ADVANCING SUPPLY CHAIN SUSTAINABILITY: CO2 ACCOUNTING IN TANK TERMINAL STORAGES

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Abstract - As the oil, gas, and chemical industries pursue sustainability, independent terminal operators are key to enhancing supply chain transparency by tracking product lifecycles. Terminal management systems (TMS) provide essential operational data that, when integrated with external platforms, support comprehensive CO_2 accounting across Scopes 1, 2, and 3. While TMS solutions do not directly capture emissions of any kind, they are the starting point of critical insights: Scope 1 emissions can be monitored using external energy management tools; Scope 2 emissions can be calculated by integrating TMS data with utility monitoring systems; and Scope 3 emissions can be estimated through detailed tracking of product movements and logistics. Integrating TMS data with CO_2 accounting platforms enables operators to optimize operations, reduce emissions, and drive the transition toward sustainable energy and chemical production.

Index Terms — Sustainability, Terminal Management Systems (TMS), CO2 Accounting, Emissions Tracking, ESG Data Readiness, Supply Chain Transparency.

I. INTRODUCTION

As regulatory bodies and industries transition toward more stringent environmental policies, independent terminal storage operators face growing pressure to enhance the transparency of carbon emissions. The supply chain is increasingly driven by sustainability metrics, with corporate reporting frameworks such as the Corporate Sustainability Reporting Directive (CSRD) and the Greenhouse Gas (GHG) Protocol mandating precise emissions accounting. However, most terminal operations still rely on fragmented data sources, making it difficult to achieve a comprehensive and verifiable carbon footprint assessment, which shall be used in the further supply chain processes.

Terminals serve as key infrastructure hubs for the movement, storage, and blending of hydrocarbons and chemicals, making them a focal point for emissions tracking. However, traditional terminal management systems are designed primarily for logistics and inventory management rather than sustainability reporting. This results in a lack of real-time visibility into emissions data and limits the ability of operators to optimize their sustainability performance.

This paper outlines a structured approach to integrating advanced emissions tracking capabilities into terminal operations. By enhancing existing management systems with real-time carbon footprint monitoring, secure data verification, predictive analytics, and cross-functional environmental, social and governance (ESG) data practices, terminals can move beyond simple inventory control toward active sustainability management. The implementation of automated data collection, secure emissions reporting, and a certification framework will enable terminals to comply with new regulatory requirements while providing transparent emissions data to industry stakeholders.

II. INNOVATIONS FOR CARBON FOOTPRINT TRANSPARENCY IN TERMINAL OPERATIONS

The primary limitation of current terminal management systems is their lack of direct integration with emissions monitoring tools. While these platforms capture operational data related to hydrocarbon movements, storage conditions, and equipment usage, they do not automatically translate this information into precise emissions calculations. To enhance carbon footprint transparency, terminals need a methodology that combines real-time monitoring, digital tracking, and automated verification across all relevant data streams. Bridging this gap requires deploying IoT sensors and an integrated data architecture that links the TMS with energy meters, sensors, and other monitoring systems into a unified emissions data platform.

One of the most effective approaches to achieving this is the implementation of a digital methodology that links hydrocarbon transactions with emissions reduction data. This system assigns a unique sustainability record to every hydrocarbon movement, ensuring that emissions data is captured at the point of transfer rather than being estimated based on annual averages. By embedding emissions tracking into each transaction, terminals can provide immediate and accurate information to logistics providers, hydrocarbon retailers, and regulators. This transaction-level tracking eliminates reliance on outdated or overly broad emissions factors and allows for real-time, granular sustainability assessments.

A complementary innovation is the use of secure digital certification to verify sustainability claims. One key challenge in emissions reporting is the risk of inaccurate or double-counted claims regarding emissions reductions. To address this, a secure certification system (for example, using an immutable digital ledger) ensures that each hydrocarbon batch is paired with a verifiable emissions record that cannot be altered or duplicated. Every transaction is recorded in a tamper-proof way and can be audited by third parties, preventing misreporting and enhancing trust among industry participants. Automating this verification process adds transparency and credibility

to terminal emissions data, which is especially valuable for compliance with regulations and for participation in carbon credit programs. Artificial intelligence also plays a significant role in improving sustainability performance within terminal operations. By analyzing operational data in real time, AI algorithms can identify patterns of excessive energy consumption or emissions and recommend adjustments to minimize these outputs without disrupting throughput. For instance, AI-driven analysis might detect suboptimal equipment performance (such as a pump using unusually high power) and alert operators to perform maintenance or adjust settings. In advanced implementations, automation can act on these insights—dynamically optimizing pump speeds or heating levels to curb emissions. In addition, user-friendly real-time dashboards can aggregate these data and insights, giving operators and managers continuous visibility of key sustainability indicators. This combination of AI-driven analytics and live dashboards enables terminal staff to make data-informed decisions on the fly, ensuring that emissions reduction opportunities are acted upon swiftly and that progress is visible to all stakeholders in the organization.

III. CARBON EMISSIONS ACCOUNTING IN TERMINAL OPERATIONS

A comprehensive carbon footprint assessment for a terminal must account for Scope 1, Scope 2, and Scope 3 emissions, which encompass direct emissions, indirect (purchased energy) emissions, and value-chain emissions respectively. Each category requires different data and integration methods:

- Scope 1 (Direct Emissions): These originate from on-site fuel combustion and processes at the terminal (e.g. emissions from diesel generators, boilers, or vapor handling equipment). Such emissions can be precisely monitored by installing sensors and fuel-use monitors on terminal equipment and integrating this data directly into the TMS or an energy management system. Real-time tracking of fuel and energy consumption provides immediate visibility into Scope 1 emissions. Additionally, transitioning to low-carbon energy sources for onsite operations—such as using electrified equipment or hydrogen fuel in place of diesel—can directly reduce Scope 1 emissions over time.
- Scope 2 (Indirect Emissions from Energy): These result from the consumption of purchased electricity or heat used to power terminal operations (for example, running pumps, lighting storage facilities, or heating product). To accurately account for Scope 2 emissions, terminal operators can integrate an energy management system with the TMS. This integration enables real-time tracking of electricity usage and applies the appropriate emissions factors for the local grid or energy source. With an automated link between power meters and the sustainability reporting platform, terminals can continuously calculate their carbon emissions from electricity and identify opportunities to conserve energy (such as peak load management or switching to renewable electricity sources).
- Scope 3 (Value-Chain Emissions): These cover the broader supply chain impacts of the hydrocarbons passing through the terminal, including emissions from upstream production, downstream combustion, and, importantly for terminal operators, transportation of products to and from the facility. Scope 3 represents the most complex and significant category of emissions for a terminal. Traditionally, estimating transport-related emissions relied on generic assumptions (average distances, standard emission factors for transport modes, etc.), which can be highly inaccurate. To address this, terminals should implement a digital emissions tracking system for logistics: every truck, ship, or rail movement linked to the terminal is recorded along with key parameters such as traveled distance, vehicle fuel efficiency, and fuel type. By capturing the CO_2 impact of each individual shipment in this manner, operators gain a detailed and accurate picture of transportation emissions. This level of precision ensures that any emissions reductions (for instance, from using more efficient vehicles or optimizing routes) are properly documented. It also prevents misreporting in sustainability audits, since the data is based on actual trip measurements rather than broad averages.

IV. IMPLEMENTATION OF A DIGITAL EMISSIONS TRACKING SYSTEM IN TERMINALS

Implementing a robust emissions tracking system in terminal operations requires a structured methodology that integrates real-time data collection, automated reporting, and secure verification of information. In practice, this means assigning a digital sustainability record to every relevant operational transaction, ensuring that emissions are tracked with accuracy and consistency from the moment they occur. By establishing a direct link between operational data and emissions calculations, terminal operators can offer stakeholders a transparent view of their carbon footprint on an ongoing basis. One of the main advantages of this real-time, integrated approach is the elimination of heavy reliance on estimated emissions factors. Instead of using industry averages or periodic manual calculations, the system captures emissions data at the source (for example, recording the exact amount of fuel consumed during a product transfer and immediately calculating the resulting CO_2). Terminal operators can thus provide precise, up-to-date carbon footprint assessments that align closely with actual operational performance. This is particularly valuable for companies required to comply with ESG reporting standards, as it allows sustainability data to feed directly into corporate reports without extensive manual data massaging. In effect, emissions accounting becomes a seamless byproduct of daily operations rather than a separate, retrospective exercise. Additionally, integrating a secure data verification mechanism within the tracking system ensures that all sustainability claims are backed by trustworthy data. By

using a digital ledger or similar technology to log emissions-related transactions, each batch of product handled at the terminal carries a permanent, auditable sustainability record. This approach prevents double-counting emissions reductions (for instance, if multiple parties claim credit for the same biofuel-related savings) and greatly enhances the credibility of the terminal's sustainability reporting. Such secure data management not only simplifies external audits but also builds confidence with business partners and regulators that the terminal's reported improvements are genuine and traceable. For terminal operators beginning this digital transformation, success will involve progressing through stages of improved ESG data readiness: first establishing comprehensive data gathering and integration capabilities, then developing data insights through analysis and visualization of that information and finally translating those insights into data-driven action and process changes. In the next sections, we outline a roadmap that follows these stages—connecting technology implementation with organizational readiness—to drive sustainable terminal operations.

V. ROADMAP FOR SUSTAINABLE TERMINALS

Achieving sustainable terminal operations is a journey that must align with evolving regulations, technological capabilities, and organizational change. The roadmap below highlights regulatory drivers, phased technology adoption, data readiness stages, and key practices to guide terminal operators toward sustainability excellence.

A. Understanding the Regulatory Landscape Governing Carbon Transparency in Terminals

Multiple external drivers are compelling terminals to enhance carbon transparency and reduce emissions. Key pressures include:

- Global climate policies: International agreements and climate targets (such as the Paris Agreement and EU Green Deal) set aggressive goals for greenhouse gas reduction, cascading requirements down to the industrial level.
- Regional legislative frameworks: Government directives and regulations are mandating detailed emissions reporting and improvements (for example, CSRD in the EU or state-level Low Carbon Fuel Standards in the U.S.).
- Investor and customer demand: Investors, business partners, and consumers are increasingly favoring companies with strong Environmental, Social, and Governance (ESG) performance, making sustainability a business imperative.

In Europe, regulatory initiatives are rapidly evolving to enforce stricter carbon reporting and reduction measures. The European Green Deal has established ambitious climate targets (aiming for a 55% reduction in GHG emissions by 2030 and net-zero by 2050), spurring a suite of regulations. The Corporate Sustainability Reporting Directive (CSRD) now mandates detailed sustainability disclosures from large and medium-sized companies, including fuel and chemical terminal operators. Under CSRD, organizations must report Scope 1, 2, and 3 emissions with a high level of detail and assurance, covering their entire value chain. By 2028, thousands of companies across Europe will be required to provide audited carbon data, meaning terminals that feed into those supply chains must be prepared to supply accurate emissions information. In parallel, the Renewable Energy Directive (RED II and III) imposes sustainability criteria for biofuels and other renewable energy carriers. Fuel producers and terminals handling these products must implement Proof of Sustainability (PoS) systems to verify the origin and lifecycle emissions of renewable fuels, ensuring compliance with mandated GHG reduction thresholds. Another major policy mechanism is the expansion of the EU Emissions Trading System (EU ETS). While independent terminals historically were not direct participants in carbon trading, the scope of ETS is extending: Starting in 2027, fuel distributors (including logistics emissions from terminal operations) will fall under ETS carbon pricing. This means carbon emissions associated with moving product through terminals could carry direct costs, increasing the financial incentive to accurately track and reduce those emissions. In the United States, federal and state regulations are also driving change. The Environmental Protection Agency's GHG Reporting Program (GHGRP) requires annual reporting of emissions for fuel storage and distribution facilities above certain thresholds. On the state level, programs like California's Low Carbon Fuel Standard (LCFS) and similar initiatives in Oregon and Washington enforce a gradual reduction in the carbon intensity of transportation fuels. These standards effectively reward the blending and distribution of lower-carbon fuels and penalize higher-carbon operations, creating economic drivers for terminals to adopt real-time carbon tracking and ensure each gallon of fuel handled meets the required benchmarks. Terminals that can provide verifiable data showing lower lifecycle emissions (for instance, by blending biofuels or using renewable energy on-site) will benefit under these schemes. At a global level, industry-specific standards also shape terminal operations. The International Maritime Organization (IMO) has introduced measures like the FuelEU Maritime initiative (effective 2025) that require tracking and reduction of GHG emissions for fuels used in international shipping. Terminals involved in marine bunkering or fuel export by sea will need systems to report the carbon intensity of those fuels. Additionally, voluntary certification frameworks such as the International Sustainability & Carbon Certification (ISCC) are becoming prerequisites for trading biofuels and sustainable chemicals internationally. Meeting these certifications demands meticulous data on the product's carbon footprint from production through terminal handling to end use. In summary, regulatory compliance is a moving target: terminal operators must be capable of granular emissions accounting and swift reporting to multiple stakeholders. Understanding and anticipating these requirements is the first step in crafting a sustainable terminal strategy.

B. Implementation Timeline for Sustainable Terminal Operations

Given the pace of regulatory and market changes, terminal operators should adopt a phased approach to implement sustainability measures. Below is a timeline

outlining milestones and capabilities that terminals should aim to achieve:

- Near Term (by ~2027): Integrate real-time emissions monitoring into terminal systems. This includes deploying smart meters and sensors on key emission sources (electricity, fuel, venting) and automating CO_2 calculations using direct operational data instead of annual averages. In this phase, terminals should also establish connectivity (e.g. via APIs) with regulatory reporting platforms to streamline compliance submissions under frameworks like CSRD and RED III. Early adoption of digital PoS certification for biofuel or renewable product handling is recommended to meet RED III requirements.
- Mid Term (by ~2030): Achieve full automation of emissions tracking and verification processes. By 2030, terminals should operate integrated, end-to-end ESG data management systems that continuously collect, verify, and store emissions data for all operations. Immutable digital certification (for example, blockchain-based PoS ledgers) should be in place to track carbon savings and attributes for each product batch, preventing any duplicate claims of emissions reduction. With carbon pricing mechanisms expanding, having an auditable record of every ton of CO_2 will be essential for participating in carbon markets or avoiding penalties.
- Long Term (by ~2035): Transition toward carbon-neutral terminal operations in line with broader energy sector decarbonization (for instance, the EU's planned phase-out of most fossil-fuel-powered vehicles by 2035). Terminals at this stage will need to incorporate advanced optimization technologies to minimize any remaining emissions. This could include AI-powered systems for intelligent scheduling of transfers to avoid peak power usage, optimized heating/cooling of stored products to prevent energy waste, and integration of on-site renewable energy generation or energy storage to offset consumption. Terminals should also be actively participating in carbon credit trading or offset programs, monetizing verified emissions reductions (e.g. if the terminal's efficiency improvements yield surplus reductions, or through services like carbon-neutral storage offerings). By 2035, leading terminals will operate as digital, sustainable hubs that not only handle products efficiently but also integrate seamlessly into the low-carbon supply chains of the future.

C. ESG Data Readiness Stages: From Data to Insight to Action

To effectively manage this transformation, terminal operators should evaluate and improve their ESG data readiness. This concept can be broken into three progressive stages, each building the foundation for the following:

1. Data Gathering – building a complete and reliable data foundation. In this initial stage, the focus is on collecting all relevant ESG and emissions data and ensuring its quality and consistency. For a terminal, this means identifying every source of emissions data (TMS records, meter readings, fuel usage logs, bills of lading, etc.) and integrating these into a single system or data platform. It's critical to standardize data formats and definitions (e.g. ensuring all volumes, energy usage, and emissions are recorded in compatible units and timeframes) so that all departments are "speaking the same language" regarding carbon data. At this stage, terminals often benefit from close collaboration between sustainability teams and IT/data teams to map out how data will flow. Early wins can be achieved by focusing on a narrow scope or a few key performance indicators (KPIs) to demonstrate the value of data integration for instance, automating the capture of electricity usage data and immediately seeing improvements in reporting accuracy and time saved. Establishing strong data governance (such as clear procedures for how data is collected, verified, and stored) is also a key outcome of the Data Gathering stage. Every staff member involved in feeding or handling sustainability data should understand the processes and their responsibilities. Cross-departmental engagement is important here: operations, maintenance, finance, and compliance departments all contribute pieces of the carbon puzzle, and a successful data gathering phase ensures input from each and assigns ownership where appropriate.

2. Data Insights – deriving meaningful analysis and reporting. Once data is being amassed and managed properly, the next stage is to convert this raw information into actionable insights. In the Data Insights stage, terminal operators implement analytics and business intelligence tools to process the gathered data. This could involve using software to automatically calculate emissions by source, generate trend lines (e.g. emissions per throughput volume over time), and highlight anomalies or inefficiencies. Real-time dashboards and visualization tools become critical at this stage, as they allow different stakeholders (from site managers to corporate executives) to quickly grasp the terminal's sustainability performance. For example, a dashboard might show current electricity-related CO_2 emissions against a target or rank the emission contributions of different product lines handled at the terminal. Terminal operators should also introduce AI or machine learning solutions here to sift through large datasets and find patterns—such as correlations between certain operational practices and higher emissions— that may not be evident on the surface. Data Insights is not just about internal analysis but also about reporting: the processes for compiling reports for regulators, auditors, or investors are streamlined and ideally automated. Digital controls for data validation are applied to

ensure that the insights and reports are based on accurate data (flagging any out-of-range values or inconsistencies for review). Additionally, this stage involves upskilling staff and stakeholders in interpreting sustainability data. Training programs can help operations teams understand the analytics output so they can make informed decisions on the ground. The organization's culture should also evolve to become more data-driven in its ESG discussions—for instance, sustainability metrics should be discussed in regular operations meetings just as financial metrics are. Overall, the Data Insights stage is reached when a terminal has both the tools and the internal know-how to translate data into knowledge, yielding clear visibility of where and how to improve.

3. Data Action – Integrating insights into decision-making and operations. The final stage is about closing the loop: using the insights gained to drive continuous improvement and strategic action. In this stage, sustainability data and analytics are embedded into the day-to-day and long-term decision processes of the terminal. Operational decisions start to be influenced directly by ESG data—for example, scheduling maintenance for equipment when data shows its efficiency is degrading and causing higher emissions, or dynamically adjusting truck loading times to reduce idling emissions based on real-time yard congestion data. Terminals at the Data Action stage often implement automated controls or alerts that trigger responses; an example would be an alert from the system when daily emissions are on track to exceed a threshold, prompting managers to investigate and intervene immediately. Strategic planning also benefits: scenario analysis tools can be used to examine "what-if" situations (e.g. what if the terminal switches to a different electricity provider or installs solar panels—how would that impact annual emissions and energy cost?). These scenarios, evaluated by cross-functional teams using actual data, help build more resilient long-term strategies. Another aspect of Data Action is performance management: sustainability KPIs are integrated into performance scorecards and reviews at all levels of the organization. Executives and operations leaders review emissions metrics alongside throughput and profitability, ensuring that ESG performance is considered in evaluating success. The company's ESG goals are aligned with its core business objectives, so that achieving emission reduction targets is seen as integral to business success (not just a side project). Culturally, innovation is encouraged; for instance, some organizations host internal hackathons or innovation challenges to crowd-source ideas from employees on reducing emissions or improving data processes, fostering a company-wide engagement in sustainability action. Finally, Data Action includes continuously updating and modernizing the technology stack to meet new demands — ensuring the data platform can handle increasing volumes and types of data (e.g. maybe integrating supply chain partner data or new sensor inputs) and that it remains secure and compliant with data privacy and security standards. In short, by the time an organization reaches the Data Action stage, it is not only responding to sustainability data but proactively managing and improving based on that data, embedding ESG considerations into the fabric of terminal operations.

D. Organizational Best Practices for ESG Integration

Successful CO_2 accounting and sustainability management in terminals is as much about people and processes as it is about technology. The following organizational best practices help ensure that the initiatives described above gain traction and deliver value:

1. Shared ESG Responsibility Across Departments: Rather than siloing sustainability tasks within an HSE (Health, Safety, Environment) or compliance team, leading terminal operators distribute ESG data responsibilities across all relevant departments. Each department—operations, maintenance, logistics, IT, finance, etc.—has clear ownership of the data and improvements related to their function.
2. Upskilling Staff and ESG Literacy: As new tools and processes are introduced, it is crucial to invest in employee training so that staff at all levels are comfortable with ESG data and understand its importance. Training programs might include educating teams on carbon accounting basics, teaching personnel how to use new software dashboards, or even providing data analysis workshops for key managers. By enhancing ESG literacy, companies enable their workforce to actively participate in sustainability efforts—employees on the ground can suggest efficiency improvements when they understand the carbon impact of their activities. An ESG-aware culture also empowers staff to flag data issues or ideas for emission reductions. Some organizations integrate sustainability topics into onboarding and annual training, reinforcing that managing environmental impact is a core competency of the business.
3. Aligning ESG with Business Strategy: Terminals should treat sustainability objectives as a strategic pillar, not just a compliance exercise. This means incorporating ESG targets into the overall business strategy and ensuring top management is directly involved in setting and reviewing these targets. When the C-suite and board consider carbon performance alongside financial and operational performance, it signals to the entire company that ESG is fundamental to long-term success. Business plans and investment decisions should be evaluated in part on their sustainability impact—for instance, when expanding a terminal or adding a new service, the decision-making process should include criteria

for emissions impact or energy efficiency. By aligning ESG goals with business goals (for example, aiming to be the most carbon-efficient terminal operator in a region as part of the company vision), terminals can pursue growth and sustainability hand in hand, rather than in conflict. This alignment also helps in securing funding for sustainability projects, as those projects can be justified in terms of business value (risk reduction, brand reputation, future readiness) in addition to environmental benefit.

4. Embedding ESG Metrics in Operational Reviews: To ensure that sustainability remains a day-to-day priority, terminals should integrate ESG metrics into their regular operational and financial review cycles. For instance, monthly performance meetings might include a review of key sustainability KPIs such as total CO_2 emissions for the month, emission per ton of product handled, energy consumption trends, or progress toward emissions reduction projects. By discussing these alongside traditional metrics (throughput, costs, incidents, etc.), management reinforces that operational excellence now encompasses environmental performance. Many operators have started to include carbon metrics on the same dashboards that show inventory or throughput, making them highly visible. Additionally, linking a portion of performance bonuses or incentives to achieving ESG targets can be a powerful way to drive focus (e.g. if a terminal management team meets its emission reduction or energy saving goal, that success is rewarded similar to how safety or efficiency achievements are rewarded). Embedding these metrics into the business rhythm ensures continuous accountability and also allows for quick response if performance deviates from targets.

VI. CONCLUSION

The transition toward sustainable and transparent terminal operations is no longer optional, but it has become a regulatory necessity and a market expectation. Governments and industry bodies are tightening emissions reporting requirements and attaching costs or penalties to carbon output, making real-time tracking and verification a critical component of compliance and business continuity. By aligning terminal operations with emerging frameworks (such as EU Green Deal objectives, CSRD mandates, RED III standards, and expanding emissions trading systems), operators can ensure long-term viability in a decarbonizing energy supply chain.

Implementing automated carbon footprint monitoring, verifiable digital certification of sustainability data, and AI-driven operational optimizations allows terminals to move beyond mere compliance into a leadership role in sustainable supply chain management. Importantly, this journey demands not only cutting-edge technology but also an organizational culture that prioritizes ESG at every level. The future of the industry will be shaped by those who embrace transparency, accountability, innovation, and a data-driven sustainability culture. Such terminal operators will ensure that their facilities contribute meaningfully to global climate goals while maintaining efficiency and competitiveness in an era of clean energy transition.

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IX. VITA

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