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Review

Regulatory and standard insights on transboundary CO_2 in the context of MRV

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ABSTRACT

As transboundary carbon capture, utilisation, and storage (CCUS) projects gain momentum globally, the need for a coherent, robust, and verifiable system for measurement, reporting, and verification (MRV) of cross-border carbon dioxide (CO_2) flows becomes increasingly critical. This paper reviews and synthesises key regulatory frameworks and technical standards, namely, the EU Emissions Trading System (EU ETS), ISO 27914 and ISO 27915, and the Verra VM0049 methodology, to assess their applicability to MRV across the CO_2 capture, transport, and storage chain. The EU ETS, under its 2024 consolidated Implementing Regulation, sets a high benchmark for uncertainty management and data integrity in CO_2 accounting; however, it lacks specific prescriptions for advanced or smart metering technologies. ISO 27914, while focused on geological storage, provides essential guidance for long-term containment and injection site monitoring, relevant to the final stages of the CCS chain. ISO 27915 provides a comprehensive framework for quantifying and verifying GHG emissions and reductions, establishing a direct link between CO_2 flow measurement and emissions reporting. The Verra VM0049 methodology, although designed for voluntary carbon markets, provides comprehensive procedures for quantifying and monitoring emissions across transport and storage stages, with practical relevance to transboundary CO_2 transfers. While none of these instruments independently address all aspects of cross-border CO_2 movement, their combined insights highlight both foundational strengths and critical gaps, such as the absence of unified custody transfer protocols and limited treatment of fugitive emissions in transitional zones. This paper aims to consolidate these insights to inform future MRV frameworks tailored to the unique technical, regulatory, and jurisdictional challenges of transboundary CO_2 flows.

1. Introduction

The Paris Agreement, along with an increasing number of national and regional commitments to carbon neutrality, underscores the critical importance of deploying carbon mitigation technologies [1-4]. Among these, Carbon Dioxide (CO_2) Capture and Storage (CCS) emerges as a pivotal solution in addressing the global climate challenge. CCS encompasses a suite of technologies designed to capture CO_2 emissions from industrial and energy-related sources, preventing their release into the atmosphere. Once captured, the CO_2 is either transported to a suitable geological formation for long-term storage or, in cases where co-location allows, injected directly into storage reservoirs beneath the capture facility [5]. In addition to storage, captured CO_2 can be utilised in various CO_2-derived products and services, including synthetic fuels, industrial chemicals, mineralised construction materials, and enhanced oil recovery (EOR). These utilisation pathways form the basis of Carbon Capture, Utilisation, and Storage (CCUS), a broader concept that incorporates both storage and the commercial use of captured CO_2 [6, 7]. CCS and CCUS technologies are central to the global effort to limit temperature rise to well below 2°C above pre-industrial levels, in line with the objectives of the Paris Agreement. Recognising their climate mitigation potential, the United Nations Framework Convention on Climate Change (UNFCCC) formally accepted CCS under the Clean Development Mechanism (CDM) of the Kyoto Protocol in 2011 [8]. Looking forward, CCS may also serve a key role in carbon dioxide removal (CDR) strategies, enabling net-negative emissions by capturing CO_2 directly from the atmosphere and storing it securely [6]. Although technical and economic challenges persist, multiple studies have confirmed the feasibility of CCS/CCUS with existing technologies [9]. In the context of ongoing reliance on fossil fuels, particularly coal and natural gas, CCUS provides a critical pathway for mitigating emissions from both energy production and heavy industry [10-12]. Large-scale deployment of CCUS systems necessitates integration with existing energy infrastructure, as capture, compression, transportation, and injection processes all require significant energy inputs [13, 14]. In light of the limited availability of alternative decarbonisation technologies for hard-to-abate sectors, CCUS remains indispensable for addressing both current and legacy emissions [15-18].

Despite its recognised potential, the global rollout of CCS remains limited. As of 2023, operational CCS facilities collectively capture over 50 million tonnes (Mt) of CO_2 per year, a modest fraction of the estimated 37.4 gigatonnes (Gt) of global annual CO_2 emissions. Currently, around 45 commercial-scale projects are active across sectors such as industrial manufacturing, fuel transformation, and power generation. While early progress was slower than anticipated, recent years have seen renewed momentum. Over 700 CCUS projects are now at various stages of development across the full value chain, indicating a growing recognition of the technology's role in supporting climate targets.

In 2023, the projected CO_2 capture capacity for 2030 increased by 35%, while announced storage capacity saw a substantial 70% growth. These developments position the anticipated CO_2 capture capacity for 2030 at approximately 435 million tonnes (Mt) annually, with the announced storage capacity reaching around 615 Mt per year. Despite these advancements, the current trajectory remains insufficient to meet the scale outlined in the Net Zero Emissions by 2050 (NZE) Scenario, which requires the capture and storage of 1 gigatonne (Gt) of CO_2 per year [7]. The announced capacities represent only 40% and 60% of the targets, respectively, highlighting the urgent need for accelerated action and investment to close this gap.

Although the projected CO_2 capture capacity for 2030 shows a 35% increase, as of 2022, there were only 137 CCS projects in operation globally. The majority of these projects are concentrated in developed regions: 36 in North America (14 operational), 65 in Europe (6 operational), and 8 in Australia (1 operational). Figure 1 illustrates the geographical distribution of the estimated CO_2 capture capacity of these facilities by country, assuming all CCS projects proceed as planned and reach their projected operational capacities. This data has been sourced and adapted from the Global CCUS Projects Database maintained by the International Association of Oil and Gas Producers [19].

Most CCS projects operate within the boundaries of a single nation, with CO_2 capture, transport, and storage occurring entirely under the jurisdiction of one State. However, for a global alignment of CO_2 sources with suitable storage reservoirs, the widespread deployment of CCS projects is essential. Expanding CCS efforts beyond developed countries is key to achieving this objective. Research suggests that many developing nations possess significant potential for CO_2 storage [20]. This storage capacity could be pivotal for countries lacking sufficient geological storage options but still seeking to leverage CCS as a tool for emissions reduction [21].

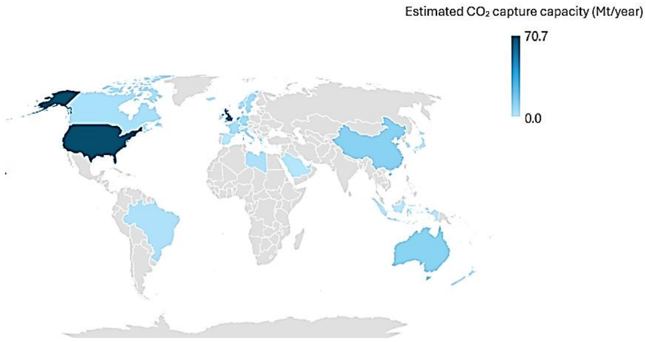

Figure 1. Estimated CO_2 capture capacity by countries

Despite this potential, several barriers prevent the widespread adoption of CCS in developing nations. These include the technical complexity of the required technologies, the substantial investment and resources needed for risk assessment and management, and the absence of robust regulatory frameworks to regulate CCS facilities. Consequently, participation by developing nations remains limited, as illustrated in Figure 1. The internationalisation of CCS projects, where CO_2 is captured in one nation or region and transported to another for permanent storage, introduces significant regulatory challenges, particularly in the areas of transboundary transport and storage. Developing a CCS supply chain that spans multiple jurisdictions necessitates the creation of comprehensive regulatory frameworks at both international and domestic levels to effectively manage associated risks and incentivise technological investment [22, 23]. These regional and domestic frameworks play a crucial role, as they can either facilitate or hinder the widespread implementation of such a supply chain. Literature consistently emphasises the importance of strong policy support for CCS, especially in regions that serve as both sources and sinks for CO_2 [24].

A critical element in the development of a comprehensive regulatory framework for the transboundary shipment and storage of CO_2 is the establishment of effective Monitoring, Reporting, and Verification (MRV) systems. This requires a robust carbon accounting system specifically designed to monitor transboundary CO_2 flows. Given the absence of a centralised MRV framework for such transboundary CO_2, this paper seeks to analyse existing standards and regulatory frameworks related to carbon management, evaluate the key criteria essential for a future MRV system, and propose best practices and lessons learned from these frameworks to guide the future development of MRV systems for transboundary CO_2 flows [25].

2. Monitoring, reporting, and verification (MRV)

MRV of emissions is fundamental to the credibility of any emissions trading system, whether within compliance carbon markets, such as the European Union Emissions Trading System (EU ETS), or voluntary carbon markets (VCMs), like the Gold Standard Marketplace and the Verra Registry. Although these systems differ in structure, the EU ETS, being based on carbon allowances, and VCMs, on carbon credits, both rely heavily on robust MRV frameworks. Within the EU ETS, MRV underpins transparency, facilitates compliance tracking, and strengthens enforcement. A comprehensive, consistent, accurate, and transparent MRV system fosters trust in emissions trading by ensuring that operators fulfil their obligation to surrender the correct number of allowances. As the world's first international emissions trading scheme, the EU ETS has developed mature and reliable MRV guidelines over time, providing a robust framework for emissions measurement and reporting. In the VCM, carbon credits are issued based on the reduction or removal of one metric tonne of CO_2-equivalent greenhouse gas (GHG) emissions through specific projects. These credits are quantified using detailed carbon accounting methodologies and MRV guidelines. For instance, Verra's Verified Carbon Standard (VCS) is the world's most widely used GHG crediting programme. It enables individuals, companies, or organisations to purchase credits that support emission-reducing activities. Verra's methodologies ensure the accurate quantification of GHG benefits and the issuance of Verified Carbon Units (VCUs). These methodologies define project boundaries, establish baselines, assess additionality, outline monitoring parameters, and quantify GHG emission reductions or removals, thus reinforcing rigorous metering and measurement practices. Specific methodologies, such as VM0049, are dedicated to CCS projects.

MRV guidelines in both compliance and voluntary frameworks are grounded in extensive scientific research, incorporating carbon accounting, remote sensing, and environmental monitoring techniques. They are aligned with international standards, including ISO 14064 (Greenhouse gases – Part 1: Specification with guidance at the organisation level for quantification and reporting of greenhouse gas emissions and removals) and ISO 14065 (Requirements for greenhouse gas validation and verification bodies). For CCS applications, standards such as ISO 27915 (Carbon dioxide capture, transportation, and geological storage - Quantification and verification) provide further specificity, ensuring that monitoring and verification processes are rigorous, consistent, and internationally standardized. Therefore, critical insights from these standards and existing regulations can be used to propose key measures for the future establishment of MRV systems for transboundary CO_2 flows. In this paper, Table 1 summarises the international standards and regulations reviewed.

In all of these standards and regulations, the review was conducted by focusing on the key aspects considered essential for establishing a robust MRV framework for transboundary CO_2 flows. These aspects serve as the evaluation criteria outlined below. While this list is not exhaustive, it captures the most critical elements deemed vital for addressing the unique challenges posed by the international shipment and storage of CO_2. A clear understanding and alignment on these aspects are crucial to ensure consistency, transparency, and reliability across different jurisdictions. The key aspects are as follows:

1. CO_2 receipt metering and monitoring requirements: Proper metering and monitoring at the point of CO_2 receipt is fundamental to ensuring that the quantity and quality of CO_2 being transported and stored are accurately recorded. This includes:

- **Selection of metering technologies:** An evaluation of the technologies recommended or required by the standards and regulations, including their suitability for different CO_2 conditions.
- **CO_2 operating conditions:** Consideration of technical parameters that impact metering and monitoring accuracy, including pressure, temperature, flowrate, composition (including levels of impurities), phase state (gaseous, liquid, supercritical), environmental conditions, and operational limits.
- **Calibration procedures:** Requirements for metering equipment to be calibrated in accordance with recognised national or international standards, ensuring traceability and accuracy across different measurement points.
- **Accuracy and uncertainty levels:** Specification of the allowable error margins and required uncertainty levels for measurement systems to maintain credibility and precision in reporting.
- **Additional guidelines:** Any supplementary procedures or considerations that support effective measurement and reporting but may not fall directly under the above categories, for example, redundancy measures or backup metering protocols.

Table 1. Standards and regulations reviewed

Details	Reference
EU ETS • Directive 2004/87/EC • Directive 2009/31/EC • Commission Implementing Regulation (EU) 2018/2066 • Commission Implementing Regulation (EU) 2018/2067 • Commission Implementing Regulation (EU) 2024/2493 • Commission Implementing Regulation (EU) 2023/2122 • Others policy/technical papers related to CCS, referencing the EU ETS	[26]
ISO • 27914 • 27915	[27, 28]
Verra's VCS • CCS overarching methodology: VM0049 Carbon Capture and Storage • Transport Module: E.g. VMD0057 (Project Emissions from CO_2 Transport for CCS Projects) • Storage Module: E.g. VMD0058 (Project Emissions from CO_2 Storage in Saline Aquifers and Depleted Hydrocarbon Reservoirs)	[29-31]

2. CO_2 metering and monitoring points: It is essential to clearly define where metering and monitoring must occur along the CO_2 value chain to maintain a complete and verifiable record of CO_2 movements. This includes:

- Identification of critical points: Such as the point of capture, before and after compression, at the point of entry and exit in transport systems (pipelines, ships, etc.), and at the injection point into storage sites.
- Specification of requirements: Including the technical specifications needed at each monitoring point to ensure consistent data collection and compatibility across jurisdictions.

3. Leakage/reversal management: Leakage or reversal events, where stored CO_2 is unintentionally released back into the atmosphere, pose significant risks to the environmental integrity of transboundary CCS operations. As such:

- **Best practices for management**: The standards and regulations are assessed for their recommended practices in detecting, reporting, mitigating, and remediating leakage or reversal incidents.
- **Requirements for contingency planning:** Including the development of monitoring plans, corrective action

measures, and financial assurance mechanisms to address potential liabilities.

4. Digital and smart solutions: The integration of digital technologies can significantly enhance the efficiency, accuracy, and transparency of MRV systems. Therefore:

- **Recommendations for digital tools:** Evaluation of guidance on the use of smart metering, real-time monitoring systems, blockchain for data integrity, remote sensing technologies, and digital platforms for automated reporting and verification.
- **Data management practices:** Standards for data security, transparency, and accessibility to ensure that data collected across different jurisdictions can be reliably used for regulatory reporting and carbon accounting.

An overall traffic light assessment was performed for each of the identified standards and regulations. The colour coding used in this assessment is as follows:

- **Green:** The standard or regulation provides a comprehensive definition or coverage of the topic, and it is fully applicable to the case of transboundary CO_2 flows.
- **Yellow:** The evaluation criteria are covered within the standard or regulation, but the coverage is either partial or not fully applicable to the specific requirements of the current case.
- **Red:** The evaluation criteria are not covered or addressed within the standard or regulation.

Detailed discussions on how each of these standards and regulations align with the evaluation criteria, together with justification for their respective traffic light ratings, are provided in the following chapters.

3. EU ETS

The overall traffic light assessment of the relevant EU ETS regulations is presented in Table 2. Adapted from EU Regulation 2018/2066 pursuant to Directive 2003/87/EC (consolidated 2024), the Monitoring and Reporting Regulation (MRR) outlines two primary methodologies for quantifying GHG emissions: the calculation-based methodology and the measurement-based methodology. The calculation-based approach estimates emissions based on fuel and material inputs, using emission factors and activity data. This method is generally simpler and more commonly applied across European installations. In contrast, the measurement-based methodology directly determines emissions by continuously measuring the concentration of relevant GHGs, primarily CO_2, in the flue gas, along with the volumetric flow rate of that gas.

Table 2. Relevant EU ETS regulations

Criterion	Remarks
Metering technology	No specific information is provided regarding recommended metering technologies.
CO_2 operating conditions related to metering and monitoring	The regulations mainly focus on CO_2 quantities (flows) and concentrations, without detailed specifications on operating conditions such as pressure, impurities, or phase state.
Calibration procedures traceable to national or international standards	A generic explanation is provided, requiring calibration to national or international standards, but without specific protocols or references.
Accuracy and uncertainty levels of metering systems	A notable feature is the use of a tiered approach for uncertainty requirements in the monitoring system.
Additional measurement and monitoring guidelines for accounting and regulatory reporting	The EU ETS provides best practices to address potential data loss in CO_2 metering, particularly under Article 45. It also introduces flexibility to measure CO_2 at either the transferring or receiving installation. This is particularly relevant to the current CO_2 value chain planned in Malaysia, where metering will occur at the receiving station. To ensure data integrity, operators must reconcile CO_2 quantities across the value chain and provide technical justifications for any discrepancies, such as uncertainties or operational deviations.
Identification and specification of critical metering and monitoring locations	Generic guidance is provided, emphasising flexibility to install metering points at transferring or receiving facilities, but without specifying detailed sitting criteria across the full value chain.
Leakage/reversal	Any CO_2 leakage (including fugitive emissions, venting, or incidents) must be accounted for in the installation's emissions report. Biogenic CO_2 leakages are treated as fossil emissions. In-transit corrections are permitted (typically reconciled at year-end). Reversals are addressed according to the standard EU ETS rules for transferred CO_2.
Digital/smart solutions to enhance CO_2 data collection, management, and analysis	No specific recommendations or requirements for digitalisation or smart solutions are provided.
Overall remarks	The EU ETS (particularly Commission Implementing Regulation (EU) 2018/2066, pursuant to Directive 2003/87/EC and its 2024 consolidation) establishes important requirements for **uncertainty management and data handling in CO_2 metering** across the CCS supply chain. It offers relevant guidance for **CO_2 measurement and monitoring** applicable to the current transboundary CO_2 flow scenario. However, it lacks detailed recommendations on specific metering technologies and the integration of digital or smart metering solutions, which would need to be supplemented through project-specific practices or by referencing additional standards.

This approach is also applied to monitor CO_2 transfers between installations, whereby both the concentration and flow of the transferred gas must be accurately measured. This is particularly relevant in the context of CCS, where the transport and storage of CO_2 demand a higher degree of accuracy than conventional combustion-based emission sources. Although the use of Continuous Emission Measurement Systems (CEMS) for monitoring flue gas emissions is relatively uncommon in Europe due to the prevalence of calculation-based methods, CEMS becomes essential in CCS applications. In such scenarios, calculating emissions based on fuel input is often impractical or inaccurate. As a result, the CCS-specific MRV, which amends the broader MRR framework, places a strong emphasis on CEMS as a critical tool for real-time CO_2 stream monitoring, especially at transfer points. Continuous monitoring of CO_2 stream composition is expected to be a standard requirement to ensure reliable accounting of transferred volumes in CCS chains. One of the defining features of the EU ETS regulatory framework is the tiered system used to define the accuracy and uncertainty requirements for emission measurements. For measurement-based methodologies, Tier 4, the highest level, must be applied for transferred CO_2, requiring an uncertainty of no more than ±2.5%. The selection of tiers depends on the scale of the installation. For example, large-scale CO_2 capture installations handling more than 50,000 tonnes per year are typically classified as Category B or C, thus requiring adherence to Tier 4 for both CO_2 flow and concentration measurements. However, the regulation provides flexibility in its application. Where achieving the highest tier is technically infeasible or would result in disproportionate costs, operators may request approval to use a lower tier, subject to justification and acceptance by the relevant competent authority. This approach maintains a balance between regulatory rigour and operational practicality, particularly for installations facing technical limitations. Table 3 summarises the applicable guidance for installations under the MRR, based on the EU ETS reference [32].

The EU ETS also provides best practices to address potential data loss in CO_2 metering, as outlined in Article 45. Another significant aspect is the flexibility to measure CO_2 at both the transferring and receiving installations. This is highly relevant to the transboundary value chain. To ensure accuracy, the measured CO_2 quantities throughout the value chain must align. If discrepancies occur, operators must provide technical explanations, such as measurement uncertainties or deviations, to justify the differences.

4. Relevant ISO Standards

The overall traffic light assessment for the ISO 27914:2017 is presented in Table 4. Moreover, the overall traffic light assessment for the ISO 27915:2017 is presented in Table 5. According to ISO 27915, GHG reporting for CCS projects is conducted annually, while the actual measurement of CO_2 flow is performed continuously, with data typically aggregated on a monthly basis. At the point of capture, the CO_2 stream is monitored using physical measurement devices such as flow meters and sensors. These instruments are used to record key parameters, including CO_2 concentration, flow rate, pressure, and temperature, as the gas enters the transportation system. For storage operations, metering is carried out at both the plant gate, marking the custody transfer point, and at the injection wellheads, ensuring comprehensive coverage of CO_2 flows into subsurface formations. To reduce calibration errors and improve overall accuracy, ISO 27915 allows for data aggregation at centralised collection points rather than relying solely on individual wellhead measurements. The standard outlines clear methodologies for calculating the annual CO_2 mass handled in a CCS system. One common approach is to sum the quarterly CO_2 concentrations, expressed either as weight or volume percentages, and multiply these by the corresponding mass or volumetric flow recorded during each quarter. Alternatively, where CO_2 concentration data are available, they can be combined with density values (expressed in metric tons per standard cubic meter or derived from the total stream mass) and volumetric flow data to calculate accurate annual totals.

Table 3. MRR guidelines for various installation categories

Installation category	Emission source category	Tier required	Minimum tier (if tier required technically not feasible or unreasonable costs)	If not at least tier 1 Is possible
Category C (>500kt)	Major	highest tier in Annex VIII	highest tier in Annex VIII minus 1 (minimum tier 1)	Fall-back approach
	Minor	highest tier in Annex VIII	tier 1	
Category B (50kt<x≤500kt)	Major	highest tier in Annex VIII	highest tier in Annex VIII minus 2 (minimum tier 1)	
	Minor	highest tier in Annex VIII	tier 1	
Category A (≤50kt)	Major	tier 2	tier 1	
	Minor	tier 2	tier 1	
Installation with low emissions (<25kt)	Major	tier 1 unless higher tier is achievable without additional effort (not applicable for N2O)		
	Minor			

Table 4. Traffic light assessment - ISO 27914:2017

Criterion	Remarks
Metering technology	No specific information is provided regarding the types of metering technology to be used.
CO_2 operating conditions related to metering and monitoring	The standard addresses the composition of the CO_2 stream and outlines expected ranges for pressure, temperature, and flow rate at the receiving storage facility. It also includes injection rate and design specifications, though these are primarily intended for storage site operations.
Calibration procedures traceable to national or international standards	General reference is made to calibration procedures, but specific traceability requirements are not detailed.
Accuracy and uncertainty levels of metering systems	No explicit information or thresholds regarding accuracy or uncertainty levels are included.
Additional measurement and monitoring guidelines for accounting and regulatory reporting	The quantity of CO_2 injected must be recorded for purposes of accounting, engineering, and regulatory compliance. However, guidance remains high-level.
Identification and specification of critical metering and monitoring locations	The standard recommends individual meters be installed at each injection well, downstream of the custody transfer meter, to ensure detailed tracking at the point of storage.
Leakage/reversal	General guidelines are provided on leakage management. These include requirements for primary seals, assessment of potential leakage pathways, installation of secondary containment barriers, and the use of flow modelling to evaluate potential leakage scenarios.
Digital/smart solutions to enhance CO_2 data collection, management, and analysis	No specific information is provided regarding digitalisation or smart solutions.
Overall remarks	ISO 27914 is focused on geological storage of CO_2 and is most applicable to the storage phase of the CCS value chain. It is highly relevant when the **transported CO_2 is intended for long-term containment in geological formations**. While the standard **does not explicitly address transportation metering and monitoring**, it does cover essential requirements for injection site monitoring, safety assurance, and leakage prevention. It provides a useful reference for evaluating monitoring approaches at the point of CO_2 injection.

Table 5. Traffic light assessment - ISO 27915:2017

Criterion	Remarks
Metering technology	The standard mentions the use of mass and volume flow meters for CO_2 measurement, in addition to chemical analysis systems (e.g. sampling and laboratory testing) and general leakage detection technologies, such as laser and infrared systems, particularly relevant for storage applications.
CO_2 operating conditions related to metering and monitoring	Key parameters prioritised for measurement and monitoring include CO_2 concentration, flow rate, pressure, and temperature. The standard also highlights the importance of pre-treatment systems to remove impurities (e.g. annex gases, minor components, organics) before capture or transport, which affects monitoring requirements.
Calibration procedures traceable to national or international standards	To minimise calibration errors, the standard recommends data aggregation at centralised collection points rather than relying exclusively on wellhead meters, particularly in storage contexts. However, specific traceability requirements are not extensively detailed.
Accuracy and uncertainty levels of metering systems	The Tier 3 methodology is introduced, involving flow metering during gas loading and discharge. This method relies on site-specific or plant-level data, including direct measurements and modelling, to enhance measurement accuracy.
Additional measurement and monitoring guidelines for accounting and regulatory reporting	The standard discusses aggregation methodologies for CCS systems, which involve combining CO_2 measurements across different points within the supply chain to calculate the total CO_2 captured, transported, and stored, crucial for both accounting and regulatory reporting.
Identification and specification of critical metering and monitoring locations	Measurement and monitoring points across the CCS value chain are outlined for quantification and verification (Q&V) of CO_2 flow and emissions. These include capture outlets, transport interfaces, and injection points.
Leakage/reversal	The standard provides general guidance on leakage management, primarily in the context of emissions quantification. Accurate leakage estimation is essential for reliable GHG accounting.
Digital/smart solutions to enhance CO_2 data collection, management, and analysis	No specific recommendations are provided regarding the application of digital or smart metering technologies.
Overall remarks	ISO 27915 offers guidelines for the Q&V of GHG emissions and reductions from CCS activities. It covers all elements of the CCS chain, capture, transport, and storage, with a particular emphasis on ensuring the accuracy of emissions reporting. While its focus is on GHG Q&V, it offers valuable guidance on CO_2 metering and monitoring, especially because leak rates must be measurable. Thus, **the standard creates a direct link between CO_2 flow measurement and broader GHG reporting across the CCS chain.**

By integrating chemical analysis techniques, either in-line or through periodic sampling and laboratory testing, with flow measurements, operators can obtain a detailed understanding of the CO_2 stream's composition and quantity. This precision is essential not only for reporting but also for operational efficiency and regulatory compliance. In addition to pure CO_2, the gas stream often contains annex gases such as nitrogen (N_2), oxygen (O_2), hydrogen (H_2), and argon, as well as minor components like methane (CH_4), carbon monoxide (CO), and water. Trace impurities, including sulfur dioxide (SO_2), nitrogen oxides (NO_x), hydrogen sulfide (H_2S), mercury, various metals, and volatile organic compounds like benzene, may also be present. ISO 27915 emphasises the importance of removing these substances prior to CO_2 transport or injection through dedicated treatment units integrated within the conversion and separation process. Although the standard does not delve into the direct impacts of these impurities on surface infrastructure or storage formations, it recommends that monitoring plans account for the associated risks.

The concept of data aggregation is another critical aspect of ISO 27915, particularly in the context of complex CCS networks. Aggregation enables project developers to combine CO_2 measurements taken at different points along the value chain to calculate the total amount captured, transported, and stored. Two primary aggregation methods are identified. The first, known as post-segregation aggregation, involves summing the CO_2 mass values recorded by separate meters at key points throughout the system. The second, pre-segregation aggregation, calculates total annual CO_2 mass by subtracting the sum of internal CO_2 uses or losses, measured downstream, from the upstream total captured at the main flow meter. This approach is useful for tracking and accounting for process-related CO_2 consumption or losses before final storage.

Leakage detection and management are also addressed through a multi-faceted approach. ISO 27915 recommends the use of pressure monitoring, regular visual inspections, and advanced detection technologies such as laser-based and infrared systems to identify leaks in buried pipelines or storage infrastructure. These techniques are essential for ensuring the long-term containment of CO_2 and maintaining environmental safety. Furthermore, ISO 27915 aligns with key elements of the U.S. Environmental Protection Agency's (EPA) Greenhouse Gas Reporting Program (GHGRP), specifically Subpart RR, which pertains to geologic sequestration. Under Subpart RR, facilities injecting CO_2 underground are required to develop and implement a robust MRV plan approved by the EPA. Required data points include the mass of CO_2 received for injection, the amount injected into subsurface formations, any CO_2 produced back to the surface, surface leakage, and emissions from equipment leaks or venting. Additionally, emissions occurring between production flow meters and wellheads must be reported, along with the mass of CO_2 successfully sequestered and the cumulative total reported over time.

In cases where CO_2 is transported by ship, ISO 27915 introduces a Tier 3 methodology for accurately metering gas quantities during loading and discharge. This methodology is consistent with the 2006 IPCC Guidelines (Volume 2, Section 3.3), which describe three tiers of accuracy for estimating emissions from energy systems. Tier 3 methods are the most precise, relying on site-specific or facility-specific data derived from direct measurements, real-time monitoring, and tailored modelling approaches. These methods are particularly suitable for high-integrity CCS operations involving transboundary CO_2 transport and storage.

5. VERRA CCS-related methodology/modules

The overall traffic light assessment for the Verra CCS-related methodology and modules is presented in Table 6. Under the Verra CCS Methodology VM0049 , the eligibility of a CO_2 stream for storage is contingent upon its purity and compliance with relevant regulations. Specifically, the captured CO_2 must be at least 95% pure and must meet all applicable national, regional, or local standards concerning co-injected substances. This ensures that the stream is suitable for geological storage and minimizes environmental risks. To measure the flow of CO_2, the methodology provides two main options: mass flow meters and volumetric flow meters. For supercritical CO_2, where impurities can distort volumetric readings, project proponents must either use mass flow meters while accounting for all impurities exceeding 0.25% mole fraction, or use volumetric meters while accurately determining both CO_2 density and concentration. Importantly, the cumulative mole fraction of unmeasured impurities cannot exceed 2%.

When using mass flow meters, the total mass flow is multiplied by the CO_2 concentration (mass fraction), which is derived from sampled mole fractions. These measurements are carried out continuously, with data captured at least every 15 minutes. Commercially available technologies such as Coriolis, thermal, impeller, and twin turbine meters are recommended by the methodology as well. Similarly, volumetric flow measurement at STP requires multiplying the total volumetric flow by the CO_2 concentration (volumetric fraction) and its density at STP. Devices like rotameters, turbines, wedges, ultrasonic, and vortex meters are recommended to be used, with the same 15-minute monitoring interval. Pressure and temperature at the flow meter must also be recorded continuously under operating conditions using digital or analog instruments such as pressure transducers, thermocouples, or thermistors. Sampling of the gas stream focuses on components exceeding a mole fraction of 0.5% under standard conditions or 0.25% under supercritical conditions. Two options are offered: Option A involves gas chromatography with data aggregated weekly, while Option B adds IR spectroscopy and aggregates monthly. Calibration of all metering and monitoring equipment must adhere to either manufacturer specifications, national/local standards, or international benchmarks (e.g., IEC, ISO), ensuring traceability and data reliability. Equipment must operate within specified conditions and undergo routine maintenance. The transport module (VMD0057) defines its boundary at the custody transfer point and includes intermediate storage and all transport legs. Each leg is considered separately when different transport modes are involved or when crossing borders, enabling clear attribution of emissions across jurisdictions. The methodology underscores the importance of emissions monitoring at each intermediate storage site and transport leg, identifying these as critical metering points.

Table 6. Traffic light assessment - Verra CCS Methodology VM0049

<table>
<tr><th rowspan="2">Criterion</th><th colspan="3">Remarks</th></tr>
<tr><th>Verra CCS Methodology VM0049</th><th>Verra Transport Module VMD0057</th><th>Verra Storage Module VMD0058</th></tr>
<tr><td>Metering technology</td><td colspan="3">The modules VMD0057 and VMD0058, based on methodology VM0049, outline that CO_2 measurements must be conducted using commercially available devices.
• Mass flow: Measured using Coriolis, thermal, or impeller meters and multiplied by the CO_2 concentration (mass fraction).
• Volumetric flow: Measured using rotameters, turbine, ultrasonic, or vortex meters at standard temperature and pressure (STP), multiplied by CO_2 concentration (volumetric fraction) and CO_2 density.
• Measurements must be continuous, with a minimum reading every 15 minutes.</td></tr>
<tr><td>CO_2 operating conditions related to metering and monitoring</td><td colspan="3">The CO_2 stream must meet the following requirements:
• Minimum purity of 95% CO_2.
• Compliance with applicable national/regional/local regulations regarding CO_2 purity and concentrations of co-injected substances.</td></tr>
<tr><td>Calibration procedures traceable to national or international standards</td><td>Metering equipment must be installed and calibrated in line with local/national standards or manufacturer specifications. If these are unavailable, international standards (e.g., IEC, ISO) must be used.</td><td colspan="2">Equipment must operate within the manufacturer's operating conditions and be routinely calibrated, inspected, and maintained.</td></tr>
<tr><td>Accuracy and uncertainty levels of metering systems</td><td colspan="3">No specific levels for accuracy or uncertainty are defined. However, a statistical approach is required for quantifying overall uncertainty in emission reductions and removals, considering potential measurement errors.</td></tr>
<tr><td>Additional measurement and monitoring guidelines for accounting and regulatory reporting</td><td colspan="3">Pressure and temperature must be continuously monitored at the flow meter under operating conditions using recordable electronic signals (e.g., pressure transducers, thermocouples, or thermistors). Sampling requirements:
• Applies to components with >0.5% mole fraction at standard conditions or >0.25% under supercritical conditions.
• Sampling is done with commercially available devices:
  ○ Option A: Gas chromatography, data aggregated weekly.
  ○ Option B: Gas chromatography + IR spectroscopy, data aggregated monthly.
• Minimum monitoring frequency: every 15 minutes.</td></tr>
<tr><td>Identification and specification of critical metering and monitoring locations</td><td>No direct specification.</td><td>The modules emphasise the need to measure emissions at each intermediate storage site and transport leg – deemed critical for CO_2 measurement.</td><td>Mandatory monitoring points are required for CO_2 injection downstream of all intermediate storage, compression, and conditioning units, both onshore and offshore.</td></tr>
<tr><td>Leakage/reversal</td><td>No specific procedures outlined for leaks or reversal under transport modules. (Note: Verra defines leakage as an unintended increase in GHG emissions outside project boundaries because of project activities).</td><td>Fugitive or vented emissions from transported CO_2 are acknowledged, but quantification or measurement details are not provided.</td><td>The storage module includes quantification methods for both intentional and unintentional leaks from surface and subsurface.</td></tr>
<tr><td>Digital/smart solutions to enhance CO_2 data collection, management, and analysis</td><td colspan="3">A working group has been established to advance Digital Measurement, Reporting, and Verification (DMRV) technologies. The initiative is ongoing and under development.</td></tr>
<tr><td>Overall remarks</td><td colspan="3">The Verra Methodology VM0049 provides a framework for quantifying GHG reductions from CCS projects within the VCM, using a baseline-versus-project approach across the CO_2 capture, transport, and storage chain. Modules VMD0057 and VMD0058 specifically address emissions from transport and storage, which is highly relevant for transboundary CO_2 activities, such as shipping or pipeline transfer between countries. While the methodology does not explicitly define transboundary protocols, its detailed provisions on CO_2 stream purity, metering technologies, and leakage quantification provide valuable technical insights.</td></tr>
</table>

For certain transport scenarios, particularly when using ships, trucks, or rail, the methodology allows emissions estimation using default values and measured CO_2 mass. When CO_2 is transported in detachable containers, the total weight, including the container, must be monitored using flow meters or weighing scales. Fugitive emissions during transport are acknowledged but not comprehensively quantified. While CH_4 emissions from fuel use are considered, CO_2 fugitive emissions are referenced only in terms of likely sources like valves or connectors, with limited calculation guidance. Conversely, the storage module (VM0058) provides more detailed treatment. The storage site boundary includes all surface facilities, injection and monitoring wells, and subsurface areas up to the extent of the CO_2 plume.

Mandatory monitoring points must be located downstream of intermediate storage, compression, and any conditioning units, both for onshore and offshore wells. The methodology addresses both intentional and unintentional CO_2 releases. Surface venting may result from maintenance (e.g., blowdowns) or safety mechanisms (e.g., pressure relief valves) and must be quantified using one of three approaches: direct measurement, estimation for isolated volumes, or estimation for non-isolated volumes. Subsurface venting, often associated with injection well maintenance, must follow Approach 1 (direct measurement). Unintended surface leaks (e.g., pipeline leaks) are quantified using emission factors, with a default value of 0.26 kg CO_2/hr/km provided. Subsurface leakage from the storage complex requires model-based estimation using reservoir and monitoring data. Across all modules, metering and weighing devices must remain within operational specifications and be regularly calibrated. For CO_2 and fuel-related measurements, cross-verification with energy balances and purchase documentation is recommended to ensure data consistency.

6. Conclusions

This paper has examined the EU ETS, ISO 27914 and 27915 standards, and the Verra VM0049 methodology to assess their technical provisions, practical relevance, and regulatory applicability to future transboundary CO_2 MRV frameworks. Each instrument brings valuable strengths. The EU ETS, through its 2024 Implementing Regulation, provides a robust compliance regime with strong provisions on uncertainty management and data handling, although it lacks detailed direction on digital and advanced metering technologies, which will be vital for cross-border integration. ISO 27914, while limited to geological storage, offers critical insight into injection site monitoring and leakage prevention, making it especially relevant at the receiving end of transboundary CO_2 flows. ISO 27915 enhances the chain-wide accountability of CCS by linking accurate flow measurement with broader GHG quantification and verification requirements. It reinforces the importance of consistent metering and monitoring across all CCS components, especially when emission reductions are claimed across jurisdictions. The Verra VM0049 methodology contributes significantly to the technical definition of project boundaries, stream purity, emissions accounting, and leakage quantification. Modules VMD0057 and VMD0058 are particularly applicable to shipping and pipeline-based transboundary movements. However, as a voluntary mechanism, Verra does not explicitly address governance structures or liability allocation across borders, which will be critical for enforceability in a regulated international context. Taken together, these standards and methodologies offer critical building blocks for the development of future transboundary CO_2 MRV frameworks. They highlight both the technical rigour already available and the systemic gaps that must be addressed. Among these are the absence of standardised protocols for custody transfer, underdeveloped quantification of fugitive emissions during cross-jurisdictional transport, and insufficient integration of digital monitoring technologies. This paper seeks to bring coherence to the fragmented landscape of current standards and regulations by identifying how each addresses (or overlooks) the specific challenges posed by transboundary CO_2 flows. The analysis offers a consolidated knowledge base to guide regulators, project developers, and policymakers in shaping a credible, transparent, and internationally harmonised MRV system. Such a system will be fundamental to supporting the scalability of cross-border CCUS projects, enabling their contribution to global net-zero targets.

Ethical issue

The author is aware of and complies with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the author.

Conflict of interest

The author declares no potential conflict of interest.

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