

From Greenhouse Gas Inventories to Mitigation-Strategy Diagnosis: A First-Principles Mechanism-to-Lever Framework

Yao-Ming Hong

hongyaoming@gms.ndhu.edu.tw

National Dong Hwa University

Method Article

Keywords: climate-change mitigation, corporate greenhouse gas accounting, decarbonization strategy, emission mechanisms, mitigation decision support, Scope 3

Posted Date: September 30th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10989465/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Organizational greenhouse gas (GHG) inventories quantify attributed emissions but often provide limited guidance on the physical process that should change or the organizational pathway through which change could be pursued. We present a first-principles diagnostic method separating how emissions enter the atmosphere (HOW), where the emitting process is located (WHERE), and how the reporting organization is connected to it (MEDIATION). A necessary formation-versus-release distinction is derived from species-level mass conservation; the newly formed branch is then operationally partitioned into combustion-associated, biologically mediated, and other non-combustion abiotic physicochemical formation. Across a purposive evidence base of 675 records from 31 cases, the equal-weight case mean for HOW resolution was 81.9%; the pooled record-weighted rate was 90.7% (587/647 evaluable records). A frozen two-field procedure agreed with 613 of 647 analyst-coded assignments (94.7%; $\kappa = 0.911$), providing a restricted-field rule-concordance audit rather than independent validation. Only 128 records contained analysis-ready tCO₂e values, so the study does not estimate emissions-weighted priorities or mitigation potential. The method is a pre-screening device: it excludes physically incoherent options and identifies missing process information, while feasibility, authority, cost, trade-offs, mitigation magnitude, and realized effectiveness require subsequent assessment.

1. Introduction

Limiting global warming requires rapid GHG reductions across energy, industry, transport, buildings, agriculture, land use, and supply chains. Central options include demand reduction, efficiency, electrification, low-GHG fuels and feedstocks, circular material flows, process change, and carbon management [1]. Yet corporate commitments and disclosure do not necessarily produce equivalent physical mitigation; gaps remain among ambition, accounting outcomes, implemented actions, and observed reductions [2–7].

Organizational GHG inventories provide the quantitative basis for corporate mitigation, but their strategic value depends on the resolution and uncertainty of the underlying source information. Emission inventories support monitoring and policy only when their uncertainty and system boundaries are transparent [8]. ISO 14064-1 and the GHG Protocol distinguish direct emissions (Scope 1), purchased-energy emissions (Scope 2), and other value-chain emissions (Scope 3) [9–12], while ISO 14068-1 prioritizes reductions and removal enhancements over offsetting [13]. Persistent issues include Scope 3 comparability, allocation, verification, and methodological consistency [14–17].

Recent work improves attribution and traceability across organizations through carbon-emission balance sheets, E-liability proposals, industrial-symbiosis allocation, carbon-management systems, and multi-tier supply-chain analysis [18–22]. These approaches do not, however, make the atmospheric emission mechanism an explicit record-level diagnostic dimension.

That physical distinction is consequential for mitigation. Emissions within the same accounting scope can arise from fundamentally different processes, while the same physical process can occur inside the

firm or elsewhere in its value chain. Accounting attribution and physical mechanism should therefore be treated as distinct analytical dimensions because they imply different abatement requirements and different organizational pathways for intervention [1].

A methodological gap remains between measurement and intervention: inventory categories identify attributed emissions but do not necessarily reveal the physical process that must change or the organizational pathway through which the reporting entity can influence it. Participatory assessment of firm-level reduction options likewise shows that usable process information and organizational engagement condition strategy development [23]. Carbon information supports mechanism-specific screening only when the physical mechanism, a coherent abatement direction, and an influence pathway to the emitter can be resolved.

The method complements established approaches. GHG Protocol and ISO inventories define attribution and reporting boundaries; life-cycle assessment, material or substance flow analysis, and environmentally extended input-output analysis characterize burdens and flows; and carbon-management systems organize implementation. The present method adds a record-level diagnostic layer separating atmospheric formation or release from organizational position and mediation (Table 1).

Table 1
Positioning of the mechanism-to-lever method relative to established approaches

Approach	Primary analytic object	Resolution supplied	Incremental role of this method
GHG Protocol and ISO 14064-1	Organizational inventory and reporting boundary	Attribution by Scope, category, gas, and organizational boundary	Retains the inventory attribution, then resolves the atmospheric mechanism and organizational influence pathway at record level
Process life-cycle assessment	Product system and unit processes across a life cycle	Process contributions, exchanges, and life-cycle burdens	Adds a uniform formation-versus-release classification and an explicit reporting-organization mediation pathway
Material or substance flow analysis	Physical stocks, flows, and conservation within a system	Material or substance balances and transfer pathways	Uses species balance as the physical constraint and translates the atmospheric pathway into a bounded intervention space
EEIOA or MRIO	Sectoral monetary transactions and embodied environmental pressures	Economy-wide indirect attribution and supply-chain screening	Provides process-level diagnosis after screening when source evidence is sufficient; otherwise records uncertainty as U
Organizational carbon-management systems	Management routines, controls, and implementation arrangements	Organizational governance and implementation levers	Supplies the physical target and distinguishes organizational position from the relationship through which influence may be exercised
Note: GHG = greenhouse gas; EEIOA = environmentally extended input-output analysis; MRIO = multiregional input-output analysis; U = unresolved. The comparison defines analytical complementarity rather than superiority. Representative foundations are provided in references [8–12, 18, 19, 22, 23].			

This study develops and evaluates a first-principles mechanism-to-lever method for organizational mitigation-strategy diagnosis. It asks whether heterogeneous inventory records can be represented by a parsimonious operational partition and whether physical and organizational diagnoses provide non-substitutable information that constrains subsequent intervention screening. The method connects attributed emissions to formation or release processes, aligns HOW with WHERE and MEDIATION, and assesses predefined-class coverage, restricted-field rule concordance, reporting-granularity sensitivity, and boundary stress cases. HOW-resolution is treated as a descriptive information-status measure, not as an independent organizational capability or actionability construct.

The claim is deliberately bounded: physical diagnosis changes the decision set to which strategy is applied but does not substitute for strategy. HOW resolution narrows the physical intervention set; WHERE identifies position relative to the emitter; and MEDIATION differentiates the influence

relationship. Their alignment reduces ambiguity without establishing authority, resources, or implementation capability.

Design criterion 1—Physical resolution. Resolving HOW must identify the physical intervention target and exclude abatement options inconsistent with the formation or release mechanism.

Design criterion 2—Influence-pathway resolution. Resolving WHERE and MEDIATION must identify the organizational position and relationship through which the reporting entity may influence the emitting process.

Design criterion 3—Diagnostic alignment. A resolved record supports mechanism-informed pre-screening only when the physical mechanism is aligned with at least one coherent abatement direction and an identifiable organizational influence pathway. Authority, feasibility, resources, and implementation effectiveness remain separate assessment dimensions.

These criteria are examined through descriptive HOW-resolution, a restricted-field rule-concordance audit, reporting-granularity sensitivity, and boundary stress cases. These checks evaluate use and reproducibility of the predefined rules within the assembled evidence; they are not independent validation of the operational partition or of mitigation performance.

2. Methods

The study links first-principles diagnosis to mitigation-decision preparation. Species-level mass conservation establishes only the necessary formation-versus-release distinction. The subdivision of newly formed GHGs into M1, M3, and M4 is an operational partition by dominant transformation pathway, not a unique deduction from the mass-balance equation. A physical branch (HOW) and a nested organizational branch (WHERE followed by MEDIATION) then constrain the physical-abatement space and identify a potentially relevant organizational relationship. Their alignment produces a descriptive diagnostic output: either HOW is resolved and mechanism-consistent options can be screened, or additional process information is required. Organizational evidence assesses predefined-class coverage, restricted-field rule concordance, reporting-granularity sensitivity, and boundary stress conditions. Unresolved HOW (U) triggers information acquisition rather than a mechanism-specific recommendation (Fig. 1). Scope and conventional source labels were retained as accounting attributes but were not used to derive HOW or intervention assignments.

2.1 First-principles basis for classifying atmospheric GHG emission mechanisms

The framework begins with species-level mass conservation rather than by reorganizing accounting categories. This first-principles step yields a necessary binary distinction: an atmospheric emission is either release of the same pre-existing GHG species or formation of a new GHG molecule from precursors. It does not uniquely determine the subsequent M1/M3/M4 subdivision, which is an

operational partition by dominant transformation pathway. The unit of analysis was an inventory observation representing, or potentially representing, a physical GHG transfer to the atmosphere. Scope and conventional source labels did not define the candidate physical mechanisms.

For a specific greenhouse gas species g within a control volume, conservation of mass requires that its rate of accumulation equal the inflow of that species minus its outflow, plus internal formation minus internal consumption. The governing species balance is:

$$\frac{dM_g}{dt} = \dot{m}_{g,\text{in}} - \dot{m}_{g,\text{out}} + \dot{m}_{g,\text{form}} - \dot{m}_{g,\text{cons}}$$

1

where M_g is the mass of GHG species g within the control volume; $\dot{m}_{g,\text{in}}$ and $\dot{m}_{g,\text{out}}$ are the total inflow and outflow rates of GHG species g ; and $\dot{m}_{g,\text{form}}$ and $\dot{m}_{g,\text{cons}}$ are its internal formation and consumption rates, respectively. Figure 2 illustrates the physical interpretation of this balance. At the atmospheric boundary, an emitted GHG either existed as the same molecular species before release or was newly formed within the emitting process from precursor matter.

For Fig. 2, the control-volume boundary is selected so that the displayed outflow is the atmospheric-emission outflow used for classification. HOW is assigned to the process immediately responsible for crossing that boundary. Earlier molecular formation is retained as context but does not override the immediate release mechanism. Classification is therefore conditional on an explicitly stated control-volume and temporal boundary; internal transport alone is not an atmospheric emission.

The first route corresponds to release of a pre-existing GHG. When the same GHG molecular species exists before atmospheric release and no new formation is required to explain the emission, the pathway is classified as M2. Examples include leakage, venting, or other release of a previously produced, stored, transported, or contained GHG. Importantly, transport of a GHG across an internal control-volume boundary is not itself an atmospheric emission; M2 is assigned only when the pre-existing GHG is released across the relevant atmospheric emission boundary.

The second route corresponds to new GHG formation within the emitting process. In these cases, the emitted molecule is generated from precursor matter, and the formation pathway is distinguished by the dominant transformation process. Combustion-associated formation is classified as M1 because fuel oxidation couples chemical transformation with energy release. Formation mediated by organisms, microbial metabolism, or biologically controlled biochemical pathways is classified as M3. Newly formed GHGs produced through other non-combustion abiotic physicochemical transformations are classified as M4; examples include carbonate decomposition, metallurgical reduction, chemical-process by-product formation, and formation of fluorinated GHGs during industrial processes.

Elemental conservation and energy transformation serve as interpretive constraints. Atoms in a newly formed GHG must originate from precursor matter, and energy transformation helps distinguish

combustion from non-combustion formation. The species balance supplies the formal conservation statement; the immediate physical history of the emitted molecule determines its class.

The binary formation-versus-release split follows directly from the species balance. M1, M3, and M4 are an operational partition of the newly formed branch by dominant pathway: combustion-associated, biologically mediated, or other non-combustion abiotic physicochemical formation. M2 denotes release of a pre-existing GHG. Mutual exclusivity follows from the sequential rule, not from an assumption that real systems contain only one process. Mixed records are split only when evidence supports component assignments; otherwise they remain unresolved (U). Because M4 is the residual category within the newly formed, non-combustion, non-biological branch, the study evaluates applicability and boundary clarity rather than claiming empirical proof of universal exhaustiveness.

2.2 Classification and multidimensional representation: HOW, WHERE, and MEDIATION

The first-principles basis defines HOW a GHG physically becomes an atmospheric emission but does not by itself specify the organizational position of the physical emitter or the relationship through which the reporting entity may influence it. Each inventory observation was therefore represented through two non-substitutable branches: HOW as the physical branch, and WHERE followed by MEDIATION as a nested organizational branch.

HOW was assigned using Fig. 3 and the frozen rules in Supplementary Information (ESM 1), Table S5 and Frozen_HOW_Rules. Records with insufficient process evidence were coded U rather than inferred from Scope, industry, gas identity, or inventory labels. Resolved observations were evaluated sequentially as M2, M1, M3, or M4 according to the process immediately responsible for atmospheric release or molecular formation. A captured stream that does not cross the atmospheric boundary is not an emission; leakage of stored CO₂ is M2; and newly formed CO₂ follows M1, M3, or M4 according to the dominant pathway. Biogenic versus fossil precursor origin was recorded separately. Aggregated, conflicting, or unspecified records remained U unless evidence supported splitting.

After HOW had been assigned using the sequence in Fig. 3, WHERE describes the position of the physical emitting process relative to the reporting organization and was restricted to three states: Inside, when the physical emitting process occurred within the relevant organizational or operational boundary; Upstream, when it occurred before the reporting organization's own operations in the value chain; and Downstream, when it occurred after those operations. WHERE was assigned from the physical emitter rather than inferred directly from Scope classification. Consequently, the same HOW mechanism could occur Inside, Upstream, or Downstream, while multiple HOW mechanisms could occur at the same WHERE location.

MEDIATION describes the relationship connecting the reporting entity to the physical emitter within WHERE. Five states were used: Direct/control-mediated; Energy-mediated; Transport-mediated; Material/service-mediated; and Composite/unresolved when aggregated evidence did not permit a

unique pathway. Coding followed that fixed priority. WHERE is topological and MEDIATION relational, but they are not assumed statistically independent. MEDIATION principally differentiated Upstream and Downstream observations; commuting, business travel, and contracted logistics were assigned according to their functional relationship and retained as Transport-mediated. Full rules and coding are provided in ESM 1, Tables S3 and S6.

Each resolved observation was represented formally as:

$$X_i = (H_i, W_i, D_i)$$

2

where the multidimensional representation of each observation comprises HOW, WHERE, and MEDIATION. Scope and category information was retained independently so that correspondence between conventional accounting structures and the proposed representation could be evaluated subsequently. Classification followed a fixed sequence: source-evidence screening, HOW, WHERE, and MEDIATION. Where a record combined multiple unsplit emitting processes or supported conflicting pathways, it was split only when the source permitted; otherwise HOW was coded U. This order reduced circular classification based on existing accounting labels.

2.3 Empirical evidence and coverage assessment

The purposive assessment used a 24-case frozen backbone (S01–S24) and seven prespecified extension cases (S25–S31), collectively comprising 11 routine, seven sectoral, and 13 adversarial assessments. The backbone included organizational inventories and public disclosures; the extension cases broadened mechanistically testable source-domain coverage. Eligible sources identified an organization and boundary plus at least one traceable activity, facility, or emission-source record. Product carbon footprints were excluded because they use a different accounting object. Zero-emission, removal, storage, and non-emission flows were retained for traceability but excluded from positive mechanistic evidence. Selection was purposive for breadth and does not support population representativeness. The analyst-coded reference set was established before restricted-field reassessment using the available source and process evidence. Evidence level, source status, rationale, splitting decisions, and source links were retained by record. No case was used to discover or modify M1–M4. Selection, evidence tiers, exclusions, and freeze reconciliation are documented in ESM 1.

A traceability record was defined as one reported activity, facility, or emission-source entry retained at the source's original reporting granularity. The 675 records comprised 652 backbone-case records and 23 records from the seven extension cases. Twenty-six explicit-zero records and two removal/storage or non-atmospheric-emission records were retained for auditability but excluded from the 647-record HOW evaluation set. Resolved HOW plus unresolved U constituted evaluable records. Analysis-ready tCO₂e values were available for only 128 records; consequently, all main analyses are record- or case-based rather than emissions-weighted. Initial classifications, evidence levels, rationales, and source status are preserved in ESM 1, Table S3.

Boundary clarity was examined using deliberately challenging cases classified with Fig. 3. Cases with sufficient evidence were assigned within M1–M4, whereas cases lacking unique process evidence remained U. The exercise tests whether the stated rules handle difficult release, formation, mixed-process, and control-volume conditions consistently; it does not test a separate fifth mechanism or establish universal closure. Decision rationales are reported in ESM 1, Table S4.

Sectoral breadth was audited against ISIC Rev. 5, while physical coverage was audited against major anthropogenic source domains synthesized by the IPCC, including energy, transport, oil and gas, industrial processes, agriculture and land-related emissions, waste and wastewater, and fluorinated gases [1, 24]. These classifications tested breadth but did not derive HOW. The complete coverage matrix is reported in ESM 1, Tables S2 and S13.

Coverage of the predefined HOW classes was examined cumulatively across the 31 cases in the prespecified sequence. The purpose was descriptive: to record when each predefined class first appeared, not to discover classes, estimate population prevalence, or claim theoretical saturation. M1 and M2 appeared in S01, M3 in S02, and M4 in S12; cases S13–S31 added contexts but no additional predefined class (ESM 1, Table S11). Because M4 is a residual operational category, this exercise demonstrates applicability only within the examined evidence.

All 647 evaluable observations were reassessed with a frozen deterministic procedure using only Activity/Facility and Emission Source fields. Original assignments, rationales, mappings, and actionability fields were withheld. The frozen HOW rules and automated reassessment dictionary in ESM 1 document the decision sequence, minimum evidence, ambiguity rules, preprocessing, and prohibited shortcuts; ESM 1, Tables S8–S10 report outputs and disagreements. U was assigned rather than forcing insufficient evidence into M1–M4. Exact agreement, Cohen's κ , and the M1–M4–U confusion matrix were calculated without post-hoc tuning. This is a restricted-field rule-concordance audit against the analyst-coded reference set, not independent human, construct, or predictive validation.

Because observation counts were nested within organizations and varied substantially across cases, an organization-level sensitivity analysis was conducted for HOW resolution. The resolution rate was calculated separately within each organization using evaluable records, followed by an equal-weight organization mean, distributional summaries, and leave-out analyses excluding the largest record contributors. These descriptive analyses assessed dependence of the record-weighted HOW-resolution rate on reporting granularity rather than estimating a population-level organization effect (ESM 1, Table S12).

2.4 Translation from physical diagnosis to organizational mitigation strategies

Following diagnosis, HOW constrained four generic abatement functions: Avoid, Substitute, Control, and Capture. WHERE and MEDIATION identified the organizational position and relationship through which the reporting organization could plausibly influence the target. A record was mechanism-resolved when

evidence supported a unique HOW assignment; a mechanism-consistent generic abatement direction and an identifiable influence pathway were then recorded as decision-preparation information. An evaluable atmospheric source with unresolved HOW was classified as requiring additional process information; explicit-zero, removal/storage, non-emission, and non-evaluable records were not assessable/not applicable. These states do not measure implementation capability or organizational actionability. Observation-level decisions are reported in ESM 1, Table S6 and the physical functions in Table 2.

Table 2
Physical abatement functions constrained by GHG emission mechanism

HOW	Physical condition	Mechanism-consistent abatement functions
M1	Combustion-associated formation	Avoid—reduce energy/service demand or eliminate combustion need; Substitute—electrification or low-GHG fuels/energy carriers; Control—efficiency and combustion/process optimization; Capture—CO₂ capture and storage/use where technically applicable.
M2	Release of pre-existing GHG	Avoid—eliminate or reduce GHG-containing systems/processes; Substitute—use lower-GWP or non-GHG alternatives; Control—prevent leaks/vents, detect and repair, and strengthen containment; Capture—recover, reclaim, or destroy residual gases.
M3	Biologically mediated formation	Avoid—reduce the emitting activity or relevant input where feasible; Substitute—change feed, substrate, nutrient, or management pathway; Control—modify biological, environmental, or process conditions; Capture—recover, treat, or destroy CH₄ where feasible.
M4	Non-combustion abiotic physicochemical formation	Avoid—reduce demand for emission-intensive material/process output; Substitute—change material, feedstock, chemistry, or technology; Control—redesign reactions/processes and abate by-products; Capture—capture, treat, or destroy residual GHGs.
Note: GHG = greenhouse gas; GWP = global warming potential; CO₂ = carbon dioxide; CH₄ = methane; N₂O = nitrous oxide. The four abatement modes are generic physical functions, not mutually exclusive technologies or a ranking hierarchy. Their implementation depends on process conditions and organizational feasibility. Supporting evidence is provided in references [1, 25–30].		

HOW constrains how these modes are implemented. M1 targets combustion demand, fuels, efficiency, or residual CO₂ capture; M2 targets GHG-containing systems through substitution, leak prevention, recovery, or destruction; M3 targets activities, substrates, biological pathways, or environmental conditions; and M4 targets material demand, feedstocks, reaction pathways, process conditions, by-product abatement, or residual capture (Table 2).

WHERE and MEDIATION translate physical coherence into an organizational influence pathway. Inside/Direct-control-mediated observations emphasize operations, maintenance, equipment replacement, and capital investment. Upstream observations may require energy contracting, transport procurement, supplier specifications, engagement, or collaborative investment depending on MEDIATION. Downstream observations emphasize product/service design, use-phase transition, recovery systems, and downstream engagement. The framework therefore requires alignment between a mechanism-consistent abatement direction and an identifiable influence pathway; it does not establish that the organization possesses the capability or bargaining power to implement that pathway.

For a specified dataset, the HOW-resolution rate is the proportion of evaluable records for which available information supports a unique M1–M4 assignment. Mechanism-consistent abatement functions and influence pathways are reported as descriptive mappings, not as an additional coverage metric or an independent actionability construct.

The mapping constrains intervention direction but does not estimate organization-specific abatement potential or rank technologies. Quantitative prioritization requires additional evidence on baseline emissions, reduction potential, cost, timing, organizational capability, life-cycle trade-offs, and verified performance.

2.5 AI-assisted manuscript preparation and quality control

During manuscript preparation, the author used ChatGPT (OpenAI; accessed August–September 2026) to assist with drafting, language editing, document organization, and consistency checking. The tool did not classify records, make evidence-sufficiency decisions, calculate results, or serve as an independent validator. All classifications, calculations, interpretations, citations, and final wording were reviewed and verified by the author, who accepts full responsibility for the manuscript.

3. Results

3.1 Empirical evidence base and source-domain coverage

The empirical evidence base comprised 31 organizations spanning diverse economic activities and major anthropogenic GHG source domains. All organizations were evaluated under the same predefined rules and none was used to derive or modify M1-M4. Together they contributed 675 traceability records; 647 were evaluable for HOW, of which 587 (90.7%) resolved to M1-M4 and 60 (9.3%) remained

unresolved because physical evidence was insufficient. Organization characteristics, observation-level classifications, and quality-control procedures are provided in ESM 1, Tables S1, S3, and S5.

Coverage was assessed across both economic activities and major anthropogenic GHG source domains. The evidence represented energy production and use, transportation, oil and gas systems, industrial processes, fluorinated gases, agriculture, land-related processes, waste, and wastewater treatment. Multiple mechanisms occurred within several source domains, demonstrating that source-domain labels were not equivalent to physical HOW. The coverage matrix is provided in ESM 1, Table S13, with detailed evidence in ESM 1, Table S2.

The combined sectoral and source-domain assessment showed that additional cases increasingly reproduced predefined physical pathways already represented in the dataset. Source-domain breadth was therefore distinguished from coverage of the predefined HOW classes; neither measure is interpreted as theoretical saturation.

3.2 Empirical distribution and applicability of HOW

Among the 587 observations with resolved HOW, 172 (29.3%) were classified as M1, 373 (63.5%) as M2, 36 (6.1%) as M3, and six (1.0%) as M4 (Table 3). These frequencies describe the occurrence of mechanisms within the empirical evidence base and were not interpreted as estimates of their relative contribution to global or organizational GHG emissions.

Table 3
Summary of the empirical evidence base and mechanistic classification

Category	Item	n	Percentage
Dataset	Organizations	31	—
Dataset	Traceability records	675	—
Evaluation	Evaluable for HOW	647	95.9% ^a
Evaluation	Resolved HOW	587	90.7% ^b
Mechanism	M1 — Combustion-associated formation	172	29.3% ^c
Mechanism	M2 — Release of pre-existing GHG	373	63.5% ^c
Mechanism	M3 — Biologically mediated formation	36	6.1% ^c
Mechanism	M4 — Non-combustion abiotic physicochemical formation	6	1.0% ^c
Notes: HOW = physical emission mechanism. a Percentage of the 675 traceability records. b Percentage of the 647 records evaluable for HOW. c Percentages of the 587 observations with resolved HOW. Sixty evaluable observations remained unresolved because the available physical evidence was insufficient to determine HOW. Unresolved observations were not treated as boundary-challenge cases. Detailed organization-level information, observation-level classifications, and quality-control procedures are provided in ESM 1, Tables S1, S3, and S5.			

M2 dominated the record count because inventories repeatedly reported refrigerant and other pre-existing GHG releases, while M1 was broadly represented by stationary and mobile combustion. M3 occurred mainly in agricultural, waste, and wastewater systems, and M4 in specialized industrial transformations. These frequencies reflect reporting granularity and the composition of the purposive evidence base; they are not emissions-weighted prevalence estimates or indicators of mitigation importance.

More importantly, the mechanism rules were applicable across conventional inventory labels and GHG species within the assembled evidence.

3.3 Multidimensional representation of organizational emissions

Cross-classification showed that HOW, WHERE, and MEDIATION performed different diagnostic functions. HOW varied within the same organizational location, and the same HOW occurred Inside, Upstream, and Downstream. MEDIATION further differentiated relationships within a location: Upstream observations included energy-mediated, transport-mediated, and material/service-mediated pathways, directing attention respectively to generation or contractual information, mobility/logistics policy, and supplier or procurement mechanisms. Representative combinations and their constrained action pathways are shown in Table 4; complete classifications are provided in ESM 1, Tables S3 and S6.

Table 4
Representative HOW–WHERE–MEDIATION mappings from physical diagnosis to organizational influence pathways

HOW	Representative observation	WHERE / MEDIATION	Constrained intervention space	Organizational lever
M1	On-site fuel combustion	Inside / Direct/control-mediated	Efficiency; electrification; fuel substitution	Operational / capital control
M2	Refrigerant leakage	Inside / Direct/control-mediated	Prevention; detection; recovery; substitution	Maintenance / equipment control
M3	Enteric fermentation	Inside / Direct/control-mediated	Feed/input and biological-pathway management	Operational management
M4	Cement calcination	Inside / Direct/control-mediated	Feedstock/process change; residual capture	Process / capital control
M1	Upstream combustion	Upstream / Material/service-mediated	Efficiency; electrification; fuel substitution	Procurement / supplier engagement
M1	Downstream combustion	Downstream / Material/service-mediated	Avoid combustion; electrify use phase	Product / service redesign
U	Purchased electricity; generation unspecified	Upstream / Energy-mediated	No mechanism-specific assignment	Additional process information
Note: HOW = physical emission mechanism; WHERE = organizational location of the emitting process; MEDIATION = organizational influence relationship; U = unresolved. Representative observations were selected from ESM 1, Tables S3 and S6. The table illustrates diagnostic mapping, not organization-specific feasibility or mitigation effectiveness. U triggers additional process information rather than a mechanism-specific intervention.				

Purchased electricity illustrates why the three dimensions must remain separate. A record could be identified as Upstream in WHERE and energy-mediated in MEDIATION even when the generation technology was unspecified. In that situation, HOW remained unresolved rather than being inferred as M1 from the accounting category. Thus, WHERE and MEDIATION could be determined even when the physical mechanism could not. The converse was also observed: the same physical HOW could be linked to the reporting organization through different mediation pathways and could occur at different positions in the value chain.

3.4 Mitigation-strategy application and framework evaluation

The decision procedure was applied to all empirical records as a mitigation-strategy pre-screen. Resolved observations were mapped first to mechanism-consistent Avoid–Substitute–Control–Capture functions and then to organizational influence pathways using WHERE and MEDIATION; unresolved observations remained information requirements. Table 4 presents representative mappings, and ESM 1, Table S6 provides the complete observation-level record.

The application separates physical coherence from organizational influence. M2 leakage is not addressed by combustion efficiency, and M1 combustion is not addressed by leak detection. Conversely, the same M1 physical target may require direct investment, transport or supplier procurement, or downstream product redesign depending on WHERE and MEDIATION. The framework therefore removes physically inconsistent options and differentiates influence pathways before technology-specific and organization-specific evaluation.

Table 5
HOW-resolution and information status by organizational location

Analysis group	n	Mechanism-resolved	HOW unresolved—information required	Not assessable / N.A.	HOW-resolution rate (%)
All records	675	587	60	28	—
Evaluable records	647	587	60	0	90.7
Inside	549	537	2	10	99.6
Upstream	98	28	54	16	34.1
Downstream	25	22	2	1	91.7
WHERE unresolved	3	0	2	1	0.0
Note: HOW = physical emission mechanism; WHERE = organizational location; N.A. = not applicable. Mechanism-resolved denotes an evaluable record for which available evidence supported a unique M1–M4 assignment. HOW unresolved—information required denotes an evaluable record for which additional process evidence is needed before mechanism-specific screening. The HOW-resolution rate is calculated only across evaluable records; it is not reported for the all-record row and must not be interpreted as organizational capability or mitigation effectiveness.					

Table 5 reports location-specific information status. Across all 675 records, 587 (87.0%) were mechanism-resolved, 60 (8.9%) required additional process information, and 28 (4.1%) were not assessable/not applicable. Among 647 evaluable records, the HOW-resolution rate was 90.7% (587/647).

HOW-resolution varied by organizational location (Table 5). Among evaluable records, resolution was 99.6% for Inside records (537/539) and 91.7% for Downstream records (22/24), but 34.1% for Upstream records (28/82). Fifty-four upstream records required additional process information. This contrast identifies a mechanistic-information bottleneck in the assembled records: accounting visibility beyond

direct operations did not necessarily include the process evidence required for mechanism-specific screening. It does not by itself demonstrate weak supplier governance or limited organizational capability.

The M1 comparison illustrates the joint role of the three dimensions. The physical target remained combustion, while the organizational lever shifted from operational/capital control Inside, to procurement and supplier engagement Upstream, and to product/service redesign Downstream. HOW therefore constrains what must change, whereas WHERE and MEDIATION constrain where and how the organization can act.

Unresolved HOW creates an information requirement rather than a mechanism-specific recommendation. For example, purchased electricity with unspecified generation technology can be identified as Upstream and energy-mediated, but requires additional generation or contractual information before mechanism-specific intervention mapping.

Three applications illustrate the bounded decision value. Refrigerant leakage is M2: coherent options include avoiding refrigerant demand, substituting lower-GWP fluids, controlling leaks through maintenance and monitoring, and recovering refrigerant at servicing or end of life; for owned equipment, the pathway is principally operational and capital-mediated. Purchased electricity with unspecified generation remains Upstream, Energy-mediated, and U: generation mix, contractual instruments, and emission-factor evidence must be obtained before claiming a mechanism-specific intervention; renewable contracting becomes assessable only after those attributes are verified. Cement calcination is M4 and points to material-efficiency, clinker substitution, reaction or process redesign, and residual process-CO₂ capture, whereas kiln-fuel combustion is separately M1. These mappings identify targets and candidate levers, not quantified recommendations.

Table 6
Evidence-bounded mitigation-strategy assessment for three illustrative applications

Application and diagnosis	Candidate strategy functions	Organizational lever and information required	Main barrier or uncertainty
Refrigerant leakage M2; Inside; Direct/control-mediated	Avoid refrigerant demand; substitute lower-GWP fluids; prevent leaks; recover or destroy residual gas	Maintenance, procurement, and capital replacement; verify refrigerant inventory, leakage rate, equipment age, GWP, and recovery performance	Equipment replacement cycles, safety and compatibility, servicing capacity, and unquantified mitigation magnitude
Purchased electricity with unspecified generation U; Upstream; Energy-mediated	No mechanism-specific assignment until generation evidence is resolved; demand reduction and efficiency remain cross-cutting options	Energy management and procurement; obtain generation mix, contractual instrument, emission factor, and temporal/location attributes	Attribution and additionality of contractual claims, supplier dependence, and incomplete generation data
Cement calcination M4; location and mediation depend on the inventory boundary	Material efficiency; clinker substitution; reaction or process redesign; residual process-CO ₂ capture	Process/capital control or procurement and supplier engagement; verify clinker ratio, chemistry, process configuration, capture readiness, and product requirements	Product standards and performance, technology maturity, infrastructure, cost, and life-cycle trade-offs
Note: The matrix is a qualitative decision-preparation demonstration. It does not estimate reduction potential, feasibility, cost, or realized effectiveness.			

The restricted-field procedure reproduced 613 of 647 HOW assignments exactly (94.7%), with Cohen's $\kappa = 0.911$. The 34 disagreements (5.3%) concentrated in abbreviated, mixed, or boundary-sensitive descriptions and were retained without post-hoc tuning (ESM 1, Tables S8–S10). These statistics quantify concordance between deterministic two-field rules and the analyst-coded reference set; they do not constitute independent inter-rater, construct, or external validation.

The record-weighted HOW-resolution rate of 90.7% exceeded the equal-weight organization mean of 81.9% and the median organization-level rate of 81.8% (IQR 66.7–99.8%; range 50.0–100.0%). Excluding the largest record contributor reduced pooled resolution to 82.4%; excluding the two and three largest contributors yielded 86.2% and 85.5%, respectively. Thus, the pooled estimate was sensitive to reporting granularity, while most evaluable records remained HOW-resolved under the leave-out analyses (ESM 1, Table S12).

All four predefined HOW classes had appeared by S12: M1 and M2 were represented in S01, M3 first appeared in S02, and M4 in S12. Cases S13–S31 added empirical contexts but no new predefined class. This is a descriptive class-coverage result, not evidence of theoretical saturation or universal completeness (ESM 1, Table S11).

Boundary stress cases examined whether deliberately challenging industrial, release, biological, land-related, mixed-process, and carbon-capture conditions could be classified consistently under the four-mechanism rules (ESM 1, Table S4).

Venting of pre-existing methane and fluorinated gases was assigned to M2; biologically formed CH₄ and N₂O to M3; and industrially generated N₂O, carbonate calcination, metallurgical reduction, and industrial formation of fluorinated GHGs to M4. Cases lacking unique process information remained U. Because M4 is a residual operational category, these results demonstrate rule applicability within the examined evidence rather than universal completeness.

4. Discussion

4.1 From inventory attribution to mitigation-strategy diagnosis

The central contribution is to distinguish accounting attribution, physical diagnosis, and organizational influence as sequential but non-substitutable elements of mitigation-strategy design. ISO 14064-1 and the GHG Protocol define boundaries, quantify emissions, and allocate responsibility [9–12]. The proposed architecture adds the physical pathway by which a GHG becomes an atmospheric emission and the organizational relationship through which that pathway may be influenced.

Empirically, the results support the premise that gas identity, sector, Scope, and source labels do not uniquely determine HOW. The same species occurred under different classes depending on whether it was released pre-existing or newly formed through combustion, biological transformation, or another physicochemical process. This record-level distinction responds to the need to treat materially different source subsystems explicitly rather than allowing aggregated inventories to create false strategic certainty [8].

The representation contributes a physical–organizational alignment principle. HOW identifies the physical target and excludes incoherent options; WHERE identifies organizational position; and MEDIATION differentiates the influence relationship. Their alignment connects carbon information to operations, procurement, supplier engagement, and product or service redesign without replacing Scope accounting.

4.2 A mechanism-to-lever logic for decarbonization strategy

The mechanism-to-lever contribution is an alignment rule for decision preparation: a resolved physical mechanism constrains coherent abatement functions, and WHERE–MEDIATION identifies a potentially relevant organizational influence pathway. Attribution establishes responsibility and visibility; HOW constrains the target; WHERE identifies position; and MEDIATION specifies the relationship through

which intervention may be pursued. This alignment does not itself establish feasibility, authority, or effectiveness.

Avoid–Substitute–Control–Capture compactly represents the physical abatement space. The contribution is the constraint linking HOW to physically coherent functions and WHERE–MEDIATION to the route by which the organization may influence the emitter.

Organizational influence changes with location and mediation. Inside emissions typically connect to operational or capital levers. Upstream emissions may require contracting, procurement, supplier engagement, logistics policy, or collaborative investment. Downstream emissions may require product, service, use-phase, or recovery-system redesign. These are identifiable pathways, not demonstrated capabilities [19, 22, 23].

The descriptive intervention mapping added no numerical discrimination beyond HOW resolution because every resolved positive-emission record could be linked to at least one broad generic-abatement function and an influence pathway. The study therefore reports HOW-resolution and information status rather than treating the mapping as an organizational capability or benchmarking metric.

The framework does not predict mitigation magnitude; it resolves what must physically change and through which organizational pathway. Firms must subsequently compare reduction potential, cost, timing, maturity, life-cycle effects, capability, and implementation risk. The sequence is therefore diagnosis, coherent abatement modes, organizational pathway, and only then technology-specific prioritization.

4.3 Parsimony, empirical applicability, and boundary stress tests

The predefined HOW classes were usable across the assembled evidence: 587 of 647 evaluable records resolved to M1–M4, while insufficiently documented observations remained U. The boundary stress cases exposed ambiguities in evidence sufficiency, mixed records, and control-volume definition but did not require alteration of the operational rules. Because M4 is residual, this result is evidence of applicability within the assembled cases, not a falsification test or validation of universal exhaustiveness. Broader transferability requires independently assembled datasets, coders, and decision contexts.

The cumulative exercise documents coverage of the four predefined classes; it does not establish theoretical saturation. New sectors, technologies, gases, or reporting practices may expose boundary problems or motivate finer subclasses. Any future revision should therefore be based on reproducible cases that cannot be classified coherently under explicitly stated control-volume and evidence rules, rather than on missing information alone.

Parsimony may support strategic usability by linking recurring physical problems to reusable intervention knowledge without creating a new class for every sector label. Strategic usability itself was not directly tested with managers or implementation outcomes; the present evidence establishes descriptive coverage and restricted-field rule concordance, while WHERE and MEDIATION preserve differences in organizational position and influence.

4.4 Decision implications, limitations, and future research

For decision makers, the method separates three questions: what physical process must change, where that process sits relative to the organization, and through which relationship influence might be exercised. The low upstream diagnostic coverage identifies missing process information as a practical value-chain constraint. This finding reinforces the strategic lesson that assessment and engagement must be matched to the information and organizational context of the firm [23]; whether an organization can obtain or act on that information remains a separate governance and capability question.

The restricted-field procedure provides a rule-concordance audit, not independent validation. Agreement was high, while disagreements concentrated where abbreviated labels did not fully specify the physical process. Independent human coding, blinded replication, and construct validation remain necessary future tests.

Several limitations bound interpretation. The 31 cases were selected purposively for breadth, not as a probability sample, and records were nested within cases with unequal granularity. The 24-case backbone and seven extension cases are reported separately in ESM 1; extension cases broaden source-domain coverage but do not constitute a validation sample or support population inference. Access restrictions limit verification of some underlying sources, although anonymized processed fields, rationales, and source status are preserved. Only 128 of 675 records contained analysis-ready tCO₂e values, preventing emissions-weighted prevalence, mitigation-priority, or abatement-potential inference. Sixty evaluable records remained unresolved, and M4 had only six observations. Results indicate use of the predefined classes within the assembled evidence, not population prevalence, independent validity, theoretical saturation, or universal closure. The residual M4 class may require future subclassification, and boundary sensitivity was not independently tested across alternative control-volume or temporal definitions.

The intervention mapping identifies physically consistent directions, not independently validated recommendations or quantified outcomes. The study does not test inter-analyst agreement for intervention assignments or estimate reduction potential, cost, barriers, life-cycle trade-offs, or realized reductions. Future work should connect the mechanism layer to technology databases, techno-economic criteria, inter-rater reliability, semi-automated classification, and verified before-after performance.

5. Conclusions

This study develops a first-principles mechanism-to-lever method that extends organizational GHG inventories with a mitigation-strategy diagnosis of physical processes and organizational influence. HOW identifies the emission mechanism and constrains coherent abatement directions; WHERE identifies organizational position; and MEDIATION differentiates the relationship through which influence may be pursued. Their alignment prepares mitigation decisions by narrowing the physical intervention set and clarifying the organizational pathway. It does not establish capability, implementation, or mitigation magnitude.

Across 675 records from 31 cases, the equal-weight case mean for HOW resolution was 81.9%, while the pooled record-weighted rate was 90.7% (587/647 evaluable records). A restricted-field procedure showed 94.7% concordance with the analyst-coded assignments ($\kappa = 0.911$). Boundary stress cases were handled within the predefined rules, but the residual definition of M4 precludes treating that result as evidence of universal completeness. Technology selection, organizational feasibility, emissions-weighted prioritization, independent coder validation, and realized mitigation remain subsequent tests and decisions.

The principal strategy lesson is that organizations should not move directly from ranked inventory categories to technology selection. They should first resolve HOW, then locate WHERE and MEDIATION, and only thereafter screen Avoid–Substitute–Control–Capture options for technical feasibility, cost, authority, timing, and trade-offs. Records with unresolved HOW should trigger targeted acquisition of process or supplier data rather than generic abatement claims. This sequence is especially consequential for upstream value-chain records, where accounting visibility often exceeds mechanistic information.

Declarations

Data availability

The anonymized observation-level classifications, frozen decision rules, source status, diagnostic mappings, quality-control summaries, disagreement records, case-level sensitivity analyses, and formula-based rule-concordance calculations are provided in ESM 1. Identity-bearing links for restricted organizational records are not publicly redistributed; a controlled-access source register can be provided to the editor where provider permissions allow.

Funding

No funding was received for conducting this study or preparing this manuscript.

Competing interests

The author declares no competing interests.

Author contributions

Yao-Ming Hong conceived and designed the study, developed the methodology, curated and analyzed the data, prepared the figures and supplementary material, and wrote, reviewed, and approved the manuscript.

Ethics approval and consent to participate

Not applicable. The study did not involve human participants, animals, identifiable personal data, or biological materials.

Consent for publication

Not applicable.

References

1. Intergovernmental Panel on Climate Change (IPCC). Climate change 2022: mitigation of climate change. Cambridge: Cambridge University Press; 2022. <https://doi.org/10.1017/9781009157926>.
2. Bjørn A, Lloyd SM, Brander M, Matthews HD. Renewable energy certificates threaten the integrity of corporate science-based targets. *Nat Clim Change*. 2022a;12:539–46. <https://doi.org/10.1038/s41558-022-01379-5>.
3. Bjørn A, Tilsted JP, Addas A, Lloyd SM. Can science-based targets make the private sector Paris-aligned? A review of the emerging evidence. *Curr Clim Change Rep*. 2022b;8:53–69. <https://doi.org/10.1007/s40641-022-00182-w>.
4. Ruiz Manuel I, Blok K. Quantitative evaluation of large corporate climate action initiatives shows mixed progress in their first half-decade. *Nat Commun*. 2023;14:3487. <https://doi.org/10.1038/s41467-023-38989-2>.
5. Cenci S, Burato M, Rei M, Zollo M. The alignment of companies' sustainability behavior and emissions with global climate targets. *Nat Commun*. 2023;14:7831. <https://doi.org/10.1038/s41467-023-43116-2>.
6. Leffel B, Lyon TP, Newell JP. Filling the climate governance gap: do corporate decarbonization initiatives matter as much as state and local government policy? *Energy Res Social Sci*. 2024;109:103376. <https://doi.org/10.1016/j.erss.2023.103376>.
7. Weaver I, Abrams JF, Oliver J, Dimakis N, Parry A, Lenton TM. An audit of corporate decarbonisation ambition against low carbon futures. *Sci Rep*. 2026;16:923. <https://doi.org/10.1038/s41598-025-20203-6>.
8. Jonas M, Bun R, Nahorski Z, Marland G, Gusti M, et al. Quantifying greenhouse gas emissions. *Mitig Adapt Strat Glob Change*. 2019;24:839–52. <https://doi.org/10.1007/s11027-019-09867-4>.
9. International Organization for Standardization (ISO). ISO 14064-1:2018 Greenhouse gases—Part 1: specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals. Geneva: ISO; 2018.

10. World Resources Institute and World Business Council for Sustainable Development (WRI and WBCSD). (2004) The Greenhouse Gas Protocol: a corporate accounting and reporting standard, revised edition.
11. World Resources Institute and World Business Council for Sustainable Development (WRI and WBCSD). (2011) Corporate value chain (Scope 3) accounting and reporting standard.
12. World Resources Institute and World Business Council for Sustainable Development (WRI and WBCSD). (2015) GHG Protocol Scope 2 guidance.
13. International Organization for Standardization (ISO). ISO 14068-1:2023 Climate change management—Transition to net zero—Part 1: carbon neutrality. Geneva: ISO; 2023.
14. Klaaßen L, Stoll C. Harmonizing corporate carbon footprints. *Nat Commun.* 2021;12:6149. <https://doi.org/10.1038/s41467-021-26349-x>.
15. Mejia C, Kajikawa Y. Estimating Scope 3 greenhouse gas emissions through the shareholder network of publicly traded firms. *Sustain Sci.* 2024;19:1409–25. <https://doi.org/10.1007/s11625-023-01460-8>.
16. Cenci S, Biffis E. Lack of harmonisation of greenhouse gases reporting standards and the methane emissions gap. *Nat Commun.* 2025;16:1537. <https://doi.org/10.1038/s41467-025-56845-3>.
17. Bendig D, Schulz C, Erbar F, Heubeck T. Apples to apples: accurately assessing corporate carbon performance. *J Clean Prod.* 2025;486:144338. <https://doi.org/10.1016/j.jclepro.2024.144338>.
18. Kim H-W, Ohnishi S, Fujii M, Fujita T, Park H-S. Evaluation and allocation of greenhouse gas reductions in industrial symbiosis. *J Ind Ecol.* 2018;22(2):275–87. <https://doi.org/10.1111/jiec.12539>.
19. Melville NP, Whisnant R. Energy and carbon management systems. *J Ind Ecol.* 2014;18(6):920–30. <https://doi.org/10.1111/jiec.12135>.
20. Brander M, Gatzweiler M. A commentary on E-liability: does it bring something new to GHG accounting? *Carbon Manag.* 2024;15(1):2372331. <https://doi.org/10.1080/17583004.2024.2372331>.
21. Reichelstein S. Corporate carbon accounting: balance sheets and flow statements. *Rev Acc Stud.* 2024;29:2125–56. <https://doi.org/10.1007/s11142-024-09830-y>.
22. Yang X, Smith TM, Prado AM, Yang Y. Net-zero greenhouse gas mitigation potential across multi-tier supply chains. *Commun Earth Environ.* 2025;6:230. <https://doi.org/10.1038/s43247-025-02173-9>.
23. Stalpers SIP, van Amstel AR, Dellink RB, Mulder I, Werners SE, Kroeze C. Lessons learnt from a participatory integrated assessment of greenhouse gas emission reduction options in firms. *Mitig Adapt Strat Glob Change.* 2008;13:359–78. <https://doi.org/10.1007/s11027-007-9117-2>.
24. United Nations Statistics Division (UNSD). International standard industrial classification of all economic activities (ISIC), Revision 5. New York: United Nations; 2024.
25. United Nations Environment Programme (UNEP). Decision XXXV/11: life-cycle refrigerant management. Montreal Protocol on Substances that Deplete the Ozone Layer; 2023.

26. United Nations Environment Programme (UNEP). Decision XXXVI/2: life-cycle refrigerant management. Montreal Protocol on Substances that Deplete the Ozone Layer; 2024.
27. Qian H, Zhu X, Huang S, Linquist BA, Kuzyakov Y, Wassmann R, et al. Greenhouse gas emissions and mitigation in rice agriculture. *Nat Reviews Earth Environ.* 2023;4:716–32. <https://doi.org/10.1038/s43017-023-00482-1>.
28. Gailani A, Cooper S, Allen S, Pimm A, Taylor P, Gross R. Assessing the potential of decarbonization options for industrial sectors. *Joule.* 2024;8(3):576–603. <https://doi.org/10.1016/j.joule.2024.01.007>.
29. Zhuang Z, Guan B, Chen J, Zheng C, Zhou J, Su T, et al. Review of nitrous oxide direct catalytic decomposition and selective catalytic reduction catalysts. *Chem Eng J.* 2024;486:150374. <https://doi.org/10.1016/j.cej.2024.150374>.
30. Zhou Y, Li Y, Ong E. Advancements in greenhouse gas emission reduction methodology for fluorinated compounds and N₂O in the semiconductor industry via abatement systems. *Front Energy Res.* 2024;11:1234486. <https://doi.org/10.3389/fenrg.2023.1234486>.

Figures

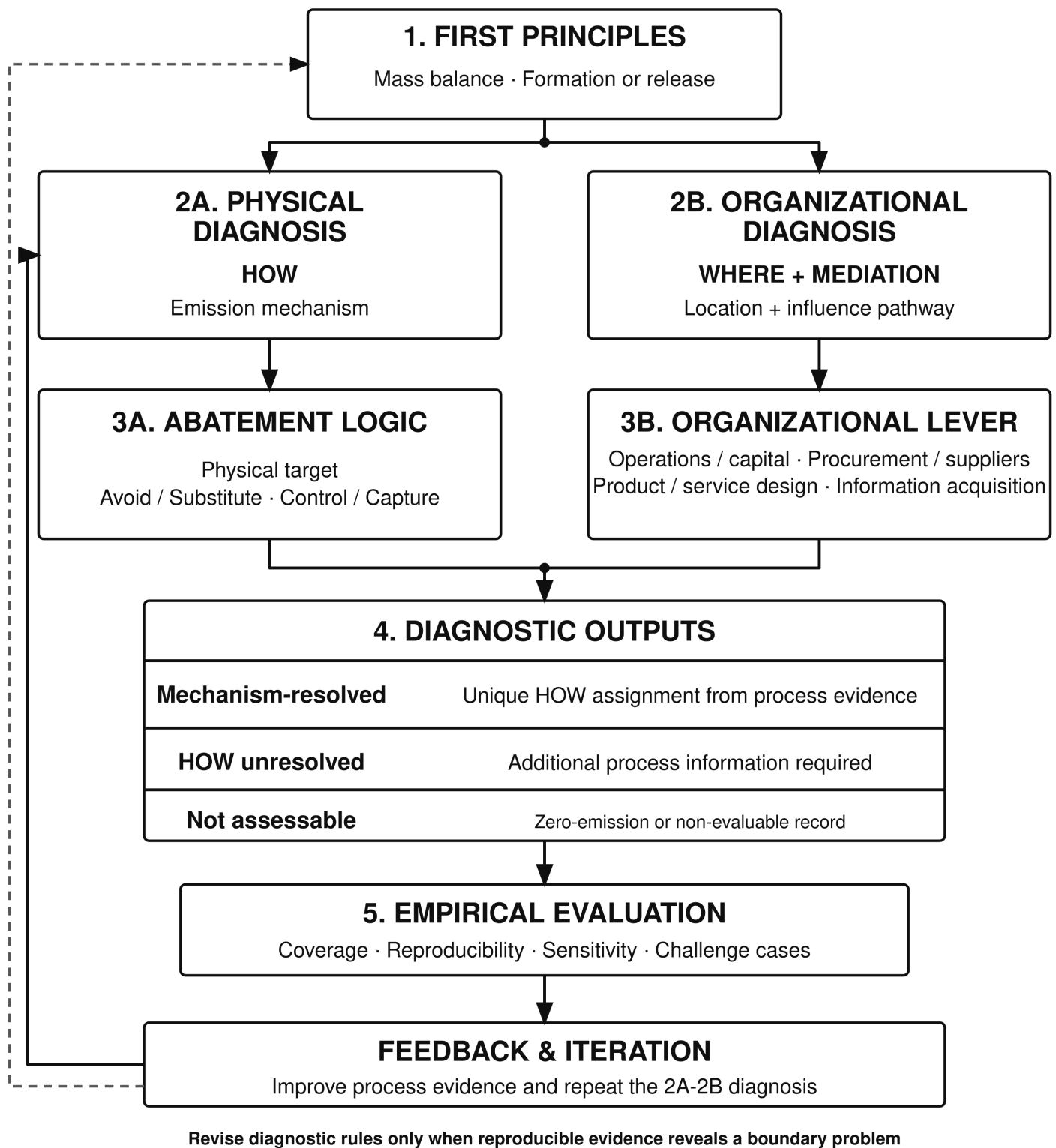


Figure 1

Dual-pathway theory-to-decision framework. HOW supports physical diagnosis and constrains abatement logic; WHERE followed by MEDIATION identifies organizational position and influence relationships. The branches converge in descriptive diagnostic outputs and are examined through HOW-resolution, restricted-field rule concordance, reporting-granularity sensitivity, and boundary stress cases. Feedback repeats the 2A–2B diagnosis after evidence improvement; diagnostic rules are reconsidered

only when reproducible evidence reveals a boundary problem. HOW = physical emission mechanism; WHERE = organizational location of the emitting process; MEDIATION = organizational influence relationship

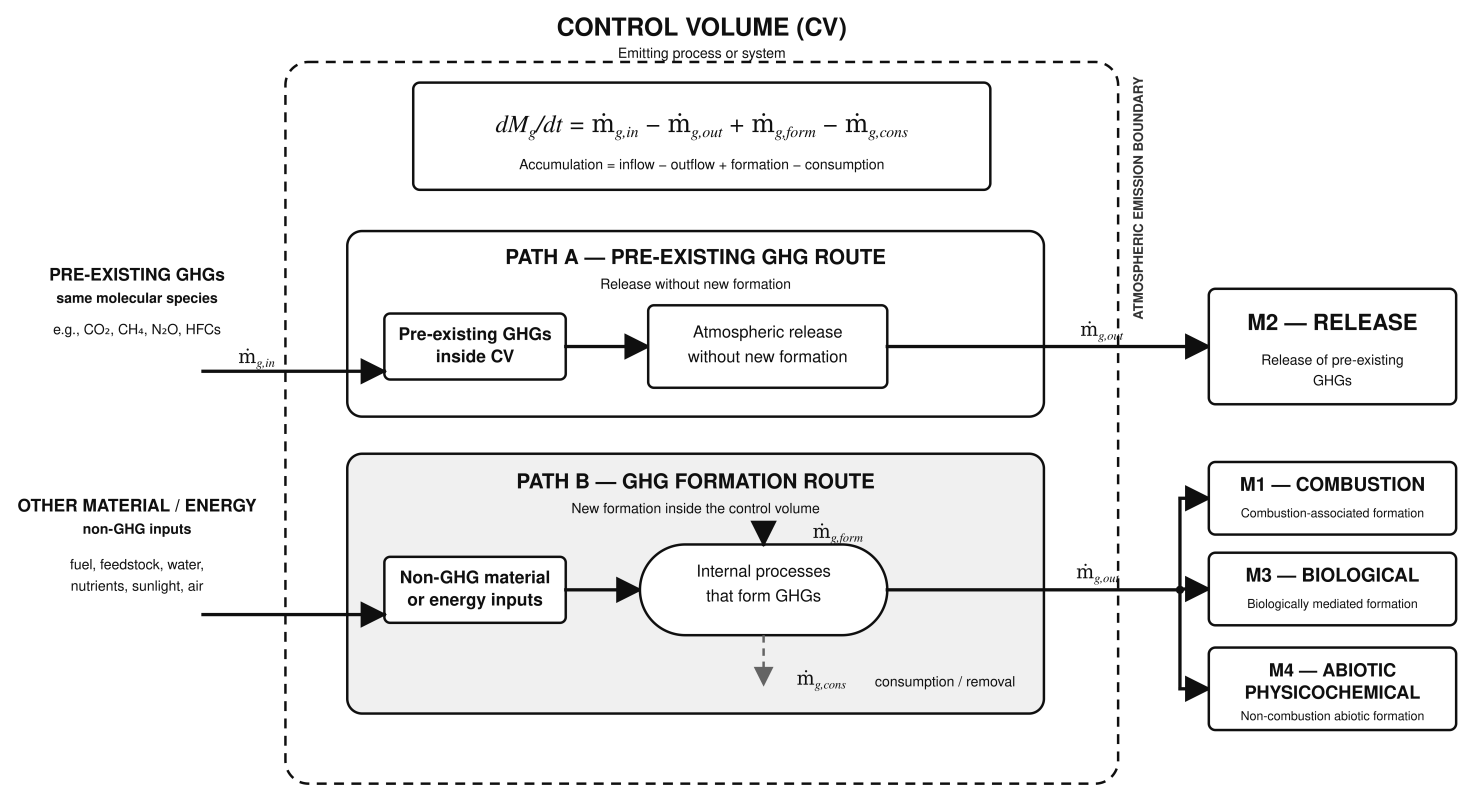
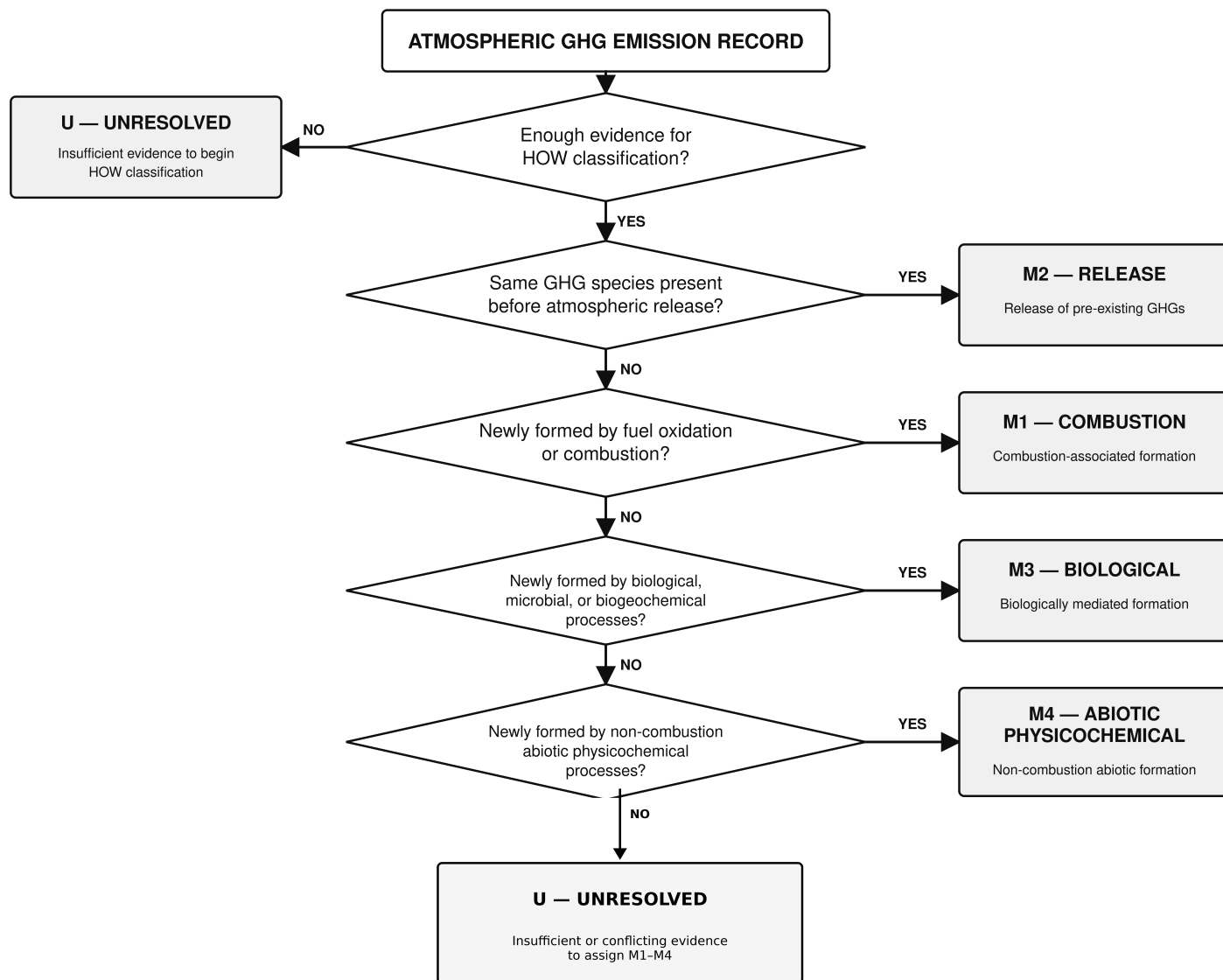


Figure 2

Control-volume basis for distinguishing release from formation and organizing physical greenhouse gas (GHG) emission mechanisms. The relevant control-volume (CV) boundary is selected so that the displayed outflow is the atmospheric-emission outflow. Path A represents atmospheric release without new molecular formation (M2); Path B represents new formation through M1, M3, or M4. Internal transport alone is not an atmospheric emission. M_g is the mass of GHG species g in the CV; subscripts in, out, form, and cons denote inflow, atmospheric outflow, internal formation, and internal consumption or removal, respectively



U denotes insufficient or conflicting process evidence; M1-M4 are the predefined operational classes.

Figure 3

Sequential decision procedure for assigning HOW. Insufficient or conflicting process evidence leads to unresolved HOW (U). Resolved observations are evaluated as release of a pre-existing GHG (M2), combustion-associated formation (M1), biologically mediated formation (M3), or other non-combustion abiotic physicochemical formation (M4). The diagram operationalizes classification within the predefined M1–M4 partition; it does not establish universal exhaustiveness

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Supplementaryinformation.docx](#)

- [ESM1.xlsx](#)