Introduction:
Carbon sequestration is essential for reducing CO_2 levels and combating climate change but has various barriers and operational challenges to overcome. This paper will address and discuss some of the key operational challenges associated with the development of CCUS industrial clusters and CO_2 transportation networks.

CO2 Sources and Specification:
CO_2 emitter selection significantly impacts the impurities in the CO_2 stream, which affects the ability to meet transportation system specifications, operating pressures, and flow rates. Onshore industrial sites (e.g., steel, petrochemicals) have consistent emissions but experience shutdowns, while onshore power generation (e.g., gas, biomass) is intermittent. Distributed sources (e.g., domestic heat, transport) are challenging to capture, and offshore industry (e.g., oil and gas) is remote from storage sites. Impurities like SO_x, NO_x, H_2S, and O_2 can form corrosive acids or deposit sulphur, while non-condensable components expand the multi-phase region, increasing operational risks and compression power requirements. Specifications are crucial for design, impacting operability, emitter selection, and materials choice.

Phase Behavior:
Review of the phase behavior of CO_2 highlights that pipelines tend to consist of CO_2 that is either within the gas phase or dense phase. Shipping tends to require a liquid state which becomes a challenge offshore for making it suitable for injection.

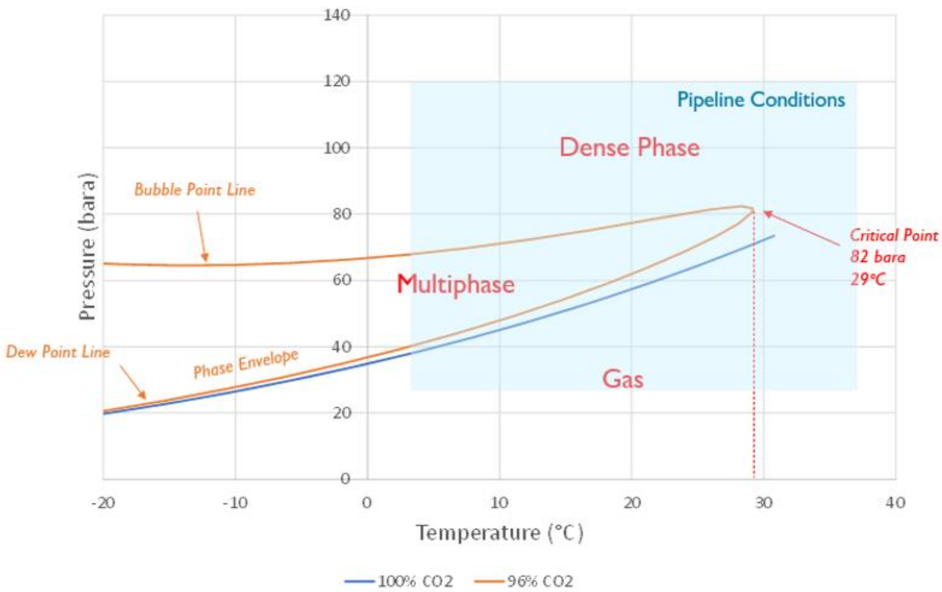

Figure 1 *Carbon dioxide, Temperature – pressure diagram for comparing pure and contaminated CO2 streams.*

Specification Considerations:
Off Spec considerations in CO_2 transportation systems will focus on key impurities such as water, which poses corrosion and hydrate risks, and non-condensables, which increase multiphase risk and impact compressor power. Critical decisions regarding the location of analysers must be made, determining whether to rely on emitter analysers or incorporate them into the Transport & Storage (T&S) system design. Brief off-spec excursions can affect corrosion and evaporation rates, with water exhibiting higher solubility in the dense phase compared to the gas phase. Inline inspection (ILI) is essential for pipeline integrity management, though it remains relatively unproven for CO_2 service and large

diameter pipelines. Pre-commissioning processes, including de-watering and drying prior to start-up, require stringent dryness criteria, potentially extending project schedules and cost estimates.

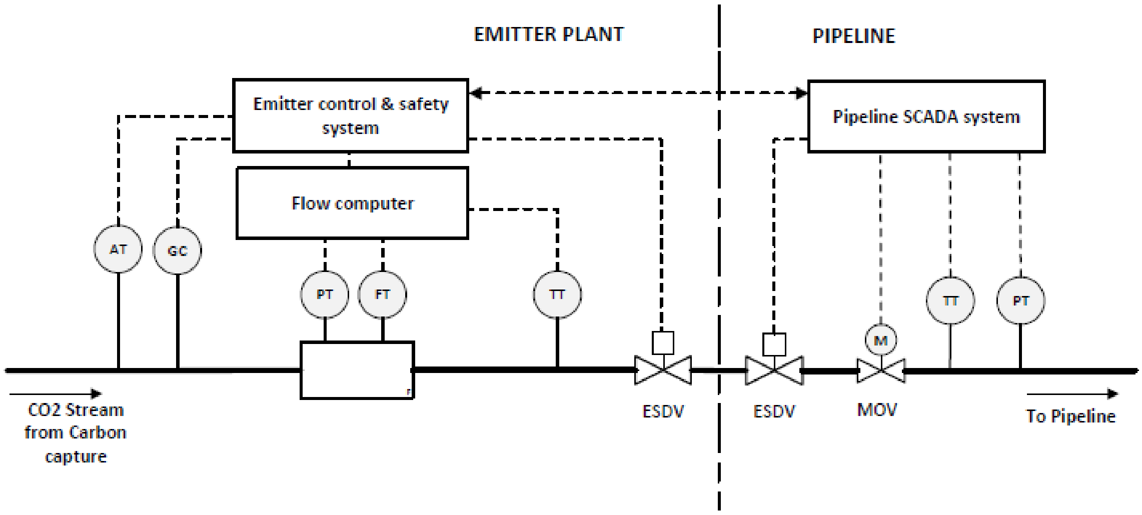

***Figure 2** Example process flow diagram for CCUS*

Variable Output and System Control:
Variable flow challenges arise from intermittent flow from dispatchable power plants and industrial emitter turndowns or shutdowns. These fluctuations impact pipeline pressure, requiring systems to maintain minimum pressure for dense phase or maximum pressure for gas phase. Wells may need frequent choke operations or frequent opening/closing to stay within operating limits, which is atypical for offshore oil and gas production networks. This frequent cycling increases risks of well completion damage, loss of injectivity, halite formation in saline aquifer storage sites, choke cycling, and pipeline fatigue. Solutions include designing and qualifying subsea tree valves to minimize valve failures, using "swing" wells to reduce valve cycling, implementing retrievable choke designs for easier maintenance, considering wash water facilities for saline aquifer sites, buffer storage to smooth flow variations, and onshore pressure control vents with flexible compressor operating strategies.

Early Life System Control:
Early Life Challenges involve low storage site pressures, particularly in depleted oil and gas reservoirs. Operational Impacts include Joule-Thomson (JT) cooling risks for gas phase operations and low bottomhole temperatures, which increase the risk of reservoir damage and affect pipeline minimum design temperatures. These issues are exacerbated by offshore injection well or platform outages. Solutions include the use of offshore heaters to ensure bottomhole temperature limits are maintained across all potential operating scenarios.

Late Life System Control:
Late Life Challenges arise as reservoirs pressurize, necessitating a switch from gas to dense phase operations. Operational impacts include increased pipeline operating pressure, requiring re-use and fitness assessments, and the need for offshore pressure control to maintain dense phase operation. There is also an increased heating requirement immediately after the switch when reservoir pressures are still low. Solutions involve ensuring heater capacity is available for the entire field life, including during operating phase transitions. The use of downhole choke valves can minimize wellbore Joule-Thomson (JT) cooling and heater load demand, though their operation, along with wellhead choke valves, can be complex, especially with variable flow. Downhole choke valves may need to be changed out if flow rates increase to prevent pipeline back pressures from exceeding design limits. Regular inline inspections (ILI) throughout the pipeline's life are essential to ensure suitability for dense phase operation, and ductile fracture risk assessments should be incorporated into the design.

Conclusions:

A feasible Carbon Capture, Utilization, and Storage (CCUS) Transportation and Storage (T&S) system must ensure steady state for both pipeline and well operations, with identified and assessed phase transitions and choke designs. It must operate within transportation system pressure and temperature limits, with a clear understanding of the operating limits of individual wells, including maximum and minimum flows and tolerance to cycling. The system should be designed for profile and operability limits, manage initial flows (small baseload), and accommodate overall maximum and minimum flows. An effective operating strategy for excursions is essential. Additionally, a feasible system must demonstrate complete integration, encompassing emissions profile, emitter/T&S interfaces and control, sequestration, compression, pipeline transportation, well control, and storage.

References

1. Peletiri SP, Mujtaba IM and Rahmanian N (2019) Process Simulation of Impurity Impacts on CO2 Fluids Flowing in Pipelines. Journal of Cleaner Production. 240: 118145.