

Article

A Digital Delivery Framework for Precision Carbon Management in Gas Gathering Systems: From Tiered Accounting to Reduction Optimization

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Abstract

With the tightening of global methane regulations (EU Methane Regulation 2024/1787, U.S. EPA GHG rules, OGMP 2.0) and China's dual-carbon commitments, precise and traceable carbon accounting for natural gas gathering systems has become an urgent engineering imperative. To tackle manual workflows, data isolation, low precision, and poor traceability in carbon accounting for natural gas field surface systems, this study develops a four-tier digital delivery framework. The main goal is to establish an end-to-end engineering paradigm that transforms carbon management from passive post-hoc statistics into an active, traceable decision-support tool. By embedding carbon attributes into seed files and adopting a unified one-code-through equipment coding scheme, static design data, dynamic SCADA measurements, and emission factor databases are interoperably consolidated within a central data hub. The hub implements a three-stage progressive accounting workflow and closed-loop emission mitigation. Methodologically, a three-tier progressive accounting model (Tier 1: system-level, Tier 2: process-level, Tier 3: equipment-level) is constructed, with Tier 3 supported by OGMP 2.0 source-level emission factors locally calibrated against 386 field LDAR measurements. Deployed at Gas Field A, the framework realizes full diagram-model consistency and narrows systematic error from $\pm 30\%$ to $\pm 3.5\%$. Tier-2 accounting quantifies gathering, compression, and dehydration emissions at 322,000, 504,300, and 162,500 tCO₂e, while Tier-3 analysis pinpoints reciprocating compressors and heaters as the primary contributors (51.70% of total emissions). Optimizations including compressor energy conservation, enhanced LDAR, and waste heat recovery provide an estimated annual mitigation potential of 97,400 tCO₂e (10.10%). In conclusion, this framework mitigates data fragmentation and accuracy defects, delivering a transferable technical route for oil and gas operators to advance methane abatement and dual-carbon targets.



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1. Introduction

Global climate change has emerged as a critical challenge restricting the sustainable development of the energy industry. Controlling methane and CO₂ greenhouse gas (GHG)

emissions from the oil and gas sector and advancing the goals of carbon peaking and carbon neutrality have reached a universal consensus among regulatory authorities and enterprises worldwide. In addition to China's strategic vision of reaching carbon peaking before 2030 and achieving carbon neutrality by 2060, the EU Methane Regulation and U.S. EPA GHG control rules for oil and gas operations have imposed mandatory requirements on the accounting accuracy and data traceability of carbon emissions generated during natural gas production, gathering and transportation, while the UNEP Oil and Gas Methane Partnership 2.0 (OGMP 2.0) framework provides participating companies with a voluntary, measurement-based high-standard reporting framework to promote transparency and traceability of methane emissions data [1,2]. Methane emissions from China's oil and gas industry account for over 15% of the country's anthropogenic methane emissions, with process venting and fugitive leaks from equipment seals at surface gathering and transportation systems serving as the primary emission sources [3]. Gas field gathering and transportation systems consist of multiple types of stations, including gas gathering stations, compressor stations, and dehydration stations, and accommodate high-energy-consumption and high-leakage-risk equipment such as compressors, process heaters, triethylene glycol (TEG) dehydration units, and atmospheric storage tanks. The corresponding emission sources cover CO₂ emissions from fuel combustion, fugitive and vented CH₄ emissions from process operations, as well as indirect emissions from purchased electricity and heat [4]. Conventional carbon emission accounting relies on offline manual statistics, which suffer from low efficiency, long calculation cycles, substantial measurement errors, inability to update dynamic baselines, and insufficient audit traceability, failing to satisfy refined domestic and international regulatory constraints.

Digital engineering delivery has evolved from simple drawing and document handover to structured digital asset delivery. By establishing full-life-cycle databases under unified standards, it provides robust support for operational maintenance and data analytics. Nevertheless, prevailing digital delivery practices primarily focus on equipment maintenance and process scheduling without deep integration with carbon accounting workflows. Critical datasets required for carbon accounting—including energy efficiency parameters, sealing configurations, process topology, and leak inspection logs—are scattered across heterogeneous professional files, resulting in isolated data silos. Internationally, the IPCC Guidelines have formulated Tier 2 process-level and Tier 3 equipment-level accounting methodologies [5], the OGMP 2.0 has established a five-tier quantitative reporting framework [6], while the U.S. EPA and American Petroleum Institute (API) have issued standardized oil and gas emission accounting specifications [7,8]. Domestically, China National Petroleum Corporation (CNPC) has released corporate-level carbon accounting guidelines [9]. Xu et al. [10] further proposed suggestions for optimizing methane accounting methods in China's oil and gas industry. However, existing studies predominantly concentrate on model optimization and emission factor refinement, while neglecting standardized bottom-up data collection and automatic data correlation [11–13]. This bottleneck hinders the large-scale implementation of Tier 3 high-precision accounting.

At the international standardization level, ISO 15926 and CFIHOS have laid out specifications for factory data integration and exchange [14,15], and digital delivery engineering has been deployed in the Norwegian and UK North Sea oil and gas fields [16]. Domestically, CNPC issued the enterprise standard Q/SY 01015-2022 governing digital engineering delivery [17], and Feng et al. constructed a technical architecture for digital twins of oil and gas equipment [18]. Even so, current digital-delivery and digital-twin systems show critical gaps for carbon management: carbon-relevant attributes are rarely natively embedded; unified full-lifecycle coding linkage is missing; and few workflows merge static design assets with dynamic SCADA for multi-tier accounting. Notably, OGMP

2.0 provides a well-accepted reporting framework but lacks supporting engineering data infrastructure [6]; existing Tier-3-relevant studies mostly rely on manual data aggregation, limiting field-scale deployment [19]. Achieving equipment-level hourly quantification with actionable mitigation assessment remains a key bottleneck. While individual building blocks (intelligent P&ID, 3D models, SCADA, LDAR, emission-factor libraries) are existing technologies, the novelty of this work lies in the end-to-end engineering paradigm: seed-file-embedded carbon attributes, “one-code-through” unified asset-coding for automatic cross-source linkage, and a full closed-loop workflow combining multi-tier accounting, hotspot screening, and retrofit benefit evaluation. Our work is not merely assembling existing tools; we propose an end-to-end engineering paradigm with seed-file-embedded carbon attributes, “one-code-through” indexing, shared-platform tiered accounting, and a closed-loop mitigation workflow to fill this gap.

To bridge the identified gaps, this study aims to establish a precise carbon emission management system for gas-field surface gathering and transportation engineering, using digital engineering delivery as the foundational data infrastructure. Specifically, we (1) design a four-tier digital delivery architecture with embedded carbon-specific attribute fields and unified equipment coding, enabling seamless integration of static design data, real-time SCADA readings, and emission factor libraries; (2) develop a multi-tier progressive accounting framework (Tiers 1–3) that allows flexible precision switching and supports hourly dynamic quantification at the equipment level; and (3) construct a closed-loop management workflow that covers emission hotspot identification, low-carbon retrofit design, engineering implementation, and post-evaluation. This holistic approach transforms carbon management from passive, post-hoc statistics into an active, traceable decision-support tool that accommodates both regulatory compliance and decarbonization planning.

This paper innovates in three dimensions:

- (1) Innovation of underlying data infrastructure: A four-tier digital delivery architecture dedicated to carbon emission accounting is proposed. Unlike existing digital delivery practices that primarily serve equipment maintenance and process scheduling—with carbon accounting parameters retrofitted through manual data entry after project completion [20,21]—our architecture embeds carbon-specific attribute fields (e.g., sealing structure type, vent pipeline specifications, driving mode) within intelligent P&ID drawings and 3D model seed files. A full-chain carbon data indexing system based on unified equipment tag coding is developed to realize seamless cross-linkage of static design parameters, real-time SCADA operational data, and emission factor databases—eliminating data silos and manual matching errors at the engineering design source, rather than passively remediating them during the operation phase.
- (2) Innovation of accounting methodology: We clarify that the innovation here is not in the mathematical formulation of individual equations—which indeed follow the established activity-data $\times$ emission-factor paradigm consistent with IPCC and OGMP 2.0 protocols—but rather in the progressive multi-tier architecture and the data-driven dynamic precision-switching mechanism that existing frameworks lack. A multi-tier progressive carbon emission accounting model fed by layered digital assets is constructed, consisting of Tier 1 macroscopic statistical accounting, Tier 2 process decomposition accounting, and Tier 3 high-precision equipment-level accounting. Unlike existing methods that typically employ fixed accounting precision (mostly system-level or process-level) without flexible switching [4,14], our three tiers share a unified underlying data platform, enabling dynamic adjustment of accounting precision according to the digital construction maturity of each station—stations with low digital maturity can adopt Tier 1 for rapid estimation, while digitally mature stations can upgrade to Tier 3 equipment-level refinement. The methodological advance-

ment lies in three aspects: (i) the progressive tier-switching mechanism that allows seamless upgrading from system-level to equipment-level accounting within a single unified data infrastructure, which no existing framework provides; (ii) the integration of locally calibrated OGMP 2.0 source-level emission factors derived from 386 field LDAR measurements, replacing generic literature factors with site-specific values; and (iii) the incorporation of dynamic correction coefficients (sealing aging correction, standby correction, seasonal gas composition correction) that adapt static emission factors to real-time operational conditions. The Tier 3 module supports hourly dynamic emission quantification based on individual equipment geometric characteristics, real-time operational loads, and OGMP 2.0 source-level emission factors calibrated against field measurements [19], breaking through the temporal resolution limitations of conventional annual or quarterly static accounting.

- (3) Innovation of carbon management paradigm: A fully closed-loop precise carbon management workflow is established, following the logical chain of “emission hotspot identification → digital design of low-carbon retrofits → synchronous updating of post-transformation digital assets → quantitative evaluation of emission reduction benefits”. Distinct from current practices that typically stop at the “accounting—reporting” stage without a complete closed loop from identification to evaluation [22], our workflow targets high-emission equipment screened through Tier 3 accounting and provides quantitative calculation methods for assessing emission reduction contributions from three typical low-carbon renovation measures—compressor energy efficiency improvement, enhanced LDAR implementation, and waste heat recovery—elevating carbon management from “post-hoc statistics” to a closed-loop decision-making tool enabling “ex-ante simulation, in-process tracking, and ex-post verification”.

2. Integrated Technical System for Digital Delivery of Gas Field Surface Gathering and Transportation Facilities

The four-layer technical architecture of digital delivery is illustrated in Figure 1: Layer1 seed-file standardization (embed carbon attributes at design source), Layer2 unified entity-coding (global primary key for cross-source linking), Layer3 multi-disciplinary deliverables (multi-granularity assets as accounting inputs), Layer4 collaborative parsing (data validation, API interfacing, and version control). Information flow: Layer1 templates → Layer2 embedded coding → Layer3 structured deliverables → Layer4 parsing & API feeding to tiered-accounting platform; retrofits trigger backward asset updating via closed-loop version control. This framework serves two core business scenarios: operational maintenance management and multi-tier carbon accounting. It fundamentally eliminates traditional pain points including missing data, conflicting data, and unstructured datasets that cannot be automatically parsed at the engineering design stage, forming the unified standardized data foundation supporting Tier 1–Tier 3 progressive carbon-emission accounting. For detailed implementation (interface specification, update mechanism, automation boundary), see Appendix A.

2.1. Standardization Layer of Seed Files

Seed files serve as unified standardized templates for the entire project. All process drawings, three-dimensional (3D) models, and equipment attribute libraries are derived from standardized seed files [23,24], in which a complete set of exclusive attribute fields for carbon accounting is embedded in advance. This layer consists of two core standardized libraries.

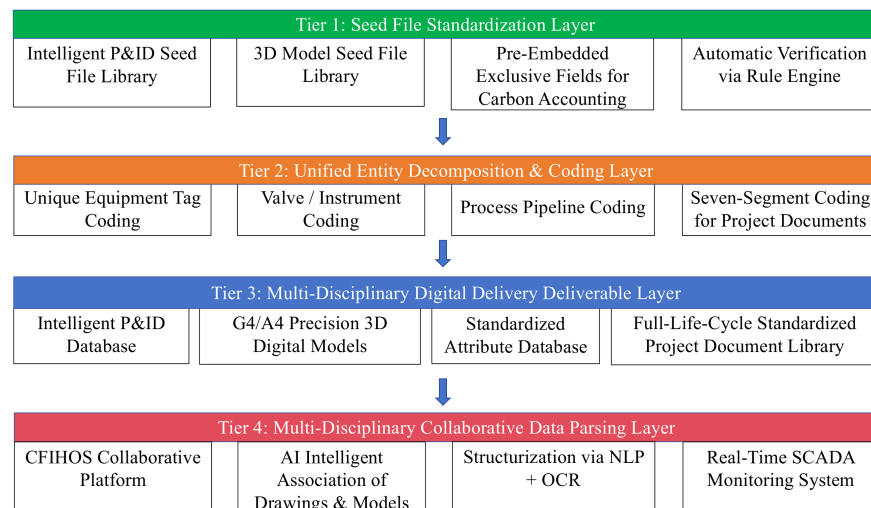


Figure 1. Four-Tier Technical Architecture of Digital Engineering Delivery.

2.1.1. Intelligent P&ID Seed File Library

This library integrates a unified Plant Breakdown Structure (PBS), global equipment tag coding templates, mandatory equipment attribute templates for carbon accounting, standardized legend libraries, and automatic rule verification scripts. All process equipment, isolation valves, metering instruments, and gathering-transmission pipelines are required to record fundamental parameters for carbon emission calculation, including equipment model, rated processing capacity, design load, natural gas composition, standard operating temperature-pressure range, sealing structure type, vent pipeline specification, and driving mode (electric drive/gas drive). A supporting rule engine conducts real-time verification of tag completeness and missing carbon accounting fields, eliminating blank basic parameters for subsequent accounting at the design source.

2.1.2. 3D Model Seed File Library

The 3D model seed file library comprises standard equipment component libraries, piping specification libraries, material property databases, spatial color mapping libraries, and bidirectional model-attribute binding templates. Unified modeling depth standards are defined for all disciplines: process equipment and gathering pipelines adopt G4 geometric precision coupled with A4 full attribute depth, which completely stores core parameters for methane fugitive emission calculation such as equipment dimensions, vessel volume, number of sealing points, and total quantity of valves and instruments. Secondary structures, including cable trays and floors, are simplified in modeling, with only spatial positioning attributes retained. Built-in automatic collision detection and drawing-model consistency verification rules ensure one-to-one correspondence between 3D models and equipment entities in intelligent P&IDs, eliminating data separation between drawings and models.

2.2. Unified Entity Decomposition and Coding Rule Layer

Unique coding rules for all engineering entities are formulated in accordance with the oil and gas digital delivery specification Q/SY 01015-2022 [17]. A single fixed tag number is assigned to each individual piece of equipment, pipeline, and document, which acts as the unique primary index key of the carbon accounting database. This fundamentally addresses the industry-wide problem of unmatched equipment information scattered across traditional drawings, paper ledgers, and operational monitoring data. Four standardized coding systems directly support refined tiered carbon emission calculation for single equipment:

- (1) Equipment tag coding: Region Code-Equipment Category-Serial Number-Spare Identifier (e.g., 0206K-P-13001-A for centrifugal pumps). This coding system clearly distinguishes high-emission core facilities, including reciprocating compressors, process heaters, triethylene glycol (TEG) dehydration units, and atmospheric storage tanks.
- (2) Valve/Instrument coding: Module-Equipment Category-Serial Number (e.g., 01-BV-1001 for block valves, 01-PG-1001 for pressure gauges). The system automatically counts the quantity and type of leak-prone equipment across the whole station to support batch methane fugitive emission accounting via Leak Detection and Repair (LDAR) [25].
- (3) Process pipeline coding: Region-Pipe Diameter-Medium Type-Skid Number-Serial Number-Pipe Class-Insulation Form. It provides basic parameters for calculating CH₄ medium composition, pipeline volume, and process venting volume.
- (4) Seven-segment coding for project documents: Region-Skid-Discipline Classification-Document Type-Serial Number-Version Number, enabling automatic retrieval of matched design specifications, equipment data sheets, annual maintenance ledgers, and gas composition analysis reports for every single piece of equipment.

A full-chain standardized carbon data linkage named “One-Code Integration” is constructed based on unified coding. The unique equipment tag connects intelligent P&ID graphics, 3D geometric models, structured attribute databases, complete design and construction documents, real-time SCADA operation databases, and tiered emission factor libraries. Once an equipment tag is input into the carbon accounting program, all calculation parameters can be automatically extracted without manual cross-file retrieval and manual data entry.

2.3. Core Deliverables of Multi-Disciplinary Digital Delivery

Digital delivery outputs four categories of structured digital assets, which supply standardized data with distinct granularities for Tier 1, Tier 2 and Tier 3 carbon accounting models respectively. This constitutes the core differentiated advantage compared with conventional paper drawing delivery.

2.3.1. Intelligent P&ID Database

As the core data source for Tier 2 process-level accounting, intelligent P&IDs differ from static, non-editable DWG drawings by adopting a database-driven architecture. Each pipeline, equipment, and valve exists as a database object attached with structured attributes, which fully store the topological correlation of the whole process flow:

- (1) Supplying complete process data for the Tier 2 process decomposition emission factor method, including full-process topology of gas gathering stations, compressor stations and dehydration stations, rated flow rates of flare vent pipelines, quantity of process vent branches, fuel gas pipelines for heaters, and TEG regeneration circulation loops;
- (2) Automatically identifying all emission sources throughout the process, including flare combustion systems, process vent branches, fuel combustion equipment, leak-prone valves and instruments, and splitting independent accounting units to replace manual sorting of process flows.

The deliverables include native drawing files, background structured database backups, and machine-readable SVG files, which allow automatic extraction of topological structures by carbon accounting programs without manual drawing interpretation and parameter input.

2.3.2. G4/A4 Precision 3D Digital Models

The 3D models feature high-precision geometric dimensions and complete structured equipment attributes, directly supporting refined Tier 3 carbon accounting for key facilities:

- (1) Static basic parameters: number of compressor cylinders, rated fuel consumption of heaters, effective storage tank volume, accurate total quantity of valves and instruments across the station, total pipeline length and statistical number of sealing points;
- (2) Spatial positioning information: 3D coordinates of leak-prone equipment to support partition planning for LDAR management and precise layout of on-site methane detection points [26];
- (3) Automatic drawing-model consistency verification: the system automatically matches equipment tags in P&IDs with corresponding entities in 3D models, achieving a 100% matching rate and eliminating undercounting or duplicate calculation errors caused by inconsistent drawings and models.

2.3.3. Standardized Attribute Database

The standardized attribute database serves as a universal structured parameter library for three-tier accounting. Its fields are uniformly regulated following four depth grades from A1 to A4, and all parameters required for carbon accounting are stored in a standardized structured format. Reserved standard API interfaces enable direct docking with automatic carbon emission calculation programs:

- (1) A1 Identification Layer: equipment tag, station region, and equipment category (for rapid screening of high-emission facilities);
- (2) A2 Correlation Layer: affiliated skids, upstream and downstream pipelines, and supporting instrument lists (to establish topological correlations among emission sources);
- (3) A3 Technical Parameter Layer (core fields for carbon accounting): rated flow rate, design pressure, volumetric concentration of CH₄ in natural gas, fuel consumption indicators, annual operating load, sealing structure type, annual operating hours of equipment and matching parameters for emission factors;
- (4) A4 Management Layer: equipment commissioning date, periodic maintenance cycle and aging correction coefficients of sealing materials (to support dynamic revision of emission factors).

2.3.4. Full-Life-Cycle Standardized Project Document Library

Equipment data sheets, process calculation books, annual gas composition analysis reports, equipment maintenance records, original manufacturer parameters, and annual LDAR inspection ledgers are classified and stored via seven-segment coding. For unstructured documents such as PDFs and scanned paper files, optical character recognition (OCR) combined with natural language processing (NLP) semantic analysis is adopted to extract structured fields into the database, and all documents are archived bound to the unique equipment tag. During carbon verification and emission reduction effectiveness evaluation, original design parameters from equipment manufacturers can be retrieved with one click, realizing full-chain traceability of carbon emission data. This meets mandatory requirements such as domestic environmental supervision and third-party carbon auditing, and is also aligned with the reporting standards of the voluntary OGMP 2.0 framework [6].

2.4. Automatic Collaborative Parsing Technology for Multi-Disciplinary Data

Traditional engineering data exist in heterogeneous and non-standard formats, which cannot be directly imported into automatic carbon accounting programs. Six sets of supporting collaborative parsing technologies are integrated into digital delivery to realize fully automatic data circulation between static digital assets and dynamic operational data:

- (1) Unified CFIHOS international standard collaborative platform: all multi-disciplinary engineering data comply with unified field standards to eliminate data silos among process, instrumentation, electrical, and civil engineering disciplines [15];
- (2) AI intelligent drawing-model correlation algorithm: automatically binds P&ID process graphics with 3D model entities and synchronizes the complete set of structured equipment attributes bidirectionally. Evaluated on project dataset, entity-matching accuracy = 98.2%, mismatching error rate = 1.8%;
- (3) Automatic rule verification engine: detects missing mandatory carbon accounting parameters, tag coding errors, and logical parameter contradictions before digital delivery acceptance, so as to rectify underlying data defects in advance;
- (4) NLP + OCR structured transformation for unstructured data: built on mature off-the-shelf toolchains (not novel algorithm development within this study), it batch-converts PDF specifications and paper-scanned maintenance ledgers into structured database fields. Field-extraction F1-score reaches 94.7% for high-quality native-PDF documents and drops to 76.3% for aged scanned-paper documents requiring manual review. Our contribution is integrating parsed outputs into unified-coding and carbon-accounting workflows.;
- (5) Closed-loop version control for engineering changes: P&ID drawings, 3D models, and equipment attribute libraries are synchronously updated after station process reconstruction or equipment replacement, and carbon accounting programs automatically access the latest equipment parameters to avoid long-term accounting deviations induced by outdated data;
- (6) Standardized interface docking between the digital asset library and the EAM equipment management system/real-time SCADA monitoring system/carbon accounting platform: bidirectional data exchange between static design parameters and real-time dynamic operational data is realized to support hourly automatic dynamic carbon emission quantification [24]. This technical framework also provides a system implementation reference for precise carbon emission management of oil and gas fields [25].

2.5. Mitigation of Fundamental Deficiencies in Conventional Carbon Accounting via Digital Delivery

Conventional carbon accounting relies on manual statistics, paper ledgers, and scattered materials, resulting in a series of typical drawbacks including low statistical efficiency, rough accounting accuracy, mismatched equipment information, inaccurate leakage calculation, delayed data updates, and difficult audit traceability. These issues have long restricted the authenticity, timeliness, and standardization of corporate carbon management data. The four-tier digital delivery architecture precisely targets all deficiencies of traditional accounting, comprehensively consolidating the underlying data foundation for carbon management from six core dimensions: statistical efficiency, accounting accuracy, equipment matching, leakage quantification, data updating, and audit traceability. It realizes standardized, refined, and intelligent upgrading of the whole carbon accounting workflow. The specific traditional pain points, corresponding digital solutions, and quantitative improvement effects of each dimension are presented in Table 1.

Table 1. Drawbacks of Conventional Carbon Accounting, Targeted Digital Delivery Solutions, and Quantified Improvement Effects of Carbon Management.

Drawbacks of Conventional Carbon Accounting	Targeted Solutions via Digital Delivery	Quantified Improvement Effects on Carbon Management
Drawings and paper ledgers are stored separately; manual statistics lead to extremely low efficiency, with an accounting cycle exceeding 7 days.	All engineering data are structured and stored in databases; system interfaces automatically extract parameters, compressing the accounting duration to only 5 min.	Accounting efficiency improved by 99% (cycle reduced from >7 days to <5 min).
Fundamental equipment parameters are incomplete; only coarse system-level accounting can be performed, making it impossible to identify individual high-emission units.	The A4 full-depth attribute library stores complete parameters of each item of equipment, with unique equipment tags as the exclusive index.	Tier 3 high-precision equipment-level refined carbon accounting is realized.
Equipment coding in P&IDs, equipment ledgers and 3D models are independent of one another, resulting in data conflicts and duplicate records.	Unified global coding plus fully automatic drawing-model consistency verification, achieving a 100% tag matching rate.	The systematic error of carbon accounting is reduced from $\pm 30\%$ to within $\pm 3.5\%$.
The quantity and specifications of methane leakage-prone equipment rely on manual on-site counting, which easily causes undercounting and miscalculations.	3D models automatically batch-calculate the total number of valves, instruments and sealing components across the entire station.	The calculation accuracy of fugitive CH ₄ emissions is significantly enhanced.
Data fail to be updated synchronously after station process retrofits, and outdated equipment parameters are persistently adopted for long-term carbon accounting.	Closed-loop version control for engineering changes enables real-time synchronous updates of digital assets.	High precision of long-term carbon accounting can be continuously maintained.
Original design documents are unavailable during carbon audits and environmental inspections, bringing great difficulties to emission data traceability.	The standardized document library binds complete original manufacturer design data to corresponding equipment tags.	Fully traceable compliance requirements are satisfied for domestic environmental supervision and international methane audits under OGMP 2.0.

3. Three-Tier Progressive Carbon Emission Accounting System Driven by Digital Engineering Delivery

Based on the four-tier digital delivery framework elaborated in Chapter 2 (the seed file standardization layer, unified entity coding layer, structured digital asset deliverable layer, and multi-source data collaborative parsing layer), five categories of digital assets—intelligent P&ID database, G4/A4 high-precision 3D models, standardized attribute database, full-life-cycle project document library, and real-time SCADA operation database—are integrated as a unified underlying data platform for tiered carbon accounting. The system matches the input parameter requirements of three accounting methodologies in a hierarchical manner: the Tier 1 macroscopic statistical emission intensity method, Tier 2 process decomposition emission factor method, and Tier 3 equipment-level high-precision accounting. Dynamic upgrading of accounting accuracy can be realized in accordance with the digital construction maturity of each gathering station.

Clarification: Tier-1, Tier-2 and Tier-3 are complementary and sequentially upgradable (rather than mutually exclusive alternatives) under identical study boundaries: Gas-Field-A, calendar-year 2024, Scope 1 + Scope 2 (Scope 3 excluded). Note that Table 3 Tier-3 outputs only represent key station-equipment subsets and exclude dispersed long-distance-

pipeline emission sources; therefore, its aggregated total is not directly comparable to Table 2 full-system total, even with consistent system boundaries.

Table 2. Calculation Results of Greenhouse Gas Emissions via the Process Decomposition Emission Factor Method.

Process Module	CO ₂ Emissions (t)	CH ₄ Emissions (t)	Total CO ₂ e (t)
Gas Gathering Process	297,650	975	322,025
Compressor Station Process	498,360	236	504,260
Dehydration Station Process	144,210	732	162,510
Waste Gas Recovery & Utilization	−16,200	−324	−24,300
Total Aggregate	924,020	1619	964,495

3.1. Case Study Site Description

The case study site is Gas Field A, located in Southwest China, representing a typical onshore natural gas production and gathering operation, with its specific name and geographic location withheld for commercial confidentiality. The surface gathering system of Gas Field A comprises 3 gas gathering stations, 2 compressor stations, 2 dehydration stations, and 1 central processing plant, with a total of 47 major equipment units (including 12 reciprocating compressors, 8 centrifugal compressors, 6 TEG dehydration units, 9 process heaters, and 12 unstable condensate storage tanks) and 3842 leak-prone components (valves, flanges, instruments, and seals). The reporting period for this study is the 2024 calendar year (January 1 to December 31), and the operational boundaries cover Scope 1 (CO₂ emissions from fuel combustion, fugitive CH₄ emissions from process operations, vented CH₄ emissions, and flaring emissions) and Scope 2 (CO₂ emissions from purchased electricity and heat), while Scope 3 emissions are excluded from this study. The average volumetric composition of natural gas in Gas Field A is CH₄ 92.3%, CO₂ 3.8%, and C₂H₆ 2.1%, with the balance comprising C₃₊ hydrocarbons and inert gases, and seasonal CH₄ concentration varies within the range of 91.0–93.5% throughout the year. In the 2024 accounting period, the system processed 32.15×10^8 m³ of natural gas and produced 1.85×10^4 t of condensate oil, with major equipment operating for an average of 7824 h per year at load factors ranging from 72% to 85% (72% for compressors, 85% for heaters). Regarding emission factor sources, Tier 2 accounting adopts default emission factors from the CNPC Guidelines for Greenhouse Gas Accounting of Oil and Gas Production Enterprises (2014) and the IPCC 2006 Guidelines (2019 Revision), while Tier 3 accounting employs OGMP 2.0 Level 3 source-level emission factors calibrated using field LDAR inspection data from Gas Field A (measurements at 386 sealing points). The key assumptions of this study include: flare combustion carbon oxidation efficiency of 98% (IPCC default value), methane global warming potential of 25 (IPCC AR4, consistent with CNPC guidelines), condensate-to-natural gas conversion coefficient of 0.1255×10^4 m³/t, and fugitive CH₄ emission factors categorized by OGMP 2.0 equipment type and multiplied by equipment operating time correction factors.

3.2. Macroscopic Statistical Emission Intensity Method (Tier 1: System-Level)

3.2.1. Data Sources from Digital Delivery

Tier 1 accounting only requires aggregated macroscopic system-level data, and invokes three types of digital assets exclusively: the A1 identification attribute library, full-life-cycle standardized project document library, and real-time production interface of the SCADA system. No subdivided equipment or process parameters are demanded:

- (1) Standardized project document library (historical ledgers): Annual total natural gas throughput, annual condensate oil output, total annual fossil fuel consumption, annual

purchased electricity and heat consumption, cumulative annual CO₂ recovery volume, cumulative annual CH₄ recovery volume, and total annual fugitive methane loss of the system;

- (2) Real-time SCADA data interface: Natural gas throughput and condensate oil output within the current accounting period;
- (3) A1 identification attribute library: Boundary of the accounting station, condensate-to-natural gas conversion coefficient and IPCC global warming potential of methane;
- (4) Gas composition analysis document library (annual gas quality reports): System-wide average volumetric concentration of CH₄, adopted to convert total fugitive methane volume into mass.

3.2.2. Data Circulation Workflow

The digital delivery document library batch-reads multi-year historical production and energy consumption ledgers → the system automatically aggregates cumulative direct and indirect CO₂ emissions as well as total fugitive and vented CH₄ emissions (converted to CO₂-equivalent) over years → the historical comprehensive emission intensities D_c and D_H are derived by dividing total emissions by the cumulative oil-and-gas equivalent throughput across years. Real-time oil and gas production data are automatically extracted via the SCADA interface, and the estimated total emissions of the current period are obtained by multiplying the real-time throughput with historical emission intensities.

3.2.3. Core Calculation Formulas

(1) Historical emission intensities

$$D_c = \frac{\sum E_{CO_2}}{\sum (G_q + G_n r_g)} \quad (1)$$

$$D_H = \frac{\sum E_{CH_4}}{\sum (G_q + G_n r_g)} \quad (2)$$

where:

D_c —system CO₂ emission intensity, tCO₂/10⁴ m³;

D_H —system CH₄ emission intensity, tCO₂/10⁴ m³;

$\sum E_{CO_2}$ —cumulative total direct and indirect CO₂ emissions, tCO₂;

$\sum E_{CH_4}$ —cumulative total fugitive and vented methane emissions, tCH₄;

G_q —natural gas throughput in a single accounting period, 10⁴ m³;

G_n —condensate oil output in a single accounting period, t;

r_g —condensate-to-natural gas conversion coefficient, fixed at 0.1255×10^4 m³/t.

(2) Total system emissions of the current period

$$E_{sum} = (D_c + D_H \times GWP_H) \times (G_q + G_n \times g_n) - E_{rec} \quad (3)$$

where:

E_{sum} —total system greenhouse gas emissions of the current period, tCO₂e;

GWP_H —global warming potential of CH₄ relative to CO₂, the GWP value adopted in this study is 25, taken from the IPCC Fourth Assessment Report (AR4, 2007). The basis for this selection is that the CNPC Guidelines for Greenhouse Gas Accounting of Oil and Gas Production Enterprises (2014) explicitly mandates the use of this value for corporate greenhouse gas accounting and reporting. This choice ensures consistency between the accounting results of this study and domestic industry standards;

E_{rec} —total emission reduction equivalent converted from recovered CO₂ and CH₄ of the system, tCO₂e.

3.2.4. Case Calculation

Taking Gas Field A as an example: the total oil and gas throughput of the system in 2024 reached $32.15 \times 10^8 \text{ m}^3$; direct and indirect CO_2 emissions from energy consumption amounted to $84.35 \times 10^4 \text{ tCO}_2\text{e}$; fugitive natural gas loss during gathering and transportation was $0.043 \times 10^8 \text{ m}^3$, equivalent to 3072 t CH_4 or $7.68 \times 10^4 \text{ tCO}_2\text{e}$; 15,200 t CO_2 and 272 t CH_4 were recovered, corresponding to an emission reduction of $2.20 \times 10^4 \text{ tCO}_2\text{-e}$. The aggregated total emissions from the three items were $89.85 \times 10^4 \text{ tCO}_2\text{-e}$.

The comprehensive emission intensity is calculated as:

$$D_{\text{comprehensive}} = 89.85 \times 10^4 / 32.15 \times 10^8 = 2.795 \text{ tCO}_2\text{e}/10^4 \text{ m}^3.$$

The oil and gas throughput in 2025 was $35.68 \times 10^8 \text{ m}^3$. The macroscopic estimated total emissions for 2025 are:

$$E_{2025} = 2.795 \text{ tCO}_2\text{-e}/10^4 \text{ m}^3 \times 35.68 \times 10^8 \text{ m}^3 = 99.7256 \times 10^4 \text{ tCO}_2\text{-e}.$$

3.2.5. Method Positioning and Applicable Boundaries

The core advantage of the Tier 1 macroscopic statistical emission intensity method lies in its extremely low data requirement: estimation can be completed merely relying on system-level historical energy consumption and production ledgers, without any subdivided equipment or process data. This method serves as a rapid rough estimation tool for scenarios with insufficient underlying data. Its applicable scenarios include pre-assessment of carbon emissions during the feasibility study stage of oil and gas projects, emission trend forecasting for medium- and long-term production capacity planning, and horizontal benchmarking estimation for old stations lacking digitized engineering data.

Estimates generated by this method are extrapolated based on historical average emission intensities, which cannot automatically reflect baseline variations induced by process reconstruction and equipment renewal, nor can they identify high-emission units within stations. Therefore, when the accounting objective shifts from “macroscopic forecasting” to “design of targeted precise emission reduction schemes”, the accounting accuracy should be upgraded to Tier 2 or Tier 3.

3.3. Process Decomposition Emission Factor Method (Tier 2: Process-Level)

3.3.1. Digital Delivery Data Sources

Tier 2 accounting takes the intelligent P&ID database as the core data source, supplemented by the A3 technical parameter layer of the standardized attribute library, unified coding library for valves and pipelines, and project document library. The accounting units are decomposed by process modules corresponding to gas gathering stations, compressor stations, and dehydration stations:

- (1) Parameters delivered by the intelligent P&ID database: (i) Full-process topological structure: division of independent accounting units for gas gathering stations, compressor stations and dehydration stations, quantity of flare vent branches, rated flow rate of vent pipelines, and layout of fuel gas pipelines; (ii) Flare system parameters: total flare gas flow rate, volumetric CO_2 concentration of flare gas, volumetric CH_4 concentration of flare gas, and carbon oxidation efficiency of flares; (iii) Process vent branches: natural gas throughput discharged from dehydration units and volume of vent pipelines.
- (2) Parameters delivered by the A3 technical parameter layer of the standardized attribute database: (i) Total station equipment inventory: total number of process heaters, compressors and TEG pumps, reboilers; total annual fuel consumption (natural gas, diesel oil); (ii) Inventory of leak-prone facilities: total quantity of valves, instruments and

- check valves; (iii) Basic medium parameters: unified volumetric CH₄ concentration of natural gas across the station, low heating value of fuel, and carbon content per unit heating value; (iv) Purchased energy parameters: annual purchased electricity volume, mass of purchased hot water/steam, steam enthalpy and hot water temperature.
- (3) Parameters delivered by the digital document library: Default emission factors specified in CNPC Guidelines for Greenhouse Gas Accounting of Oil and Gas Production Enterprises, emission factors for process vented CH₄, and generic fugitive emission factors for equipment.

3.3.2. Data Circulation Workflow

The intelligent P&ID system automatically identifies three major process units → five emission source categories (flare combustion, process venting, fuel combustion, fugitive leakage, and purchased energy) are split by unit → the attribute library matches the total equipment quantity and gas composition parameters of each process → generic industrial default emission factors are retrieved from the document library → segmented CO₂ and CH₄ emissions are calculated per unit → CH₄ emissions are converted into CO₂-equivalent by multiplying with the GWP of methane → results of all processes are summed, and emission reductions from waste gas recovery are deducted to obtain the total greenhouse gas emissions of the whole system.

3.3.3. Core Calculation Formulas for Each Process

- (1) Comprehensive equivalent greenhouse gas emissions from flares at gas gathering stations

$$E_h = E_{h,C} + E_{h,H} \times GWP_H \quad (4)$$

where:

E_h —total greenhouse gas equivalent emissions from a single flare system, tCO₂e;

$E_{h,C}$ —CO₂ emissions generated by flare combustion, tCO₂e;

$E_{h,H}$ —fugitive CH₄ emissions from incomplete flare combustion, tCH₄.

- (2) Segmented calculation formula for flare CO₂ emissions

$$E_{h,C} = \sum_i \left[Q_h \times \left(CC_{n,c} \times OF \times \frac{44}{12} + V_C \times 19.7 \right) \right]_i \quad (5)$$

where:

i —serial number of station flares;

Q_h —flare gas flow rate of the i -th flare system, 10⁴ m³;

$CC_{n,c}$ —total carbon content of all carbon-containing compounds in flare gas excluding CO₂, tC/10⁴ m³;

OF —carbon oxidation efficiency of flares;

V_C —volumetric CO₂ concentration of flare gas.

- (3) Segmented calculation formula for fugitive CH₄ from flares

$$E_{h,H} = \sum_i [(Q_h \times V_H \times (1 - OF) \times 7.17)]_i \quad (6)$$

where:

V_H —volumetric CH₄ concentration of flare gas;

Other symbols are defined as above.

- (4) Formula for fugitive methane emissions from station valves and instruments

$$E_{g,H} = \sum_j (num_{g,j} \times EF_{g,j}) + num_k \times EF_k \quad (7)$$

where:

$E_{g,H}$ —total fugitive methane emissions from all leak-prone equipment in the gas gathering station, tCH₄;

j —classification serial number of leak-prone equipment;

$num_{g,j}$ —quantity of the j -th type of leak-prone facilities (valves, instruments), piece;

$EF_{g,j}$ —fugitive methane emission factor of the j -th type of facilities, tCH₄/(piece·a);

num_k —total quantity of check valves in the station, piece;

EF_k —dedicated fugitive methane emission factor for check valves, tCH₄/(piece·a).

(5) Process vented CH₄ emissions from triethylene glycol (TEG) dehydration units

$$E_{e,H} = Q_g \times EF_{e,H} \quad (8)$$

where:

$E_{e,H}$ —methane emissions generated by maintenance and pressure relief venting of dehydration equipment, tCH₄;

Q_g —annual total natural gas throughput of the dehydration station, 10⁴ m³;

$EF_{e,H}$ —emission factor for vented methane from dehydration processes, tCH₄/10⁴ m³.

(6) Fugitive methane emissions from pipelines and equipment of TEG dehydration processes

$$E_{d,H} = Q_g \times EF_{d,H} \quad (9)$$

where:

$E_{d,H}$ —total fugitive methane emissions from pipeline and valve seals in dehydration processes, tCH₄;

$EF_{d,H}$ —fugitive methane emission factor per unit throughput for dehydration processes, tCH₄/10⁴ m³.

(7) Total full-process greenhouse gas equivalent emissions of dehydration stations

$$E_d = (E_{e,H} + E_{d,H}) \times GWP_H + E_{e,C} + E_{d,ffc} - E_{rec} \quad (10)$$

where:

E_d —annual total greenhouse gas equivalent emissions of the TEG dehydration station, tCO₂e;

$E_{e,C}$ —indirect CO₂ emissions from purchased electricity and heat consumed by the dehydration station, tCO₂;

$E_{d,ffc}$ —direct fuel combustion greenhouse gas equivalent emissions from heaters, compressors and other equipment in the dehydration station, tCO₂e;

E_{rec} —equivalent emission reductions converted from recovered waste gas at the dehydration station, tCO₂e.

3.3.4. Case Calculation

Based on the Tier 2 process-decomposed emission factor method for greenhouse gas (GHG) accounting in Gas Field A, and with reference to the sub-item data in Table 2 and the stacked bar chart in Figure 2, the differences in carbon emission contributions among the various production processes are clearly evident. The total GHG emission equivalent of the entire gas field is 96.45×10^4 tCO₂e. Among the processes, the compressor station contributes the highest share, with a total CO₂e of 504,260 t, making it the core emission unit of the field. In this process, direct CO₂ emissions amount to 498,360 t, while methane fugitive emissions are only 236 t, indicating that fuel combustion at the compressor station is the dominant emission source. The gas gathering process ranks second, with a total equivalent of 322,025 t, comprising 297,650 t of CO₂ and 975 t of methane; notably, this process exhibits the highest methane fugitive emissions among

all production stages. The dehydration station shows relatively lower emissions, with a total CO₂e of 162,510 t (CO₂: 144,210 t, CH₄: 732 t). The recycling and utilization stage achieves emission reductions through CO₂ recovery, reducing CO₂e by 24,300 t through CO₂ recovery, which partially offsets the GHG emissions from the production side. Overall, the GHG emissions from the gas field are dominated by CO₂ from fuel combustion, with methane fugitive emissions contributing only marginally. The two pressurization and gathering/transportation processes (compressor station and gas gathering) account for the vast majority of carbon emissions, while the carbon recovery step shows certain emission reduction benefits. Future mitigation efforts should therefore focus on optimizing combustion energy consumption in the compressor station and gas gathering processes.

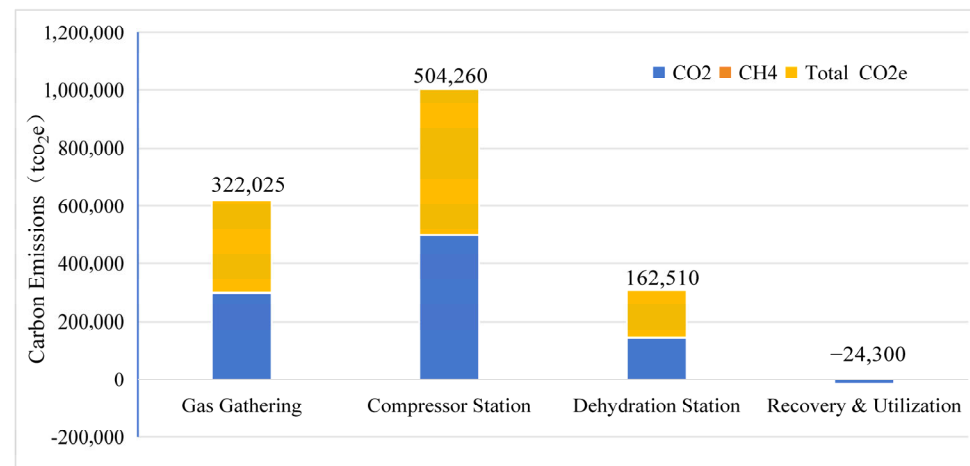


Figure 2. Stacked bar chart of greenhouse gas emissions by Tier 2 processes in Gas Field A. Note: total CO₂e is an aggregated indicator and is not additionally stacked on CO₂ and CH₄.

3.3.5. Method Positioning and Applicable Scope

Centered on the intelligent P&ID database as the core data source, the Tier 2 process decomposition emission factor method separates emission sources by process units, including gas gathering, compression, and dehydration. Its prominent advantage lies in the capacity to identify high-emission segments at the process level (e.g., excessive emission contributions from flare combustion of a specific dehydration station). With moderate data input requirements, this method is applicable to routine annual corporate carbon accounting, carbon data reporting to superior regulatory authorities, and baseline quantification for third-party carbon verification.

This methodology serves as a process-level accounting and management tool. Nevertheless, it universally adopts industry-wide generic emission factors, which fail to capture individual disparities among single equipment units arising from sealing grade, commissioning age and actual operating load. Fugitive methane emissions are merely calculated by multiplying the total quantity of leak-prone facilities by generic emission factors, rendering the method incapable of pinpointing individual high-emission equipment. When carbon management demands shift from “identifying high-emission processes” to “developing targeted emission reduction retrofitting schemes for single equipment”, the Tier 3 equipment-level refined algorithm should be embedded within the Tier 2 process decomposition framework for deeper precision.

3.4. Equipment-Level High-Precision Carbon Accounting (Tier 3: Equipment-Level)

3.4.1. Data Sources from Digital Engineering Delivery

Tier 3 represents the highest-precision accounting tier, which invokes all assets of the four-tier digital delivery system. The G4/A4 high-precision 3D models, full-depth

A3 + A4 attribute libraries, hourly dynamic SCADA data, Leak Detection and Repair (LDAR) maintenance documents, and OGMP 2.0 equipment-specific emission factor libraries collaboratively supply exclusive parameters for individual equipment units. This framework covers six categories of critical facilities: reciprocating compressors, centrifugal compressors, triethylene glycol (TEG) dehydration units, unstable condensate storage tanks, process heaters, and general leak-prone equipment.

- (1) Static geometric parameters delivered by G4/A4 high-precision 3D digital models: Compressors: cylinder quantity, total number of sealing points, total unit count; Dehydration units: equipment quantity, vessel volume, total volume of regeneration circulation pipelines; Unstable condensate tanks: effective tank volume, annual throughput of produced water and condensate; Process heaters: rated fuel consumption, furnace chamber volume; Site-wide leak-prone equipment: number of sealing points for each valve, flange and instrument, as well as 3D spatial coordinate positioning.
- (2) A3 technical parameter layer of standardized attribute library: Index via unique equipment tag of each unit, equipment model, design throughput, long-term design load, volumetric CH₄ concentration of process medium, sealing structure type, factory-rated emission factor of equipment, and equipment operation scenario classification (well site/gas gathering station/central processing plant).
- (3) A4 management layer of standardized attribute library (dynamic correction parameters): Equipment commissioning year, sealing aging correction coefficient, annual field-measured leakage correction factor from LDAR inspections, standby correction factor, and seasonal gas composition correction parameters.
- (4) Operational parameters delivered by real-time SCADA database: Annual actual operating hours and standby hours of single equipment, real-time equipment load rate, and actual natural gas throughput.
- (5) Parameters delivered by full-life-cycle document library: Tier 3 quantified field-measured emission factors specified by OGMP 2.0, single-unit LDAR inspection ledgers, equipment modification and change records, and monthly gas composition analysis reports. Clarification on temporal resolution of input parameters: The term “hourly dynamic emission quantification” refers to the temporal resolution of the activity data (equipment operating hours, load rates, throughput) that are updated in real time via SCADA interfaces. The CH₄ concentration parameter, which varies seasonally within a narrow range of $\pm 2\%$ (91.0–93.5%), is updated monthly based on gas chromatography analysis reports. We acknowledge that true continuous composition monitoring (e.g., online gas chromatography) would further improve temporal precision; however, given the narrow seasonal variation band of CH₄ concentration ($\pm 2\%$), the use of monthly-updated composition data introduces a negligible error contribution to hourly emission estimates, as confirmed by the sensitivity analysis in Section 3.6, which ranks gas composition as the fourth most influential parameter (after emission factors, operating hours, and GWP). In the current deployment at Gas Field A, online gas chromatography is not available at all station types; therefore, the framework is designed to accommodate the best available data frequency at each station, with monthly composition updates representing the current practical limit. Future deployment with continuous composition monitoring would enable true real-time composition-adjusted hourly quantification.

3.4.2. Data Circulation Workflow

- (1) Retrieve geometric parameters from 3D models and A3/A4 equipment attributes through unified indexing by exclusive equipment tags under the One-Code Integration framework;

- (2) Synchronize hourly runtime and actual load data of individual equipment via SCADA interfaces;
- (3) Automatically match aging correction coefficients and medium CH₄ concentrations from LDAR maintenance documents and gas composition reports;
- (4) Substitute parameters into OGMP 2.0 dedicated calculation formulas separately by equipment category: compressors, dehydration units, storage tanks, process heaters, and leak-prone facilities;
- (5) Convert CH₄ emissions of every single unit into CO₂-equivalent, aggregate emissions across all equipment, and deduct emission reductions from equipment-level waste gas recovery;
- (6) Render high-emission equipment via 3D spatial visualization and output ledgers detailing the emission proportion of each individual unit.

3.4.3. Core Calculation Formulas by Equipment Category

It should be emphasized that the core calculation formulas (Equations (11)–(14)) follow the established activity-data × emission-factor paradigm, consistent with IPCC Tier 3 and OGMP 2.0 Level 3–4 protocols. The advancement of this framework over standard protocols lies not in the mathematical form of individual equations, but in: (1) the automated data pipeline that feeds these equations with real-time, equipment-specific parameters extracted from digital delivery assets, eliminating manual data aggregation; (2) the local calibration of emission factors using field LDAR measurements (386 sealing points), which replaces generic literature values with site-specific, statistically validated factors; and (3) the dynamic correction mechanism that adjusts emission factors based on equipment aging, standby status, and seasonal gas composition variations. These three aspects collectively elevate the practical accuracy and temporal resolution of Tier 3 accounting beyond what is achievable with standard protocols alone.

- (1) Fugitive methane equivalent emissions from centrifugal compressor seals

$$E_{c,c} = \sum_{i=1}^n (h_i + EF_i \times V_h) \times GWP_H \quad (11)$$

where:

$E_{c,c}$ —total annual fugitive methane equivalent emissions converted from centrifugal compressor, tCO₂e;

n —total number of centrifugal compressors at the station;

h_i —actual annual operating hours of the i -th compressor, h;

EF_i —sealing methane emission factor of the i -th compressor, m³/h;

V_h —volumetric CH₄ concentration of natural gas medium passing through compressors.

- (2) Scenario-based fugitive methane equivalent emissions from reciprocating compressors

$$E_{r,c} = \sum_{i=1}^n \sum_j EF_i \times C_i \times con_j \times (t_{i,j0} + t_{i,jS} \times f_s) \times GWP_H \quad (12)$$

where:

$E_{r,c}$ —total annual fugitive methane equivalent emissions converted from reciprocating compressor, tCO₂e;

i —serial number of reciprocating compressor units;

j —serial number of equipment operation scenarios (well site/gas gathering station/central processing plant, etc.);

$EF_{i,j}$ —single-cylinder methane emission factor of the i -th compressor under scenario j , m³/h;

- C_i —cylinder quantity of the i -th compressor;
 con_j —volumetric CH_4 concentration of natural gas under scenario j ;
 $t_{i,j0}$ —annual normal operating hours of the equipment under scenario j , h;
 $t_{i,jS}$ —annual standby shutdown hours of the equipment under scenario j , h;
 f_s —leakage correction coefficient for compressors under standby status.
 (3) Total methane equivalent emissions from TEG dehydration units

$$E_{de} = \sum_i T_i \times EF_i \times GWP_H \quad (13)$$

where:

- E_{de} —total methane equivalent emissions from all TEG dehydration units, tCO₂e;
 T_i —annual natural gas throughput of the i -th dehydration unit, 10⁴ m³;
 EF_i —methane emission factor of the dehydration unit under corresponding working conditions, m³/10⁴ m³.

(4) Volatilization methane equivalent emissions from unstable condensate and produced water storage tanks

$$E_u = \left(\sum_k Q_k \times EF_k + \sum_l Q_l \times EF_l \right) \times GWP_H \quad (14)$$

where:

- E_u —total methane volatilization equivalent emissions from all storage tanks on site, tCO₂e;
 k —serial number of condensate tanks;
 Q_k —annual medium throughput of the k -th condensate tank, m³;
 EF_k —methane emission factor of condensate tanks, kgCH₄/m³;
 l —serial number of produced water tanks;
 Q_l —annual medium throughput of the l -th produced water tank, 10³ m³;
 EF_l —methane emission factor of produced water tanks, kgCH₄/m³.

Unless otherwise noted, throughput is expressed in 10⁴ m³, methane volumetric fraction is dimensionless, and CO₂e is obtained by multiplying CH₄ mass by GWP.

3.4.4. Case Calculation

By embedding Tier 3 equipment-level refined algorithms into the Tier 2 process framework, with emission factors derived from the OGMP 2.0 Tier 3 quantification specifications and fuel parameters referenced to the CNPC Greenhouse Gas Accounting Guidelines [4,7], the detailed Tier 3 equipment-level accounting results are presented in Table 3, while the pie chart (Figure 3) and the equipment emission comparison bar chart (Figure 4) visually illustrate the contributions of different facility types.

Table 3. Calculation Results of Equipment-Level Greenhouse Gas Emissions.

Equipment Type	CO ₂ Emissions (t)	CH ₄ Emissions (t)	Total CO ₂ e (t)
Reciprocating Compressors	278,610	17	279,035
TEG Dehydration Facilities	0	281	7025
Unstable Condensate Tanks	0	34	850
Heating Equipment	218,530	42	219,580
General Leak-Prone Equipment	0	1476	36,900
Total Aggregate	497,140	1850	543,390

Note: Centrifugal compressors were included in the Tier 3 accounting framework and evaluated using Equation (11); in Table 3, their emissions are aggregated with other compressor-related contributions for concise presentation rather than omitted from the accounting boundary.

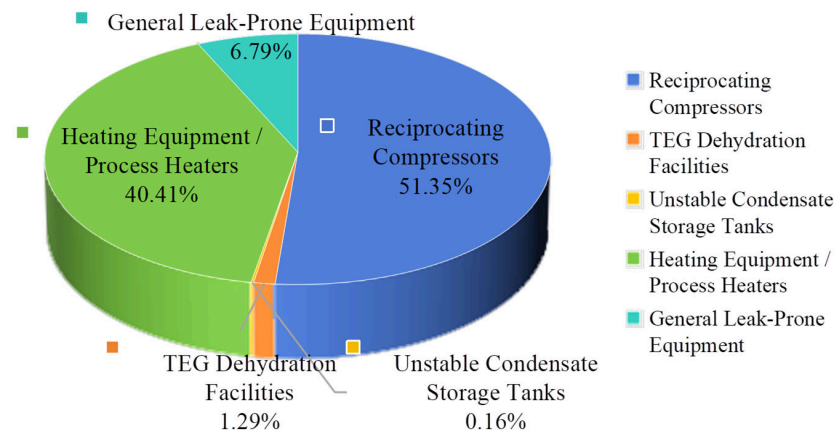


Figure 3. Pie Chart of CO₂e Emission Proportions for Various Equipment Types.

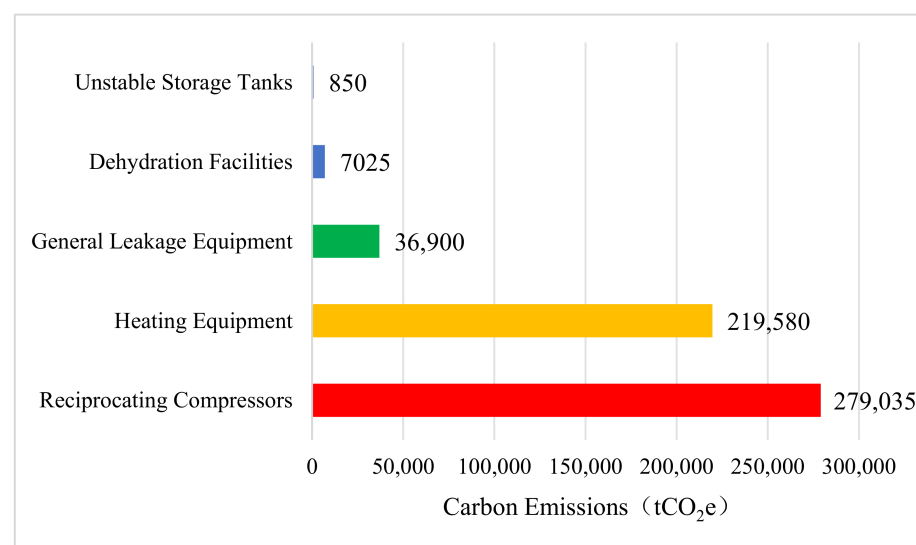


Figure 4. Comparison of Tier 3 equipment-level emissions in Gas Field A.

The results show that the total GHG emission equivalent from field station equipment in Gas Field A amounts to 543,390 tCO₂e, which is the major emission segment identified by the Tier 2 process-level accounting. Within this equipment-level breakdown, reciprocating compressors and heating equipment together contribute 91.76% of the station equipment emissions, confirming them as the primary targets for mitigation. In terms of emission magnitude and share, reciprocating compressors contribute the highest emissions, at 279,035 tCO₂e (51.35% of total equipment emissions), followed by heating equipment at 219,580 tCO₂e (40.41%). Together, these two equipment categories account for 91.76% of the equipment-related CO₂e emissions. Their emissions are predominantly CO₂ from fuel combustion, with negligible methane fugitive releases, making them the primary mitigation targets within the station. General leakage equipment emits 36,900 tCO₂e (6.79%), all of which originate from methane leakage without any CO₂ contribution, thus representing a key focus for fugitive emission management. Dehydration equipment and unstable storage tanks show significantly lower emissions, at only 7025 tCO₂e and 850 tCO₂e, corresponding to 1.29% and 0.16%, respectively, with negligible impact on the overall carbon footprint. Overall, equipment-related carbon emissions at the field station exhibit a highly concentrated pattern, with combustion-driven dynamic equipment (compressors and heaters) being the dominant sources. At the same time, the methane fugitive reduction potential from general leakage components such as valves and fittings should not be overlooked. Future mitigation strategies may target optimized fuel consumption of these units along-

side leak detection and repair (LDAR) programs to achieve effective decarbonization at the equipment level. Tier 2 and Tier 3 should not be interpreted as directly equivalent full-system totals. Tier 2 covers the complete process-level system boundary, whereas Tier 3 in this study focuses on key station-level equipment subsets for high-resolution hotspot identification. Consequently, the Tier 3 total is lower than the Tier 2 total because dispersed long-distance pipelines, auxiliary facilities, and other non-core sources are outside the current Tier 3 accounting subset.

3.4.5. Method Positioning and Applicable Boundaries

Tier 3 equipment-level high-precision accounting represents the highest accuracy tier within the accounting framework proposed in this study. Its core characteristic lies in treating each individual piece of equipment as an independent accounting unit. The framework retrieves 3D geometric parameters, full-depth A3/A4 attribute fields, hourly SCADA operational data, on-site LDAR inspection ledgers, and OGMP 2.0 equipment-specific emission factors for every single facility to implement refined equipment-by-equipment emission calculations. This method serves as an equipment-level accounting and management tool tailored for precise emission reduction decision-making.

Full deployment of Tier 3 imposes rigorous preconditions on underlying digital assets. It requires comprehensive digital delivery deliverables including G4/A4 precision 3D models, an hourly dynamic SCADA operational database, digitized LDAR inspection ledgers, and the Tier 3 quantified emission factor library specified by OGMP 2.0. Accordingly, this methodology is more applicable to regional central stations or key high-emission stations with complete digital delivery construction and well-established data acquisition systems.

3.4.6. Tier 3 Accuracy Validation Methodology

- (1) Validation design and dataset separation. To ensure the reliability of Tier-3 equipment-level refined accounting results, systematic field-based validation was performed at Gas Field A. Note that absolute ground-truth total-site GHG emission cannot be directly measured; independent field-measured benchmarks at individual-point/equipment-level are adopted for validation. The 386 sealing points were selected using stratified random sampling from the full inventory of 3842 leak-prone components, stratified by equipment type (process valves, flange connections, instrument connectors, compressor shaft seals), station type (gathering/compression/dehydration), and service age (0–5 years, 5–10 years, >10 years). The sample size of 386 was determined using Cochran's formula for infinite populations with a 95% confidence level and 5% margin of error, which yields a minimum required sample of 384; we rounded up to 386 to ensure balanced representation across all strata. The validation dataset was strictly separated from the calibration dataset: of the 386 measured sealing points, 242 were used for emission-factor calibration, while 144 sealing points and 12 fuel-burning units were reserved exclusively for independent validation and were not used for factor fitting. The 144 validation sealing points represent a hold-out proportion of 37.3%, which exceeds the conventional 20–30% hold-out ratio recommended in statistical learning practice, further ensuring the independence of validation results.
- (2) Statistical representativeness verification. Representativeness of the 386-point sample against the full 3842-component population was verified using a two-sample Kolmogorov-Smirnov (KS) test on equipment-type distribution, which yielded $p > 0.05$, confirming that the sample distribution is statistically indistinguishable from the population distribution. Bootstrap resampling (10,000 iterations) was applied to compute 95% confidence intervals for the locally calibrated scaling factors (see Appendix C for details).

- (3) Field measurement protocols. Field LDAR measurements were conducted following EPA Method 21 protocols using a portable CH₄ analyzer (measurement range 0–100 vol%, limit of detection 0.1 ppm, reading uncertainty $\pm 5\%$) equipped with a high-flow sampling hood. Measurements were taken under steady-state operating conditions; transient operations (startup, shutdown, pressure swing) were avoided. Ambient temperature, pressure, and humidity were recorded for each measurement point. Each sealing point was measured three times, and the median value was adopted to minimize random instrument error.
- (4) Emission factor calibration procedure. OGMP 2.0 baseline emission factors were locally calibrated using the 242-point calibration subset. For each equipment category k , a scaling factor SF_k was computed as the ratio of the mean measured emission rate to the mean OGMP 2.0 baseline emission rate. The locally calibrated emission factor was then obtained as $EF_{local,k} = EF_{OGMP,k} \times SF_k$. Bootstrap resampling (10,000 iterations) was used to derive 95% confidence intervals for all scaling factors. The calibrated factors, along with their uncertainty ranges, are reported in Appendix C.
- (5) Clarification of $\pm 3.5\%$ validation error vs. input uncertainty. We emphasize that the $\pm 3.5\%$ figure represents the relative deviation between modeled and reference values for independent validation samples (i.e., model validation error), not the propagated uncertainty of all input parameters. These are two distinct concepts: validation error measures how well the model reproduces independent field observations, while input uncertainty reflects the range of possible values for individual parameters. To quantify the cumulative effect of input uncertainties, a rigorous Monte Carlo uncertainty propagation analysis (10,000 iterations) was performed, yielding 95% confidence intervals of $52.1\text{--}56.7 \times 10^4$ tCO₂e for the Tier 3 subset (see Section 3.6 and Appendix D for full details). The Monte Carlo results demonstrate that even when all uncertain inputs vary simultaneously within their specified ranges, the total emission estimate remains within a well-bounded confidence interval.
- (6) Treatment of seasonal and operational variability. Seasonal gas composition variation (CH₄ $\pm 2\%$) and equipment load fluctuation ($\pm 5\text{--}10\%$) are explicitly accounted for in the Tier 3 model through: (i) monthly gas composition analysis reports that update the CH₄ concentration parameter; (ii) seasonal gas composition correction coefficients applied to emission factors; and (iii) real-time SCADA load data that feeds into the hourly dynamic quantification module. The $\pm 3.5\%$ validation error was achieved under the condition that these dynamic correction mechanisms are active; without them, the error would be substantially larger (see Appendix B for full details).
- (7) Sensitivity analysis of mitigation estimates. A global sensitivity analysis via Standardized Regression Coefficients (SRC) was performed to assess the robustness of mitigation estimates under operational variability. The results (Section 3.6, Appendix D) identify emission factors, equipment operating hours, and methane GWP as the three most influential parameters. For the mitigation scenarios, we conducted additional sensitivity checks by varying the assumed reduction percentages (15%, 30%, 20%) within ± 5 percentage points; the resulting total mitigation potential ranges from 8.7×10^4 to 10.9×10^4 tCO₂e, confirming that the ranking of mitigation measures (waste heat recovery > compressor energy saving > enhanced LDAR) remains unchanged across the sensitivity range.

3.5. Multi-Dimensional Comparison of the Three-Tier Accounting Framework

The disparities among the three tiers of accounting methodologies are compared across seven dimensions: data dependency, digital asset requirements, accounting error, computation duration, spatial resolution, decision support capacity, and applicable project

stages. A multi-dimensional performance comparison table is provided in Table 4, while the corresponding radar chart of multi-dimensional performance indicators is illustrated in Figure 5. Higher completeness of digital assets corresponds to improved accounting accuracy and finer management granularity. Table 5 presents a comparative summary of the present study and representative previous studies.

Table 4. Multi-Dimensional Performance Comparison of the Three-Tier Progressive Accounting System.

Comparison Dimension	Tier 1 Macroscopic Statistical Emission Intensity Method	Tier 2 Process Decomposition Emission Factor Method	Tier 3 Equipment-Level High-Precision Accounting
Data Dependency	System-level multi-year energy consumption and production ledgers	Process-level total equipment inventory, fuel consumption, generic emission factors	Individual equipment geometric parameters, real-time operational data, sealing configurations, equipment-specific field-measured emission factors
Required Digital Delivery Support	A1 identification attribute library, historical document library, SCADA production interface	Intelligent P&ID database, A3 technical parameter library, valve & pipeline coding library	G4/A4 precision 3D models, full-depth A3 + A4 attribute libraries, drawing-model consistency verification, hourly dynamic SCADA data [19]
Accounting Accuracy	$\pm 16\% \sim \pm 32\%$	$\pm 6\% \sim \pm 11\%$	Within $\pm 3\%$
Accounting Cycle	1–2 working days	2–3 working days	5 min (fully automatic calculation via system interfaces)
Spatial Resolution	Full plant system scale	Station/process unit scale	Single equipment scale, enabling precise localization of high-emission individual units
Temporal Resolution	Static annual calculation	Annual/quarterly periodic calculation	Hourly dynamic real-time quantification
Support for Emission Reduction Decision-Making	Only rough estimation; incapable of locating emission reduction hotspots	Identification of high-emission units at the process level	Precise quantification of emission reduction potential for single equipment, directly supporting the design of low-carbon retrofitting schemes
Applicable Engineering Stages	Planning stage, pre-assessment during feasibility studies	Routine annual carbon verification, coarse carbon management for production operation	Refined carbon asset management, low-carbon retrofit design

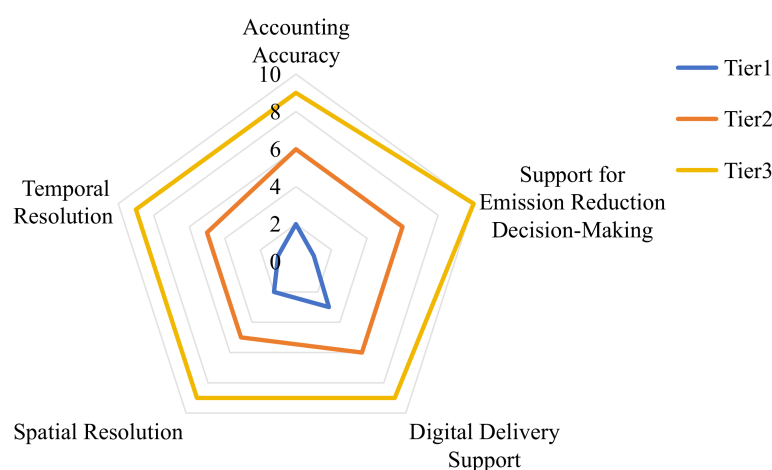


Figure 5. Radar Chart for Multi-Dimensional Performance Comparison of the Three-Tier Progressive Accounting System.

Table 5. Comparative Summary With Representative Previous Studies.

Reference	Accounting Level	Spatiotemporal Resolution	Data Requirements	Accuracy	Automation	Closed-Loop Mitigation	Mapping vs. IPCC/OGMP2.0
Gao et al., 2023 [4]	Process/system	Annual static	Manual inventory, generic EF	$\pm 10\text{--}15\%$	Low	No	Roughly corresponds to IPCC Tier1; OGMP Level1
Feng et al., 2025 [18]	Equipment prototype	Snapshot	Manually imported parameters	Not quantified	Medium	No	-
OGMP2.0 [6]	Five-tier reporting	Periodic report	Diverse manual inputs	Case-dependent	None	No	Original OGMP 2.0 reporting standard
Arshad et al., 2025 [19]	System simulation	Hourly simulation	External dataset	Simulation uncertainty	Medium	Partial simulation	Roughly corresponds to IPCC Tier2; OGMP Level2–3
This work	T1-system; T2-process; T3-equipment	T1: annual; T2: Q/annual; T3: hourly	Native digital-delivery assets + SCADA + LDAR	T1: $\pm 16\text{--}32\%$; T2: $\pm 6\text{--}11\%$; T3: $\leq \pm 3.5\%$	High (unified-code auto-extraction)	Yes	T1: IPCC Tier1/OGMP L1; T2: IPCC Tier2/OGMP L2-3; T3: IPCC Tier3/OGMP L3-4

Note: Our “Tier-1/2/3” progressive accounting nomenclature describes granularity levels driven by digital-delivery assets; it is not identical to IPCC inventory tiers nor OGMP 2.0 reporting levels. The right-most column provides only approximate conceptual mapping for reference purposes, without strict one-to-one equivalence.

3.6. Uncertainty and Sensitivity Summary

Major uncertain inputs include emission factors, methane GWP, flare oxidation efficiency, gas composition, equipment operating hours, conversion coefficients, and LDAR measurements. Monte-Carlo uncertainty propagation (10 000 iterations, see Appendix D) [7,27] yields 95% confidence intervals: Tier1: $82.1\text{--}97.6 \times 10^4$ tCO₂e; Tier2: $90.2\text{--}102.8 \times 10^4$ tCO₂e; Tier3 (subset): $52.1\text{--}56.7 \times 10^4$ tCO₂e. Global sensitivity via standardized regression coefficients indicates emission factors, equipment operating hours, and methane GWP are the three most influential parameters. Gas composition and flare efficiency contribute moderately; the condensate-gas conversion coefficient shows low sensitivity. “The reported Tier 3 validation error should be interpreted as the relative deviation between modeled and reference values for independent validation samples, rather than as the propagated uncertainty of all input parameters. To quantify the influence of uncertain inputs, a Monte Carlo-based uncertainty propagation and sensitivity analysis was performed. The results indicate that emission factors, equipment operating hours, and methane GWP are the most influential parameters, followed by gas composition and flare oxidation efficiency”.

4. Full-Process Precise Carbon Management System Based on Digital Engineering Delivery

The standardized digital delivery data platform not only realizes high-precision automatic tiered carbon emission accounting, but further constructs a complete closed-loop carbon management framework featuring “emission hotspot identification—digital design of low-carbon schemes—synchronous update of digital assets after retrofitting implementation—quantitative evaluation of emission reduction benefits”. All modules operate automatically based on digital assets, addressing industry pain points of traditional station management, including experience-based rough estimation of emission reduc-

tion potential, inability to quantify decarbonization capacity, and lack of traceability for retrofitting effects.

4.1. Automatic Digital Identification of Carbon Emission Hotspots

Based on Tier 3 equipment-by-equipment accounting results, the system automatically sorts all facilities in descending order of CO₂e emissions and categorizes two types of high-emission hotspots: combustion-related sources and fugitive leakage sources. Combustion hotspots include inefficient aging heaters and gas-driven low-efficiency compressors; fugitive hotspots cover valves, instruments, reciprocating compressors, and large triethylene glycol (TEG) dehydration units with long service life and low sealing grades. Meanwhile, spatial rendering via 3D digital twin models delivers a digital visual display, where high-emission equipment is highlighted in red to intuitively present the spatial distribution of station emissions. Users can also export one-click reports containing single-equipment emission proportions and annual cumulative emissions. Calculations from Oilfield A demonstrate that reciprocating compressors and heating equipment jointly contribute about 91.8% of the station equipment emissions, ranking as the highest-priority retrofitting targets for emission reduction.

4.2. Three Categories of Emission Reduction Solutions Supported by Digital Delivery

4.2.1. Energy-Saving Retrofit Management for Compressors

Digital delivery provides compressor-rated efficiency curves, annual load distribution, and raw gas consumption parameters to accurately quantify energy-saving potential for variable frequency transformation and aging unit replacement. Calculations show that retrofitting a single low-efficiency compressor reduces energy consumption by 15%, and synchronous revamp of all station compressors achieves an annual emission reduction of 4.23×10^4 tCO₂e, accounting for 4.39% of total emission cuts. The system also calculates total retrofitting investment, annual gas cost savings, and static payback period to provide data support for corporate investment decisions. Existing research can be referenced for optimization ideas of waste heat coupling recovery of compressors.

4.2.2. Enhanced Leak Detection and Repair (LDAR) Management

G4/A4 high-precision 3D models automatically count the total quantity, equipment type, and service life for all leakage points, including valves, flanges, and instruments across the station, and establish a leakage risk grading model. High-risk points are prioritized for intensified inspections and advance replacement of sealing components. All sealing points are bound to unique equipment tags, and digital ledgers track variations in fugitive methane emissions before and after maintenance. This measure can cut overall fugitive CH₄ emissions by 30%, delivering an annual emission reduction of 1.02×10^4 tCO₂e. Field measurement and simulation methods for LDAR can support quantitative calculation [28].

4.2.3. Optimization Management of Station Waste Heat Recovery

Intelligent P&IDs fully display the topological structure of the whole-site heat exchange process, while digital assets supply waste heat output parameters of heaters and reboilers as well as circulation pipeline specifications to support precise design of waste heat recovery pipeline retrofits, which reduce fuel consumption by 20%. This solution yields an annual emission reduction of 4.49×10^4 tCO₂e, representing the most effective decarbonization technical path among the three retrofitting types [29].

4.3. Estimated Mitigation Benefits of Retrofit Schemes

Upon completion of retrofits, the system automatically runs Tier 3 refined equipment-level accounting to compare carbon emissions of individual facilities and the whole station

under identical production conditions before and after reconstruction, so as to accurately quantify actual emission reduction volumes. It should be noted that the retrofitting projects were at the design and planning stage at the time of this study; therefore, the reported reduction figures are ex-ante estimates of mitigation potential rather than ex-post measured reductions. A waterfall chart illustrating the three types of decarbonization retrofits is shown in Figure 6. The simultaneous implementation of all three schemes is estimated to provide an annual mitigation potential of 9.74×10^4 tCO₂e for the case station, corresponding to an overall emission reduction rate of 10.10%. These values are ex-ante engineering estimates based on assumed retrofit performance and should be verified through post-retrofit Tier 3 accounting. It should be noted that the above reduction figures are engineering estimates based on pre-retrofit baseline emissions and post-retrofit design parameters, representing the theoretical mitigation potential of the three technical pathways. The actual emission reductions will need to be verified through Tier 3 equipment-level accounting after the retrofitting projects are implemented. All reduction estimates are based on the following assumptions: compressor energy-saving retrofits achieve 15% energy consumption reduction, enhanced LDAR achieves 30% fugitive CH₄ reduction, and waste heat recovery achieves 20% fuel consumption reduction. A sensitivity analysis was performed by varying each assumed reduction percentage within ± 5 percentage points. The total annual mitigation potential ranges from 8.7×10^4 to 10.9×10^4 tCO₂e (8.9–11.3% reduction rate), confirming the robustness of the mitigation ranking and the overall decarbonization potential.

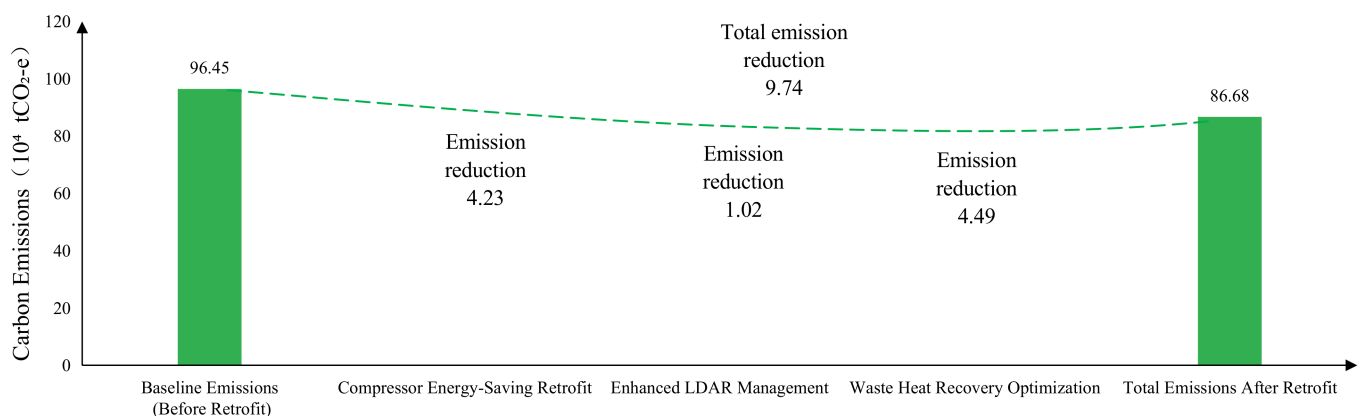


Figure 6. Waterfall Chart of Estimated Mitigation Potentials of Three Types of Retrofit Schemes.

4.4. Long-Term Regular Digital Carbon Management Mechanism

- (1) **Real-Time Dynamic Carbon Monitoring:** Static equipment parameters from digital delivery are linked with hourly real-time SCADA operational data to realize fully automatic dynamic carbon emission calculation, and automatic early warnings are triggered for equipment exceeding emission thresholds [30,31].
- (2) **Closed-Loop Digital Methane Management:** On-site LDAR inspection records are archived in the standardized document library by equipment tag, forming a full-process closed-loop digital ledger covering “leakage point identification-on-site inspection-sealing repair-quantitative emission reduction accounting”, which meets the data retention requirements for methane management under OGMP 2.0 [32].
- (3) **Full-Life-Cycle Carbon Asset Ledger for Single Equipment:** An independent carbon account is established for each facility at the digital engineering delivery stage, covering the whole lifecycle of construction, production & operation, and decommissioning. The account fully records cumulative carbon emissions, historical low-carbon retrofits, and annual LDAR inspection data for each piece of equipment.

- (4) Paperless Digital Support for Carbon Verification: During environmental supervision, third-party carbon audits and international OGMP verification, the full set of design parameters, operational ledgers, and raw data of the entire emission calculation workflow can be retrieved with one click via equipment tags, drastically shortening verification cycles and lowering manual document sorting costs.

5. Conclusions

This paper systematically investigates the tiered carbon accounting and closed-loop carbon management system driven by digital engineering delivery for gas field gathering and transportation facilities. A methodological framework consisting of a four-tier digital delivery data foundation, three-tier progressive carbon accounting system, and full closed-loop emission reduction management is established and verified via engineering applications at Gas Field A. The core conclusions are summarized as follows:

- (1) A standardized digital delivery system dedicated to carbon accounting is developed. By embedding exclusive carbon emission attribute fields into seed files, adopting unified equipment tag coding, and constructing a full-chain data linkage named “One-Code Integration”, automatic correlation and matching of static design parameters, real-time SCADA operational data, and emission factor libraries are realized, fundamentally eliminating data silos. Engineering applications demonstrate that the overall carbon accounting efficiency is improved by 99%, the systematic accounting error is reduced from $\pm 30\%$ to within $\pm 3.5\%$, and the matching rate between process drawings and 3D models reaches 100%.
- (2) A three-tier progressive carbon emission accounting model supported by layered digital assets is constructed. The Tier 1 macroscopic statistical method relies on extrapolation of historical emission intensities and is applicable to preliminary macroscopic emission assessment. The Tier 2 process decomposition method quantifies the emissions of three core processes: 322,000 tCO₂e for gas gathering, 504,300 tCO₂e for compression, and 162,500 tCO₂e for dehydration. The Tier 3 equipment-level high-precision accounting reveals that reciprocating compressors and heating equipment jointly contribute 51.70% of the station-wide total CO₂e emissions, which are identified as the primary targets for emission reduction. The three tiers share a unified underlying data platform, enabling dynamic switching of accounting precision according to the maturity of on-site digital construction, and the Tier 3 module supports hourly dynamic emission quantification.
- (3) A full closed-loop precise carbon management framework covering “emission hotspot identification—retrofitting design—implementation & asset update—emission reduction evaluation” is established. Targeted at high-emission equipment screened via Tier 3 accounting, the quantitative emission reduction potentials of three low-carbon technical routes are calculated: compressor energy-saving retrofits deliver an annual emission reduction of 42,300 tCO₂e, enhanced LDAR implementation achieves an annual cut of 10,200 tCO₂e, and waste heat recovery yields an annual emission reduction of 44,900 tCO₂e. Simultaneous deployment of all three schemes is estimated to provide a total annual mitigation potential of 97,400 tCO₂e at Gas Field A, corresponding to an overall emission reduction rate of 10.10%. In addition, full-life-cycle carbon asset ledgers for individual equipment are formulated to guarantee full traceability, auditability, and reproducibility of all carbon-related data.

Limitations of the current study are acknowledged as follows: Ex-ante mitigation estimates: The emission reduction potentials for the three retrofitting measures (15% energy, 30% fugitive, 20% fuel) are engineering estimates based on manufacturer data, literature benchmarks, and pilot observations. Ex-post validation through Tier 3 accounting after

actual retrofit implementation is still required to confirm these estimates. Scope boundary: The current study covers Scope 1 and Scope 2 emissions only; Scope 3 emissions (including downstream combustion and value-chain emissions) are excluded. Additionally, the Tier 3 accounting subset focuses on key station-level equipment and does not include dispersed long-distance pipelines and certain auxiliary facilities.

This study provides an integrated engineering solution of “standardized data foundation—tiered carbon accounting—practical emission reduction implementation” for precise carbon quantification and closed-loop methane management of onshore natural gas gathering stations. It delivers practical engineering references for the oil and gas industry to fulfill global methane mitigation commitments and the dual carbon goals. From an engineering perspective, phased deployment is suggested: new projects shall embed carbon-related attributes at the design stage, while legacy stations may adopt Tier-1/Tier-2 first before rolling out Tier-3 for key high-emission units. Locally calibrated emission factors are recommended for Tier-3 calculation. Two future research priorities are proposed: local field calibration of OGMP 2.0 equipment-level emission factors for diverse gas blocks, and development of digital-twin-coupled dynamic carbon-emission prediction models.

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Abbreviations

Abbreviation	Full Term
API	American Petroleum Institute
CCUS	Carbon Capture, Utilization and Storage
CFIHOS	Capital Facilities Information Handover Specification
CH ₄	Methane
CI	Confidence Interval
CNPC	China National Petroleum Corporation

CO ₂	Carbon Dioxide
CO ₂ e	Carbon Dioxide Equivalent
DCS	Distributed Control System
DWG	Drawing (AutoCAD2023 file format)
EAM	Enterprise Asset Management
EF	Emission Factor
EPA	Environmental Protection Agency (U.S.)
G4/A4	Geometric Precision Grade 4/Attribute Depth Grade 4
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KS test	Kolmogorov-Smirnov Test
LDAR	Leak Detection and Repair
LOD	Limit of Detection
MC	Monte Carlo
NLP	Natural Language Processing
OCR	Optical Character Recognition
OGMP 2.0	Oil and Gas Methane Partnership 2.0
P\&ID	Piping and Instrumentation Diagram
PBS	Plant Breakdown Structure
ppm	Parts Per Million
Q/SY	Q/SY 01015-2022, CNPC Enterprise Standard for Digital Delivery
RESTful	Representational State Transfer (API architecture)
SCADA	Supervisory Control and Data Acquisition
SRC	Standardized Regression Coefficient
SVG	Scalable Vector Graphics
TEG	Triethylene Glycol
UNEP	United Nations Environment Programme
VFD	Variable Frequency Drive

Appendix A. SM-1. Four-Layer Digital-Delivery Brief Implementation Notes

1. Information flow: Seed-file templates (Layer1) → embedded unified-coding (Layer2) → structured digital deliverables (Layer3) → parsing/API/version-control (Layer4) → feed carbon-accounting module. Plant retrofits trigger backward asset version updates.

2. Interfaces: RESTful JSON-API for SCADA, EAM and carbon-computing platform; supports parameter reading and engineering-change event push notifications.

3. Automation boundary:

Fully-auto: tag validation, drawing-model matching, parameter extraction, Tier1-Tier3 calculation.

Manual assistance: OCR correction for old scanned documents; manual field LDAR data collection before database import.

4. Version control: Each P&ID/3D-model/attribute-database modification increments version number and binds to equipment unique tag for audit traceability.

Appendix B. SM-2. Tier-3 Validation Error Calculation

Metric definitions for independent validation samples (N = 156; 144 sealing points + 12 fuel-burning units; calibration samples excluded):

$$\text{Relative error}_i = (\text{Calculated}_i - \text{Reference}_i) / \text{Reference}_i \times 100\%$$

$$\text{Max absolute relative deviation} = \max(|\text{Relative error}_i|)$$

$$\text{Mean absolute relative deviation} = (1/N) \sum_{i=1}^N |\text{Relative error}_i|$$

Reference sources:

Fugitive methane: portable-analyser high-flow-sampling (EPA Method 21).

Combustion CO₂: DCS metered fuel-gas consumption records.

Appendix C. SM-3. LDAR-Based Emission-Factor Local Calibration Summary

1. Sampling: Stratified-random sampling by equipment type, station type and service age. Total 386 sealing-points: 242 for calibration, 144 held-out for validation.

Table A1. Measured-point distribution.

Equipment Category	Count	Proportion
Process valves	172	44.6%
Flange connections	116	30.1%
Instrument connectors	62	16.1%
Compressor shaft seals	36	9.3%
Total	386	100%

2. Instrument: Portable CH₄ analyser (0–100 vol%, LOD 0.1 ppm, reading uncertainty $\pm 5\%$); high-flow sampling hood following EPA Method 21. Measurements taken under steady-state operation; transients avoided.

3. Calibration formula:

$$\text{SF}_k = \text{Mean_measured},k / \text{Mean_OGMP-baseline},k; \text{EF_local},k = \text{EF_OGMP},k \times \text{SF}_k$$

Bootstrap resampling (10 000 iterations) gives 95% CI for scaling factors.

Representativeness: Two-sample KS-test comparing sample vs. full-site 3842 leak-components population, $p > 0.05$. * Caveat: rare heavily-retrofitted legacy components are under-sampled.

Appendix D. SM-4. Uncertainty-Sensitivity: Monte-Carlo Setup & Sensitivity Workflow

Table A2. Key uncertain input parameters.

Parameter	Distribution	Range
Emission factors	Triangular	± 15 –30%
Methane GWP	Uniform	24–26 (baseline 25)
Flare oxidation efficiency	Triangular	95–99% (baseline 98%)
CH ₄ mole fraction	Normal	mean 92.3%, σ 0.6%
Equipment operating hours	Triangular	$\pm 10\%$
Condensate-gas conversion factor	Uniform	0.1200–0.1310
LDAR fugitive estimates	Triangular	$\pm 12\%$

Monte-Carlo simulation is performed with 10 000 random sampling iterations.

Global sensitivity analysis is implemented via the Standardised Regression Coefficient (SRC) approach.

Sensitivity ranking (from highest to lowest impact on total-emission outputs):

1. Emission factors; 2. Equipment operating hours; 3. Methane GWP; 4. Gas composition; 5. Flare efficiency; 6. Condensate-gas conversion coefficient.

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