CO_2 MEASUREMENT FOR CARBON CAPTURE, UTILIZATION AND STORAGE – ANALYTICAL QUALITY REQUIREMENTS

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KEYWORDS

CO_2 Measurement, CCUS Measurement, CDR Measurement, Carbon Management Measurement, CO_2 Purity Measurement, CO_2 Impurity Measurement, Supercritical CO_2, 45Q Tax Credit, Voluntary Carbon Market, Compliance Carbon Market, High-integrity Carbon Market

ABSTRACT

This paper is an overview of measurement system requirements for Carbon Capture, Utilization, and Storage (CCUS) and Carbon Dioxide Removal (CDR) from the capture source to the sequestration or utilization site.

There are multiple stakeholders with a variety of measurement requirements in a CCUS or CDR program. All the requirements are important to success and profitability. This paper considers the range of stakeholder requirements including regulatory permit guidelines, pipeline and reservoir integrity, custody transfer, carbon accounting, maintenance, operations surveillance, project execution, vendors and suppliers.

The solution is a combination of flow measurement and analyzer technologies that meet the stakeholder requirements. The solution also includes industry-accepted validation and verification methodologies.

This is a young industry; the development of the carbon markets and associated industry standards and regulations are ongoing. Participating in the ongoing development of industry standards and research projects will ensure that suppliers and end users are aligned with the multiple stakeholder requirements and expectations.

INTRODUCTION

The carbon management industry emerged in response to the desire to mitigate greenhouse gas (GHG) emissions and meet global climate commitments. As industrial activities elevate atmospheric carbon monoxide (CO) and carbon dioxide (CO_2) concentrations, Carbon Capture Utilization and Storage (CCUS) and Carbon Dioxide Removal (CDR) provide pathways for reducing the amount of these GHGs in the atmosphere. CCUS captures emissions at their source, preventing their release into the atmosphere. CDR removes CO_2 that is already in the atmosphere. (Note: CCUS is also referred to as "Carbon Capture, Utilization, and ***Sequestration***" in some references.)

Climate models from the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) indicate that both CCUS and CDR must scale dramatically to meet 1.5 °C and net-zero targets, particularly in hard-to-abate sectors such as shipping and air travel.

Governments worldwide have adopted policies to accelerate deployment of both CCUS and CDR, acknowledging their complementary roles: CCUS reduces ongoing emissions while CDR removes residual or historical emissions. Together, they form the backbone of emerging carbon management strategies, with a rapidly growing number of engineered CCUS and CDR projects advancing.

To reduce atmospheric CO_2, industrial carbon capture and engineered CDR systems are combined with:

- Geologic storage where CO_2 is permanently sequestered (isolated in deep formations such as saline aquifers or depleted hydrocarbon fields for hundreds or thousand of years), or

- Utilization pathways where CO_2 becomes an input to industrial processes (e.g., synthetic fuels, chemicals, building materials).

INDUSTRIAL CO_2 CAPTURE

Heavy-industry sectors such as refining, petrochemicals, steel, cement, natural-gas processing, and power generation create large quantities of CO_2 that cannot be easily abated through fuel switching or efficiency gains alone. CCUS addresses this challenge by capturing CO_2 at the point of emission, compressing it, and transporting it for sequestration or utilization.

CARBON DIOXIDE REMOVAL

CDR encompasses a class of engineered and nature-based technologies designed to remove legacy CO_2 already accumulated in the atmosphere. It offers durable, verifiable pathways for achieving net-negative emissions. While CCUS prevents future emissions by treating industrial exhaust streams, CDR creates net-negative emissions, an essential requirement for meeting long-term climate targets once residual emissions are minimized. Engineered pathways include Direct Air Capture (DAC) combined with sequestration or utilization.

CCUS / CDR ILLUSTRATION

See Figure 1:

- A DAC plant pulls CO_2 out of ambient air, resulting in negative emissions. Hence, DAC CDRs can be purchased by corporations and individuals as a carbon offset. Each ton of CO_2 removed represents 1 CDR credit, which can be traded in the carbon markets.

- An industrial capture plant captures CO_2 that would otherwise be vented.

- Once captured, the CO2 is compressed and transported to be sequestered underground or to industrial users for use in products.

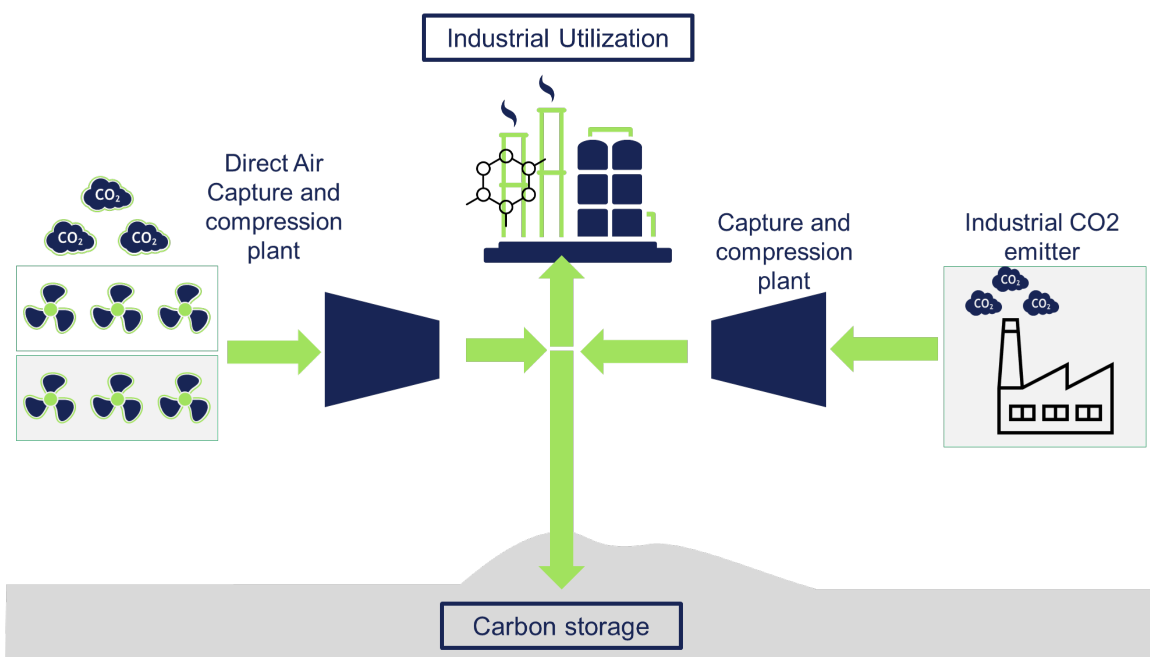

Figure 1. DAC and Industrial capture

CARBON REVENUE STREAMS

There are three main revenue streams for carbon capture enterprises in the U.S. Similar opportunities exist in other countries.

- Tax credits
- Voluntary market
- Compliance market

TAX CREDITS

The 45Q tax credit in the U.S. is a federal incentive designed to accelerate deployment of CCUS and CDR technologies by providing a performance-based, per-ton credit for securely storing or beneficially using captured CO_2 or CO. This is defined in Section 45Q of the U.S. Internal Revenue Code.

To qualify, a project must capture “qualified carbon oxide” at an eligible industrial, power-generation, or direct-air-capture facility and either permanently store it in a geologic formation or utilize it in a manner that reduces emissions as defined by federal requirements. The credit can be claimed for 12 years after carbon-capture equipment is placed in service. The credit is available to the owner of the capture equipment, who may also contractually transfer the credit to another party responsible for storage or utilization.

Current credit levels provide $85 per metric ton for industrial point-source CO_2 and $185 per metric ton for Direct Air Capture projects. These incentives have made 45Q a mechanism for enabling project financing, and large-scale carbon-management deployment.

VOLUNTARY CARBON MARKET

The voluntary carbon market (Figure 2) enables companies and individuals to purchase carbon credits outside of any regulatory obligation as a way to reduce or counterbalance their emissions.

The voluntary market provides “non-compliance” credit purchases, where organizations voluntarily acquire and retire carbon credits to meet corporate climate commitments, enhance environmental performance, or maintain stakeholder confidence. These credits may represent avoided emissions (e.g., preventing deforestation) or removed emissions (e.g., DAC-based CDR), and are typically bought directly from project developers via brokers or carbon-credit retailers.

Because the voluntary market operates independently of governments, there are multiple certification standards such as Verra Verified Carbon Standard (VCS), Gold Standard, American Carbon Registry (ACR) and others. The voluntary market also relies heavily on third-party verification bodies for quality assurance. Voluntary-market buyers often assemble portfolios tailored to their goals. This market plays an important role in justifying investment for climate projects.

COMPLIANCE CARBON MARKET

The compliance market (Figure 2) is created by government policy and requires companies to reduce or offset emissions as a condition of law or regulation. In many cases, regulated entities must obtain sufficient verified carbon credits to meet their mandated emissions limits. For example, an airplane cannot directly reduce CO_2 emissions at the source, so the CO_2 generated by the airplane can be offset with purchased credits to meet the regulatory emission cap.

Compliance markets are driven by statutory requirements, jurisdictional rules, allowance caps, and formal monitoring and verification controls. So, compliance demand arises from companies subject to jurisdictional or sectoral carbon taxes, where credits may be used to meet emissions-reduction obligations and avoid fines. These markets tend to have more oversight, and more stringent monitoring, reporting and verification (MRV) requirements compared to the voluntary market.

These are generally based on a "cap and trade" principle. The cap refers to the limit set on the total amount of GHG that can be emitted by installations and operators covered under the scope of the regulation. Under this system, companies must monitor and report their emissions on a yearly basis and surrender enough allowances to fully account for their annual emissions. If these requirements are not met, heavy fines are imposed. Companies may also trade allowances among themselves as needed. If an installation or operator reduces emissions, the company can either sell the spare allowances and/or keep them to use in the future. The European Union Emissions Trading System (EU ETS) is an example of a cap-and-trade system. (reference: website: About the EU ETS - Climate Action - European Commission)

Credit Demand

Carbon credits are bought for various reasons, depending on the intended use case of those credits. This can be classified into three overarching categories:

	Voluntary	Compliance: Jurisdictional	Compliance: Sectoral
Definition	Demand from companies seeking to meet their emissions targets, partly through reducing emissions, and partly through offsetting remaining emissions	Demand from companies regulated by jurisdictional compliance carbon pricing systems (ETS, carbon tax) where carbon credits may be used to meet their compliance obligations	Demand from companies subject to sectoral compliance carbon pricing systems, such as CORSIA (for international aviation) and IMO (for maritime shipping)

Figure 2. Cabon markets.

HIGH INTEGRITY CARBON MARKET

A high-integrity carbon market (Figure 3) is one in which every issued credit corresponds to a real, additional, accurately measured, independently verified, and durable reduction or removal of GHG. There are rules that prevent double counting and ensure proper retirement. This involves MRV, third-party validation/verification bodies (VVBs), registry reviews of MRV reports before issuance, controlled transfer, and credit retirement flows so buyers can trust that a retired unit truly offsets residual emissions.

	Credit Supply			Credit Demand	
	Carbon is captured	Carbon is verified	Credit is deposited into a registry	Credit is transferred	Credit is retired
Description	Supplier calculates carbon captured using Low Carbon Accounting	Independent third-party VVBs assess project monitoring reports against Registry's methodology	Registry reviews verified monitoring report and MRV report submitted by supplier Registry creates credits record and deposits credits into supplier's account	Supplier transfers credits from supplier account to the buyer's account based on buyer requests	Customers retire credits to offset emissions
Executing entity	CDR Supplier (capture source)	VVBs	Supplier & Registri(es)	Supplier (registry provides the platform for credit transfer)	Customers (notify registry) & Registry (retire in registry platform)

Figure 3 - High Integrity Carbon Market

High-integrity market registry protocols and contracts require that measurement uncertainty be specified for composition and mass-rate measurement for CO_2 streams so that credit quantities match metered, verified tonnes. These protocols enable credible financing of climate projects while protecting corporate claims and regulatory/assurance reviews.

Carbon credits are commodities that represent a unit of measurement of either avoided, reduced or removed CO_2 or other greenhouse gases from the atmosphere. Companies that produce negative emissions can certify their carbon removals with carbon credits at carbon registries after a verification process. These credits can be sold by suppliers and then retired by companies that have residual emissions that need to be counter-balanced. Carbon finance from carbon credits enables various carbon removal activities to receive payment for the carbon they remove, making them economically feasible.

CO_2 MEASUREMENT FOR CDR/CCUS

STAKEHOLDERS

The question comes up often: "Why is this measurement of CO_2 for CDR/CCUS different than what we've done for decades in enhanced oil recovery (EOR)?" The difference is that the integrity of the measurement could potentially be scrutinized and analyzed by many more stakeholders. For example, a CO_2 sequestration well falls under a different Environmental Protection Agency (EPA) permit than an EOR injection well, and so will have different measurement requirements.

Interestingly, the measurement methods and uncertainty requirements are not generally specified in regulations, industry standards, or registry protocols. The requirements are agreed by parties in custody contracts, sequestration permit applications, pipeline specifications, carbon registry contracts, and carbon credit agreements. Thus, it is important to define measurement methods, verification procedures, and uncertainty tolerance requirements for both mass measurement and quality measurements.

This is an important point. Credit suppliers undertaking projects should make sure that reasonable expectations are defined and consistently written into the variety of permit applications and contracts associated with a CCUS or CDR project. They must also be ready to demonstrate that the agreed tolerance requirements are met.

A credit supplier's internal stakeholders include:

- Commercial teams contracting for CO_2 sources and transportation
- Groups responsible for permitting capture, transportation and sequestration projects
- Teams contracting verified carbon registry services and sales of CDR credits
- Operations, maintenance, and measurement teams performing field verifications and meter maintenance
- Project teams procuring and installing measurement systems
- Teams developing systems and procedures for carbon accounting and tracking
- Carbon accounting teams

External stakeholders include:

- CO_2 transporters
- CO_2 suppliers
- Tax authorities
- Regulatory authorities
- Carbon verifiers
- Carbon registries
- Credit purchasers

MEASUREMENTS IN THE CHAIN

There are three main measurement points considered in this paper (M1, M2, and M3 in Figure 4). This example is for a typical onshore capture/transport/sequester scenario. The transportation and sequestration are typically at high pressure and ambient temperature, and so the CO_2 product is usually in supercritical phase (Figure 5) increasing the challenge of measurement and sampling.

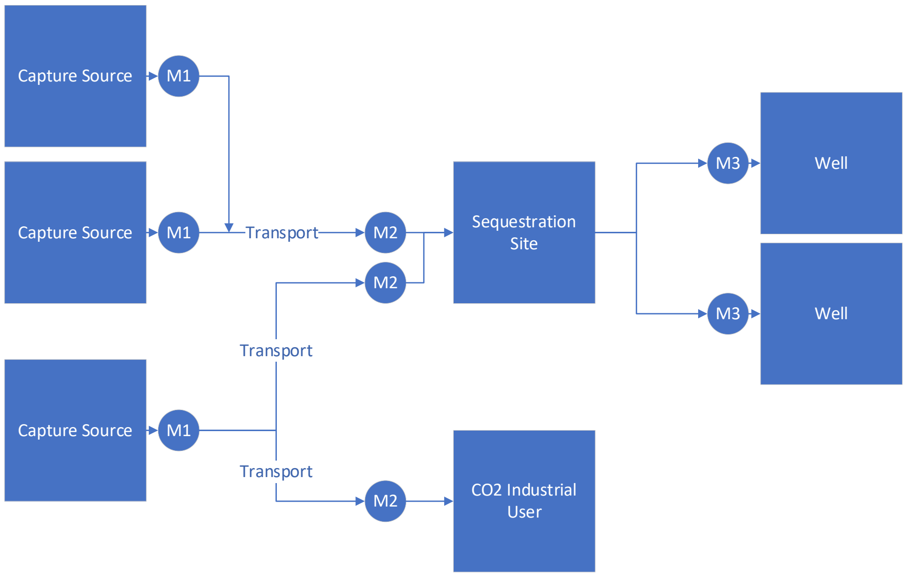

Figure 4. Measurement points.

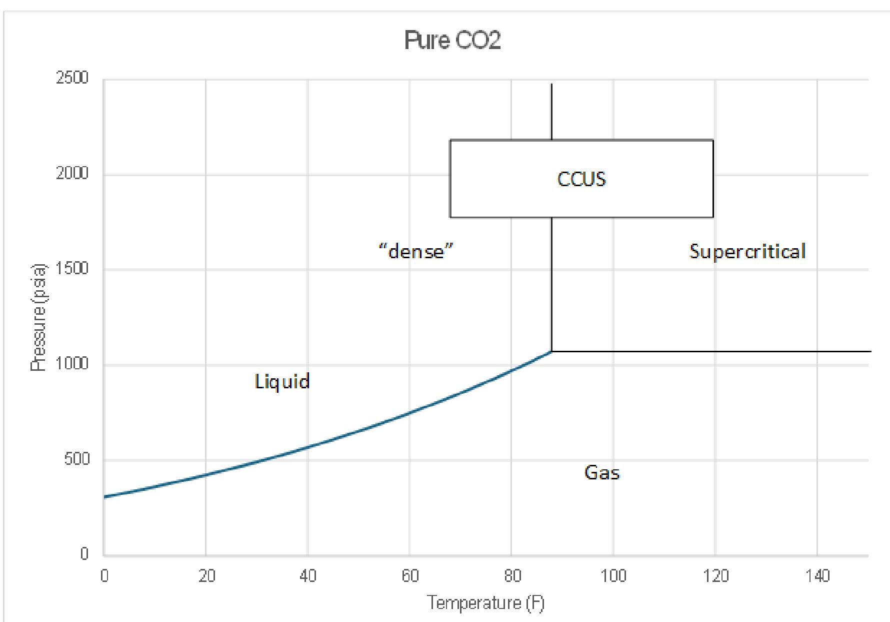

Figure 5. Product phase diagram.

Table I is an example of how these measurement points might be instrumented, but these will be decided for each project based on agreements in custody contracts, permits, and registry contracts.

Table I. Measurement points.

Meter Identifier	Component	Purpose
M1 Capture source to pipeline	Mass meter	• Custody transfer (fiduciary quality) • Leak Detection
	Online analyzer for %CO_2	• Allocation of sequestered product to sources • Mass balance
	Online analyzer for impurities	• Pipeline integrity – prevent corrosion from impurities
	Manual sample station	• Permit and contract compliance • Verification of online analyzer
M2 Pipeline to sequestration hub	Mass meter	• Custody transfer (fiduciary quality) • Leak Detection
	Online analyzer for %CO_2	• M2 will be the fiduciary meter used to calculate the net CO_2 injected for CDR credits (Verified Carbon Units for Verra methodology).
	Online analyzer for impurities	• Wellbore and reservoir integrity from impurities • Permit compliance
	Manual sample station	• Permit and contract compliance
M3 Sequestration well	Mass meter	• Permit compliance (fiduciary quality) • Operations and engineering surveillance • Injection rate control
	Manual sample station	• Permit compliance

NET CARBON UNIT CALCULATION FOR CDR

For carbon dioxide removal credits, the measurement protocol is generally defined by the registry. For this paper, the Verra Methodology VM0049 v1.0 will be used as an example.

The Verra Methodology calculation for the net credit issued requires calculating the amount of CO_2 sequestered then deducting the amount of CO_2 generated in the process of capturing, transporting, and sequestering the product (Figure 6).

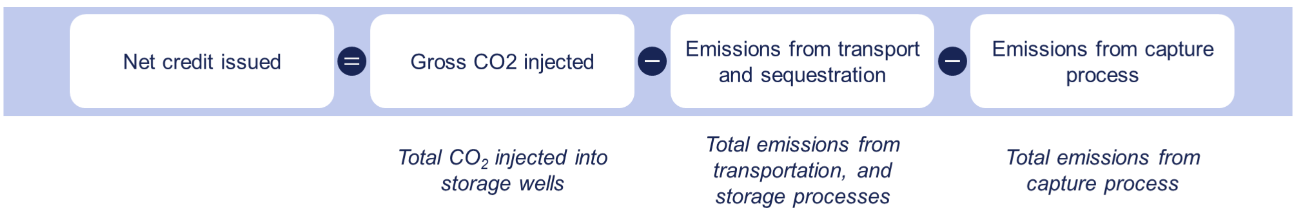

Figure 6. Net carbon unit calculation from Vera.

There are many measurements involved in calculating the CO_2 emissions generated in transportation and the capture process, but those vary widely depending on the process. These measurements can include fuel gas quantity and composition, electric power use, chemical use, and many others. This paper will only focus on the product leaving a capture source, transported, and sequestered.

It is important to understand that the total combined uncertainty of all measurements in this scope must be within the uncertainty requirement stated in the supplier's contract with the registry. For example, say the total combined uncertainty promised in the contract is ±3%. If the capture process and transportation consume large amounts of electricity and fuel gas, then the measurements of gas quantity, gas composition, and electricity all have uncertainties that, combined, might leave only ±1% uncertainty tolerance for the calculation of Gross CO_2 Injected.

This paper focuses on calculating the Gross CO_2 Injected from Figure 6. The uncertainty tolerance for that calculated value must be determined by the supplier after deducting the uncertainties of all the emissions-related measurements.

CALCULATION OF GROSS CO_2 INJECTED

The product stream injected into the sequestration wells will contain impurities, sometimes up to 5% of the total mass injected. So, the mass of the impurities must be deducted to calculate the gross CO_2 injected. Based on the Verra Methodology this requires the measurement system to provide the total mass of product sequestered and the fraction of the product that is CO_2.

The Verra methodology allows using a mass flow meter while measuring the concentration of all impurities in the stream that are greater than 0.25% (2500 ppm) by mole fraction. The cumulative mole fraction of all neglected impurities shall not exceed a 2% threshold. The mole fraction for non-CO2 components may be from periodic spot samples analyzed in a lab, or from online measurements. The mole fraction of CO2 is usually obtained using an online analyzer close to the M2 meter.

The Verra calculations for the net CO_2 are shown in Equations 1 and 2.

$$m_{CO_2} = m_{total} \times mass\%CO_2 \qquad \text{Equation 1}$$

m_{CO_2}	mass of CO_2 (tonne)
m_{total}	mass of total product stream sent to sequestration (tonne) measured using a Coriolis mass flow meter at M2 in Figure 4
mass%CO_2	From Equation 2

$$mass\%CO2 = \frac{M_{CO_2} \times X_{CO_2}}{\sum_{k=1}^{n} M_k \times X_k} \qquad \text{Equation 2}$$

mass%CO_2	Fraction of the sequestration stream that is CO_2
M_{CO_2}	Molar mass of CO_2
X_{CO_2}	Mole fraction of CO_2 (from online analyzer)
M_k	Molar mass of component *k*
X_k	Mole fraction of component *k*
n	Number of components in the mixture with a mole fraction greater than 0.25%

MEASUREMENT REQUIREMENTS

INTRODUCTION

There are currently no industry standards or regulations defining fiduciary-quality measurement of CO_2, but the American Petroleum Institute (API) and others are working on standards. In the meantime, requirements are defined in permit applications, contracts, and carbon registry protocols. There are two main measurements addressed in this paper: mass and composition.

MASS MEASUREMENT

The mass flow measurement is not the main topic of this paper, but will be addressed briefly.

Accurate mass measurement is foundational to CCUS and CDR accounting because carbon credits, tax incentives, and custody-transfer agreements are all based on the mass of CO_2 delivered, transported, and permanently stored. Coriolis mass flow meters are a popular choice for since Coriolis meters make a direct mass measurement. Inferred mass measurement methods may also be used, but have added uncertainty related to the additional instrumentation and equations of state used to measure or calculate the density.

The flowmeter must be monitored, maintained, and verified to ensure that reported CO_2 mass is defensible to VVBs, registries, regulatorss, credit purchasers, and tax authorities. Impurities, phase behavior, and CO_2 density variations under supercritical conditions introduce additional complexity that mass flow measurement must accommodate, reinforcing the need for high-precision instrumentation, proper installation, and verification practices.

ANALYTICAL (QUALITY) MEASUREMENT

Accurate analytical measurement is essential in CCUS and CDR operations (Figure 7).

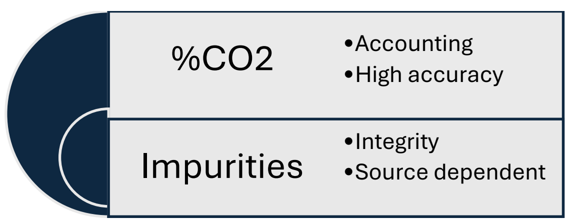

Figure 7. Analytical Measurements required.

Credit issuance, custody transfer, regulatory compliance, and carbon-accounting frameworks all depend on knowing the CO_2 purity and the mole fractions of impurities in the sequestration stream. Analytical data feed directly into the mass-percentage calculation used to determine the injected CO_2 mass, so the $\%CO_2$ measurement uncertainty tolerance will be driven by the tolerance for the calculated gross mass injected and the uncertainty of the flow meter.

Additionally, impurities are measured to meet permit requirements, contractual requirements, and to ensure the integrity of piping, downhole tubulars, and the sequestration reservoir itself. Typical impurities found in CO_2 capture streams are listed in Table II. This is an example of a CDR or CCUS product quality specification that might be part of a contract or a permit application. The set of impurities expected depends on the capture source, so product specifications are made on a project basis. Some recommendations on establishing specifications are given in the Wood report "*Industry Guidelines for Setting the CO_2 Specification in CCUS Chains.*" These guidelines were the outcome of a Joint Industry Project led by Wood.

In addition to the reasons listed in Table II, chemical interactions of the components and impact of the components on the system are still being studied. Some of these components can react to form particulates, or form acids which are a concern for corrosion. Also, large amounts of impurities decrease efficiency of compression and use up valuable sequestration storage space. Pipeline Research Council International (PRCI) and others are actively studying the full impact of the impurities on the system.

Table II. Example impurity requirements.

Component	Limit	Reason
CO/CO_2	> 95%	Main product
Water	600 ppm wt	Corrosion
Oxygen	< 10 ppm	Corrosion Contributes to bacteria grown in the reservoir
Hydrogen	< 4 vol%	Stress cracking
Hydrogen Sulfide	< 200 ppmv	Corrosion Sulfide stress cracking Toxicity
SOx & NOx	<100 ppmv each	Corrosion Toxicity
Ammonia	25 ppm	Toxicity Particulate formation with other impurities
Methane	< 5%	Combustible
COS		Corrosion

Online analyzers might only be required for the set of impurities that can be detrimental to piping integrity, reservoir integrity, or contribute to growth of bacteria. These include water, hydrogen sulfide, NOx, SOx, and Hydrogen. A combination of analytical methods may be required to monitor the complete set of impurities expected for an application. For example, a gas chromatograph might be used to measure the %CO_2 very repeatably for accounting, then simple electrochemical sensors for water and oxygen for pipeline integrity. Or, a tunable diode laser device might be used for %CO_2 and some of the impurities.

Sample probes and sample handling systems for online analyzers must consider temperature and phase change when dropping from pipeline pressure to the analyzer pressure. It is possible to drop from supercritical into the solid phase when gas phase is the target.

Other impurities that are monitored for permit compliance or other reasons might only require spot sampling or composite sampling and laboratory analysis. These could include entrained oil or particulates, nitrogen, and argon. A probe should be provided at each meter location for acquiring a manual sample. Floating piston cylinders are often preferred for collecting the high-pressure samples to safely maintain the sample at process conditions until they are analyzed.

DNV in The Netherlands is currently carrying out a Joint Industry Project with the goal to assess and develop guidelines for sampling and detection methods for impurities and trace components in CCS systems.

CONCLUSION

Achieving credible, scalable carbon management depends not only on the successful deployment of CCUS and CDR technologies but also on the rigor and transparency of the measurement systems. As this paper has shown, CO_2 quantification is no longer a routine industrial task—its accuracy now carries financial, regulatory, and environmental weight. The rise of carbon markets, the expansion of federal incentives such as 45Q, and increasingly stringent monitoring and verification requirements have transformed CO_2 measurement into a multidimensional discipline involving engineering, policy, compliance, and market assurance.

Each stakeholder—capture facilities, transport operators, sequestration sites, verifiers, regulators, and credit purchasers—relies on precise mass and analytical data to ensure that reported CO_2 reflects reality. This requires mass meters and robust analytical instrumentation with defensible uncertainty statements. Sampling methodologies are also important.

Equally important is the need for well-defined uncertainty tolerance that align with carbon registry methodologies, permits, and contractual requirements. As CCUS and CDR projects move toward larger scales and more complex multi-source networks, system-level integrity, traceability, and validation will define which projects earn trust in emerging high-integrity carbon markets.

Looking forward, continued industry collaboration will be essential. Standards bodies, operators, researchers, and technology providers must work together to refine measurement protocols, develop standards, and reduce measurement uncertainty. Ongoing research will address the impurity and phase-behavior challenges of supercritical CO_2 systems. By participating in the development of industry standards, stakeholders can ensure that carbon credits genuinely represent verifiable climate impact with realistic and reasonable equipment expectations.

Ultimately, accurate measurement of CO_2 mass and composition is the foundation on which durable climate claims, regulatory compliance, and long-term market credibility are built. As carbon management continues to expand, the projects that succeed—technically, financially, and societally—will be those that treat measurement not as a compliance burden, but as a strategic enabler of high-integrity climate solutions.

REFERENCES

Jones, Angela C.; Marples, Donald J., “The Section 45Q Tax Credit for Carbon Sequestration”, IFI 1455, Congressional Research Service, Washington, DC, August 2023.

“Carbon Capture and Storage” Verified Carbon Standard, Methodology VM0049 v1, CCS+ Initiative and Verra, June 2024.

Chinello, Gabriele; Arellano, Yessica; Span, Roland; van Putten, Dennis; Abdulrahman, Ara; Joonaki, Edris; Arrhenius, Karine; Murugan, Arul, “Towards Standardised Measurement of CO_2 Transfer in the CCS Chain”, S2950-1601(24)00011-1, Nexus, 2024.

“Industry Guidelines for Setting the CO_2 Specification in CCUS Chains – Introduction to the Guidelines”, 522240-WP12-REP-001 Rev 2, Wood, September 2024.

“45Q Tax Credit for Carbon Capture Projects”, Carbon Capture Coalition, August 2025.

Lebling, Katie; Hausker, Karl; Byrum, Zachary, “7 Things to Know About Carbon Capture, Utiliization, and Sequestration”, World Resources Institute website, May, 2025. Accessed January 2026. https://www.wri.org/insights/carbon-capture-technology

Other web links (all accessed January 2026):

Understanding the Compliance and Voluntary Carbon Trading Markets | Deloitte UK

Global Compliance Carbon Markets: Structure Explained

Compliance Carbon Credit Market Share, Outlook 2025-2034

A Guide to Compliance Carbon Credit Markets • Carbon Credits

EU Emissions Trading System (EU ETS) - Climate Action - European Commission

Mastering CO2 fluid compositions (DNV JIP on Quality)

Carbon Capture, Utilization & Storage | Department of Energy