VSL

National Metrology Institute

MetCCUS project overview

Seminar Metrology Support for Carbon Capture Utilization and Storage

Iris de Krom

26 October 2023 – Online

METCCUS

Carbon Capture Utilization and Storage (CCUS)

- Climate change
- Reduce greenhouse gas emission
  - 55 % by 2023
  - Carbon Neutral by 2050

- European Green Deal → Clean Energy
  - Clean hydrogen
  - Fuel cells and alternative fuels
  - Energy storage
  - **CCUS**
    - Decrease CO_2 emissions
    - Primary greenhouse gas

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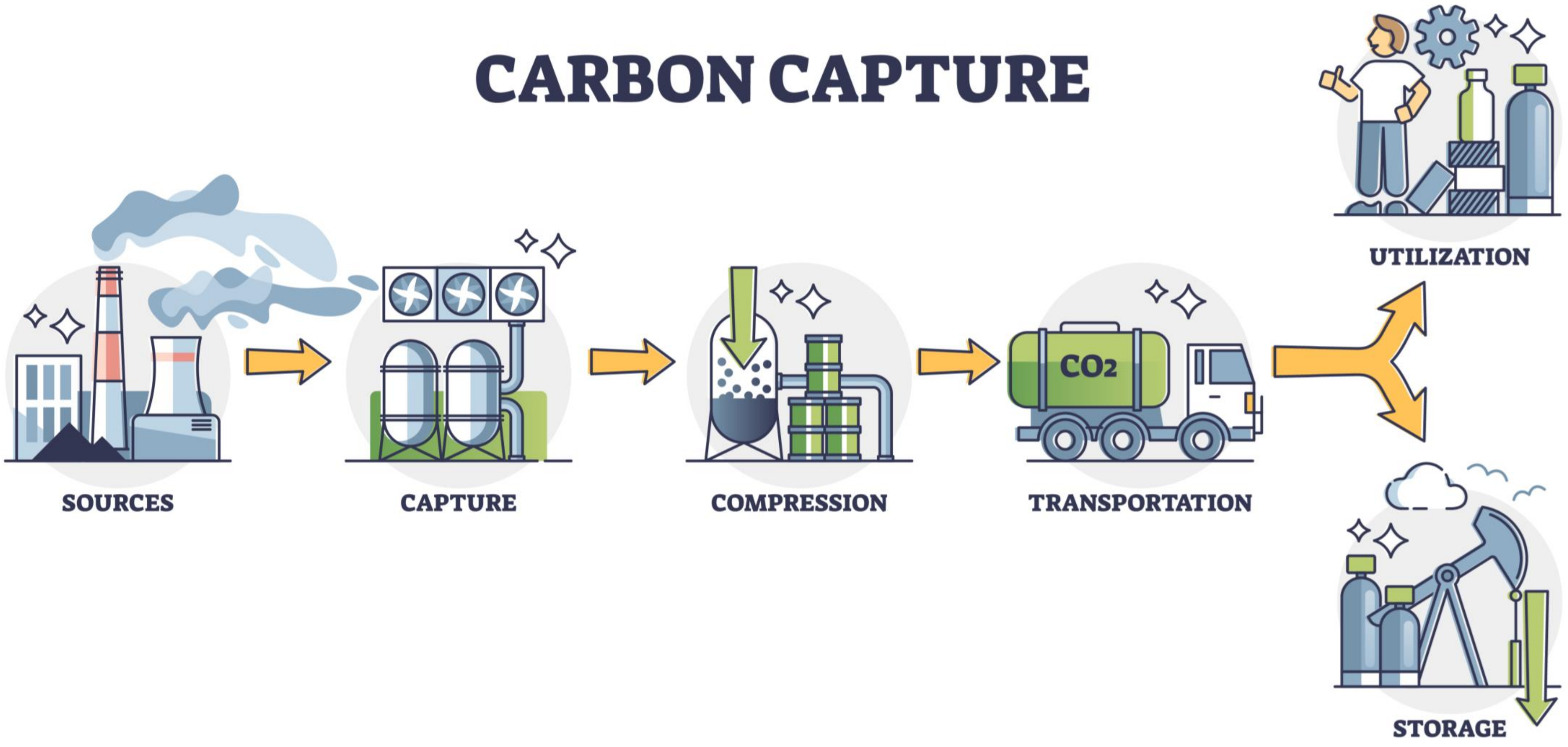
CCUS process

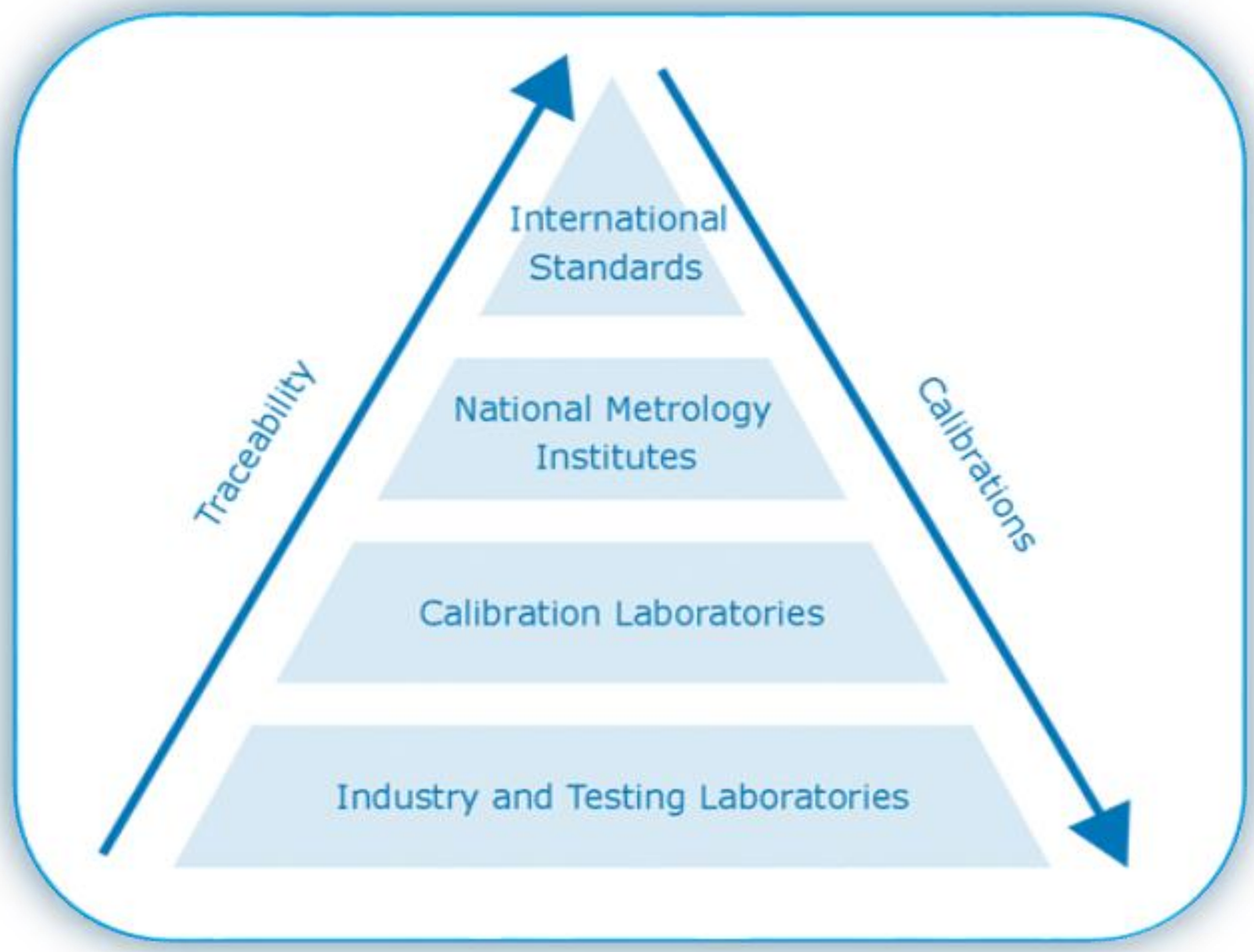


Metrology support for CCUS

- 1 October 2022 – 30 September 2025
- 21 participants

"The project has received funding from the European Partnership on Metrology, co-financed by European Union Horizon Europe Research and Innovation Programme and from the Participating States."

Metrology



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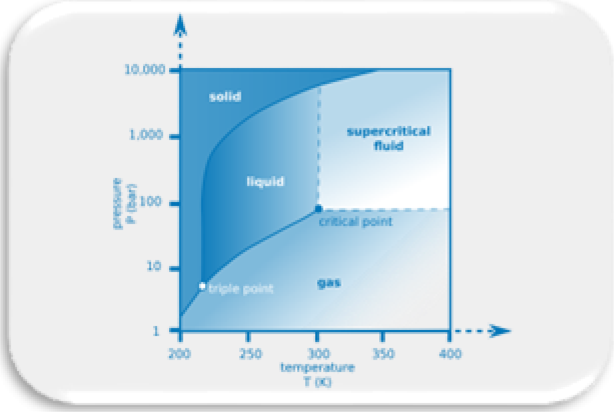
CCUS measurement challenges

Flow metering

Emission monitoring

Chemical metrology

Physical properties



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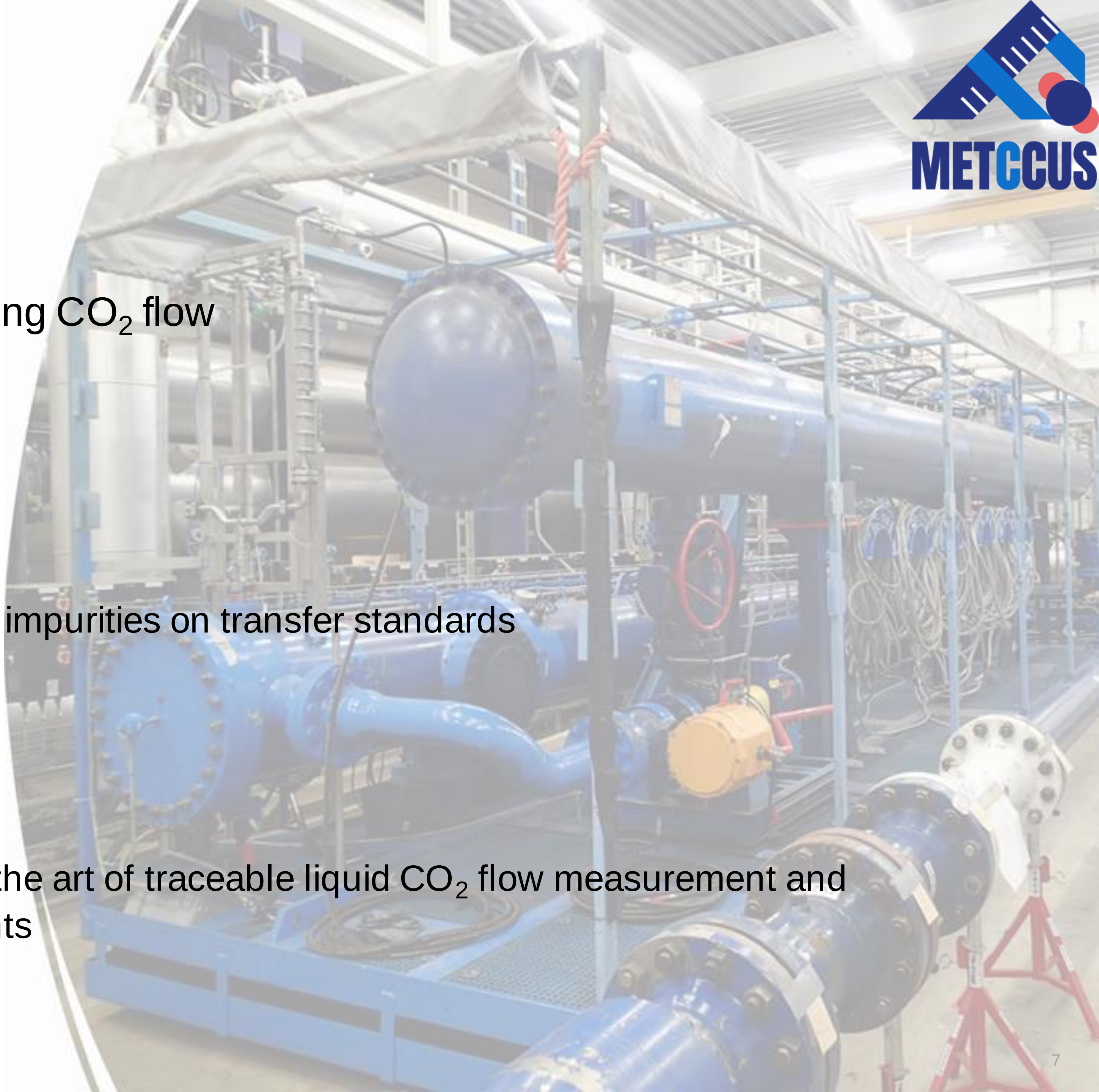
Flow metering



Gas-flow

- Metrology infrastructure for monitoring CO_2 flow
  - < 50 m^3/h and low pressure
  - Up to 400 m^3/h and higher pressure
- Primary and transfer standards
  - Intercomparison
  - Theoretical investigate the impact of impurities on transfer standards
- Uncertainty 1.5 % - 2.5 %

Liquid flow

- Study to determine the current state of the art of traceable liquid CO_2 flow measurement and liquid CO_2 primary standard requirements

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Emission monitoring

METCCUS

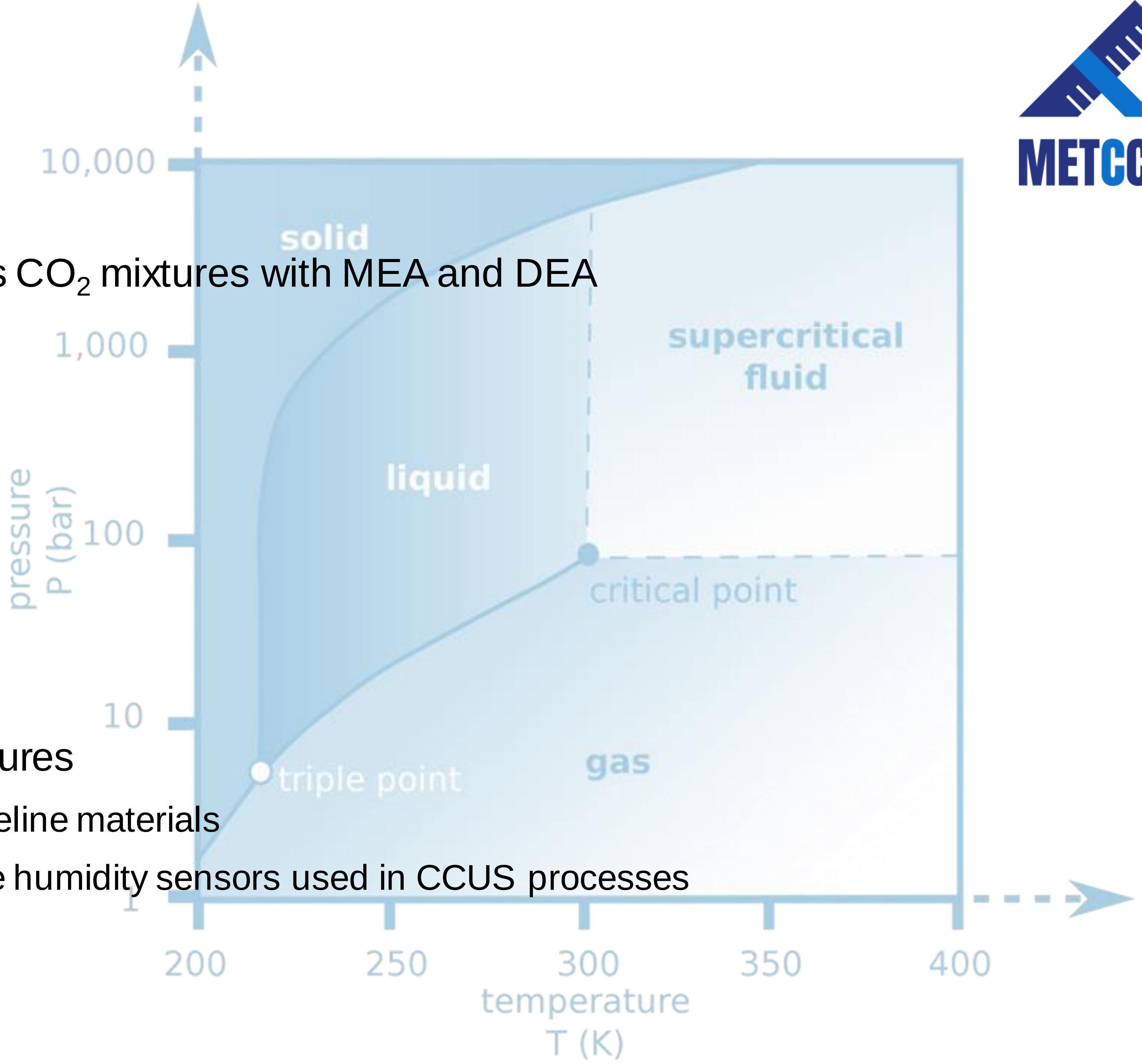
- Atmospheric emissions of CO_2 from CCUS
- Measurement of degradation products from capture solvents
  - First European reference methods for monitoring breakdown products from amine-based solvents (CEN/TC 264)
- Measurement and quantification of CO_2 emissions from equipment and infrastructure
  - Leaks → fugitive emissions
  - Facility scale → diffuse and fugitive emissions
- Detection and quantification of CO_2 emissions from geological storage
  - Isotopic measurements
  - Addition of tracers
  - Use of acoustic techniques

Chemical metrology

- Primary reference materials for impurities in CO_2
  - Key impurities e.g.; H_2O, NO_x, sulphur compounds, hydrocarbons, alcohols and amines
  - Permanent gases: O_2, Ar, N_2, CH_4, CO, H_2
- Material compatibility for CO_2 sampling
- Online CO_2 monitoring
  - Development and validation of online methods
  - Round Robin Test for the measurement of impurities in CO_2
- Offline analytical methods for CO_2 quality
  - CO_2 capture, transport and storage
  - CO_2 conversion, utilisation and recycling

Physical properties

- Experimental measurements CO_2 mixtures with MEA and DEA
  - Density
  - Speed of sound
  - Viscosity
  - Heat capacity
- Equation of state models
  - CCUS processes
  - Flow metering
- Monitoring CCUS infrastructures
  - Corrosion testing of CO_2 pipeline materials
  - Calibration method for online humidity sensors used in CCUS processes



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Impact MetCCUS

- Development of
  - Standards and reference materials
  - Calibration and measurement methods
  - Good practice guides
  - Literature reviews & peer reviewed articles

- Support
  - Development of key documentary standards, specifications and regulation
  - Safe and efficient CCUS operation
  - CCUS industry to become carbon neutral and overcome climate change

Thank you for your attention

- Visit
  - www.metccus.eu
  - MetCCUS: Overview | LinkedIn

- Contact

Project coordinator
Iris de Krom
idekrom@vsl.nl

The European Metrology Network for Energy Gases

Annarita Baldan
EMN Chair

26 October
MetCCUS seminar

Drivers

- International:
  - 1.5-degree ambition set under the Paris Agreement

- Europe:
  - Binding target of 55% reduction in GHGs by 2030 compared with 1990
  - Green Deal and “Fit for 55” Package

- Foreseen complex energy mix in the next decades: natural gas, LNG, biogas, biomethane, hydrogen and any future renewable gas

ENERGY GASES

How can metrology support the energy gas transition?

Need

Ensure the compliance with quality, efficiency, safety requirements

Ensure fair energy gas exchange between countries and trade

Challenge

Reliability and robustness of measurement results to address the energy transition beyond national boundaries and beyond a single technology

Solution

European coordinated effort to interface and collect stakeholder needs and to address these needs in the most efficient way at metrological, standardization, and policy level

European Metrology Network for Energy Gases

ENERGY GASES

EMN for Energy Gases

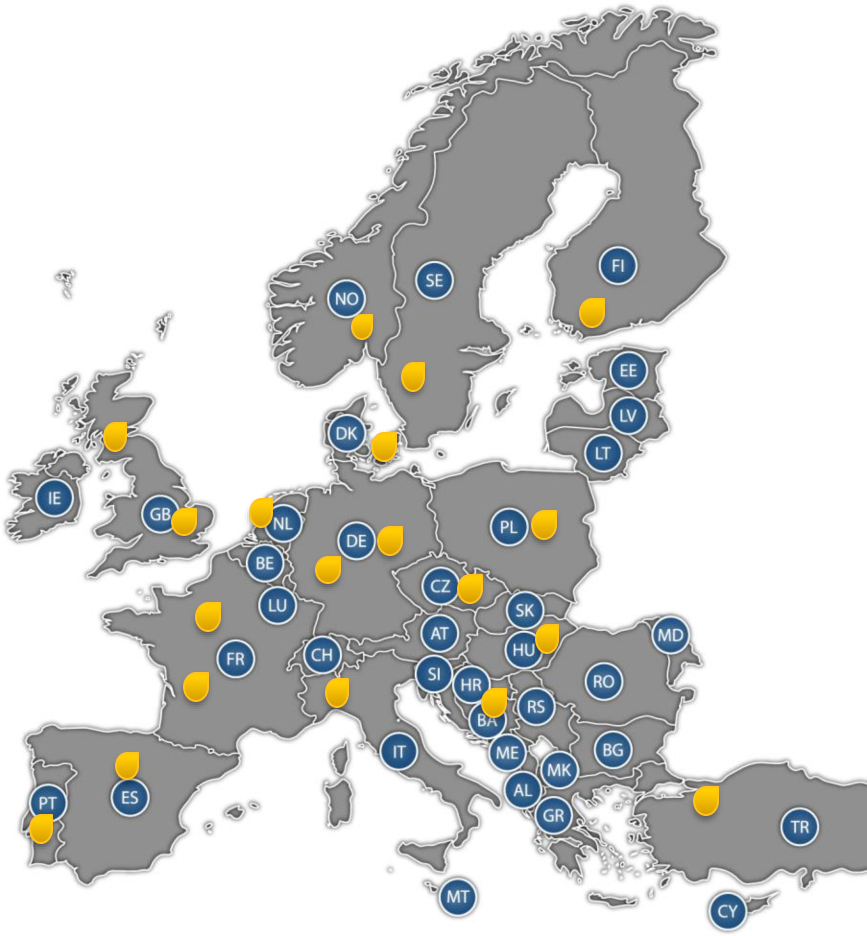
EURAMET

Under EURAMET

Official start: February 2019

19 NMI/DI members

Organisation		Task Groups
Chair:	Annarita Baldan (VSL, NL)	1 – Strategic Research Agenda
Vice-chair	Karine Arrhenius (RISE, SE)	2 – Measurement Service Platform
Secretary	Marcel Workamp (VSL, NL)	3 – Stakeholder Engagement & Standardisation
Steering committee	Henri Foulon (LNE-LADGFR) Heinrich Kipphardt (BAM, DE) Arul Murugan (NPL, UK) Florbela Dias (IPQ, PT) Vito Fernicola (INRiM, IT)	4 – General Communication & Impact 5 – Funding opportunities 6 - Synergies



VSL National Metrology Institute · CESAME-exadébit SA · nel flow measurement services · FORCE TECHNOLOGY · BAM · PTB · IMBIH · IPQ · Justervesenet · NPL · TÜBİTAK UME · LNE · Budapest Főváros Kormányhivatala · MIKES METROLOGY · RISE · CEM Centro Español de Metrología · Central Office of Measures · INRiM Istituto Nazionale di Ricerca Metrologica · CMI Czech Metrology Institute

ENERGY GASES

EMN for Energy Gases Fact Sheet

- Focus on **metering and use of energy gases**: conventional fluids and fluids related to (emerging) renewable/ sustainable energy sources, including CCUS

- **Mission**: To provide the world's leading metrology network comprising experts in the field of measurement science to **drive forward innovation** and to **accelerate decarbonisation and emissions reductions** within the energy gas industry in Europe

❖ **Engage** with industry, regulation, standardization, policy (e.g. Hydrogen Europe, Clean Hydrogen Partnership, GERG, MARCOGAZ, DG Energy)

❖ **Act** as **European metrology knowledge center** for energy gases (www.euramet.org/energy-gases)

❖ **Facilitate energy transition** by coordinating measurement research based on stakeholder needs

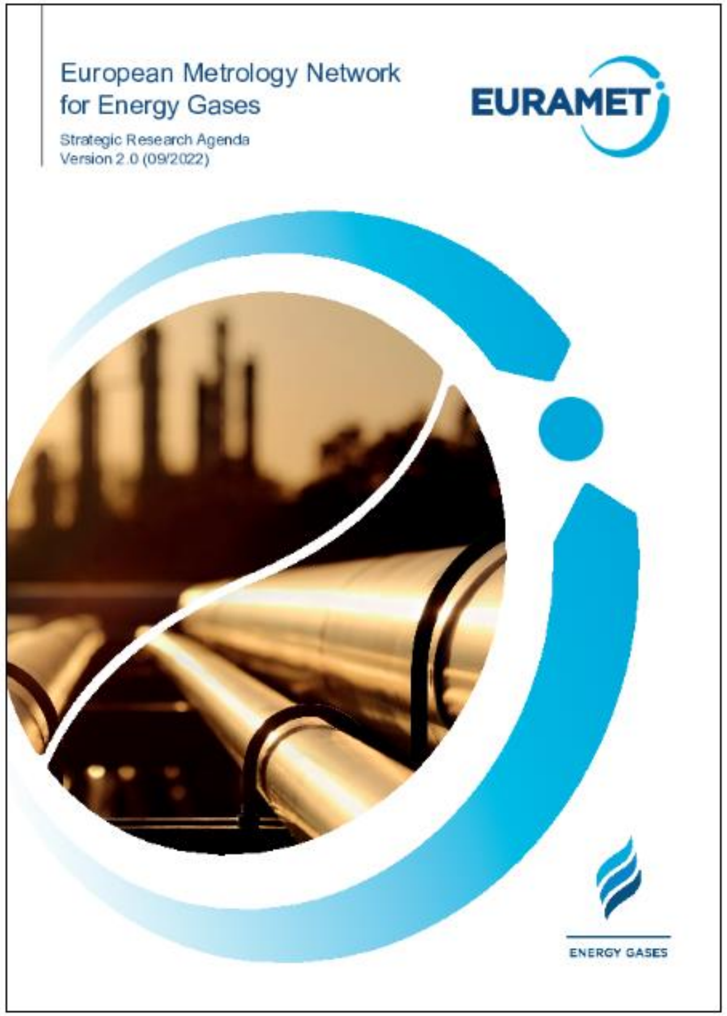
❖ **Boost access** to metrological services and calibration facilities

Cross-cutting character:

Gas composition	**Calorimetry**
Certified Reference Materials	**Particles**
Flow	**Humidity**
Temperature	**Material data**
Pressure	**Material testing**

EMN Strategic Research Agenda

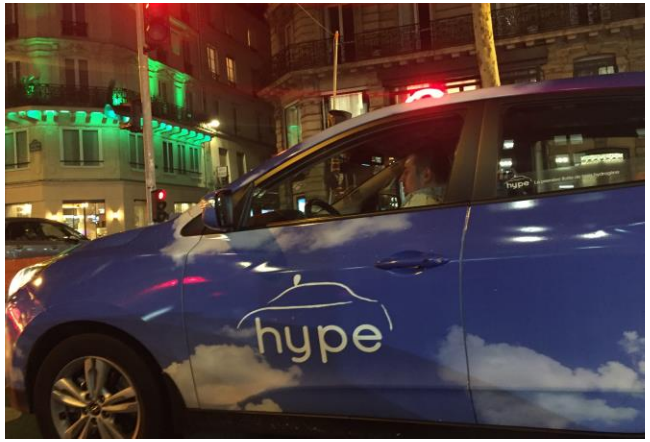
- SRA published on EMN website (2nd revision 09/ 2022)
- Focused on measurement needs covering energy gases (natural gas, LNG and LBG, biogas and biomethane and hydrogen) and carbon sequestration and use (CO_2)
  - **Decarbonising natural gas**
  - **Decarbonising industry**
  - **Energy transport and storage**
  - **Cleaner fuel for mobility**



Objective:

Facilitate new projects in Research & Innovation and collaboration with industry and other research parties

European Metrological Research in Energy Gases - Portfolio



GAS
MultiFlowMet

NEWGASMET
Decarb
MetCCUS

LNG
I, II, III

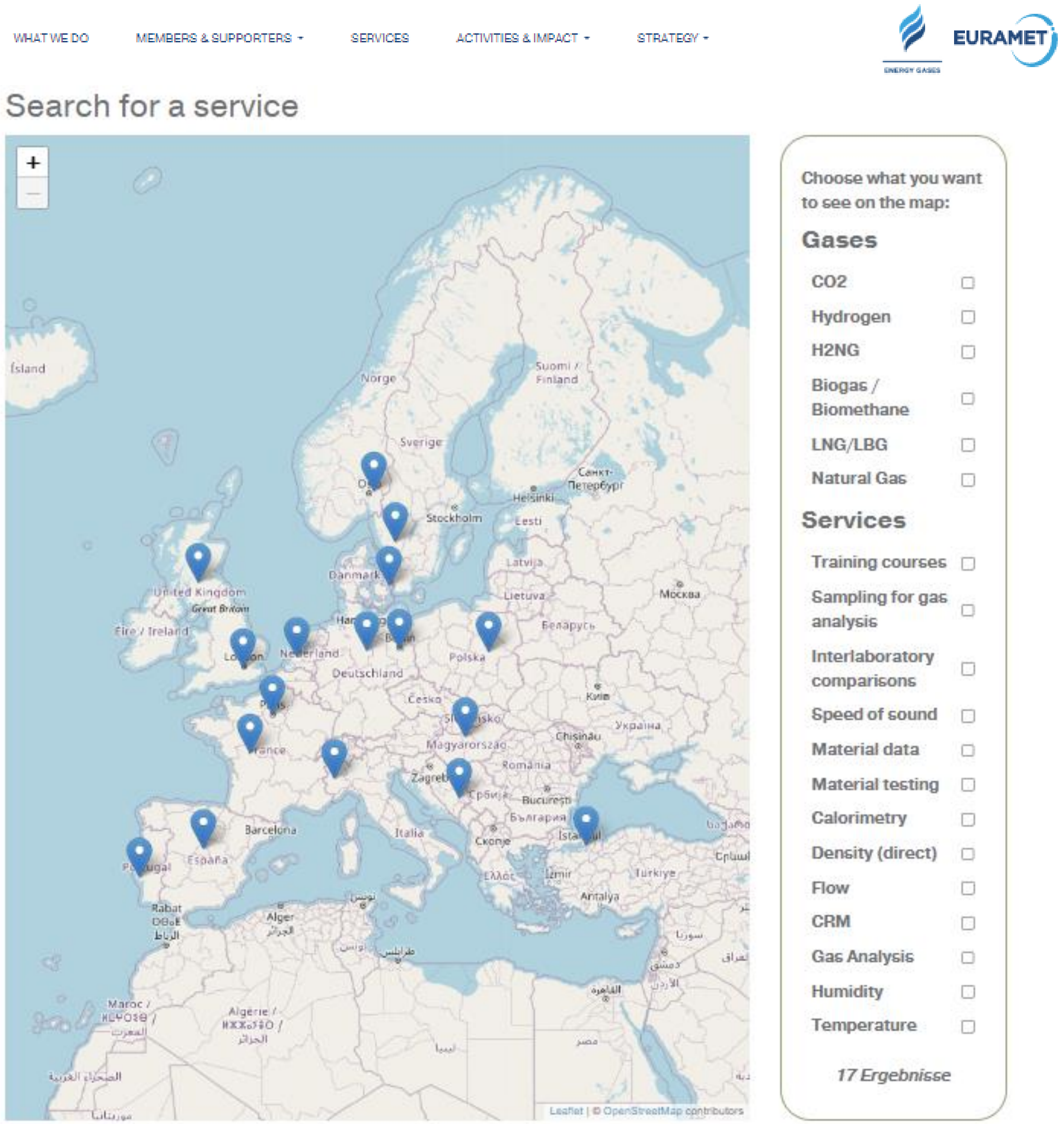
EMRP/EMPIR/EPM
2010 - 2023

Mefhysto
MetHyinfra
Met4H2
MetHyTrucks

BIOGAS
BIO-METHANE
Si-S/Biogas
BiometCAP

HYDROGEN
MetroHyVe 1, 2

Measurement Service Platform



- Overview of the metrological services in Europe
- EMN for Energy Gases website

www.euramet.org/energy-gases/

ENERGY GASES

Conclusions

- Call to action for addressing climate change and energy transition in Europe and worldwide
- European Metrology Network for energy gases established with focus on sustainable energy gases and decarbonization
- Role of Metrology and related research projects to develop measurement methods and standards in support of the energy gas transition
- We look forward engaging with the parties involved in CCUS

Interested in becoming stakeholder ?

More info:

EnergyGases@euramet.org

www.euramet.org/european-metrology-networks/energy-gases/

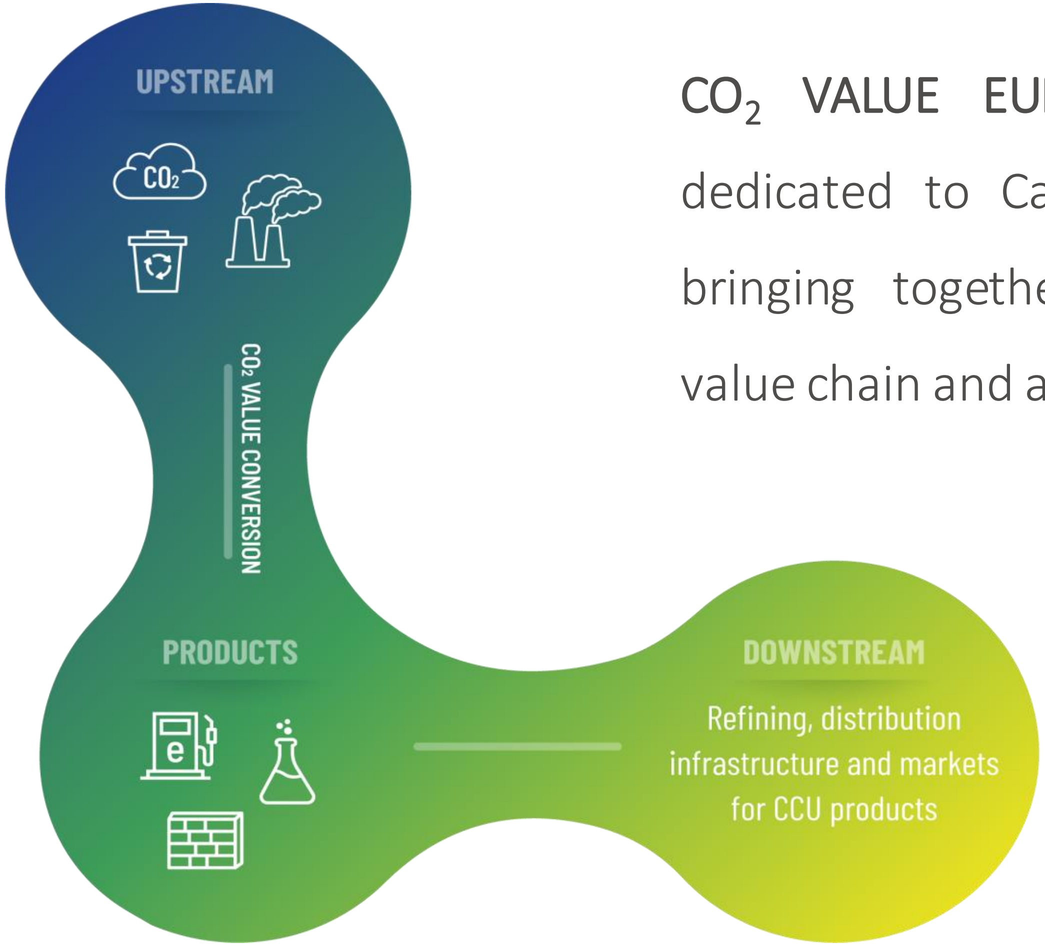
CCU in Europe – A broad overview

Anastasios Perimenis, Secretary General

MetCCUS

25 October 2023

The Association



CO_2 VALUE EUROPE is the European association dedicated to Carbon Capture & Utilisation (CCU), bringing together stakeholders from the complete value chain and across industries.

Membership base (91)

30 Large Companies

ALBIOMA, Axens (Powering integrated solutions – An IFP Group company), CARMEUSE, climeworks, CRH, CRISTAL_UNION, drax, Endress+Hauser (People for Process Automation), ENGIE, FLUOR, fortum, HOLCIM, Keppel Seghers, Lhoist, lyondellbasell, Mitsubishi Corporation, MITSUBISHI HEAVY INDUSTRIES, NEA GROUP, ORLEN, SAINT-GOBAIN, SAIPEM, SIBELCO, SOLVAY, Stepan, Svante, TERĒGA, VEOLIA, VICAT, WIEN ENERGIE

25 Research Organisations

cea, DIFFER (Dutch Institute for Fundamental Energy Research), EPFL, GHENT UNIVERSITY, ICIQ (Institute of Chemical Research of Catalonia), IFP Energies nouvelles, iit (Istituto Italiano di Tecnologia), imec, KIT (Karlsruher Institut für Technologie), LEITAT (managing technologies), nova Institute, NOVAID, SOTACARBO, SWERIM, tecnalia, TNO (innovation for life), UCLouvain, Universidad LOYOLA, Alma Mater Studiorum Università di Bologna, LIÈGE université, UMONS (Université de Mons), Universidad de Sevilla, University of Surrey, vito, VTT

30 SMEs

accelera (by Cummins), again, Biostoom, carbon8, carbon clean, CarbonWorks, Carbon Recycling International, cynergie, D-CRBN, eChemicles, Dioxycle, econic, Enviro Ambient, HYSYTECH, IC2R, INFINIUM, KHIMOD, LanzaTech, MGH energy, NeoCarbons, neustark, Nordic Electrofuel, norsk e-fuel, Paebbl, orbix, sunfire, Synkero, TES (Hydrogen for life), VERSO energy, ZETON

6 Clusters

axelera, cdec, ePURE (european renewable ethanol), EURAÉNERGIE (Parc d'innovation), GREENWIN, THE JAPAN GAS ASSOCIATION

CO2 VALUE EUROPE

Priorities

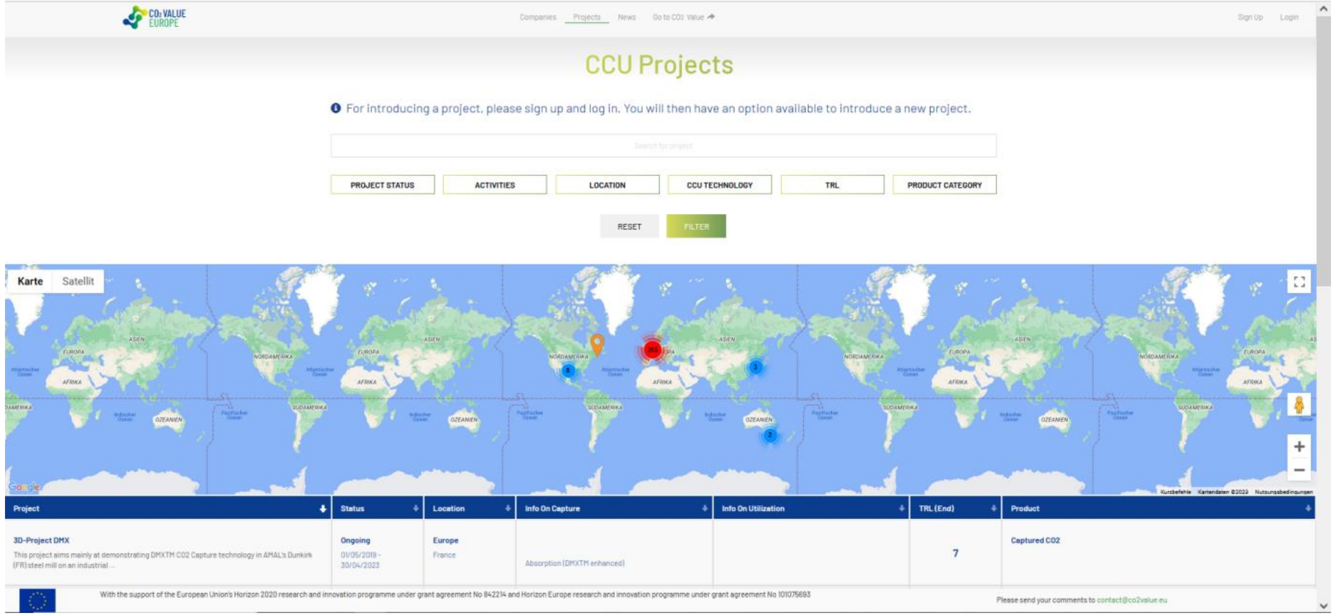
Provide scientific & technical knowledge and evidence-based information on CCU

Raise awareness, engage with stakeholders, communicate about CCU and CVE

Create a supportive and consistent regulatory framework for large-scale deployment of CCU

Support and accompany the development of both innovative and industrial-scale projects

CCU Database



- https://database.co2value.eu/
- Ongoing and upcoming CCU projects
- CCU technology providers
- News on EU-funded projects
- Metrics last 3 months
  - 1.7 k new users
  - 2m 21s average engagement time

Funding

- Innovation Fund 3rd large scale call
  - 41 projects selected → over €3.6 billion to be granted
  - 12 projects have a CCU or CCS element
  - Next: IF23 call (small-, medium-, large-scale call) → 23/11/23 – 09/04/2024 → €4 billion
  - Next: IF23 auction on renewable hydrogen → 23/11/23 – 08/02/2024 → €800 million
- Horizon Europe: more than €235 million granted to R&D&I projects so far

NEW Legislations published in 2023

SOON Legislations in the pipeline

Policy framework

NEW REDIII & REDII Delegated Acts	ETS revision	ReFuel EU Aviation	Fuel EU Maritime	Energy Taxation Directive	Carbon Removal Certification	Restoring Sustainable Carbon Cycles
EU Taxonomy for sustainable Finance	Carbon Border Adjustment Mechanism	SOON EU climate targets for 2040	NEW Net Zero Industry Act	SOON Industrial Carbon Management	EU gas & hydrogen package	SOON ETS Delegated Act
SOON Low Carbon Fuels Delegated Act	Sustainable Products Initiative	SOON Delegated Act on cars CO_2 standards	Hydrogen Strategy	Alternative Fuels Infrastructure	NEW Heavy Duty Vehicles Regulation	EU Wind Power Package
Effort Sharing Regulation	NEW Temporary Crisis & Transition Framework	NEW General Block Exemption Regulation	Packaging & Packaging Waste Directive	Energy Efficiency Directive	Climate, Energy, Environmental Aid Guidelines	National Energy Climate Plans
		Recovery and Resilience Facility	Waste Framework Directive	Cross-border renewable energy projects		

CO2 VALUE EUROPE

Policy framework

Instrument	Impact on CCU
EU ETS revision	✓ CO_2 which is chemically and permanently bound in a product under normal use (e.g. mineralisation) is excluded from the obligation to surrender allowances; ✓ Avoid double-counting of emissions released by the use of RFNBOs
RED revision (REDIII)	✓ Combined target of advanced biofuels + RFNBO*: minimum 5.5% of energy in transport by 2030 ✓ Sub-target for RFNBO: minimum 1% of energy in transport by 2030 ✓ 42% of the use of hydrogen in the industry to be RFNBOs by 2030, 60% by 2035
REDII Delegated Acts	✓ Rules on additionality, geographical and temporal correlation of RFNBO production ✓ Methodology to calculate 70% GHG emission reduction for RFNBO/RCF; eligibility of CO_2 sources (e.g. DAC, bioCO_2, industrial ETS CO_2 until 2036/2041)
ReFuelEU Aviation	✓ SAFs quotas : min 6%, 20%, 34%, 42%, 70% by 2030/25/40/45/50 respectively ✓ Synthetic aviation fuels quotas : min 0.7%**, 5%, 10%, 15%, 35% by 2030/35/40/45/50 respectively
Fuel EU Maritime	✓ Binding GHG reduction targets for ships: 2%, 6%, 14.5%, 31%, 62%, 80% in 2025/30/35/40/45/50, respectively ✓ 2% RFNBOs quota in 2034 if RFNBOs account for less than 1% in fuel mix in 2031; multiplier "2"
Sustainable Carbon Cycles *(non legislative)*	✓ Min. 20% of carbon in chemical and plastic products should be from sustainable non-fossil sources by 2030 ✓ Tracing the origin of CO_2 used in products
Energy Taxation revision (on-going)	✓ Minimum taxation rate of zero for 10 years for RFNBOs for specific types of air and waterborne navigation.
Net Zero Industry Act (new)	✓ CCU is a net-zero technology, but not a "strategic" net-zero technology
EU Certification for Carbon Removals	✓ DAC/BioCO_2 to mineralisation recognised as removal

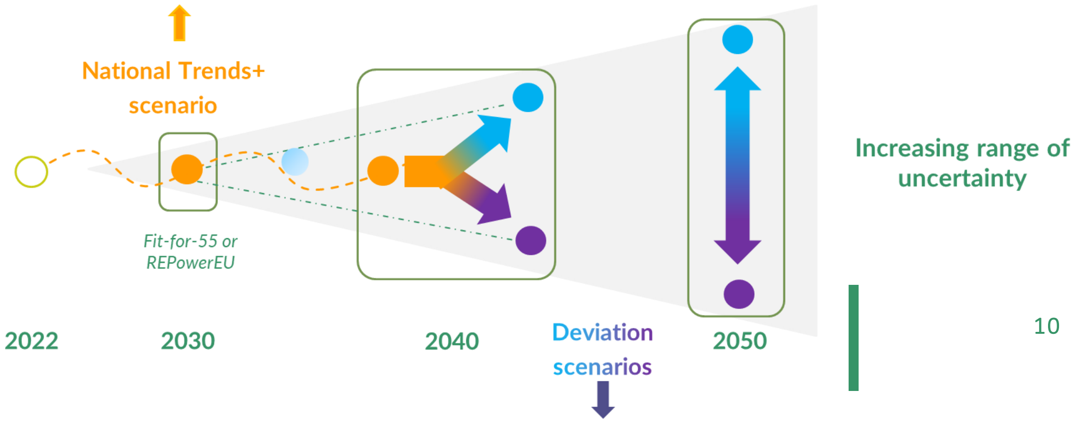
** RFNBO = Renewable fuel of non-biological origin ; ** further average and minimum shares to be covered between 2030-2034*

CCUS Forum & the Industrial Carbon Management Strategy

- Stakeholder Platform providing inputs for the elaboration of the ICMS (CCS, CCU, CDR)
- Working Groups on Industrial Partnership, Infrastructure, Public perception, Strategy elaboration
  - *Infrastructure focus:*
    - *Issue paper: Towards a European cross-border CO_2 transport and storage infrastructure*
    - *Issue paper: An interoperable CO_2 transport network – towards specifications for the transport of impure CO_2*
    - *Study: EU regulation for the development of the market for CO2 transport and storage*
    - *Study under preparation by JRC on scenarios of infrastructure development for cross-border CO_2 transport*
- CCUS Forum plenary 27-28/11 in Aalborg
- ICMS to be published during Q1 2024

Ten Year Network Development Plan (TYNDP)

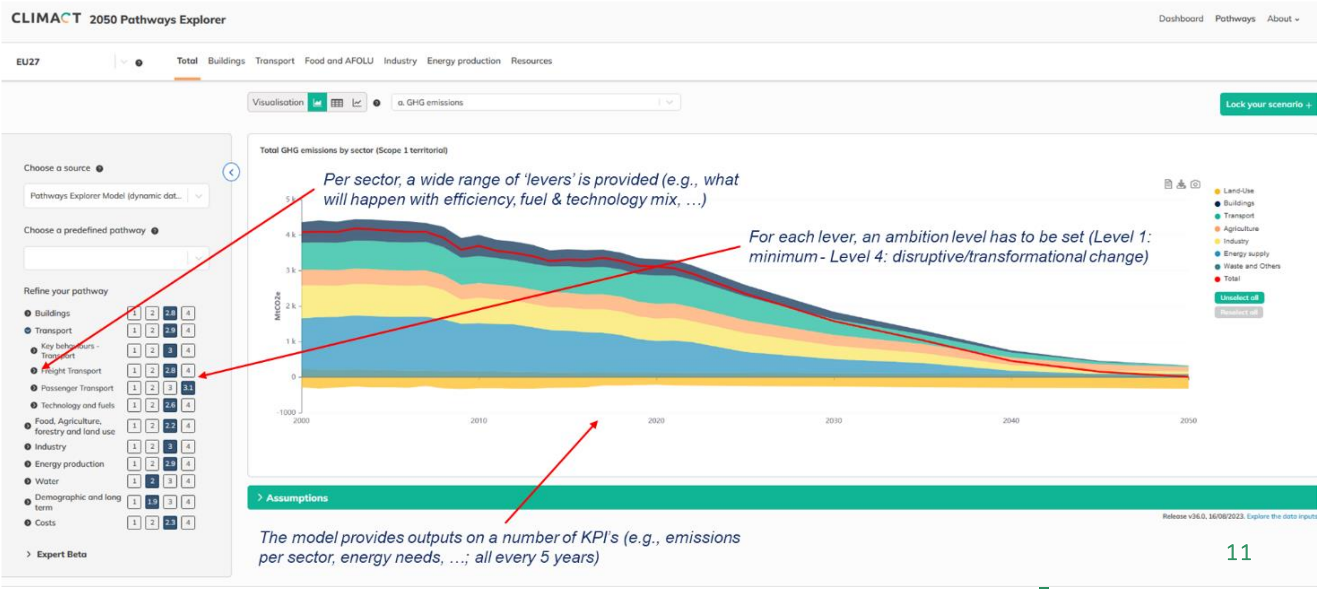
- Bi-annual exercise for the develop of scenarios for the future energy system conducted by ENTSO-E and ENTSO-G
- Building from national investment plans prepared by TSOs & stakeholder feedback on parameters and methodologies, the TYNDP models scenarios of future infrastructure development.
- CVE is part of the External Technical Advisory Group as CCU/CCS stakeholders have been expressly requested
- To be seen how CO_2 transport will be integrated in the TYNDP
- Webinar on future system needs on 06/11



CCU's contribution to net-zero

CVE's EU Roadmap for CCU deployment by 2050

- ❑ Scenario development and modeling of CCU pathways
- ❑ How much can CCU contribute towards EU's climate neutrality goals ?
- ❑ How much carbon do we need to capture ?
- ❑ How much captured carbon can be converted to fuels, chemicals and materials ?
- ❑ How much electricity will we need ?
- ❑ *Available as of mid-November*



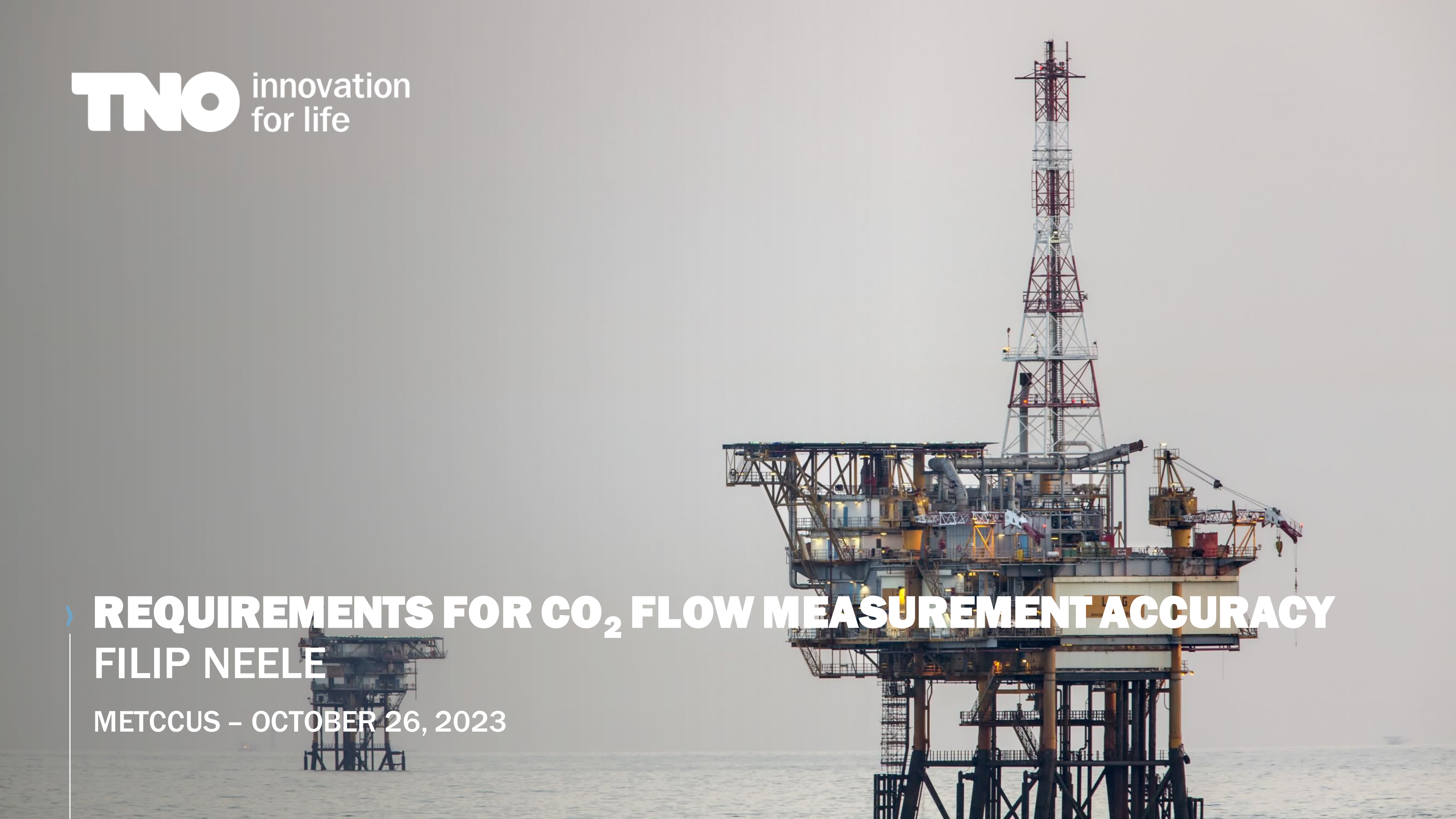
CO2 VALUE EUROPE

Thank you!

anastasios.perimenis@co2value.eu

www.co2value.eu

FOLLOW US ON



TNO innovation for life

REQUIREMENTS FOR CO_2 FLOW MEASUREMENT ACCURACY

FILIP NEELE

METCCUS – OCTOBER 26, 2023

CCS DEVELOPMENTS IN EUROPE
FROM SIMPLE TO COMPLEX

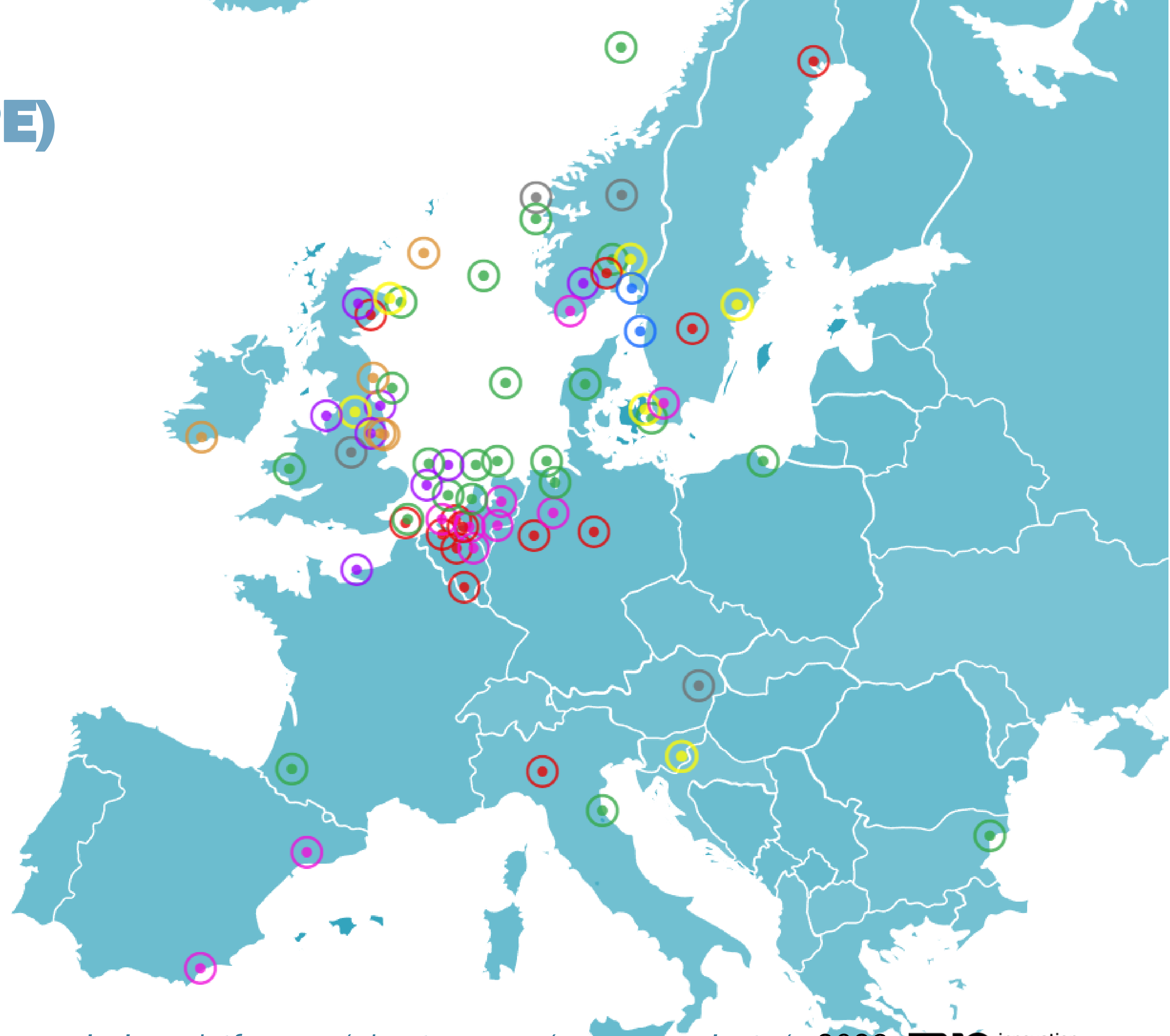
1. CCS developments switching to higher gear
   - *Many* new projects in recent years
   - No commercial CCS transport & storage projects in operation yet
2. Focus on NL
   - Several projects in development
   - Complex CCS infrastructure expected
3. Transport modalities
   - First projects: pipeline, ship
   - More modalities to follow soon

CO_2 leaking from truck
Netherlands, 1960s

Artist's impression of CO_2 tranker
at Northern Light ship terminal

CCS PROJECTS (EUROPE)

- Project count (mid 2023): >60
- Several storage projects to come online in period 2025 – 2030
  - Linking onshore emitters to offshore storage capacity



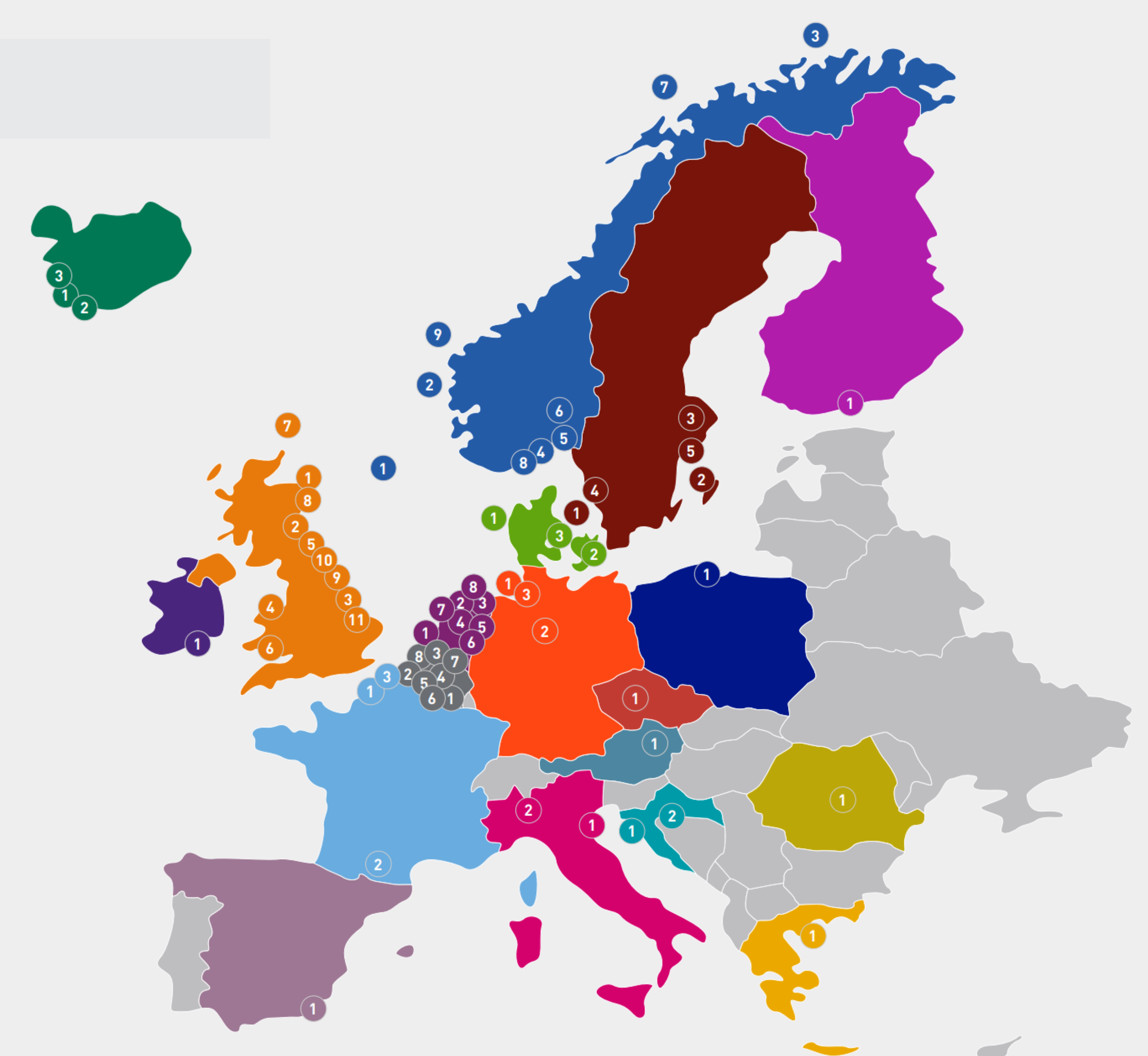
- Full-chain CCS – 4 (Orange)
- CO2 transport and storage – 19 (Green)
- CCS in industry – 12 (Red)
- CCS in energy production – 7 (Yellow)
- Low-carbon hydrogen production – 8 (Purple)
- Carbon Capture and Utilisation – 9 (Pink)
- Test centre – 4 (Grey)
- Limited information available (3) (Blue)

https://zeroemissionsplatform.eu/about-ccs-ccu/css-ccu-projects/, 2023

CCS PROJECTS (EUROPE)

- 65 CCS projects in Europe in development
- Several modes of transport
  - Pipeline, ship, barge
  - Train, truck
- Many interfaces

Total number of projects: **65**
Around 60 MtCO_2/yr stored by 2030

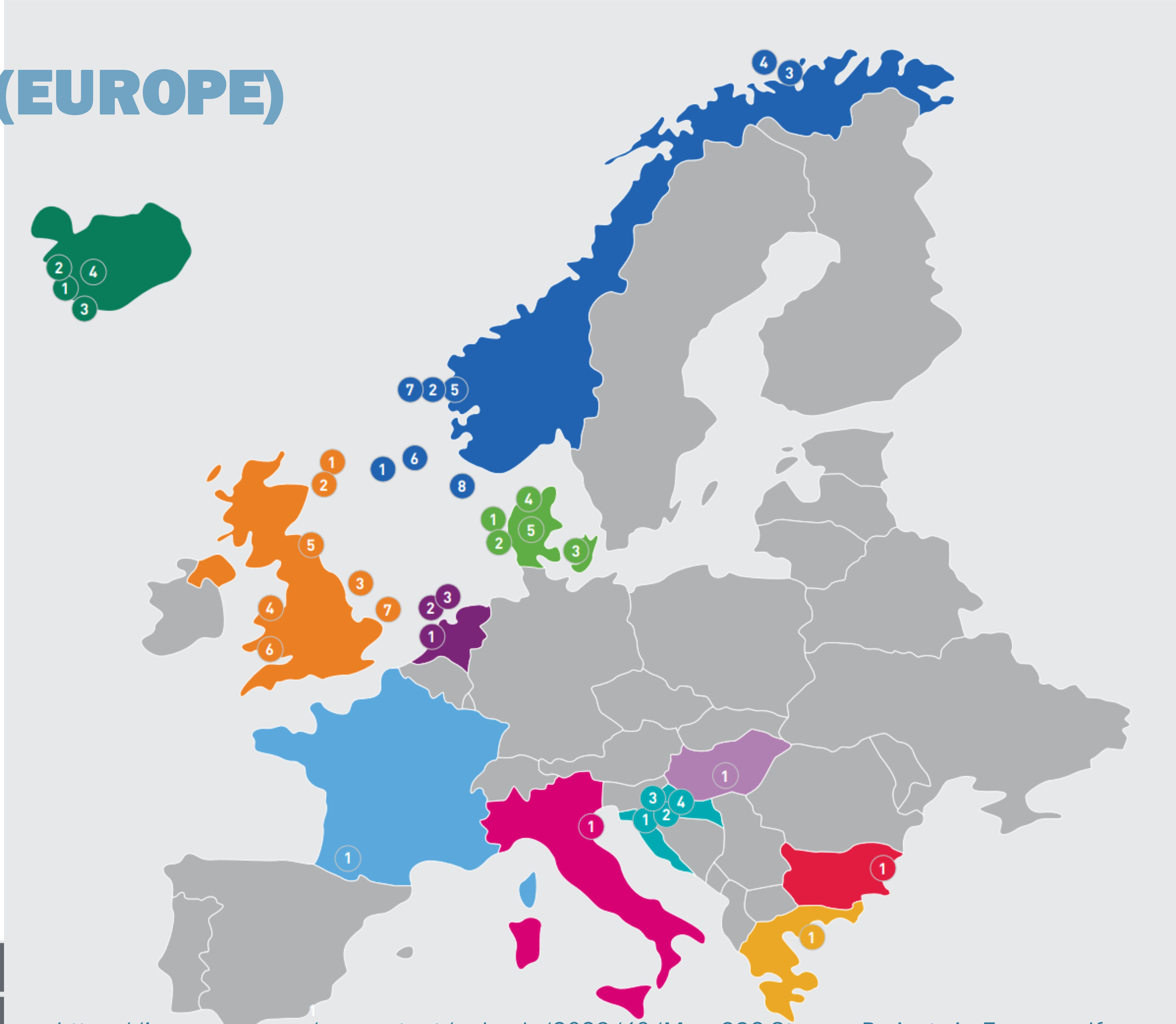


https://www.iogp.org/bookstore/product/map-of-ccs-projects-in-europe/

CO_2 STORAGE PROJECTS (EUROPE)

- Many CCS projects around the North Sea
- Many storage projects close to financial investment decision; many projects in feasibility phase
- Transport *to* these projects
  - Pipeline (gas phase)
  - Pipeline (dense phase)
  - Pipeline gas *and* dense phase
  - Ship (medium pressure)
  - Ship (low pressure)

EU	**17 projects** - 35 $MtCO_2$/yr by 2030
Europe	**36 projects** - 110 $MtCO_2$/yr by 2030



https://iogpeurope.org/wp-content/uploads/2023/10/Map-CO2-Storage-Projects-in-Europe.pdf

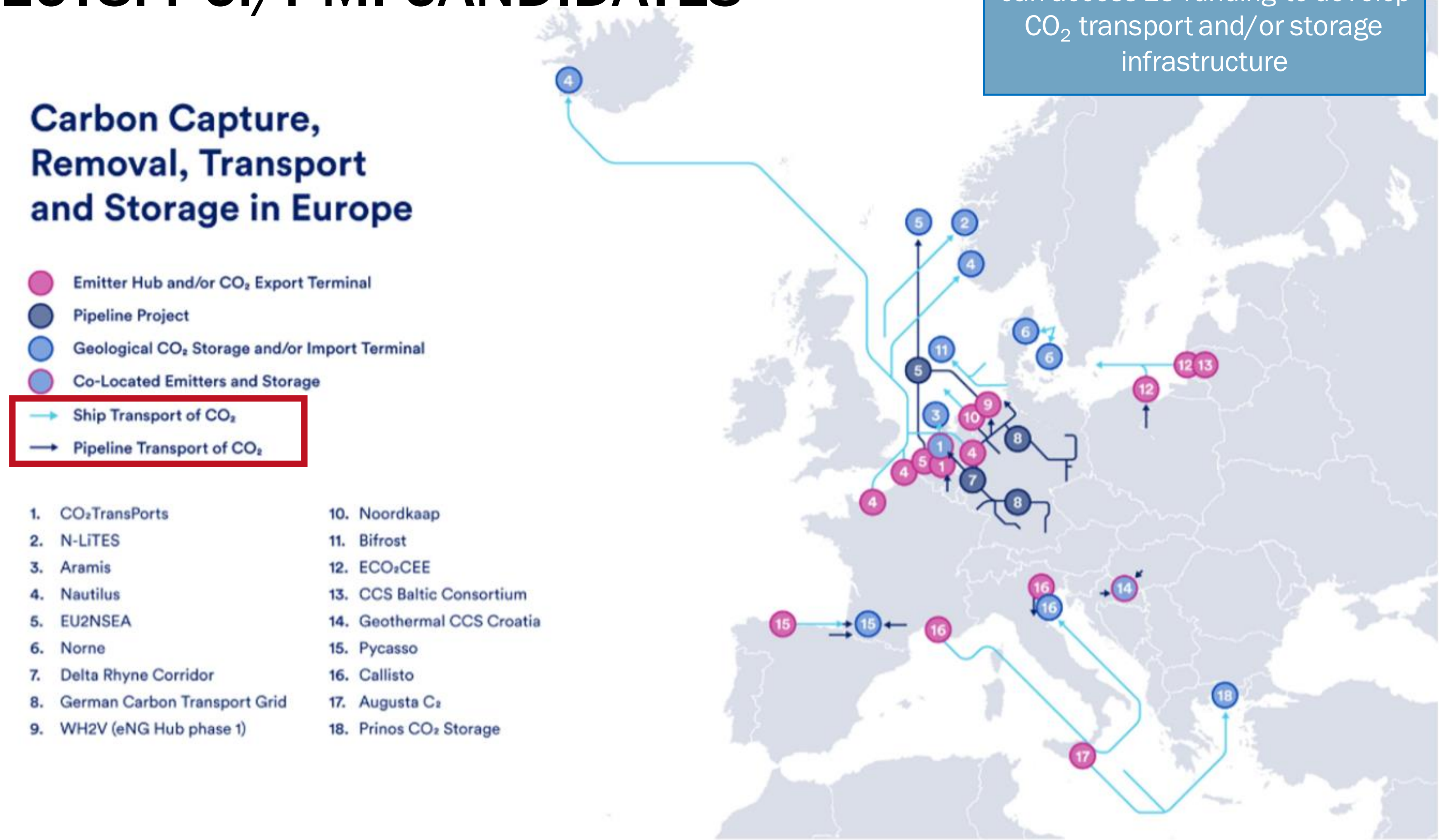
CO_2 TRANSPORT AND STORAGE

CURRENT PROJECTS: PCI/PMI CANDIDATES

PCI: Project of Common Interest
PMI: Project of Mutual Interest

Projects with PCI and PMI status can access EU funding to develop CO_2 transport and/or storage infrastructure

- First elements of pan-European transport infrastructure
- Offshore:
  - Pipeline
  - Ship to port
  - Ship to well
- Onshore:
  - Train, barge
  - Truck being considered

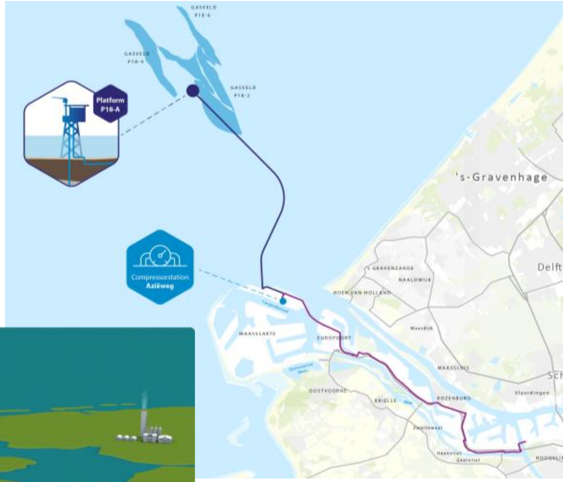


[List of 6th PCI list candidate projects](#)

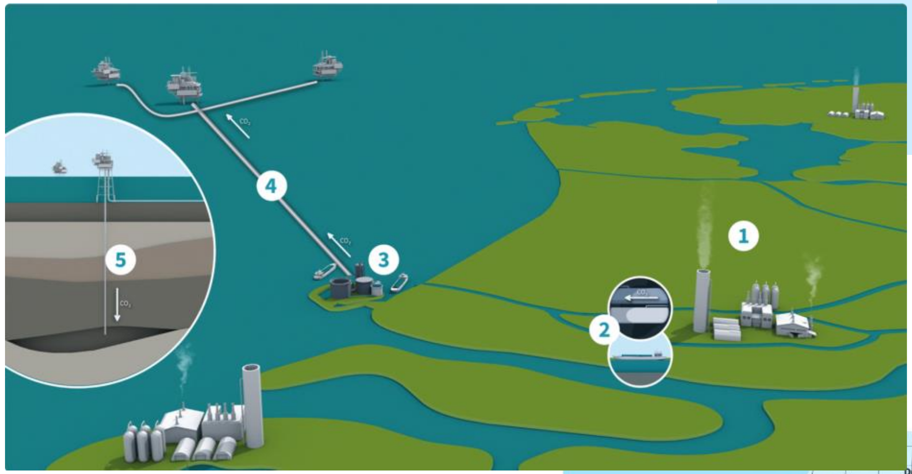
[Illustration: CATF, 2022](#)

CO_2 TRANSPORT AND STORAGE IN NL
SIMPLE FIRST, COMPLEX LATER?

- **Porthos** project (*FID taken Oct 2023*)
  - P18 gas field cluster (~40 Mt, 2.5 Mtpa)
- **Aramis** project
  - Trunkline Rotterdam – K,L blocks: 22 Mtpa (!)
  - Shell: K14-FA (47 Mt, 2.5 Mtpa)
  - TotalEnergies: L4-A, K6-CA (40 Mt, 2.5 Mtpa)
- **CO2Next** collection hub + ship terminal Rotterdam
- **Neptune Energy**
  - L10 fields (120-150 Mt, 5 Mtpa)
- **WintershallDEA CMS**
  - Q1B, P6 (~60-70 Mt, ? Mtpa)
- All expected to start in period 2026 - 2030



Porthos

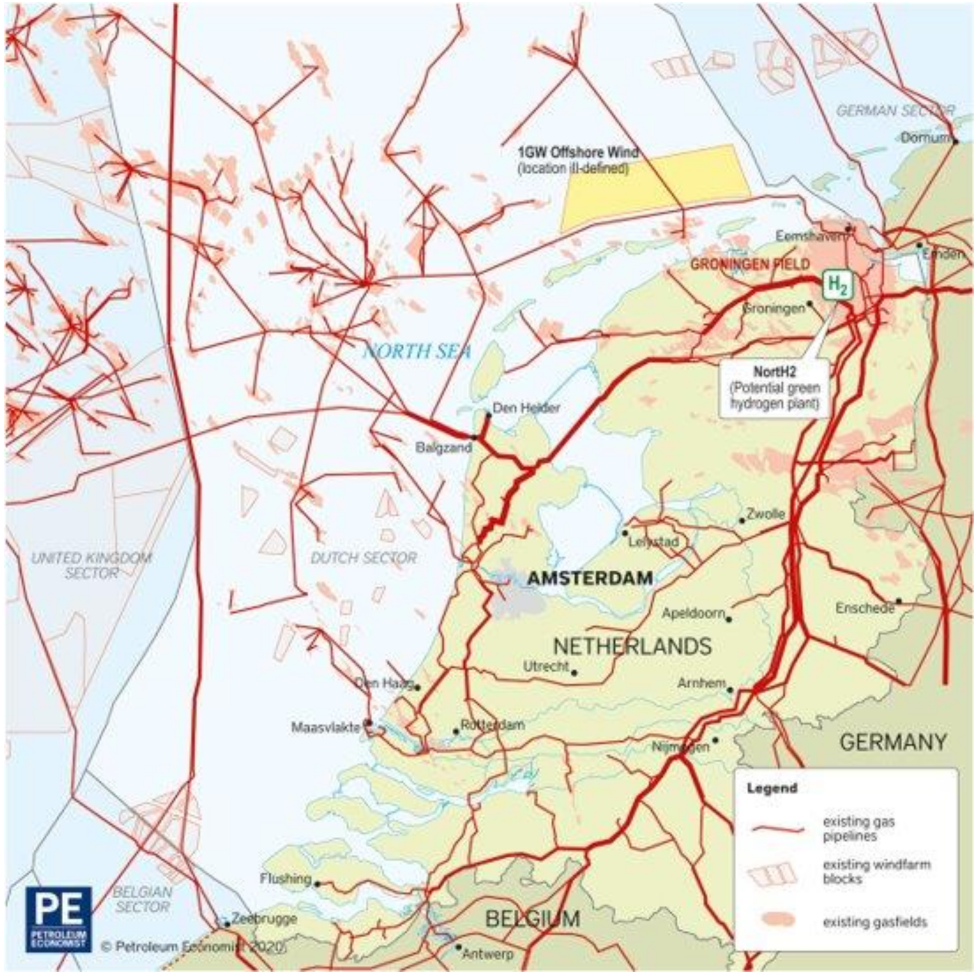


Aramis

Neptune Energy

NETHERLANDS: FOCUS ON DEPLETED FIELDS
TOWARDS COMPLEX NETWORKS

- ~100 fields, ~1700 Mt capacity (EBN-Gasunie, 2017)
- Domestic capture rates could go to **dozens of Mtpa**
- Neighbouring countries Belgium, Germany, France
  - Little or no domestic storage capacity
  - Likely to connect to Netherlands offshore
  - Volume also **dozens of Mtpa** (post-2035)
- Storage in NL fields: at capacity by ~2060
  - Connections needed with UK, DK, NO networks and stores
- Metering needed at *many* interfaces along CCS chains



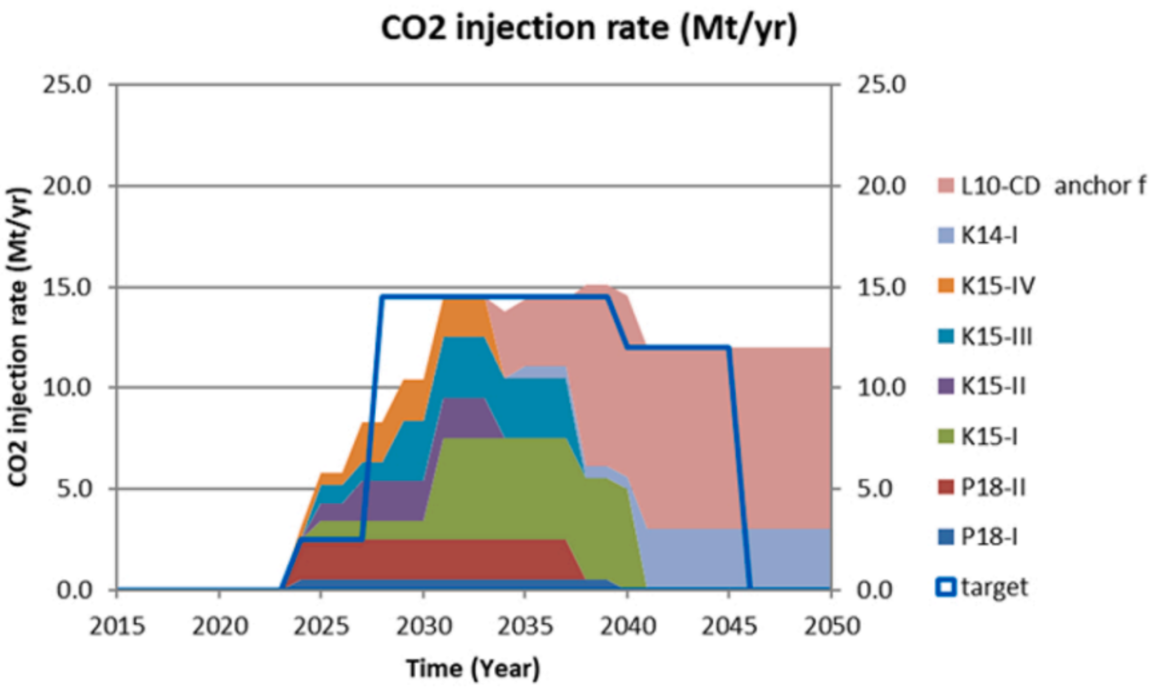
Current gas pipelines and gas fields

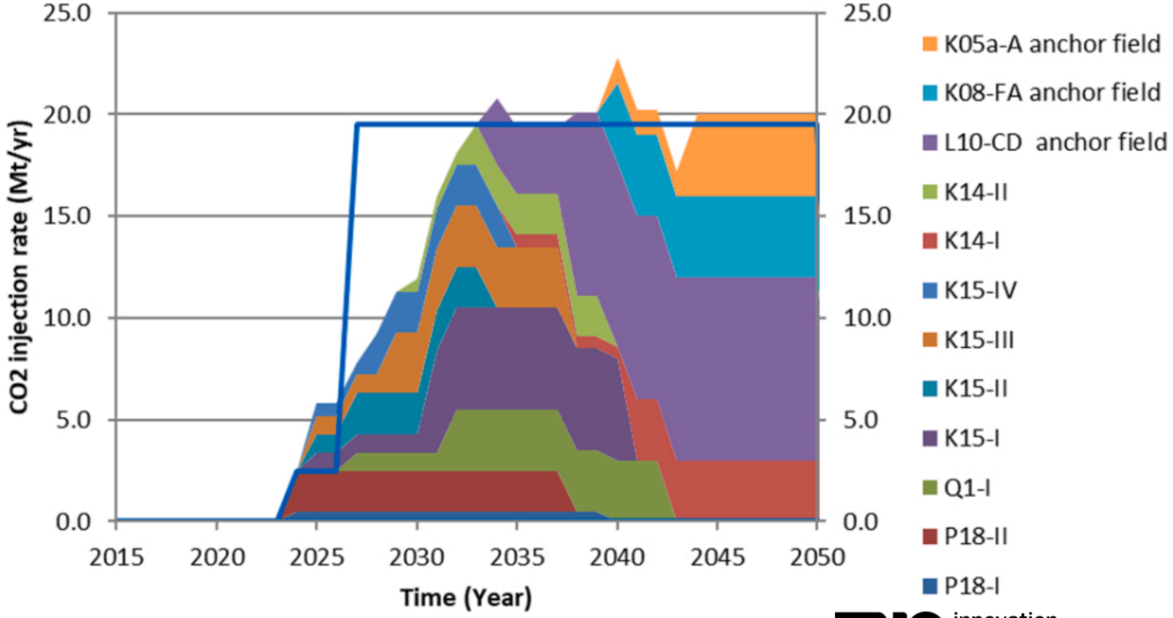
FOCUS ON DEPLETED FIELDS
STACKING OF FIELDS

- NL offshore: many gas fields
  - Storage capacity 10-50 Mt (typically)
  - Fields to be operated in parallel to reach significant rates
- Examples of supply scenarios
  - 'Stacking' of fields
  - Need several / many fields simultaneously

- Variability in CO_2 streams
  - Composition
  - Uptime, downtime of suppliers and network elements

- Flow rate uncertainty ~1%
  - *Much* larger than potential (geological) leakage…





Wildenborg et al., IJGGC, (2022)

CCS DEVELOPMENT
METERING ASPECTS

- Transport and storage system elements
  - Pipelines, ships, buffers, train, truck
- CO_2 conditions
  - Gas phase (collection networks)
  - Liquid phase (buffer, ship
  - Dense phase (high-p pipelines)
- CO_2 composition
  - Variable, 95 – 99% purity

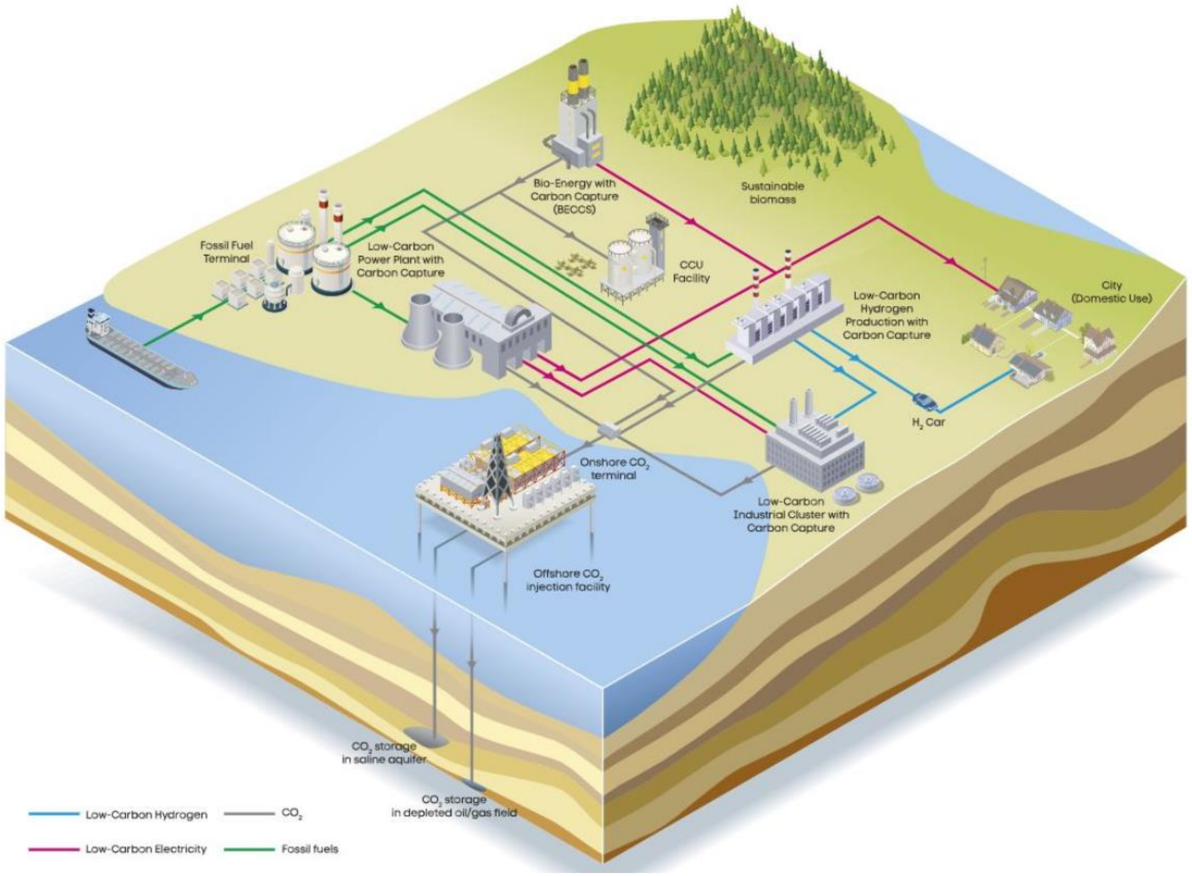
Requirements for flow measurements

- CCS Directive (permitting storage)
  - Flow into each well
- Storage operator (contracts with emitters)
  - Flow to storage site (= one or more wells)
- Ship terminal (buffering flow into pipeline)
  - Inflow, outflow
- Hub / node in network (distributing flow)
  - Flow to hub, flow to each branch

CCS DEVELOPMENTS
WRAP UP

- CO_2 transport and storage
  - Rapidly growing interest, projects are developing
- Transport modalities
  - Pipeline, ship, train (, truck)
- CO_2 specifications
  - Variable, purity 95% and higher

- There is a clear need for metering of:
  - CO_2 flows with CO_2 in gas, liquid, dense phase
  - CO_2 with variable purity
  - Flow rates in range of up to 20 Mtpa



THANK YOU FOR YOUR TIME

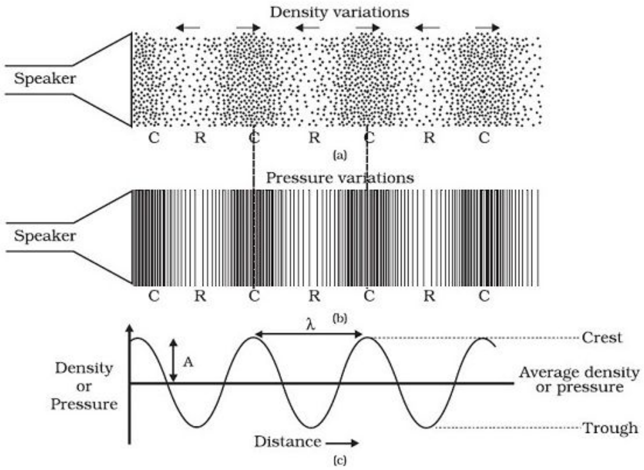
Metrology support for Carbon Capture Utilization and Storage
26th October 2023

Seminar on Metrology Support for Carbon Capture, Utilisation and Storage

Exploitation of speed of sound measurements for monitoring CCUS processes

P. Alberto Giuliano Albo (INRiM)
(a.albo@inrim.it)

Ultrasonic propagation



Acoustic waves are a phenomenon of **transportation of mechanical energy** through an **elastic medium** (solid, liquid, gas, supercritical, ...)

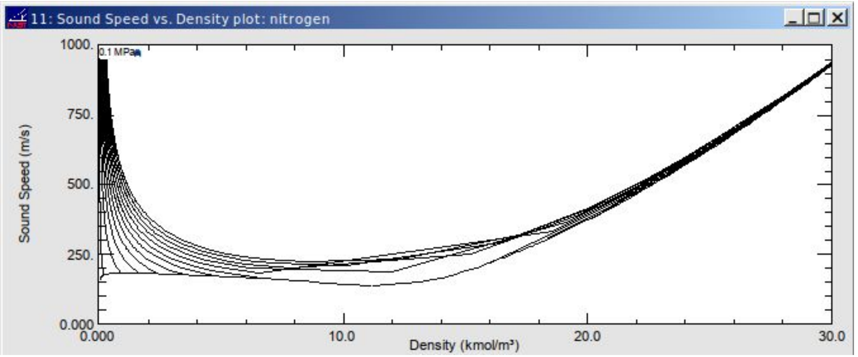
Acoustic waves are used to **perturbe the thermodynamic system** and setting it out of its equilibrium. **Monitoring** how the system backs to its equilibrium, it is possible to **characterize some properties** of a physical system;

Speed of sound is a **thermodynamic property** useful to implement high accurate **equations of state of a fluid**.

Ultrasonic waves are widely used in industrial for **non-invasive measurements** and **non-destructive-testing** (NDT);

Acoustic wave are used to **create pseudo-images** including **quantitative information** (elastic properties, acoustic impedance, ecc);

CO_2 phase identification



Fluid phase can be monitored by measuring temperature and pressure when the **composition** is known, however when it is not known with the necessary accuracy, **two low-cost transducers** can be adopted:

- one at low-frequency ~250 kHz;
- one at ~5 MHz (or more for pressure higher than 6 MPa).

High frequency ultrasonic waves are **absorbed** by gases and they do not propagate (usually below 6 MPa for 5 MHz signals).

Noisy signals at 5 MHz in liquids indicate presence of bubbles and the presence **multiphase-fluid**.

In **supercritical fluids** very high **frequency signals can be absorbed**.

References:
Two freq.: https://doi.org/10.1016/j.measen.2021.100040
VLE/VLLE:https://doi.org/10.1016/S0378-3812(00)00380-0

Ultrasonic flow meters calibration

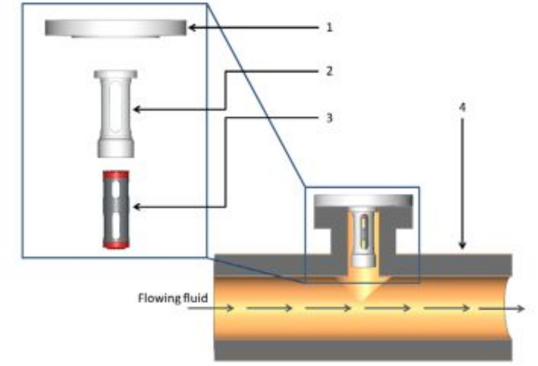


Fig. 8. Scheme which shows how the ultrasonic cell can be used as a transfer standard by mounting it directly on the pipelines where LNGs flow, in vicinity of the ultrasonic flowmeters to be calibrated. (1) DN 50 flange; (2) Stainless steel support for the ultrasonic cell; (3) Ultrasonic cell; (4) LNG pipeline T-connection.

On-line 2nd calibration:
We are checking the possibility to use a **primary standard** to transfer the measurement **of speed of sound** from laboratory to installed ultrasonic flowmeters, exploiting the possibility of meters to determine the speed of sound of the fluid at rest.

Calibration check:
We are developing a **clamp-on system**:
- able to operate both in **gas and in liquid**;
- **fully traceable** (but with an higher uncertainty in the begin);
- equipped with **laboratory instrumentation**, suitable to work in field, for waveform analysis;

References:
https://doi.org/10.1016/j.measurement.2021.109526

IoT and Equations of state

IoT technology can **support** the development of low cost **metrological measurement networks**, easily adaptable for specific scopes (flow metering, leak detection, tanks and reservoir monitoring, ecc).

IoT allows to **integrate established** instrumentation with **new technologies**.

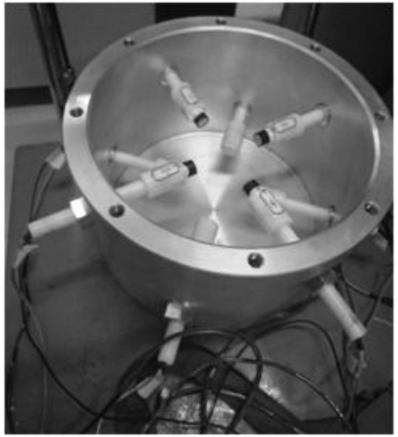
Equations of state are **the core of flow-computers** used to account for transferred fluids.

- They **convert** volume to mass flow, knowing the composition;
- They can be used **design** chemical and measurement processes;
- They can be used to **check** the instrumentation, when composition is known;
- Using some **particular fluid**, equation of state can be used to **calibrate instrumentation**;

GERG-2008 is a standard equation of state that proved to be consistent with the best experimental measurements from cryogenic to high temperature. However it has some limitations (fluid matrix and compositions)

Updating new equations including amines and CO_2

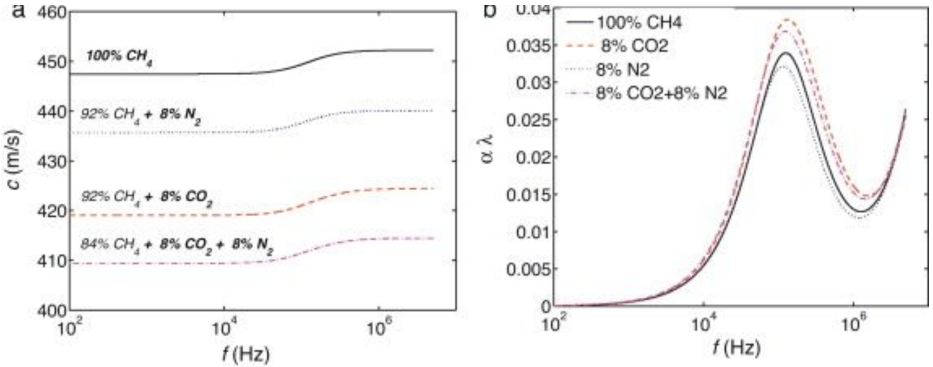
Impurities



Quantitative Acoustic Relaxation Spectroscopy (QARS) can be used to monitor che content of CO_2, in presence of impurities, by using **transducers** working at **two different frequencies**. At the moment the error is in the order of 1 % but it is a **promising**, **fast**, and **cheap** solution.

Main impurities: Amine, N_2, O_2, Ar, NO_x, SO_x, CO, H_2S, H_2, CH_4, C_2+, NH_3

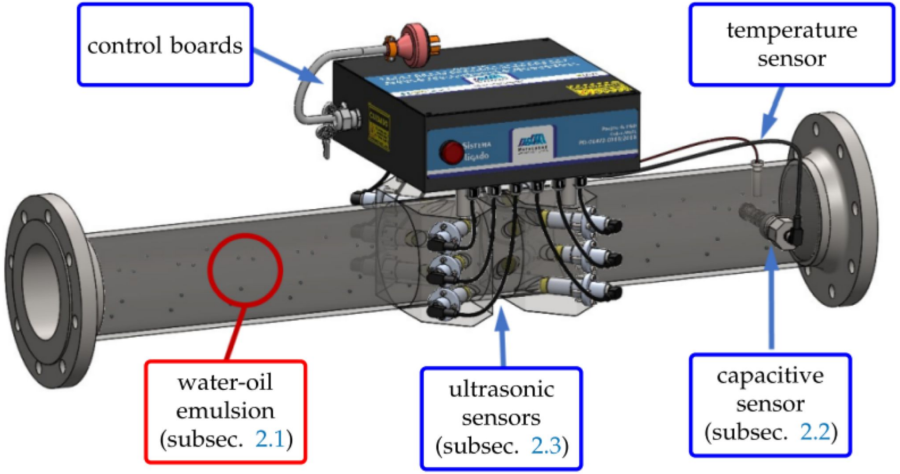
Effects on **speed of sound** can be **predicted** using Gerg 2008 with few exceptions.



Reference:

- https://doi.org/10.1016/j.measen.2021.100040
- https://doi.org/10.1016/j.snb.2012.03.086
- https://blog.sintef.com/sintefenergy/energy-efficiency/what-else-is-there-in-co2-except-co2/

Monitoring Methanation and e-fuels production



Combined ultrasonic and capacitive sensors are under development and characterization for obtaining quantitative information on the quality of the produced oil or fuel.

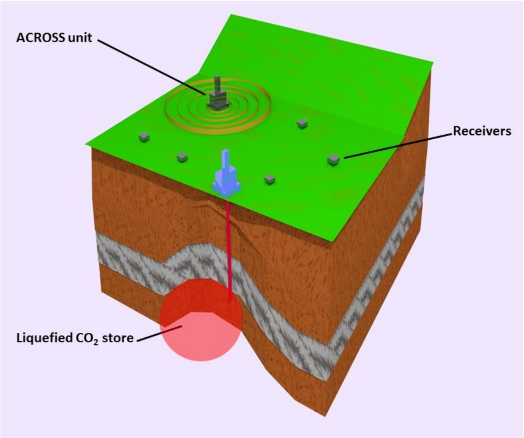
At the moment, **density** is **estimated** with an uncertainty better than **1%** but significative improvements are expected since research just started.

The idea of combining **dielectric constant** and **speed of sound** seems promising. If not those quantities, some other might be more useful.

Reference:

- https://www.mdpi.com/1424-8220/21/23/7979#
- https://doi.org/10.5194/jsss-2-103-2013

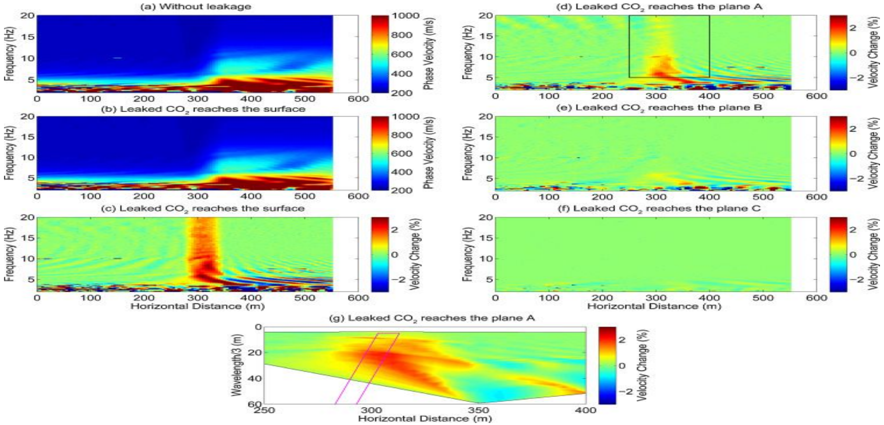
CO_2 storage: site monitor



An example of **monitoring** system **based on subsonic** wave propagation is called Accurately Controlled Routinely Operated Signal System (ACROSS).

Frequencies between (5 and 15) Hz.

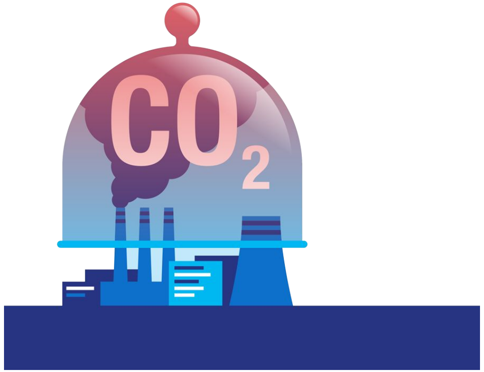
Variation of **speed of sound** in rocks is used to monitor CO_2 **leakage** from the storage site.



References:

- https://doi.org/10.1016/j.ijggc.2012.07.026
- https://doi.org/10.3390/en16010012
- https://doi.org/10.1016/j.ijggc.2015.11.030

Conclusions



- **Applications** of ultrasonic and subsonic waves in different fields of CO_2 processing;
- **New and established technologies** based on mechanical wave propagation;
- New technologies can provide necessary information on CO_2 systems and **reduce costs**;
- **Research** to support of the energy transition needs to **be directed by industry** to be of real impact. A tight collaboration would be useful for both;
- **Keep in touch! Stay tuned with** MetCCUS activities and participants;

Capabilities and Opportunities

Salvatore Pitti
Application Engineer Custody Transfer / Meter Performance
Emerson – Metrology Department

METCCUS

EMERSON

Agenda

- Scope
- Approval stage
  - Regulations – Standards and Legislations
  - JIPs and advisory boards
- Applications and Measurements in CCUS
- Prove of transferability
- Summary

Scope

- For conventional measurement, like oil and gas, regulations are decennia in place. Locally, Regional dependent and even up to a level of harmonization (think of OIML or MID).

- For H2 and for CO2 regulations are in development and in the strength and speed of the world we are all aware for good accommodation of this necessity.

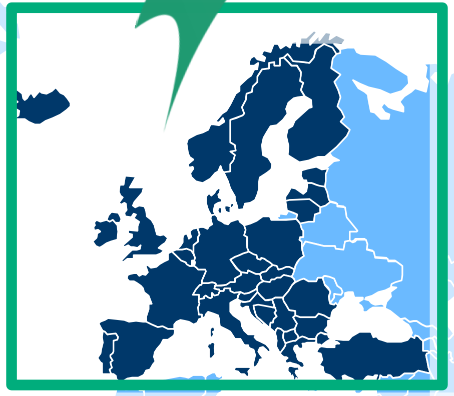
- What are the capabilities in measurement per today, and what are the capabilities of regulations in the world per today and do we have challenges forward are all questions we would like an answer on.

Approval stage

Standards and Legislations for H_2 and CCUS Economy

	ISO	API	OIML	MID
Ind. H_2/Blending			R81 R117 R137	MI002
H_2 Mobility	TC 197		R139	
Carbon Capture	TC 265	CH 6.x	R117 R137	MI002 MI005

- Wide Coverage
- Some Coverage
- Excludes/Does not apply
- Elective



Ind. H_2/Blending

- MID – MI002
- OIML R137 (Gas meters)
- OIML R117 and OIML R81

H_2 Mobility

- OIML R139 Dispensing
- OIML R137 Tube Trailers

CCUS

- MID – Gas Applications
- MID – Liquid Applications
- OIML R137 (Gas/Supercritical)
- OIML R117 (Liquid)

Standards and Legislations for H_2 and CCUS Economy

H_2

Relevant Regulations/Recommendations on H_2 Measurement:

- OIML R137 2012, Gas meters, Section 5.3.2, **Accuracy class 0.5, 1 and 1.5.**
- OIML R139 2018R, Hydrogen Dispensing Section 5.2.1, **Accuracy Class 1.5, 2 and 4 for the system and Accuracy Class 1, 1.5 and 2 for the Meter respectively**

CCUS

Relevant Regulations/Recommendations on CO_2 Measurement:

- EU, 8 June 2010 amending Decision 2007/589/EC, Section 5.7 Transferred CO_2: The mass of annually transferred CO_2 or carbonate shall be determined with **a maximum uncertainty of less than 1,5%** either directly by using volume or mass flow meters.
- ETS M&R Regulation 2018/2066, Annex VIII CO_2 transfer Tier 4: In case of CO_2, the uncertainty is to be applied to the **total amount of CO_2 measured ± 2.5%**
- EU MID (Directive 2014/32) Liquefied CO_2, Annex VII Accuracy class 1.5: **Measuring Systems ± 1.5% and Meters ± 1%**
- OIML R 117 2007E, Liquefied CO_2 Section 2 Accuracy class 1.5: **Measuring Systems ± 1.5% and Meters ± 1%**
- NIST Handbook 44-2017, Liquid CO_2 Measuring Devices Section 3.38 Accuracy class 2.5: **Acceptance Tolerance ± 1.5% and Maintenance Tolerance ± 2.5%**
- OIML R137 2012, Gas meters, Section 5.3.2, **Accuracy class 0.5, 1 and 1.5.**

Leading with Technical Expertise

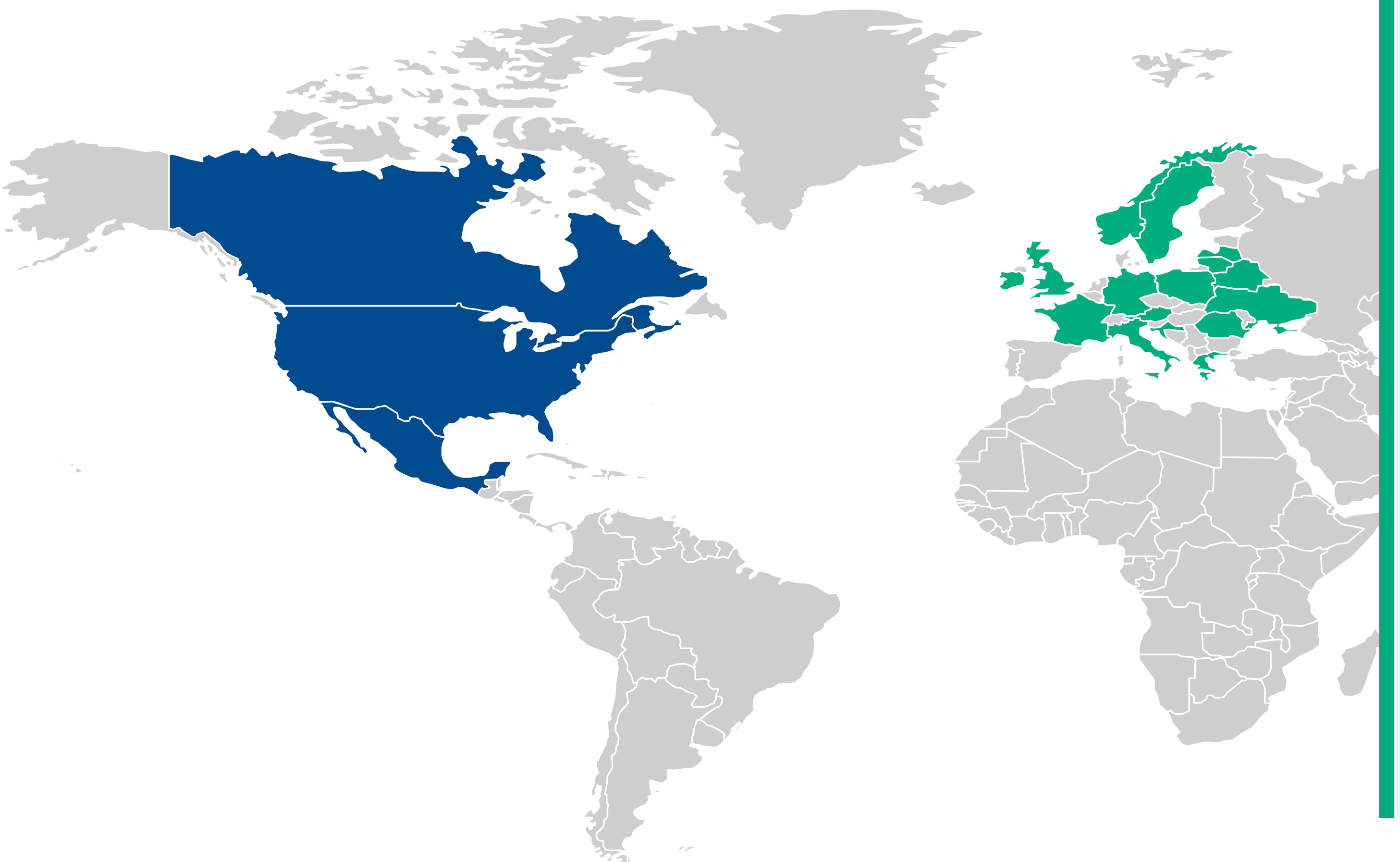
North America

Standards:

- API Chapter 6.X Supercritical Fluids (CO_2)
- Measurement Canada - Development Committee for H2 T&C

Research Institute:

- NIST - Master Meter study, training, and tech support
- NCWM/NTEP NIST HB44 - Specifications and Tolerances



Europe

Regulations and Directive Development Connects us with Policy Makers and Coordinators for Technical Discussions

- Submit 3 amendments to directives and regulations on “Internal markets for renewable and natural gas for Hydrogen”
- Consult on major review proposal of Measuring Instrument Directives (MID) to address H2 and CO2 measurement gaps

Joint Industry Projects

- Chairman of Advisory Board – MetHyInfra
- Advisory Board Member – MetCCUS
- Advisory Board Member – MetHyVE2
- Consortium Member – RHeaDHy Project
- Consortium Member – H2FlowTrace
- DNV JIP CO_2
- DNV JIP H_2

Standards Committees

- NEN (Netherlands Royal Standardization Institute)

Industry Partnerships:

- Consultant to IGOP – CO_2 instrumentation

Applications and Measurement in CCUS

CCUS Carbon Capture & Storage / CO_2 Transportation & Distribution Challenges with CO_2 measurement

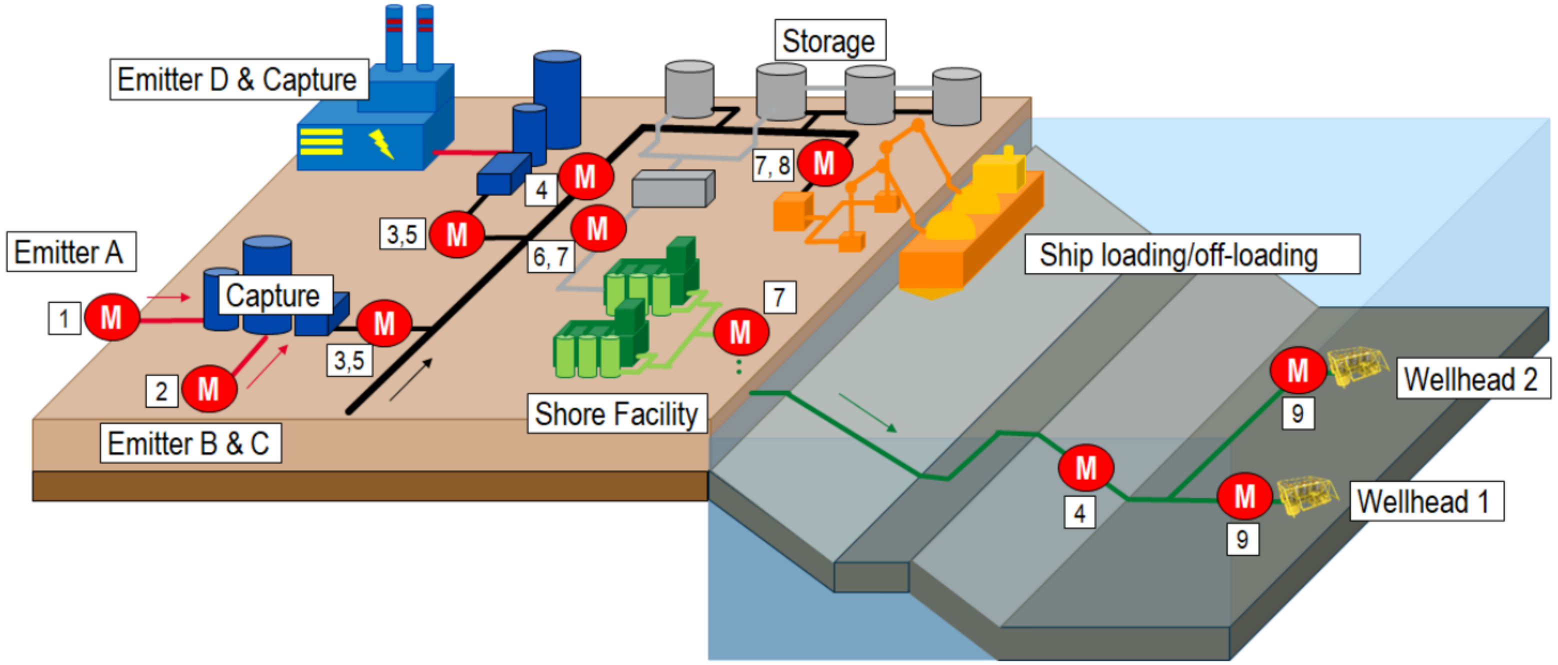
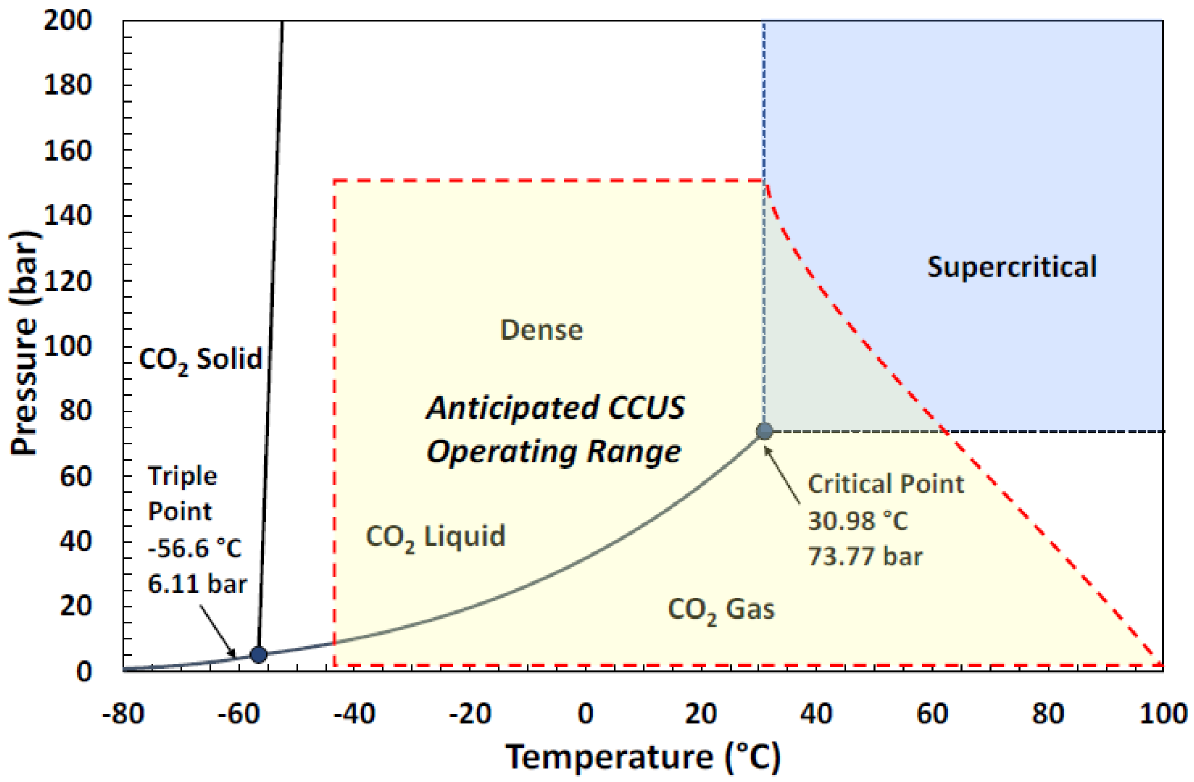


Figure 3: CCUS transportation measurement nodes. Adapted from [15]. For measurement node

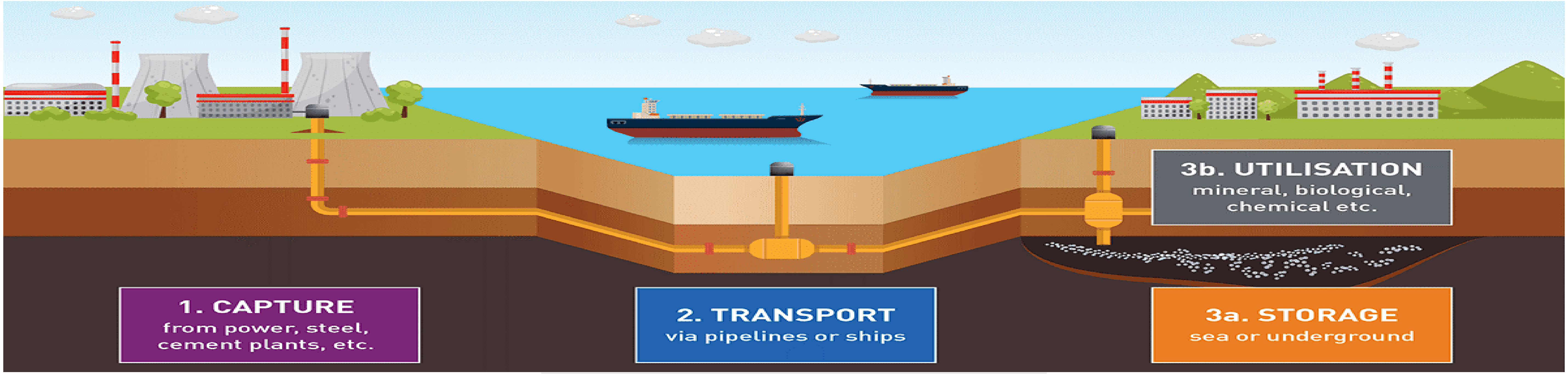


- Gas at 1 bar and 20 °C
  - Compressibility effect on measurement
- small changes in temperature and pressure may result in large changes in fluid properties
- Impurities amplifies significant shifts in phase boundaries
- CO2 has acoustic attenuation
  - Not relevant to Coriolis

- Liquid at 57 bar and 20°C
- Supercritical at critical point of 31.1 °C and 73.9 bar
- small changes in temperature and pressure may result in large changes in fluid properties
- Impurities amplifies significant shifts in phase boundaries

Compressed Gas → **Liquified CO2**

Typical CCUS Applications



Production

- Models CMF300
- Pressure 36 Bars

Tube Trailer Loading / Unloading

- Models Up to HC2
- Pressure Capture at 16 bars
- Transport at pressures > 100 bars

Large Industrial Consumers

- Models CMF300 to HC4
- Pressure 15 bars
- Liquified <'50°C

Compressed Gas → Liquified CO2

Measuring Gaseous fluids with Coriolis

- Due to Compressibility of Gases, there is a potential shift in Mass measurement in Coriolis
- This is applicable to all gases measured by all Coriolis meters
- The error can be estimated and corrected based on a scientific method as described by Hemp and Kutin.

$$E_{\dot{m}} = \frac{1}{2}\left(\frac{\omega_1}{c} b\right)^2$$

Where:

ω_1 is resonance frequency of the meter

b is flowmeter tube inner radius

c is velocity of sound through the gaseous fluid

MicroMotion Coriolis Flow Meters has the lowest resonance frequency; therefore, the estimated error is much lower

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Flow Measurement and Instrumentation 17 (2006) 359–369

Flow Measurement and Instrumentation

www.elsevier.com/locate/flowmeasinst

Theory of errors in Coriolis flowmeter readings due to compressibility of the fluid being metered

J. Hemp[a,*], J. Kutin[b]

[a] Wolfson College, Oxford OX2 6UD, UK

[b] Laboratory of Measurements in Process Engineering, Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva 6, SI-1000 Ljubljana, Slovenia

Received 2 May 2006; received in revised form 24 July 2006; accepted 25 July 2006

Note: The referenced Hemp and Kutin paper describe the approach to estimate the error in a straight tube.

Measuring Gaseous CO_2 with Coriolis

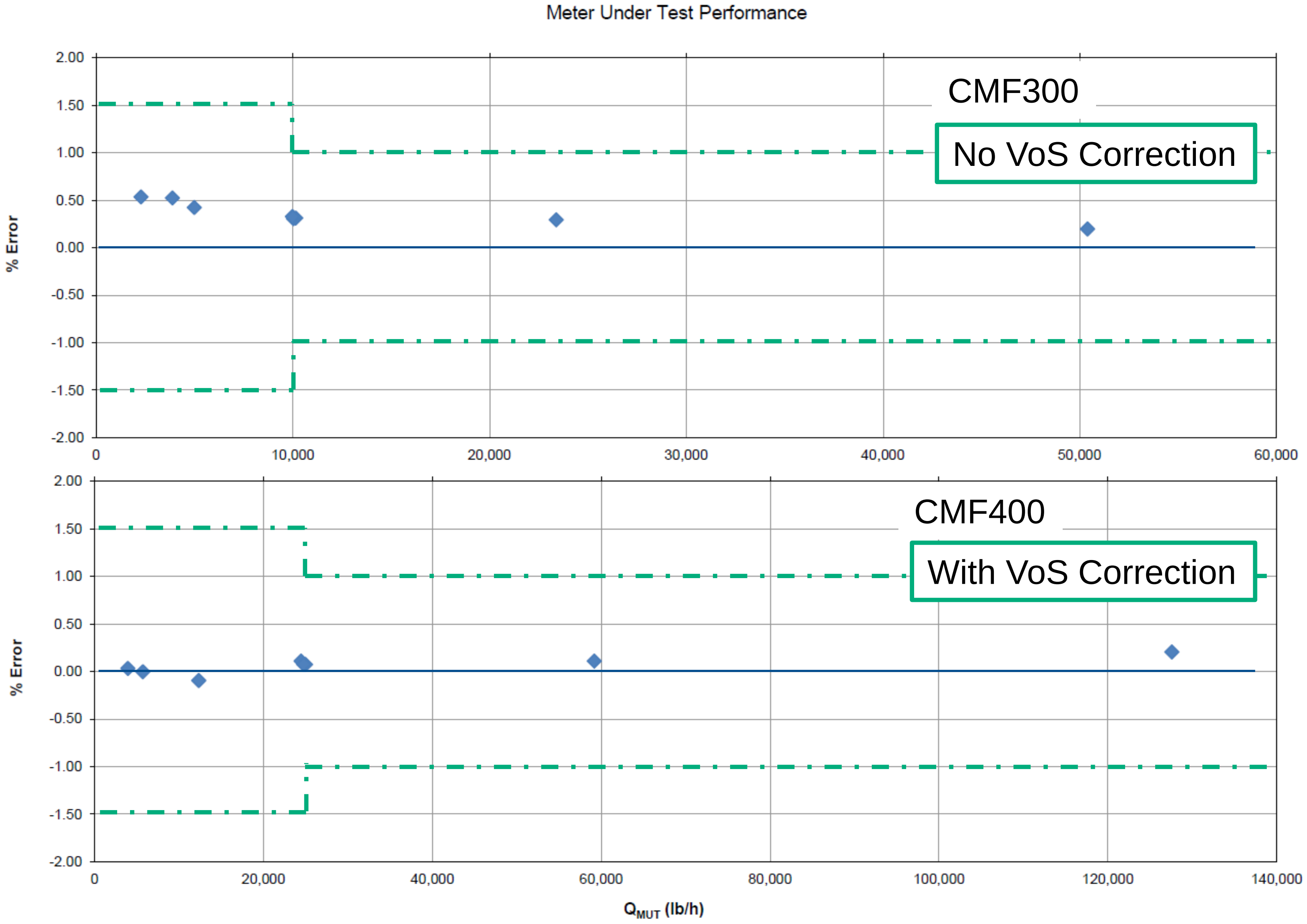
- The estimated error with CO_2 is attributed largely to the low Velocity of Sound (VoS) through the medium
- As with other gases, the error increases with larger meter sizes and negligeable in smaller meter sizes

This effect is negligeable or non-existent in smaller MicroMotion Coriolis flow meters

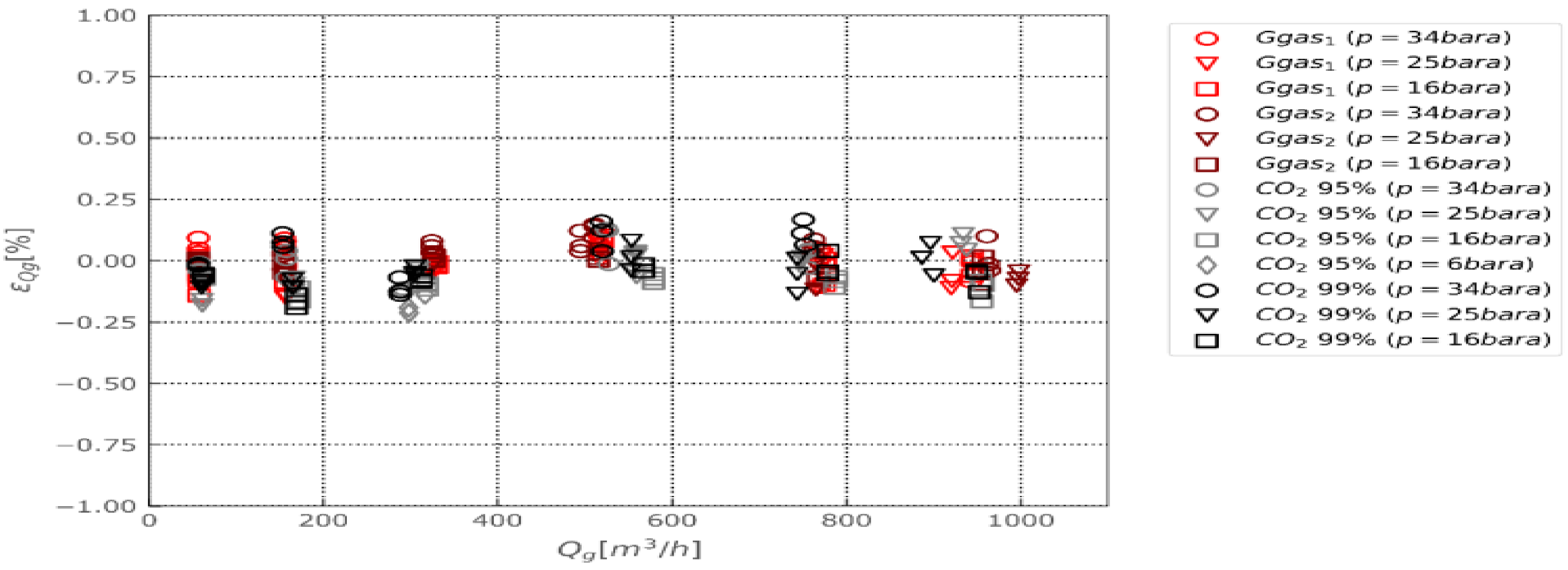
- Mass Error Correction is correlated to VoS
- VoS (c) is extrapolated with Live measurement of:
  - Density
  - Temperature
  - Coriolis Operating Frequency

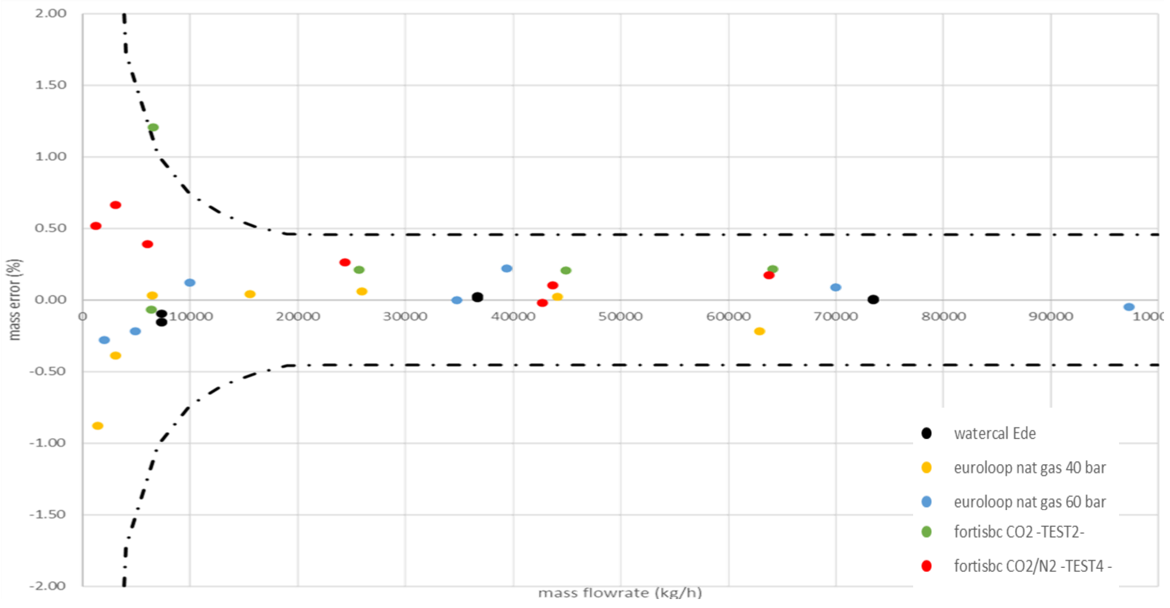
Measuring Gaseous CO2 with Coriolis

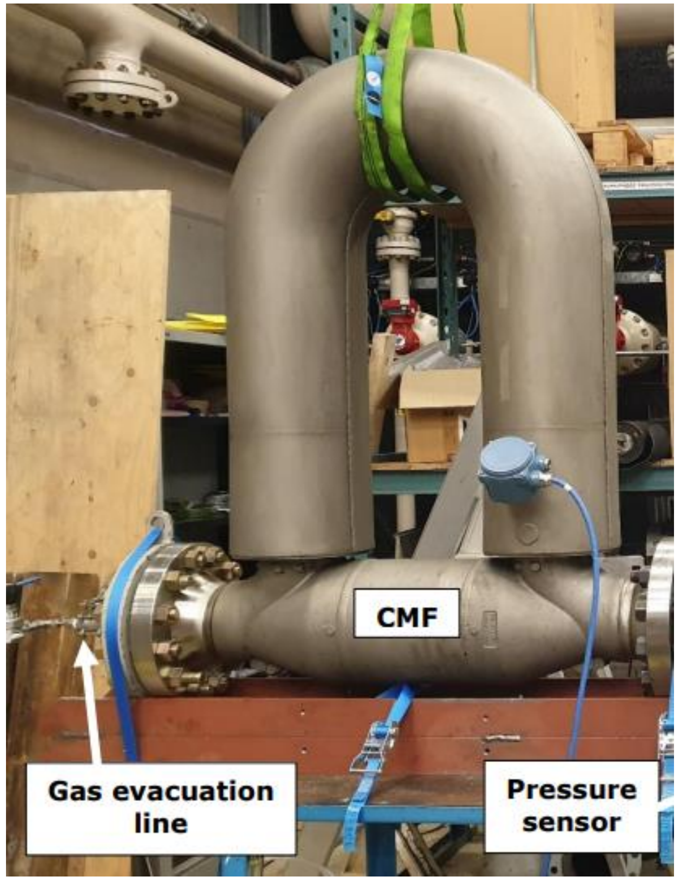
- As Found Calibration at FortisBC for CMF300 and CMF400
- Calibration on CO_2 done with same parameter settings as in water calibration
- Part of Type Approval testing with NMi for OIML R137 certification
- Performance is compliant with Accuracy class 0.5 and 1.0



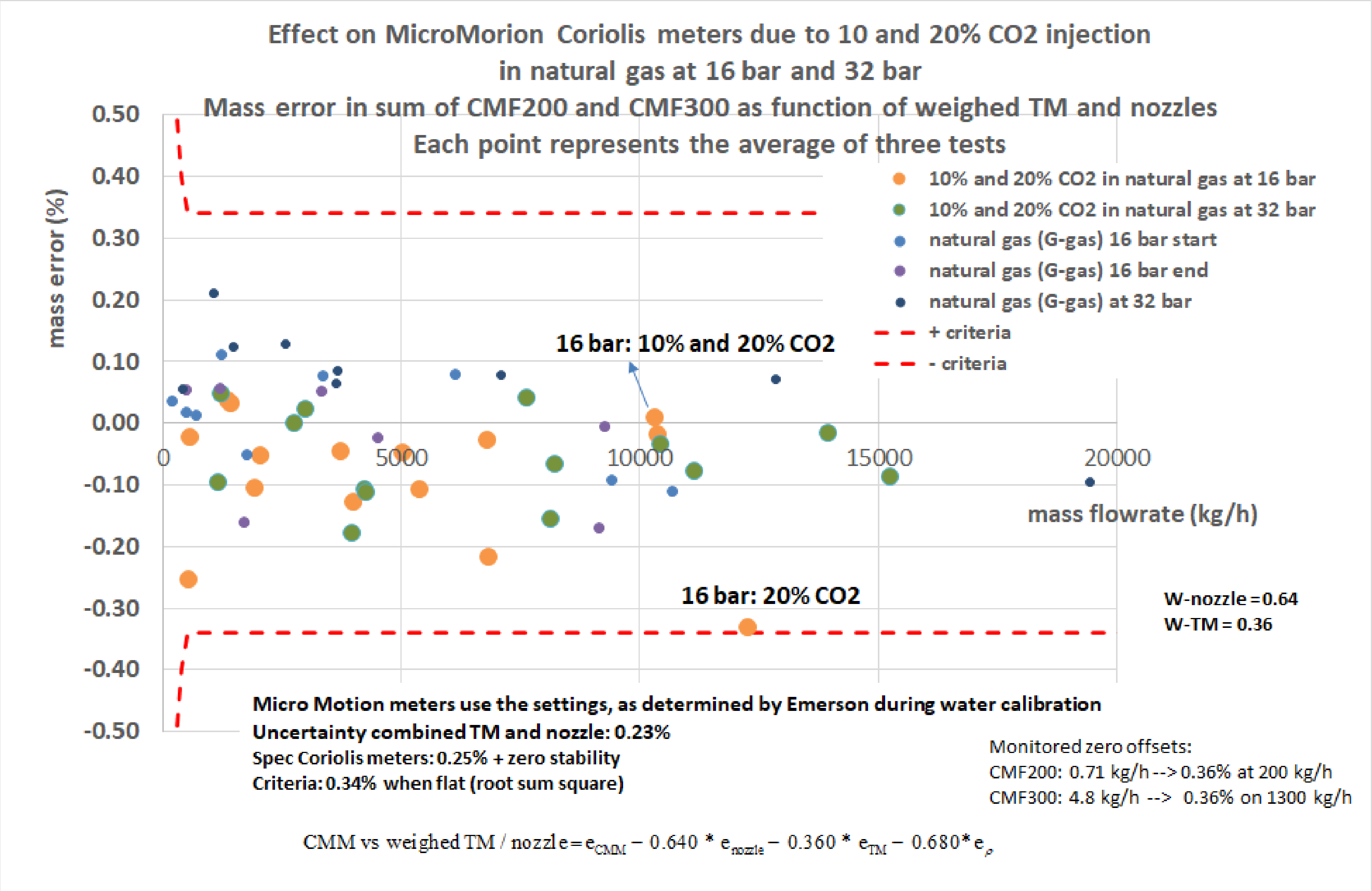
Measuring CO_2 in Gas Phase with Impurities







Measuring CO_2 injection up to 20% with Coriolis



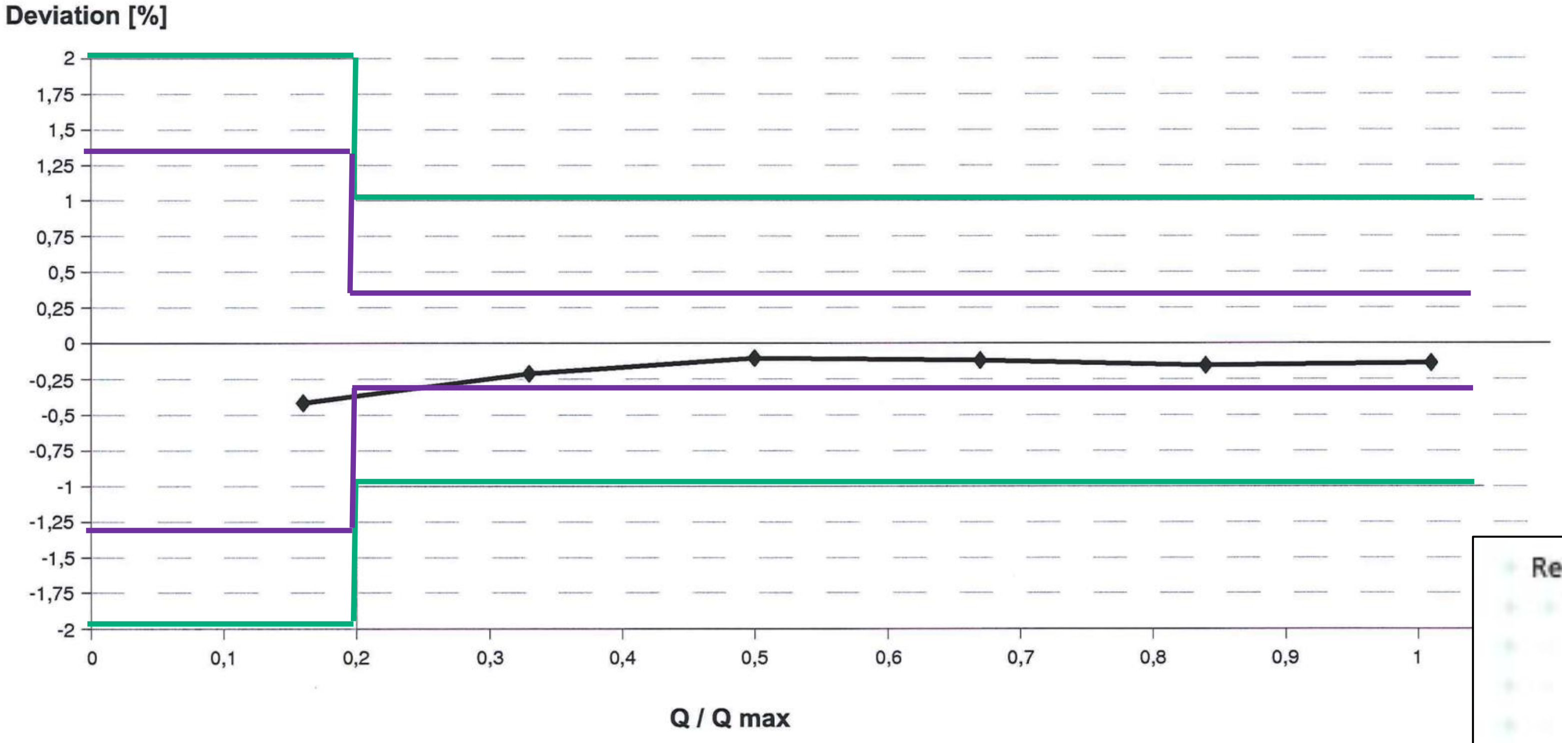
Natural Gas with CO_2 injection up till 20% at 16 and 32 bar

- Mass errors assessed to a criteria of 0.34%
- Population is within uncertainty criteria of 0.34%
- Presented results based on water settings

Prove of Transferability and Traceability

Water Transferability – Approach & Certification

STEP 1: New meter with no FCF
STEP 2: Establish FCF through water calibration
STEP 3: Verify on other gases with FCF (established in STEP 2)
STEP 4: Verify MPE according to table in NMI Statement



MPE for GAS

MPE for Water (to follow transferability)

NMi

DECLARATION

Number NMi-SO14200852-04
Page 1 of 2
Project number SO14200852

Issued by: NMi Certin B.V.
Hugo de Grootplein 1
3314 EG Dordrecht
The Netherlands

Applicant: Emerson Process Management Flow B.V.
Neonstraat 1
6718 WX Ede
The Netherlands

Submitted: Coriolis meters
Manufacturer : Micro Motion
Sensor Models : CMF025, CMF050, CNG050, CMF100, CMF200, CMF300, CMF350, CMF400, CMFHC2, CMFHC3 and CMFHC4

Scope of investigation: Investigation of the Micro Motion coriolis meters, model CMF025, CMF050, CNG050, CMF100, CMF200, CMF300, CMF350, CMF400, CMFHC2, CMFHC3 and CMFHC4 with both water and natural gas or nitrogen as medium. The background of the investigation is to find out whether those meters can be used for custody transfer purposes with a certain gas, while they are verified with water, without testing them with that particular gas.

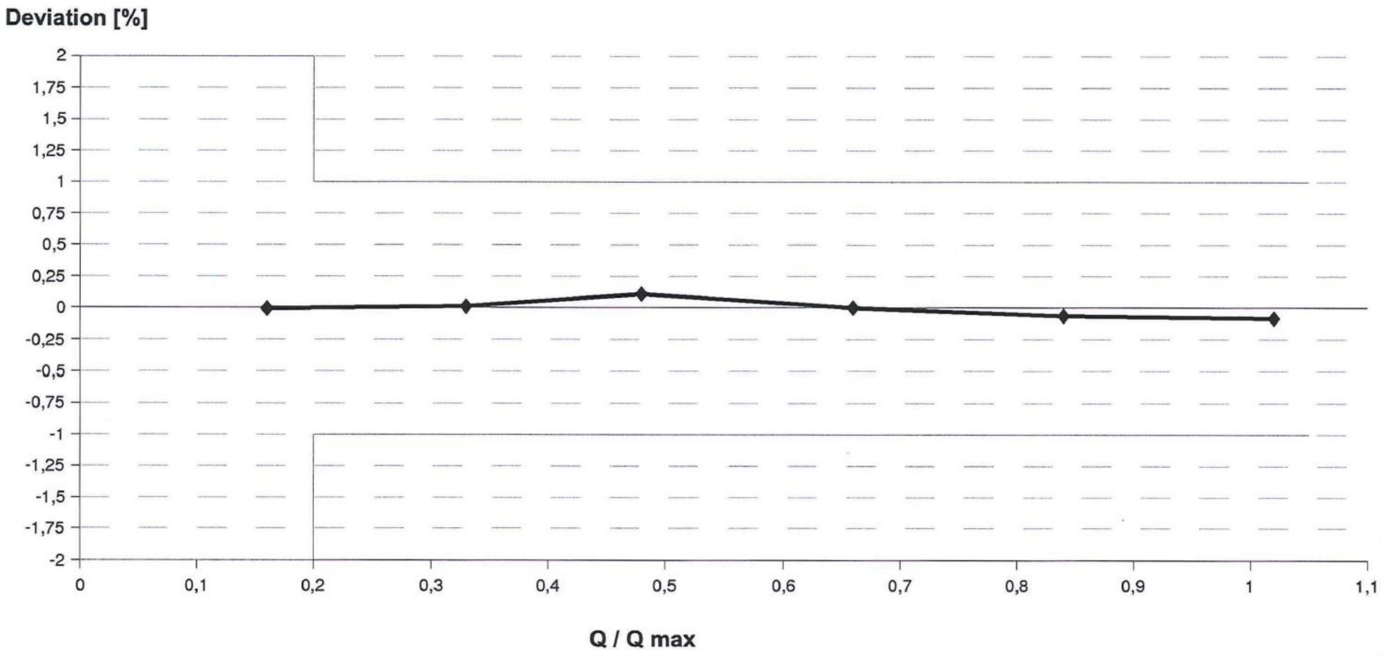
Tests: With several meters of the above mentioned models an accuracy test is performed with water. After that the accuracy test is repeated with natural gas or nitrogen, under high pressure. During both tests each meter is programmed with the same calibration parameter (FlowCal factor).

Result: The maximum measured difference between both accuracy tests is 0,5% for all above mentioned sensor models, except for the CMF025 where 0,6% is found. Concerning this maximum measured difference, while adding an extra safety margin the verification of the coriolis meters may be performed with water, without testing them with the particular gas, when using the maximum permissible errors with water, as stated in the table below.

Flow range	Maximum permissible errors with gas	Maximum permissible errors with water
Q_{min} - 0,2 Q_{max}	± 2,0%	± 1,3%
0,2 Q_{max} - Q_{max}	± 1,0%	± 0,3%

Water Transferability – Example Natural Gas CMF300

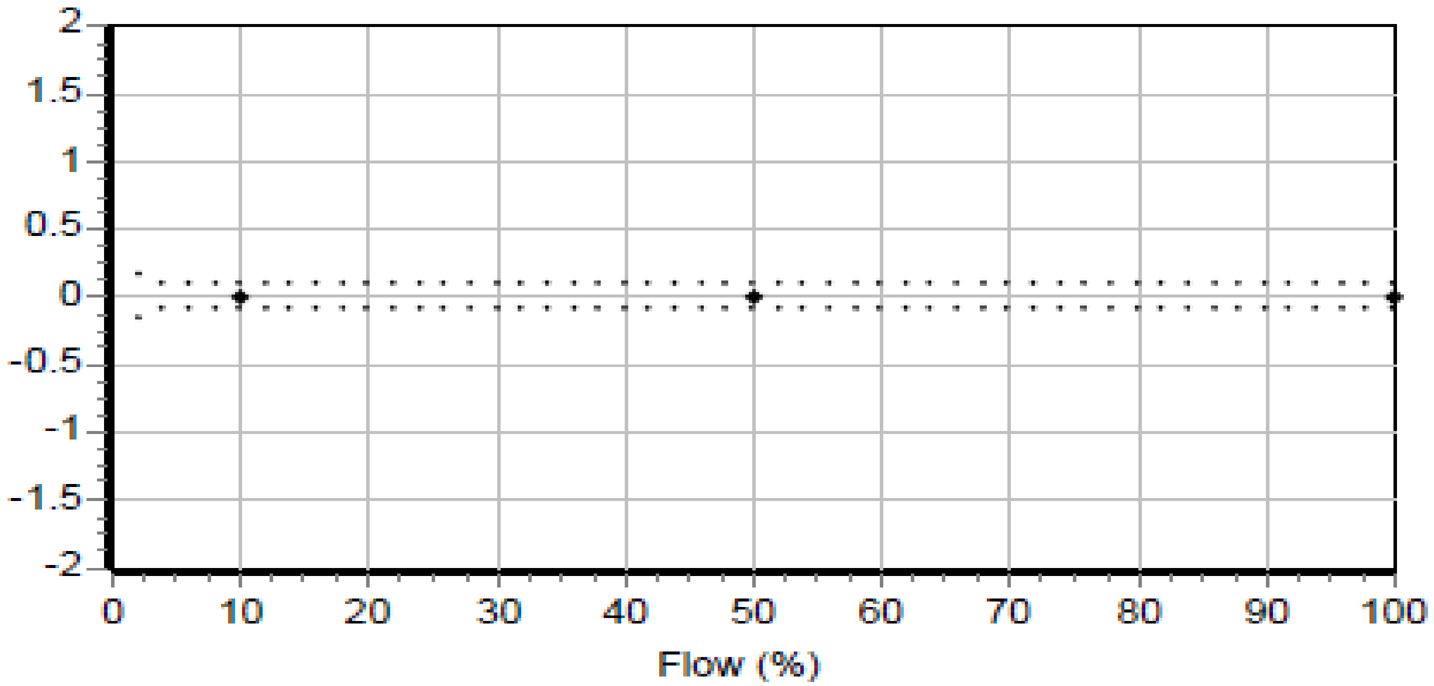
Results (as left)	Qi / Qmax	Qi (kg/h)	Reynoldsnumber	Deviation (%)	n	Umeter (%)	Utot (%)
	0,16	**634,23**	0,20 *10⁶	**-0,01**	4	0,09	0,25
	0,33	**1303,60**	0,41 *10⁶	**0,01**	4	0,13	0,26
	0,48	**1903,45**	0,59 *10⁶	**0,11**	3	0,03	0,23
	0,66	**2623,26**	0,81 *10⁶	**0,00**	3	0,03	0,23
	0,84	**3358,17**	1,04 *10⁶	**-0,06**	4	0,04	0,23
	1,02	**4065,73**	1,26 *10⁶	**-0,08**	3	0,00	0,23



Note: calibration on Natural Gas done with same parameter settings as in water calibration

Flow (%)	Flow Rate (kg/min)	Meter Total (kg)	Reference Total (kg)	Error (%)	Specification (±%)
100.0	2268	2250.083	2250.149	-0.003	0.100
10.0	226.8	511.1505	511.1675	-0.003	0.100
50.0	1134	1117.784	1117.797	-0.001	0.100
100.0	2268	2250.083	2250.098	-0.001	0.100

Water Calibration uncertainty of ±0.03%

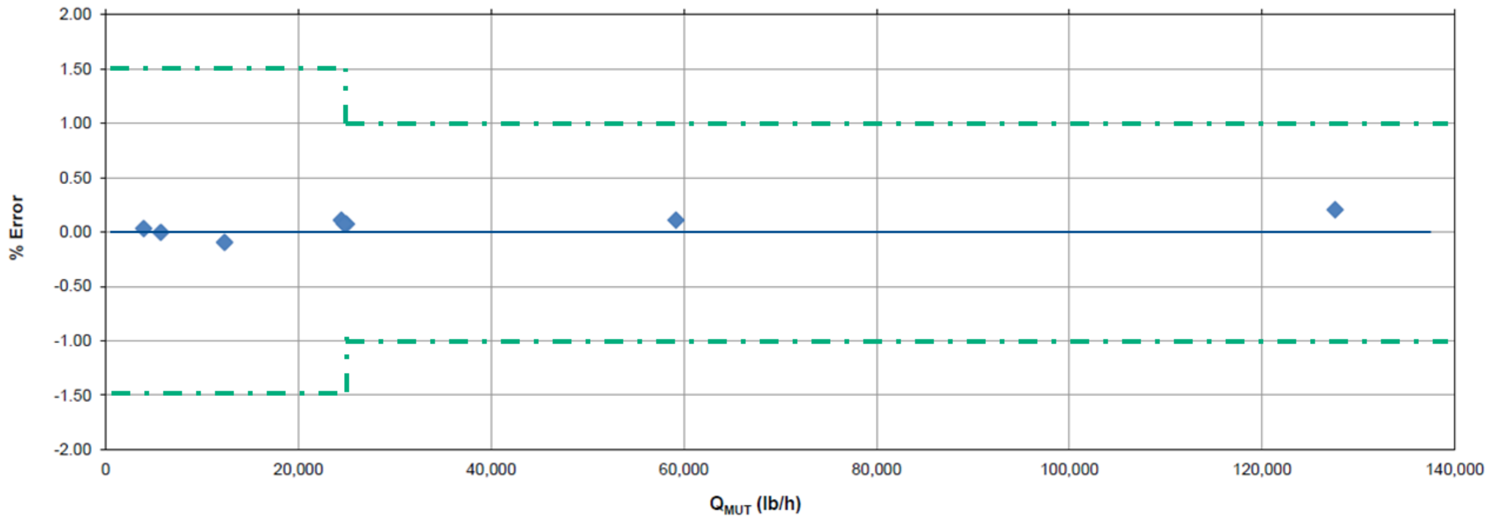


Water Transferability – Example CO_2 CMF400

Configuration File Data File ☑ Customer Config ☑ As Found ☐ As Left ☐ Final Config

Test Point	P_{REF} (psia)	T_{REF} (ºF)	$Density_{REF}$ (lb/ft³)	Q_{REF} (lb/h)	Q_{MUT} (lb/h)	% Error HF	K-Factor pulses/lb	CMC (%)	Utot (%)
1	240.1	73.6	2.0276	127,276	127,533	0.20	136.3523	0.29	0.32
2	240.0	71.3	2.0394	59,080	59,143	0.11	136.2245	0.29	0.30
3	240.1	75.6	2.0177	24,935	24,954	0.07	136.1767	0.29	0.29
4	240.0	78.0	2.0049	12,309	12,297	-0.10	135.9463	0.29	0.30
5	239.4	79.3	1.9925	5,696	5,695	-0.01	136.0700	0.29	0.30
6	238.7	80.5	1.9807	3,893	3,894	0.03	136.1168	0.29	0.29
7	238.9	82.4	1.9729	24,405	24,431	0.11	136.2233	0.29	0.29
8	240.4	80.2	1.9972	24,725	24,742	0.07	136.1740	0.29	0.29

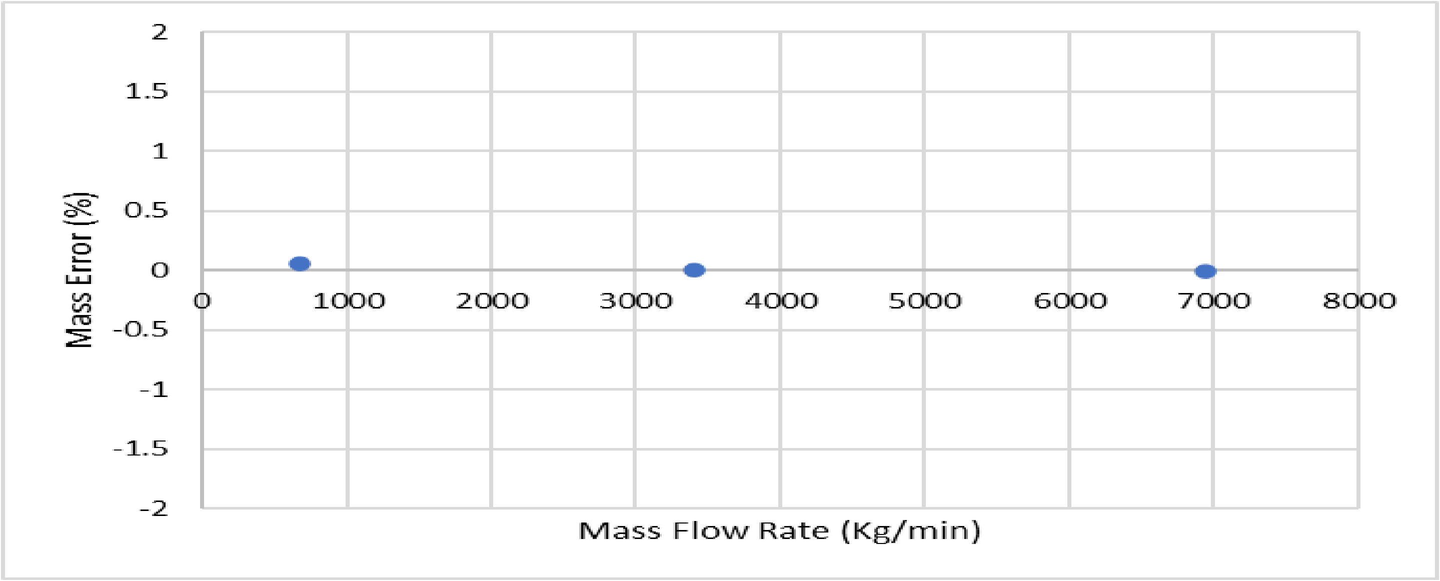
Table 1 Meter Calibration Results



Note: calibration on CO_2 gas done with same parameter settings as in water calibration

Average Calibration Results for Meter Under Test

Grp	Mass Rate (kg/min)	Mass Total (kg)	Mass Error (%)	Volume Rate (l/min)	Volume Total (l)	Volume Error (%)	Density (kg/m³)
1	6944	6950.853	-0.005	6961	6967.753	-0.019	997.575
2	672.3	673.2936	0.060	674.0	675.0061	0.057	997.463
3	3405	3408.634	0.004	3414	3417.365	0.001	997.445

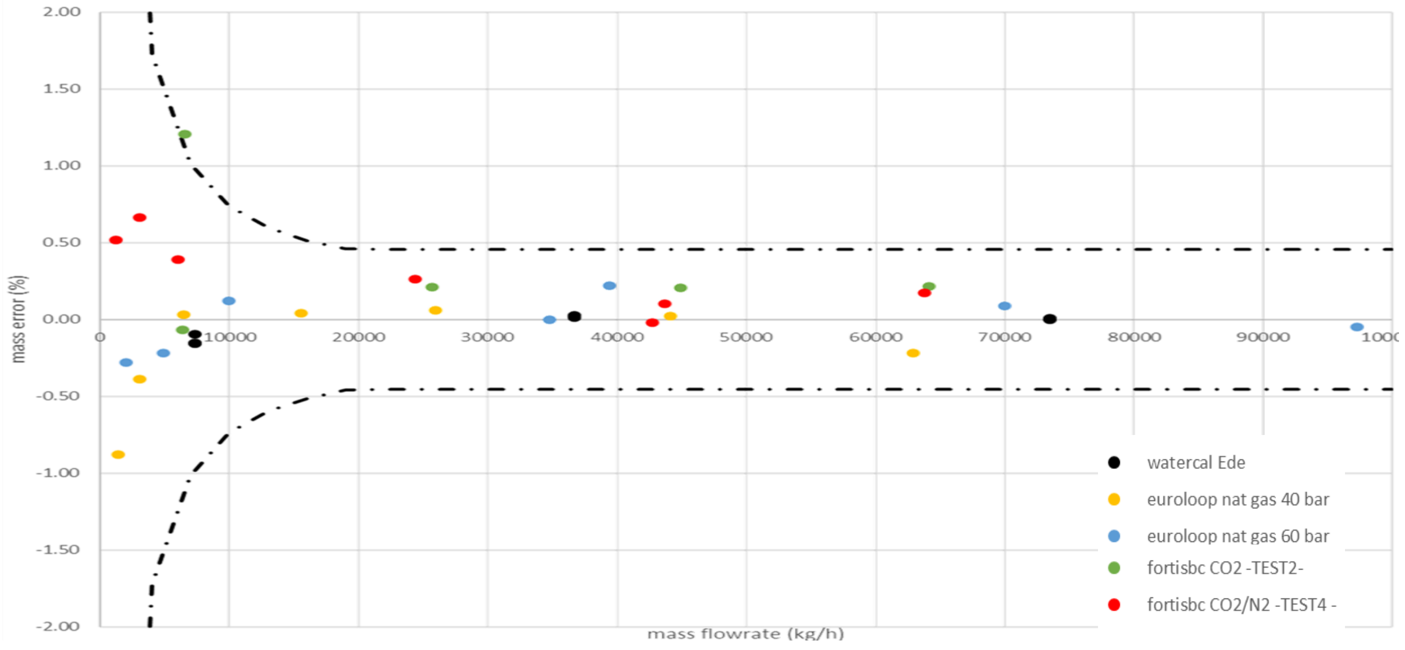


***** Water Calibration uncertainty of ±0.03%***

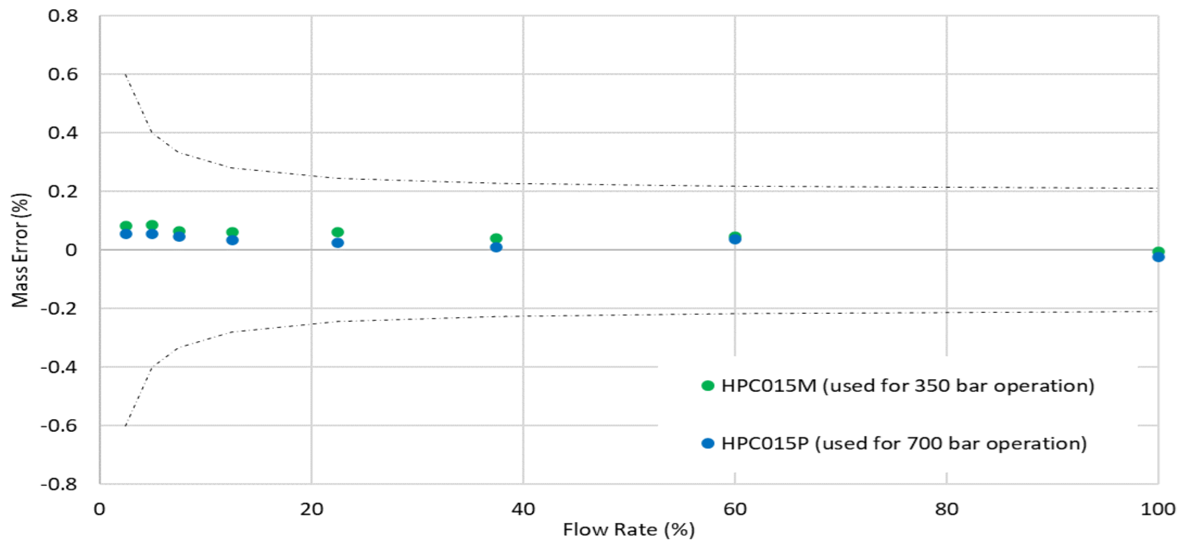
Water Transferability for the H_2 and CCUS Economy

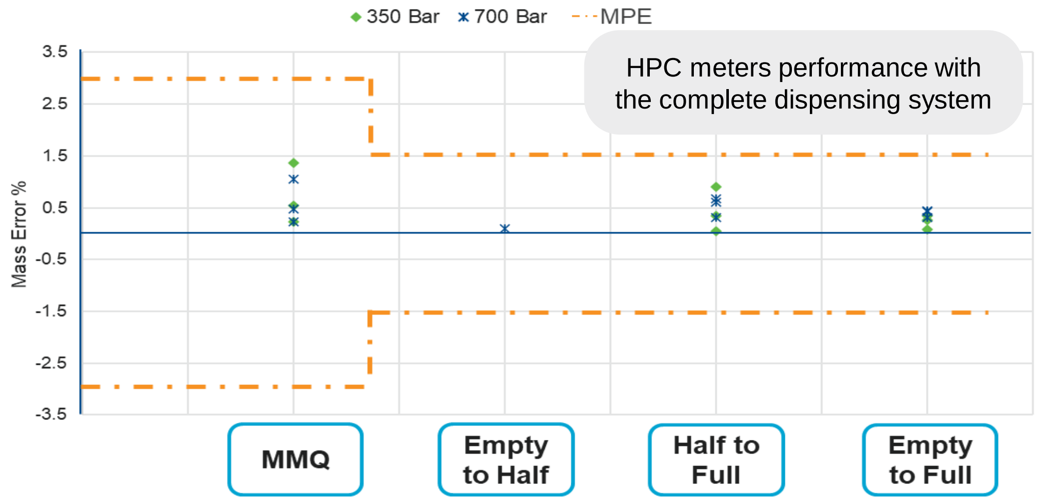
CO_2 performance transferability from Water and Other gases

- Calibration on CO_2 with impurities (90% to 100% CO_2)
- Calibration on NG
- Calibration on Water
- Performance within Class 0.5 for gas meters (OIML R137)



H_2 performance transferability from Water





Summary

- Coriolis Flow Meter are Fit for Purpose:
  - H_2 applications
  - CO_2 applications
- On-going work to build traceability facilities for H_2 and CO_2 Economy
  - Consideration for transferability from Water and Alternative Gases
- Coverage of Standards on H_2 and CO_2 is limited but OIML offers the best Fit

[Q?]

Stay Connected, Stay Safe

metrologyeurope-msol@emerson.com

EMERSON

SICK
Sensor Intelligence.

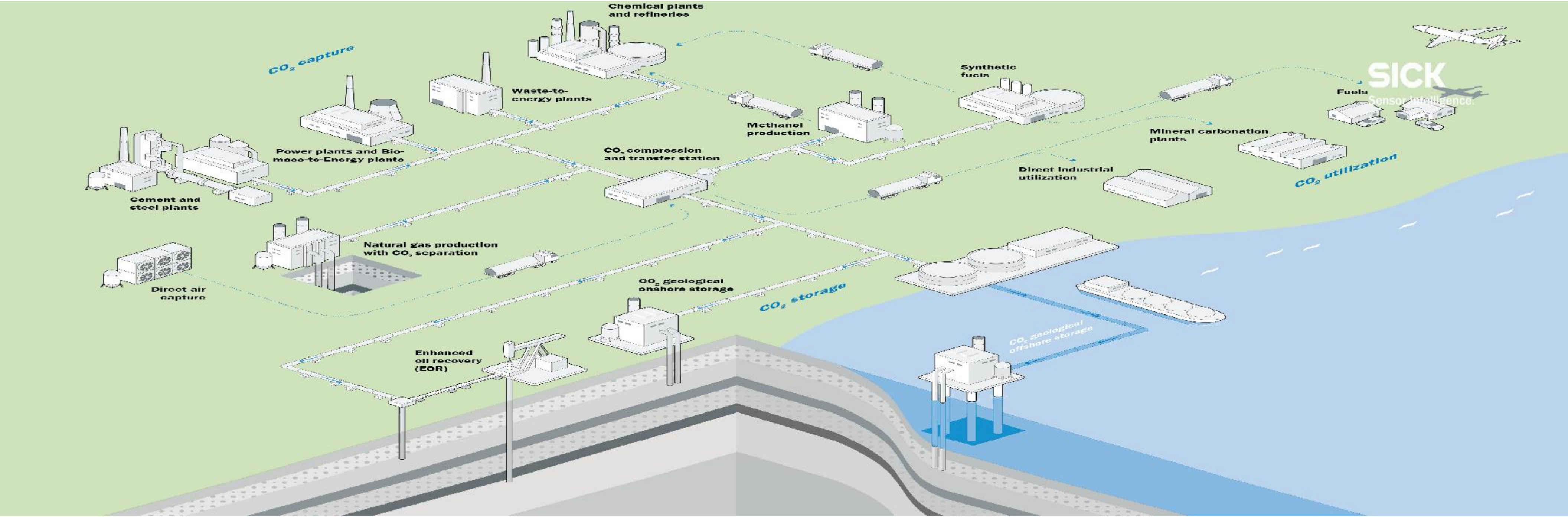
CO_2 Measurement needs along the CCUS Value Chain

Aurélie Moll
Head of Industry Group Energy & CCUS

26.10.2023

Agenda

1. Introduction
2. Decarbonization and CCUS Market trend
3. Sensor Solutions for the CCUS Value Chain



1. Introduction

SICK at a glance

Key figures (fiscal year 2022)

2,190
SALES
(IN EUR MILLION)

365
SALES IN GERMANY
(IN EUR MILLION)

734
SALES IN EMEA
(IN EUR MILLION)

509
SALES IN AMERICAS
(IN EUR MILLION)

583
SALES IN ASIA-PACIFIC
(IN EUR MILLION)

11,909
EMPLOYEES

2,511
ORDERS RECEIVED
(IN EUR MILLION)

SICK
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3,965
PATENTS

241
R&D EXPENDITURE
(IN EUR MILLION)

165
EBIT
(IN EUR MILLION)

Process automation business fields

Overview

Buildi

CCUS is a key milestone to support the **decarbonization** in those industries

Metals & Mining

Oil and gas

Power

Waste and Recycling

Wide product and technology portfolio

Innovative portfolio from our Global Business Centers

PRESENCE DETECTION

INDUSTRIAL SAFETY

ANALYZERS

FLOW MEASUREMENT

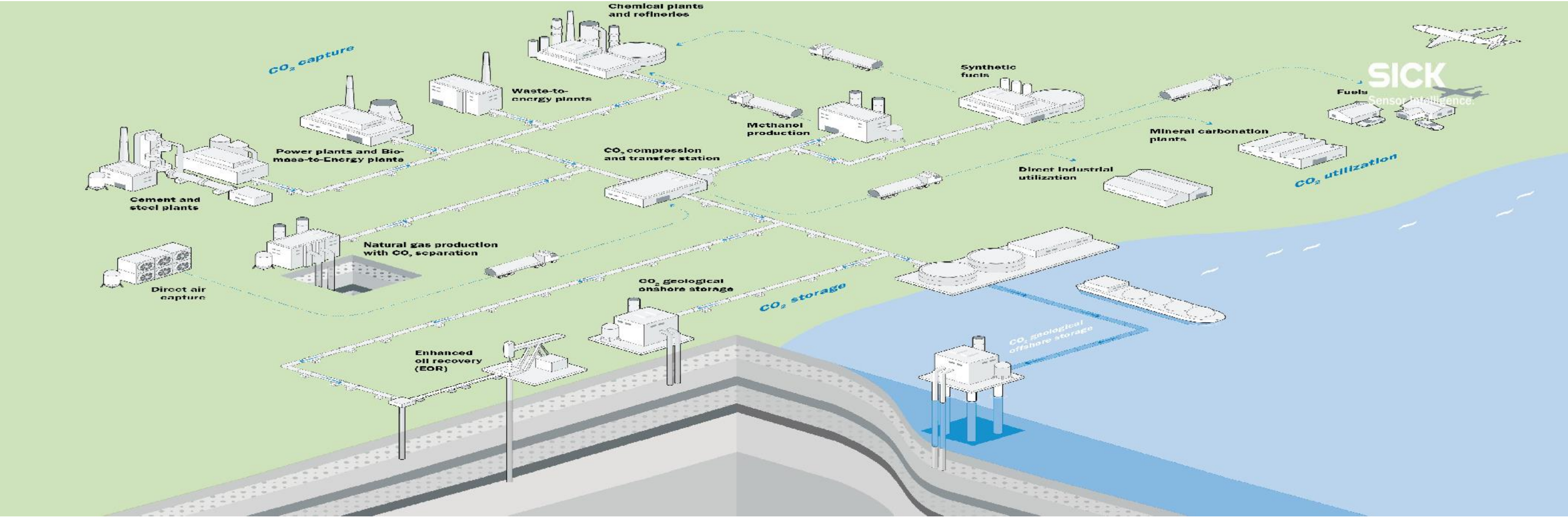
SYSTEMS

INDUSTRIAL INTEGRATION SPACE

MOTION CONTROL SENSORS

IDENTIFICATION & MEASURING

NEW BUSINESS



2. Decarbonization and CCUS Market Trend

Carbon Capture Utilization and Storage

CCUS and Decarbonization

Net Zero Emissions 2050 is only achievable by using CCUS
to offset for remaining emissions

- **The IPCC Sixth Assessment Report 08/2021**
  - Temperatures expected to **reach 1.5°C earlier than anticipated**
  - **Carbon dioxide removal** to compensate for residual CO_2 emissions **to reach net zero** or generate **net negative CO_2 emissions**

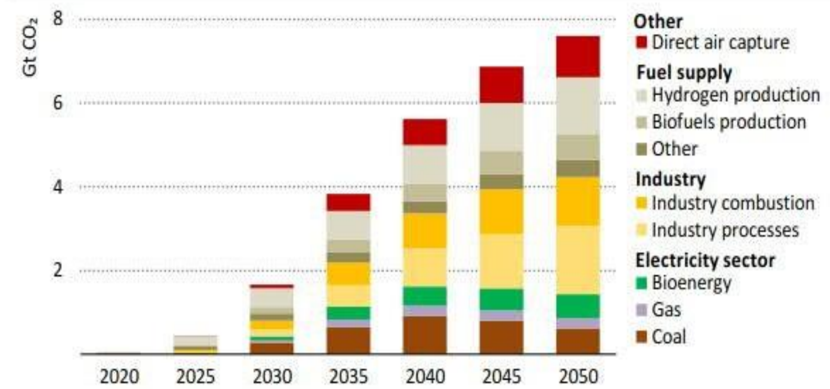
- **IEA Net zero by 2050** - *A Roadmap for the Global Energy Sector*
  Needed CCUS capacity to reach the climate targets
  2030: 1,7 Gt CO_2 /year (7,6 Gt in 2050)

- **Policies Regulations: i.e. Europe "Fit for 55" EU Target 2030**
  Climate targets **: 55% GHG emission reduction until 2030**

- **CO_2 price and tax/credit systems**
  i.e. in **Europe**: EU ETS **huge growth**

- **High Private-public funding in Billions €**

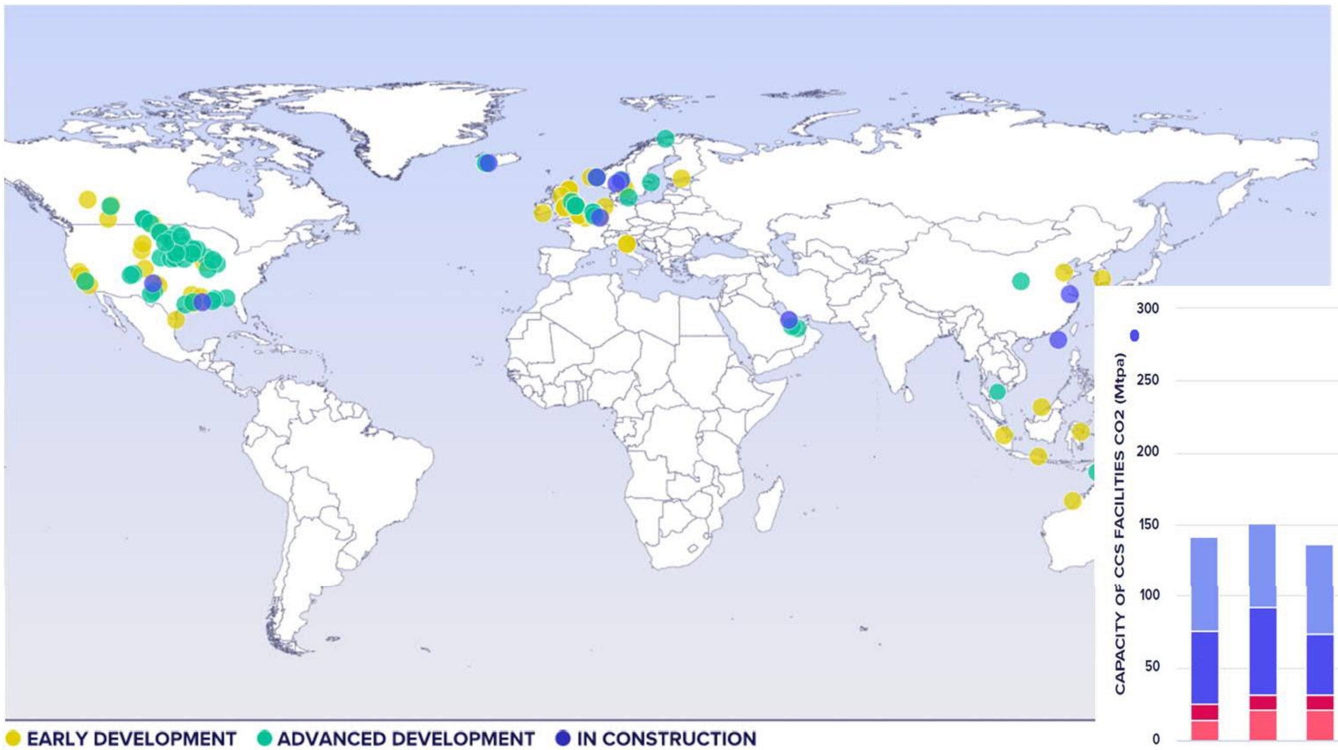
Figure 2.21 ▷ Global CO_2 capture by source in the NZE



EU ETS

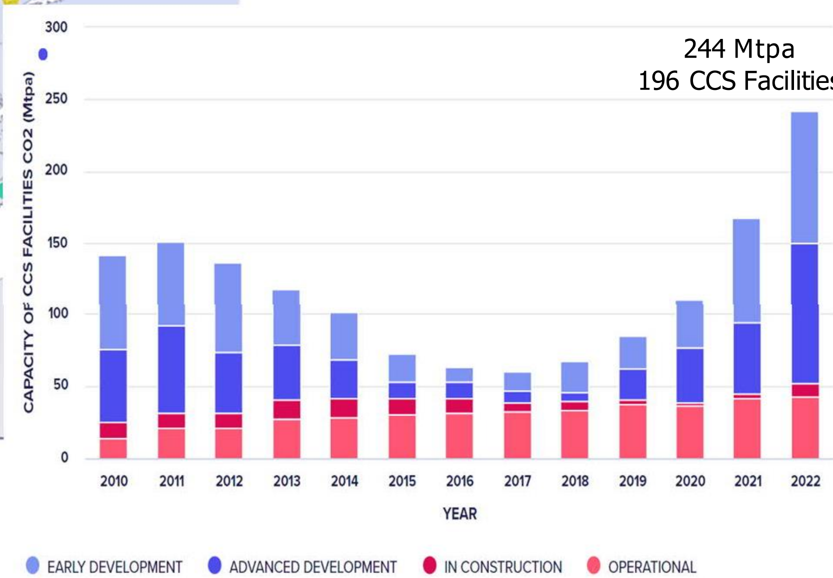
CCUS Market Trend

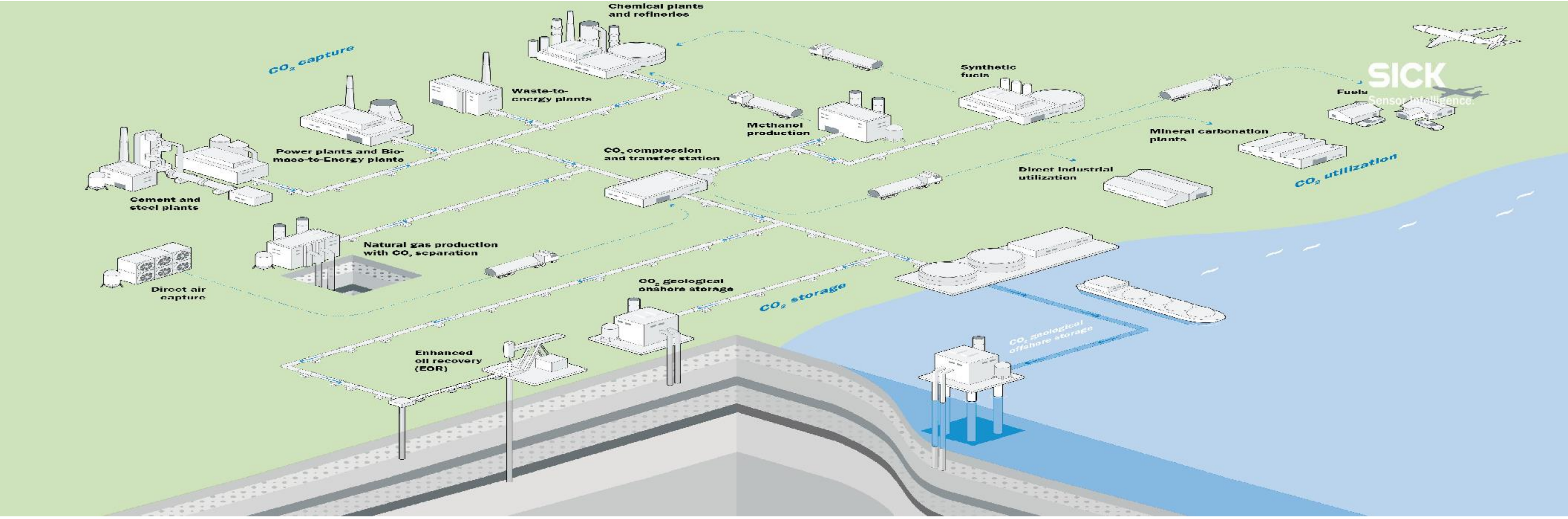
GCCSI – CCS Status Report 2022



GLOBAL CCS INSTITUTE

GCCSI Status report 2022:
commercial facilities since 2010 by capture capacity (Mtpa)



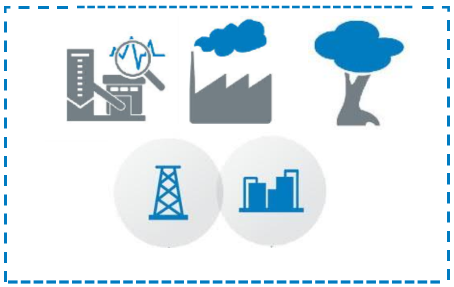


3. SICK Sensor Solutions for the CCUS Value Chain

Carbon capture utilization and storage

CCUS Value chain

Capture

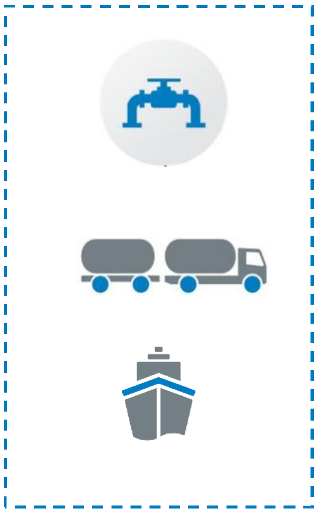


Industry
Steel & cement production, Power plants, WtE, Chemical plants, Refineries…

Gas Processing
Natural gas, hydrogen, Ammonia production…

Direct Air Capture

Transport



Storage

CO_2 Injection deep underground

- Onshore
- Offshore

Utilization

Chemical conversion
Mineralization
Direct utilization
Biological conversion

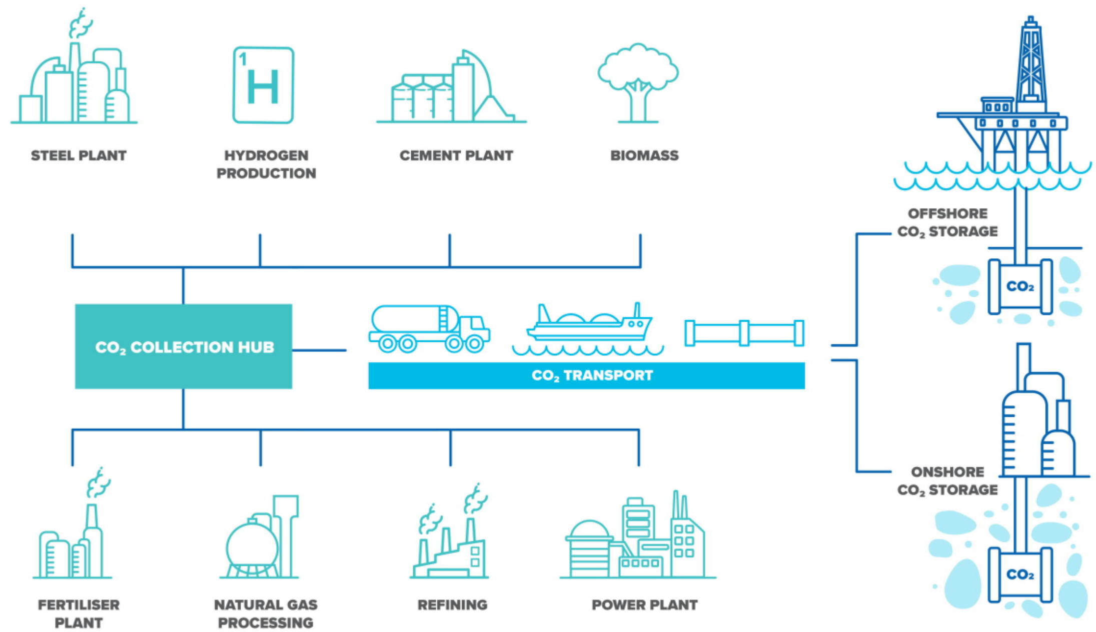
Carbon capture utilization and storage

Development of CCUS Networks

Development of hubs and cluters in industrial areas

- Proximity of industrial emitters
- Common use of existing infrastructure
  - Pipelines
  - Industrial harbours
- Construction of new common infrastructure
- Cost optimization

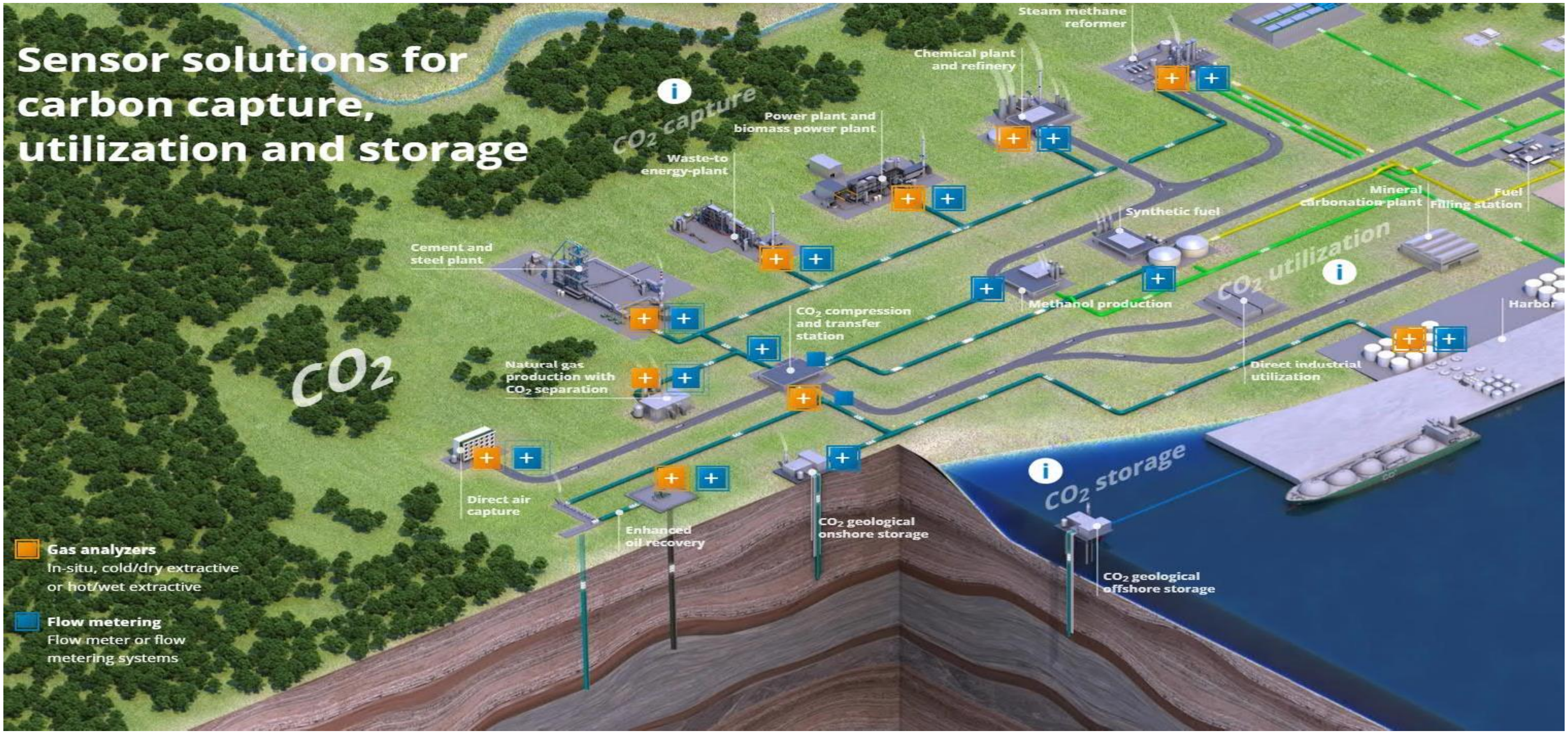
Need for precise and continuous CO_2 Measurement!



Source: Global CCS Institute

CCUS Value Chain

Analyzer and Flowmeter solutions

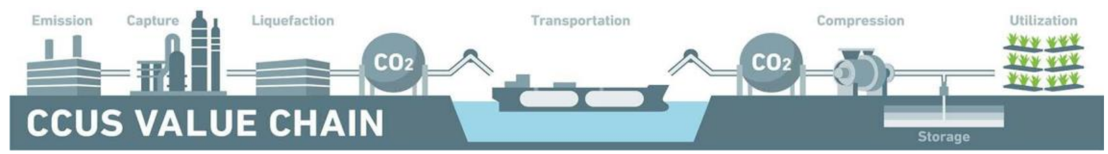


SICK Solutions for the CCUS Value Chain

CO_2 Flow Metering & Gas Analysis

SICK Solutions for the CCUS Value Chain

- **Capture efficiency** with CO_2 concentration
- **Quality** control (impurities)
- **Reporting** (removed CO_2 quantity)



Source MHI Group

Gas & Dust analyzers

- Single component analyzer (i.e. CO_2) with insitu technology
- Quality / Impurity measurement with Multicomponent extractive analyzers
- Dust analyzers for dry & wet gases

Insitu analyzers

Multi-component extractive analyzers

Dust analyzers

Flowmeters

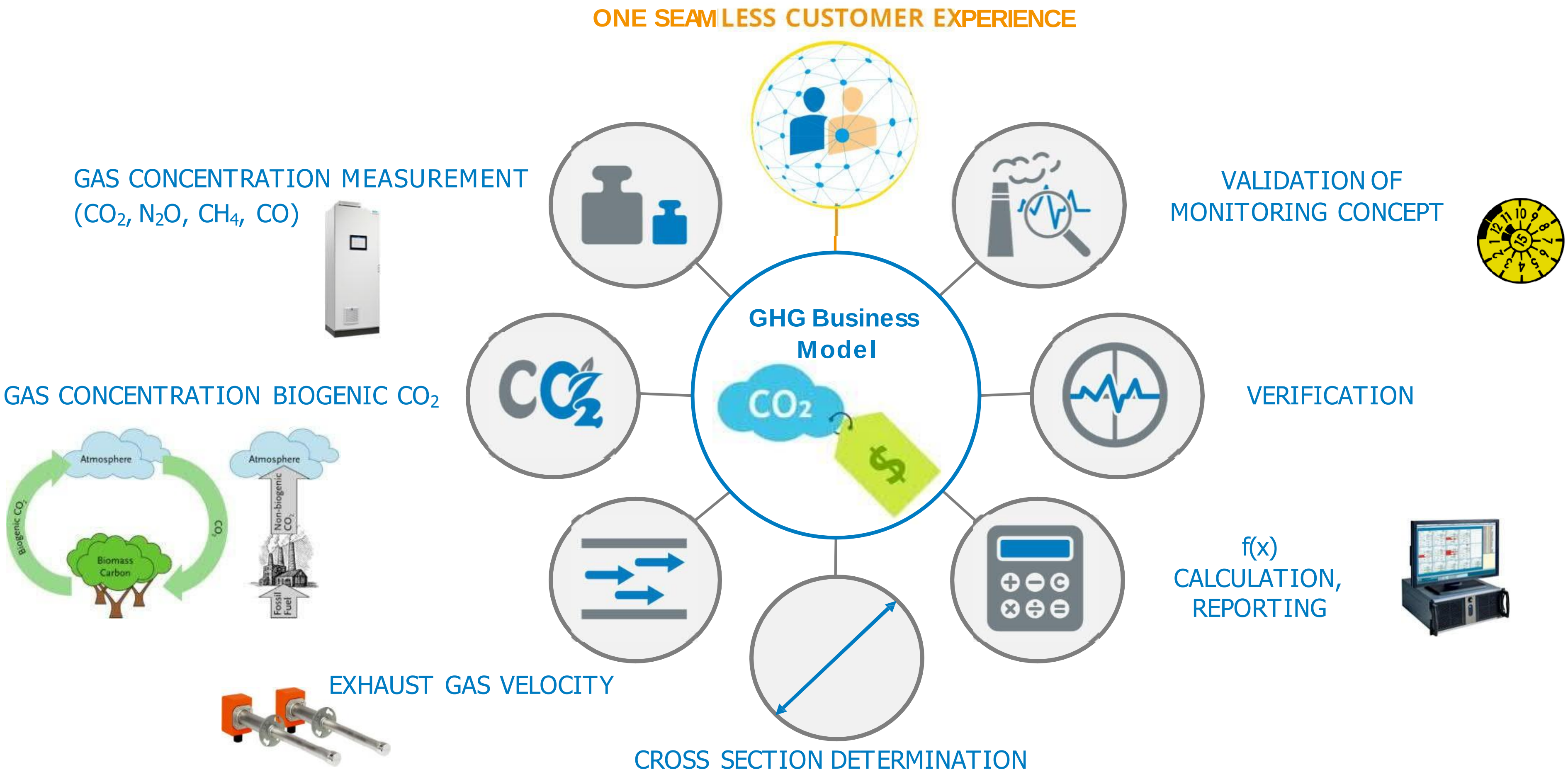
- Ultrasonic Flowmeters

Integrated Measuring Systems

- Metering skids
- Analyzer shelters

SICK Solutions for the CCUS Value Chain

GHG Complete solution incl. digitalzation

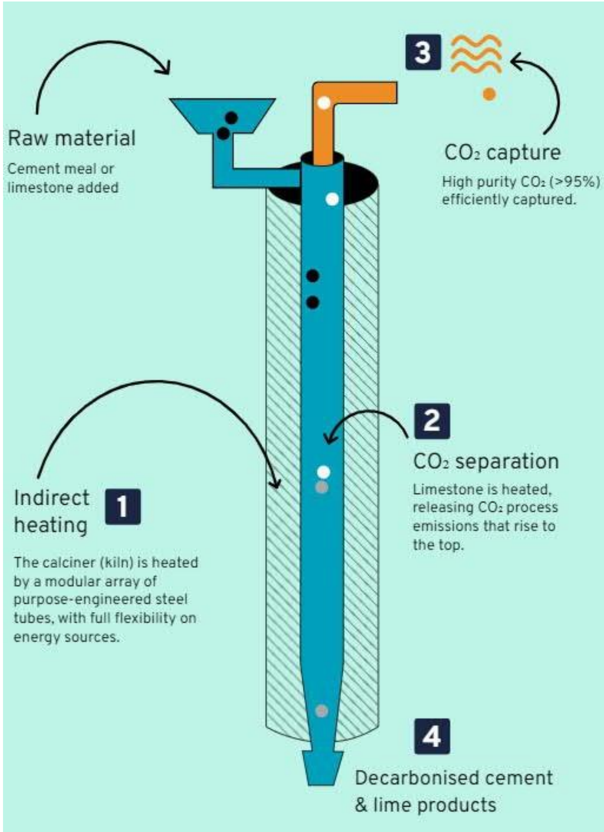


SICK Solutions for the CCUS Value Chain

Specific carbon capture process for cement production

Direct CO_2-Separation for Cement: LEILAC 1

- unavoidable CO_2 emitted from the limestone
- indirect heating of the limestone in a special steel reactor
- Direct separation of the pure CO_2 released by the limestone
- No additional separation process needed



Source:

Leilac 1 (Low Emissions Intensity Lime And Cement)

SICK Solutions for the CCUS Value Chain

SICK experiences with the Leilac 1 project

Carbon capture at a cement plant – LEILAC1 Pilot

› Carbon Capture pilot plant with CALIX Europe and HeidelbergCement in Belgium

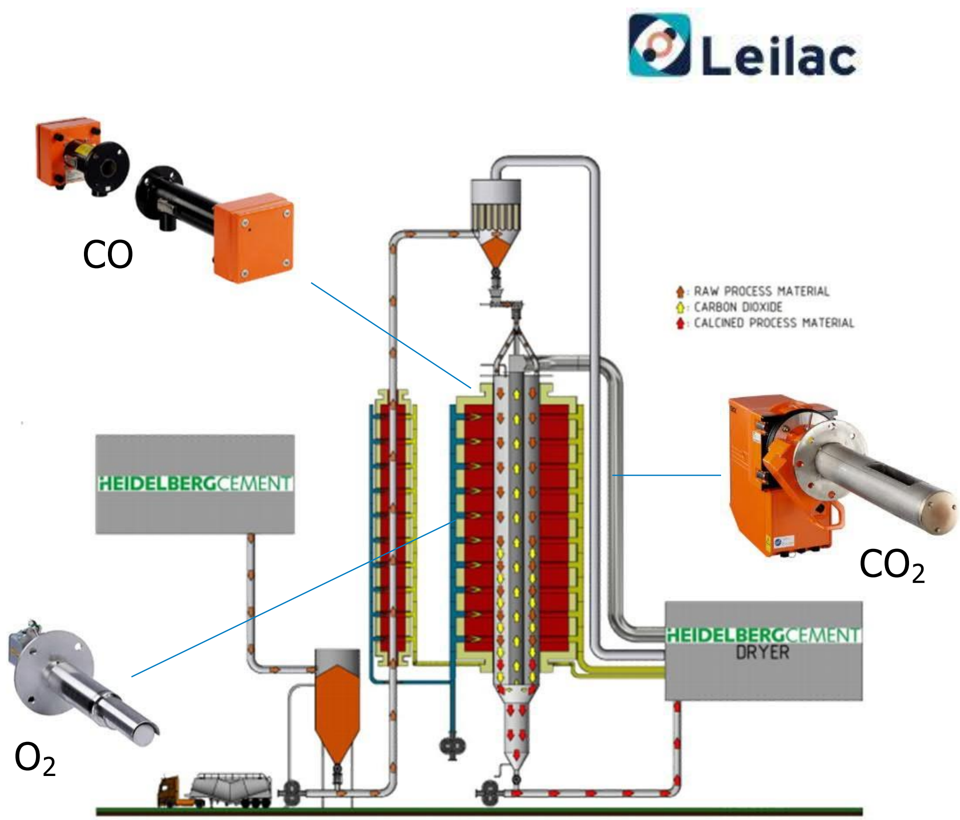
› **Provided SICK Solutions:**

– Process gas analyzer : separated CO_2 concentration with GM35

– Combustion control: with GM901 (CO) and Zirkor100 (O_2)

Link to Leilac:

Leilac 1 (Low Emissions Intensity Lime And Cement)



SICK Solutions for the CCUS Value Chain

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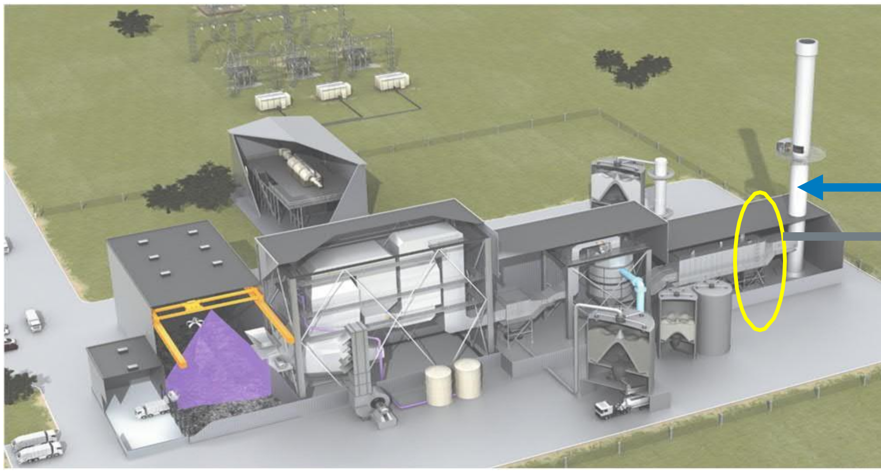
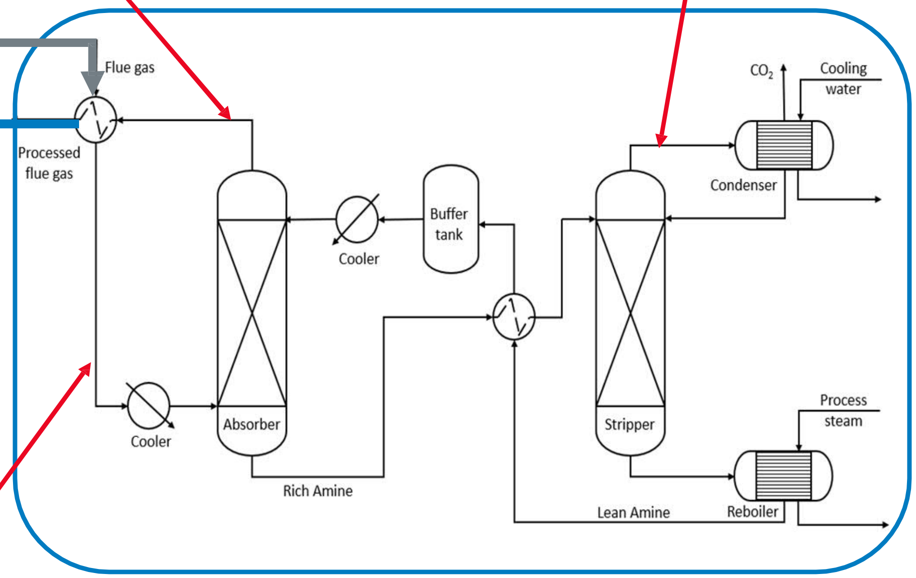
Measurements for post-combustion carbon capture



Outlet Carbon Capture
CO_2 lean gas
& other required components

Outlet Carbon Capture
CO_2 rich gas



Part of the flue gas treatment, can be retrofitted to each industrial plant

Example with solvent based scrubber

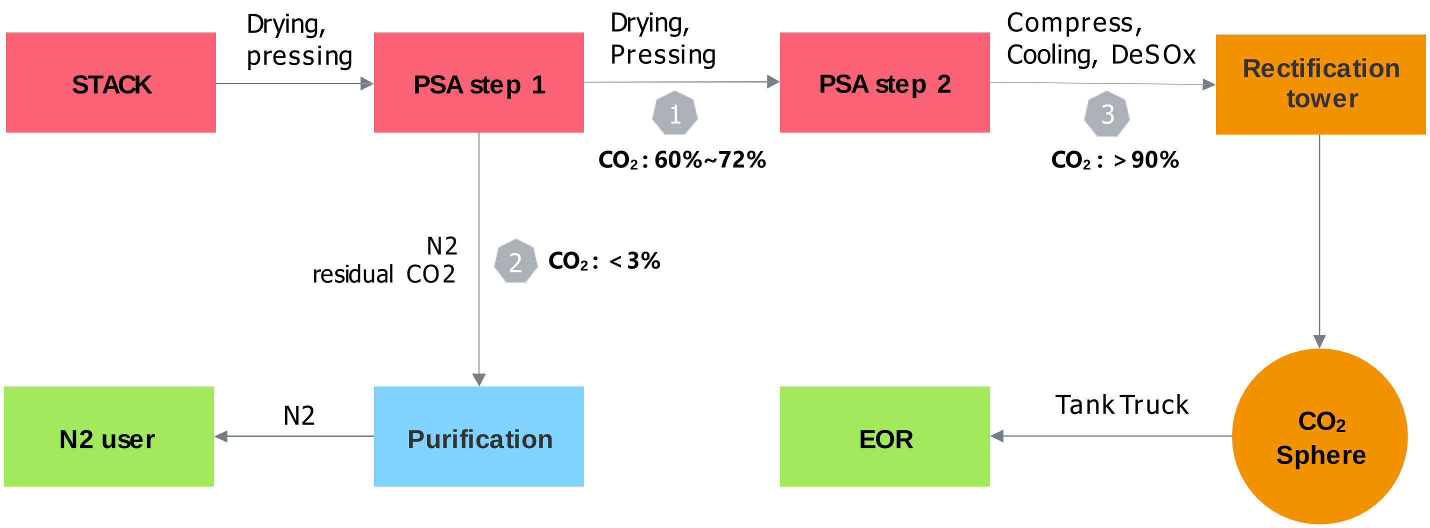
Inlet Carbon Capture Raw gas after the standard FGT
CO_2 & other required components like SO_2, dust…

Solvent based scrubber

SICK Solutions for the CCUS Value Chain

Example with a PSA capture process

CO_2 & N_2 Capture at a Coal Fired Power Plant
Using Pressure Swing Absorption process



3 measuring points:

1. The bottom outlet of PSA step 1, CO_2 60%~72% **(SIDOR CO2 60%~100%)**, pressure 21kpa, pressure stable
2. The top outlet of PSA step 1 , residual CO_2 < 3% **(SIDOR CO2 0%~5%)**, pressure 0.78MPa,pressure stable
3. The bottom outlet of PSA step 2 , CO_2 > 90% **(S710 UNOR CO2 80%~100%)**, pressure 2.27kpa, pressure stable

SICK Solutions for the CCUS Value Chain

Summary

CCUS is a key element for mitigating climate change and to reach the high CO_2-emission reduction targets

- CO_2 separation for the production of fossil-based energie
- Reduction of unavoidable CO_2 from hard-to-abate industries (Cement, steel, petrochemical plants…).
- Clean gas production: natural gas production, blue hydrogen / Ammonia production with CCUS

Continuous measuring technologies to control the complete CCUS ecosystem

- Efficiency of CO_2-capture processes
- Quality of the gas matrix
- Flow metering

Challenges and diversity of applications

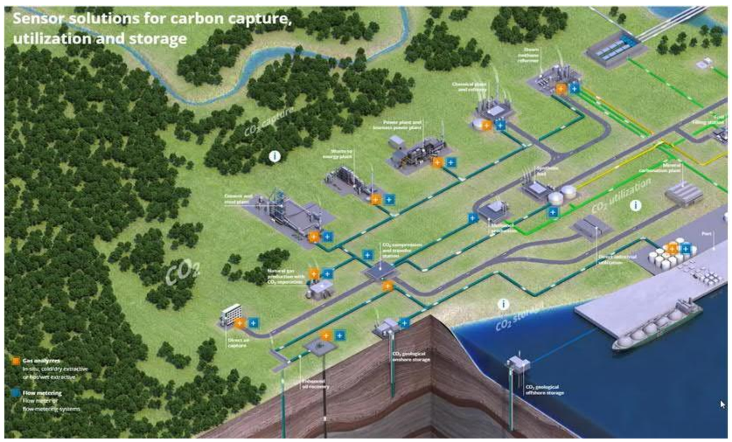
- Unclear Specification for CO_2 and impurities
- Diversity of applications along the CCUS value chain

Carbon Capture, Utilization and Storage

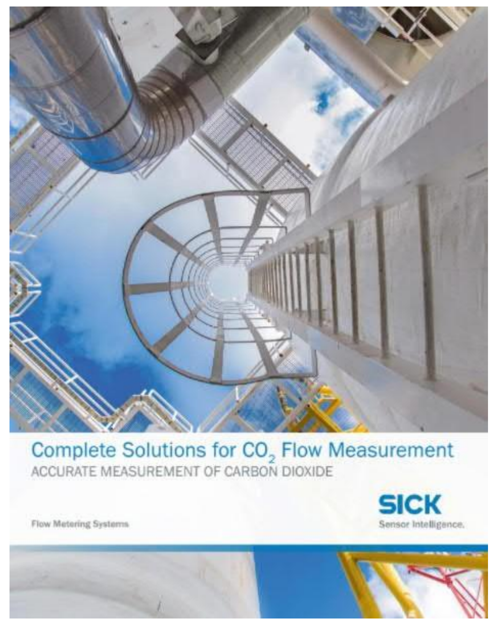
Dedicated brochures and tools for CCUS

Useful links:

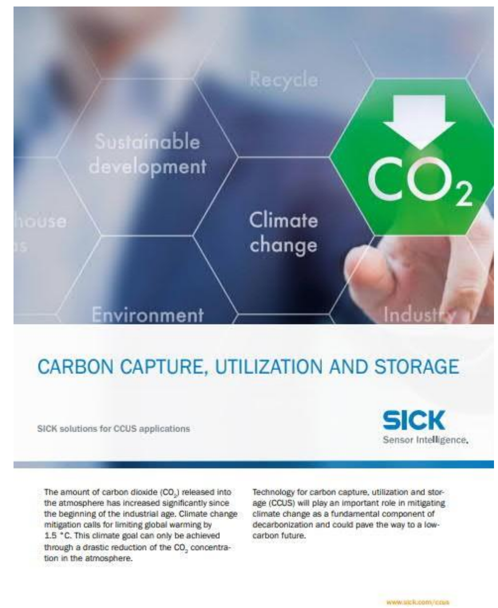
SICK Solutions for Carbon Capture Utilization and Storage



Special Information about CO2 Flow Measurement



Special information CCUS



Carbon Capture, Utilization and Storage

For further information

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Mobile: +49 172 76 68 601
E-Mail: aurelie.moll@sick.de
Website: www.sick.com
linkedin.com/in/aurelie-moll/

Link to the SICK CCUS website:

www.sick.com/ccus

NPL
National Physical Laboratory

METROLOGY PARTNERSHIP | EURAMET

METCCUS

Measurement of emissions from CCUS

Rod Robinson, rod.robinson@npl.co.uk

Principal Scientist, Emissions and Atmospheric Metrology Group, NPL

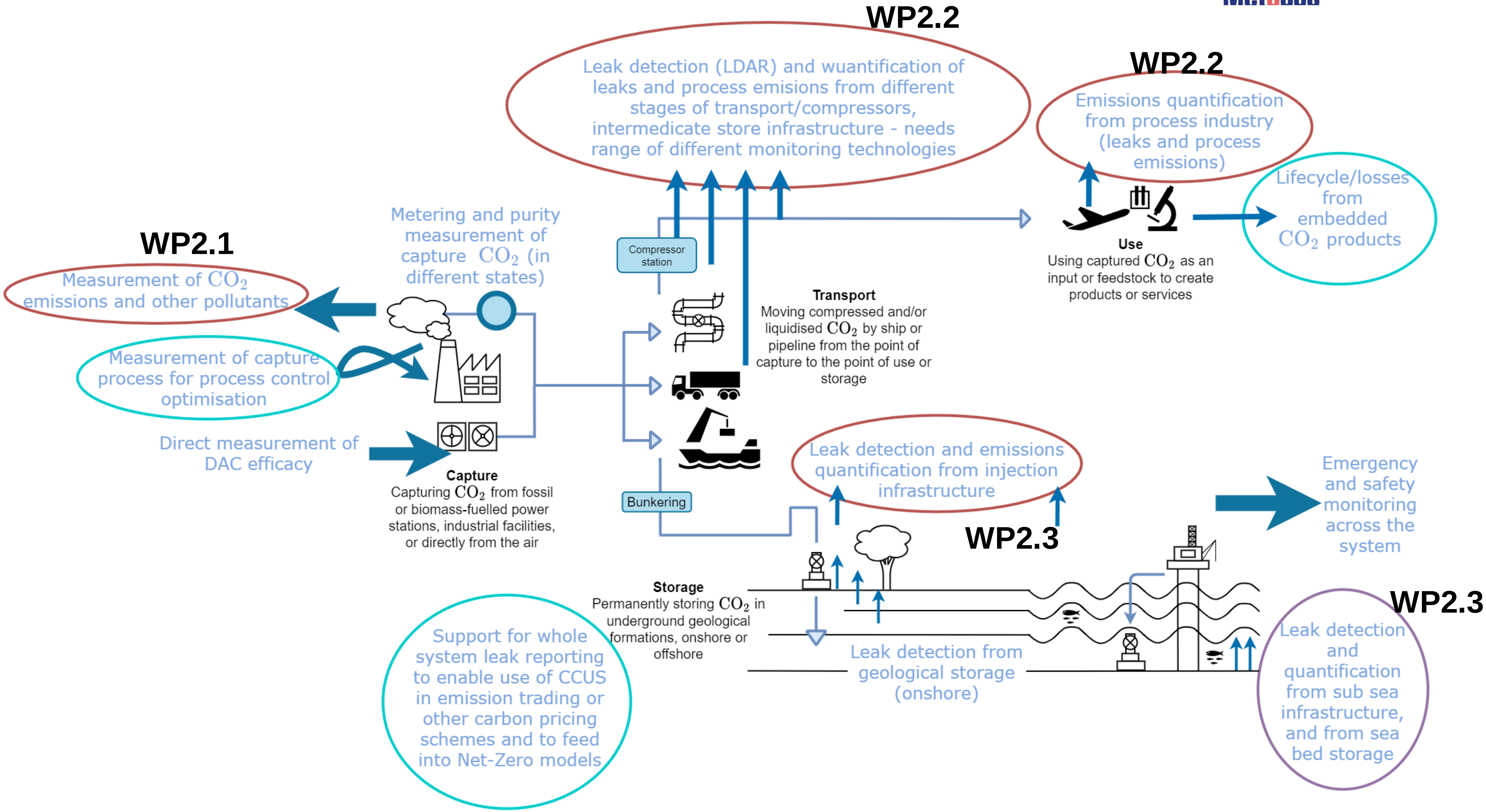
WP2 Lead

WP2 Metrological support for the measurement and reporting of CO_2 emissions to air

- Three tasks
  - Task 2.1 will develop novel methods to determine CO_2 and other emissions to the atmosphere from carbon capture processes. (**NPL**, **Force**, PTB)
  - Task 2.2 will develop the metrological capability needed for the measurement and quantification of emissions of CO_2 from CCUS equipment and infrastructure. (**NOVA**,**NPL**,**FORCE**,SINTEF, GERG)
  - Task 2.3 will assess the potential approaches needed to enable the detection and quantification of emissions of CO_2 into the environment from geological storage. (**PTB**,**NPL**,**VTT**,GERG,NOVA)

	D3	Good practice guide for the measurement of nitrosamines in post-combustion flue gas in order to enable the direct determination of emissions of CO_2 and to address the measurement of air pollutants resulting from the capture process, such as degradation products from capture solvents	Good practice guide	NPL, Force	Jul 2025 (M34)
	D4	Report on the options for the measurement and reporting of emissions to air from different stages of the CCUS process and the performance and capabilities of techniques to monitor emissions into the environment through carbon capture processes, infrastructure (leaks), or geological storage	Report	PTB, VTT, NPL, NOVA, GERG	Sep 2025 (M36)

Monitoring the CCUS System



Measurement of emissions of CO_2

- We can assume the main sources will be similar in a CCUS system as in the gas system
  - Fugitive leaks from components/seals/etc
    - LDAR programmes, optical gas imagining (OGI)
  - Process related vents/releases
    - Lower emission designs, OGI
  - Maintenance and repair operations
    - Engineering, design
- Measurement requirements
  - LDAR – leak detection and repair
  - Source level quantification
  - Site/area scale quantification
- CCUS specific issues
  - Requirements very challenging to meet CCS Directive
  - Ambient background levels of CO2
  - Dispersion characteristics
  - Phase of contained fluid
  - Similar techniques to methane are available

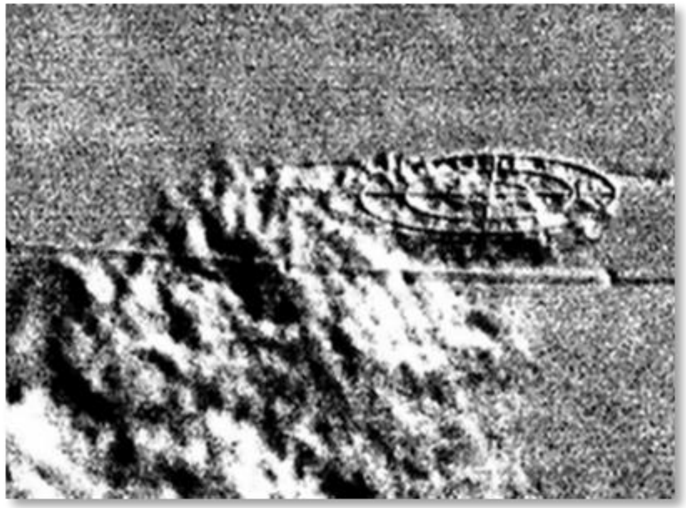
Development of test benches to determine the detection limit of CO_2 sensitive gas imaging cameras

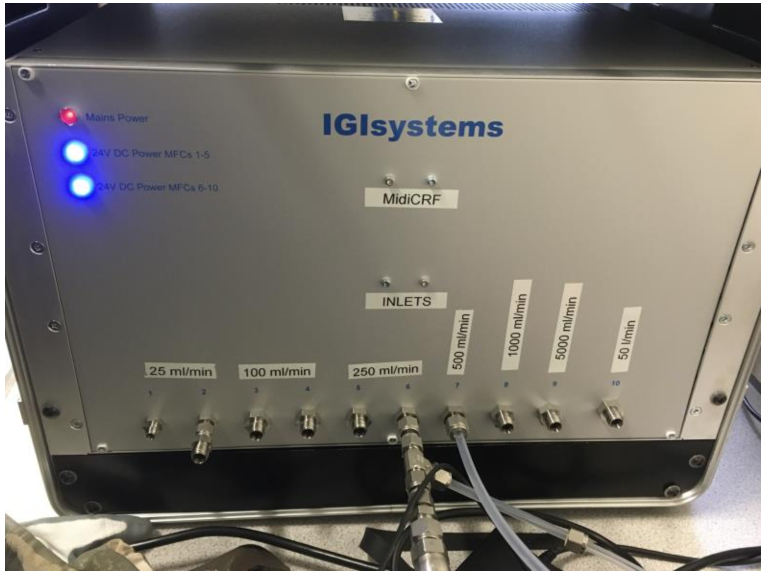
Z. Khan, J. Helmore

Adaption of controlled release and test facilities for CO_2

- NPL currently operates several systems which allow for the creation of controlled emissions between 5 ml/min and 500 l/min (0.2 g/h – 20 kg/h) for methane (natural gas). Expanded uncertainties are typically ≤ 7.5 %.

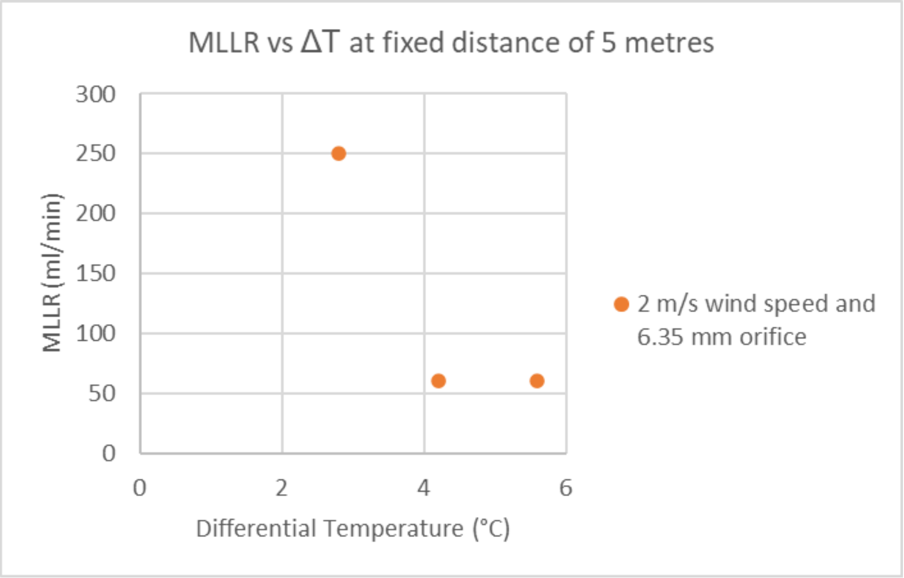
- Within the MetCCUS project activities, release facilities were calibrated for accurate delivery of CO_2 emissions, with rates between 5 ml/min and 50 l/min (0.6 g/h to 5.9 kg/h). Expanded uncertainties achieved ≤ 3 %.





Assessing the detection limits of CO_2 gas imaging cameras

- Adaption of test protocols used for assessing the performance of hydrocarbon sensitive gas imaging cameras to those sensitive to CO_2 under controlled and uncontrolled environmental conditions.
- Assessing detection limits as a function of range, differential temperature and windspeed.
- If ΔT is sufficient (>4 °C) leaks of ~60 ml/min (~7 g/h) can be consistently detected.



Adaption of test facilities for CO_2

- Modification of existing test benches used for methane (natural gas) for use with CO_2.

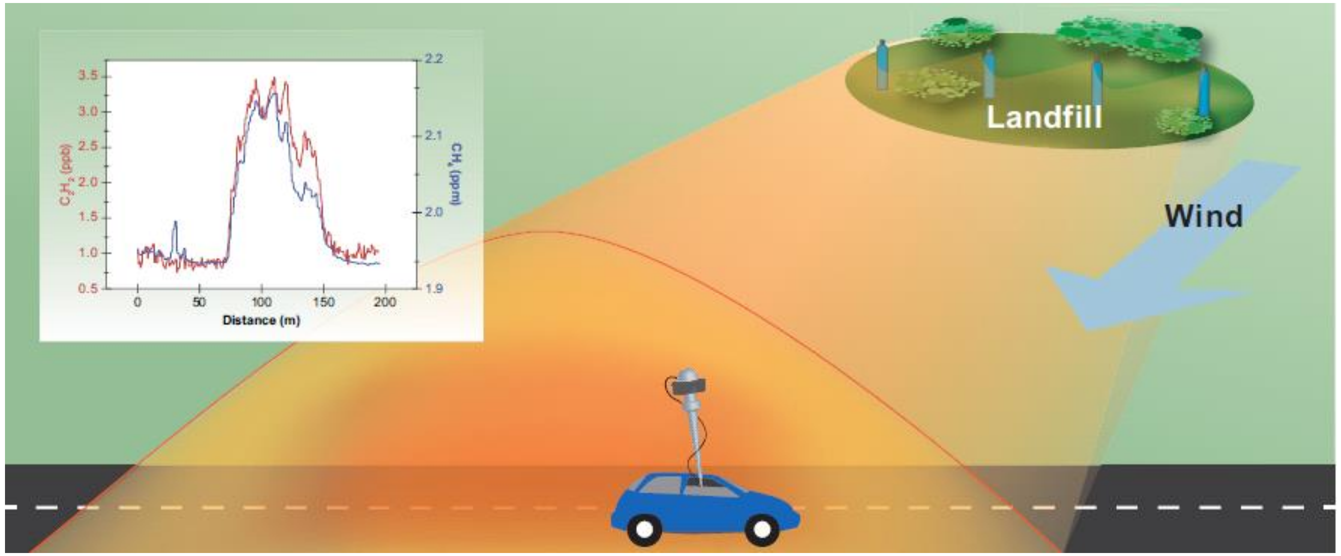
- Adaption of test protocols used for assessing the performance of hydrocarbon sensitive gas imaging cameras to those sensitive to CO_2.

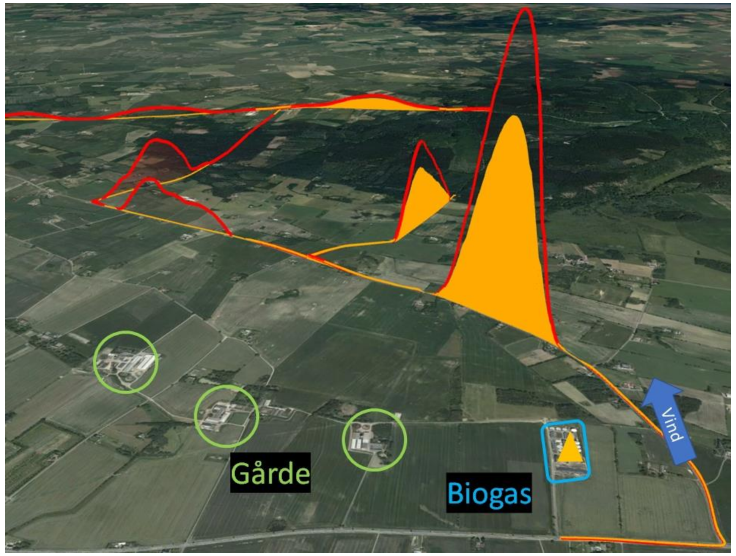
- As with hydrocarbon sensitive gas imagers detection will be dependent of ΔT conditions in the field, which may not be possible to accurately determine, and relies heavily on operator experience.

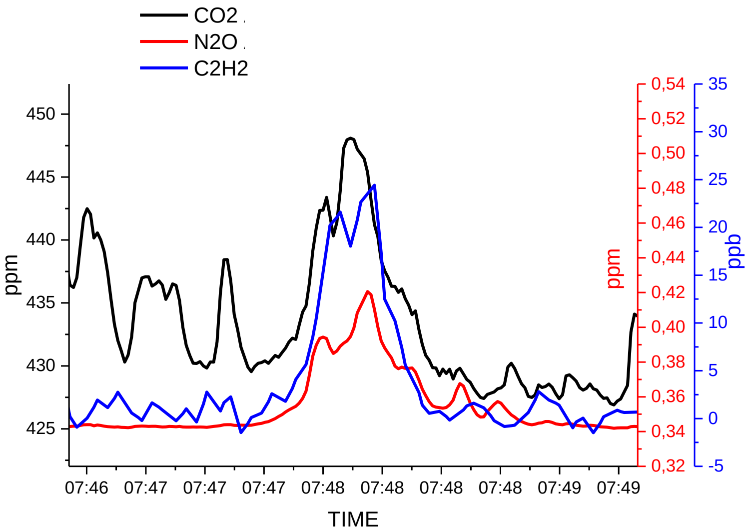
Future work with respect to CO_2

- Future work will look to increase the range of our capability in terms of controlled CO_2 emissions, to enable testing of DIAL and other methods.
- There are significant challenges with handling CO_2 in larger quantities and delivering higher flow rates due to the energy required to vaporise the fluid.
- Development and testing of a high flow sampling method for quantifying CO_2 emissions.

Tracer correlation method



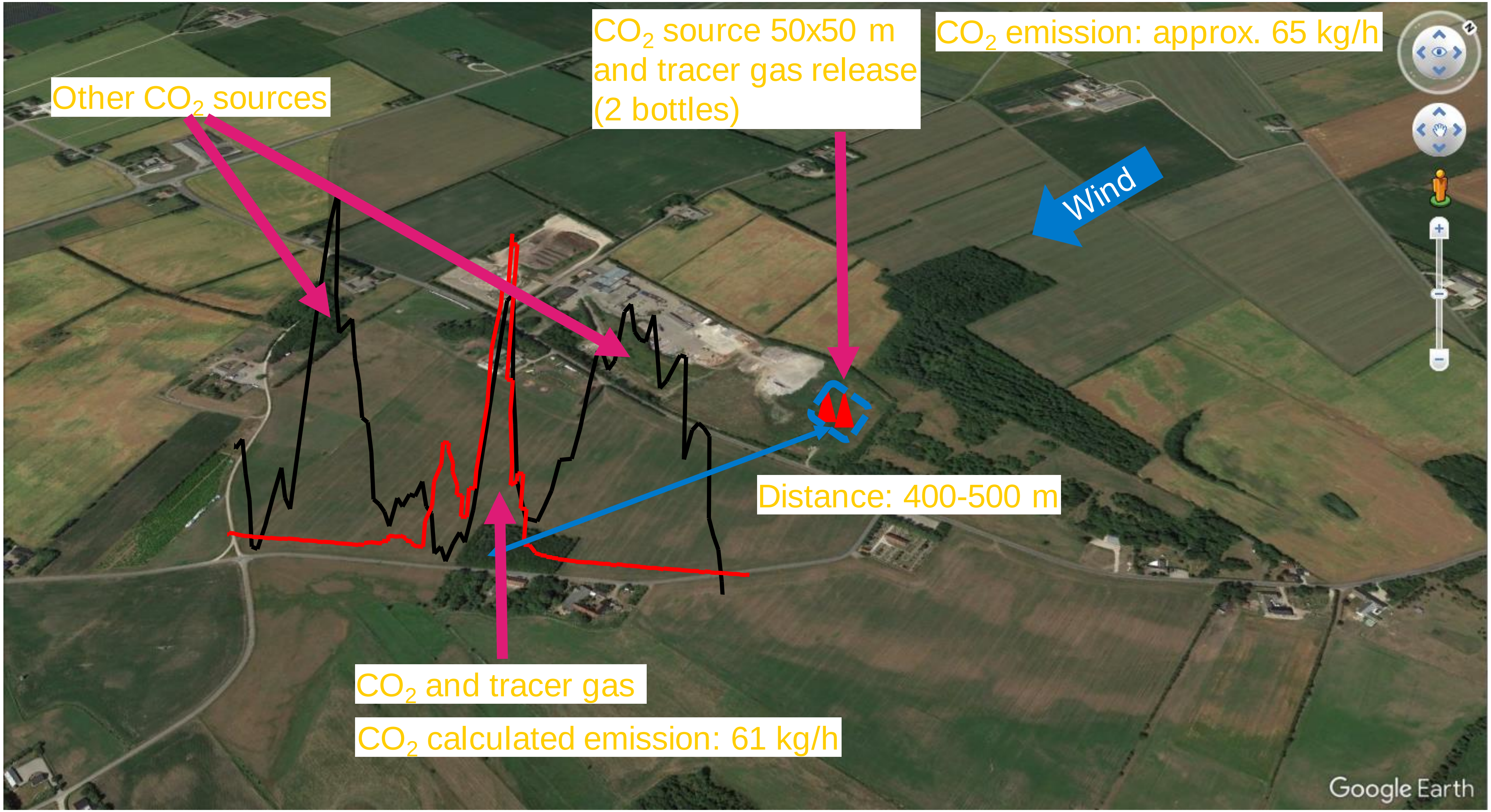




CO_2 emission:
Size (m^2)
Strength (g/s)

Distance needed/possible
Choice of tracer gas

Tracer correlation method for diffuse CO_2 emission



MetCCUS, Subsea leakage from storage

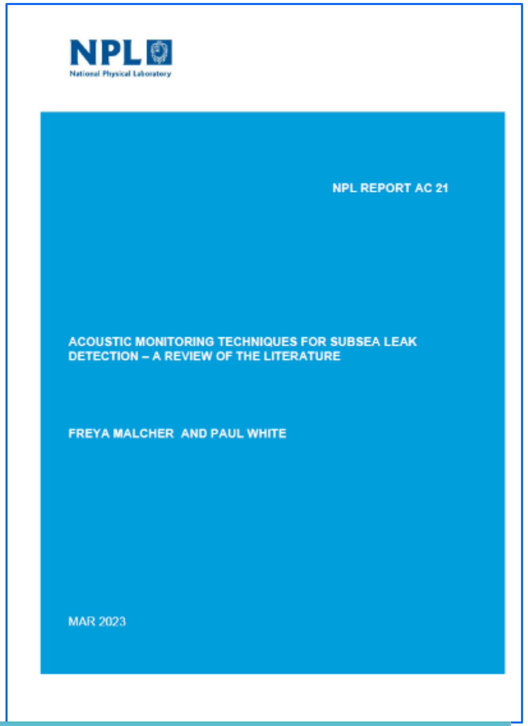
- **NPL review of acoustic techniques**

- **NPL report AC21 published**
- reviews physics of sound-bubble interaction, active and passive techniques, and existing offshore projects

- **Active and passive acoustic techniques**
- passive uses only hydrophones to listen for leaks
- active insonifies target and detects sound scattered by bubbles

- **Review of existing in-situ offshore projects**
- ECO2 (2011-2015)
- QICS (2012)
- STEMMS-CCS (2016-2020)

- **Next steps and knowledge gaps**
- re-evaluation of existing datasets using new models
- better understanding of depth dependence
- Greensands new active acoustics project (Denmark)

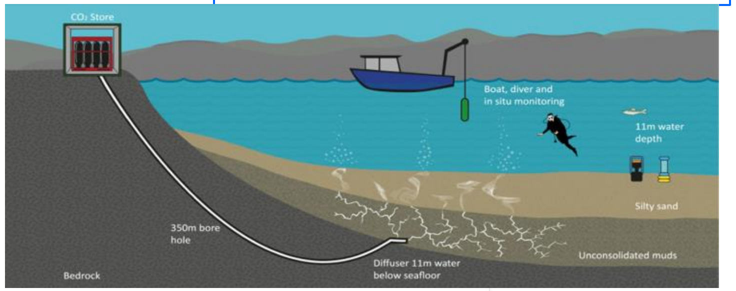

NPL
National Physical Laboratory

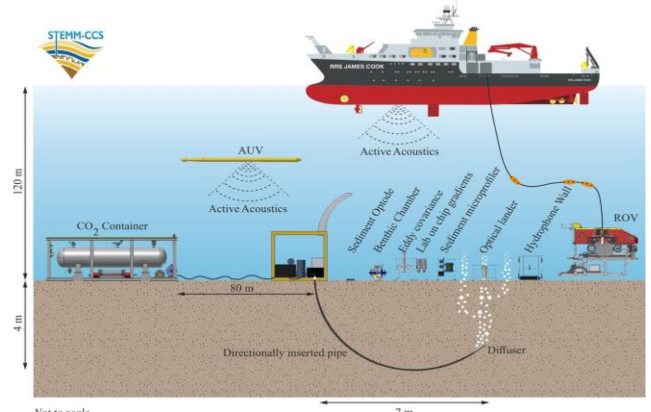
NPL REPORT AC 21

ACOUSTIC MONITORING TECHNIQUES FOR SUBSEA LEAK DETECTION – A REVIEW OF THE LITERATURE

FREYA MALCHER AND PAUL WHITE

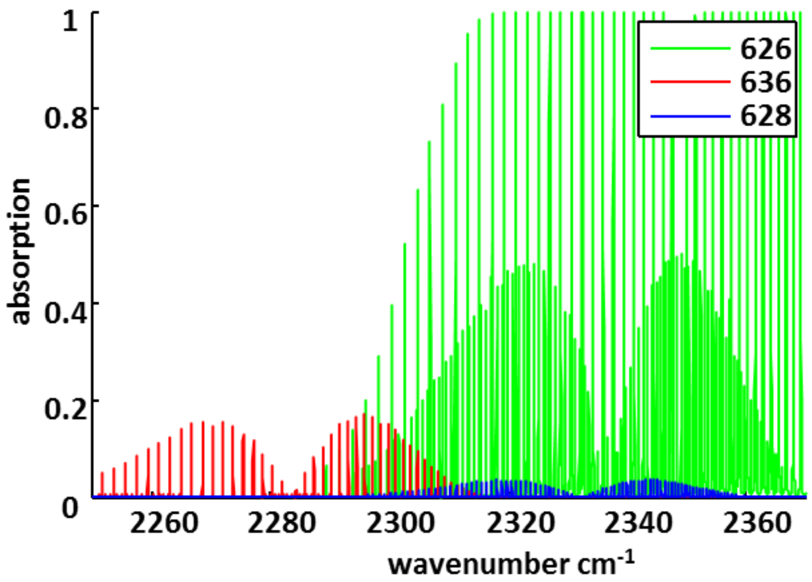
MAR 2023



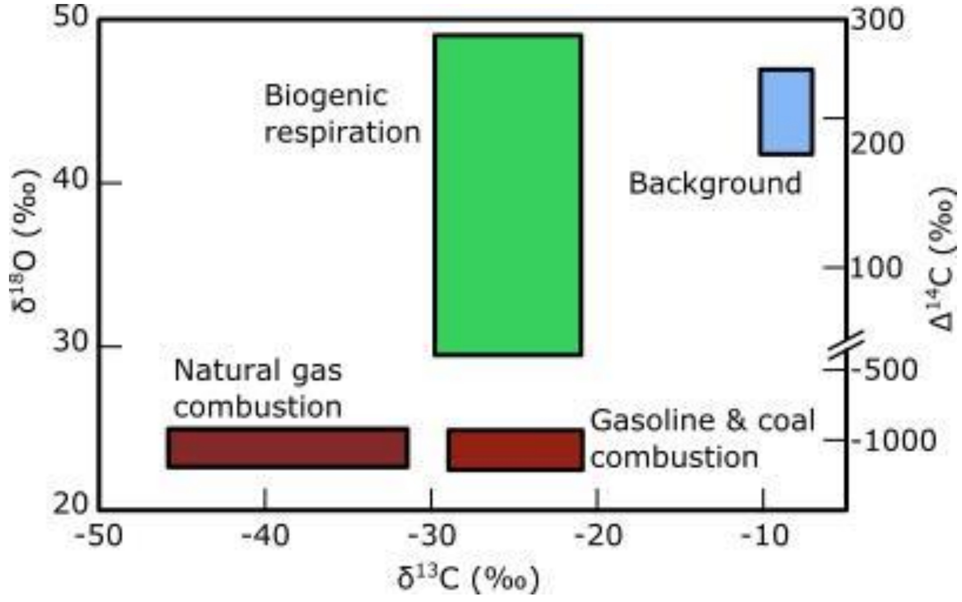


Analyser for leak detection from CCUS

- Stored CO_2 has a **distinctive isotopic composition** which is different from atmospheric CO_2
- **Can be used as a tracer of leaks**
- Compact device based on mid-infrared laser sources will be used for **on-line monitoring**
- Adapt existing instrument for **in situ leak detection** ,e.g., by adding a multi-pass cell
- Investigate limitations and how it can be used to **quantify** leaks



Source identification diagram for CO_2



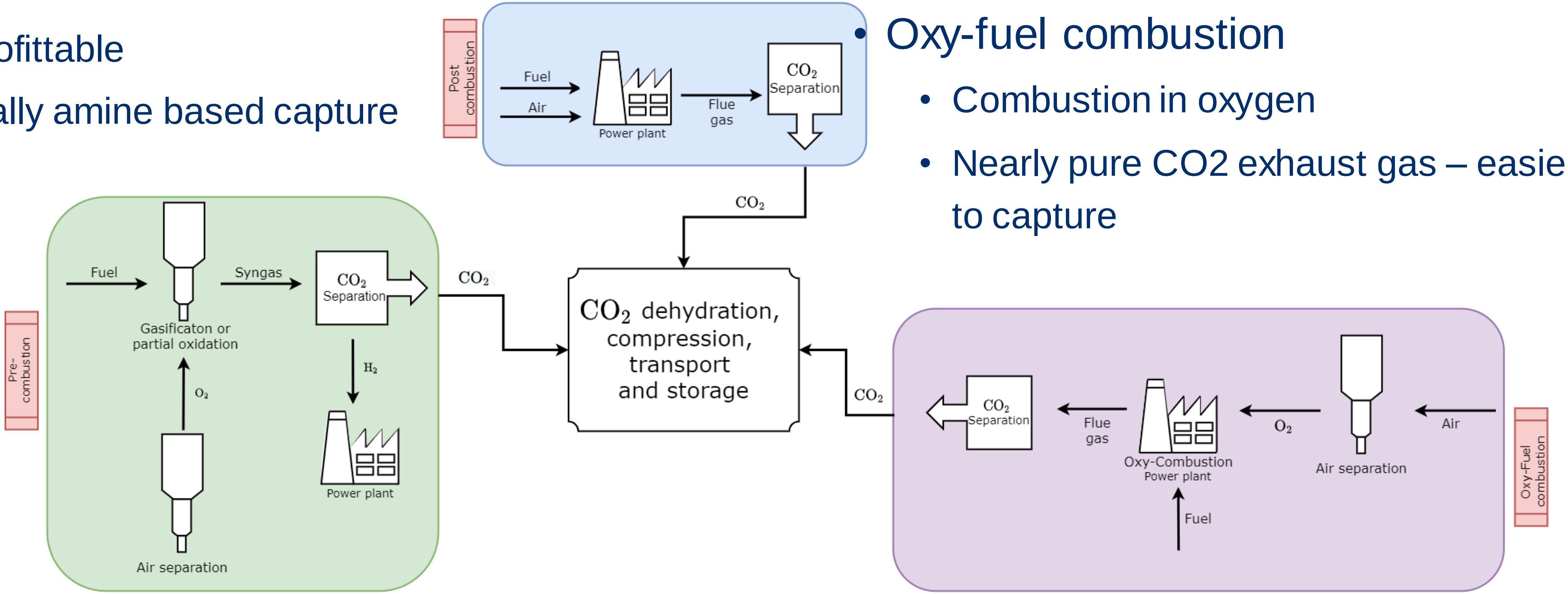
Monitoring emissions from the capture process

Haydn Baros, Richard Harvey, Hannah Cheales, Chris Dimopoulos, Rod Robinson

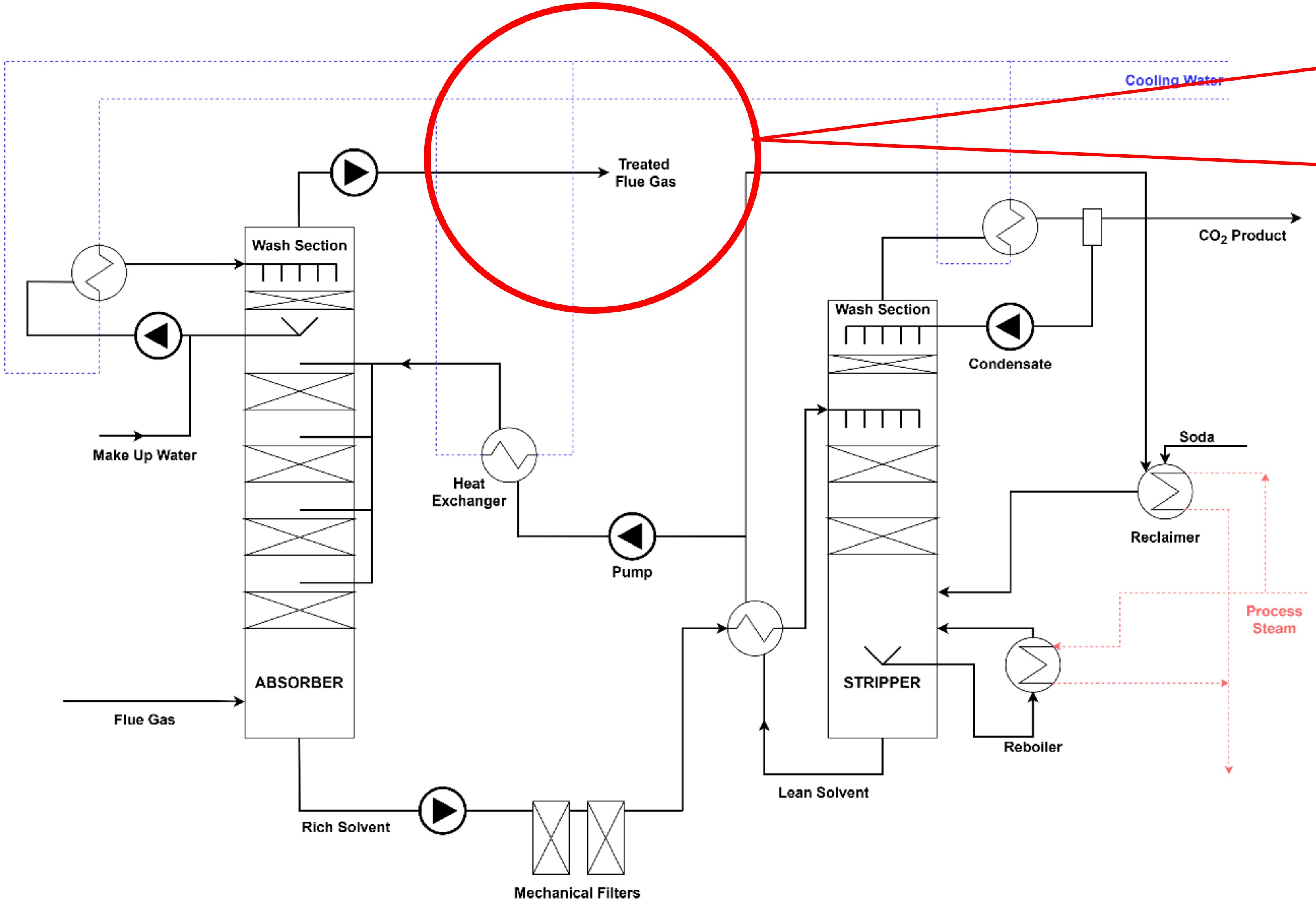
(Joint activities – MetCCUS and UK EA project)

Carbon capture

- There are three main approaches to capture CO_2 from combustion processes
- Post combustion
  - Retrofittable
  - Usually amine based capture
  -
- Pre-combustion carbon capture
  - Gasification of fossil fuel,
  - Generally linked to hydrogen production
- Oxy-fuel combustion
  - Combustion in oxygen
  - Nearly pure CO2 exhaust gas – easier to capture



Post Combustion Capture



Flue gas conditions,
Low flow rate
Low CO2
High water content
Low temperature
Effects of NOx

Measurement needs

- Direct measurement of CO_2, post capture

  Determination of capture efficiency from mass balance involves subtraction of two large numbers so uncertainty is high

  Direct measurement – has potential for lower uncertainty – need sensitive analyser – ambient levels, with sampling system able to handle stack conditions, dilution probe

- Effect of post capture gas matrix on regulated pollutant monitoring

  Reference methods not validated for low CO2, high water vapour conditions, droplets

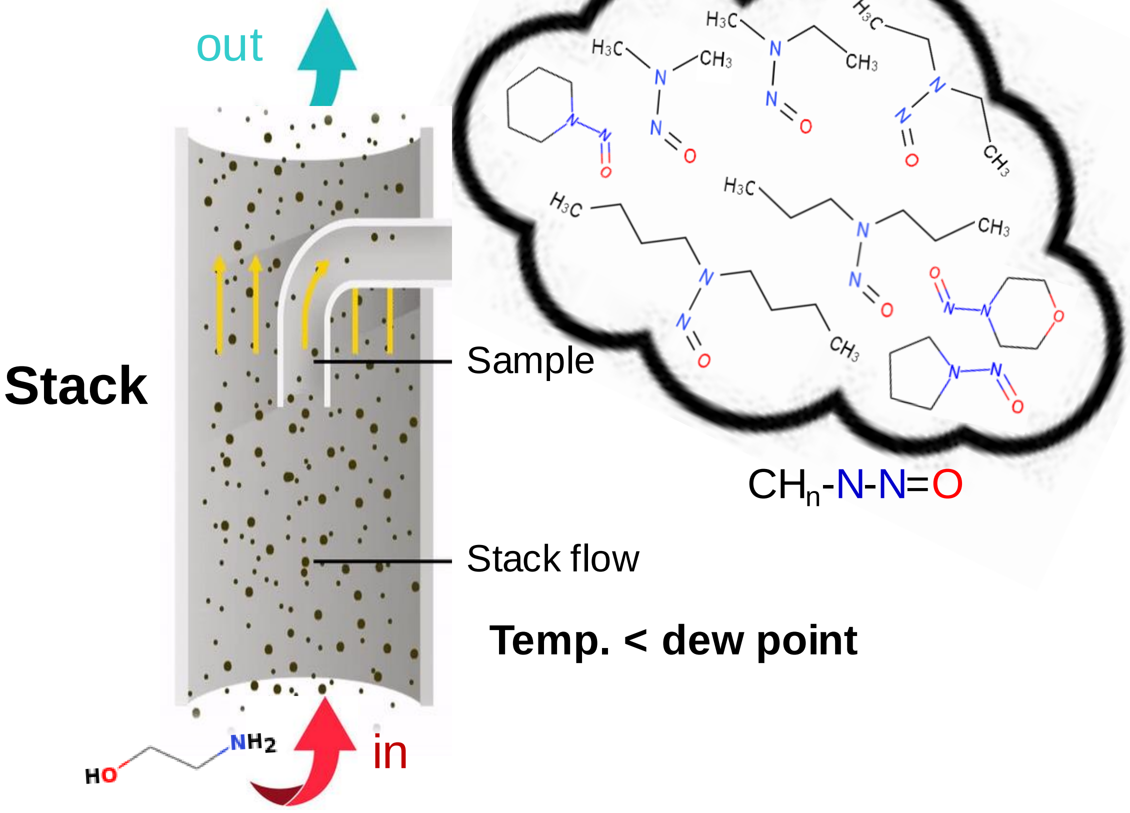
  Post capture is a new class of emission (reference levels different)

- Dispersion characteristics different

- New pollutants
  - Amines and break down products
  - SO3

CO_2 Capture Emissions Monitoring:
Proposal of nitrosamine's sampling methods

- Exit gas (CO_2-depleted) + water droplets
- Complex amines & nitrosamines
- Traces of the used amine



- Exhaust gas (N_2, CO_2, H_2O, O_2, NOx, SO_2, CO, etc.)
- Sorbent solution (simple amines like MEA @ 30%)

Metrological challenges

- Complex transport (gas + water droplets)
- Volatility covering 5 orders of magnitude
- Solubility not well known
- Oily and sticky
- Reactive with several substances/surfaces
- Formation of new NNS within the sample

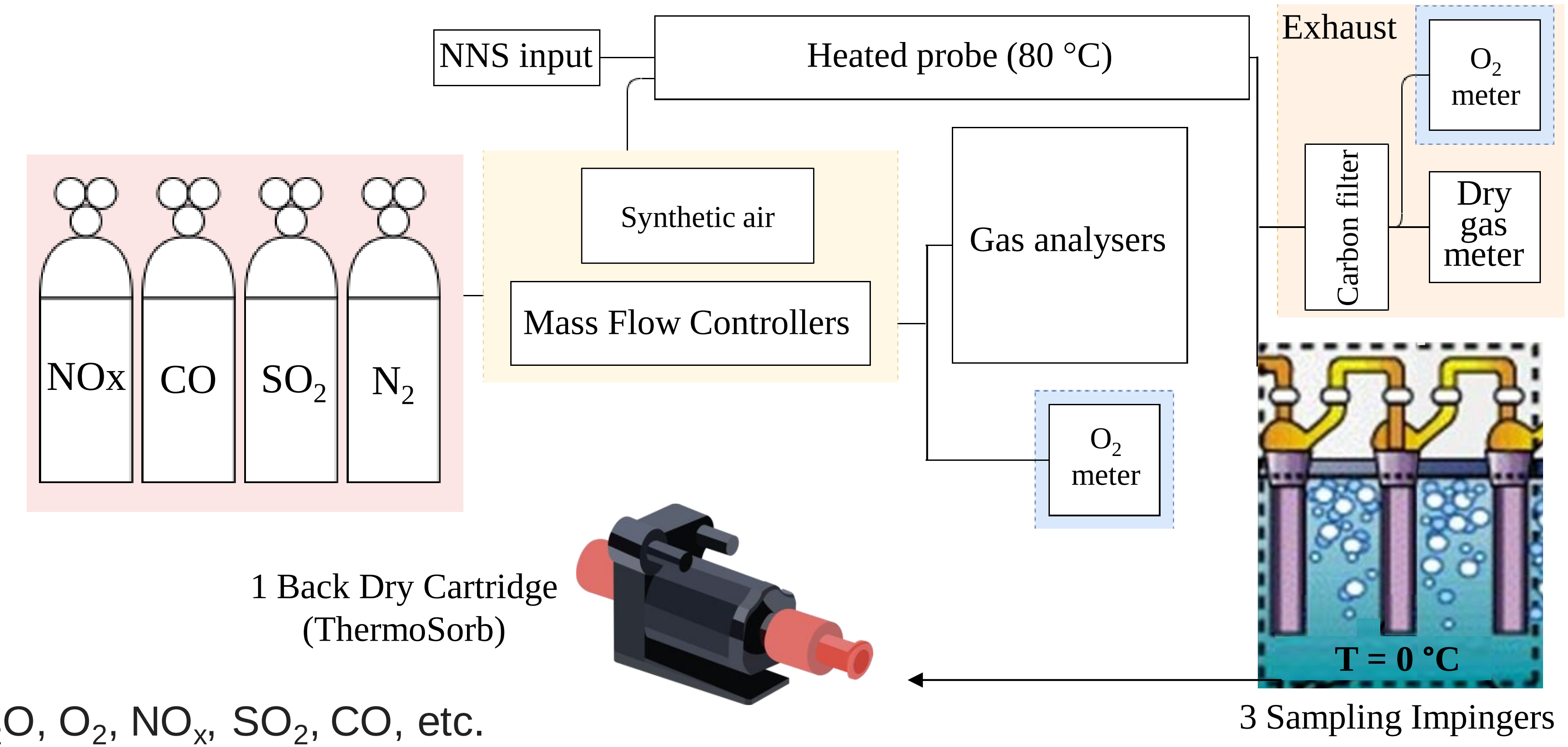
Environmental and health challenges

- Corrosive
- Carcinogenic
- Mutagenic
- Teratogenic

Testing

- Scaled down stack simulator at NPL
- Controlled conditions (Lab)
- Wet and dry isokinetic sampling
- Stack testing (CCUS post combustion plant)

Test bench developed for nitrosamine/amine sampling testing

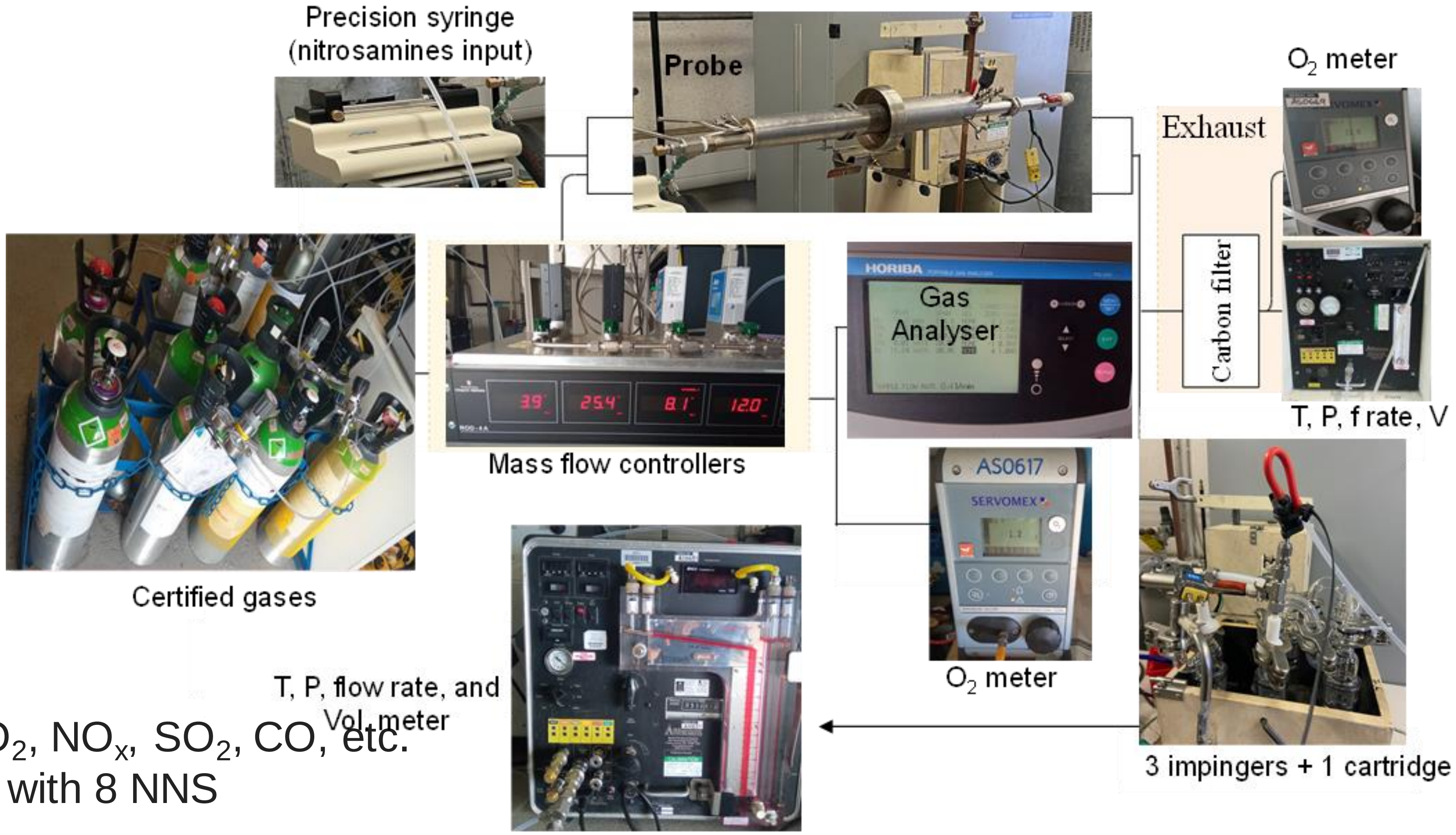


Gas matrix: H_2O, O_2, NO_x, SO_2, CO, etc.
Experimental tests with 8 NNS

Liquid sampling method (impingers 1 M H_3NSO_3)
Dry sampling method (Thermo-Sorb cartridges)

Samples measured by GM-TEA (Muller Lab.)

Test bench developed for nitrosamine/amine sampling testing



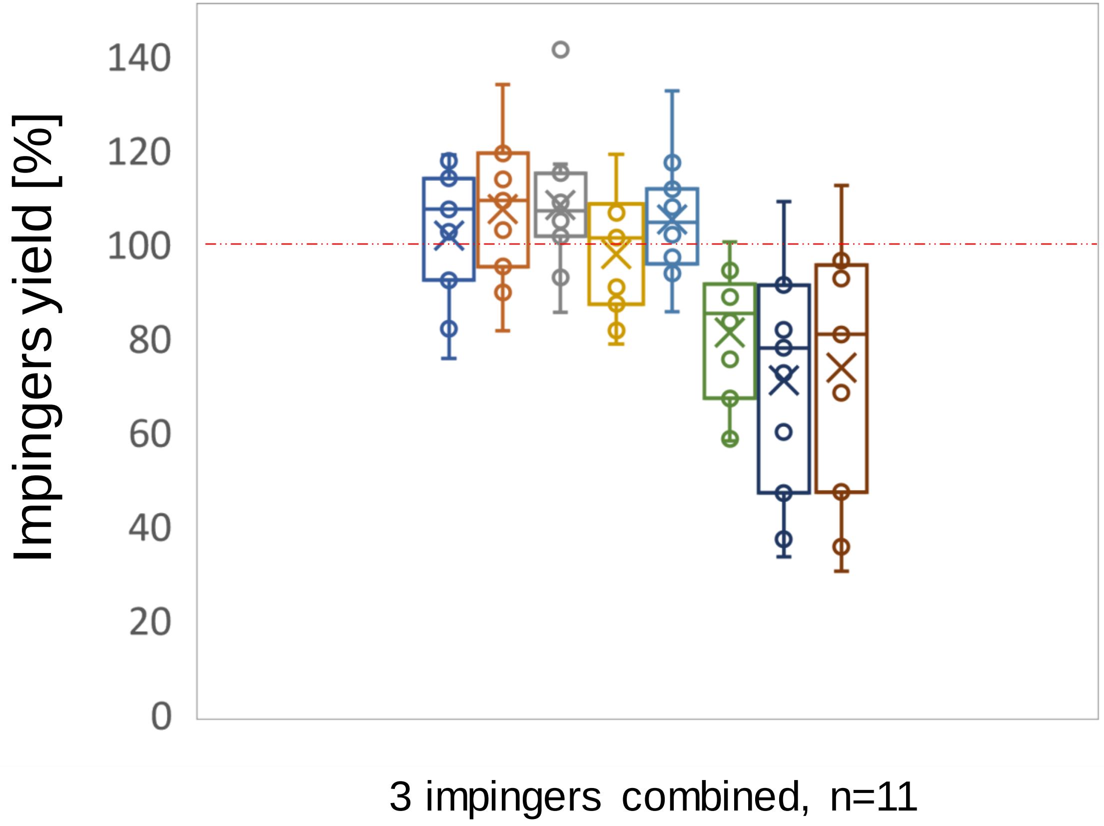
Gas matrix: H_2O, O_2, NO_x, SO_2, CO, etc.
Experimental tests with 8 NNS

Liquid sampling method (impingers 1 M H_3NSO_3)
Dry sampling method (Thermo-Sorb cartridges)

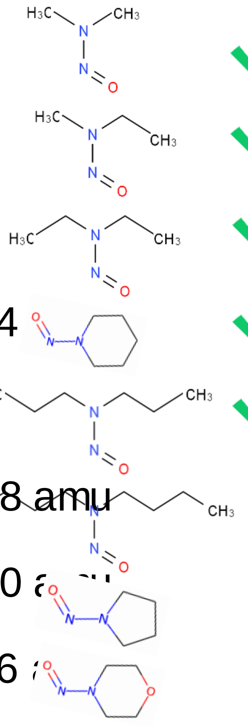
Samples measured by GM-TEA (Muller Lab.)

Results: Liquid sampling method

Criterion 1: Total nitrosamine's sampling yield [%]



NNS	VP@20°C	m. mass	
NDMA	0.4 kPa	74 amu	✓
NMEA	0.15 kPa	88 amu	✓
NDEA	0.11 kPa	102 amu	✓
NPIP	0.012 kPa	114	✓
NDPA	0.011 kPa	130 amu	✓
NDBA	0.006 kPa	158 amu	
NPYR	0.005 kPa	100 a	
NMOR	0.005 kPa	116	

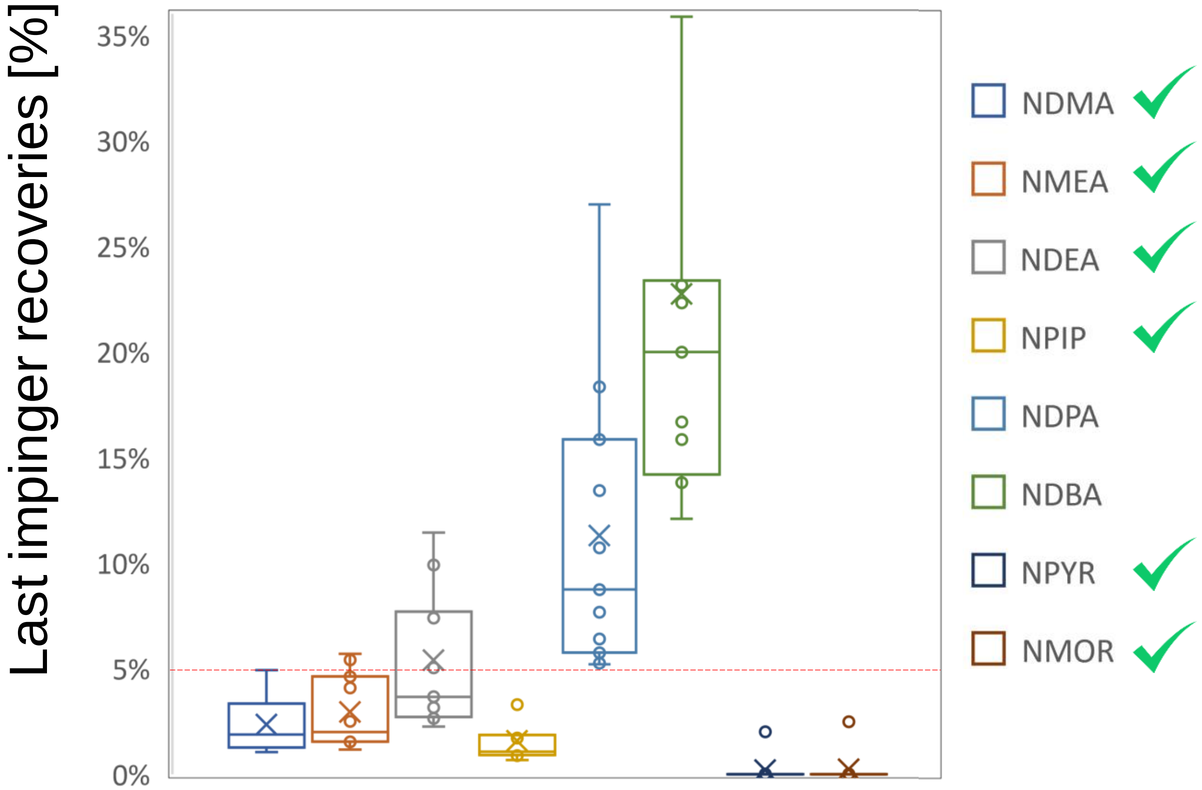


Each total (100%) is defined as the addition of the mass collected in the three impingers

The three nitrosamines with lower volatility were partially trapped within the test system (yield < 80%)

Results: Liquid sampling method

Criterion 2: Nitrosamine's sampling yield of the last impingers (# 3)



Yield of the 3rd impinger, n =11

Nitrosamine	3rd impinger yield
NDMA	2 ± 1 %
NMEA	3 ± 2 %
NDEA	5 ± 3 %
NPIP	2 ± 1 %
NDPA	11 ± 7 %
NDBA	23 ± 12 %
NPYR	0.2 ± 0.6 %
NMOR	0.2 ± 0.7 %

The check is passed if last impinger < 5%.

Performance standard for manual stack emission monitoring. Environment Agency. January 2019. V 8.

The two linear nitrosamines with lower volatility were significantly trapped within last impinger

SUMMARY

- Impingers recoveries range 70 – 110 %, while the total recovery shows analytical overestimation
- Nitrosamines volatilities play a major role in the sampling methods, and its influence is expected in
- PCC processes, stacks dynamics and environmental dispersion
- Ring-type NNS have lower recovery as compared with linear ones with similar volatility
- Cross contamination was observed, and a better probe/impinger cleaning is now applied
- Surfaces conditions affect drastically the impingers recoveries for low volatile NNS
- Repeatability exhibit a large variability
- The “sampling method + analytical measurement” must be considered as semiquantitative
- It is necessary to test with different conditions and concentrations to see if the observed trends holds
- Dry sampling method was discarded since results are largely affected by the required dilution
- Solubility is another key parameter, however available data have large variation

NPL

Monitoring of CO_2 emissions using DIAL

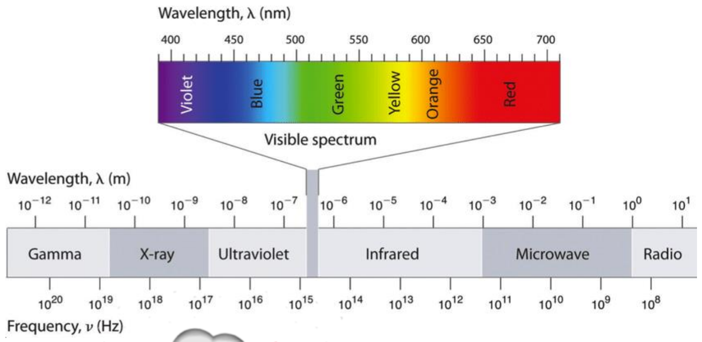
N. Howes, F. Innocenti, A. Finlayson, C. Dimopoulos, T. Gardiner and R. Robinson

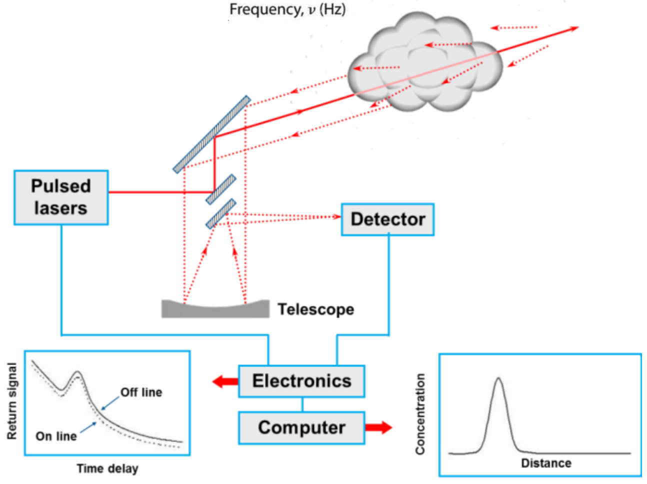
(Decarb project and UK programme)

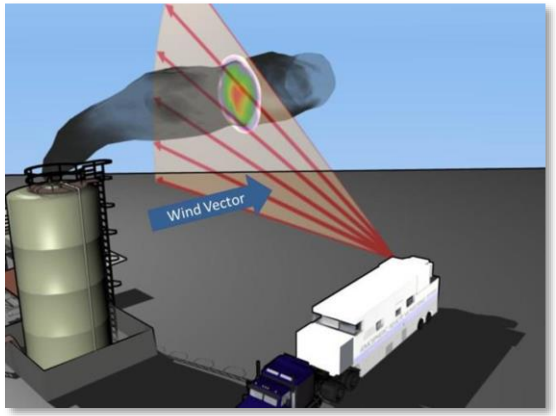
DIAL measurement principle

DIAL - Differential Absorption LIDAR

- ‘LIDAR’ Laser Radar system, which can be targeted on specific gas emissions.
- Gives range-resolved concentration along optical path (Range ~500 metres in IR, ~1 km in UV).
- Spatial resolution < 8 metres.
- Vertical scans enable plume mapping and emission calculation.
- Different wavelengths of light are used to measure different gases, e.g. Near-IR: (3.3-3.4 µm) - methane, methane, VOCs (including general hydrocarbons)
- Combine integrated concentration with wind field to give quantified emission rate.





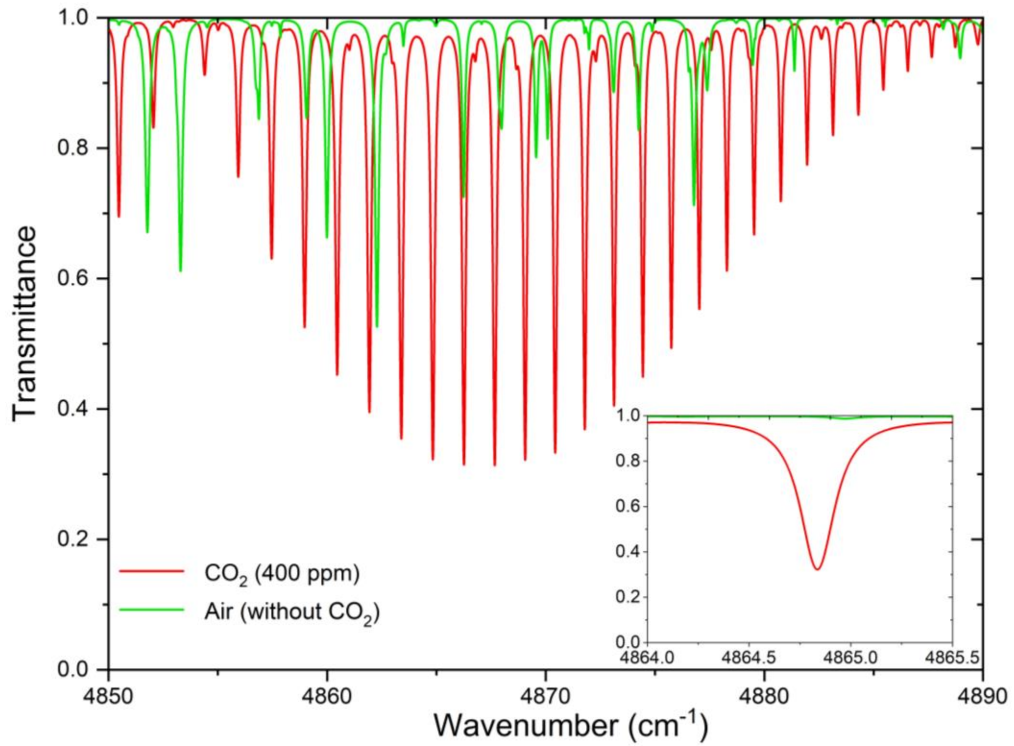


Developing a measurement method for CO_2

- As CO_2 has a significant atmospheric concentration (~400 ppm, compared to ~2 ppm for methane), careful selection of absorption peaks is required.

- Too strong an absorption peak and the on-resonant energy will be absorbed by the atmosphere. Too weak and detection limit will be extremely high.

- NPL identified a potential region in the 2 µm range where interference from other species is minimal.

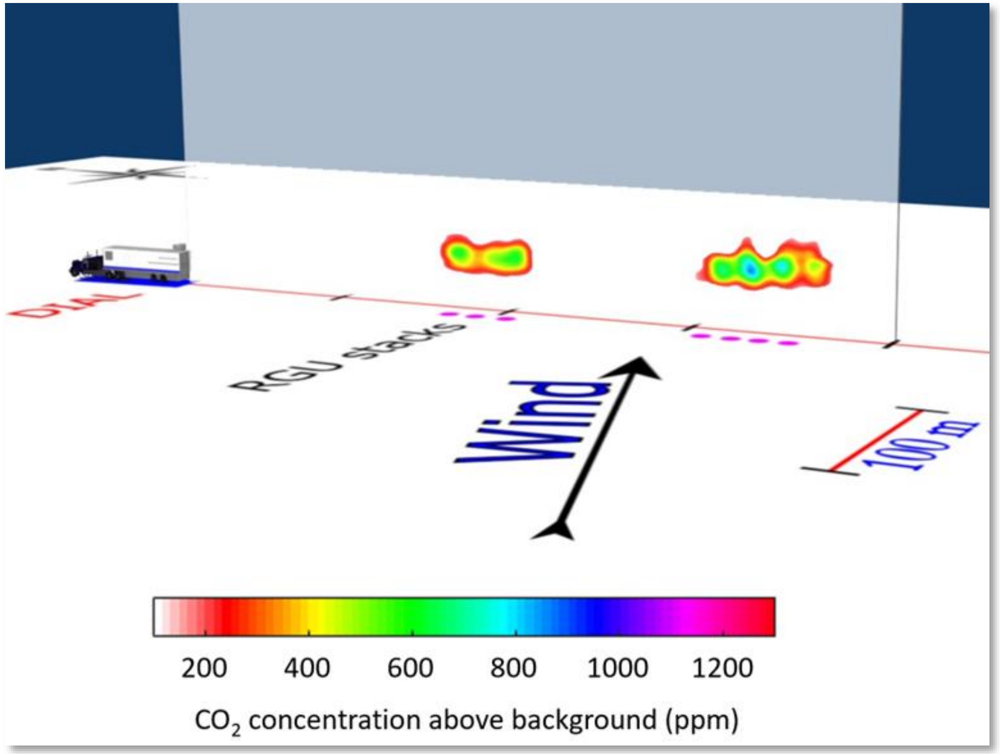


Validation of CO_2 emissions measurements using DIAL

- In November 2022, NPL carried out a validation exercise at a Liquified Natural Gas storage and regasification site.
- CO_2 emissions from the regasification plant process were measured simultaneously by NPL teams using DIAL and in-stack monitoring.

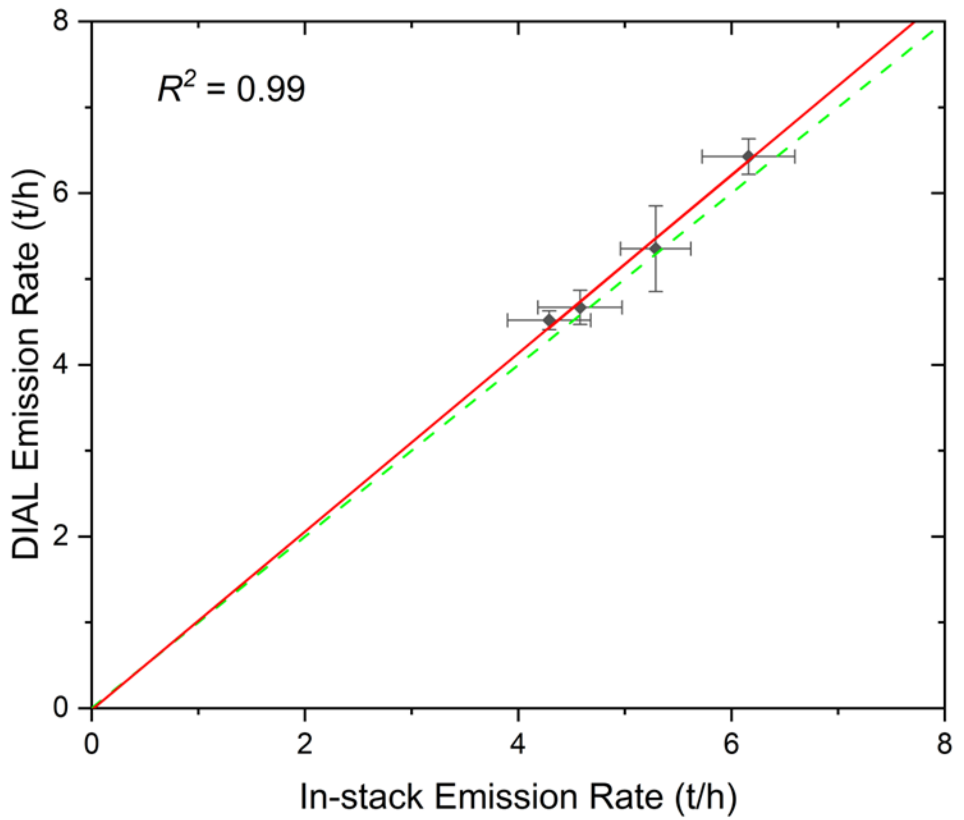
Validation of CO_2 emissions measurements using DIAL

- During the campaign, CO2 emissions were measured downwind of seven active stacks simultaneously, as shown below.
- An average emission rate measured from four scans was 42.2 ± 5.4 t/h with the reported uncertainty expanded to provide a 95% level of confidence.
- Using data provided by the operator, it was possible to calculate a comparative emission rate of 40.3 t/h. This value is within the coverage interval of the DIAL measurement.



Validation of CO_2 emissions measurements using DIAL

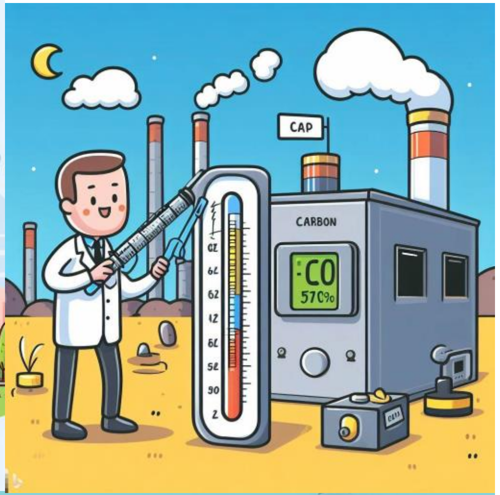
- The results from the DIAL measurements compare well with simultaneous in-stack measurements and suggest that any bias in the DIAL data is likely small.
- Moreover, using the definition outlined in EN 15267-3, a detection limit of 0.12 t/h was estimated for the 2 µm wavelength DIAL data.
- This result is a three orders of magnitude improvement with respect to previous NPL DIAL measurements of CO_2, made in the 1.5 µm wavelength region.



Conclusions

NPL

- MetCCUS is tackling a number of the issues related to monitoring emissions from CCUS
- Outputs will feed into guidance and standards
- Feedback and inputs from the stakeholder community is important



I asked an AI bot to generate a cartoon of measurement of emissions from industrial carbon capture and storage

NPL

METROLOGY PARTNERSHIP | EURAMET

METCCUS

Thank you for your attention, any questions?

rod.robinson@npl.co.uk

The project METCCUS has received funding from the European Partnership on Metrology, co-financed from the European Union’s Horizon Europe Research and Innovation Programme and by the Participating States.

CO_2 Specifications for Transport and Thermo-dynamic Properties

26.10.2023
Online

Roland Span
Sub-Project Leader CO_2 Transport
EERA JP CCS
Chair of Thermodynamics
Ruhr-University Bochum

Background

- **DG Energy wants to develop a European Transport-Network**
  - Discrimination free access, regulated asset basis, multimodal transport
  - Politics is concerned to see structural disadvantages for regions far from storage sites
  - Industry as driver of the development – situation has changed!
  - Development dynamic, standards / network code urgent!

- **Need for European standards**
  - So far, specifications for (impurities in) CO_2 are project specific
  - In some countries development of national standards (in Germany DVGW, focussed on pipelines)

Mission Statement

- **Expert group on CO_2 specifications as spin off of the CCUS Forum process**
  - Not aiming at the development of a standard (DIN, ISO, CEN, ...)
  - Pointing out issues that have to be considered by a standard and making suggestions for how to formulate standards
  - Difficult balance: Send the message "we can and must go ahead now" while pointing out areas of missing knowledge at the same time
  - DG Energy will hopefully consider advice in future calls, one starting point of the upcoming discussion on a CCS Center of Excelence
  - Report was completed end of June, was published online September 22nd
  - https://circabc.europa.eu/ui/group/75b4ad48-262d-455d-997a-7d5b1f4cf69c/library/13c2a475-c705-432d-8ca3-17ce799ba502/details

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Volker Hoenig	VDZ
Xavier Sturbois	Fluxys

Organization of the expert group: Per-Olof Granstrom / Charles-Albert Bareth

Content of the Report

THERMODYNAMIK RUHR UNIVERSITÄT BOCHUM RUB

EERA CCS

Guiding Principles

- **Three *(plus one)* guiding principles**
  - Two-phase flow should be avoided as much as is practicable
  - The formation of corrosive phases must be avoided
  - The concentration of all impurities in a CO_2 stream should be specified to be such that their health and safety impact is always less than that of the carbon dioxide itself
  - *Given limits, e.g., on impurities should be science based and traceable with at least a rough idea regarding their uncertainty*

Negotiable and Non-Negotiable Impurities

Non-Negotiable Impurities

- Formation of solids has to be avoided
- Corrosion has to be avoided
- Water and impurities that reduce the dew point need to be strictly limited
- Poisonous impurities have to be limited to levels that do not increase the toxicity of CO_2

Negotiable Impurities

- Non-condensable gases increase the pressure on the saturated liquid line
- High concentrations increase the cost of transport, but reduce the cost of CO_2 processing
- Optimisation has to consider whole chain cost
- Hub concepts versus processing to high purity before first transport

Specifying the Level of Non-Condensable Gases

Specifying the level of non-condensable gases

- Different non-condensable gases have a different impact on the pressure on the saturated liquid line
- The pressure on the saturated liquid line is particularly important for tank transport (medium pressure ship transport / rail cars)
- Define the minimum temperature required for liquefaction at a certain pressure rather then composition

Conversion of standards

- In pipelines compositions will be measured, not saturation pressures
- A standard for the conversion needs to be defined from beginning on

R&I Initiatives Transport

Examples for identified research areas

- Flow and composition measurements in two phase systems
- Fast (sub second?) online composition measurement
- Hazardous impurities: Assessment of the health threat for combined exposure
- Effect of acid forming impurities on phase equilibria (at ppm level)
- Chemical reactions in mixed CO_2 streams, catalytic effects
- Formation of LLE / SLE at low temperature (glycols, in particular TEG, amines, ...)
- CO / CO_2 stress corrosion cracking?
- Corrosion without a corrosive phase?
- System analysis combining CO_2 transport (with impact of impurities), H_2 transport, regional availability of renewable energy

Development of Standards

- **Need for European standards**
  - So far, specifications for (impurities in) CO_2 are project specific
  - In some countries development of national standards (in Germany DVGW, focussed on pipelines)
  - National standardisation bodies and ISO are usually well connected
  - ISO is working on standards both for ship pipeline and for ship / tank transport
  - ISO standards will always be rather general, not detailed enough as basis for development
  - CEN process will cost much time, investment decisions have to be made soon
  - **DVGW tries to align national initiatives to come to a common understanding**
  - **Develop CEN standard on this common basis later on**

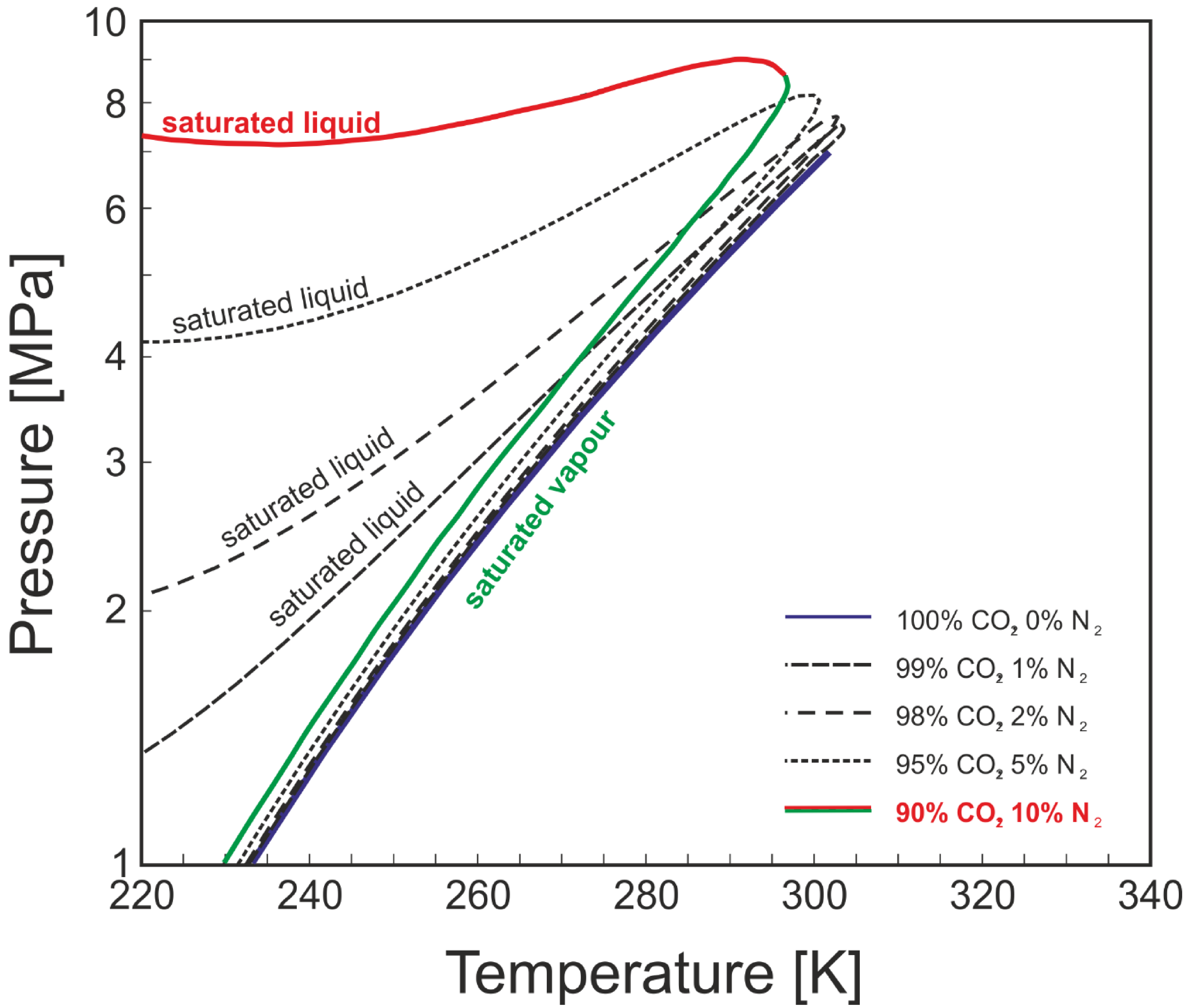
- Currently largely independent development of standards for pipeline and ship / tank transport in different communities – synergies for an optimal system might get lost

Treatment of Impurities in Standards

- **ISO standard (for pipeline transport) will likely ...**
  - Contain a value for the minimum purity of CO_2
  - Not contain a list with strict limits for certain impurities
  - Contain an appendix with examples for practically feasible compositions
  - Specification of composition limits on national / CEN level, deviating agreements possible

- **An open question is how to deal with impurities that are not specifically listed**
  - Northern Lights claims that substances not listed must not be contained (strictly!)
  - Not a feasible approach for a network – different processes will always result in a variety of trace components (ppb range), which may partly be below current analytical limits
  - Development of analytics or simply analysis considering trace components not looked at before must not become a challenge for made investments

Thermophysical Properties of CO_2-rich Mixtures



- Air components have a strong impact on phase equilibria
- The position of the dew line (saturated vapor) changes noticeably
- The position of the bubble line (saturated liquid) changes drastically

- Consequences, e.g., for centrifugal pumps
- **Arrest pressure** to avoid running ductile fracture depends on the pressure on the saturated liquid line

GERG-2008 – Using a Natural Gas Standard for CCS

- Helmholtz-model for mixtures of up to 21 components by Kunz and Wagner (2012)
- General approach introduced independently by Lemmon & Tillner-Roth in mid 90's
  - Pure fluid equations of state (EOS)
  - Mixing rules for reduced input parameters δ_m and τ_m

$$\alpha(\delta,\tau,\bar{x}) = \sum_{i=1}^{N} x_i \left[\alpha_{oi}^{0}(\rho,T) + \ln x_i\right] + \sum_{i=1}^{N} x_i \alpha_{oi}^{\mathrm{r}}(\delta_\mathrm{m},\tau_\mathrm{m}) + \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} x_i x_j F_{ij} \alpha_{ij}^{\mathrm{r}}(\delta_\mathrm{m},\tau_\mathrm{m})$$

Methane (CH_4)	n-Pentane (n-C_5H_{12})	**Hydrogen (H_2)**
Nitrogen (N_2)	Isopentan (i-C_5H_{12})	**Carbon monoxide (CO)**
Carbon dioxide (CO_2)	n-Hexane (n-C_6H_{14})	Hydrogen sulphide (H_2S)
Ethane (C_2H_6)	n-Heptane (n-C_7H_{16})	**Water (H_2O)**
Propane (C_3H_8)	n-Octane (n-C_8H_{18})	**Oxygen (O_2)**
n-Butane (n-C_4H_{10})	n-Nonane (n-C_9H_{20})	**Argon (Ar)**
Isobutane (i-C_4H_{10})	n-Decane (n-$C_{10}H_{22}$)	Helium (He)

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Methane (CH_4)
Nitrogen (N_2)
Carbon dioxide (CO_2)
Ethane (C_2H_6)
Propane (C_3H_8)
n-Butane (n-C[illegible]H[illegible])

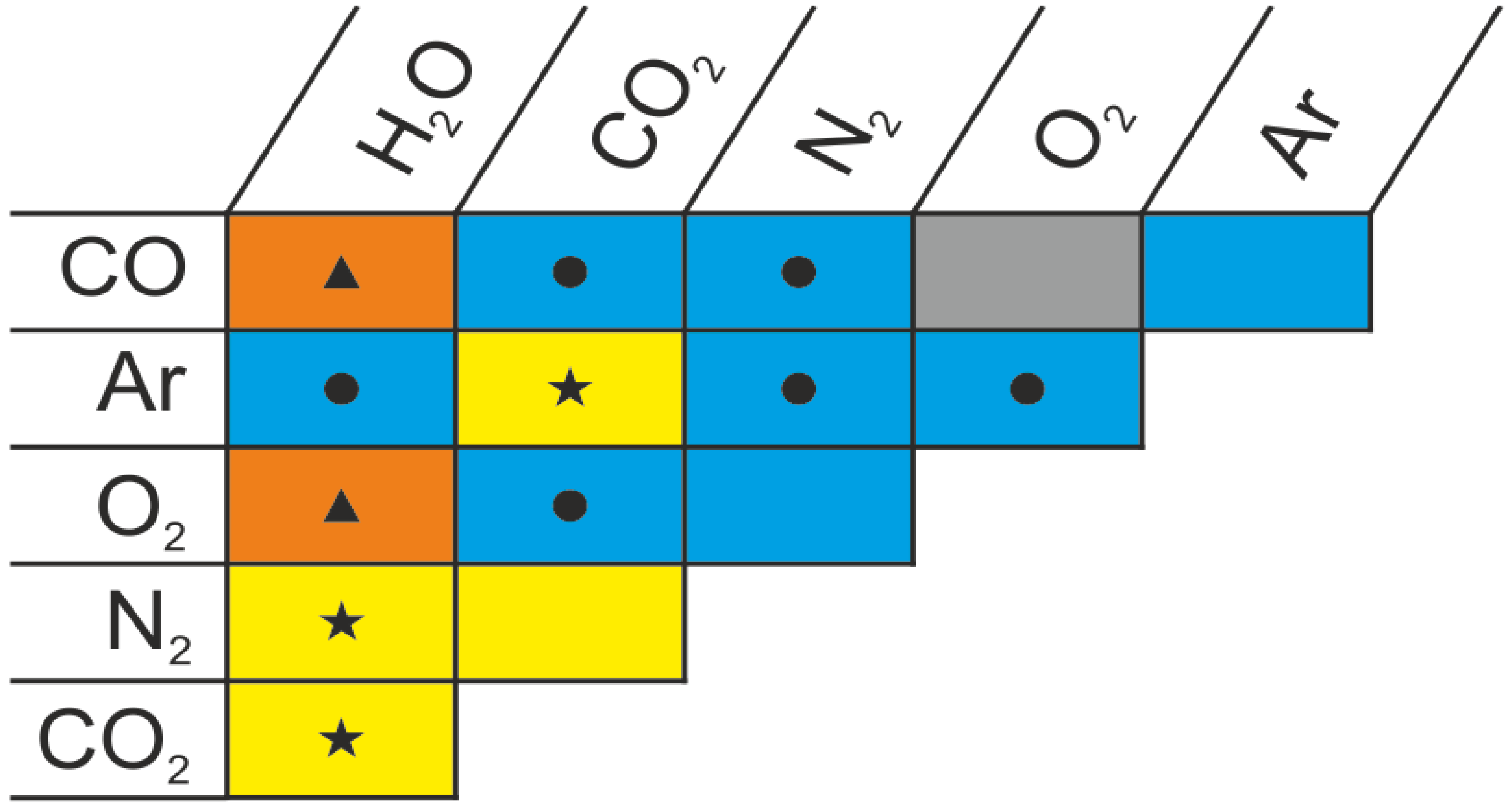
n-Pentane (n-C_5H_{12})
Isopentan (i-C_5H_{12})
n-Hexane (n-C_6H_{14})
n-Heptane (n-C_7H_{16})
n-Octane (n-C_8H_{18})
n-Nonane (n-C[illegible]H[illegible])

Hydrogen (H_2)
Carbon monoxide (CO)
Hydrogen sulphide (H_2S)
Water (H_2O)
Oxygen (O_2)
Argon (Ar)
(He)

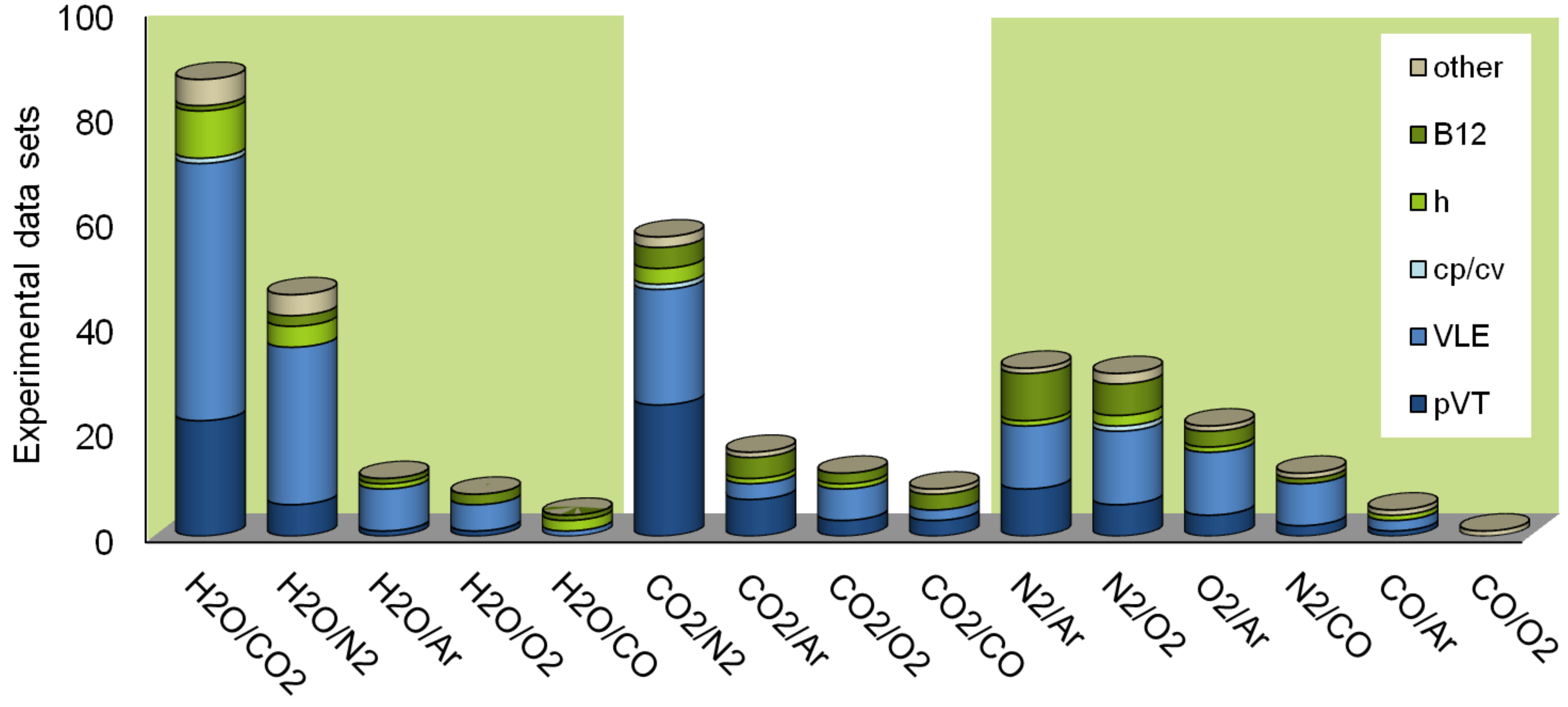
Standard for natural-gas properties according to ISO 20765-2:2015

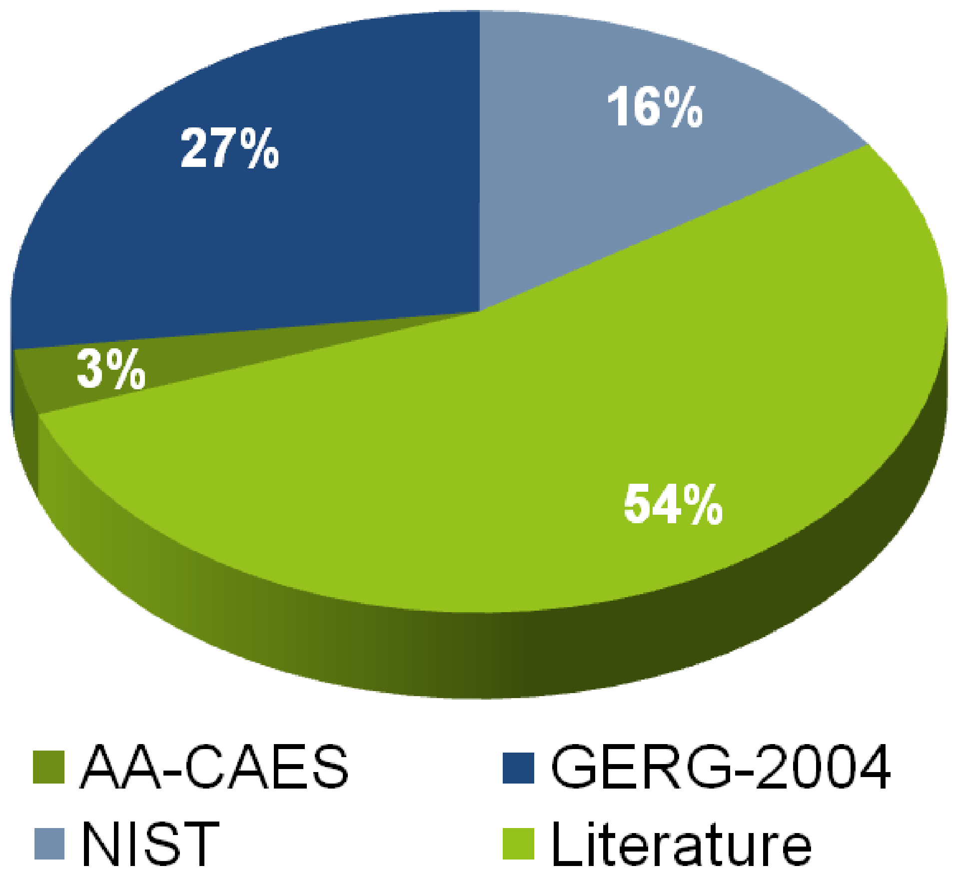
EOS-CG – A Model for CO_2-Rich Mixtures

EOS-CG describes 15 binary Systems, is compatible to GERG-2008 for other systems



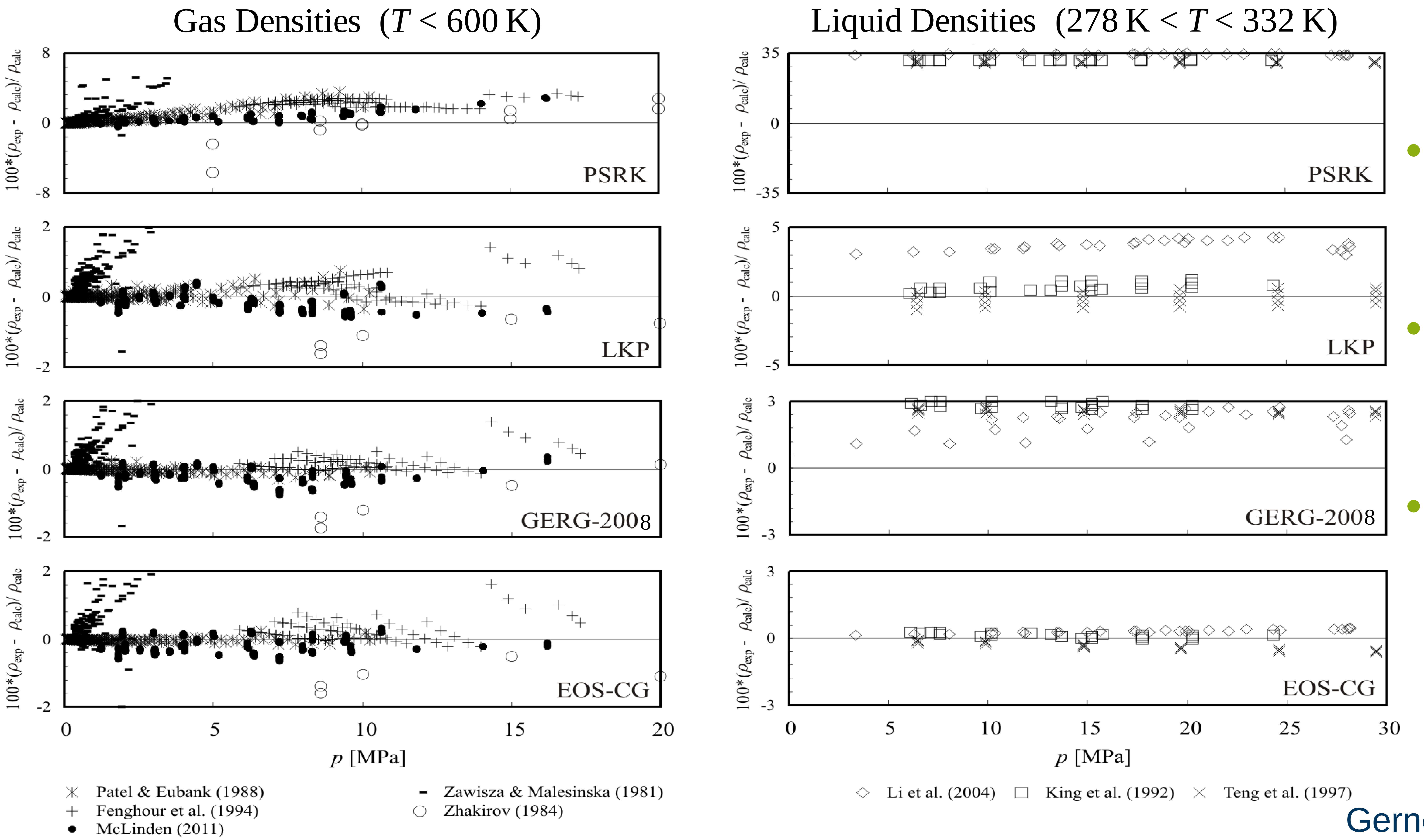
- ★ Binary specific departure function α^r_{ij}
- ▲ Common departure function with fitted F_{ij}
- ● Fitted reducing functions ρ_r and T_r
- General combination rules for ρ_r and T_r





Gernert (2013), Gernert & Span (2015)

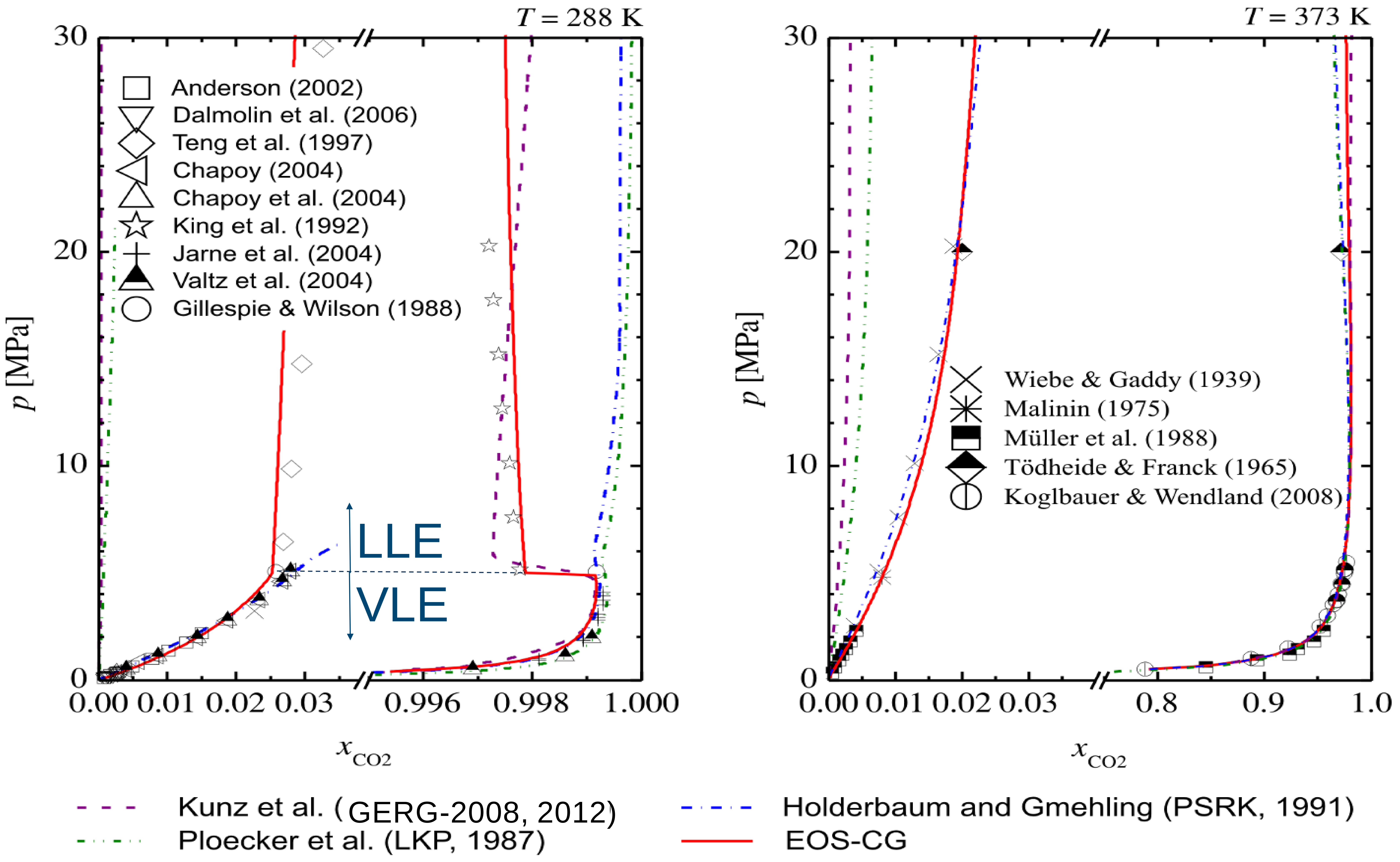
EOS-CG – A Model for CO_2-Rich Mixtures



- Most significant improvements for the System CO_2 / H_2O
- Gas densities are described well by different EOS
- Only EOS-CG describes liquid densities equally good

Gernert (2013), Gernert & Span (2015)

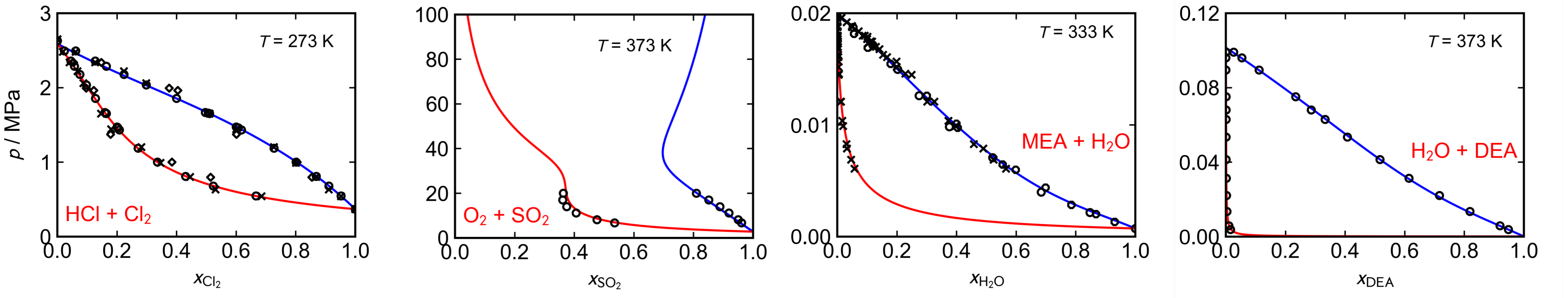
EOS-CG – A Model for CO_2-Rich Mixtures

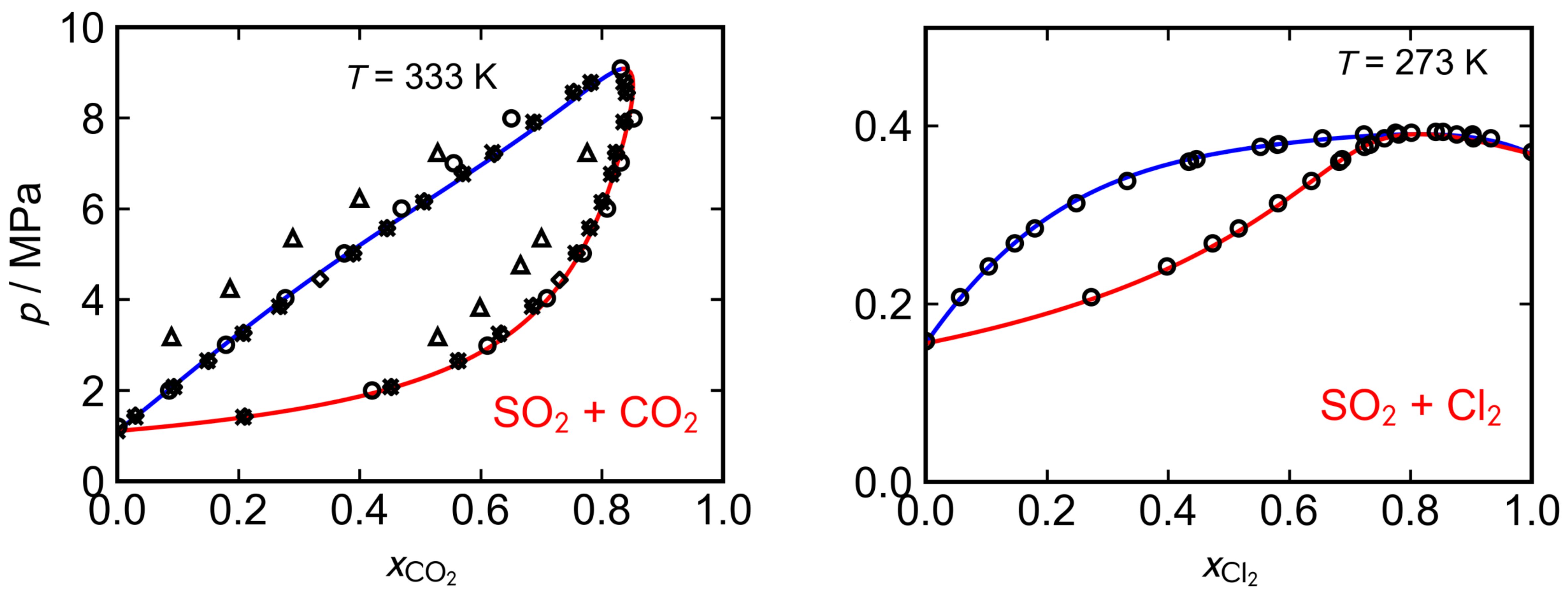


- Most significant improvements for the System CO_2 / H_2O
- VLE / LLE equilibria need to be calculated
- CO_2-rich phase described well by different models
- H_2O-rich phase described well by EOS-CG

Gernert (2013), Gernert & Span (2015)

Consideration of Minor Impurities

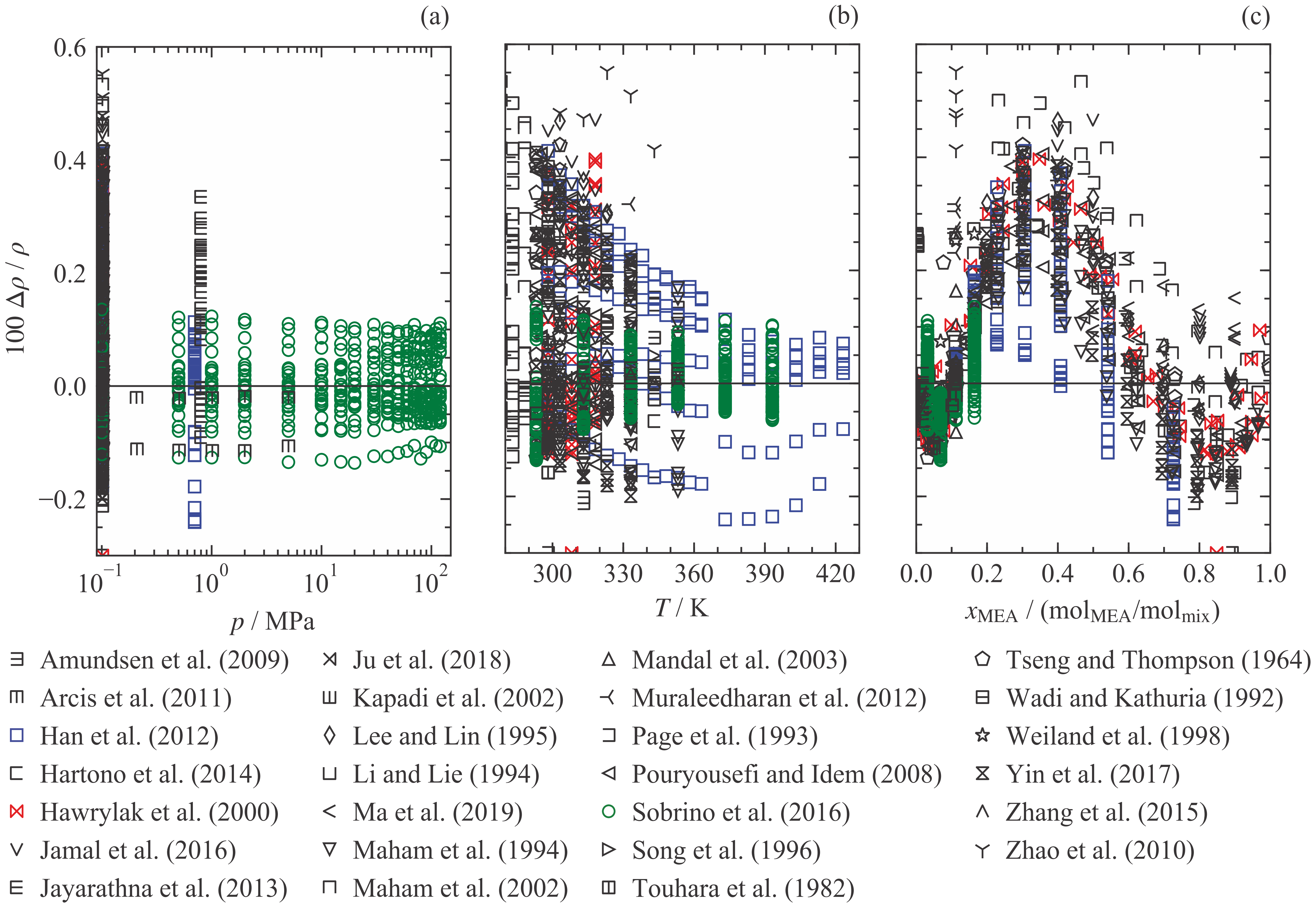


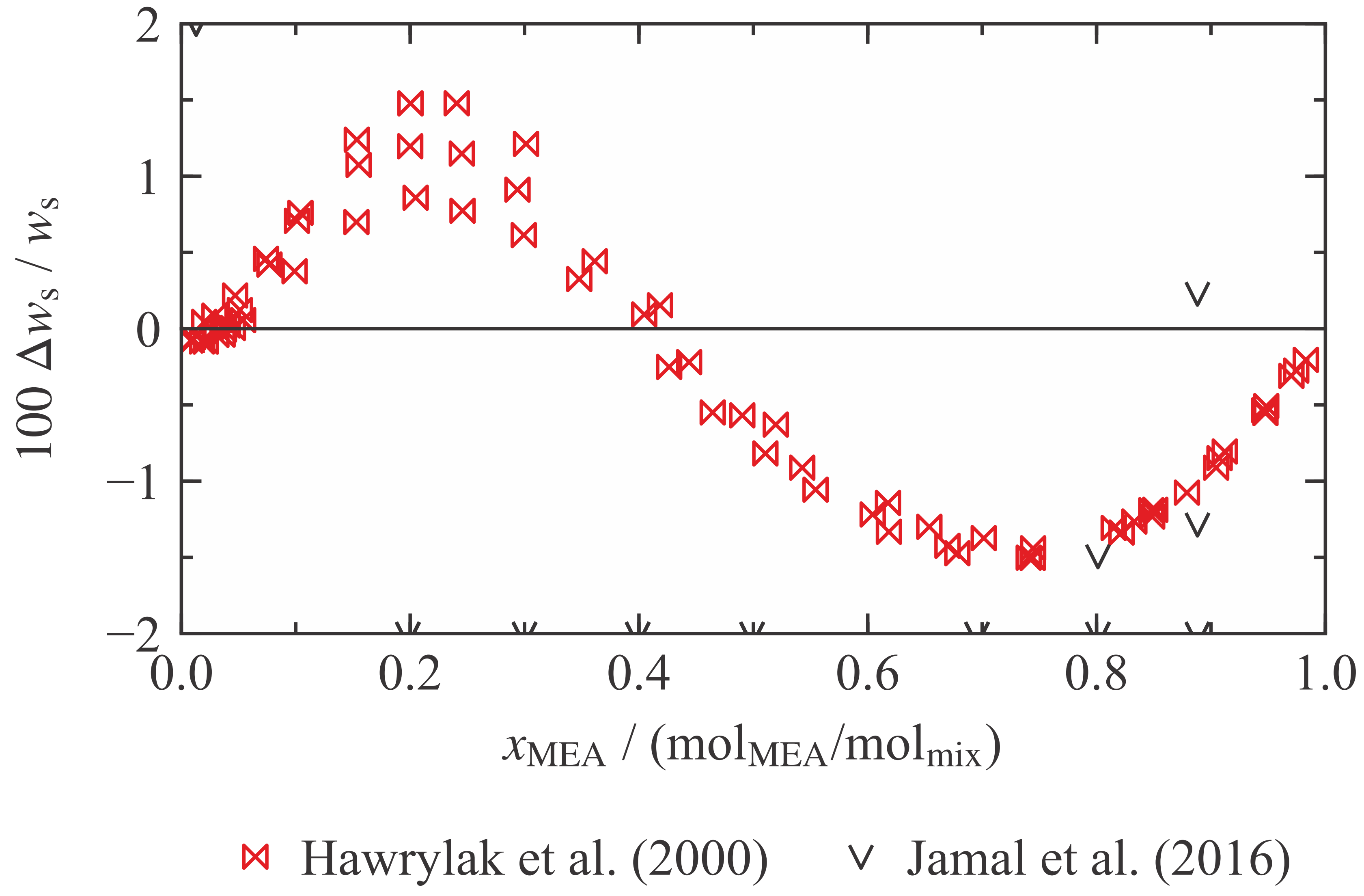


- Minor impurities mostly relevant for VLE
- Available data limit the accuracy
- Multiparameter models can describe the systems, but advantages shrink

Herrig et al. (2018)

Consideration of Minor Impurities





- Where data are available in homogeneous regions, they are represented quite well
- Example: MEA / Water, density and speed of sound

Neumann et al. (2023)

Consideration of Minor Impurities

Group	Component	methyl diethanolamine	ammonia	chlorine	hydrogen chloride	diethanolamine	monoethanolamine	sulfur dioxide	hydrogen sulfide	methane	hydrogen	carbon monoxide	argon	oxygen	nitrogen	water
major components	carbon dioxide	•	•	H	H	H	N2	H	KW	KW	B	S	L	GS	KW	GS
	water	•	R	H	H	•	•	H	H	H	KW	GS	GS	GS	GS	
	nitrogen	•	N1	H	H	H	H	H	KW	KW	B	GS	GS	KW		
	oxygen	•	N1	H	H	H	H	H	KW	KW	KW	GS	GS			
	argon	•	N1	H	H	H	H	H	KW	KW	KW	KW				
↕	carbon monoxide	•	N1	H	H	H	H	H	KW	KW	B					
	hydrogen	•	N1	H	H	H	H	H	KW	B						
	methane	•	N1	H	H	H	H	H	KW							
minor components	hydrogen sulfide	•	N1	H	H	H	H	H								
	sulfur dioxide	•	N1	H	H	H	H									
	monoethanolamine	•	N1	H	H	H										
	diethanolamine	•	N1	H	H											
	hydrogen chloride	•	N1	H												
	chlorine	•	N1													
	ammonia	•														

Colour legend:
- Specific departure function
- Generalized departure function
- Adjusted reducing functions
- Lorentz-Berthelot combining rules
- Linear combining rules

•	This work	B	Beckmüller et al.
H	Herrig	N2	Neumann et al.
KW	Kunz and Wagner	R	Published within Refprop
GS	Gernert and Span	S	Souza et al.
N1	Neumann et al.	L	Løvseth et al.

- The matrix of described systems has been extended
- In many cases hardly any data available
- (Weakly) reacting systems can be described on an empirical basis

Neumann et al. (2023)

CO_2 Specifications for Transport and Thermo-dynamic Properties

26.10.2023
Online

Roland Span
Sub-Project Leader CO_2 Transport
EERA JP CCS
Chair of Thermodynamics
Ruhr-University Bochum

Questions?

Air Liquide

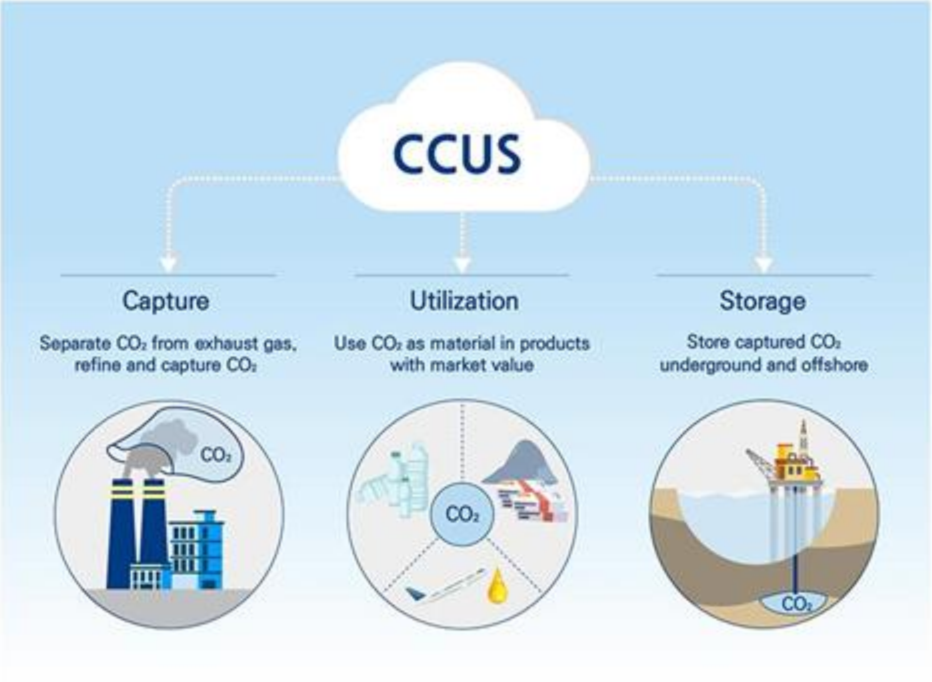
CCUS Process & Metrological challenges from Industry Perspective

METCCUS Seminar 26.10.2023

Martine Carré - Scientific Director Analytical Science
Lucie Chaubet - Pole Manager Low Carbon Hydrogen

Contents

- ❑ Air Liquide R&D in brief
- ❑ CCUS solutions portfolio
- ❑ Impurity Management
- ❑ Metrological challenges



METCCUS

Air Liquide R&D

Air Liquide: A world leader in gases, technologies, and services for…

©Adrien Daste

R&D KEY FIGURES

AS OF DECEMBER 2022

5 CAMPUSES & **3** SATELLITES

60% R&D PROJECTS CONDUCTED IN PARTNERSHIPS
with laboratories, start-ups, industrial players and customers

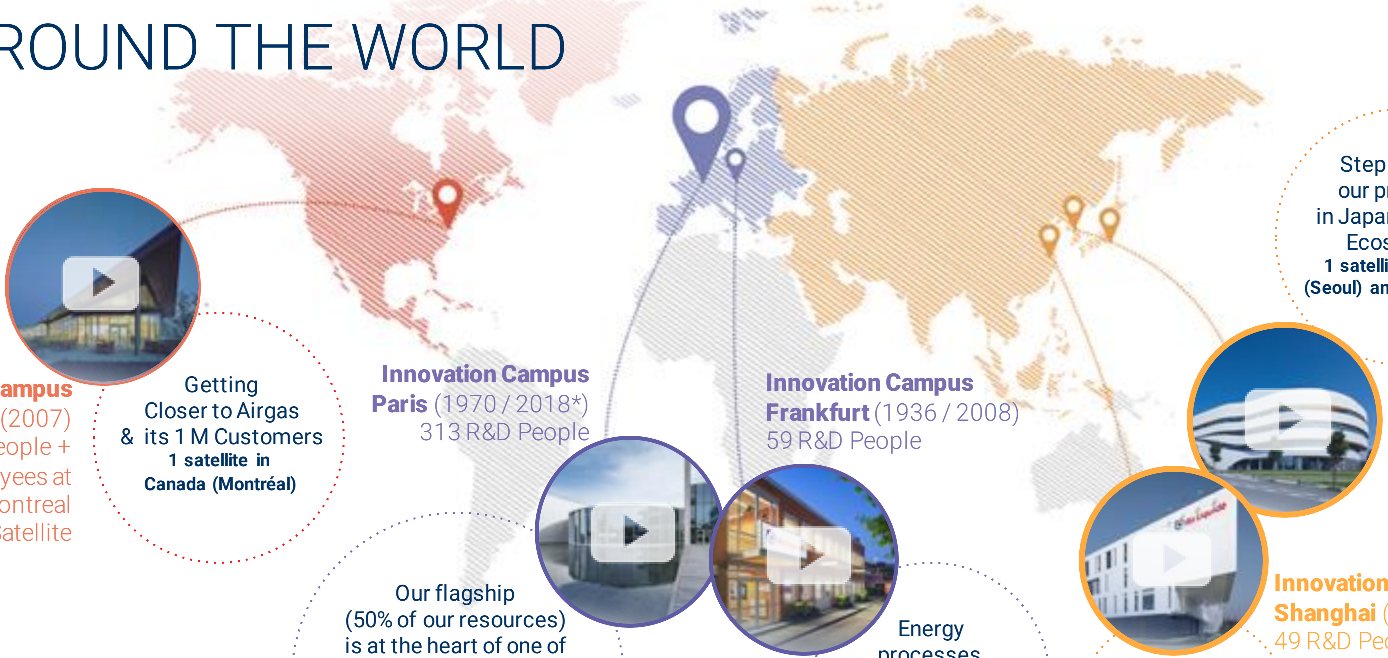
18 ESSENTIAL SMALL MOLECULES

60% R&D PORTFOLIO IS DEVOTED TO REDUCE CO_2 EMISSIONS*

557 EMPLOYEES

**by reducing the carbon content of Air Liquide products or those of its customers*

INNOVATION CAMPUSES
AROUND THE WORLD



Innovation Campus Delaware (2007)
81 R&D People +
3 R&D employees at the Montreal Satellite

Getting Closer to Airgas & its 1 M Customers
1 satellite in Canada (Montréal)

Innovation Campus Paris (1970 / 2018*)
313 R&D People

Our flagship (50% of our resources) is at the heart of one of the biggest European innovation ecosystems.
+ Host Accelair: a deep-tech startups Accelerator
1 satellite in Germany (Krefeld)

Innovation Campus Frankfurt (1936 / 2008)
59 R&D People

Energy processes within 1st european economy

Step change our presence in Japanese Tech Ecosystem
1 satellite in Korea (Seoul) and 1 in Taïwan

Innovation Campus Tokyo (1986 / 2019*)
45 R&D People

Innovation Campus Shanghai (2005 / 2016*)
49 R&D People

Leverage the Chinese Tech Powerhouse

*Renovation date

INNOVATION CAMPUS FRANKFURT

EXPERTISE : Science, Methods & Tools, Experiments, Large-scale industrial operations

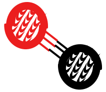
Science:
Process engineering, chemistry, analytics, catalysis, simulation, applied math & data science

Methods & Tools:
LCA (Life Cycle Assessment), TEA (Techno Economic Analysis), digital tools, process simulation

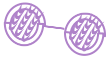
Experiments:
pilot plants, lab-scale, analytics, …

Knowledge of **large-scale industrial operation**

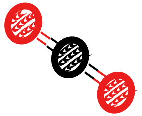
CAMPUS STRATEGY based on 2 axes : **carbon management and low carbon emission + 3 essential small molecules**



CO
Carbon monoxide



H_2
Hydrogen



CO_2
Carbon dioxide

INNOVATION CAMPUS **PARIS**

59 **Laboratories**

350
Persons

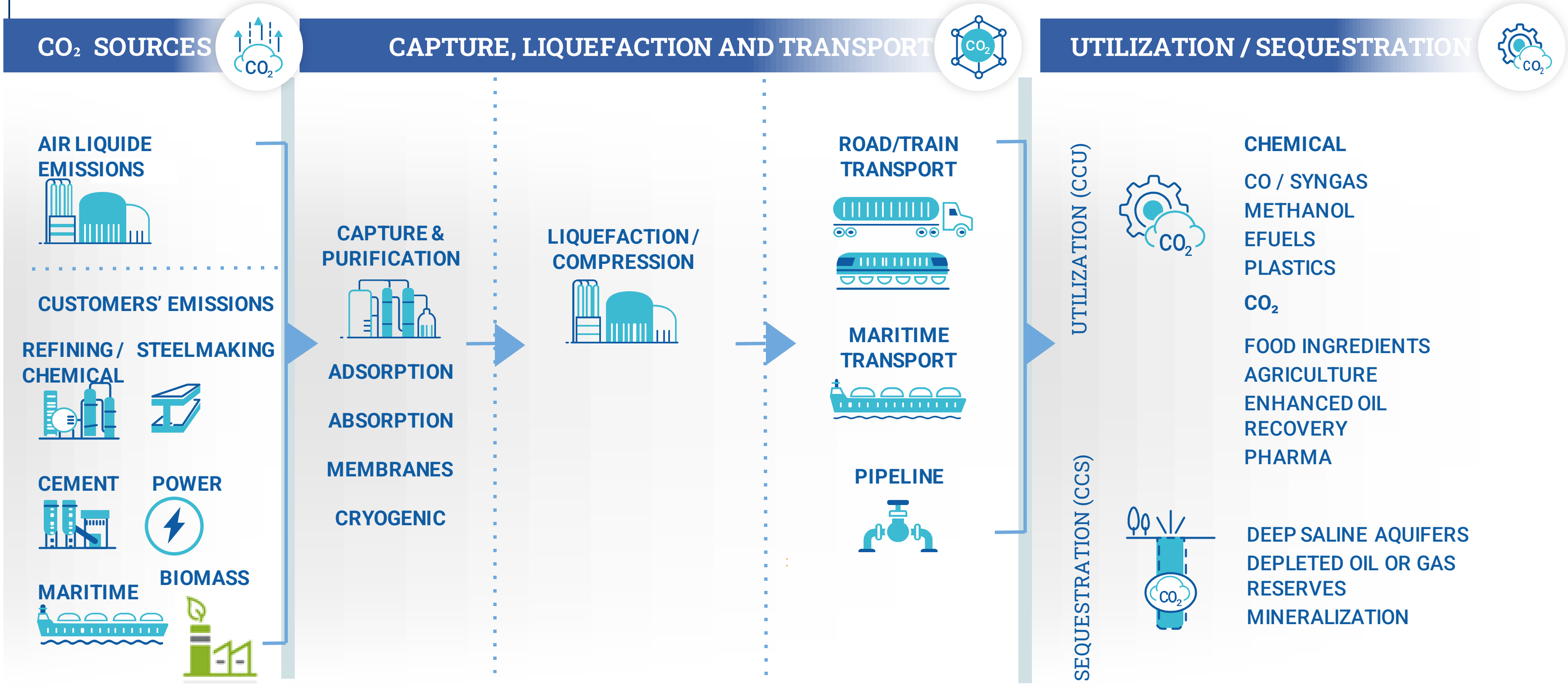
8 technical platforms

Gas Security - Process Engineering - Computational and data sciences - Material qualification- Combustion - Food production - Additive production- - Gas Analysis

Découvrez le campus en vidéo

CCUS Solutions portfolio

CO2 value chain



Air Liquide in the CCUS value chain

Capture → **Pressurisation / Liquefaction** → **Transport / Distribution**

Air Liquide

CO2 Emitter Plant (e.g. SMR)

G-CO2 →

CO2 Capture and Liquefaction Unit (Cryocap)

Liquefaction Unit incl. Intermediate storage

L-CO2 →

Loading facility

Rail, barges or pipeline logistics to the harbor LCO2 terminal

→ *Un-loading facility*

Harbor Export Terminal

L-CO2 Terminal

Shipping

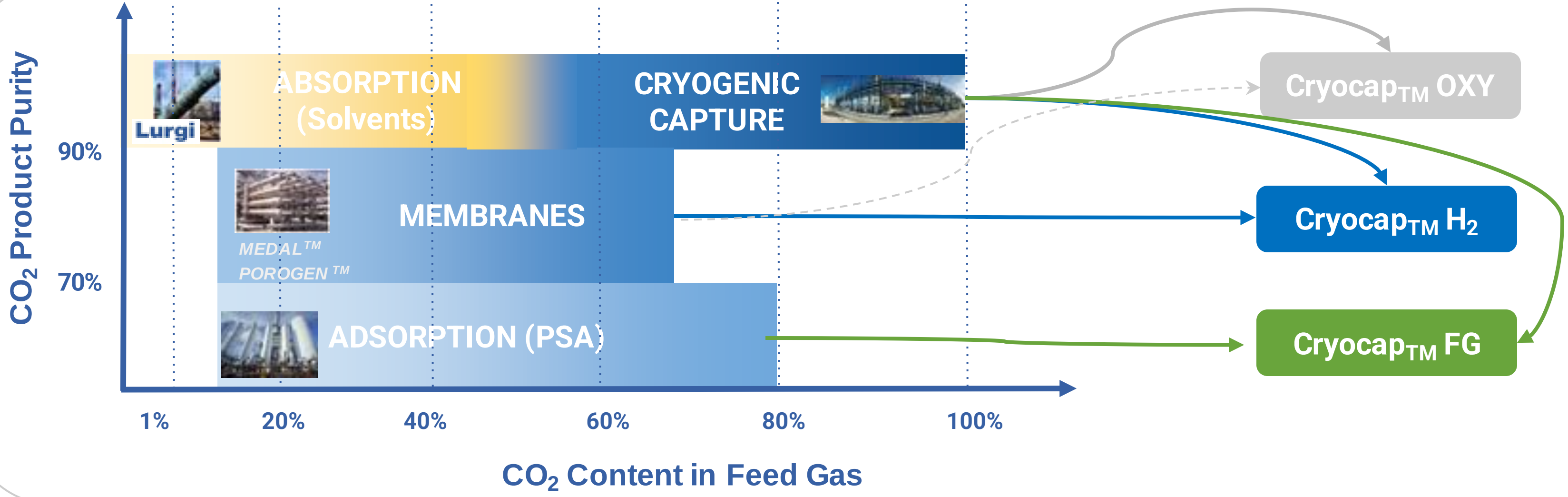
Air Liquide expertise:

- Various CO2 capture technologies (Cryocap FG, H_2, Oxy, Steel Amine wash, Rectisol) for different flue gas compositions
- CO2 compression, liquefaction and storage expertise
- CO2 pipeline experience

Air Liquide motivation:

- Carbon Capture for own plants and as a service
- Reduction CO2 emissions -33% compared to 2020 by 2035

Combining technologies for lowering CAPEX and OPEX



Absorption: The most suitable solution for low concentrated feed gas

Cryocap™ combines cryogenic with membranes & adsorption, addressing any CO2% > 15%, electrical power only.
Can produce HP CO_2 or Liq CO_2 at marginal extra cost.

HP CO2/Liq CO2: Looking for synergies between capture and compression / liquefaction steps is key

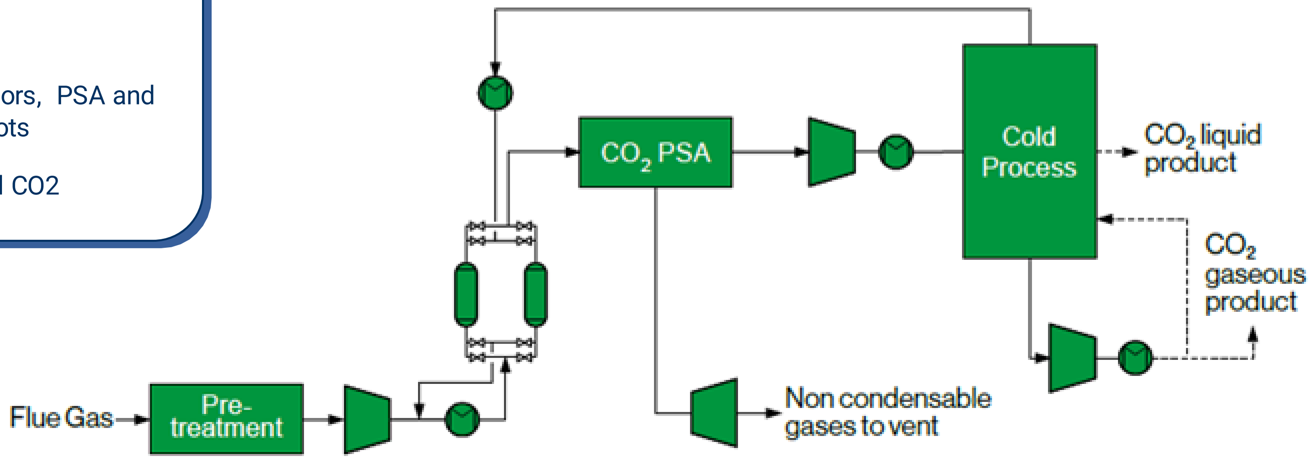
Cryocap™ FG: CO2 capture from flue gas (15%-40% CO2)

❑ Technical highlights:

- ➢ Suitable for any flue gas with > 15mol% CO2 (dry basis): SMR, cement, limestone
- ➢ Electrically driven solution
- ➢ Gaseous or liquid CO2
- ➢ CO2 capture rate: 90% to 95%
- ➢ Compact & Flexible footprint: Compressors, PSA and Coldbox can be located in 3 different plots
- ➢ Range: min 400 tpd CO2 - max 5000 tpd CO2

❑ Indicative utility figures

- ➢ Gas CO2 at ~30 bara: 310 kWh/tCO2
- ➢ Liq. CO2: 390 to 450 kWh/tCO2



Selected recent references - Carbon Capture on cement / lime applications

Ste Genevieve

- CO2 capture from a single line kiln
- Cryocap FG: 10,000 tpd CO2
- Capture rate: 95%

Lime kiln

- CO2 capture from a lime kiln
- Cryocap FG: 1,650 tpd CO2
- Capture rate: 95%

EQIOM

- CO2 capture from cement plant converted to oxycombustion
- Cryocap Oxy: 3,000 tpd CO2
- Capture rate: 95%

Air Liquide's involvement in CCS projects & sink developments

Northern Lights

Starvenger

Project: Northern Lights consortium project focuses on transport, reception and permanent storage of CO_2 in a reservoir in the northern part of the North Sea.

Role AL: evaluating CO2 capture and transport

Porthos

Rotterdam

Project: Open access CO2 transport and storage system through a public-private initiative by PoR.

Role AL: evaluating CO2 capture, aggregation and transport

Antwerp@C

Antwerp

Project: Consortium of industrial players to develop- feasibility study of building CO2 infrastructure for CCS(U)

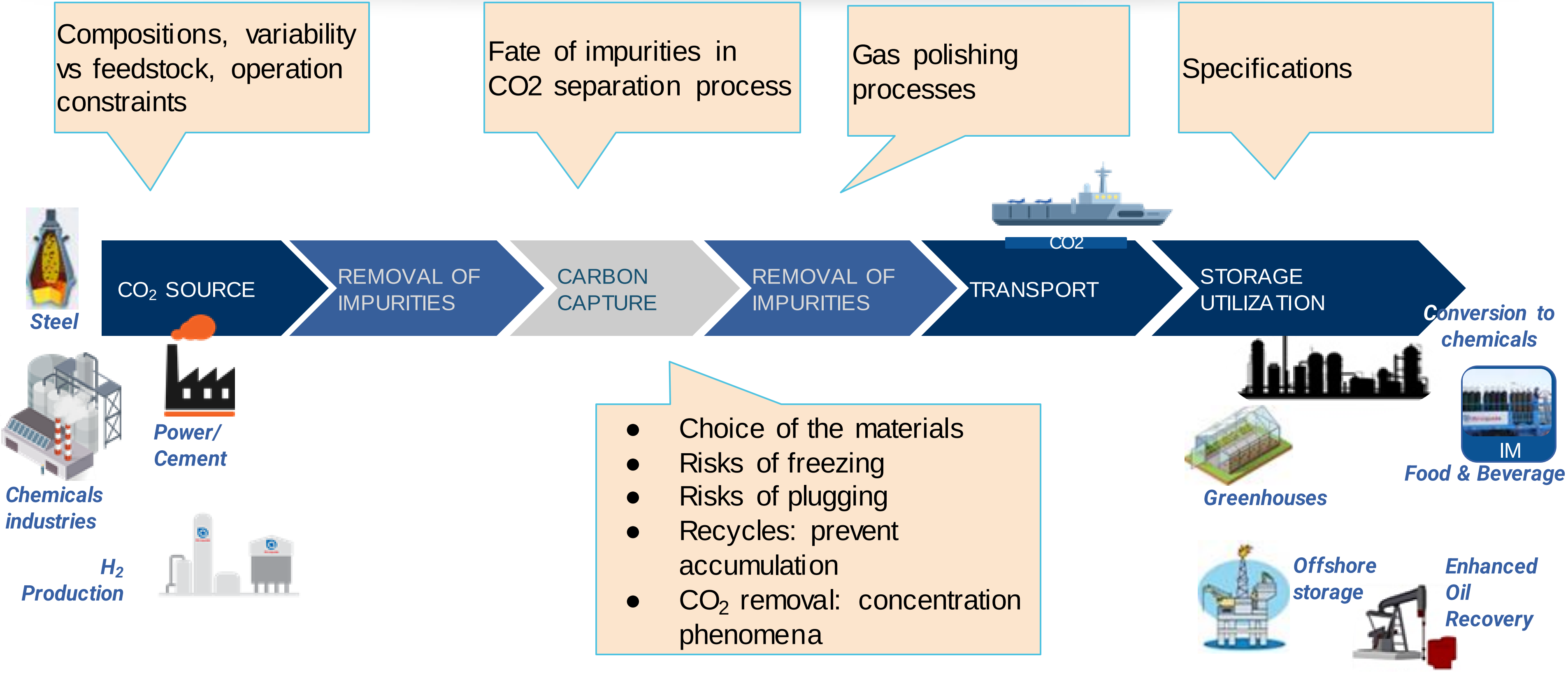
Role AL: evaluating CO2 capture, aggregation and transport

Impurities management

Typical impurities in flue gas and process off-gases

	Refinery FCC flue gas	Steel Blast Furnace gas	Steel Coke Oven gas	Cement Kiln Off-gas
Main components	N_2, CO_2, H_2O	N_2, CO_2, CO, H_2, H_2O	H_2, N_2, CO, CH_4, CO_2	N_2, CO_2, O_2, H_2O
Typical impurities	- SOx - NOx, HCN - unburnt CO - O_2 - Dust	- H_2S, COS, SOx - NOx, NH_3, HCN - O_2 - Hydrocarbons including BTEX - Halides - Metals, metal carbonyls - Dust	- H_2S, COS, C2S, mercaptans - NOx, HCN, NH_3 - O_2 - Hydrocarbons including BTEX - H_2O	- SO_2 - NOx - CO - HCl - Metals - Dust

Key questions of impurity management

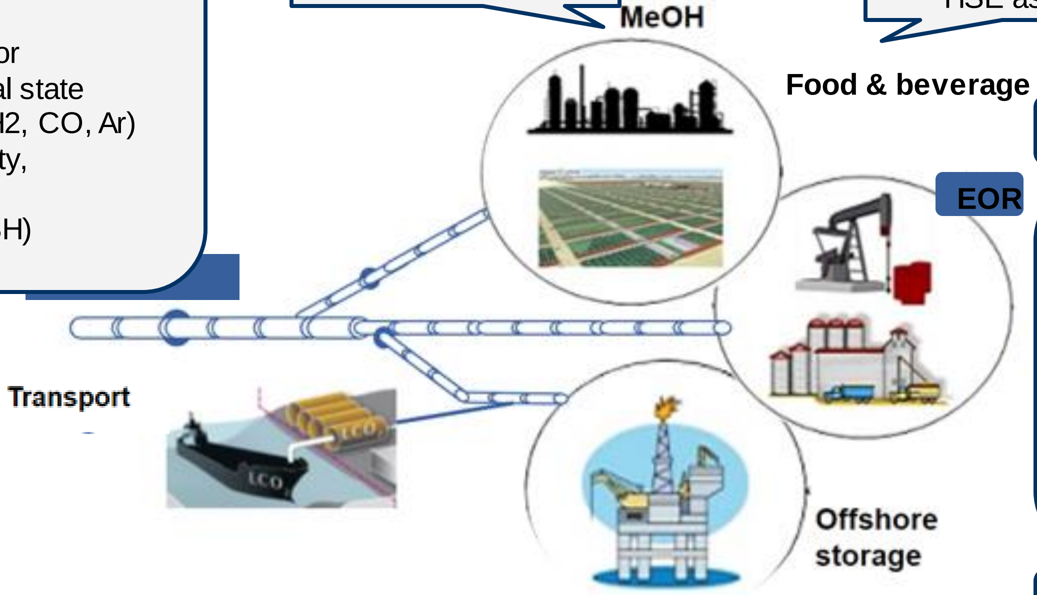


Specifications designed by the transport and CO_2 usage

- hydrate formation, corrosion (H2O+ S)
- plugging (dust)
- maintaining liquid or supercritical physical state (CH4, N2, H2, CO, Ar)
- HSE aspect (toxicity, eutrophication, …) (H2S,COS,CO, R-SH)
- strong odour

Catalyst deactivation (poisoning, sintering)

Sensorial effect, HSE aspects



- Transport phase

- Injection phase:
  - inflammability risk, aerobic formation (O2)
  - permeability of the well
  - miscibility w oil
  - reservoir capacity (CH_4, HC, Ar, N_2, CO, H_2)
  - mineral formation
  - acid and hydrate formation

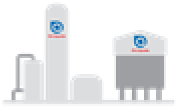
-HSE aspects

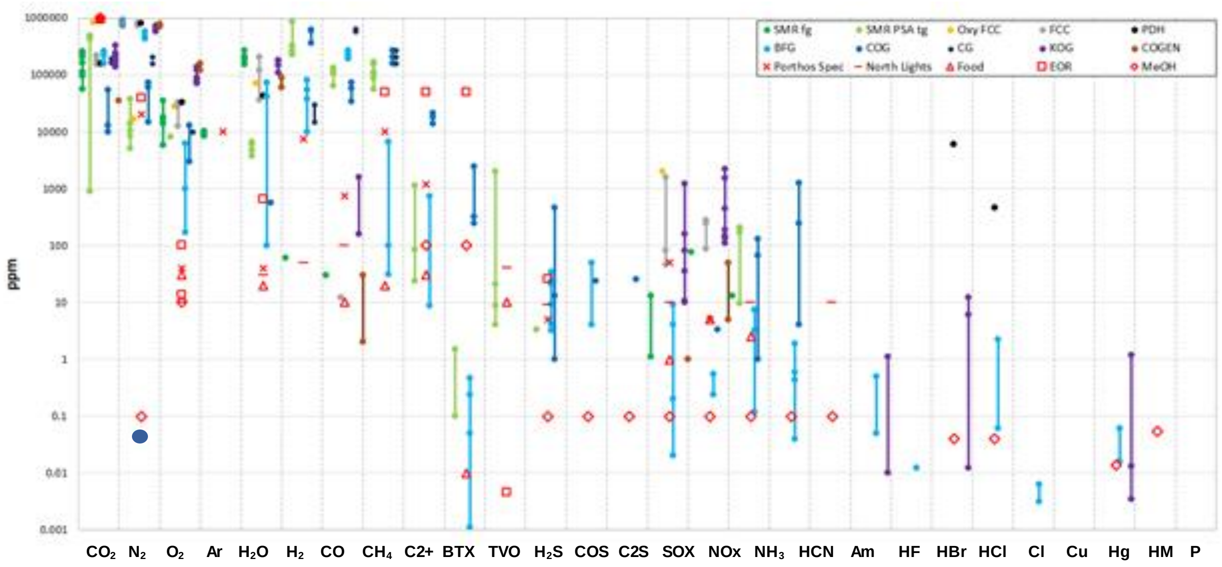
Metrological challenges

Key challenge : Raw gas composition ?

Compositions, variability vs feedstock, operation constraints

CO_2 SOURCE





- **How insure the reliability of the analytical results ?**
  - *Need reliable analytical techniques*
  - *Need reference gas mixtures in CO_2 matrix*
  - *Need sampling protocols adapted to the operation constraints (P, T, flow rate, gas composition) with compatible materials*

Key challenges for process management

Fate of impurities in CO_2 separation process

CARBON CAPTURE

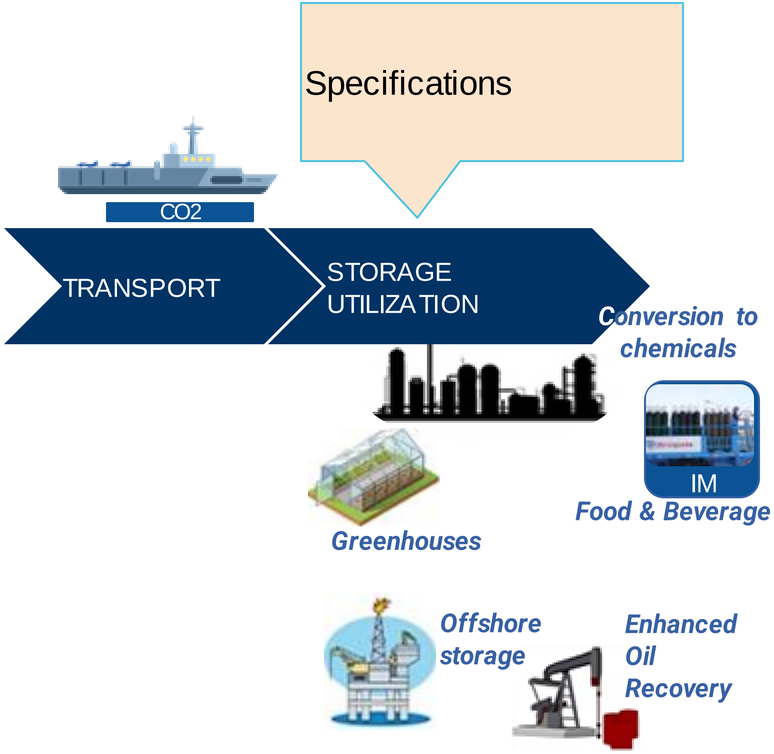
REMOVAL OF IMPURITIES

- Choice of the materials
- Risks of freezing
- Risks of plugging
- Recycles: prevent accumulation
- CO_2 removal: concentration phenomena

- **How insure the accuracy of the flow rate at each part of the process ?**
  - *Need **primary flow standards** to enable calibration of flow meters for liquid and gaseous-phase of CO_2 with low uncertainties*
  - *Need **data verified models** to predict physical properties (e.g. phase equilibria, density and viscosity)*
- **How insure the material compatibility with CO_2 and impurities?**
  - ***Testing methods** to produce validated data for pipeline corrosion, material degradation*
- **How control the impurities on line ?**
  - *Need **validated sensors** and online analytical system*
  - *Need reference gas mixtures in CO_2 matrix*

Key challenges for transport , storage and utilisation

- **How measure CO_2 leaks at each step?**
  - *validation of **systems capable of quantifying CO_2 leaks** from pipelines, transport (e.g. shipping) or storage sites*
  - *Need **data verified models** to predict physical properties*
- **How insure the material compatibility with CO_2 and impurities in storage?**
  - ***Testing methods** to produce validated data **for corrosion** or chemical reactions*
- **How insure the quality of CO_2 for utilisation**
  - *develop methods for CO_2 purity analysis (ISO/TR 27921 or ISBT)*
  - *Need reference gas mixtures in CO_2 matrix*



Conclusion

- *MetCCUS : a project addressing industrial challenges*

WP 1	- metrology infrastructure for monitoring the **CO_2 gas flow** and **CO_2 liquid flow**
WP 2	- the meteorological support to enable the **measurement** and reporting of **emissions** to air during CCUS (capture process, infrastructure [leaks], geological storage)
WP 3	- new standards and analytical methods to perform gas composition measurement for CO_2 within CCUS (**Reference materials,** sampling methods for representative sampling of key impurities, **online impurity analysis**)
WP 4	Study and model the **thermophysical properties** of CO_2 (mainly **liquid CO_2**) to support the design, monitoring and maintenance of industrial infrastructures for CCUS

- *But only the first step: Need to address other challenges: raw gas analysis, on line control…*

Thank you

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Dew-Point Measurements for Water in Compressed Carbon Dioxide

Christopher Meyer

Thermodynamic Metrology Group
Physical Measurements Laboratory
National Institute of Standards and Technology, USA

MetCCUS Seminar on Metrology Support for Carbon Capture, Utilization and Storage

October 26, 2023

NIST

PML

Working with

Allan Harvey

Applied Chemicals and Materials Division

NIST

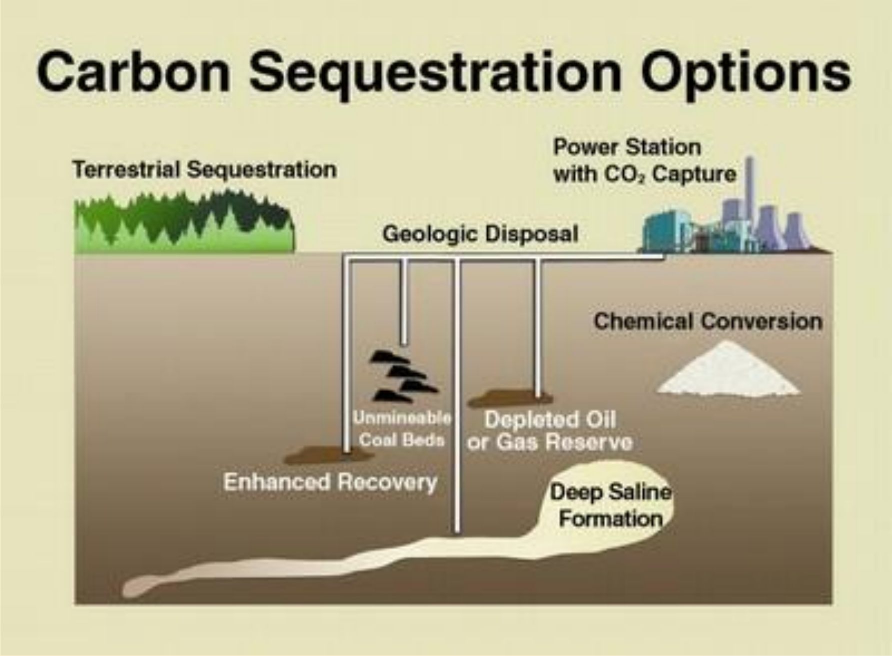
Boulder CO, USA

Paper published in AIChE Journal

C.W. Meyer and A.H. Harvey, “Dew-point Measurements for Water in Compressed Carbon Dioxide”, AIChE J. 61, 2913 – 2925, (2015).

NIST PML

Carbon Capture, Utilization and Storage



Principle :

1) Flue gases are captured after coal is burned
2) CO_2 is separated from other flue gases
3) CO_2 is stored deep inside the earth at high pressures
   a. in depleted oil or gas reserves
   b. in unmineable coal beds
   c. In saline aquifers

Importance of removing H_2O from humid CO_2

1) Moisture can rust steel pipes
2) Compression of moist CO_2 requires more energy

Designing CO_2 capture systems requires accurate knowledge of dew point in CO_2 as function of mole fraction and pressure.

Accurate knowledge of $T_{DP}(x,P)$ could save CCUS process as much as 300M/yr.

NIST PML

Determining the CO_2 Dew-point Relations

$$x_w = \frac{e_w(T_{DP})}{P} f(T_{DP}, P)$$

x_w: water amount (mole) fraction

T_{DP}: dew point temperature

$e_w(T_{DP})$: saturated water vapor pressure at T_{DP} (gas independent)

P: pressure

$f(T_{DP}, P)$: water vapor enhancement factor (gas dependent)

$e_w(T_{DP})$ is known
$f(T_{DP}, P)$ needs to be determined

NIST PML

Facility for determining $f(T_{DP},P)$

1) Saturation system for compressed CO_2 (generates unknown x using P and T_{DP})
2) Gravimetric hygrometer (measures x_w)

$$x_w = \frac{e_w(T_{DP})}{P} f(T_{DP}, P)$$

NIST

PML

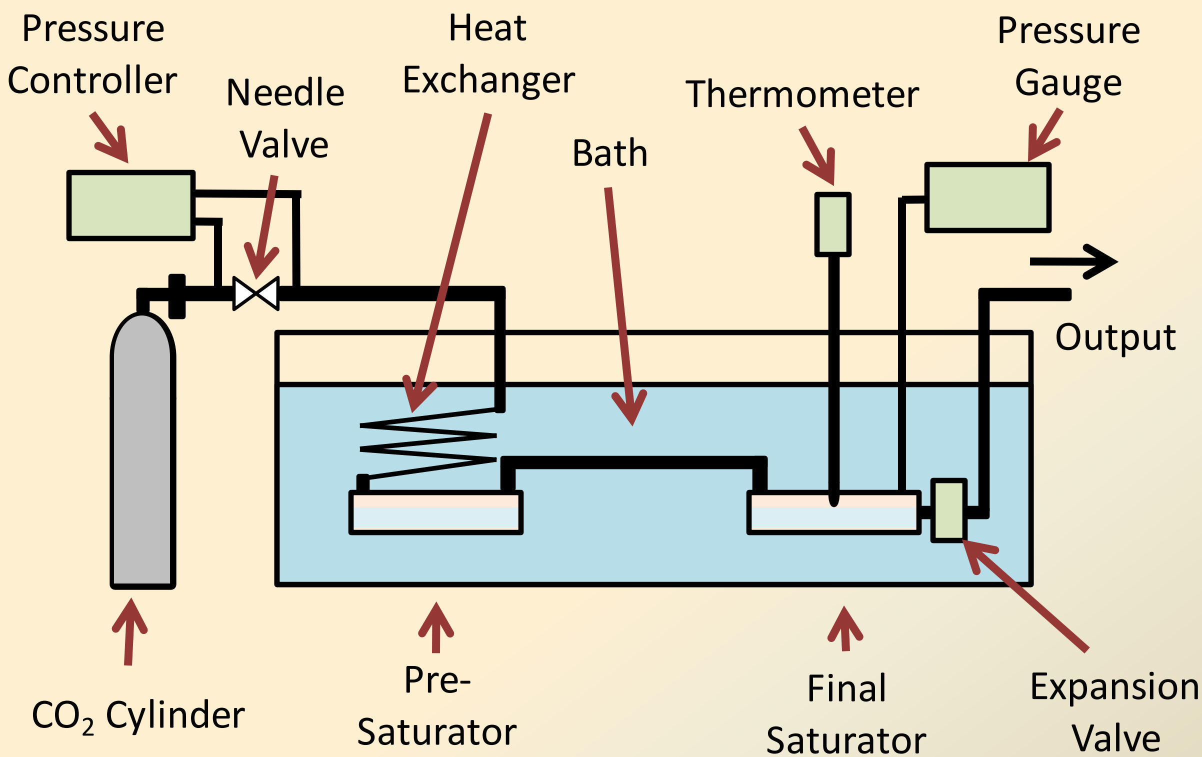
Saturation System for Compressed CO_2

Features:

1) Saturates CO_2 completely
2) Operates at pressures up to 7 MPa
3) Allows frequent changes of water in saturator (CO_2 can react with water to make carbonic acid, but process is slow).

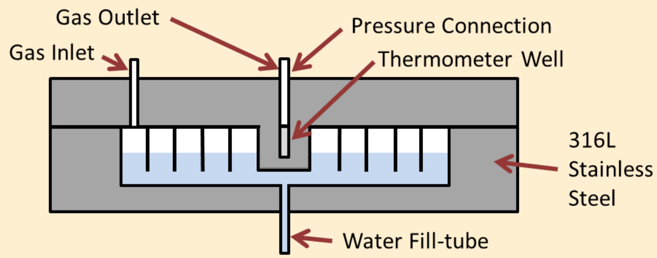
NIST PML

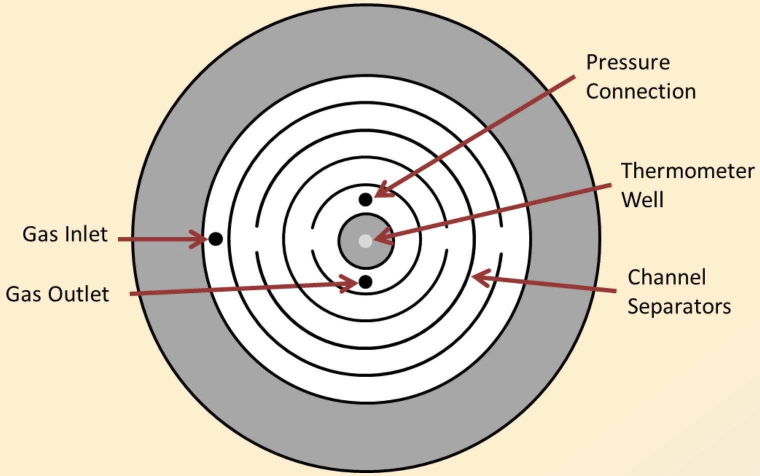
Design for Saturation System



NIST PML

Design for Saturator





316L Stainless Steel

NIST Gravimetric Hygrometer

Provides a primary method of humidity measurement giving water amount fraction x_w:

$$x_w = \frac{m_w / M_w}{m_w / M_w + m_g / M_g}$$

m_w: mass of water vapor
m_g: mass of carrier gas
M_w: molecular weight of water vapor
M_g: molecular weight of carrier gas

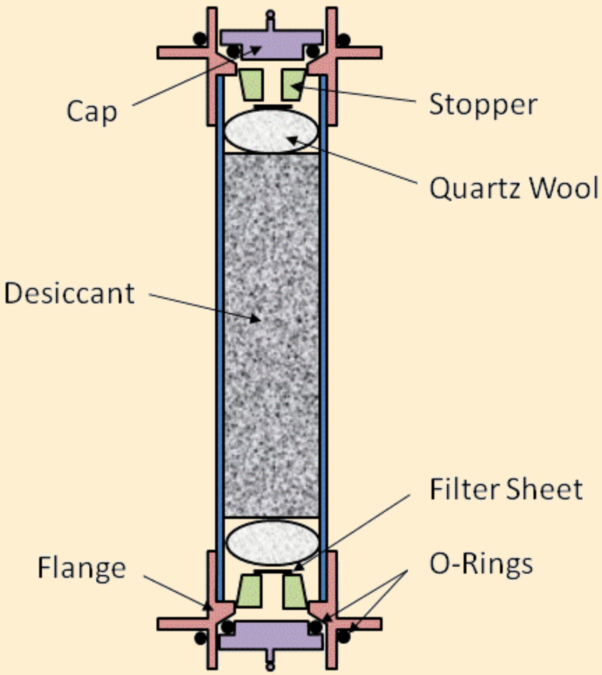
Principle of Operation:

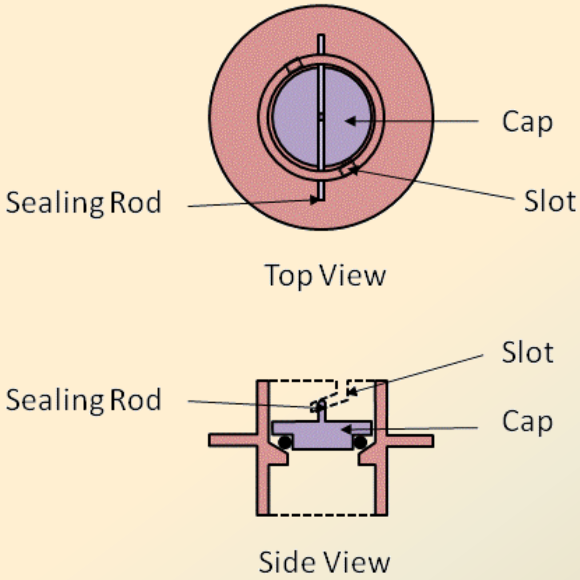
1) Separates moisture from dry gas using desiccants
2) Determine m_w by measuring increase in mass of water collection tubes
3) Determine m_g using volume, temperature and pressure measurements and using equation of state

Relative Uncertainty of amount fraction measurements using Gravimetric Hygrometer: 0.1%

NIST PML

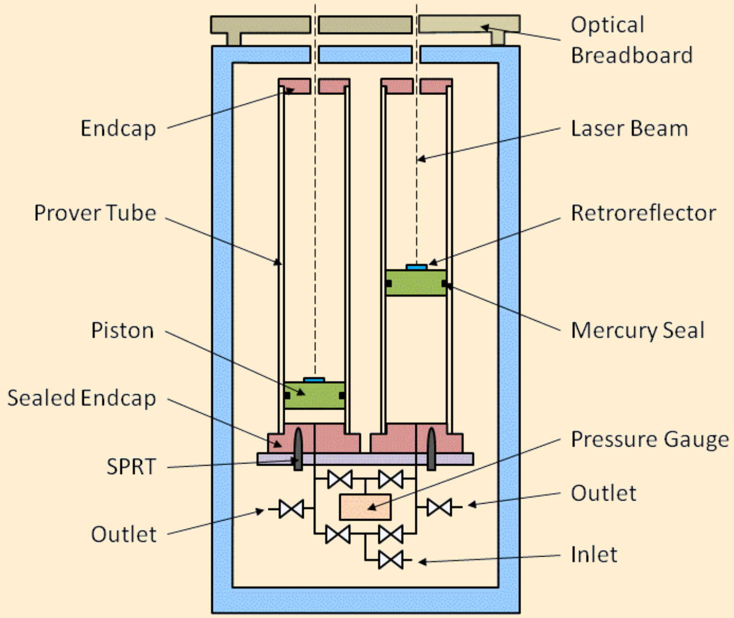
Water Collection Tubes





- Desiccant used: Magnesium Perchlorate
- Mass measurements made before and after water collection using electronic balance that compares tube mass to standard mass.
- Three tubes used in series. Most all water collected in 1st tube.

Prover Tube Gas Collection System



- Laser interferometer measures piston displacement to determine gas volume
- Pressure and temperature measurements determine gas density
- Gas mass under piston calculated from volume and density
- Alternating pistons allow continuous gas flow
- Prover tube collects gas underneath piston

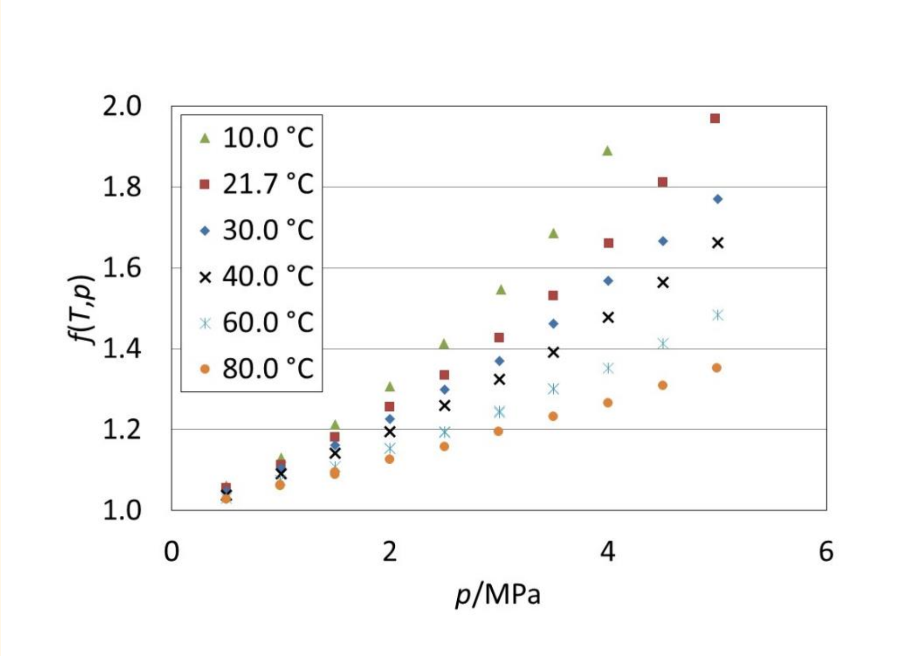
NIST PML

Measurement Plan

1) Perform measurements on 6 isotherms between 10 °C and 80 °C
2) Perform measurements from 0.5 MPa to 5 MPa in 0.5 MPa increments
3) Pressure range limited by
   a) CO_2 sat. vapor pressure at ambient temperature
   b) CO_2 hydrates (high pressures at low temperatures)

NIST PML

Water-vapor Enhancement Factor in CO_2



Note:

1) *f* increases monotonically with pressure

2) *f* decreases monotonically with temperature

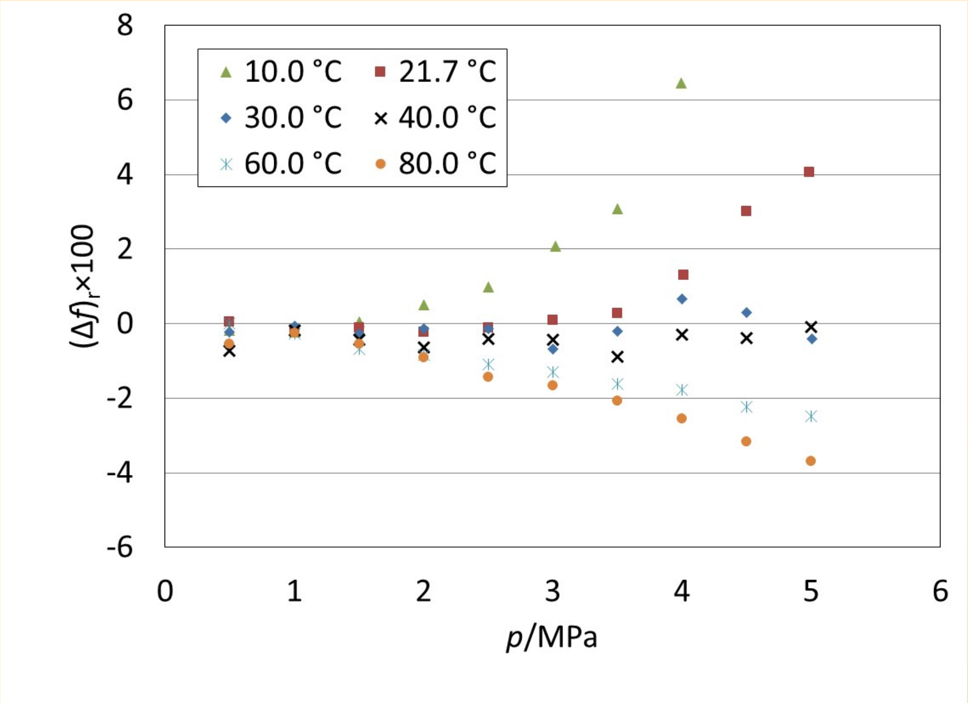
3) Over range studied, *f* varies from 1 to 2.

4) Difference between *f*=1 and *f*=2 corresponds to a dew point change of 9.5 °C. (for constant x_w, higher f means lower T_{DP}).

NIST PML

Comparison with Theoretical Results

$(\Delta f)_r = [f(\text{measured}) - f(\text{calculated})] / f(\text{calculated})$



Theoretical Results:

f calculated using interaction second virial coefficient B_{12} values of

R. J. Wheatley and A. H. Harvey, *J. Chem. Phys.* **134**, 134309 (2011).

Conclusion: *C_{112} and C_{122} values must also be considered!*

$$\frac{p}{\rho RT} = 1 + B\rho + C\rho^2 + \ldots$$

$$B = x_1^2 B_{11} + 2x_1 x_2 B_{12} + x_2^2 B_{22}$$

x_1: CO_2 amount fraction

x_2: H_2O amount fraction

B_{11}: CO_2 2nd virial coeff.

B_{22}: H_2O 2nd virial coeff.

B_{12}: CO_2/H_2O interaction 2nd virial coeff.

NIST PML

C_{112} and C_{122} considered

$$\frac{p}{\rho RT} = 1 + B\rho + C\rho^2 + \ldots$$

$$C = x_1^3 C_{111} + 3x_1^2 x_2 C_{112} + 3x_1 x_2^2 C_{122} + x_2^3 C_{222}$$

x_1: CO_2 amount fraction

x_2: H_2O amount fraction

C_{11}: CO_2 3rd virial coeff.

C_{22}: H_2O 3rd virial coeff.

C_{112}: $CO_2/CO_2/H_2O$ interaction 3rd virial coeff.

C_{122}: $CO_2/H_2O/H_2O$ interaction 3rd virial coeff

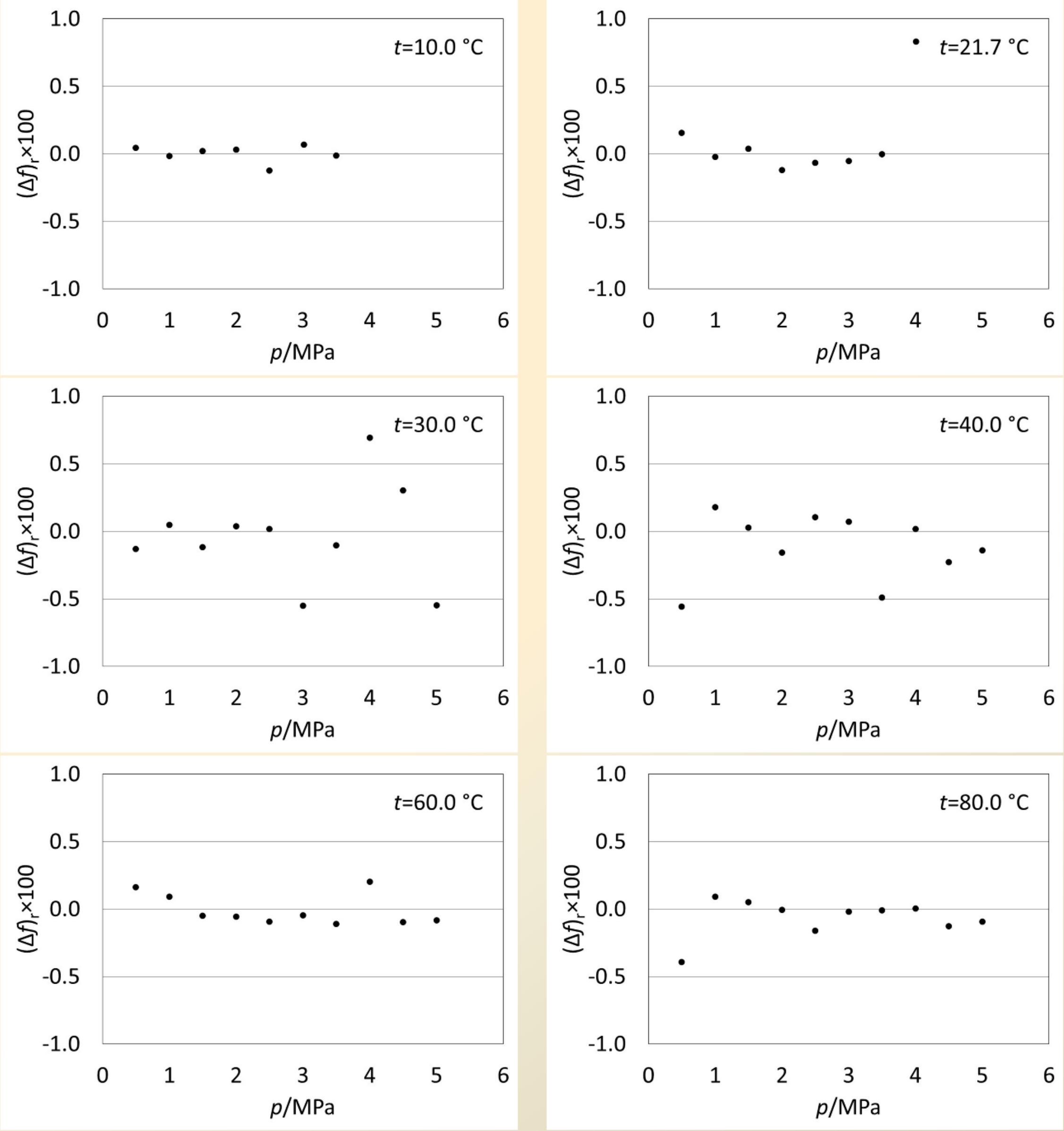
Best-fit values of C_{122} used

Theoretical values of C_{122} used

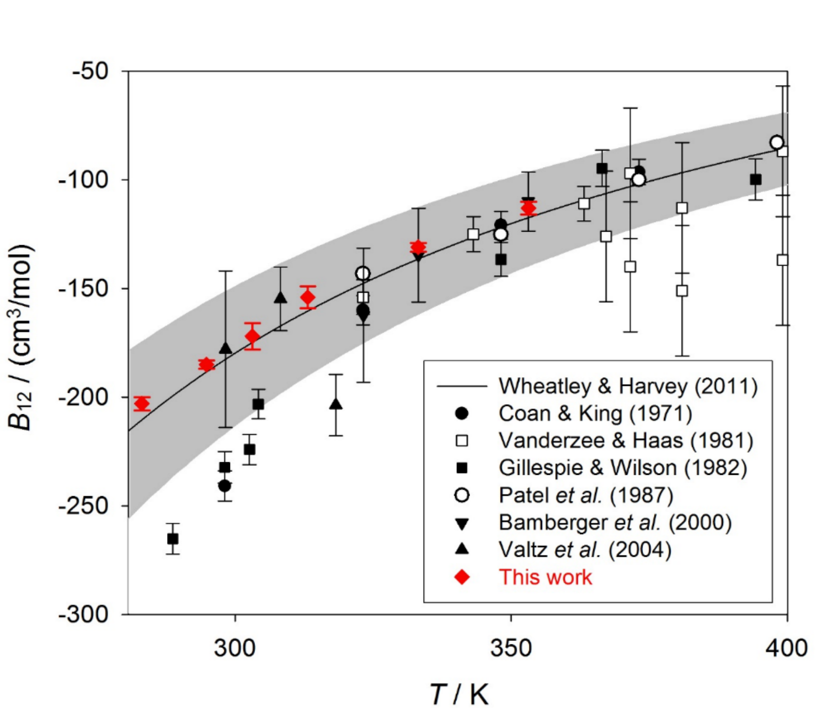
Comparison with Theoretical Results

Theoretical Results:

f calculated using best-fit values of B_{12} and C_{112}.



Water-CO_2 Cross Second Virial Coefficient



Temp, K	Wheatley and Harvey	Meyer
283	-210 ± 40	-203 ± 3
295	-188 ± 35	-186 ± 2
303	-175 ± 30	-173 ± 6
313	-160 ± 27	-155 ± 5
323	-136 ± 23	-132 ± 2
343	-117 ± 20	-113 ± 3

Conclusion

- Carbon Capture, Utilization and Storage (CCUS) has the potential of greatly reducing emissions of CO_2 from power plants into the atmosphere.

- Water-vapor enhancement factor is an important thermophysical property for CCUS

- Facility constructed for measuring the water-vapor enhancement factor; facility uses humidity generator that saturates CO_2 with water at pressures up to 5 MPa

- Measurements made on 6 isotherms; measurements in good agreement with theoretical predictions of Wheatley and Harvey but with much less uncertainty

NIST PML

METCCUS

SAMPLING OF CO2 FOR PURITY ASSESSMENT: METHODS AND CHALLENGES

Karine Arrhenius, RISE

EURAMET METCCUS

SAMPLING OF CO_2 FOR PURITY ASSESSMENT: METHODS AND CHALLENGES

METCCUS

- Introduction
- Challenges
- Vessels
- Considerations
- Material compatibility

INTRODUCTION

- Due to the production methods or the origin of the carbon dioxide, it usually contains species in traces that can have a negative impact on the equipment they come into contact with
- Several standards contain requirements for CO_2 quality assessment for different applications
- These standards requires often analysis in a laboratory and therefore requires the collection and transport of a gas sample from the point of use
- The sample taken must be **representative** of the gas supplied; this assumes that no compounds are added to or removed from the gas during sampling

CHALLENGES

The main challenge is for species at trace levels for which the risk of loss of contaminants in the vessels and sampling lines must be taken into consideration

- ❑ partial adsorption or irreversible adsorption
- ❑ reaction (chemical reaction between species or between species and the matrix)

Other challenges arise from the need for flow measurement specifically for the enrichment methods, the exact composition of which may not be known until it has been fully analysed in a laboratory.

Important challenges arise from the physical properties of CO_2 itself. The critical point of pure CO_2 is close to the ambient temperature. Therefore, phase changes and multiphase conditions can occur at the sampling points. There may be a partitioning of species between the different phases, and if only the gas phase is analysed, the composition may be underestimated

VESSELS

Gas cylinders

Canisters

Sampling bags

Impingers

Sorbents

No enrichment

Enrichment

DIFFERENT CONSIDERATIONS

THE CONDITIONS AT THE SAMPLING POINT MUST FIT THE REQUIREMENT FOR THE VESSELS

- Pressure: if the pressure at the sampling point is low (less than 1 bar), it would be difficult to fill a cylinder for example. If the pressure is high (>3 bar), a reduction is needed for sorbents, impingers and bags
- Temperature: Bags, sorbents.. have max. operating temperature
- Flow: needs to be controlled for some vessels such as sorbent tubes and limited (for example 0.5 l/min)
- Gas permeability (mostly for bags)

- Enough volume sampled to perform all analyses (all replicates) and all instruments
- Enough pressure if needed by the instruments, pressure from the vessels may need to be reduced
- Adequate temperature, many instruments work at ambient temperatures

THE REQUIREMENT FOR THE VESSELS MUST FIT THE CONDITIONS OF THE ANALYTICAL INSTRUMENTS

MATERIAL COMPATIBILITY

Materials in contact with gases that may contain reactive impurities should be impermeable to all species and should have a minimum of sorption and chemical inertness to the constituents being sampled.

The same considerations apply to all parts of the sampling line and especially to those parts where pressure reduction takes place

Material compatibility issues are often not well demonstrated experimentally, it is of great importance to increase the knowledge of adsorption effects of relevant species on different materials under relevant conditions (matrix, pressure, concentration)

Need for systematic recovery experiments and short-term stabilities at defined and relevant conditions in terms of pressure, matrix and concentration

The results of these investigations should be compiled in material compatibility tables to assist industry in selecting suitable materials for vessels and sampling lines.

TESTS PERFORMED DURING METCCUS: VESSELS

TRUE BLUE

From Airborne labs

Specifically designed for CO_2 sampling

Proprietary multi-layer barrier film

CALI5BOND

From Calibrated Instruments inc.

Multi layer foil Sampling Bags

MULTIFOIL

From Restek

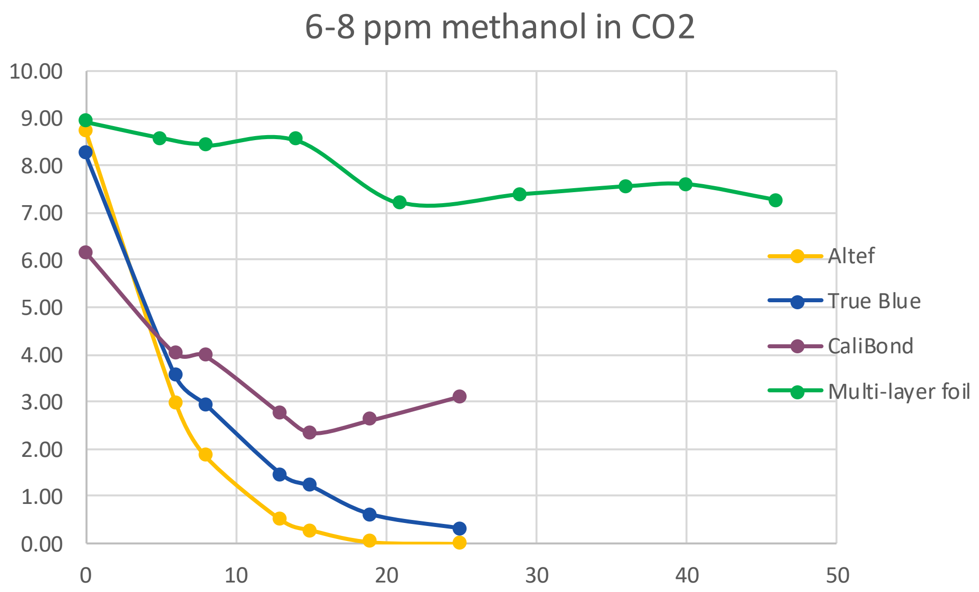
Multi layer foil Sampling Bags

ALTEF

From Restek

Polyvinylidene fluoride (PVDF) film, alternative to Tedlar

TESTS PERFORMED DURING METCCUS: RESULTS

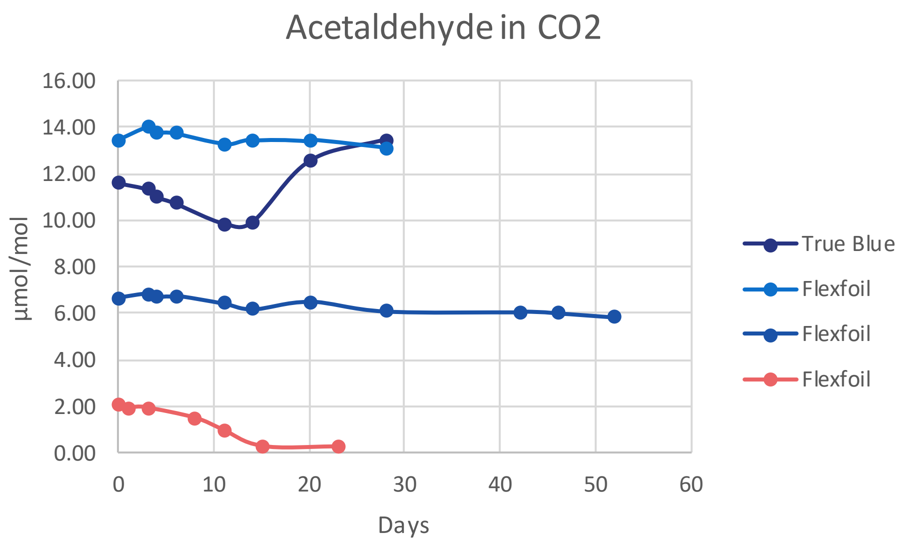


Methanol Limit required: 10 µmol/mol (beverage, EIGA 70/17)

Bags	concentration	Stability	Comments
True Blue	8.6		
Multi-layer foil	9.0		
Cali5Bond	6.1		
Altef	9.0		

TESTS PERFORMED DURING METCCUS: RESULTS

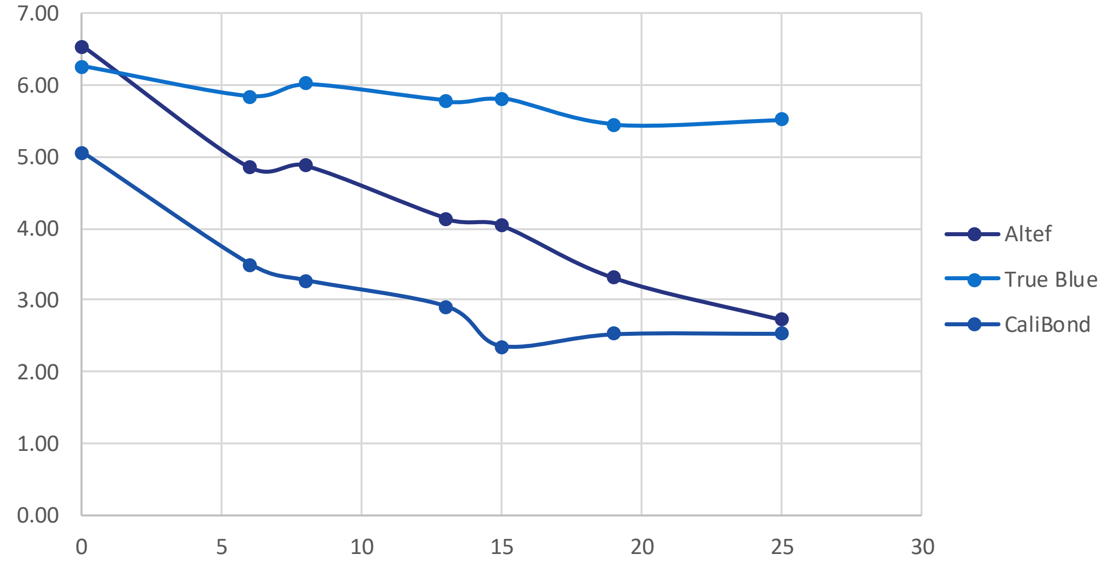
Acetaldehyde. Limit required: 0.2 µmol/mol, (beverage, EIGA 70/17)



Bags	concentration	Stability	Comments
True Blue	12		Bag not enough filled, acetaldehyde in blank
Multifoil	14		Bag not enough filled, acetaldehyde in blank
Multifoil	7		Acetaldehyde in blank
Multifoil	2		Bag not enough filled, acetaldehyde in blank

TESTS PERFORMED DURING METCCUS: RESULTS

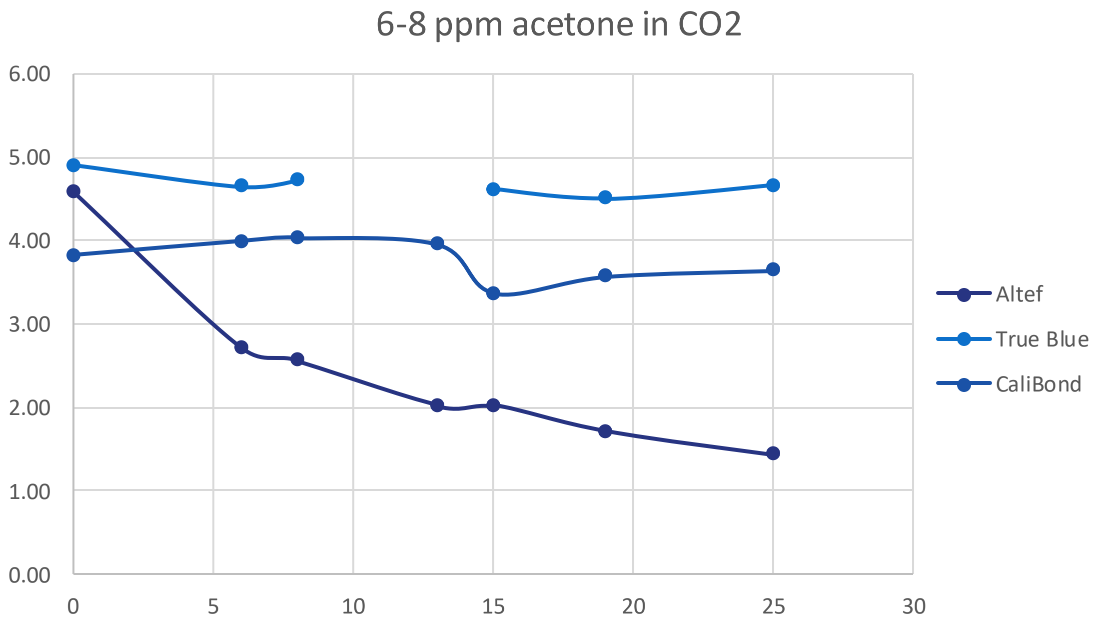
6-8 ppm ethanol in CO_2



Ethanol Limit required: ? µmol/mol

Bags	concentration	Stability	Comments
True Blue	6.3		
Multi-layer foil	-		
Cali5Bond	5.0		
Altef	6.5		

TESTS PERFORMED DURING METCCUS: RESULTS

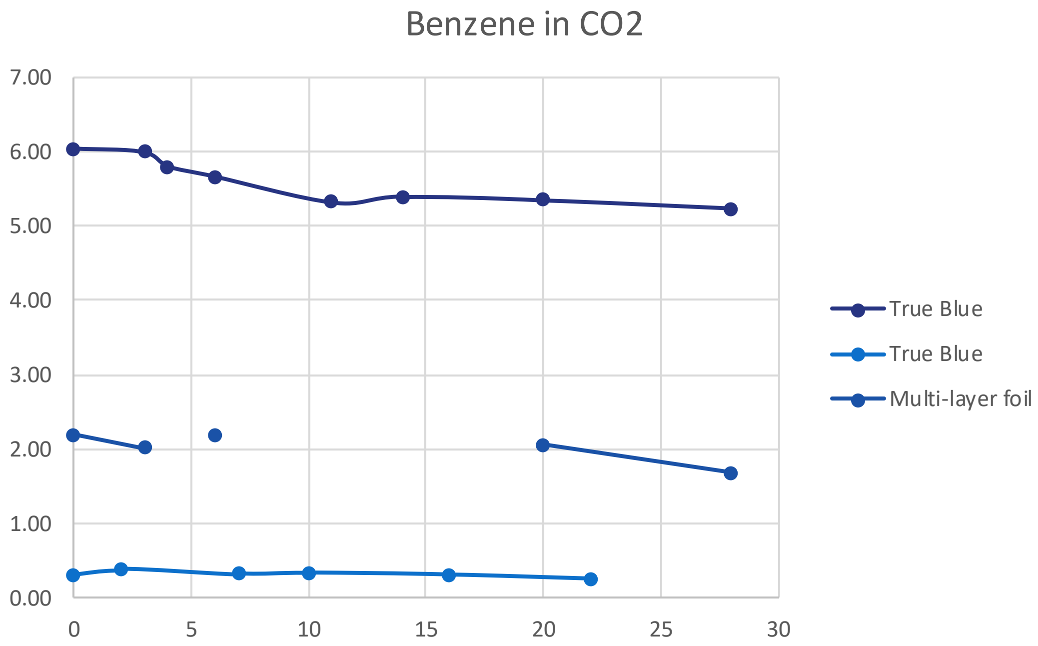


Acetone Limit required: ? µmol/mol

Bags	concentration	Stability	Comments
True Blue	4.9		
Multi-layer foil	-		
Cali5Bond	3.9		
Altef	4.7		

TESTS PERFORMED DURING METCCUS: RESULTS

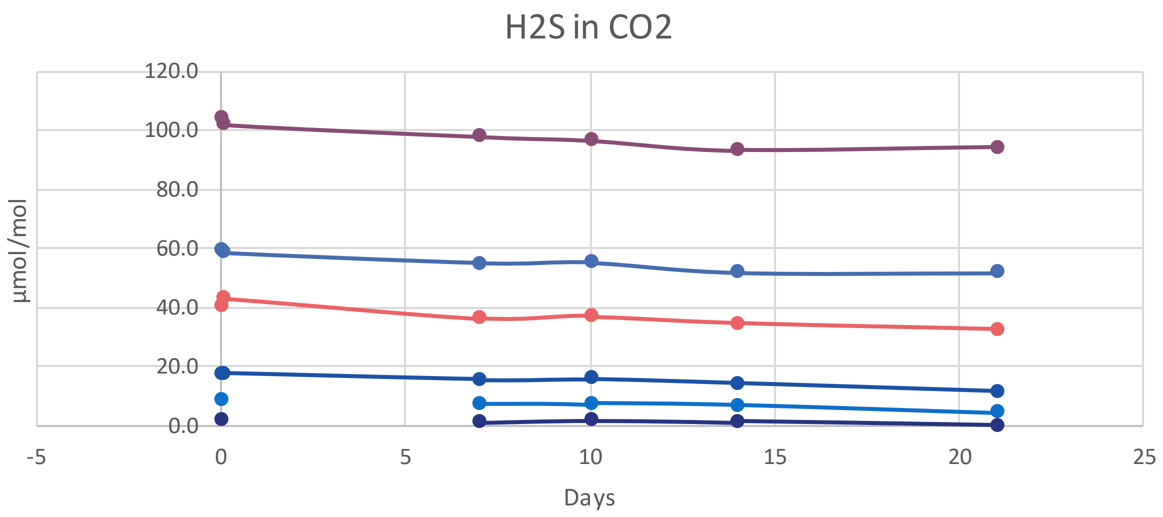
Not appropriate for benzene

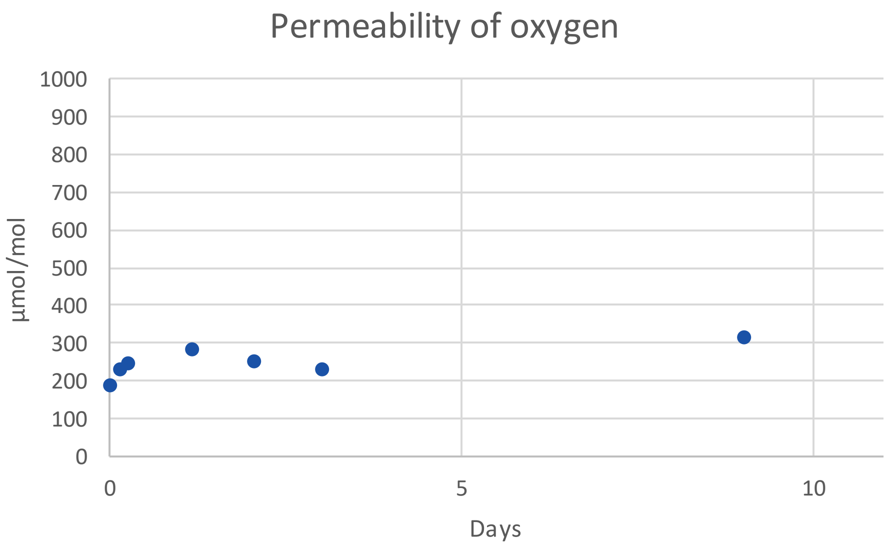


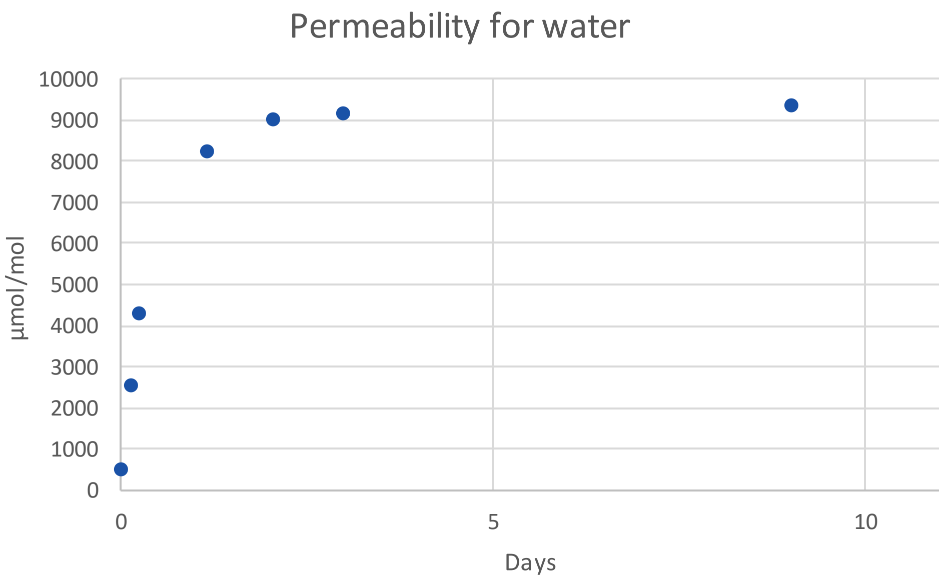
Benzene Limit required: 0.02 µmol/mol

Bags	concentration	Stability	Comments
True Blue	6.0		
True Blue	0.3		
Multi-layer foil	3.9		Stable but value lower at D0 (3.6 µmol/mol)

TESTS PERFORMED DURING METCCUS: RESULTS







TESTS PERFORMED DURING METCCUS: SUMMARY

Bags	Methanol	Ethanol	Acetone	Benzene	Hydrogen sulphide	Acetaldehyde
True Blue						
Cali5Bond						
Restek Multi-layer foil						
Restek Altef						

More tests to be performed:

- H2S in True Blue and restek multifoil
- Acetaldehyde and benzene at lower concentrations
- Ethanol and acetone in Restek multilayer

CONCLUSIONS

- The overall conclusion is that no single bag is suitable for sampling all the impurities present in CO_2. A combination of vessels is likely to be required to cover the wide range of impurities which have a wide range of boiling points, polarities, water solubilities, and reactivities
- Best results for True Blue (except for methanol) and potentially for Restek multilayer which is suitable for methanol
- Results highlight the needs to perform stability studies in relevant conditions
- Other studies of interest not planned: Influence of combined impurities

THANK YOU!

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VSL

National Metrology Institute

CCUS challenges

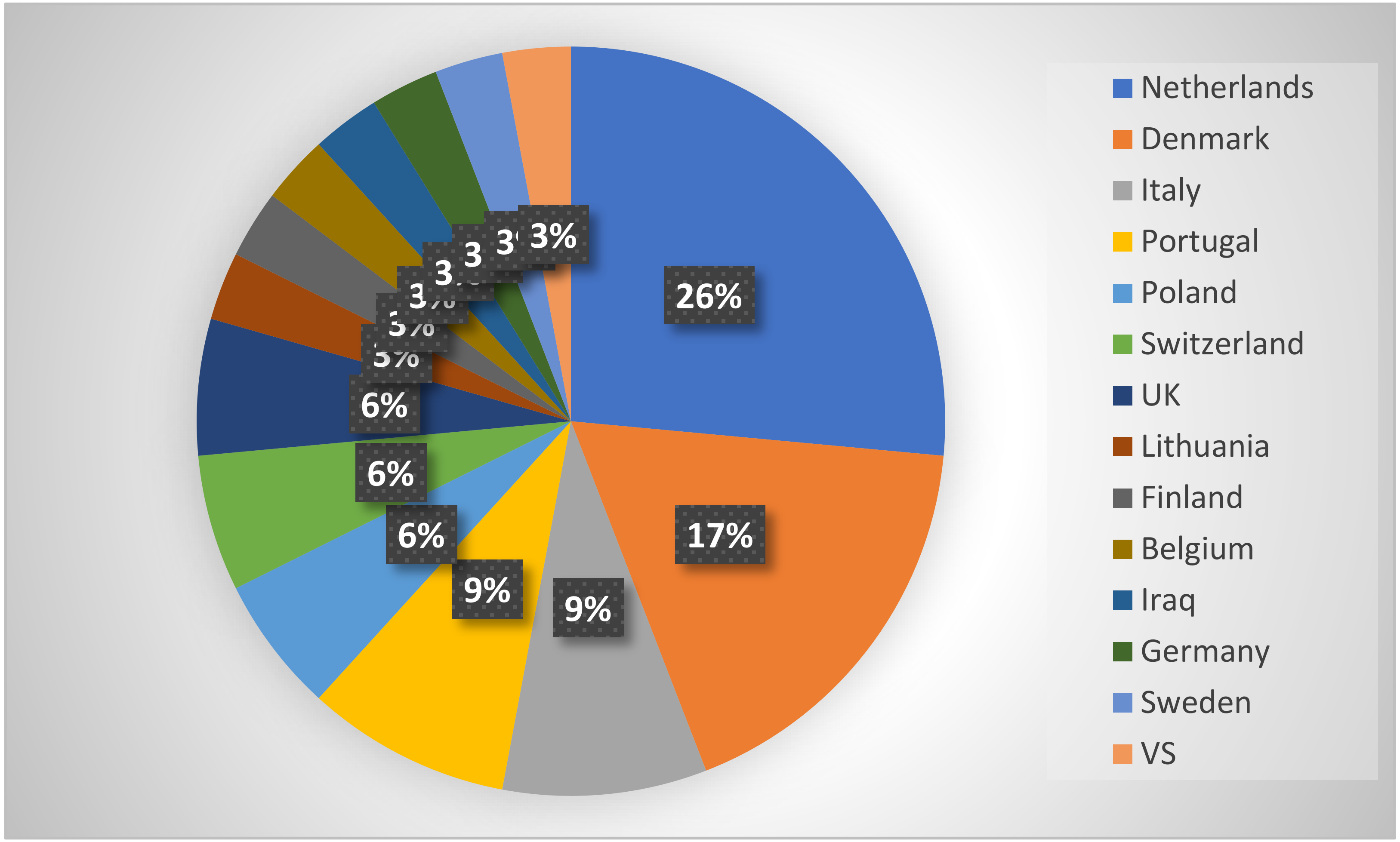
Seminar Metrology Support for Carbon Capture Utilization and Storage

Iris de Krom

26 October 2023 – Online

METCCUS

Participants



Note: this is based on a survey shared during the first 10 minutes of the seminar. People from other countries, including the Americas, joined later on.

CCUS general challenges

- Organization of ring tests
- DAC - Direct Air Capture
- Tracing of the origin of CO_2
- Standardization
- Unclear specifications for CO_2 and impurities
- Diversity of applications along the CCUS value chain
- Storage
- Legislation & Carbon accounting
- How much carbon do we need to capture ?
- How much captured carbon can be converted to fuels, chemicals and materials?
- How can we connect different CO_2 networks?

CCUS measurement challenges

Flow metering

- Ensuring accuracy of measurements across a wide flow range and CO_2 with variable purity
- Calibrated, accredited and accurate flow measurements for supercritical CO_2 flow with acceptable uncertainties
- Measuring for allocation
- Flow meters suitable for Fiscal Flow measurement traceable to SI
- Transferability of alternative fluid calibrations (i.e. Coriolis with water)

Emission monitoring

- Amines break through products emissions
- SO_3 emissions
- Amines in flue gas – number of species and concentration levels.
- Pipeline leak detection
- Direct measurements of CO_2, post capture

CCUS measurement challenges

Chemical metrology

- CO_2 traceable Standards/Reference gas mixtures
  - Amines, NOx, SOx (ppm level)
  - Metals such as Hg and Cd (ppb level)
  - Dust
- Reliable analytical techniques for online measurement of impurities
- Need sampling protocols adapted to the operation constraints (P, T, flow rate, gas composition) with compatible materials
- Raw gas analysis

Physical properties

- Need data verified models to predict physical properties
- Thermodynamic state and gas properties after capture
- Equations of state, how will they be implemented in flow computers for fiscal metering?
- Accurate measurement and analysis of moister in CO_2

National Metrology Institute

Thank you for your attention

- Visit
  - www.metccus.eu
  - MetCCUS: Overview | LinkedIn

- Contact

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