



1. The Role of CCUS and Its Value Chain

WHY IS CCUS ESSENTIAL ?

- Reaching net-zero will be virtually impossible without CCUS [1].
- Primary solution for cement, steel and chemical industry.
- CCUS could contribute up to 15% of global CO₂ emissions reduction required by 2050 [1].
- Cost-effective pathway for low-carbon hydrogen production.

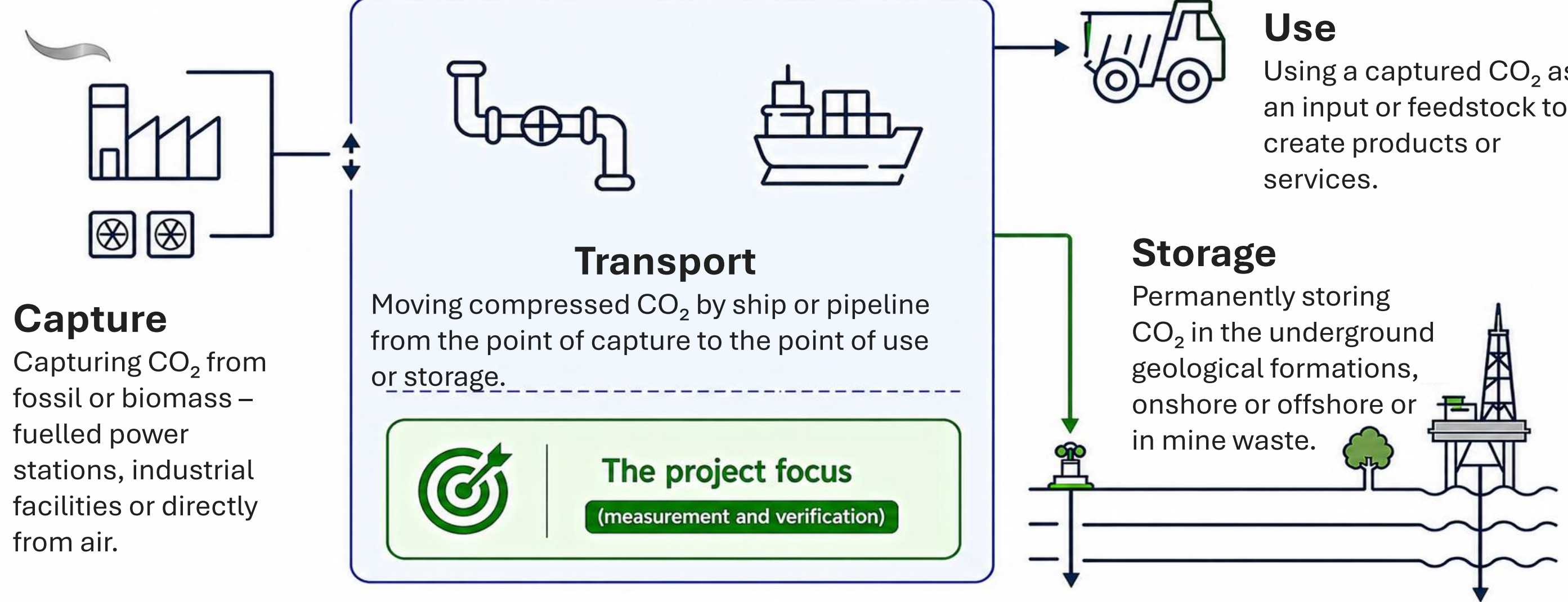


Figure 2: CCUS Value Chain [2]

2. WHY THE FOCUS ON METERING?

- Trusted Carbon Accounting:**
Verifiable CO₂ quantities → credible emissions reporting.
 - Financial Confidence :**
Accurate billing between operators.
 - Safe and Reliable Operation :**
Detects leaks and abnormal flow behaviour.
- Also enables, process optimisation, validation, uncertainty reduction, and the scalable deployment of CCUS systems.

3. CO₂ TRANSPORT PATHWAYS AND PHASE REGIMES



- Transport mode selection is **context-dependent** based on infrastructure availability & the deployment stage.
- CO₂ is generally preferred to be transported in the **dense phase** (density > 500 kg·m⁻³) for **pipelines**, while **ship, rail, and truck** transport favour the **liquid phase** (> 1000 kg m⁻³) at low temperatures.
- Gas-phase** (<100 kg m⁻³) is generally limited to short-distance or transitional operations.

4. FLOW PROPERTIES OF CO₂

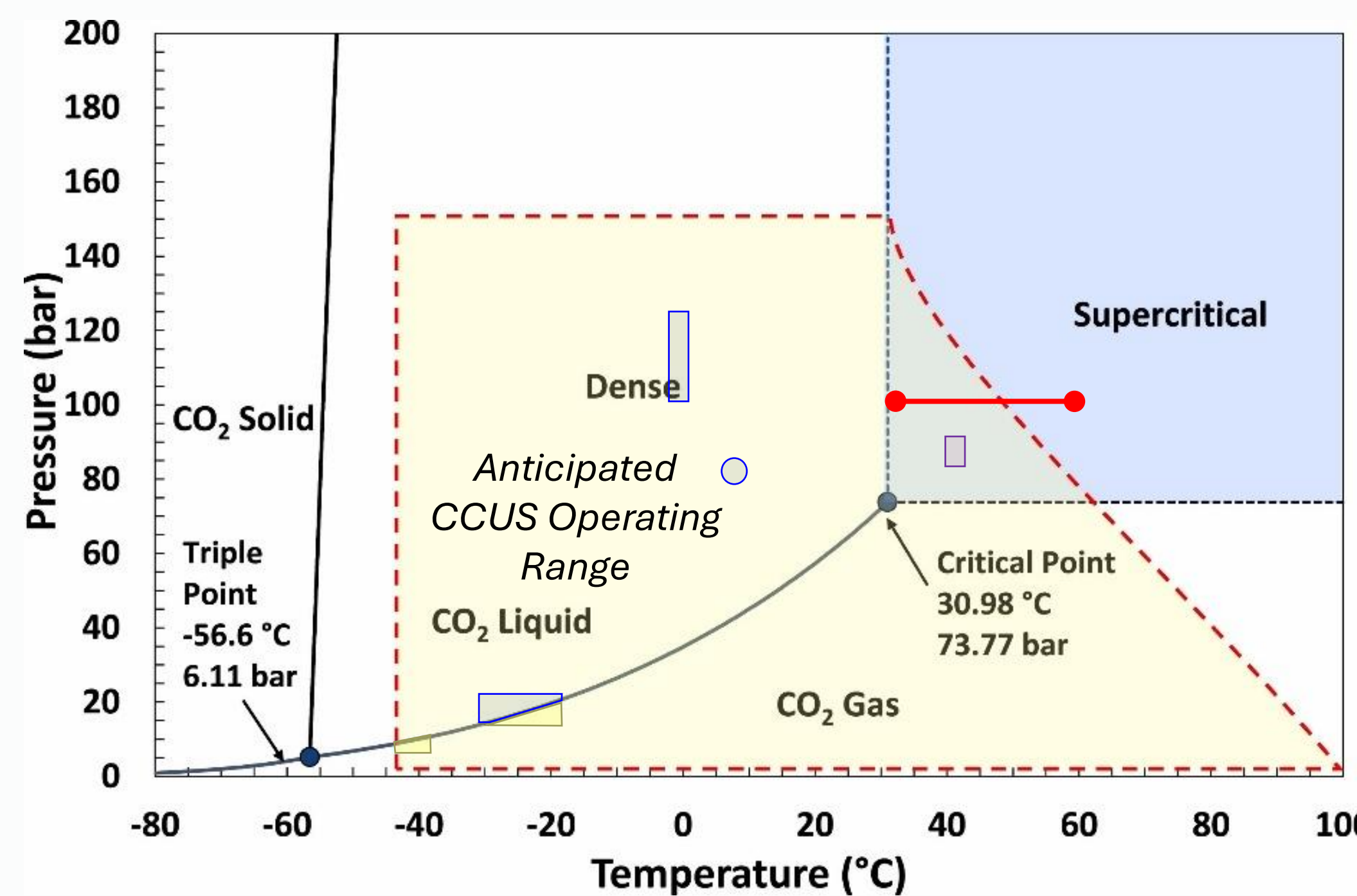


Figure 3: CO₂ phase diagram [5]

- CO₂ thermophysical properties (density, viscosity, speed of sound, compressibility) vary nonlinearly with pressure and temperature.
- This sensitivity becomes extreme near phase boundaries and the critical point (30.98 °C, 73.8 bar).
- The pseudocritical region (34.5 °C, 77–80 bar) is especially unstable. A safety margin (5-10% above critical pressure) is required to avoid flow oscillations [4].

Examples of operating regimes in the Northern Lights project

- Liquid (blue circle)
- Supercritical (red circle)
- Gas (yellow circle)

The target operating region of the project
 T = 40–45 °C, P = 85–90 bar

5. MEASUREMENT TECHNOLOGIES

- | DIFFERENTIAL PRESSURE | TURBINE METERS | CORIOLIS METERS | ULTRASONIC METERS |
|--|---|--|--|
| <ul style="list-style-type: none"> Density required to convert to mass. Standardised design ISO 5167. High pressure drop. | <ul style="list-style-type: none"> Volumetric, density required to convert to mass More mechanically sensitive. Limited performance under CCUS conditions. | <ul style="list-style-type: none"> Direct mass flow Relatively high pressure drop (1-2 bar). Larger sizes (>3-inch) require fluid SoS correction. Size constraints to < 12-inch. | <ul style="list-style-type: none"> Volumetric, density required. Low pressure drop. Sensitive to flow profile and composition. Suitable for large diameters. |

! Density (ρ) and speed of sound are required for accurate flow quantification.

6. MEASUREMENT CHALLENGES

- Impurity effects** (type & concentration). Changes fluid properties (density, SoS, phase envelope). Total concentration of non-condensable components should not exceed 4 mol% [3].
- Phase behaviour and two-phase formation.** This can cause the meter to significantly over-read or under-read. Also, can also cause “slugging”, where fluid move unevenly, creating vibrations that may damage turbine meters or ultrasonic transducers.
- Near-critical sensitivity**
When transporting CO₂ in the dense phase, it is highly compressible, even small changes in pressure or temperature can result in significant changes in density.
- Metering technology-specific issues**
the need for a precise fluid density (USM, DP, Turbine) and speed of sound (Coriolis).

! Accurate quantification is challenged by the strong sensitivity of thermophysical properties to small pressure-temperature variations, in the near-critical region.

Measurement Requirement

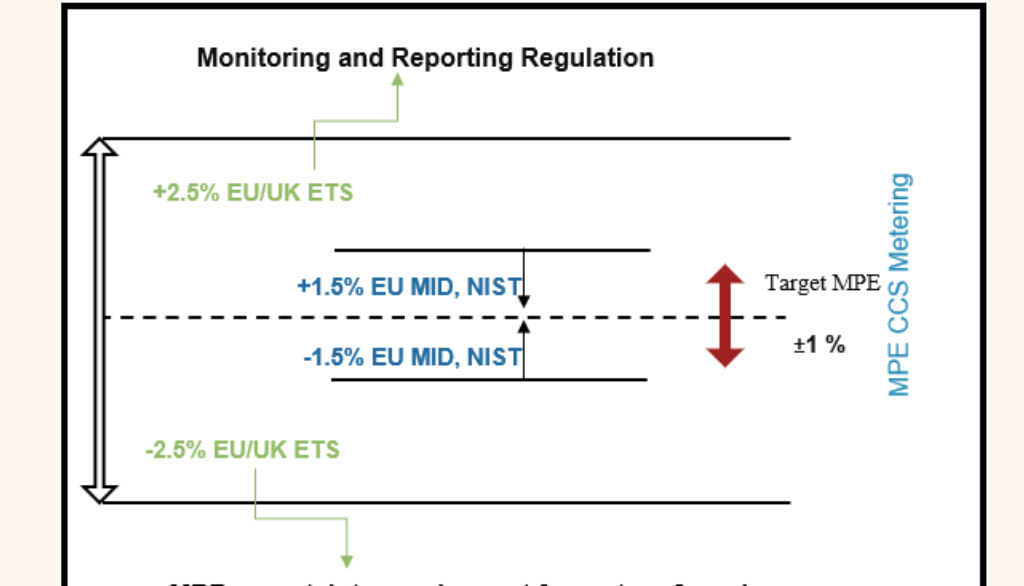
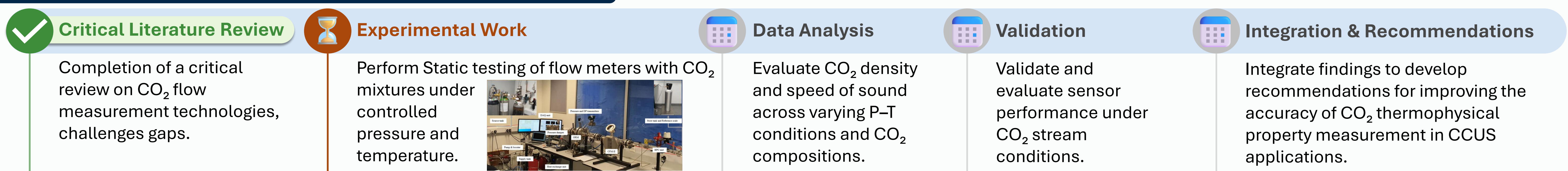


Figure 4: Flow measurement requirements across referencing systems (EU/UK ETS)

7. AIM AND OBJECTIVES

- AIM**
To improve the accuracy of CO₂ flow measurement, especially under dense and near-critical conditions for CCUS applications.
- OBJECTIVES**
- To experimentally investigate flow meter performance using CO₂ mixtures under controlled pressure and temperature conditions.
 - To measure key thermophysical properties (e.g. density and speed of sound) through advanced signal processing techniques.
 - Quantify measurement uncertainty across different CO₂ compositions and flow regimes.
 - To evaluate the performance and reliability of sensors under representative CO₂ stream conditions.

8. METHODOLOGY AND PLANNED TASKS



- Experimental Work includes:**
- Hardware Setup & System Understanding Phase 1:** Full system inspection, component verification, and development of a complete understanding of rig operation and configuration.
 - Phase 2:** Installation and configuration of pressure, temperature and flow meter sensors, with validation of real-time data acquisition and logging.
 - System Integration and Leak & Safety Testing Phase 3:** Integration of all system components, followed by system checks and verification through pressure testing using N₂, along with leak detection, pressure drop and safety validation to ensure stable and safe operation with CO₂.
 - Phase 4:** Gradually filling the system with CO₂ and running initial tests to check system response and stability and spot any issues.
 - Baseline Static Testing Phase 5:** Establishing baseline measurements under controlled P-T conditions and ensuring repeatability in the gas phase.
 - Near-Critical Investigation Phase 6:** Conducting tests near the critical region, applying controlled P-T variations while monitoring system behaviour and instabilities.
 - Validation & Optimisation Phase 7:** Repeating tests to ensure consistency, improving data quality and system stability, and resolving any experimental issues.

[1] IEA, CCUS in Clean Energy Transitions. Paris, France: IEA, 2020.
 [2] Department of Energy, Mines, Industry Regulation and Safety, Western Australian Government, “Carbon capture utilisation and storage: what is it?” Western Australia Government, Jan. 29, 2025.
 [3] J. Jimba, G. Chinello, R. Brown, S. Higgins, and M. M. Maroto-Valer, “Assessing Coriolis meter performance in multicomponent carbon dioxide-rich mixtures,” International Journal of Greenhouse Gas Control, vol. 136, Art. no. 104191, Jul. 2024, doi: 10.1016/j.ijggc.2024.104191.
 [4] I. Min, S.-G. Kang, and C. Huh, “Instability Analysis of Supercritical CO₂ during Transportation and Injection in Carbon Capture and Storage Systems,” Energies (Basel), vol. 11, 2018
 [5] J. Kocbach, M. B. Holstad, A. M. Skålvik, K. D. Lohne, B. Ystad, K. Folgerø, E. L. Soldal, S.-E. Losnegård, A. Paulsen, G. Mouton, and L. Teberikler, “Where do we stand on flow metering for CO₂ handling and storage?,” in *Proc. 38th Int. North Sea Flow Measurement Workshop*, Oct. 2020.