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Evidence Quality and Carbon Credit Outcomes in a Methane Abatement Project

Andewi Rokhmawati[1*], Akbari Indra Basuki[2], Boyke Setiawan Soeratin[3], Lailan Tawila Berampu[1], Iskandar Iskandar[4]

[1] The Faculty of Economics and Business, Universitas Riau, 28293 Pekanbaru, Indonesia
[2] Artificial Intelligence and Cybersecurity Research Center, National Research and Innovation Agency, 40135 Bandung, Indonesia
[3] BINUS Business School, BINUS University, 11530 Jakarta, Indonesia
[4] Master of Management Program, Universitas Riau, 28293 Pekanbaru, Indonesia

[*] Correspondence: Andewi Rokhmawati (Andewi.rokhmawati@lecturer.unri.ac.id)

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Abstract: The research analyzes whether monitoring system design, calibration management, timestamp consistency, data traceability, and verification procedures relate to the risk control of the financial aspects of methane-abatement engineering projects. An analytical case study based on a single project and involving a before-and-after comparison of the implementation of an monitoring, reporting, and verification (MRV) regime was conducted under fixed engineering and accounting conditions. This design allows the comparison to focus on differences in MRV evidence management conditions rather than on changes in physical mitigation technology. Conservative issuability was estimated using the low-confidence adjustment metric (LCAM). This analytical metric scales engineering emission reductions by evidence-related factors without supplanting registry rules or verifier judgment. With the enhanced MRV regime, the conservatively supportable fraction was 77.0% to 91.3%, while the realized price wedge declined from 0.30 to 0.12. The monitoring-to-issuance period was also shortened by 50 days.

Keywords: MRV system management; Evidence quality; Methane abatement; Engineering project risk; Carbon revenue; Calibration governance; Data traceability; Conservative issuability

1 Introduction

Methane-abatement projects are engineering systems whose finance-relevant outcomes are associated not only with physical mitigation but also with the quality of the monitoring, reporting, and verification (MRV) system used to document, validate, and support carbon-credit revenue claims [1–3]. In practice, the conversion of measured mitigation into carbon-credit revenue is constrained by evidentiary and institutional conditions. Carbon credits are more than environmental units; they are evidence-based claims whose value depends on the credible demonstration and defense of avoided emissions [1, 4, 5]. In this study, carbon credits are treated analytically as evidentiary claims that become financial assets only when they are defensibly supported.

These evidentiary weaknesses are especially visible at the project level because they are closely linked to finance-relevant project outcomes. While a methane-reduction project might create measurable physical reductions, the commercial realization of the revenues generated by such reductions is less certain when data gaps, a lack of proper audit-trail documentation, or poor MRV governance prevail. Verification agencies tend to exercise conservative practices when reviewing data that is either incomplete or hard to verify [1, 2, 6]. The lack of consistency in monitoring data, poor calibration documentation, lack of timestamps, or difficulty verifying evidence could make verifiers question the evidence and defer issuing or even issuing credits to avoid over-crediting [2, 3, 7–11]. Such issues are not merely procedural evidentiary problems but rather concern whether the measured reductions are defensible for issuance, can trade close to benchmark prices, and are financially viable.

The financial implications of the evidentiary issues above are often overlooked. In an environment where one party possesses more knowledge than another, the buyer might exercise discounts, contingency clauses, or other methods of mitigating risks, and this might have economic consequences [4, 12–16]. This issue is especially relevant in carbon transactions because settlement confidence often depends on the verification-readiness of technical records. Issuance delays may further increase financial uncertainty by extending the interval between mitigation and monetization. Credits remain illiquid until verification and issuance are completed [1]. Therefore, delays in verification and issuance may widen the gap between risk reduction and credit monetization, reduce present value, and elevate working-capital requirements, even when nominal credit volumes remain constant [17, 18]. From a project-finance perspective, MRV quality should therefore be viewed not only as a compliance requirement but also as part of the project's engineering and management architecture for revenue-risk control.

Prior research has made important contributions to carbon market integrity and MRV governance. Still, it offers only limited project-level explanations of how engineering evidence-management practices are associated with finance-relevant project outcomes. Two studies focusing on integrity most consistently find systemic over-crediting and identify fundamental structural vulnerabilities in crediting mechanisms [19, 20]. Governance-related research highlights the roles of transparency, disclosure, and institutional reform as preconditions for rebuilding trust [21]. Emerging work on digital MRV suggests that enhanced data infrastructures may improve traceability and auditability, while also noting that such advances do not necessarily address more fundamental issues such as counterfactual uncertainty, additionality, or baseline rigor [3, 22–27]. For engineering project managers, the unresolved issue is not only whether mitigation has occurred, but whether monitoring records, calibration status, timestamps, and data lineage can be managed as a verification-ready system [10, 28, 29]. What remains underdeveloped is a transparent project-level mechanism for examining how evidentiary quality is associated with finance-relevant outcomes. Such a mechanism can connect monitoring continuity, calibration validity, timestamp coherence, and data traceability to project-finance-related indicators: the defensible fraction of measured reductions, realized settlement outcomes, and the timing of monetization.

In this analysis, a project-specific approach is adopted to examine the relationships among MRV system management, evidence defensibility, revenue-risk indicators, and finance-related project outcomes. The empirical setting involves a complete methane-abatement project in Indonesia, evaluated under two analytical MRV regimes: a legacy regime and an enhanced regime. Two MRV regimes are examined: a legacy regime and an enhanced regime. The research uses a within-project before-and-after design, with engineering activities and accounting practices held constant. In contrast, the evidence systems differ between the two regimes in monitoring consistency, calibration management, timestamp matching, and data traceability.

The analysis evaluates whether stronger MRV evidence is associated with a larger conservatively supportable portion of measured reductions, a smaller realized-price wedge, and a shorter lag from monitoring to issuance. The framework is analytical and does not replicate registry rules or serve as a substitute for verification. Its role is to make the gap between measured mitigation and defensible claims explicit.

The analysis is limited in scope. It does not state that improved MRV fixes higher-order integrity problems in carbon markets. A stronger evidentiary chain cannot address concerns about additionality, baseline construction, leakage, or permanence [19, 20, 30, 31]. Instead, stronger evidentiary conditions may be associated with lower project-level evidentiary uncertainty in the chain from quantified abatement to financially usable revenue. In doing so, the paper contributes to the discussion of MRV as part of the financial and institutional infrastructure through which evidence quality is associated with conservative issuability, settlement outcomes, and issuance timing within a project context.

Accordingly, the study is guided by three analytical expectations. Stronger MRV evidence is expected to be associated with a larger conservatively supportable share of measured emission reductions, a smaller realized-price wedge, and a shorter lag between monitoring closure and issuance. These expectations are evaluated within a single-project comparison under fixed engineering and accounting conditions.

2 Materials and Methods

2.1 Research Design and Analytical Scope

An analytical single-project before-and-after case-study design was applied to compare two MRV regimes within the same methane-abatement engineering project, with engineering operations and accounting rules held constant [22, 29]. This frames the analysis as a project-management question: whether differences in the MRV evidence structure are associated with the degree to which measured mitigation can be defensibly supported, made transaction-ready, and linked to revenue realization on a reasonably predictable timeline [7, 19, 20, 32].

The analysis is limited to within-project associations and does not support cross-project generalization. Carbon credit outcomes are also influenced by factors beyond project-level MRV, including market conditions, contract design, verifier capabilities, and institutional procedures [8, 9, 33]. Neither is a single-site project design immune to these problems, yet such a design helps reduce variation in engineering processes, site-specific factors, and accounting criteria across MRV frameworks. The novelty is the application of a management-based concept whereby the quality of evidentiary material is considered a project variable that is related to certain revenue and risk signals downstream [7, 9, 10, 12, 20].

To keep the analysis clear, an attempt is made to distinguish between the observed and calculated data. The former includes monitoring statements, calibration validity periods, issuance dates, and settlement prices. The latter comprises emissions reductions from engineering calculations, conservative issuability assessed using the low-confidence adjustment metric (LCAM), price differential, and present value adjustment [7, 12].

2.2 Context of the Study and the Comparison Framework

The empirical context consists of a large-scale methane abatement project situated in Indonesia, using the UNFCCC methane recovery in wastewater treatment (AMS-III.H) guidelines on methane recovery from wastewater, as well as the CDM guidelines related to project emissions through flaring [8, 9]. These protocols define baseline emissions, project emissions, and monitoring requirements. The present study does not modify these methodological rules. Instead, it focuses on how project-level evidence management supports the implementation of those rules and how different MRV evidence conditions are associated with finance-relevant project outcomes.

The project examined in this study is the Utilization of Palm Oil Mill Effluent (POME) for Biogas Co-Firing project, implemented at PKS Lubuk Dalam in Siak Regency, Riau Province, Indonesia. The project captures methane-rich biogas from anaerobic POME treatment using a Covered in-Ground Anaerobic Reactor (CIGAR), a covered lagoon anaerobic biodigester. The captured biogas is directed to a boiler via a biogas co-firing system, while excess biogas is flared. The project is owned and operated by PT Perkebunan Nusantara IV Regional III, while PT SUCOFINDO ICS conducted validation and verification. Further project-context details are provided in Appendix A, Table A1.

The official monitoring period reported in the project documents is 19 November 2021 to 18 November 2024. For the within-project before-and-after comparison, this period was divided into two analytical MRV regimes. The legacy MRV regime covers the period from 19 November 2021 to 31 December 2023, comprising 773 daily observations. The enhanced MRV regime covers the period from 1 January 2024 to 18 November 2024, comprising 323 daily observations. These terms are analytical labels used in this study to distinguish earlier and later evidence-management conditions within the same official monitoring period. They are not official labels used in the project design, monitoring, registry, or verification documents.

The legacy MRV regime is described as the earlier evidence-management condition, involving greater evidence fragmentation in preparation, manual record reconciliation, less calibration management, and lesser integration between the operation record and verification evidence. The enhanced MRV regime is described as the latter evidence-management condition, involving greater continuity in monitoring, calibration register management, timestamp management, missing data management, record management, and linkage among the raw monitoring record, the project monitoring calculation sheet, and verification evidence. The comparative description of the two MRV regimes is presented in Appendix A, Table A2.

In a before-and-after research design, the comparative analysis needs to be conducted carefully because the design cannot control all time-varying external factors. The physical mitigation technology, project location, methodology, and overall project boundary can be considered constant across the two MRV regimes. However, other time-dependent variables, such as buyer traits, contractual provisions, market mood, registry handling, verifier workload, and institutional factors, cannot be controlled for in this research design. It would therefore be inappropriate to attribute the observed differences in the project's finance-relevant indicators solely to the shift from the legacy MRV regime to the enhanced MRV regime. This study aims to examine whether the enhanced MRV evidence condition is associated with higher conservative issuability, a lower realized-price wedge, and shorter issuance cadence [7, 20, 32].

2.3 Monitoring, Reporting, and Verification System-Management Framework

The MRV process is considered an engineering management process consisting of seven interrelated steps: data acquisition, instrument calibration, recordkeeping, internal audit, verification inquiry management, issuance, and revenue realization [1, 10]. There is a management activity associated with each step of the MRV process as well as potential failure modes [10, 28, 29]. Data acquisition may fail because of missing data and faulty sensors. Instrument calibration may fail due to an expired certification or a lack of traceability for the instruments. Recordkeeping may fail due to record destruction and a lack of spreadsheet management controls. An internal audit may fail if gaps are not identified before verification. Verification inquiry management may fail because of an untimely response without proper documentation. Issuance may be delayed when the evidence package is difficult to assemble, while price reductions or cash-flow delays may affect revenue recognition.

This workflow frames MRV as a project risk-control infrastructure [1, 28, 34]. This interpretation is consistent with risk-management and project-management standards that emphasize integrating risk control, monitoring, accountability, and performance measurement into routine project decision-making [35, 36]. These indicators are therefore interpreted as management indicators that connect engineering performance to conservative issuability, price-wedge exposure, issuance cadence, and revenue forecasting. The MRV system-management framework and its connection to revenue-risk control are summarized in Figure 1.

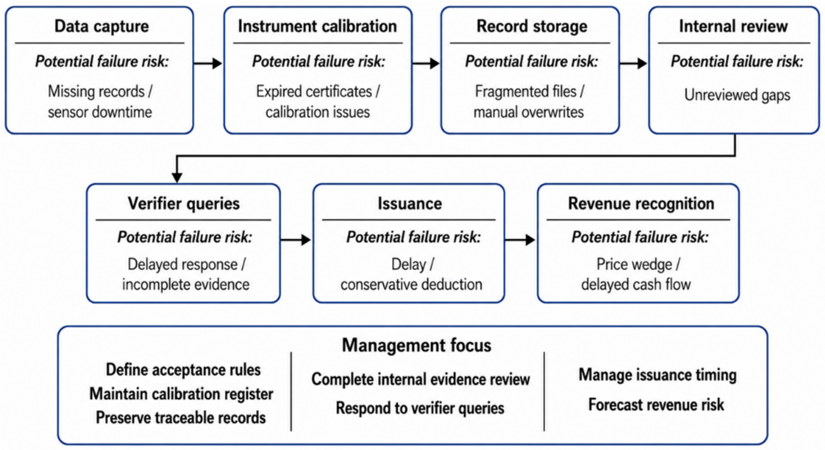

Figure 1. Monitoring, reporting, and verification (MRV) system-management framework for revenue-risk control in a methane-abatement project

2.4 Data Sources and Traceability Protocol

The analysis combines observed project records with calculated analytical variables. To improve reproducibility, the study separates observed records from calculated constructs. Observed records include monitoring logs, activity data records, calibration certificates, instrument service records, verification process logs, issuance-related documentation, settlement records, and benchmark price references. Calculated constructs include engineering emission reductions, LCAM, the realized-price wedge, issuance cadence, and present-value adjustment. Detailed information on data sources, coverage, screening, exclusion and treatment procedures, cross-checking procedures, and confidentiality restrictions is provided in Appendix B, Table B1.

The observed data structure follows the operating boundary of the POME for Biogas Co-Firing project at PKS Lubuk Dalam, Siak Regency, Riau Province, Indonesia. Methane-related emission reductions were estimated using time-series monitoring data, including wastewater-flow activity data, untreated and treated chemical oxygen demand (COD) values, biogas combusted, methane fraction, temperature, pressure, flaring-related information, and operational logs recorded at regular intervals [8, 9, 37]. These records consist of timestamped operational measurements, logs, and quality indicators required to apply the relevant UNFCCC methodologies [8, 9]. For MRV systems, high-resolution and traceable data structures are necessary to support auditability and reproducibility [3, 17, 20, 24, 25, 38]. The project monitoring documentation reports ex post activity data for the monitoring period, including wastewater volume, untreated COD, treated COD, biogas combusted, methane fraction, temperature, and pressure, all of which are directly relevant to quantifying methane-recovery performance.

Instrument governance documentation was employed to assess the adequacy of evidence of monitored values. Instrument governance documentation is made up of calibration certificates, the validity of the calibration period, instrument service documentation, and instrument maintenance documentation [25, 30]. A measurement would be considered adequate evidence only if the instrument documenting it was traceable and its calibration or servicing documents were within the monitoring period. The methodology is consistent with the theory that the presence of data is not sufficient for the adequacy of evidence [2, 18, 25, 30]. Further, it corresponds to the verification scope of implementing monitoring, calibrating measuring instruments, and dealing with data gaps.

The records of the verification process were examined to document the path from monitoring closeout to report issuance. Such records include verifier query logs, correspondence, evidence-submission records, corrective-action records, verification opinions, and issuance-related timestamps. The verification report states that the verification process evaluated the completeness, accuracy, and credibility of the project monitoring data and monitoring sheets, the presence of double issuance, and any material differences between the project implementation and the validated design recognition and approval mechanism. The records were also used to analyze issuance frequency as a process output indicative of evidential friction and verification readiness [17, 20].

Transaction-level data were used in their anonymized aggregate form. The data includes settlement prices in Rp/tCO_2e, settlement timings, and contractual provisions. Transaction-level data are not part of technical project-design and monitoring datasets and contain commercially sensitive information. Thus, buyer identifiable terms, confidential contractual provisions, and commercially sensitive transactional data were filtered out before any analysis was performed. The benchmark price is used solely to illustrate the price wedge calculation and is not a reference for the universal market price.

In the intra-project comparison, the data collection period is 19 November 2021 to 18 November 2024, yielding 1,096 daily observations. The old regime spans 19 November 2021 to 31 December 2023, with 773 daily observations, whereas the new regime spans 1 January 2024 to 18 November 2024, with 323 daily observations. Observations were excluded from the evidence-supported dataset when they were missing, corrupted, duplicated, outside the applicable calibration-validity period, not traceable to a source file, or not reconcilable with the corresponding operational or verification record. If an evidentiary weakness was limited to one instrument, parameter, or time interval, exclusion was applied only to the affected record, instrument, parameter, or period, not to the entire project dataset. Detailed evidence-screening rules are provided in Appendix B, Table B2.

Because some project and transaction records are commercially sensitive, the study uses a layered disclosure approach. Information on technical aspects and monitoring is presented at a level sufficient to replicate the analytical process, whereas information related to specific buyers and contract conditions is anonymized. If the primary source of transaction information needs to be protected from disclosure, a template for anonymized transaction records is provided in Appendix B, Table B3.

2.5 Variable Definitions and Measurement

To enhance notation consistency and clarity of analysis, a list of the principal variables considered in the analyses of engineering, evidence, prices, timing, and revenues is presented in Table 1. A more comprehensive list of variables, with details on their data sources and time resolutions, is provided in Appendix C, Table C1. The variables are grouped into those observed in project records, those that serve as reference values, and analytical constructs that have been calculated. This distinction is important because not all analytical constructs are treated as institutional outputs.

Table 1. Important variables considered in the analysis

Symbol	Variable	Unit	Measurement Role
BE_y	Baseline emissions	$\mathrm{ktCO_2e{\cdot}y^{-1}}$	Calculated reference emissions without the project
PE_y	Project emissions	$\mathrm{ktCO_2e{\cdot}y^{-1}}$	Calculated emissions under project operation
ER_y	Engineering emission reductions	$\mathrm{ktCO_2e{\cdot}y^{-1}}$	Physical mitigation before evidence adjustment
f_{int}	Interval completeness factor	Ratio, 0–1	Monitoring-record completeness
f_{cal}	Calibration-validity factor	Ratio, 0–1	Instrument-governance support
f_{sync}	Timestamp-coherence factor	Ratio, 0–1	Temporal alignment of evidence records
f_{MRV}	Composite evidentiary support factor	Ratio, 0–1	Combined evidence-support factor
LCAM_y	Low-confidence adjustment metric	$\mathrm{ktCO_2e{\cdot}y^{-1}}$ or $\mathrm{tCO_2e{\cdot}y^{-1}}$	Analytical proxy for conservative issuability
P_{bench}	Benchmark price	$\mathrm{Rp/tCO_2e}$	project-specific registry reference price for wedge calculation
P_{real}	Realized settlement price	$\mathrm{Rp/tCO_2e}$	Observed project-level settlement price
α	Realized-price wedge	Ratio, 0–1	Proportional gap between benchmark and realized price
$\mathrm{Cadence}_y$	Issuance cadence	Days	Duration from monitoring closure to issuance
$\Delta\mathrm{PV}_{\mathrm{rel}}$	Relative present-value uplift	Percent	Relative present value (PV) effect of earlier revenue realization
R_y	Realized annual revenue	Rp/y	Annual revenue from supportable volume and realized price

Note: The subscript y denotes the annual analytical period used in this study and does not imply a multi-year panel model.

Source: Authors' compilation based on project records, the analytical framework, UNFCCC methane recovery in wastewater treatment (AMS-III.H) [9], clean development mechanism (CDM) flaring-tool equations, low-confidence adjustment metric (LCAM) formulation, realized-price wedge calculation, and present-value adjustment used in this study [39, 40].

The notation provided in Table 1 will be used consistently throughout the following equations and tables. Price notation has been standardized, with P_{bench} denoting the benchmark price and P_{real} denoting the realized price. Similarly, timing notation has been standardized using the Cadence_y and ΔPV_{rel} notations.

The variable LCAM_y should be interpreted with particular caution. It is not an official registry metric, does not reproduce formal issuance rules, and is not intended to replace verifier judgment. It is used only as an analytical proxy to make explicit the gap between engineering emission reductions and the portion of those reductions that is conservatively supportable under the specified evidence conditions. Similarly, α is interpreted as an illustrative realized-price wedge rather than as a causal estimate of MRV quality's effect on carbon-credit pricing.

2.6 Engineering Emission Reductions

Annual engineering emission reductions [8, 9, 37] are calculated using the standard accounting identity:

$$\text{ER}_y = \text{BE}_y - \text{PE}_y \tag{1}$$

where, ER_y denotes emission reductions; BE_y denotes baseline emissions; and PE_y denotes project emissions.

Baseline emissions are defined as [9]:

$$\text{BE}_y = \text{BM}_{\text{CH}_4,\text{baseline},y} \times \text{GWP}_{\text{CH}_4} \tag{2}$$

where, $\text{BM}_{\text{CH}_4,\text{baseline},y}$ denotes baseline methane mass; GWP_{CH_4} denotes the methane global warming potential.

Project emissions are expressed as [9, 37]:

$$\text{PE}_y = \text{PE}_{y,\text{flare}} + \text{PE}_{y,\text{residual}} \tag{3}$$

where, $\text{PE}_{y,\text{flare}}$ is the emission related to flaring; $\text{PE}_{y,\text{residual}}$ is the residual emissions (without considering methane destruction) [8, 9, 37]. This provides the volume of engineering mitigation before evidentiary scaling. The separation of engineering assessment from evidentiary analysis is analytically important because it makes explicit the assumption that realized mitigation is not necessarily equivalent to defensible, financially usable mitigation. The numerical emission-reduction input used in the LCAM and sensitivity calculations is documented in Appendix D, Tables D1–D2.

2.7 Low-Confidence Adjustment Metric as an Analytical Proxy for Conservative Issuability

Engineering emission reductions are translated into a conservatively supportable quantity using LCAM as an evidence-adjusted analytical proxy for conservative issuability. LCAM is not a registry metric, does not reproduce formal issuance rules, and is not intended to replace verifier judgment.

$$\text{LCAM}_y = \text{ER}_y \times f_{\text{int}} \times f_{\text{cal}} \times f_{\text{sync}} \tag{4}$$

where, f_{int} denotes interval completeness; f_{cal} calibration validity; and f_{sync} timestamp coherence.

Interval completeness is defined as:

$$f_{\text{int}} = \frac{T_{\text{valid}}}{T_{\text{total}}} \tag{5}$$

where, T_{valid} is the portion of the monitoring period supported by valid and usable monitoring records; T_{total} is the entire monitoring period considered.

Calibration validity is defined as:

$$f_{\text{cal}} = \frac{T_{\text{calibrated}}}{T_{\text{total}}} \tag{6}$$

where, $T_{\text{calibrated}}$ is the portion of the monitoring period during which a documented in-date calibration status covered the relevant instruments.

Timestamp coherence is defined as:

$$f_{\text{sync}} = \frac{N_{\text{aligned}}}{N_{\text{total}}} \tag{7}$$

where, N_{aligned} is the number of observations satisfying the predefined time-alignment rule; N_{total} is the total number of observations in the monitored dataset. Each factor is computed as the ratio of valid observations to total observations within the monitoring period. LCAM adopts a multiplicative form because the three evidence factors are treated as conjunctive conditions. A complete monitoring interval is less defensible if the relevant instrument calibration has expired, and calibrated measurements are less useful if timestamps cannot be aligned with operational records [41]. The multiplicative structure, therefore, reflects the conservative assumption that weakness in any critical evidence condition is treated as lowering the defensibility of the overall mitigation claim. The construct is deliberately conservative and does not reflect registry rules.

The equation is developed based on the multiplicative structure of emission estimation models, in which activity data or base emission rates are combined with multiple correction factors, as outlined in the UNFCCC CDM methodological tool for project emissions from flaring (version 04.0, 2022) [10]. Because this functional form is an analytical simplification, the robustness of the LCAM comparison is assessed using $\pm 5\%$ evidence-factor sensitivity checks and alternative equal-weighted-average and weakest-link specifications. The base LCAM input values and multiplicative LCAM calculations are documented in Appendix D, Tables D1–D2, while the LCAM sensitivity calculations are reported in Appendix E, Tables E1–E2.

2.8 Evidence-Screening Rules

The same evidence-screening rules were applied to both MRV regimes to ensure that the before-and-after comparison used consistent data-acceptance criteria [2, 28, 29]. These rules were used to convert raw monitoring, calibration, operational, verification, and transaction-related records into evidence-supported observations. The purpose of the screening process was not to maximize the estimated issuability of emission reductions, but to identify the portion of monitored mitigation that could be defended under conservative evidence conditions.

The screening protocol follows the operating structure of the POME Biogas Co-Firing project at PKS Lubuk Dalam. The monitoring system contains records with mixed temporal resolutions. Logbook entries, anaerobic-process data, POME flow, COD, pH, temperature, methane fraction, and operating status were primarily recorded daily. In contrast, burner and biogas-supply parameters were recorded hourly during operating periods. Accordingly, daily records served as the primary monitoring unit, while hourly equipment-level records served as supporting traceability evidence for burner operation, biogas supply consistency, and verification of operating conditions.

Five screening rules were applied. First, to ensure complete monitoring, each record had to include the required activity-data field, a timestamp or a monitoring-period identifier, and a traceable source reference. Records were excluded when they were missing, corrupted, duplicated, or not traceable to an original monitoring file, operational log, project monitoring calculation sheet, or verification [2, 3, 17, 20, 25].

Second, calibration validity was assessed at the instrument-record level. A measurement was treated as evidentially valid only when the relevant instrument was supported by valid calibration or service documentation for the corresponding monitoring period. If the evidentiary weakness was limited to one instrument, parameter, or time interval, exclusion was applied only to the affected measurement and period, not to the entire project dataset. This rule was used to avoid both over-inclusion of unsupported measurements and over-exclusion of otherwise valid records [18].

Third, temporal coherence was assessed by reconciling daily monitoring records, hourly operating records, logbook notes, project monitoring sheets, and verification evidence. Because the project files do not specify a fixed minute-level tolerance, this study did not impose an unsupported tolerance such as ± 1 minute or ± 1 hour. Instead, records were retained only when they could be matched to the same monitoring day or operating interval and reconciled with the corresponding operational or verification record. Records that could not be temporally reconciled were excluded from the evidence-supported dataset.

Fourth, data traceability required each processed value to be linked to a source record, storage location, calculation file, or verification evidence. Manual entries, spreadsheet values, or derived figures without a source file, audit trail, or verifiable calculation pathway were not treated as evidence-supported observations [3, 25, 38]. This rule was applied to prevent unsupported processed data from being treated as equivalent to traceable monitoring evidence.

Fifth, verification readiness required the evidence package to be internally consistent before it was used in the analytical calculation. Monitoring values had to be supported by source records, calibration evidence where relevant, operational explanations for abnormal values, and verification-related documentation. Records linked to unresolved inconsistencies, missing supporting files, or incomplete query-response evidence were flagged and excluded until the inconsistency was resolved.

The screening rules were defined before calculation and applied consistently across the legacy and enhanced MRV regimes. This approach adheres to the principle of measurement control and risk-based project governance, which stipulates that the criteria for acceptance of data must be pre-specified and applied consistently to prevent selective treatment of data [35]. These rules are not meant to replicate all aspects of formal verification. Rather, they provide a consistent and conservative basis for assessing the association between evidence fragility and the defensibility of mitigation claims. The detailed decision criteria, exclusion conditions, affected data fields, and examples are provided in Appendix B, Table B2.

2.9 Realized-Price Wedge

Settlement results are assessed by separating benchmark and realized prices:

$$P_{\text{real}} = P_{\text{bench}} \times (1 - \alpha) \tag{8}$$

where, α is the realized-price wedge defined as:

$$\alpha = 1 - \frac{P_{\text{real}}}{P_{\text{bench}}} \tag{9}$$

where, α represents the proportional difference between benchmark and realized prices. In this study, it is used as an illustrative revenue-risk indicator that is consistent with information and delivery-risk exposure, rather than as a universal pricing relation or a causal estimate of MRV impact on prices [4, 16, 31, 33, 38, 42]. The base price-wedge calculation and benchmark-price sensitivity are reported in Appendix E, Tables E3–E4.

2.10 Issuance Cadence and Present-Value Adjustment

Issuance cadence is measured as the duration between monitoring closure and issuance and is defined as:

$$\text{Cadence}_y = t_{\text{issuance}} - t_{\text{monitoring}} \tag{10}$$

where, Cadence_y denotes the duration between monitoring closure and issuance.

The present-value impact of earlier revenue recognition is calculated as:

$$\text{PV} = \frac{\text{CF}}{(1 + r)^t} \tag{11}$$

where, CF is a cash flow; r is the discount rate; and t indicates the time to receipt, which is measured in days. Earlier issuance is represented as a relative present-value uplift from receiving the same nominal cash flow sooner, according to standard discounting principles [14, 18, 24, 39, 40].

To convert timing into a finance-relevant indicator, the study computes the relative present-value uplift from receiving the same nominal cash flow Δt days earlier at an annual discount rate r.

$$\Delta\text{PV} = (1 + r)^{\Delta t/365} - 1 \tag{12}$$

2.11 Integrated Revenue Identity

Realized annual revenue is the following:

$$R_y = \text{LCAM}_y \times P_{\text{real}} \tag{13}$$

The present value of the realized annual revenue is defined as [42, 43]:

$$\text{PV}\left(R_y\right) = \frac{\text{LCAM}_y \times P_{\text{realized}}}{(1 + r)^t} \tag{14}$$

These three aspects can be classified into analytically distinguishable elements: mitigation [43], conservatively supportable mitigation (represented by LCAM), and monetary value (R_y). This identity separates engineering performance, evidentiary defensibility, and monetary value into distinct analytical components.

2.12 Analytical Expectation

Under fixed engineering and accounting conditions, the enhanced MRV regime is analytically expected to be associated with three more favorable finance-relevant project indicators.

First, a greater share of engineering emission reductions is expected to be conservatively supported by the evidence-screening rules. This relationship is captured in larger values of f_{MRV} and LCAM_y, which indicate that complete monitoring records, valid calibration evidence, and time-consistent documentation support a greater share of measured mitigation.

Second, the realized-price wedge is expected to be smaller under the enhanced MRV regime. A lower α would indicate that the realized settlement price is closer to the benchmark price. However, this indicator should be interpreted cautiously because realized prices may also reflect buyer characteristics, contractual terms, bargaining position, payment timing, and broader market conditions.

Third, the monitoring-to-issuance period is expected to be shorter under the enhanced MRV regime. A shorter Cadence_y would be consistent with lower timing friction between monitoring closure and issuance and may increase the relative present value of the same nominal cash flow.

This is not an automatic outcome, but it is consistent with the analytical mechanism presented here. Other factors, including market conditions and procedural constraints, may also influence the observed outcomes [21, 33]. The goal of this analysis is not to identify all possible causes, but to examine whether the observed patterns are consistent with stronger evidentiary conditions and lower evidentiary friction within the project.

3 Results

The results are organized around four aspects of project management: emission-reduction engineering, conservative issuability, price-wedge realization, and issuance cadence. This categorization separates physical mitigation performance from evidentiary robustness, realized settlement outcomes, and cash-flow timing. The approach follows the principle of analytical separability across three dimensions: emission-reduction engineering, conservative issuability under evidentiary constraints, and financial realization through price and timing. Since the engineering and accounting systems are held fixed under the two MRV regimes, the results describe differences in evidentiary conditions rather than changes in physical mitigation performance [9, 19, 32].

3.1 Engineering Emission Reductions

Annual emission reductions were computed using the accounting relations in Section 2. The baseline emission was 21.53 $ktCO_2e{\cdot}y^{-1}$, and the project emission was 2.845 $ktCO_2e{\cdot}y^{-1}$, resulting in an annual engineering emission reduction of 18.69 $ktCO_2e{\cdot}y^{-1}$ (21.53-2.845) (Table 2). The same engineering emission-reduction input is used in the base LCAM and sensitivity calculations reported in Appendix D, Tables D1–D2. This value is held constant across the legacy and enhanced MRV regimes, allowing subsequent differences in LCAM, the realized-price wedge, and issuance cadence to be interpreted as associated with evidentiary conditions rather than with changes in methane-abatement technology or accounting rules. Such differences are interpreted as being associated with variations in how identical quantified mitigation is supported, validated, and handled within the system of proof [19, 20].

Table 2. Annual engineering accounting outcomes

Step	Equation	Inputs Shown	Result
Baseline emissions	$BE_y = BM_{CH_4,baseline,y} \times GWP_{CH_4}$	$BM_{CH_4,baseline,y} = 0.7915$ $GWP_{CH_4} = 27.2$	21.53 $ktCO_2e{\cdot}y^{-1}$
Project emissions	$PE_y = PE_{y,flare} + PE_{y,residual}$	$PE_{y,flare} = 2.176$ $PE_{y,residual} = 0.669$	2.845 $ktCO_2e{\cdot}y^{-1}$
Emission reductions	$ER_y = BE_y - PE_y$	–	18.69 $ktCO_2e{\cdot}y^{-1}$

Source: Authors' calculations based on project monitoring records, the emission-reduction equations described in Section 2.6, UNFCCC AMS-III.H [8] , and the CDM flaring methodological tool [9].

Table 3. Evidence factors and conservative issuability

Component	Legacy MRV	Enhanced MRV	Basis of Construction
Interval completeness, f_{int}	0.930	0.980	Share of monitoring period supported by valid and usable records
Calibration validity, f_{cal}	0.920	0.970	Share of the monitoring period covered by documented in-date calibration status
Timestamp coherence, f_{sync}	0.900	0.960	Share of observations satisfying the time-alignment rule
Composite evidentiary support factor, f_{MRV}	0.770	0.913	$f_{int} \times f_{cal} \times f_{sync}$
Engineering reduction, ($ktCO_2e{\cdot}y^{-1}$)	18.690	18.690	Calculated from baseline and project emissions
Conservative issuability, $LCAM_y$ ($ktCO_2e{\cdot}y^{-1}$)	14.390	17.070	$ER_y \times f_{MRV}$

Note: Detailed calculations are provided in Appendix D, Tables D1–D2. MRV = monitoring, reporting, and verification; LCAM = low-confidence adjustment metric.

Source: Authors' calculation based on the LCAM formulation, evidence-screening rules, and project MRV records.

3.2 Conservative Issuability under Alternative Monitoring, Reporting, and Verification Regimes

Conservative issuability was quantified using LCAM. For the legacy MRV regime, interval completeness, calibration validity, and timestamp coherence were 0.93, 0.92, and 0.90, respectively. These values produced a composite evidentiary factor of 0.770 (0.93 × 0.92 × 0.90). When applied to the annual engineering emission reductions of 18.69 $ktCO_2e{\cdot}y^{-1}$, this yielded a conservative estimate of issuability of 14.39 $ktCO_2e{\cdot}y^{-1}$. For the enhanced MRV regime, the corresponding factors were 0.98, 0.97, and 0.96, yielding a composite evidentiary factor of 0.913 ($0.98 \times 0.97 \times 0.96$) and a conservative issuability estimate of 17.07 $ktCO_2e \cdot y^{-1}$. The conservatively supportable fraction of engineering emission reductions therefore increased from 77.0% to 91.3%, equivalent to an increase of 2.68 $ktCO_2e \cdot y^{-1}$ ($17.07 - 14.39$) in supportable mitigation. Table 3 reports the evidence factors and resulting conservative issuability under both MRV regimes. The detailed input values and multiplicative LCAM calculation supporting these results are provided in Appendix D, Tables D1–D2. This classification highlights the relationship between the quality of evidence and the share of engineering mitigation that can be considered with high confidence. The implication here is that equal engineering mitigation measures are not always supported by equal evidence quality [1, 2, 13, 14, 24, 25, 32].

From the perspective of project managers, each of the three LCAM criteria is reflected in tangible MRV key performance indicators. Completeness of intervals reflects the reliability of the monitoring system, validity of calibrations reflects discipline in the governance of measurements, and coherence of timestamps reflects the ability to compile verifiable evidence.

3.3 Realized Settlement Price and Price Wedge

The benchmark price of Rp150,000/tCO_2e was taken from the SRN-PPI/IDXCarbon marketplace record for the same project: "POME for Biogas Co-Firing PT Perkebunan Nusantara IV (PTPN IV PalmCo Regional 3)" (Registration Number: SPE-11-PR-VI-2024-18003) [44]. In this study, this value is used as a project-specific registry reference price for the illustrative price-wedge calculation. It is not treated as a universal market price, nor as evidence that all methane-abatement credits should transact at that level.

With the benchmark price held at Rp150,000/tCO_2e, the realized settlement price was Rp105,000/tCO_2e under the legacy MRV regime and Rp132,000/tCO_2e under the enhanced MRV regime. This corresponds to a realized-price wedge of 0.300 for the legacy regime and 0.120 for the enhanced regime (Table 4). In terms of value capture, the project captured 70% of the benchmark value under the legacy regime and 88% under the enhanced regime. The base price-wedge calculation and benchmark-price sensitivity are reported in Appendix E, Tables E3–E4. This pattern is interpreted as an illustrative revenue-risk indicator rather than as evidence that MRV enhancement alone caused the pricing difference [4, 5, 31].

Table 4. Realized settlement price and wedge

MRV Regime	Benchmark Price, P_{bench} (Rp/tCO_2e)	Realized Settlement Price, P_{real} (Rp/tCO_2e)	Realized-Price Wedge, α
Legacy MRV	150,000	105,000	0.30
Enhanced MRV	150,000	132,000	0.12

Note: The realized-price wedge is defined as: $\alpha = 1 - (P_{\text{real}}/P_{\text{bench}})$. The base calculation and benchmark-price sensitivity are provided in Appendix E, Tables E3–E4. MRV = monitoring, reporting, and verification.

Source: Authors' calculation based on anonymized settlement data and the benchmark-price reference described in Section 3.3.

From a managerial perspective, the realized-price wedge can support buyer negotiations and revenue risk assessment. The lower wedge indicates that the realized settlement price is closer to the benchmark price in this within-project comparison. However, actual realized prices may also reflect buyer characteristics, contractual arrangements, settlement timing, bargaining position, and broader market conditions. The price-wedge result should therefore be read only as an illustrative within-project revenue-risk indicator, not as a general MRV price-premium estimate or a causal estimate of an MRV-driven pricing effect [4, 5, 31, 33].

Table 5. Issuance cadence and present-value effect

Item	Legacy MRV	Enhanced MRV	Output
Issuance cadence (days)	130	80	$\Delta t = 50$
Discount rate	10.41%	10.41%	–
Present-value uplift from earlier receipt	–	–	1.37%

Note: The relative present-value uplift is calculated for receipt of the same nominal cash flow 50 days earlier. The base calculation and discount-rate sensitivity are provided in Appendix E, Table E5. MRV = monitoring, reporting, and verification.

Source: Authors' calculation based on issuance-timing records and the present-value adjustment described in Section 2.10.

3.4 Issuance Cadence and Timing Effect

The issuance cadence was shorter in the enhanced MRV period, declining from 130 days under the legacy MRV regime to 80 days under the enhanced MRV regime, a 50-day difference (Table 5). At a 10.41% annual discount rate, which represents the project's estimated WACC used for internal financial analysis, a 50-day reduction in issuance lag corresponds to a relative present-value uplift of approximately 1.36%–1.37%. The relative present-value uplift and discount-rate sensitivity are reported in Appendix E, Table E5. For project managers, issuance cadence is a liquidity and working-capital indicator because it is reflected in the timing of expected cash inflows, even when nominal credit volume and realized prices remain unchanged [10, 14, 31].

3.5 Integrated Realized Revenue

Annual realized revenue was examined under two analytical scenarios using the LCAM and realized-price inputs reported in Table 3 and Table 4 and supported by Appendix D, Tables D1–D2, and Appendix E, Table E3. Conservative issuability was fixed at 14,390 $tCO_2e\cdot y^{-1}$ in the price-only case. Under this price-only scenario, the calculated revenue differs from Rp 1,510,950,000 (14,390 × 105,000) to Rp 1,899,480,000 (14,390 × 132,000), corresponding to a scenario difference of Rp 388,530,000 under the higher realized settlement price used for the enhanced-regime scenario. In contrast, both the conservative issuability and realized prices were allowed to vary by regime.

Under the full scenario, calculated revenue increases from Rp 1,510,950,000 to Rp 2,253,240,000 (17,070 × 132,000), corresponding to an aggregate scenario difference of Rp 742,290,000. This comparison separates the price-related channel from the combined effect of price and conservative issuability, allowing project managers to assess the potential financial relevance of MRV improvement scenarios relative to the costs of calibration systems, data management, personnel training, and verification-file preparation. The annual realized revenue under the alternative MRV scenarios is presented in Table 6.

Table 6. Annual realized revenue under alternative scenarios

MRV Regime	Conservative Issuability, $LCAM_y$ ($tCO_2e\cdot y^{-1}$)	Realized Price, P_{real} (Rp/tCO_2e)	Realized Revenue, R_y ($Rp\cdot y^{-1}$)
Legacy MRV	14,390	105,000	1,510,950,000
Enhanced MRV (price-only scenario)	14,390	132,000	1,899,480,000
Enhanced MRV (full scenario)	17,070	132,000	2,253,240,000

Note: The issuability values using conservative figures are calculated on a $tCO_2e\cdot y^{-1}$ basis rather than a $ktCO_2e\cdot y^{-1}$ basis. The adjusted complete scenario employs a figure of 17,070 $tCO_2e\cdot y^{-1}$. This figure corresponds to the low-confidence adjustment metric (LCAM) result provided in Table 3 and Appendix D (Table D2). MRV = monitoring, reporting, and verification.

Source: Authors' calculation based on conservative issuability, realized settlement price, and revenue identity described in Sections 2.9–2.11.

3.6 Sensitivity Analysis

Four sensitivity analyses were conducted to assess whether the underlying LCAM specification, benchmark price assumption, or discount rate assumption influences the project's central pattern. The detailed workings of these four sensitivity analyses are shown in Appendix E, Tables E1–E6. First, each LCAM evidence factor was adjusted by ±5%. Second, alternative LCAM calculations based on weighted-average and weakest-link specifications were performed. Third, alternative benchmark prices for the price-wedge calculations were used, adjusted by ±10%. Fourth, the uplift in relative present value was recalculated with discount rates of 6%, 8%, 10.41% and 12%.

The purpose of the sensitivity analyses is not to prove a cause-and-effect relationship but rather to assess whether this pattern holds under different assumptions. A summary of the sensitivity analysis is presented in Table 7.

Across all scenarios considered, the enhanced MRV regime remains associated with a higher conservative estimate of issuability, a lower realized-price wedge, and a positive relative PV uplift. These results are consistent with directional stability in the within-project pattern under the non-causal analytical design used in this study.

4 Discussion

4.1 Low-Confidence Adjustment Metric as an Monitoring, Reporting, and Verification Project Management Indicator

These results highlight an important distinction in carbon project management: engineered emission reductions do not automatically become financially usable carbon revenue [1, 4, 31]. The project's underlying engineering emission reduction remained constant across the two MRV regimes. Nonetheless, the conservatively defensible proportion increased from 77.0% to 91.3%, the realized-price wedge declined from 0.300 to 0.120, and the monitoring-to-issuance interval shortened by 50 days under the enhanced MRV regime. These calculations are reported in Appendix D (Tables D1–D2) and Appendix E (Tables E1–E6).

Table 7. Sensitivity analysis of LCAM, price wedge, and relative PV uplift

Sensitivity Test	Legacy MRV	Enhanced MRV	Interpretation
Base multiplicative LCAM	14.39	17.07	Main analytical proxy
LCAM factors reduced by 5%	12.35	14.63	Enhanced remains higher
LCAM factors increased by 5%	16.67	18.69	Enhanced remains higher
Equal-weighted average LCAM	17.13	18.13	Alternative functional form; enhanced remains higher
Weakest-link LCAM	16.82	17.94	Conservative weakest-condition rule; enhanced remains higher
Wedge at benchmark reduced by 10%	0.222	0.022	Enhanced wedge remains smaller
Wedge at benchmark increased by 10%	0.364	0.200	Enhanced wedge remains smaller
PV uplift at 6%	–	0.80%	Lower discount-rate assumption
PV uplift at 8%	–	1.06%	Moderate discount-rate assumption
PV uplift at 10.41%	–	1.37%	Base discount-rate assumption
PV uplift at 12%	–	1.56%	Higher discount-rate assumption

Note: LCAM values are expressed in $ktCO_2e{\cdot}y^{-1}$, price wedges are unitless, and relative PV uplift is based on a 50-day acceleration in receipt time using an annual discount rate. Detailed calculations are provided in Appendix E, Tables E1–E6. LCAM = low-confidence adjustment metric; PV = present value; MRV = monitoring, reporting, and verification.

Source: Authors' sensitivity calculation based on the LCAM, realized-price wedge, and present-value assumptions described in Section 3.6 and Appendix E.

In other words, this indicates that engineering mitigation and financially usable carbon revenue are two distinct analytical outputs. The financial usability of a carbon project, therefore, depends upon the degree of completeness, calibration, temporal coherence, traceability, and verification readiness without much evidentiary friction [2, 3, 19, 20, 24, 32]. From a pragmatic viewpoint, the question of usability lies beyond whether the mitigation took place, but rather the possibility of verifying whether such evidence is reconstructible and defensible before trading [9, 19, 20].

From this perspective, MRV processes should be viewed as evidentiary infrastructure for the project rather than simply as an implementation-monitoring function [1–3, 19, 20, 24, 32, 38]. In essence, MRV evidence quality is associated with how defensible, transaction-ready, and timely the carbon-revenue claim is. At the same time, financial outcomes may also depend on market, contractual, buyer-related, and institutional factors [4, 5, 14, 17, 18, 23, 31, 33].

4.2 Conservative Issuability and the Defensible Share of Measured Mitigation

In particular, this point becomes evident when considering the effect of the engineering input on LCAM. With the same engineering emission-reduction input, LCAM rises from 14.39 to 17.07 $ktCO_2e{\cdot}y^{-1}$. The rise suggests a larger share of the measured mitigation is defensible under the specified evidence-screening criteria. Therefore, it can be interpreted as further supporting the statement that the measured mitigation may not necessarily mean defensible mitigation in light of conservative evidentiary criteria [1, 2, 6, 25].

LCAM helps clarify which portion of the measured mitigation remains defensible under specified evidence conditions. This interpretation is consistent with verification-based approaches that emphasize traceability, documentation, and justified evidence [32]. This interpretation is also consistent with broader integrity studies showing that carbon-credit credibility depends not only on technical performance but also on sufficient supporting evidence. Rather than simply restating that evidence quality matters, LCAM provides a transparent analytical device for showing how evidentiary weakness affects the conservatively supportable fraction of measured mitigation [7, 32, 45].

Therefore, LCAM cannot be treated as a replication of the carbon-credit issuance procedure but as a deliberately conservative analysis. Its purpose is to illustrate how evidence deficiencies are associated with the defensible share of measured mitigation. Terms such as "verified reduction" may blur the distinction between measured mitigation and the conservatively defensible share of mitigation [12].

This distinction also raises an important practical issue for project developers. In addition to the general discrepancy between the credited and actual emissions reduction, there is also a difference between measured environmental performance and the portion of it that can be claimed with specified evidentiary considerations. From this perspective, conservative issuability can be understood as an indicator of how defensible measured environmental performance is within institutional and verification settings [6, 19, 20, 32].

4.3 Realized Settlement Outcomes: Cautious Interpretation of the Price Wedge

The price-wedge result should be interpreted with particular caution. In the within-project comparison, the realized settlement price increased from Rp 105,000 to Rp 132,000 per tCO_2e, while the realized-price wedge decreased from 0.30 to 0.12. Although this pattern is consistent with lower information and delivery-risk exposure, the study design cannot rule out other explanations, including contractual terms, buyer characteristics, payment timing, bargaining position, and broader market conditions. The result should therefore not be interpreted as evidence that stronger MRV necessarily produces a market premium. Such a generalization would go beyond the scope of this single-project analysis and the observed variation in voluntary carbon-offset prices [4, 5, 31]. More cautiously, the within-project pattern indicates that stronger evidence is associated with smaller discounts relative to the benchmark, consistent with lower information and delivery-risk exposure [13, 14, 17, 18].

In particular, the decline in the realized-price wedge (0.30 → 0.12) may indicate lower perceived information and delivery-risk exposure in this within-project setting [15] When counterparties cannot fully assess the quality or deliverability of an asset, they may rely on discounts, contingencies, selective contracting, or conservative settlement practices to limit exposure [4, 15, 16, 18, 33]. This issue is particularly relevant for carbon-credit contracts because the underlying claims depend on technical data, procedural documentation, and verification records that counterparties may not be able to audit independently. In such situations, enhanced evidence does not mean a rise in the benchmark price, but it can rather reflect reduced uncertainty and less depressed price levels [4, 5, 16]. The result is therefore better interpreted through an information-risk lens than as evidence of a general MRV price premium [15].

A price-premium interpretation would imply that higher MRV quality consistently commands higher prices across settings, whereas a more restrained interpretation requires fewer causal assumptions. In this case, the pricing pattern associated with stronger evidence is better interpreted as convergence toward the benchmark price under information- and delivery-risk conditions [16]. This interpretation is consistent with studies suggesting that clearer, more complete environmental information may influence third-party assessments of climate-related claims [21]. This is also aligned with the governance literature that links disclosure quality, transparency, and market confidence [14, 17]. Nevertheless, realized prices may depend on many other factors, and the current design does not rule out these effects [13, 14].

4.4 Issuance Cadence and Project Cash-Flow Timing

Timing is an important dimension of liquidity and financial usability, and it provides a third project-management indicator in addition to conservative issuability and price realization [19]. In the enhanced MRV period, the monitoring-to-issuance interval was shorter, declining from 130 to 80 days. Although issuance cadence may appear administrative, it is financially relevant because credits remain illiquid until issuance is completed [1, 31]. A shorter issuance interval is therefore consistent with more favorable expected cash-flow timing and corresponds to an estimated present-value uplift of approximately 1.4% for the same nominal cash flow [14, 24, 40]. This timing channel extends the interpretation of MRV quality beyond defensible volume and realized price, because delayed revenue is not neutral in project-finance terms [14, 39, 40].

The cadence result is consistent with the broader mechanism proposed in this paper. If the analysis had shown higher conservative issuability without a shorter issuance cadence, the finding would have been largely procedural. Conversely, faster issuance without greater supportability would have provided weaker support for the relevance of MRV evidence. The observed pattern is instead coherent across supportability, settlement, and timing, suggesting that evidence quality is associated with the pathway from measured mitigation to usable revenue rather than only with isolated verification steps [12, 33]. This interpretation should still be treated cautiously, as faster issuance may also be influenced by registry backlogs, verifier workload, administrative timing, and other procedural factors [1, 2, 14, 31, 45].

Thus, while the analysis cannot claim that MRV accounts for all variation in issuance speed, the within-project evidence indicates that higher evidence quality is correlated with faster issuance and is consistent with lower evidentiary friction [1, 2, 14, 31, 45].

4.5 Monitoring, Reporting, and Verification Governance for Project Managers

The findings indicate that MRV governance should be viewed as a project risk-management infrastructure [10, 28, 34]. This interpretation is consistent with project risk management principles, which emphasize integrating risk control into planning, monitoring, and management routines [35, 36]. For engineering project managers, MRV improvement should therefore go beyond the preparation of verification documents and be embedded in routine controls, including calibration registers, timestamp rules, data version control, internal evidence review, and verification-readiness checklists [2, 10, 28, 30]. In practical terms, project managers should maintain calibration registers with instrument ID, calibration date, expiry date, responsible officer, certificate location, and expiry warnings [25, 30]. Timestamp rules should be specified before the monitoring period begins. Monitoring records should be stored in a version-controlled repository linking raw data, processed datasets, calibration files, and verification submissions, and an internal verification-readiness checklist should be completed before external verification begins [3, 10].

Finally, MRV indicators should be integrated into carbon-revenue forecasting. Instead of forecasting revenue directly from engineering emission reductions, project managers should distinguish between engineering reductions, conservatively supportable reductions, expected realized price, expected issuance lag, and discount-rate assumptions [14, 39, 40].

This approach enables MRV weaknesses to be represented as revenue-risk scenarios before they appear in verification, settlement, or cash-flow timing [10, 28, 33].

4.6 Boundaries of the Contribution

These boundaries are important because the present study addresses evidence-management risk rather than the full environmental integrity of carbon offsetting [19, 27, 32, 46]. Neither the present results nor related studies imply that stronger MRV resolves fundamental structural critiques of offsetting. Issues such as baseline weakness, leakage, permanence, and strategic behavior remain outside the scope of the framework presented here [6, 19, 27, 46]. A project may be supported by strong evidence yet remain vulnerable to counterfactual bias, and improved documentation alone does not ensure environmental credibility when the underlying offset logic is weak [6, 27, 46, 47]. Accordingly, the findings should be interpreted as transferable analytical principles rather than transferable effect sizes.

Second, the research design is intended to identify mechanism-consistent patterns, not average financial-market effects. By relying on a within-project comparison, the study examines changes in evidence conditions while holding the engineering setting constant. Prices and issuance outcomes may still vary according to project-specific and institution-specific characteristics; therefore, the relationships observed here may be context-specific [13, 14].

Third, the analytical constructs are inherently conservative. It is important to emphasize that LCAM is neither registry-based nor verifier-oriented. The same applies to the realized-price wedge, which does not capture all transaction-specific determinants of settlement value. Such an approach has been chosen deliberately to preserve analytical simplicity and to demonstrate the link between the variables analyzed [4, 5, 31, 33].

4.7 Implications for Further Research

The above constraints also point toward possible directions for future research. First, future research should test the replicability of this framework across project types, crediting standards, and transaction structures [4, 5, 31]. Such research could assess whether the LCAM–price-wedge–issuance-cadence pattern observed here is general, conditional, or context-specific. It could also clarify where evidence quality is most relevant, such as in projects with long monitoring chains, settings with lower buyer trust, or transactions where delivery risk is more salient [13, 33].

Second, future research could examine evidential fragility and counterfactual fragility more explicitly [2, 25, 27, 46]. In other words, projects might be characterized by the strength of their monitoring claim relative to that of additionality. Exploring this difference would help us understand why certain projects can face significant challenges of evidential contestation even when they present an extensive monitoring record. In contrast, others may appear less controversial despite weaknesses in the evidence supporting additionality [25, 30]. This distinction is important if future research is to avoid collapsing different carbon-credit quality problems into a single undifferentiated category.

A third direction concerns the financial architecture of carbon projects. The analysis indicates that evidence quality may be associated with the defensibility of mitigation quantity, realized settlement outcomes, and revenue timing. Future research could examine whether these associations are also reflected in financing terms, contract design, risk allocation, or project valuation under more complex cash-flow patterns [4, 5, 14]. Such work would extend the evaluation beyond revenue usability toward carbon-project bankability. In that sense, the present analysis identifies one manageable aspect of a broader institutional dilemma. It does not seek to determine the future trajectory of carbon markets. Rather, it illustrates, more narrowly and practically, how evidence quality may be associated with whether measured mitigation can be made supportable, saleable, and timely enough to be treated as project revenue [4, 5, 14].

5 Conclusions

This study examined how MRV system management is associated with conservative issuability, realized-price wedge, and issuance cadence in a methane-abatement engineering project. Under fixed engineering and accounting conditions, the enhanced MRV regime was associated with a higher conservatively supportable share of engineering emission reductions, a smaller realized-price wedge, and a shorter monitoring-to-issuance period. Under identical engineering emission reductions of 18.69 $ktCO_2e \cdot y^{-1}$, the enhanced evidence condition was associated with a higher conservatively supportable fraction of mitigation (77.0% to 91.3%), a lower realized-price wedge (0.30 to 0.12), and a shorter monitoring-to-issuance interval (130 to 80 days). These differences correspond to an increase in conservative issuability from 14.39 to 17.07 $ktCO_2e \cdot y^{-1}$ and a shorter revenue-realization interval, with an estimated present-value uplift of approximately 1.4%.

This distinction is especially important for interpreting LCAM. In this study, LCAM is used strictly as a transparent analytical proxy for conservative supportability under specified evidence conditions, not as an issuance rule, registry indicator, or substitute for verifier judgment.

From a project management standpoint, the findings indicate that higher-quality MRV evidence is associated with three complementary revenue-risk indicators: greater defensibility of mitigation volume, lower price-wedge realization, and a shorter interval between monitoring and credit issuance. These three factors appear together in the project-level comparison, indicating that MRV evidence quality is correlated not only with the defensibility of emission reductions but also with settlement- and time-based revenue-risk factors.

The contribution of this study is intentionally limited in scope. While it does not claim that MRV can resolve structural integrity problems associated with additionality, baseline uncertainty, leakage, and permanence, it provides a bounded analysis of the correlation between evidence quality and finance-relevant metrics. By focusing on MRV as a risk control system for engineering projects, the analysis highlights the importance of monitoring consistency, calibration validity, proper timestamp alignment, and chain-of-custody traceability as project-level factors for verification readiness, revenue estimation, and carbon trading.

Future research can extend this framework across multiple project types, crediting mechanisms, and market conditions to assess whether the relationships observed here are general, conditional, or context-specific. Further studies could also examine how evidentiary quality interacts with contract design, financing terms, and institutional procedures in shaping carbon-project bankability.

Author Contributions

Conceptualization, A.R. and L.T.B.; methodology, A.R., A.I.B., and I.I.; software, A.I.B., B.S.S., and I.I.; validation, A.I.B., B.S.S., L.T.B., and I.I.; formal analysis, A.R. and A.I.B.; investigation, A.I.B. and I.I.; resources, B.S.S.; data curation, A.R. and A.I.B.; writing—original draft preparation, A.R. and L.T.B.; writing—review and editing, A.R., A.I.B., B.S.S., L.T.B., and I.I.; visualization, A.R. and A.I.B.; supervision, A.I.B. and B.S.S.; project administration, B.S.S. and I.I.; funding acquisition, A.R. All authors read and approved the final manuscript.

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Data Availability

The data that form the basis of this study comprise the project monitoring data, calibration data, verification process data, data on the timing of issuance, and anonymized transaction data. Given the data's confidentiality, individual-level records about transactions and projects cannot be released to the public. Anonymized data used in the calculations for LCAM factors, price wedge calculation, issuance cadence calculation, and sensitivity analysis are included in the appendices. They are obtainable upon request from the corresponding author.

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Conflicts of Interest

The authors declare no conflicts of interest.

Declaration on the Use of Generative AI and AI-assisted Technologies

The author used generative AI tools solely for limited language editing and formatting assistance during manuscript preparation. All scientific content, analysis, and conclusions were developed and verified by the author.

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Appendix

Appendix A. Project context and MRV-regime comparison

Table A1. Project context and analytical boundaries

Project-Context Item	Description
Project type	Methane recovery and abatement in palm oil mill effluent wastewater treatment through biogas capture and biogas co-firing. The project captures methane-rich biogas from anaerobic POME treatment and combusts it in a boiler to replace part of the palm-shell boiler fuel, while excess biogas is flared.
Site	Palm Oil Mill Effluent wastewater treatment facility at PKS Lubuk Dalam, owned and operated by PT Perkebunan Nusantara IV Regional III, located in Lubuk Dalam, Sialang Baru, and Koto Gasib area, Kampung Pangkalan Pisang, Lubuk Dalam District, Siak Regency, Riau Province, Indonesia. The reported coordinates are N 00°37'47.6" and E 101°46'04.0".
Operating unit	Existing POME treatment system upgraded with methane capture and biogas co-firing facilities. The system includes a CIGAR-covered anaerobic reactor, a biogas line to the boiler, a biogas burner for co-firing, and a flare stack for excess gas or safety control.
Number of flares or engines	The available documents confirm the presence of a flaring system or flare stack and a biogas burner connected to the boiler. The project is not described as a biogas engine power generation project. The exact number of flare stacks, burners, or boiler units is not explicitly disclosed in the available project documents.
Official monitoring period	19 November 2021 to 18 November 2024, as reported in the project monitoring and verification documents.
Legacy MRV period	19 November 2021 to 31 December 2023. This period is defined analytically as the earlier evidence-management condition within the same official monitoring period.
Enhanced MRV period	1 January 2024 to 18 November 2024. This period is defined analytically as the latter evidence-management condition after intensified verification-related data-quality strengthening.
Reason for MRV strengthening	MRV strengthening was associated with validation and verification requirements rather than a change in the underlying methane-abatement technology. The validation and verification processes assessed data completeness, calibration, missing-data handling, monitoring implementation, data-quality controls, and consistency between project implementation and validated documentation.
Upgrade components	Monitoring continuity, calibration register and equipment-calibration control, timestamp and monitoring-record consistency, missing-data handling, traceable record storage, internal evidence review, data-quality management, verification-query response management, and linkage between raw monitoring records, project monitoring calculation files, and verification evidence.
Operating arrangement	The project is owned and operated by PT Perkebunan Nusantara IV Regional III, PKS Lubuk Dalam. PT Ecody Agro Energi is identified in the project documents as the company that built the biogas project. PT SUCOFINDO ICS conducted validation and verification. The buyer or settlement party is anonymized because it is not explicitly disclosed in the available project documents.

Table A2. Comparative description of the legacy and enhanced MRV regimes

Comparison Item	Legacy MRV Regime	Enhanced MRV Regime	Relevance for Interpretation
Analytical period	19 November 2021–31 December 2023	1 January 2024–18 November 2024	Defines the two analytical periods within the official project monitoring period.
Number of daily observations	773 daily observations	323 daily observations	Indicates the relative size of the two within-project observation windows.
Project site	PKS Lubuk Dalam, Siak Regency, Riau Province, Indonesia	Same project site	Holds the project location constant across the two analytical periods.
Project technology	POME methane recovery using CIGAR/covered anaerobic reactor, biogas co-firing in boiler, and a flaring system for excess gas	Same methane-abatement technology and same project boundary	Helps separate MRV evidence-management differences from physical technology changes.
Operating status	Commercial operation under the existing POME treatment, methane capture, biogas co-firing, and flaring configuration	Continued operation under the same engineering configuration	Supports the interpretation that the comparison concerns evidence-management conditions rather than the installation of new technology.
Engineering and accounting basis	UNFCCC AMS-III.H and methodological tool for project emissions from flaring	Same methodological and accounting basis	Reduces heterogeneity in accounting rules between the two periods.
MRV condition	More fragmented evidence preparation, manual reconciliation of records, less systematic calibration tracking, and weaker integration between operational records and verification evidence	Stronger monitoring continuity, calibration-register discipline, timestamp alignment, missing-data handling, traceable record storage, and linkage between raw monitoring records, project monitoring calculation files, and verification evidence	Identifies the main management system difference examined in the study.
Verifier identity	PT SUCOFINDO ICS, based on the available validation and verification documentation	PT SUCOFINDO ICS, based on the available validation and verification documentation	Holding the verifier constant reduces one source of procedural variation, although verifier workload and review timing may still vary.
Reason for MRV strengthening	Earlier evidence-management condition before intensified verification-related data-quality strengthening	MRV strengthening was associated with validation and verification requirements, including PTK and PTS follow-up, calibration assessment, missing-data handling, monitoring-plan implementation, and GHG data information quality management	Clarifies that the upgrade is treated as a verification-readiness and management-system intervention, not as a technology-change intervention.
Contract type	Project-level carbon-credit settlement arrangement. Detailed contractual clauses are commercially confidential and are not disclosed.	Project-level carbon-credit settlement arrangement. Detailed contractual clauses are commercially confidential and are not disclosed.	Contract terms may influence realized prices. Therefore, pricing results are interpreted as illustrative revenue-risk indicators rather than causal MRV price effects.
Buyer profile	Buyer identity is anonymized because it is not explicitly disclosed in the available project documents and may be commercially sensitive.	Buyer identity is anonymized because it is not explicitly disclosed in the available project documents and may be commercially sensitive.	Buyer characteristics and bargaining position may affect the realized-price wedge and cannot be fully controlled.

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Table A2 – continued from previous page

Comparison Item	Legacy MRV Regime	Enhanced MRV Regime	Relevance for Interpretation
Benchmark price reference	Rp 150,000/tCO_2e used as a project-specific registry reference price for illustrative price-wedge calculation.	Same benchmark reference used for comparability.	Ensures that the wedge calculation applies a consistent reference value across regimes.
Market and institutional conditions	Carbon-credit pricing and issuance conditions may be affected by market sentiment, buyer demand, registry processing, verifier workload, and institutional procedures. These factors are not independently controlled in the study.	The same category of external conditions may apply, but their period-specific effects cannot be fully isolated.	Reinforces that the study reports within-project associations, not causal identification.
Analytical interpretation	The legacy regime represents the earlier evidence-management condition.	The enhanced regime represents the latter evidence-management condition following MRV strengthening.	The comparison supports mechanism-consistent association, not general causal inference.

Appendix B. Data transparency and evidence-screening protocol

Table B1. Data sources, coverage, screening, exclusion, treatment, and confidentiality

Data Type	Source	Time Span	Recording Frequency	Screening or Exclusion Treatment	Excluded Records or Exclusion Rate	Cross-Check	Confidentiality Treatment
Monitoring logs and activity data records	Project monitoring database, project monitoring sheets, and operational logbooks for the POME biogas co-firing system	Official monitoring period: 19 Nov 2021–18 Nov 2024. Legacy MRV: 19 Nov 2021–31 Dec 2023. Enhanced MRV: 1 Jan 2024–18 Nov 2024	Daily or hourly, depending on the monitored parameter; annual aggregation used for LCAM calculation.	Missing, corrupted, duplicated, or untraceable records were excluded from the evidence-supported dataset	5.5% (61 of 1,096 daily observation-equivalents)	Operational logs, project monitoring calculation files, wastewater-flow records, COD records, biogas-combustion records, and monitoring sheets	Reported only in aggregated form
Calibration certificates and instrument-governance records	Instrument service files, calibration certificates, calibration-validity records, and maintenance documentation	19 Nov 2021–18 Nov 2024, aligned with the official monitoring period	Certificate-based and event-based	Measurements outside valid calibration periods or without supporting calibration documentation were excluded for the affected instrument and period	6.5% (72 of 1,096 daily/instrument-period observation-equivalents)	Service records, certificate validity dates, instrument identification records, and verification evidence files	Certificate IDs and instrument-specific details were anonymized where required
Verification-process logs	Verifier-query records, correspondence files, evidence-submission records, corrective-action follow-up, verification-opinion documentation, and issuance-related documentation	Monitoring-to-verification and verification-to-issuance cycles within 19 Nov 2021–18 Nov 2024	Event-based	Non-substantive administrative messages were excluded; only verification-relevant queries, responses, evidence submissions, and corrective-action records were retained.	Not applicable to the 1,096 daily observation denominator	Verification report, verifier-query records, issuance-related timestamps where available, and final verification documentation	Anonymised

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Table B1 – continued from previous page

Data Type	Source	Time Span	Recording Frequency	Screening or Exclusion Treatment	Excluded Records or Exclusion Rate	Cross-Check	Confidentiality Treatment
Transaction data	Settlement records and contract-related financial records	Legacy and enhanced MRV periods	Transaction-based	Buyer-identifiable terms, confidential contract clauses, and commercially sensitive details were removed before analysis.	Not applicable to the technical monitoring dataset; confidential fields were removed rather than treated as missing observations.	Internal finance records and settlement records	Reported only in an aggregated and anonymized form
Benchmark price	Project-specific registry reference price used for price-wedge calculation.	Relevant transaction period	Periodic or transaction-reference based	Used only as a project-specific registry reference for illustrative price-wedge calculation; not treated as a universal market price.	Not applicable	Settlement records and project-relevant benchmark documentation	Reported as an aggregate benchmark

Table B2. Evidence-screening decision rules

Rule	Decision Criterion	Exclusion Condition	Affected Data Field	Example
Monitoring completeness	Each record must contain the required activity-data field, timestamp, or monitoring-period identifier, and traceable source reference.	Missing, corrupted, duplicated, or untraceable record	POME flow, COD, pH, temperature, CH_4 fraction, burner flow, burner operating hours, operational log	A daily POME or reactor record without a traceable source file is excluded from the evidence-supported dataset
Calibration validity	Instrument-based measurements must be covered by valid calibration or service documentation for the corresponding monitoring period.	Expired, unavailable, or undocumented calibration evidence	Flow, gas, temperature, pressure, or other instrument-based measurement	Data from an instrument outside its valid calibration period are excluded only for the affected instrument and period
Temporal coherence	Daily records and hourly operating records must be reconcilable with the same monitoring day or operating interval.	The record cannot be matched with the logbook, project monitoring sheet, operational record, or verification evidence.	Daily monitoring record, hourly burner record, biogas-supply record, operational remark	An hourly burner-flow value is excluded if it cannot be reconciled with the same-day operating log.
Data traceability	Each processed value must be linked to a source record, storage location, calculation file, or verification evidence.	Manual entry or spreadsheet value without source file, audit trail, or verifiable calculation pathway	Monitoring dataset, project monitoring calculation file, verification dataset	A COD or biogas-combustion value without a source-log reference is excluded.
Verification readiness	The evidence package must be internally consistent and supported by monitoring, calibration, operational, and verification records.	Missing supporting file, unresolved inconsistency, or incomplete query-response evidence	Verification file package, verifier-query record, corrective-action record, calibration attachment	A query response referring to a calibration certificate is incomplete if the certificate is not attached.

Table B3. Anonymized transaction-record template

Transaction Field	Example Format	Disclosure Treatment
Transaction identifier	TX-LEG-001 or TX-ENH-001	Synthetic identifier
MRV regime	Legacy MRV or Enhanced MRV	Reported
Monitoring period	Month, or annual monitoring period	Aggregated
Issued or supportable volume	tCO_2e	Reported in aggregated form
Benchmark price	Rp/tCO_2e	Reported as a project-specific registry reference value
Realized settlement price	Rp/tCO_2e	Reported in aggregated form
Realized-price wedge	Proportion, e.g., 0.30 or 0.12	Calculated and reported
Buyer identity	Buyer A or Buyer B	Anonymised
Contract type	Carbon-credit settlement arrangement	General description only
Confidential contract clauses	Not disclosed	Removed before analysis
Settlement timing	Days from issuance or monitoring closure to settlement	Aggregated
Payment-specific details	Not disclosed	Removed before analysis

Appendix C. Detailed variable dictionary

Table C1. Detailed variable definitions, sources, and temporal resolution

Symbol	Variable	Definition	Unit	Data Source	Temporal Resolution	Variable Type
BE_y	Baseline emissions	Estimated emissions that would have occurred in the absence of the methane-abatement project during year (y).	$ktCO_2e \cdot y^{-1}$	Project monitoring calculation files, project monitoring records, and UNFCCC methodological parameters	Annual aggregation from monitoring-period data	Calculated
$BM_{CH_4,baseline,y}$	Baseline methane mass	Estimated baseline methane mass for year (y), before conversion into CO_2-equivalent emissions.	$ktCH_4 \cdot y^{-1}$	Project monitoring calculation files and activity-data records	Annual aggregation	Calculated
GWP_{CH_4}	Methane global warming potential	Global warming potential factor used to convert methane emissions into CO_2-equivalent emissions.	tCO_2e/tCH_4	Methodological parameter used in the project calculation	Fixed parameter	Observed/ reference parameter
PE_y	Project emissions	Estimated emissions occurring under project operation during year (y).	$ktCO_2e \cdot y^{-1}$	Project monitoring calculation files, flaring records, and project-emission calculation files	Annual aggregation from monitoring-period data	Calculated
$PE_{flare,y}$	Flaring-related project emissions	Project emissions associated with flaring during year (y).	$ktCO_2e \cdot y^{-1}$	Flaring records, project monitoring calculation files, and operational logs	Annual aggregation	Calculated

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Table C1 – continued from previous page

Symbol	Variable	Definition	Unit	Data Source	Temporal Resolution	Variable Type
$\mathrm{PE}_{\mathrm{residual},y}$	Residual project emissions	Residual emissions remaining after accounting for methane recovery, combustion, or destruction during year (y).	$\mathrm{ktCO_2e{\cdot}y^{-1}}$	Project monitoring calculation files and project-emission records	Annual aggregation	Calculated
ER_y	Engineering emission reductions	Difference between baseline emissions and project emissions before evidence-based adjustment.	$\mathrm{ktCO_2e{\cdot}y^{-1}}$	Calculated from BE_y and PE_y	Annual	Calculated
T_{valid}	Valid monitoring interval	Portion of the monitoring period supported by complete, usable, and traceable monitoring records.	Days or observations	Monitoring logs, project monitoring sheets, operational records, and evidence-screening results	Daily or record-level	Observed after screening
T_{total}	Total monitoring interval	Total monitoring period considered in the analysis.	Days or observations	Official monitoring period and analytical period definition	Daily or record-level	Observed
f_{int}	Interval completeness factor	Share of the monitoring interval supported by valid and usable monitoring records.	Ratio, 0–1	Calculated from T_{valid} and T_{total}	Period-level	Calculated
$T_{\mathrm{calibrated}}$	Calibrated monitoring interval	Portion of the monitoring period during which the relevant instrument was supported by valid calibration or service documentation.	Days or observations	Calibration certificates, service records, and instrument-governance records	Instrument-period level	Observed after screening
f_{cal}	Calibration-validity factor	Share of the monitoring period covered by documented in-date calibration status for relevant instruments.	Ratio, 0–1	Calculated from calibration-validity records and monitoring-period data	Period-level	Calculated
N_{aligned}	Temporally aligned observations	Number of observations that can be reconciled with the relevant monitoring day, operating interval, project monitoring sheet, or verification evidence.	Observations	Monitoring logs, hourly operating records, project monitoring sheets, verification evidence, and operational logbooks	Record-level	Observed after screening
N_{total}	Total observations	Total number of observations in the monitored dataset considered for timestamp-coherence assessment.	Observations	Monitoring dataset and analytical period definition	Record-level	Observed

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Table C1 – continued from previous page

Symbol	Variable	Definition	Unit	Data Source	Temporal Resolution	Variable Type
f_{sync}	Timestamp-coherence factor	Share of observations satisfying the predefined temporal reconciliation rule.	Ratio, 0–1	Calculated from N_{aligned} and N_{total}	Period-level	Calculated
f_{MRV}	Composite evidentiary support factor	Composite evidence-support factor combining interval completeness, calibration validity, and timestamp coherence.	Ratio, 0–1	Calculated from f_{int}, f_{cal}, and f_{sync}	Period-level	Calculated
LCAM_y	Low-confidence adjustment metric	Evidence-adjusted analytical proxy for conservative issuability during year (y). It represents the portion of engineering emission reductions that is conservatively supportable under the specified evidence conditions.	$ktCO_2e\cdot y^{-1}$ or $tCO_2e\cdot y^{-1}$	Calculated from ER_y and f_{MRV}	Annual or regime-level	Calculated analytical proxy
P_{bench}	Benchmark price	Project-specific registry reference price used for illustrative price-wedge calculation. It is not treated as a universal carbon-credit market price.	Rp/tCO_2e	Project-specific registry reference and project-relevant market documentation	Transaction-period reference	Observed/ reference parameter
P_{real}	Realized settlement price	Realized project-level settlement price after transaction-specific conditions.	Rp/tCO_2e	Settlement records and anonymized transaction data	Transaction-level or regime-level aggregation	Observed
α	Realized-price wedge	Proportional difference between the benchmark price and the realized settlement price.	Ratio, 0–1	Calculated from P_{bench} and P_{real}	Transaction-level or regime-level aggregation	Calculated
$t_{\text{monitoring}}$	Monitoring-closure date	Date when the relevant monitoring period closed.	Date	Monitoring-period records and verification documentation	Event-based	Observed
t_{issuance}	Issuance date	Date when the relevant credit issuance or issuance-related process was completed.	Date	Issuance-related documentation and verification-process records	Event-based	Observed
Cadence_y	Issuance cadence	Duration between monitoring closure and issuance.	Days	Calculated from t_{issuance} and $t_{\text{monitoring}}$	Event-based	Calculated

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Table C1 – continued from previous page

Symbol	Variable	Definition	Unit	Data Source	Temporal Resolution	Variable Type
Δt	Reduction in issuance lag	Difference in issuance cadence between the legacy and enhanced MRV regimes.	Days	Calculated from the issuance-cadence comparison	Regime-level	Calculated
r	Discount rate	Annual discount rate used to estimate the relative present-value effect of earlier revenue realization.	Percent per year	Project financial assumption, represented by the estimated WACC	Annual parameter	Observed/ reference parameter
ΔPV_{rel}	Relative present-value uplift	Proportional present-value uplift from receiving the same nominal cash flow earlier.	Percent	Calculated from r and Δt	Regime-level	Calculated
R_y	Realized annual revenue	Annual realized revenue from conservative issuability and realized settlement price.	Rp·y^{-1}	Calculated from LCAM_y and P_{real}	Annual or regime-level	Calculated
PV_y	Present value of realized revenue	Present value of realized annual revenue after discounting for the timing of receipt.	Rp	Calculated from R_y, r, and the timing variable	Annual or regime-level	Calculated

Appendix D. Computation for engineering emission reductions and LCAM

The base LCAM specification estimates the conservatively supportable mitigation volume by multiplying the engineering emission reduction by three evidentiary support factors: interval completeness, calibration validity, and temporal coherence. The calculation is expressed as:

$$\text{LCAM}_y = \text{ER}_y \times f_{\text{int}} \times f_{\text{cal}} \times f_{\text{sync}}$$

where, ER_y is the engineering emission reduction; f_{int} is the interval-completeness factor; f_{cal} is the calibration-validity factor; and f_{sync} is the timestamp-coherence factor. Each evidence factor is bounded between 0 and 1. The same engineering emission-reduction value is used for both MRV regimes to isolate the effect of evidentiary-support conditions rather than changes in physical mitigation performance.

Table D1. Base LCAM input values

Input	Legacy MRV	Enhanced MRV	Unit
Engineering emission reduction, ER_y	18.69	18.69	ktCO$_2$e·y^{-1}
Interval completeness, f_{int}	0.93	0.98	Dimensionless
Calibration validity, f_{cal}	0.92	0.97	Dimensionless
Temporal coherence, f_{sync}	0.90	0.96	Dimensionless

Table D2. Base multiplicative LCAM calculation

Component	Formula/Calculation	Legacy MRV	Enhanced MRV	Unit/Interpretation
Engineering emission reduction	$\text{ER}_\text{y} = \text{BE}_\text{y} - \text{PE}_\text{y}$	18.69	18.69	ktCO$_2$e·y^{-1}
Interval completeness factor	$f_{\text{int}} = \frac{T_{\text{valid}}}{T_{\text{total}}}$	0.93	0.98	Dimensionless evidence factor

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Table D2 – continued from previous page

Component	Formula/Calculation	Legacy MRV	Enhanced MRV	Unit/Interpretation
Calibration-validity factor	$f_{\mathrm{cal}} = \frac{T_{\mathrm{calibrated}}}{T_{\mathrm{total}}}$	0.92	0.97	Dimensionless evidence factor
Timestamp-coherence factor	$f_{\mathrm{sync}} = \frac{T_{\mathrm{aligned}}}{N_{\mathrm{total}}}$	0.90	0.96	Dimensionless evidence factor
Composite evidentiary support factor	$f_{\mathrm{MRV}} = f_{\mathrm{int}} \times f_{\mathrm{cal}} \times f_{\mathrm{sync}}$	0.93 × 0.92 × 0.90 = 0.770	0.98 × 0.97 × 0.96 = 0.913	Dimensionless composite factor
Base LCAM	$\mathrm{LCAM_y} = \mathrm{ER_y} \times f_{\mathrm{MRV}}$	18.69 × 0.770 = 14.39	18.69 × 0.913 = 17.07	$\mathrm{ktCO_2e{\cdot}y^{-1}}$

Appendix E. Sensitivity analysis calculations

Appendix E reports the sensitivity calculations used to assess whether the main within-project pattern remains directionally stable under alternative assumptions. The sensitivity analysis focuses on three elements: the LCAM evidence factors, the benchmark price assumption, and the annual discount rate used to calculate the relative present-value uplift. These calculations are not intended to establish causal inference. Their purpose is to test whether the enhanced MRV regime remains associated with higher conservative issuability, a smaller realized-price wedge, and positive timing-related value under reasonable alternative assumptions.

E.1. LCAM sensitivity under ±5% variation of evidence factors

The first sensitivity test varies each LCAM evidence factor by ±5%. The three evidence factors are interval completeness (f_{int}), calibration validity (f_{cal}), and timestamp coherence (f_{sync}). The engineering emission reduction [2] is held constant at 18.69 $\mathrm{ktCO_2e{\cdot}y^{-1}}$ in both MRV regimes. This allows the sensitivity test to isolate the effect of changes in evidence-support factors rather than changes in physical mitigation performance.

For the -5% case, each evidence factor is multiplied by 0.95:

$$\mathrm{LCAM}_y(-5\%) = \mathrm{ER}_y \times (f_{\mathrm{int}} \times 0.95) \times (f_{\mathrm{cal}} \times 0.95) \times (f_{\mathrm{sync}} \times 0.95)$$

For the +5% case, each evidence factor is multiplied by 1.05. Because evidence-support factors are bounded between 0 and 1, values above 1.00 are capped at 1.00:

$$\mathrm{LCAM}_y(+5\%) = \mathrm{ER}_y \times \min(f_{\mathrm{int}} \times 1.05, 1) \times \min(f_{\mathrm{cal}} \times 1.05, 1) \times \min(f_{\mathrm{sync}} \times 1.05, 1)$$

Table E1. LCAM sensitivity under ±5% variation of evidence factors

MRV Regime	Sensitivity Case	Adjusted Interval Completeness, f_{int}	Adjusted Calibration Validity, f_{cal}	Adjusted Timestamp Coherence, f_{sync}	Calculation	LCAM Result
Legacy MRV	Base	0.93	0.92	0.90	18.69 × 0.93 × 0.92 × 0.90	14.39 $\mathrm{ktCO_2e{\cdot}y^{-1}}$
Legacy MRV	Factors -5%	0.93 × 0.95 = 0.8835	0.92 × 0.95 = 0.8740	0.90 × 0.95 = 0.8550	18.69 × 0.8835 × 0.8740 × 0.8550	12.35 $\mathrm{ktCO_2e{\cdot}y^{-1}}$
Legacy MRV	Factors +5%	0.93 × 1.05 = 0.9765	0.92 × 1.05 = 0.9660	0.90 × 1.05 = 0.9450	18.69 × 0.9765 × 0.9660 × 0.9450	16.67 $\mathrm{ktCO_2e{\cdot}y^{-1}}$
Enhanced MRV	Base	0.98	0.97	0.96	18.69 × 0.98 × 0.97 × 0.96	17.07 $\mathrm{ktCO_2e{\cdot}y^{-1}}$
Enhanced MRV	Factors -5%	0.98 × 0.95 = 0.9310	0.97 × 0.95 = 0.9215	0.96 × 0.95 = 0.9120	18.69 × 0.9310 × 0.9215 × 0.9120	14.63 $\mathrm{ktCO_2e{\cdot}y^{-1}}$
Enhanced MRV	Factors +5%	min(0.98 × 1.05,1) = 1.0000	min(0.97 × 1.05,1) = 1.0000	min(0.96 × 1.05,1) = 1.0000	18.69 × 1.0000 × 1.0000 × 1.0000	18.69 $\mathrm{ktCO_2e{\cdot}y^{-1}}$

Note: LCAM values are expressed in $\mathrm{ktCO_2e{\cdot}y^{-1}}$. For the +5% enhanced MRV case, all adjusted evidence factors exceed 1.00 and are therefore capped at 1.00, because evidentiary support factors cannot exceed full support. The results show that the enhanced MRV regime remains associated with higher LCAM values than the legacy MRV regime under both -5% and +5% factor variations.

E.2. Alternative LCAM functional forms

The second sensitivity test examines whether the direction of the LCAM result depends on the base multiplicative specification. Two alternative LCAM structures are used: an equal-weighted average specification and a weakest-link specification. The equal-weighted average specification treats the three evidentiary support factors as contributing equally to the share of mitigation deemed supportable. The weakest-link specification applies the most restrictive evidence factor as the binding supportability condition.

The equal-weighted average LCAM is calculated as:

$$\mathrm{LCAM}_y^{\mathrm{WA}} = \mathrm{ER}_y \times \frac{f_{\mathrm{int}} + f_{\mathrm{cal}} + f_{\mathrm{sync}}}{3}$$

The weakest-link LCAM is calculated as:

$$\mathrm{LCAM}_y^{\mathrm{WL}} = \mathrm{ER}_y \times \min(f_{\mathrm{int}}, f_{\mathrm{cal}}, f_{\mathrm{sync}})$$

where, $\mathrm{LCAM}_y^{\mathrm{WA}}$ denotes the weighted-average LCAM; $\mathrm{LCAM}_y^{\mathrm{WL}}$ denotes the weakest-link LCAM; ER_y is engineering emission reduction; f_{int} is interval completeness; f_{cal} is calibration validity; and f_{sync} is timestamp coherence. In both specifications, ER_y is held constant at 18.69 ktCO$_2$e·y^{-1} to isolate the effect of alternative evidence-aggregation rules.

Table E2. Weighted-average and weakest-link LCAM specifications

Specification	MRV Regime	Formula/Calculation	LCAM Result
Equal-weighted average LCAM	Legacy MRV	18.69 × [(0.93 + 0.92 + 0.90)/3]	17.13 ktCO$_2$e·y^{-1}
Equal-weighted average LCAM	Enhanced MRV	18.69 × [(0.98 + 0.97 + 0.96)/3]	18.13 ktCO$_2$e·y^{-1}
Weakest-link LCAM	Legacy MRV	18.69 × min(0.93, 0.92, 0.90)	16.82 ktCO$_2$e·y^{-1}
Weakest-link LCAM	Enhanced MRV	18.69 × min(0.98, 0.97, 0.96)	17.94 ktCO$_2$e·y^{-1}

Note: LCAM values are expressed in ktCO$_2$e·y^{-1}. The equal-weighted average specification tests a less restrictive aggregation rule than the base multiplicative LCAM. The weakest-link specification tests a conservative rule in which the weakest evidence condition determines the supportable share. Under both alternative specifications, the enhanced MRV regime remains associated with a higher LCAM value than the legacy MRV regime.

E.3. Price-wedge calculation

The realized-price wedge measures the proportional difference between the benchmark price and the realized settlement price. In this study, the benchmark price is used only as a project-specific registry reference price for illustrative revenue-risk analysis. It is not treated as a universal carbon-credit market price or as evidence of a causal price effect from MRV enhancement.

The realized-price wedge is calculated as:

$$\alpha = 1 - \frac{P_{\mathrm{real}}}{P_{\mathrm{bench}}}$$

where, α denotes the realized-price wedge; P_{real} denotes the realized settlement price; and P_{bench} denotes the benchmark price. A smaller α indicates that the realized settlement price captures a larger share of the benchmark value.

Table E3. Base price-wedge calculation

MRV Regime	Benchmark Price, P_{bench}	Realized Settlement Price, P_{real}	Formula/Calculation	Realized-Price Wedge, α
Legacy MRV	Rp150,000/tCO$_2$e	Rp105,000/tCO$_2$e	1 - (105,000/150,000)	0.30
Enhanced MRV	Rp150,000/tCO$_2$e	Rp132,000/tCO$_2$e	1 - (132,000/150,000)	0.12

Note: The realized-price wedge is unitless. The benchmark price is held constant across the two MRV regimes for comparability. The lower wedge under the enhanced MRV regime is interpreted as an illustrative revenue-risk indicator rather than as a causal pricing effect.

E.4. Benchmark-price sensitivity of realized-price wedge

The benchmark-price sensitivity test examines whether the realized-price wedge remains smaller under the enhanced MRV regime as the benchmark price assumption varies. The base benchmark price is Rp150,000/tCO_2e. Two alternative benchmark-price scenarios are applied: -10% and +10%. The realized settlement prices are held constant at Rp105,000/tCO_2e for the legacy MRV regime and Rp132,000/tCO_2e for the enhanced MRV regime.

The lower benchmark-price scenario is calculated as:

$$P_{\text{bench}}^{-10\%} = 150,000 \times 0.90 = 135,000$$

The upper benchmark-price scenario is calculated as:

$$P_{\text{bench}}^{+10\%} = 150,000 \times 1.10 = 165,000$$

For each scenario, the realized-price wedge is calculated as:

$$\alpha = 1 - \frac{P_{\text{real}}}{P_{\text{bench}}}$$

Table E4. Benchmark-price sensitivity of realized-price wedge

Sensitivity Case	Benchmark Price, P_{bench}	Legacy Realized Price, P_{real}	Legacy Wedge, α	Enhanced Realized Price, P_{real}	Enhanced Wedge, α
Benchmark -10%	Rp135,000/tCO_2e	Rp105,000/tCO_2e	1 - (105,000/135,000) = 0.222	Rp132,000/tCO_2e	1 - (132,000/135,000) = 0.022
Benchmark +10%	Rp165,000/tCO_2e	Rp105,000/tCO_2e	1 - (105,000/165,000) = 0.364	Rp132,000/tCO_2e	1 - (132,000/165,000) = 0.200

Note: The benchmark-price sensitivity varies only the benchmark price, holding realized settlement prices constant. The enhanced MRV regime remains associated with a smaller realized-price wedge under both benchmark-price scenarios. These results should be interpreted as sensitivity checks for an illustrative revenue-risk indicator.

E.5. Relative present-value uplift under alternative discount rates

The issuance-cadence sensitivity test estimates the relative present-value uplift from receiving the same nominal cash flow earlier. The enhanced MRV regime shortened the issuance cadence from 130 days to 80 days, resulting in a 50-day acceleration of revenue timing. The timing difference is therefore expressed as:

$$\Delta t = 130 - 80 = 50 \text{ days}$$

The relative present-value uplift is calculated as:

$$\Delta \text{PV}_{\text{rel}} = (1 + r)^{\Delta t/365} - 1$$

where, $\Delta \text{PV}_{\text{rel}}$ is the proportional present-value uplift; r is the annual discount rate; and Δt is the acceleration in receipt timing measured in days. This calculation does not estimate a general present-value difference across different cash-flow amounts. It estimates the proportional effect on the value of receiving the same nominal cash flow 50 days earlier.

Table E5. Relative present-value uplift under alternative discount rates

Annual Discount Rate, r	Time Acceleration, Δt	Formula/Calculation	Relative PV Uplift, ΔPV_{rel}
6.00%	50 days	((1+0.0600)^[50/365]-1)	0.80%
8.00%	50 days	((1+0.0800)^[50/365]-1)	1.06%
10.41%	50 days	((1+0.1041)^[50/365]-1)	1.37%
12.00%	50 days	((1+0.1200)^[50/365]-1)	1.56%

Note: The 10.41% rate represents the project's estimated WACC used in the base calculation. The relative PV uplift is calculated for the same nominal cash flow received 50 days earlier. Values are rounded for presentation; minor differences may arise from intermediate rounding.

E.6. Consolidated sensitivity analysis summary

Table E6 consolidates the sensitivity calculations reported in Appendix E. The purpose of this summary is to show whether the main within-project pattern remains directionally stable under alternative assumptions about LCAM evidence factors, LCAM functional form, benchmark price, and discount rate. The sensitivity tests do not establish causal inference. They only assess whether the enhanced MRV regime remains associated with higher conservative issuability, a smaller realized-price wedge, and a positive timing-related value effect under reasonable alternative specifications.

Table E6. Consolidated sensitivity analysis summary

Sensitivity Test	Legacy MRV	Enhanced MRV	Interpretation
Base multiplicative LCAM	14.39	17.07	Main analytical proxy
LCAM factors -5%	12.35	14.63	Enhanced remains higher
LCAM factors +5%	16.67	18.69	Enhanced remains higher
Equal-weighted average LCAM	17.13	18.13	Alternative functional form; enhanced remains higher
Weakest-link LCAM	16.82	17.94	Conservative weakest-condition rule; enhanced remains higher
Wedge at benchmark -10%	0.222	0.022	Enhanced wedge remains smaller
Wedge at benchmark +10%	0.364	0.200	Enhanced wedge remains smaller
PV uplift at 6%	–	0.80%	Lower discount-rate assumption
PV uplift at 8%	–	1.06%	Moderate discount-rate assumption
PV uplift at 10.41%	–	1.37%	Base discount-rate assumption
PV uplift at 12%	–	1.56%	Higher discount-rate assumption

Note: LCAM values are expressed in $ktCO_2e \cdot y^{-1}$. Price-wedge values are unitless. Relative PV uplift is calculated based on a 50-day acceleration in receipt timing, using annual discount rates.

Across all sensitivity specifications, the enhanced MRV regime remains associated with a higher conservative estimate of issuability, a smaller realized-price wedge, and a positive relative present-value uplift. These results support the directional stability of the within-project pattern and remain consistent with the study's non-causal analytical design.