The reviewer still keeps a record of source and date, operating mode, measurement uncertainty, model version, and accountable owner behind each input, because without it a precise-looking limit can quietly rest on assumptions no one has tested, whereas with it, later operating experience remains free to move the limit instead of leaving it fixed in a file that is never revisited. Next-generation imaging spectrometers are shown to detect and quantify point-source releases from transmission and distribution interfaces at spatial resolutions fine enough to support excursion response rather than only annual reporting (Cusworth *et al*., 2019). Gridded national inventories built from facility-level activity data provide the baseline against which such fine-resolution detections at transmission and distribution interfaces must be reconciled (Maasakkers *et al*., 2016).

Prevention, detection, control, isolation, mitigation, and emergency layers each need separate evaluation rather than being treated as one blended defense, and for well sites that evaluation has to be built around undetected fugitive leakage: how it begins, the limits of the detection method credited, the safeguards already in the design, the recovery time expected, and the downstream effects assumed. Data-quality-assurance work supports that evaluation, but a single round of quality checks does not, by itself, confirm the technical basis behind the assurance case. What is still needed is a record of source and date, operating mode, measurement uncertainty, model version, and accountable owner for each input, since that record keeps an apparently solid assurance case from resting on weak assumptions, and it is what allows later operating experience to revise the case rather than leaving it fixed once written down. Classifying prevention, detection, control, and mitigation layers as distinct barrier functions, rather than a single generic safeguard, clarifies which layer is expected to catch undetected fugitive leakage at well sites (Sklet, 2006) (Atta & Adenuga, 2022).

Gathering systems require the same layer-by-layer scrutiny of prevention, detection, control, isolation, mitigation, and emergency response, applied here to high-bleed pneumatic operation, which means representing how that operation develops, the limits of detection available, the safeguards already engineered in, the recovery time needed, and the downstream effects if it is not addressed. Management-review findings support this evaluation, but a review cycle conducted once does not, on its own, establish that the technical case is adequate. The reviewer still records source and date, operating mode, measurement uncertainty, model version, and accountable owner for every input, because that record is what prevents a reassuring-looking assurance case from concealing assumptions that were never actually tested, and it is what lets field experience gathered later revise the case instead of the case staying fixed in a file no one revisits. Functional-safety standards for safety instrumented systems establish the proof-test intervals and impairment rules that should govern shutdown and isolation valves protecting high-bleed pneumatic circuits in gathering systems (International Electrotechnical Commission, 2016). Sensor-based fault detection frameworks developed for building mechanical systems illustrate how continuous monitoring logic, originally designed outside the oil and gas sector, can inform the interlock and alarm rules that protect high-bleed pneumatic circuits (Sunday & Omoegun, 2022) (Okojie & Abioye, 2020; Sunday & Oluokun, 2020; Sunday & Oluokun, 2019) (Ogbete *et al*., 2022; Mbonu *et al*., 2021).

At processing facilities, evaluating prevention, detection, control, isolation, mitigation, and emergency layers separately means applying that evaluation to compressor seal venting specifically: how venting starts, the limits of the detection method credited, the safeguards already in the design, the recovery time expected, and the effects that follow downstream. Source-inventory figures support that assurance case, but drawing on a single inventory does not, by itself, establish that the technical picture is sound. The reviewer still keeps a record of source and date, operating mode, measurement uncertainty, model version, and accountable owner for each input, because that record keeps a confident-looking assurance case from resting on untested assumptions, and it lets later operating experience feed back into the case instead of the case being logged once and left alone. Commercial point-source imaging satellites now provide repeat coverage sufficient to test whether a compressor seal-venting repair remained effective after closure, extending barrier-assurance testing beyond periodic site visits (Jervis *et al*., 2021). Independent facility-level comparisons of methane emission estimates in a separate shale play reached consistent conclusions about the durability of compressor seal repairs across measurement techniques (Zimmerle *et al*., 2017) (Mbonu & Uzoka, 2021b) (Mbonu *et al*., 2021; Akpe *et al*., 2022).

Connecting capital cost, operating cost, downtime, recovery value, emissions, and uncertainty into one economic picture, for compressor stations, means running that connection through tank flashing rather than through loss scenarios generally. The analysis has to address how flashing starts, the limits of the detection method chosen, the safeguards already available, the recovery time expected, and the effects that follow downstream. Measurement-technology-selection data supports the economic case, but choosing one measurement method does not, on its own, establish that the underlying technical basis is adequate. What still has to accompany the economic figures is a record of source and date, operating mode, measurement uncertainty, model version, and

accountable owner for each input, because that record keeps a favorable-looking economic result from resting on assumptions nobody checked, and it means later operating experience can still adjust the economic picture instead of it being fixed once and filed away. Controlled-release testing of airborne hyperspectral detection found that per-flight survey costs compare favorably with the value of gas recovered from tank-flashing and other compressor-station losses once methane price is included (Sherwin, Chen, Ravikumar, & Brandt, 2021).

Storage assets require the same economic connection between capital, operating cost, downtime, recovery, emissions, and uncertainty, applied here to malfunctioning flares as the event driving the economics. The analysis needs to represent how the malfunction starts, the limits of the detection method used, the safeguards already in place, the recovery time expected, and the downstream effects assumed. Emission-quantification figures support that economic picture, but quantifying emissions once does not, by itself, confirm that the technical basis is sound. What still has to travel with the economic figures is a record of source and date, operating mode, measurement uncertainty, model version, and accountable owner for each input, because that record is what keeps an attractive economic outcome from concealing weak assumptions, and it is what lets operating experience gathered afterward revise the economics rather than leaving them fixed in a separate record. Marginal-abatement-cost analysis of the global oil and gas sector finds that many storage-related flaring and venting reductions can be achieved at negative net cost once recovered gas is sold (International Energy Agency, 2020). Techno-economic reviews of the broader natural gas supply chain reach a consistent conclusion, estimating that a substantial share of storage-related flaring and venting emissions can be avoided using existing, commercially available technology (Heath *et al*., 2014; Heath, Warner, Steinberg, & Brandt, 2015) (Efobi & Fasawe, 2022b; Ogbole & Akeju, 2021; Dagodzo & Aliliele, 2022) (Mbonu *et al*., 2020; Dagodzo *et al*., 2022).

For transmission and distribution interfaces, tying capital cost, operating cost, downtime, recovery, emissions, and uncertainty together means running that analysis through release during maintenance, the event that most affects the economics here. The analysis has to represent how the release begins, the limits of current detection, the safeguards already available, the recovery time involved, and the effects that follow downstream. Risk-and-abatement-ranking evidence supports the economic case, but a ranking built from one exercise does not, on its own, establish that the technical basis is adequate. What still has to travel alongside the figures is a record of source and date, operating mode, measurement uncertainty, model version, and accountable owner, since that record prevents an apparently favorable economic result from hiding untested assumptions, and it allows later operating experience to update the economics instead of leaving them recorded once and untouched. Standardized greenhouse gas quantification methodologies for transmission and distribution assets are needed so that techno-economic comparisons across operators use consistent emission factors and measurement bases (American Petroleum Institute, 2021). A synthesis of ground-level measurement campaigns across the U.S. natural gas supply chain reaches a consistent conclusion, finding that emission factors vary enough across operators and equipment types that consistent measurement bases remain a precondition for meaningful techno-economic comparison (Littlefield *et al*., 2017) (International Organization for Standardization, 2016).

Application Across Asset Classes

Emission-source inventory begins with a decision statement for well sites. The team must specify what evidence will support the decision, which operating modes are included, and which assumptions require later confirmation. For methane-emission reduction, this stage should detect, rank, repair, and verify methane sources while preserving production continuity and worker safety. The analysis should represent normal operation, startup, shutdown, turndown, maintenance, and credible upset conditions. Particular attention should be given to undetected fugitive leakage, because a locally acceptable condition may create a wider process, safety, environmental, or commercial consequence. Input records should identify source, timestamp, units, uncertainty, configuration, and accountable owner. A decision threshold should be approved before the final ranking is viewed. This reduces hindsight bias and prevents a favorable economic result from overriding mandatory safety or legal constraints. The resulting record should state the selected option, rejected alternatives, evidence gaps, interim controls, and residual-risk authority.

Validation of emission-source inventory should use independent evidence from compressor stations wherever feasible. Acceptance should depend on observable performance rather than completion of a report or work order. Suitable measures include availability, detection coverage, response time, product compliance, avoided loss, energy intensity, maintenance burden, and verified risk reduction. The team should test sensitivity to uncertain supply, composition, equipment condition, utility availability, market conditions, and model error. A credible adverse case should include tank flashing and the loss of one important safeguard or dependency. Differences between predicted and observed performance should trigger model review, not informal adjustment of the acceptance limit. Management of change should capture revised drawings, procedures, training, spares, software versions, alarm settings, and inspection requirements. This verification loop converts methane-emission reduction from a one-time study into a controlled operating capability. It also supplies comparable evidence for future investment and risk decisions (Akpe *et al*., 2021).

Measurement technology selection begins with a decision statement for gathering pipelines. The team must specify what evidence will support the decision, which operating modes are included, and which assumptions require later confirmation. For methane-emission reduction, this stage should detect, rank, repair, and verify methane sources while preserving production continuity and worker safety. The analysis should represent normal operation, startup, shutdown, turndown, maintenance, and credible upset conditions. Particular attention should be given to high-bleed pneumatic operation, because a locally acceptable condition may create a wider process, safety, environmental, or commercial consequence. Input records should identify source, timestamp, units, uncertainty, configuration, and accountable owner. A decision threshold should be approved before the final ranking is viewed. This reduces hindsight bias and prevents a favorable economic result from overriding mandatory safety or legal constraints. The resulting record should state the selected option, rejected alternatives, evidence gaps, interim controls, and residual-

risk authority (Bello & Bolaji, 2022).

Validation of measurement technology selection should use independent evidence from processing facilities wherever feasible. Acceptance should depend on observable performance rather than completion of a report or work order. Suitable measures include availability, detection coverage, response time, product compliance, avoided loss, energy intensity, maintenance burden, and verified risk reduction. The team should test sensitivity to uncertain supply, composition, equipment condition, utility availability, market conditions, and model error. A credible adverse case should include incomplete flare combustion and the loss of one important safeguard or dependency. Differences between predicted and observed performance should trigger model review, not informal adjustment of the acceptance limit. Management of change should capture revised drawings, procedures, training, spares, software versions, alarm settings, and inspection requirements. This verification loop converts methane-emission reduction from a one-time study into a controlled operating capability. It also supplies comparable evidence for future investment and risk decisions (Dagodzo & Ahiaeke Patrick, 2021b; Ogbete & Ambali, 2020; Mbonu & Uzoka, 2021a) (Ogbete *et al*., 2020; Dagodzo & Ahiaeke, 2021; Mbonu *et al*., 2021).

Quantification and uncertainty analysis begins with a decision statement for compressor stations. The team must specify what evidence will support the decision, which operating modes are included, and which assumptions require later confirmation. For methane-emission reduction, this stage should detect, rank, repair, and verify methane sources while preserving production continuity and worker safety. The analysis should represent normal operation, startup, shutdown, turndown, maintenance, and credible upset conditions. Particular attention should be given to seal venting, because a locally acceptable condition may create a wider process, safety, environmental, or commercial consequence. Input records should identify source, timestamp, units, uncertainty, configuration, and accountable owner. A decision threshold should be approved before the final ranking is viewed. This reduces hindsight bias and prevents a favorable economic result from overriding mandatory safety or legal constraints. The resulting record should state the selected option, rejected alternatives, evidence gaps, interim controls, and residual-risk authority.

Validation of quantification and uncertainty analysis should use independent evidence from storage tanks wherever feasible. Acceptance should depend on observable performance rather than completion of a report or work order. Suitable measures include availability, detection coverage, response time, product compliance, avoided loss, energy intensity, maintenance burden, and verified risk reduction. The team should test sensitivity to uncertain supply, composition, equipment condition, utility availability, market conditions, and model error. A credible adverse case should include maintenance-related releases and the loss of one important safeguard or dependency. Differences between predicted and observed performance should trigger model review, not informal adjustment of the acceptance limit. Management of change should capture revised drawings, procedures, training, spares, software versions, alarm settings, and inspection requirements. This verification loop converts methane-emission reduction from a one-time study into a controlled operating capability. It also supplies comparable evidence for future investment and risk decisions (Adeyelu, 2020).

Risk-based source prioritization begins with a decision statement for processing facilities. The team must specify what evidence will support the decision, which operating modes are included, and which assumptions require later confirmation. For methane-emission reduction, this stage should detect, rank, repair, and verify methane sources while preserving production continuity and worker safety. The analysis should represent normal operation, startup, shutdown, turndown, maintenance, and credible upset conditions. Particular attention should be given to tank flashing, because a locally acceptable condition may create a wider process, safety, environmental, or commercial consequence. Input records should identify source, timestamp, units, uncertainty, configuration, and accountable owner. A decision threshold should be approved before the final ranking is viewed. This reduces hindsight bias and prevents a favorable economic result from overriding mandatory safety or legal constraints. The resulting record should state the selected option, rejected alternatives, evidence gaps, interim controls, and residual-risk authority.

Validation of risk-based source prioritization should use independent evidence from maintenance and blowdown systems wherever feasible. Acceptance should depend on observable performance rather than completion of a report or work order. Suitable measures include availability, detection coverage, response time, product compliance, avoided loss, energy intensity, maintenance burden, and verified risk reduction. The team should test sensitivity to uncertain supply, composition, equipment condition, utility availability, market conditions, and model error. A credible adverse case should include undetected fugitive leakage and the loss of one important safeguard or dependency. Differences between predicted and observed performance should trigger model review, not informal adjustment of the acceptance limit. Management of change should capture revised drawings, procedures, training, spares, software versions, alarm settings, and inspection requirements. This verification loop converts methane-emission reduction from a one-time study into a controlled operating capability. It also supplies comparable evidence for future investment and risk decisions (Filani & Wedraogo, 2022) (Ogbete *et al*., 2019).

Repair and replacement planning begins with a decision statement for storage tanks. The team must specify what evidence will support the decision, which operating modes are included, and which assumptions require later confirmation. For methane-emission reduction, this stage should detect, rank, repair, and verify methane sources while preserving production continuity and worker safety. The analysis should represent normal operation, startup, shutdown, turndown, maintenance, and credible upset conditions. Particular attention should be given to incomplete flare combustion, because a locally acceptable condition may create a wider process, safety, environmental, or commercial consequence. Input records should identify source, timestamp, units, uncertainty, configuration, and accountable owner. A decision threshold should be approved before the final ranking is viewed. This reduces hindsight bias and prevents a favorable economic result from overriding mandatory safety or legal constraints. The resulting record should state the selected option, rejected alternatives, evidence gaps, interim controls, and residual-risk authority (Ogbete *et al*., 2018).

Validation of repair and replacement planning should use

independent evidence from well sites wherever feasible. Acceptance should depend on observable performance rather than completion of a report or work order. Suitable measures include availability, detection coverage, response time, product compliance, avoided loss, energy intensity, maintenance burden, and verified risk reduction. The team should test sensitivity to uncertain supply, composition, equipment condition, utility availability, market conditions, and model error. A credible adverse case should include high-bleed pneumatic operation and the loss of one important safeguard or dependency. Differences between predicted and observed performance should trigger model review, not informal adjustment of the acceptance limit. Management of change should capture revised drawings, procedures, training, spares, software versions, alarm settings, and inspection requirements. This verification loop converts methane-emission reduction from a one-time study into a controlled operating capability. It also supplies comparable evidence for future investment and risk decisions (Dagodzo & Ahiaeke Patrick, 2021a).

Operational control of vents and flares begins with a decision statement for maintenance and blowdown systems. The team must specify what evidence will support the decision, which operating modes are included, and which assumptions require later confirmation. For methane-emission reduction, this stage should detect, rank, repair, and verify methane sources while preserving production continuity and worker safety. The analysis should represent normal operation, startup, shutdown, turndown, maintenance, and credible upset conditions. Particular attention should be given to maintenance-related releases, because a locally acceptable condition may create a wider process, safety, environmental, or commercial consequence. Input records should identify source, timestamp, units, uncertainty, configuration, and accountable owner. A decision threshold should be approved before the final ranking is viewed. This reduces hindsight bias and prevents a favorable economic result from overriding mandatory safety or legal constraints. The resulting record should state the selected option, rejected alternatives, evidence gaps, interim controls, and residual-risk authority (Center for Chemical Process Safety, 2016).

Validation of operational control of vents and flares should use independent evidence from gathering pipelines wherever feasible. Acceptance should depend on observable performance rather than completion of a report or work order. Suitable measures include availability, detection coverage, response time, product compliance, avoided loss, energy intensity, maintenance burden, and verified risk reduction. The team should test sensitivity to uncertain supply, composition, equipment condition, utility availability, market conditions, and model error. A credible adverse case should include seal venting and the loss of one important safeguard or dependency. Differences between predicted and observed performance should trigger model review, not informal adjustment of the acceptance limit. Management of change should capture revised drawings, procedures, training, spares, software versions, alarm settings, and inspection requirements. This verification loop converts methane-emission reduction from a one-time study into a controlled operating capability. It also supplies comparable evidence for future investment and risk decisions (Obriki & Arumosoye, 2018; Obriki & Arumosoye, 2022a) (Obriki *et al*., 2022; Obriki & Arumosoye, 2018; Obriki & Arumosoye, 2020).

Verification of emission reductions begins with a decision statement for well sites. The team must specify what evidence will support the decision, which operating modes are included, and which assumptions require later confirmation. For methane-emission reduction, this stage should detect, rank, repair, and verify methane sources while preserving production continuity and worker safety. The analysis should represent normal operation, startup, shutdown, turndown, maintenance, and credible upset conditions. Particular attention should be given to undetected fugitive leakage, because a locally acceptable condition may create a wider process, safety, environmental, or commercial consequence. Input records should identify source, timestamp, units, uncertainty, configuration, and accountable owner. A decision threshold should be approved before the final ranking is viewed. This reduces hindsight bias and prevents a favorable economic result from overriding mandatory safety or legal constraints. The resulting record should state the selected option, rejected alternatives, evidence gaps, interim controls, and residual-risk authority.

Validation of verification of emission reductions should use independent evidence from compressor stations wherever feasible. Acceptance should depend on observable performance rather than completion of a report or work order. Suitable measures include availability, detection coverage, response time, product compliance, avoided loss, energy intensity, maintenance burden, and verified risk reduction. The team should test sensitivity to uncertain supply, composition, equipment condition, utility availability, market conditions, and model error. A credible adverse case should include tank flashing and the loss of one important safeguard or dependency. Differences between predicted and observed performance should trigger model review, not informal adjustment of the acceptance limit. Management of change should capture revised drawings, procedures, training, spares, software versions, alarm settings, and inspection requirements. This verification loop converts methane-emission reduction from a one-time study into a controlled operating capability. It also supplies comparable evidence for future investment and risk decisions.

Data governance and continuous improvement begins with a decision statement for gathering pipelines. The team must specify what evidence will support the decision, which operating modes are included, and which assumptions require later confirmation. For methane-emission reduction, this stage should detect, rank, repair, and verify methane sources while preserving production continuity and worker safety. The analysis should represent normal operation, startup, shutdown, turndown, maintenance, and credible upset conditions. Particular attention should be given to high-bleed pneumatic operation, because a locally acceptable condition may create a wider process, safety, environmental, or commercial consequence. Input records should identify source, timestamp, units, uncertainty, configuration, and accountable owner. A decision threshold should be approved before the final ranking is viewed. This reduces hindsight bias and prevents a favorable economic result from overriding mandatory safety or legal constraints. The resulting record should state the selected option, rejected alternatives, evidence gaps, interim controls, and residual-risk authority (Mbonu & Oluoha, 2018) (Mbonu *et al*., 2019).

Validation of data governance and continuous improvement should use independent evidence from processing facilities wherever feasible. Acceptance should depend on observable performance rather than completion of a report or work order.

Suitable measures include availability, detection coverage, response time, product compliance, avoided loss, energy intensity, maintenance burden, and verified risk reduction. The team should test sensitivity to uncertain supply, composition, equipment condition, utility availability, market conditions, and model error. A credible adverse case should include incomplete flare combustion and the loss of one important safeguard or dependency. Differences between predicted and observed performance should trigger model review, not informal adjustment of the acceptance limit. Management of change should capture revised drawings, procedures, training, spares, software versions, alarm settings, and inspection requirements. This verification loop converts methane-emission reduction from a one-time study into a controlled operating capability. It also supplies comparable evidence for future investment and risk decisions (Agbabiaka & Okeke, 2019; Okonkwo & Okeke, 2018b) (Ogunwole *et al*., 2021; Okonkwo *et al*., 2021; Agbabiaka *et al*., 2019).

Implementation Roadmap

Establish scope, accountable roles, minimum evidence, approval criteria, and a documented output. Apply the phase first to high-consequence scenarios involving well sites. Record assumptions about undetected fugitive leakage, test the decision with sensitivity analysis, and assign closure evidence. Advance to the next phase only when unresolved uncertainty has an explicit treatment and owner. Review interfaces with operations, maintenance, inspection, process safety, environmental management, commercial planning, and emergency response. Statewide airborne campaigns have shown that a small fraction of well sites act as persistent point-source super-emitters, evidence that supports sequencing source-inventory development toward the highest-consequence sites first (Duren *et al*., 2019). Facility-level surveys of well pads across multiple oil and gas basins reach a parallel conclusion, finding that a small subset of pads accounts for a disproportionate share of measured emissions regardless of basin or production volume (Robertson *et al*., 2017) (Obogo & Arumosoye, 2022) (Obogo *et al*., 2020).

Establish scope, accountable roles, minimum evidence, approval criteria, and a documented output. Apply the phase first to high-consequence scenarios involving gathering systems. Record assumptions about high-bleed pneumatic operation, test the decision with sensitivity analysis, and assign closure evidence. Advance to the next phase only when unresolved uncertainty has an explicit treatment and owner. Review interfaces with operations, maintenance, inspection, process safety, environmental management, commercial planning, and emergency response. Methods for resolving individual point sources from satellite plume imagery give gathering-system operators a measurement-technology option that was not available from area-wide inventories alone (Varon, Jacob, McKeever, Jervis, Durak, Xia, & Huang, 2019) (Adeyelu, 2019).

Establish scope, accountable roles, minimum evidence, approval criteria, and a documented output. Apply the phase first to high-consequence scenarios involving processing facilities. Record assumptions about compressor seal venting, test the decision with sensitivity analysis, and assign closure evidence. Advance to the next phase only when unresolved uncertainty has an explicit treatment and owner. Review interfaces with operations, maintenance, inspection, process safety, environmental management, commercial planning, and emergency response. Repeated measurement of the same production region over time found that temporal variability in operating conditions, not measurement error alone, explains much of the divergence between top-down and bottom-up emission quantification at processing facilities (Vaughn *et al*., 2018). Independent comparisons of multiple simultaneous measurement techniques at production pads reach the same conclusion, finding that technique choice, not only measurement timing, explains part of the observed top-down and bottom-up divergence (Bell *et al*., 2017).

Establish scope, accountable roles, minimum evidence, approval criteria, and a documented output. Apply the phase first to high-consequence scenarios involving compressor stations. Record assumptions about tank flashing, test the decision with sensitivity analysis, and assign closure evidence. Advance to the next phase only when unresolved uncertainty has an explicit treatment and owner. Review interfaces with operations, maintenance, inspection, process safety, environmental management, commercial planning, and emergency response. Investigation of individual high-emitting sites found that abnormal process conditions, rather than routine component leakage, produced most compressor-station super-emissions, a distinction that should shape abatement-ranking criteria (Zavala-Araiza *et al*., 2017). Mobile-laboratory surveys of the same production region independently confirm that a small number of abnormally operating sites, rather than routine component counts, drive most observed fugitive emissions (Lan *et al*., 2015).

Establish scope, accountable roles, minimum evidence, approval criteria, and a documented output. Apply the phase first to high-consequence scenarios involving storage assets. Record assumptions about malfunctioning flares, test the decision with sensitivity analysis, and assign closure evidence. Advance to the next phase only when unresolved uncertainty has an explicit treatment and owner. Review interfaces with operations, maintenance, inspection, process safety, environmental management, commercial planning, and emergency response. Risk-based inspection practice provides the prioritization logic that repair-and-replacement planning for storage assets can adapt directly, ranking flare and tank repairs by consequence and likelihood rather than by calendar interval alone (American Petroleum Institute, 2016). Mobile-platform measurements at oil and gas production pads provide an independent, repeatable basis for the consequence and likelihood inputs such ranking requires (Brantley *et al*., 2014) (Obogo & Obriki, 2020c; American Petroleum Institute, 2016; American Petroleum Institute, 2016) (Obriki *et al*., 2022).

Establish scope, accountable roles, minimum evidence, approval criteria, and a documented output. Apply the phase first to high-consequence scenarios involving transmission and distribution interfaces. Record assumptions about release during maintenance, test the decision with sensitivity analysis, and assign closure evidence. Advance to the next phase only when unresolved uncertainty has an explicit treatment and owner. Review interfaces with operations, maintenance, inspection, process safety, environmental management, commercial planning, and emergency response. Comprehensive aerial surveys of a major production basin measured well-pad and gathering emissions five to nine times higher than official estimates, a discrepancy that verification-of-reduction protocols for transmission and distribution assets must be able to detect (Robertson *et al*., 2020). Source-apportionment studies using tracer compounds

in a comparable production region confirm that bottom-up inventories can be reconciled with atmospheric observations only when transmission and distribution contributions are estimated independently rather than assumed (Townsend-Small *et al*., 2016).

Establish scope, accountable roles, minimum evidence, approval criteria, and a documented output. Apply the phase first to high-consequence scenarios involving well sites. Record assumptions about undetected fugitive leakage, test the decision with sensitivity analysis, and assign closure evidence. Advance to the next phase only when unresolved uncertainty has an explicit treatment and owner. Review interfaces with operations, maintenance, inspection, process safety, environmental management, commercial planning, and emergency response. A national-scale synthesis combining component-level and aircraft measurements estimated that United States oil and gas methane emissions were substantially above the government inventory, a gap attributable in part to data-quality gaps at well sites (Alvarez *et al*., 2018). Field evidence that repeated leak detection and repair surveys reduce measured emissions over multiple years indicates that the data-quality gaps identified at the national level are addressable through sustained, not one-time, measurement programs (Ravikumar *et al*., 2020) (Akpe *et al*., 2022).

Establish scope, accountable roles, minimum evidence, approval criteria, and a documented output. Apply the phase first to high-consequence scenarios involving gathering systems. Record assumptions about high-bleed pneumatic operation, test the decision with sensitivity analysis, and assign closure evidence. Advance to the next phase only when unresolved uncertainty has an explicit treatment and owner. Review interfaces with operations, maintenance, inspection, process safety, environmental management, commercial planning, and emergency response. Facility-level measurement in the Alberta gathering-system fleet found emissions concentrated among a small number of sites with abnormal operating conditions, evidence that management review should weight site history over average emission factors (Zavala-Araiza, Herndon, Roscioli, Yacovitch, Johnson, Tyner, Omara, & Knighton, 2018).

Governance and Organizational Learning

Assigning ownership, decision rights, change control, competence requirements, and assurance responsibilities is what implementation governance means in practice, and at well sites that assignment has to be built around undetected fugitive leakage: how it begins, the limits of detection, the safeguards already in place, the recovery time expected, and the effects that follow downstream. Repair-and-replacement-planning records support that governance structure, but planning records alone do not establish that the underlying technical basis is sound. What is still needed is a record of source and date, operating mode, measurement uncertainty, model version, and accountable owner for each input, because that record keeps a well-organized-looking governance structure from concealing assumptions that were never actually tested, and it is what allows operating experience gathered later to feed back into governance decisions instead of being filed away and forgotten.

Gathering systems need the same clarity of ownership, decision rights, change control, competence, and assurance, applied to high-bleed pneumatic operation as the failure mode governance has to address, with attention to how it begins, the limits of detection, the safeguards already available, the recovery time expected, and the downstream effects if it persists. Verification-of-reduction evidence supports that governance structure, but a single verification round does not, by itself, confirm the technical basis is sound. Source and date, operating mode, measurement uncertainty, model version, and accountable owner still have to be tracked for each input, since that discipline keeps a well-documented governance record from hiding weak assumptions, and it lets operating experience gathered later revise governance decisions instead of leaving them fixed in a file that is not revisited. The physical-science assessment of short-lived climate forcers identifies methane from fossil fuel operations, including gathering systems, as a mitigation lever with a comparatively fast climate response, strengthening the case for governance structures that can act quickly on new evidence (Intergovernmental Panel on Climate Change, 2021). The radiative forcing basis for treating methane as a comparatively fast-acting climate lever is established in the assessment literature that quantifies its global warming potential relative to carbon dioxide (Myhre *et al*., 2013). Regulatory disclosure obligations for greenhouse gases are evolving in parallel, reinforcing the governance case for organizations that can act quickly on new evidence (Ominyi & Anichukwueze, 2022) (Medon & Oduleye, 2022).

Processing facilities require ownership, decision rights, change control, competence, and assurance assigned around compressor seal venting specifically, addressing how venting begins, the limits of detection, the safeguards already in place, the recovery time expected, and the downstream effects if it is not caught. Data-quality-assurance evidence contributes to that governance picture, but it does not, by itself, prove the technical basis is adequate. Source and date, operating mode, measurement uncertainty, model version, and accountable owner still need to be recorded regardless, since that record keeps a seemingly thorough governance structure from resting on unexamined assumptions, and it allows later operating experience to revise governance decisions instead of them being logged and left alone. United States federal performance standards for new and modified sources formalize leak-detection-and-repair, pneumatic-device, and compressor obligations for processing facilities, and implementation governance should map directly onto these regulatory requirements (U.S. Environmental Protection Agency, 2016).

Defining leading and lagging performance measures, along with the thresholds that trigger an update, is the task here, and for compressor stations those measures have to be organized around tank flashing: how it starts, the limits of detection, the safeguards already in place, the recovery time expected, and the downstream effects assumed. Management-review evidence supports those indicators, but a single review does not, on its own, establish technical adequacy. Source and date, operating mode, measurement uncertainty, model version, and accountable owner still have to be recorded for each input feeding the indicator, since that is what stops an apparently precise indicator from hiding weak assumptions, and what allows later operating experience to update the indicator rather than leaving it fixed in a separate record. Greenhouse Gas Reporting Program technical guidance for petroleum and natural gas systems specifies the calculation methods that compressor-station performance indicators should trace back to, so that leading and lagging measures remain auditable (U.S. Environmental Protection Agency,

2020).

Storage assets need leading and lagging indicators defined around malfunctioning flares, capturing how the malfunction starts, the limits of detection, the safeguards already in place, the recovery time expected, and the downstream effects that follow. Source-inventory-development evidence supports those indicators, but it does not, by itself, confirm the technical basis is sound. Source and date, operating mode, measurement uncertainty, model version, and accountable owner still have to be recorded, since that discipline is what keeps a confident-looking indicator from concealing untested assumptions, and what lets later operating experience revise the indicator instead of it remaining static in a separate file. Annual satellite-based flaring tracking shows that global flared volumes, a significant share of which originates from storage and production facilities, have remained largely flat despite voluntary reduction commitments, evidence that performance indicators should treat flaring as a distinct tracked variable (World Bank, 2022). Column-based atmospheric measurements of ethane and methane over the same period independently confirm that oil and natural gas production, rather than other sources, drove the renewed increase in emissions despite voluntary reduction commitments (Hausmann *et al*., 2016).

For transmission and distribution interfaces, leading and lagging measures need to be defined around release during maintenance, capturing how it begins, the limits of detection, the safeguards already in place, the recovery time expected, and the downstream effects. Measurement-technology-selection evidence contributes to those measures, but no single dataset establishes on its own that the technical picture is adequate. Source and date, operating mode, measurement uncertainty, model version, and accountable owner still need to be tracked for each input, because that record keeps an apparently precise measure from hiding weak assumptions, and it allows later operating experience to update the measure rather than leaving it recorded separately and unrevised. The Oil and Gas Methane Partnership's reporting framework defines a graduated set of measurement-based reporting levels that transmission and distribution operators can use to benchmark performance-measurement maturity against international peers (Oil and Gas Methane Partnership 2.0, 2020).

Literature Synthesis

Methane control requires source detection, spatial context, repair governance, and verification.

Measurement programs also need organizational learning.

Research Propositions

Turning the framework's relationships into testable propositions, for well sites, means anchoring those propositions in undetected fugitive leakage, specified clearly enough to be tested: how it initiates, the limits of detection, the safeguards already in place, the recovery time expected, and the downstream effects. Emission-quantification evidence supports that empirical basis, but no single dataset establishes on its own that the technical case is adequate. What closes the gap is a plain record showing where each input came from, the operating mode, its uncertainty, the model version, and who is accountable for it; that record keeps a seemingly well-supported proposition from resting on assumptions no one has verified, and it leaves room for later operating experience to refine the proposition instead of it sitting untouched in a separate file.

Gathering systems generate their own testable propositions, built around high-bleed pneumatic operation, with initiating conditions, detection limits, safeguards, recovery time, and downstream effects specified precisely enough to support testing. Risk-and-abatement-ranking evidence contributes to that empirical case, but it does not, by itself, confirm the technical basis is adequate. The reviewer still has to document the source and date behind each input, the operating mode, the measurement uncertainty, the model version, and the accountable owner, because that documentation is what keeps a seemingly well-supported proposition from concealing untested assumptions and what allows later operating experience to sharpen it instead of leaving it fixed in a separate record. Empirical sensitivity testing of infrared cameras under field-representative conditions offers a template for how future studies should test the detection-technology propositions proposed for gathering-system deployment (Ravikumar, Wang, McGuire, Bell, Zimmerle, & Brandt, 2018).

Processing-facility propositions have to be built around compressor seal venting, with its initiating conditions, detection limits, safeguards, recovery time, and downstream effects spelled out precisely enough to be tested empirically. Repair-and-replacement-planning evidence supports these propositions, but a single dataset does not, on its own, establish that the technical basis is sound. A record naming the source and date of each input, the operating mode, the measurement uncertainty, the model version, and the accountable owner has to travel with the proposition regardless, since that is what prevents an apparently well-supported claim from hiding weak assumptions and what lets later operating experience refine it instead of it sitting untouched in a separate file. Aerial infrared surveys of elevated hydrocarbon emissions from production sites illustrate a testing design, paired before-and-after flights, that could be adapted to evaluate processing-facility propositions empirically (Lyon *et al*., 2016). Earlier spatially resolved inventory work in the same production region, together with airborne measurement campaigns across California oil and gas facilities and comparable natural gas power plant and refinery surveys, illustrates the range of testing designs available for evaluating processing-facility propositions empirically (Lavoie *et al*., 2017; Lyon *et al*., 2015; Mehrotra *et al*., 2017).

- **P1:** Greater maturity in source inventory development improves the traceability and effectiveness of methane-emission reduction decisions when data quality and organizational context are controlled.
- **P2:** Greater maturity in measurement technology selection improves the traceability and effectiveness of methane-emission reduction decisions when data quality and organizational context are controlled.
- **P3:** Greater maturity in emission quantification improves the traceability and effectiveness of methane-emission reduction decisions when data quality and organizational context are controlled.
- **P4:** Greater maturity in risk and abatement ranking improves the traceability and effectiveness of methane-emission reduction decisions when data quality and organizational context are controlled.
- **P5:** Greater maturity in repair and replacement planning improves the traceability and effectiveness of methane-emission reduction decisions when data quality and

organizational context are controlled.

- **P6:** Greater maturity in verification of reduction improves the traceability and effectiveness of methane-emission reduction decisions when data quality and organizational context are controlled.

Limitations and Future Research

Stating the framework's evidence, transferability, model, and implementation limits, for compressor stations, requires being explicit about tank flashing: its initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Verification-of-reduction evidence supports identifying those limits, but it cannot, on its own, confirm the technical picture is complete. The gap is closed by a documented trail, source and date, operating mode, measurement uncertainty, model version, accountable owner, attached to every input, since that trail keeps an apparently thorough limitations statement from glossing over weak assumptions and lets later operating experience sharpen the statement rather than leaving it fixed in a separate file. Global bottom-up and top-down methane estimates compiled by the International Energy Agency still differ by a wide margin for compressor-station and other midstream sources, a data limitation this framework cannot resolve on its own (International Energy Agency, 2022). Long-term trend analyses of atmospheric ethane and propane attribute much of the reversal in global trends to United States oil and natural gas production, underscoring why compressor-station and midstream data gaps carry consequences beyond the basin in which they occur (Helmig *et al*., 2016) (Ahmed & Adebayo, 2021).

For storage assets, the framework's evidence, transferability, model, and implementation limits center on malfunctioning flares, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Data-quality-assurance evidence supports identifying those limits, but no single dataset settles the matter alone. What is missing without a documented trail of source date, operating mode, measurement uncertainty, model version, and accountable owner is any way to tell a genuinely complete limitations discussion from one that only looks complete; keeping that trail is also what lets later operating experience refine the discussion rather than leaving it static in a separate file. The joint United Nations and Climate and Clean Air Coalition assessment of global methane mitigation potential relies on regional default factors that may not represent storage-asset conditions in every jurisdiction, a scope limitation inherited by any framework built on that evidence base (United Nations Environment Programme & Climate and Clean Air Coalition, 2021).

Transmission and distribution interfaces carry their own evidence, transferability, model, and implementation limits, organized around release during maintenance, with initiating conditions, detection limits, safeguards, recovery time, and downstream effects made explicit. Management-review evidence contributes to stating those limits, but it cannot, by itself, establish that the technical picture is adequate. Recording the source and date of each input, the operating mode, the measurement uncertainty, the model version, and the accountable owner is what keeps an apparently complete statement of limits from concealing weak assumptions, and it is what allows later operating experience to refine the statement rather than leaving it fixed in a separate record. The International Energy Agency's methane tracking work highlights persistent underreporting in transmission and distribution segments of national inventories, a limitation that future empirical work on this framework should specifically target (International Energy Agency, 2021). Basin-scale hydrocarbon measurement campaigns conducted before this reporting period documented comparable gaps between reported and observed transmission and distribution segment emissions, suggesting the limitation is longstanding rather than a recent reporting artifact (Petron *et al*., 2014).

The wider emissions literature links credible methane reduction to transparent inventories, consistent boundaries, and verified measurements (Balcombe *et al*., 2017; Okonkwo *et al*., 2021; Fawole *et al*., 2016; Figueroa *et al*., 2008; Conrad *et al*., 2017; Songolzadeh *et al*., 2014; Kermani *et al*., 2003; Onyeke *et al*., 2022; Snytnikov *et al*., 2022; Pourmalek *et al*., 2020; Shaimardanova *et al*., 2019; Kim *et al*., 2018; Sitorus *et al*., 2018; Bagheri *et al*., 2016).

Monitoring studies support combining screening, quantification, repair confirmation, and recurrence tracking within one control cycle (Li *et al*., 2016; Wang *et al*., 2020; Allison *et al*., 2013; Henderson *et al*., 2007; International Organization for Standardization., 2015; Anomohanran, 2012; Ejiogu, 2013; Velazquez *et al*., 2022; Askari *et al*., 2019; Strizhenok *et al*., 2019; Korppoo, 2018; Yu *et al*., 2018; Ismail *et al*., 2016).

Energy-sector evidence shows why operators should rank sources by emission rate, safety consequence, persistence, and repair feasibility (Thompson *et al*., 1993; Adegboye *et al*., 2019; Cao, 2012; Anderson *et al*., 2004; NACE International *et al*., 2015; American Petroleum Institute., 2009; Strosher, 1996; Kheirinik *et al*., 2021; Chebbi *et al*., 2019; Adeyelu, 2018; Muharam *et al*., 2018; Umukoro *et al*., 2017).

Climate-governance research reinforces the need for auditable data, documented estimation methods, and clear accountability for corrective action (U.S. Environmental Protection Agency., 2016; Osiki, 2018; Skogdalen *et al*., 2012; Bui *et al*., 2018; Boot-Handford *et al*., 2014; Beavers *et al*., 2006; Cao *et al*., 2022; Roussanaly *et al*., 2021; Fang *et al*., 2019; Elias *et al*., 2018; Okonkwo *et al*., 2018; Yang *et al*., 2017).

Environmental performance studies support continuous learning from detected leaks, maintenance records, and post-repair measurements (Ben Seghier *et al*., 2021; Kukadiya *et al*., 2017; Bian *et al*., 2011; Cameron *et al*., 2018; Leung *et al*., 2014; Intergovernmental Panel on Climate Change., 2006; Caryana, 2022; Ben Seghier *et al*., 2020; Oakley, 2019; Gazheli *et al*., 2018; Ramasamy, 2018; Yazdi *et al*., 2017).

Related energy-governance studies connect methane performance with maintenance discipline, procurement controls, and environmental responsibility (Okonkwo *et al*., 2021; Okojie *et al*., 2020; Adaramola *et al*., 2018).

Ewim's environmental and energy research links operational emissions control with crude-oil pollution risk, low-carbon planning, and sectoral carbon mitigation (Dioha *et al*., 2021; Adesina *et al*., 2022; Ntuli *et al*., 2022).

Conclusion

Conclusions is central to methane-emission reduction because methane losses arise from fugitive leaks, vents, pneumatic devices, tanks, compressors, incomplete combustion, maintenance activity, and abnormal operations. The analysis should summarize the contribution and practical implications. For well sites, the decision model must

represent undetected fugitive leakage, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Source inventory development supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. Consistent with national measurement studies of the natural gas transmission and storage system, well-site methane control depends on the same combination of source inventory, verification, and asset-management discipline that this paper proposes as a decision architecture. Complementary atmospheric evidence, including basin-scale ethane tracing and urban-basin source attribution studies, supports the same combination of source inventory, verification, and asset-management discipline this paper proposes as a decision architecture.

Conclusions is central to methane-emission reduction because methane losses arise from fugitive leaks, vents, pneumatic devices, tanks, compressors, incomplete combustion, maintenance activity, and abnormal operations. The analysis should summarize the contribution and practical implications. For gathering systems, the decision model must represent high-bleed pneumatic operation, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Measurement technology selection supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. Site-level measurement work in shale gathering systems similarly found that a minority of wells and associated equipment drove most methane loss, reinforcing the paper's emphasis on risk-based prioritization rather than uniform intervention. A separate basin-scale aircraft campaign reached a parallel conclusion for unconventional production in North Dakota, reinforcing that risk-based prioritization, rather than uniform intervention, generalizes across shale plays.

Conclusions is central to methane-emission reduction because methane losses arise from fugitive leaks, vents, pneumatic devices, tanks, compressors, incomplete combustion, maintenance activity, and abnormal operations. The analysis should summarize the contribution and practical implications. For processing facilities, the decision model must represent compressor seal venting, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Emission quantification supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. The paper's specific contribution is an integrated measurement-to-mitigation architecture that links methane control with safety, reliability, and resource conservation. Future work should test the propositions with operating data and report both successful and unsuccessful applications.

The emissions-governance evidence also links methane control to transparent inventories, consistent boundaries, and decision-useful disclosure (Congressional Research Service, 2022; European Parliament, 2022; External Reporting Board, 2022; Greenhouse Gas Protocol, 2022; U.S. Securities and Exchange Commission, 2022).

Declarations

Ethics approval and consent to participate: This methane-emissions review relied on published engineering evidence and included no human or animal subjects.

Consent for publication: Not applicable.

Availability of data and materials: The cited sources contain the evidence assessed in this paper; no original monitoring dataset was created.

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