CCSA Technical Forum

28/04/2025
13:30 (BST)
14:30 (CEST)

CCSA

Agenda

	Time (BST / CEST)	Topic	Speaker
1.	13:30 / 14:30	**Introduction & CCSA competition law policy notice**	Andy Brown, Co-chair
2.	13:35 / 14:35	**Overview** of Energy Institute CCUS Projects and how to get involved	Eva Leinwather (Energy Institute)
3.	13:45 / 14:45	**Presentation:** Energy Institute Good Practice Guidance on CO2 stream measurement of impurities	Andy Brown (Progressive Energy)
4.	14:15 / 15:15	**Demonstration:** Corrosion of carbon steel pipelines when transporting CO2 streams	Matt Healy (PaceCCS)
5.	14:40 / 15:40	**External Presentation:** CarbonX Programme – Funding opportunities and innovation for CCUS projects	CarbonX
6.	15:20 / 16:20	**Conclusions and AOB**	Andy Brown, Co-chair

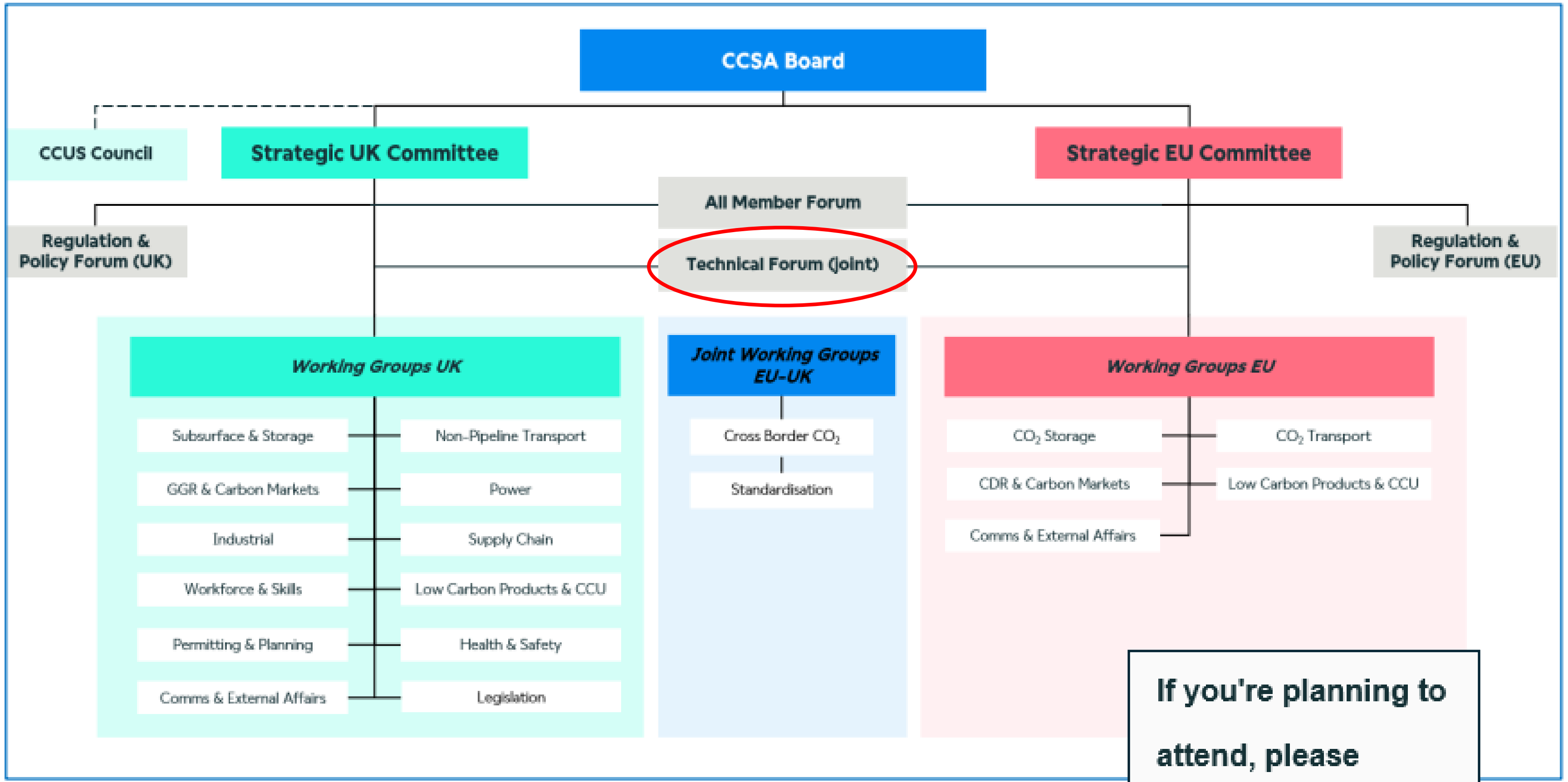
House keeping & Introductions

- Slides & Recording will be available for members after the meeting
- CCSA Competition Law Policy notice is attached to the meeting invite and available on the CCSA website
- If you are not speaking, please mute your microphone
- Please **raise your hand** if you wish to comment, you will be invited to come off of mute, if you can also turn on your camera
- Please also pose any **comments in the chat** and these will be picked up by the secretariat
- **Introductions** of any new members joining the call
- Approval of December minutes

CCSA Update

Technical Forum (joint UK & EU)

- To account for a growing number of workstreams, this Working Group has become an information-providing forum to enable technical knowledge exchange.
- This will be joint between the UK & EU.
- 3 x meetings per year to coincide with Parliamentary timetables.
- While this is now a forum, we still want to hear your views and welcome active participation and discussions!



If you're planning to attend, please download the iCal and accept the meeting invite 👇

Download the iCal

<u>We are changing the way we send CCSA Working Group & Forum email and invitations</u>, allowing members to opt in and out of meetings and distribution lists.

✓ Please ensure you **add the new additional domain to your safe sender list** in your email platform: email.ccsassociation.org

✓ Going forward we ask members to **download the iCal file from our emails and add it to your calendar.**

Overview of CCUS Projects and how to get involved

Eva Leinwather,
Energy Institute

CCSA

energy institute

Creating a better energy future

for our members and society
by accelerating a just global transition to net zero

Technical + Innovation programme

Technical + Innovation

energy institute

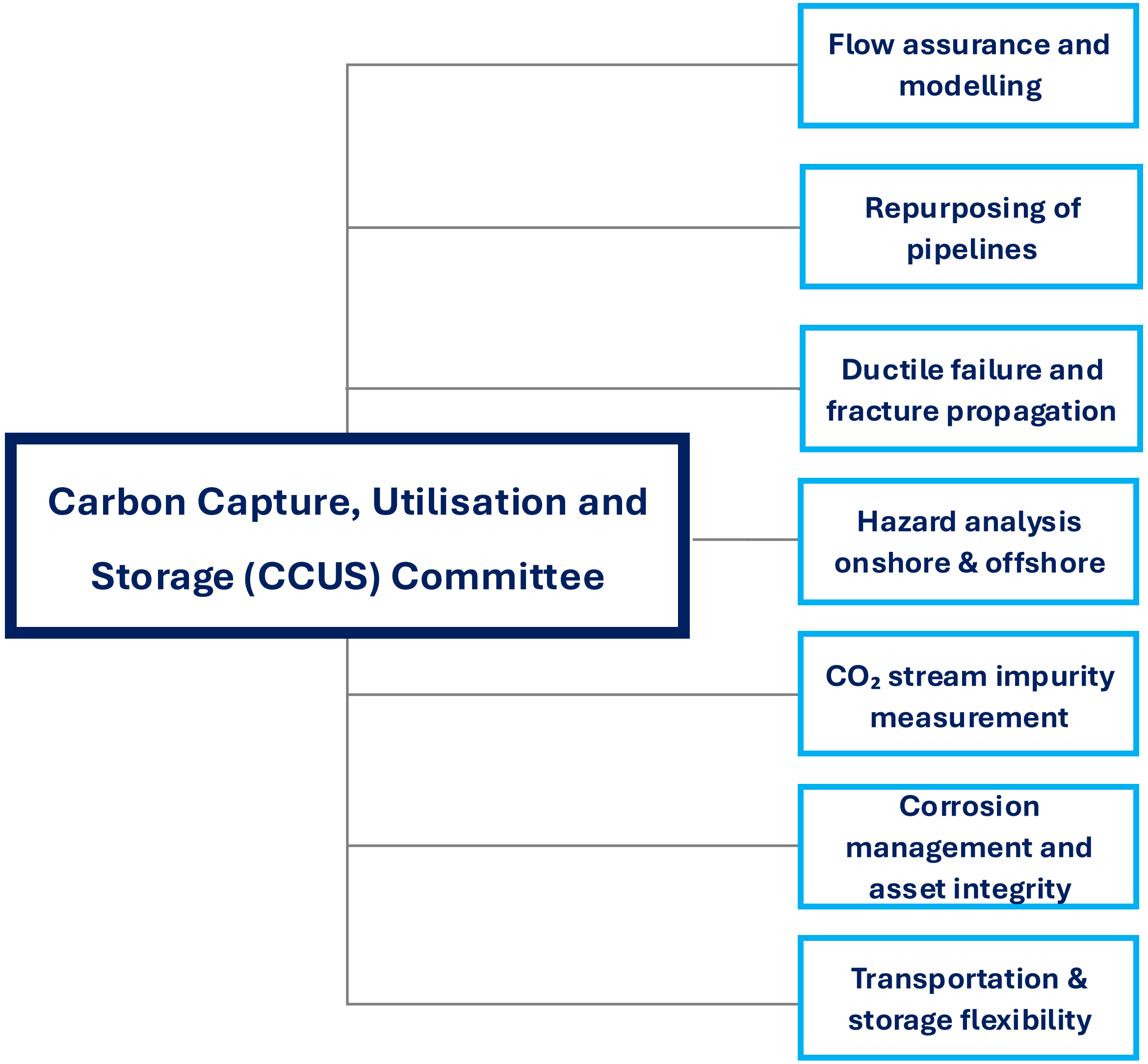
- The EI is the independent custodian of technical and innovation expertise for the global energy sector.
- Developing standards, good practice and authoritative, trusted guidance, strengthening the industry's licence to operate and its performance.
- Working across the breadth and depth of the global energy sector, from oil and gas to renewables, upstream to downstream.
- Helping to accelerate the energy transition through industry collaboration, dialogue with regulators, academia and wider stakeholders.

CCUS Committee

Technical + Innovation

energy institute

- The CCUS Committee oversees 7 working groups with total of 16 active projects
- Long-term objective is to provide guidance for all aspects of the CCUS value chain to equip developers, insurers, governments, universities and schools.
- Overarching CCUS Committee open to EI Technical member representatives and Working Group Chairs.
- Working Groups welcome new participants from EI Technical member and non-member organisations.



CCUS membership

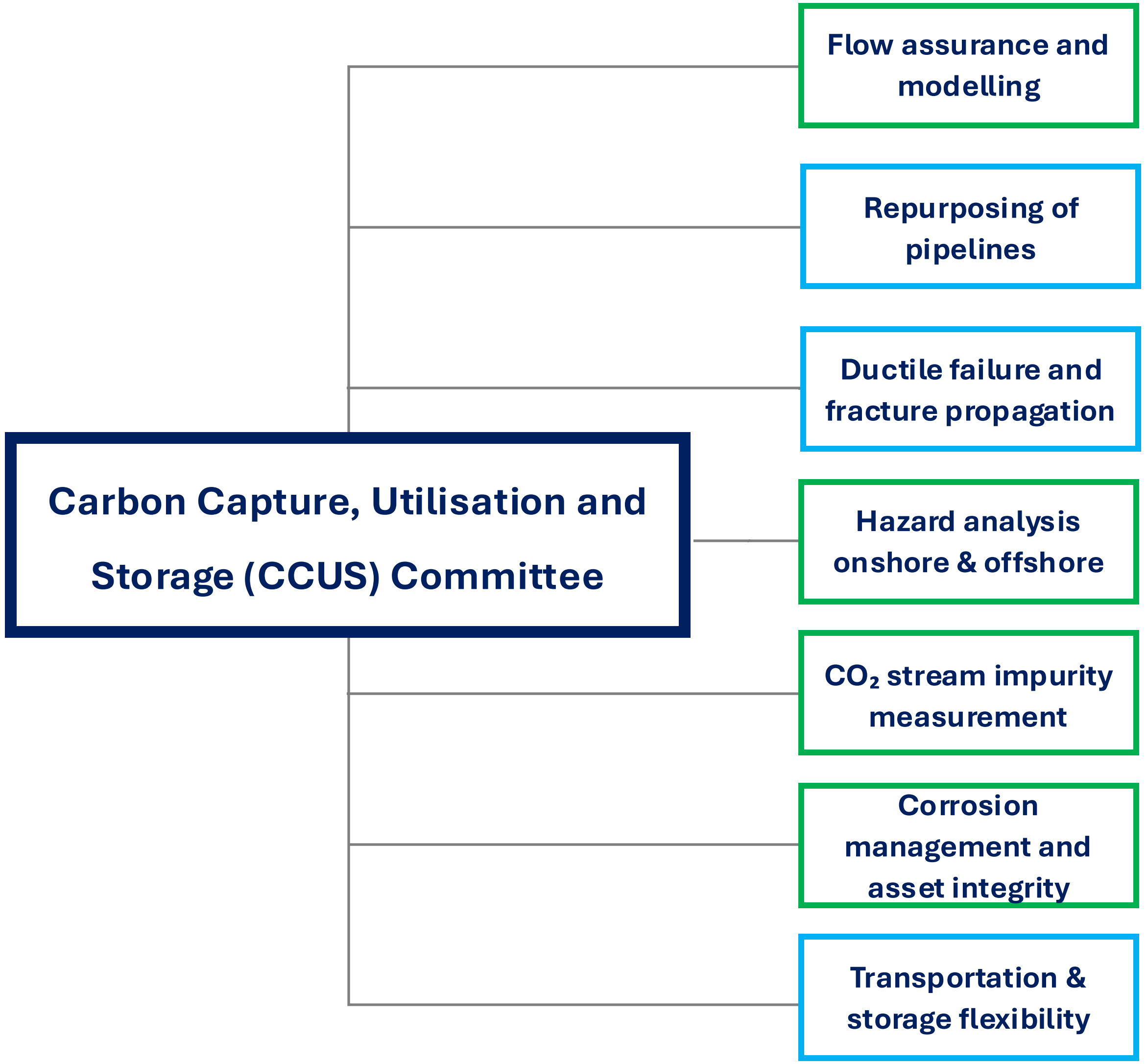
Technical + Innovation

energy institute

Progressive Energy	equinor	nationalgrid	PACE	MARSH	HSE Health & Safety Executive	Department for Energy Security & Net Zero
DNV	TECHNICAL COMMITTEES ISO/TC 265	CCSA	ipieca	Heriot Watt University	The University of Nottingham	The University Of Sheffield.
ABB	Advanced Resources International, Inc.	bp	Harbour Energy	CNOOC	drax	wood.
woodside	ExxonMobil	GENESIS	hydraulic analysis group	kent	NEPTUNE ENERGY	NPL National Physical Laboratory
PHILLIPS 66	RSSB	SAITH LIMITED	أرامكو السعودية saudi aramco	Shell	SPIRIT ENERGY	sse
STOREGGA	TÜV SÜD National Engineering Laboratory	uniper	vallourec			

Focus projects in 2025

Technical + Innovation
energy institute



- **Flow assurance and modelling WG:** Complete research project to validate EoS(s) at known thermodynamic properties (experimental data) of CO_2-rich mixture + thermodynamic modelling
- **Hazard analysis onshore & offshore WG:**
  - Publishing 3rd ed. guidance on hazard analysis for onshore and offshore CCS installations and pipelines
  - Setting up multi-year project on hazard identification and risk assessment for new and repurposed offshore structures used for CO_2 streams
- **CO_2 stream impurity measurement WG:** Publishing and promoting good plant design guide for measurement of impurities in a CO_2 stream for carbon capture and storage applications
- **Corrosion management and asset integrity WG:** Publishing literature review on material degradation and developing guidance on corrosion management and wider asset integrity for assets deploying CCuS

Further work programme items

Technical + Innovation energy institute

Other work programme topics also include:

- **Further work on equations of state for impure CO_2:** hold workshop and write guidance on good practice for design and operation of pipelines for CO_2 rich streams in multiphase flow
- **Develop training course for hazard analysis:** building training based on the hazard analysis for onshore and offshore CCS installations and pipelines document.
- **Non-pipeline transport hubs**: define potential hub scenarios, and then review their issues and risks at a high level
- **CO_2 transportation and storage flexibility:** UK clusters study to assess patterns, impacts, and limitations of flexible T&S operations
- **Subsea CO_2 storage:** form JIP to update outdated good practice guide on subsurface storage

How to get involved

Technical + Innovation energy institute

- If you are interested to join any of the EI CCUS Working Groups and/or contribute to specific projects, reach out to Eva Leinwather (eleinwather@energyinst.org)
- Visit the EI's website for more information on the Technical + Innovation programme and our membership options.
- Visit our publications website to access all EI technical publications.


energy institute
Thank you.
Questions?

Presentation:

Energy Institute Good Practice Guidance on CO_2 stream measurement of impurities

Andy Brown, Progressive Energy

CCSA

Energy Institute 'Good Practice Guidance on measurement of impurities in CO_2 streams.'

Presentation to the CCSA Technical Forum

Andy Brown, Progressive Energy

28th April 2025

Agenda

- Introduction
- Obtaining a CO_2 stream sample
- PRMs and CRMs
- Gas Analysis 1.01
- Measuring CO_2 stream impurities
- Gap analysis
- Further information

Introduction

- The purity of a CO_2 stream is set to minimise the potential for:
  - Corrosion of carbon steel components
  - Unwanted thermodynamic behaviour in the fluid
  - Severe mechanical effects
  - Downhole storage degradation

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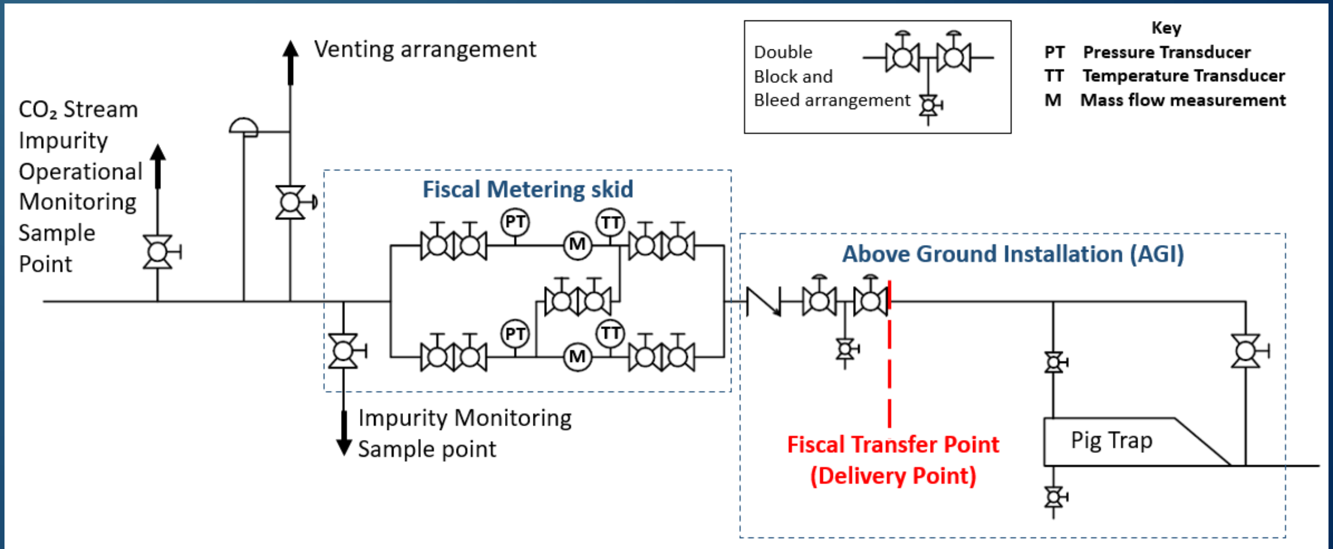

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- **PROBLEM!** It is not always possible to obtain equipment to measure impurities
  - At that level and .....
  - in a CO_2 environment (matrix)

ISO 27913:2024(en)

Table A.1 — Example of a gaseous phase CO_2 stream specification according to 6.6.2

Component	Concern(s) in a CCU context	Unit	Limit
CO_2	Asphyxiation and can act as a toxicant at high concentrations	mol%	>95,0
N_2 a	Enhances the potential for ductile fracture Occupies store pore space inefficiently	mol%	≤4,0
H_2 a, b, c	Enhances the potential for ductile fracture and hydrogen induced crack propagation Affects the size of the multi-phase zone	mol%	≤1,0
Ar a	Occupies store pore space inefficiently, enhanced potential for running ductile fractures	mol%	≤4,0
CO a	Health and safety: toxic gas	mol%	≤0,2
Methane a	Occupies store pore space inefficiently	mol%	≤4,0
Ethane a	Occupies store pore space inefficiently	mol%	≤4,0
Propane and other aliphatic hydrocarbons d	Liquid drop-out is possible	mol%	≤0,15 in total
H_2O	Enables corrosion of carbon steel	ppm mol	≤50
O_2 b, e	Enables oxidation of carbon steel Enhances bacterial growth in storage strata Other chemical reactions (e.g. with NO_x, SO_x, H_2S)	ppm mol	≤10
NO_x (NO, NO_2) f	Degradation of store caprock Takes place in the production of nitric and sulfuric acid	ppm mol	≤10
SO_x (SO, SO_2, SO_3) g	Degradation of store caprock Reactions with NO_2 can produce sulfuric acid	ppm mol	≤10
H_2S h	Health and safety: toxic gas with foul odour	ppm mol	≤5
COS	Health and safety: toxic gas with foul odour	ppm mol	≤100
CS_2	Health and safety: toxic gas with foul odour	ppm mol	≤20
NH_3	Can react to form solid ammonium carbamate and other ammonium salts	ppm mol	≤10
BTEX i	Health and safety: toxic	ppm mol	≤15 in total
Methanol	Can introduce a liquid corrosive phase	ppm mol	≤350
Solid particulates j, k	Can reduce store permeability Damage to compressor components	mg/Nm3	
Toxic metal j	Health and safety: toxic		
VOCs l	Health and safety: toxic		
Acid forming compounds m	Enabl...		
Amines n, o			
Glycol...			

Introduction

- The purity of a CO_2 stream is set to minimise the potential for:
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- **PROBLEM!** It is not always possible to obtain equipment to measure impurities
  - At that level and
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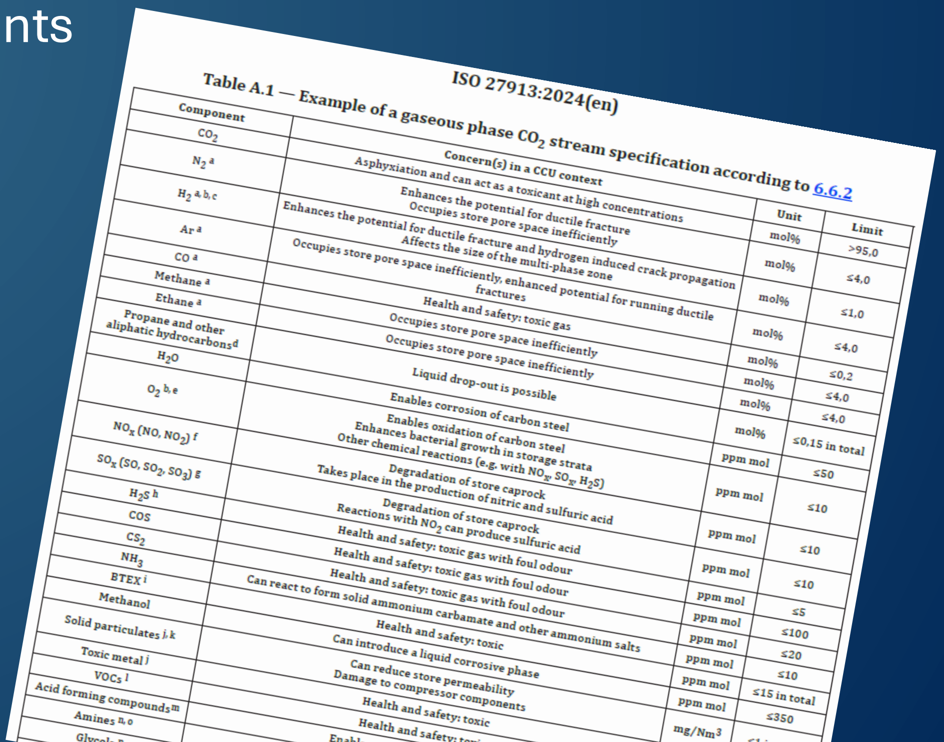
- So:
  - What is available now?
  - Where are the gaps?
  - What needs to be done?
  - What are the priorities?



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Propane and other aliphatic hydrocarbons [d]	Liquid drop-out is possible	mol%	≤0,15 in total
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H_2S [h]	Health and safety: toxic gas with foul odour	ppm mol	≤5
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CS_2	Health and safety: toxic gas with foul odour	ppm mol	≤20
NH_3	Can react to form solid ammonium carbamate and other ammonium salts	ppm mol	≤10
BTEX [i]	Health and safety: toxic	ppm mol	≤15 in total
Methanol	Can introduce a liquid corrosive phase	ppm mol	≤350
Solid particulates [j, k]	Can reduce store permeability Damage to compressor components	mg/Nm³	[illegible]
Toxic metal [j]	Health and safety: toxic	[illegible]	[illegible]
VOCs [l]	Health and safety: [illegible]	[illegible]	[illegible]
Acid forming compounds [m]	Enabl[illegible]	[illegible]	[illegible]
Amines [n, o]	[illegible]	[illegible]	[illegible]
Glycols [illegible]	[illegible]	[illegible]	[illegible]

Obtaining a CO_2 stream sample

- Off-line (indirect, grab, spot)
  - Used extensively in the industrial gasses area
  - Sample sent off-site to a laboratory for analysis
  - Often requires specialist staff
  - High accuracy, low LOD is possible
  - Results usually available within a few days

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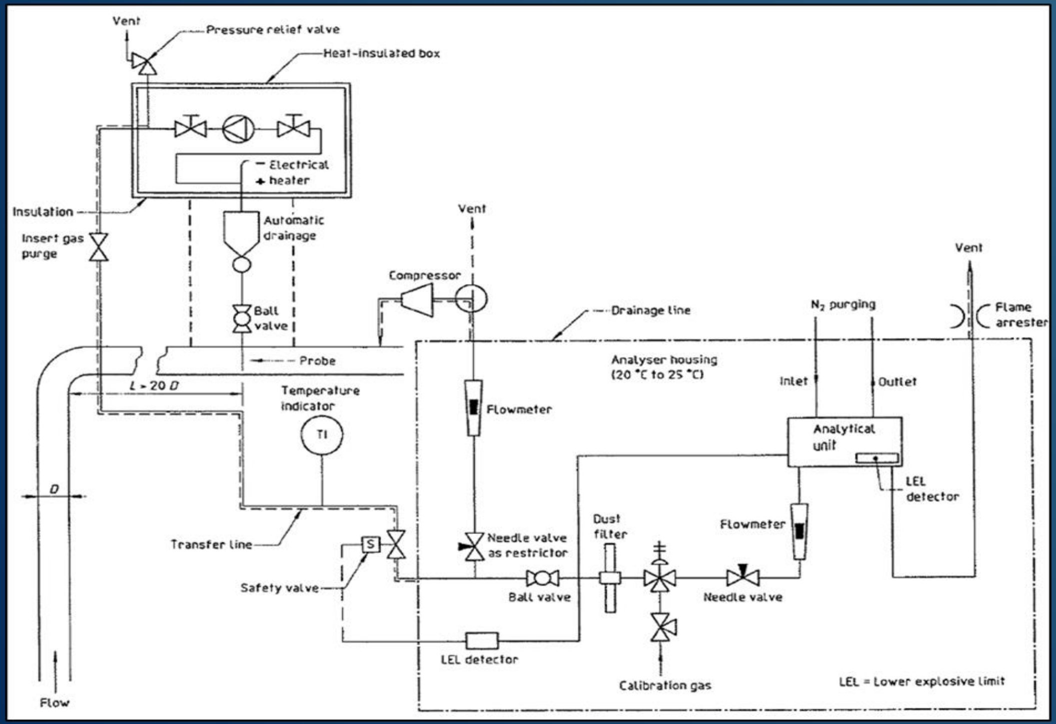
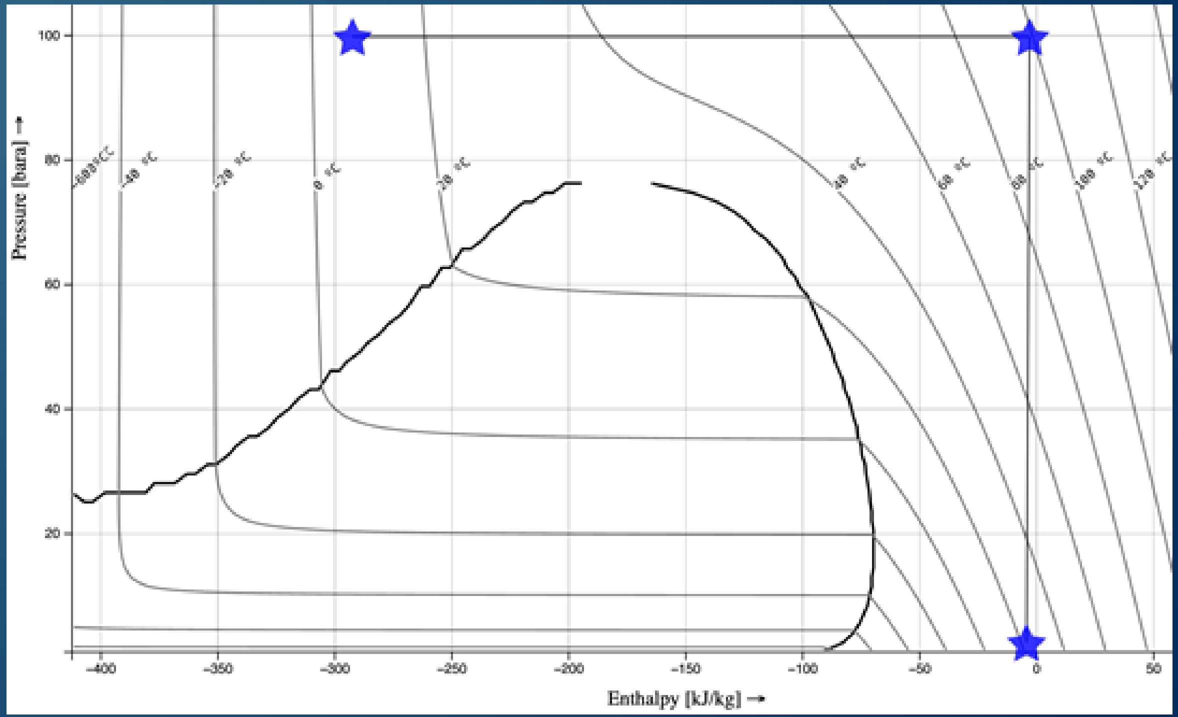
  - Results usually available within a few days
- On-line (in-situ, insertion, passive)
  - Requires a constant sample
  - Rapid analysis is necessary -
  - Results available in real time
  - May require a compromise between accuracy/repeatability/LOD
- Extractive sampling
  - Gas analysis is at low pressure
    - Potential for drop-out
    - Phase changes
    - J-T effects

Obtaining a CO_2 stream sample

- Extractive sampling
  - Gas analysis is at low pressure
    - Potential for drop-out
    - Phase changes
    - J-T effects

Requires **Sample Conditioning:**



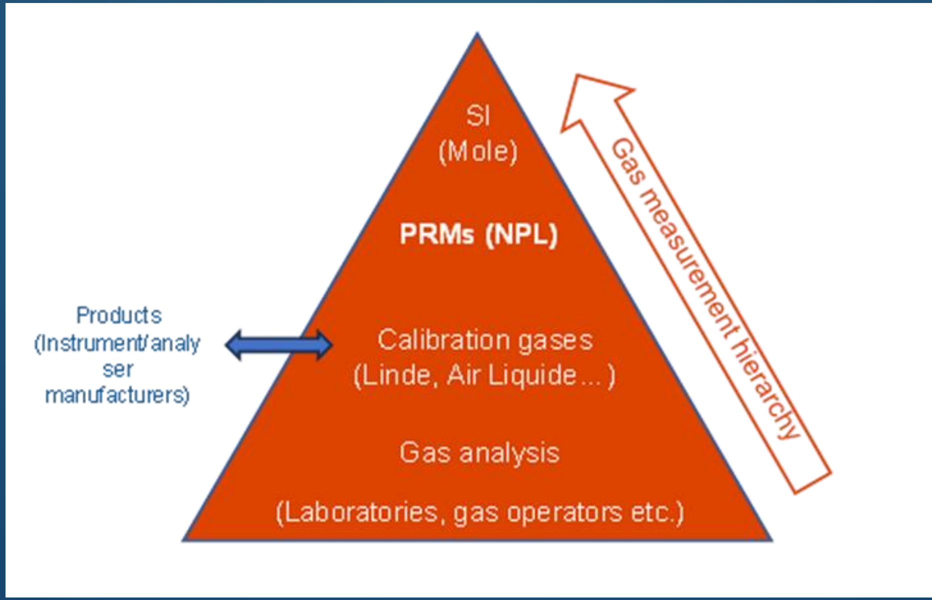


PRMs and CRMs

- Primary Reference Materials (PRMs)
  - Underpins measurement standards -traceable to SI.
  - Used to:
    - Develop analytical methods
    - Calibrate measurement equipment
    - Validate results obtained providing traceability
    - Not normally used on site
    - Held by a country's national metrology institute, NPL in the UK or NIST in the USA
- Certified Reference Materials (CRMs)
  - Developed from PRMs: without the availability of PRMs, CRMs cannot be certified.
  - Denotes authenticated traceability
  - Valid for specific period (depending on the of stability of the components).
- Use in gas analysis
  - Typically calibrated or verified using gas mixtures that may contain single (or multiple) components in a representative matrix (CO_2 in this application), described as 'the certified reference mixture or multiple components in representative concentrations (the working reference mixture)'.

PRMs and CRMs

- Availability of PRMs
  - **Available now** for: COS, H_2, H_2O, H_2S, MeOH, O_2, (Hg).
  - **Could be available** once the lower end of the range has been extended for : Ar, BTEX, CO, CH_4, C_2H_6, C_3H_8 and other aliphatic HC's, CO, N_2, acid-forming compounds, amines, glycols, naphthalene.
  - **Do not exist** for an impurity in a CO_2 matrix for: Cl_2, CS_2, NH_3, VOCs, nitrosamine, nitramine, dioxins and furans.
- Do not exist for dense phase (noting that gas analysers normally operate >≈2barg).



Gas analysis 1.01

Some methods of gas analysis:

- **Chemical Absorption:** Uses reagents selectively to absorb specific gases (e.g., CO_2, O_2).
- **Infrared (IR) Spectroscopy**: Measures gas concentrations by detecting how gases absorb IR radiation at specific wavelengths.
- **Gas Chromatography (GC)**: Separates and quantifies gases within complex mixtures, often with high accuracy.
- **Mass Spectrometry (MS)**: Analyses gases by identifying molecules based on their mass-to-charge ratios.
- **Electrochemical Sensors**: Use electrodes and electrolytes to produce current in response to target gases like CO or O_2.
- **Thermal Conductivity Detectors (TCD)**: Compare thermal conductivity of a sample gas against a reference to detect changes.
- **Photoionisation Detectors (PID)**: Ionise gases using ultraviolet light and measure the resulting current—ideal for VOCs.
- **Differential Optical Absorbtion Spectroscopy (DOAS)** measures the absorption spectra of multiple atmospheric species at once, and can separate the absorption of different species from the scattering of light by aerosols and molecules

Gas analysis 1.01

Choosing the most appropriate analyser

- **Calibration against PRM/CRM**
- **Ensuring that it has been calibrated in a representative matrix**
- **Combination of LOD, accuracy, repeatability, speed, and cost**
  - May require two analysers operating in anti-phase
  - One analyser may be capable of measuring multiple impurities
  - The presence of some impurities mask the ability of the equipment to read accurately another impurity ("interference")

Measuring CO_2 stream impurities

	AAS	AFS (QF)	EGA	FPD	FTIR	FTIR+DTGS	DOAS	GC +	HPLC	HPLC(DNPH)	HPLC-FLD	HPLC-RI	IC	ICP-MS	IMS	IR/UV	MS	NDIR	NDUV	OA-ICOS	OFCEAS	PID	QCL	TDLAS	UV/IR	XRF
CO_2																				1						
Acid-forming compounds			?		?2	?3	4						?5													
Amines					?9		?6	?7	?5				?5		?7		?7									
Ammonia					?8	?8		?8															?8		?8	
Argon								9																		
BTEX					?	?		?									?11									
Cadmium																										
Carbon Disulphide						?																				
Carbon Monoxide						?		?										?					?		?	
Carbonyl Sulphate																										
Dioxins								?5									?5									
Ethane								?									?	?					?		?	
Furans								?5									?5									
Glycols								?5				?5					?5									
Hydrogen																										
Hydrogen Sulphide																				1						
Mercury																										
Methane					?	?		?									?	?					?		?	
Methanol																										
Naphthalene											5															
Nitramines & Nitrosamines								?5									?5									
Nitrogen								?																		
Nitric Oxide					?	?										?		?	?		?		?			
Nitrogen Dioxide					?	?		?								?		?	?		?		?			
Oxygen		?																		1	?				?	
Propane & Aliphatic HC's					?			?									?9									
SOx (SO, SO_2, SO_3)					12		12	?								?		?	?		?		?			
Volatile Organic Compounds					?	14		15		13							5					14				
Water																				1						

29 impurities
26 techniques

Gap analysis

- Preparation of full suite of accurate and traceable PRMs
- Development accurate and fit for the purpose analytical methods
- Stability study of PRMs with various material types
- Testing and validation of analysers (on-line)
- Development of accurate sampling techniques
- Development of Standards against which to calibrate equipment

Gap analysis

- Priorities:
  - Amines
  - Carbon monoxide
  - Glycols
  - Hydrogen
  - Hydrogen sulphide
  - Nitrogen oxides, NOx (importantly NO_2)
  - Non-condensibles in total (Ar, CH_4, CO, H_2, O_2, N_2)
  - Oxygen
  - Sulphur oxides, SOx (importantly SO_2 and possibly SO_3)
- Timescales
  - To meet Track 1 project requirements

Thank You

Andy Brown

andy.brown@progressive-energy.com

www.progressive-energy.com

Further information

- Full report "Good Plant Design for CO_2 stream impurity measurement" is available from the Energy Institute's web site.
- Webinar 12th June 13.00 – 14.00 with technical input from
  - Manohara Veerabhadrappa, NPL
  - Godert de Keizer, KPSNL


Good Practice for the measurement of impurities in CO_2 streams in CCS applications

GOOD PLANT DESIGN FOR CO_2 STREAM IMPURITY MEASUREMENT

First Edition

April 2025

Published by
ENERGY INSTITUTE, LONDON

Presentation:

Corrosion of carbon steel pipelines when transporting CO2 streams

Matt Healy, PaceCCS

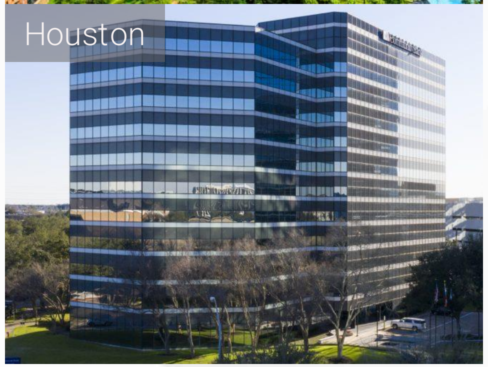
CCSA

PACECCS

CCSA Corrosion discussion

28 April 2025

Pace CCS



Pace CCS is the global leader delivering engineering solutions for CCS design.

- design for more than 120 CCS projects worldwide
- unparalleled expertise and experience.

Multidiscipline engineering design for CCS

- Pre-FEED and FEED design for CCS
- Independent CCS design review and risk assessment
- CCS training course
- New solutions for a new industry

Pace CCS Corrosion Solution software

- Bulk VLE for CO_2 mixtures: a new thermodynamic model (Pace CCS)
- Water & polar impurity behaviour: a new thermodynamic model (Pace CCS)
- Chemical reactions in CO_2: a new pathway model (Pace CCS – Oxford University)

- A new chemical scavenging solution to prevent corrosion from strong acids in CCS industrial hubs (Pace CCS – Foxconn)

Pace CCS: global footprint

CCS: project experience with corrosion risk

Gorgon CCS project

4 MTPA CCS at inlet to an LNG plant

Startup planned 2015, 2-year delay & continuing operation problems at about 50% of capacity

Engineering contractor did not understand corrosion risk for CCS.

Moomba CCS project

1.7 MTPA, central Australia, start-up September 2024.

Major modifications required before start-up due to unaddressed corrosion risk during commissioning and normal operation.

Engineering contractor did not understand corrosion risk for CCS.

CCS: project experience with corrosion risk

ADM CCS Well Leak

Pilot project abandoned due to corrosion.

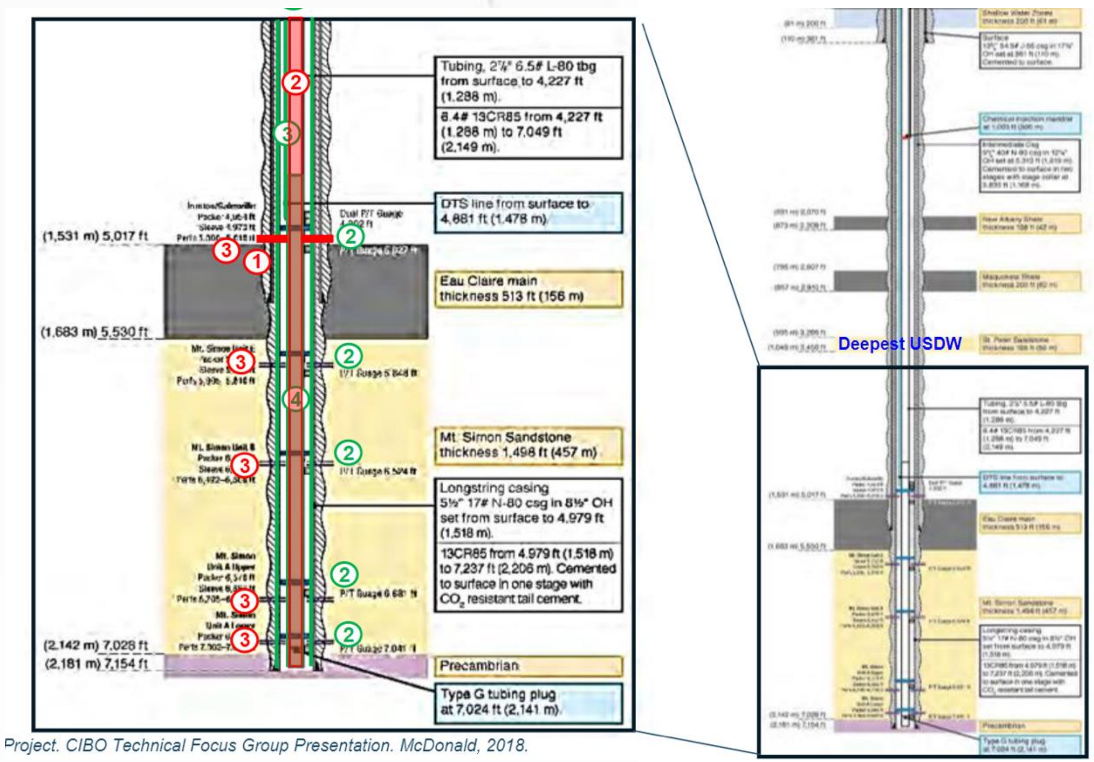
Pace CCS view:

Basis of design for well materials was incorrect.

- Cr13/SCr13 chosen for CCS downhole tubing
- Corrosion due to chloride (in reservoir water) plus trace O_2 (from the CO_2)
- No issues expected with recommended material choice: 6Mo super austenitic steel.

ADM Suspends CO2 Injections Following Second Leak

by Violet George · October 3, 2024 · 2 minute read



Project. CIBO Technical Focus Group Presentation. McDonald, 2018.

Type of Impurities

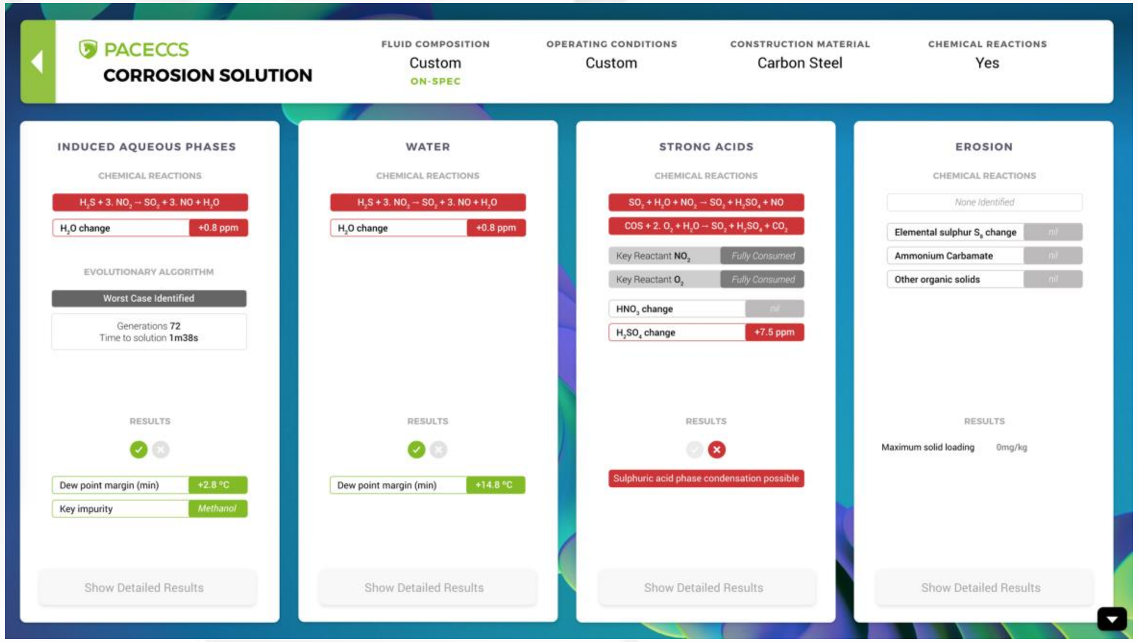
Impurity	Potential Sources of Impurity
CO_2	All
H2O	Product of combustion
N_2	Presence due to air for combustion
H_2	Byproduct of pre combustion capture
Ar	Presence due to air for combustion
O_2	Byproduct of incomplete combustion
CO	Byproduct of incomplete combustion
CH_4	Presence due to fuel / process fluid for combustion
C_2	Natural Gas and Syngas processing
C_3+	Natural Gas and Syngas processing
Other Aliphatic Hydrocarbons	Natural Gas and Syngas processing
NOx	Byproduct of combustion
SOx	Byproduct of combustion
H_2S	Pre-Combustion Coal & IGCC Fired Power Plants, Natural Gas and Syngas processing
COS	Pre-Combustion Coal Fired Power Plants, Syngas processing
NH_3	Post-Combustion Coal & IGCC Fired Power Plants
Amines (MEA, MDEA, DEA, AMP, piperazine)	Amine based absorption of CO_2, Pre-combustion
BTEX	Pulverised Coal Power Plants
Methanol	Pre-Combustion Coal & IGCC Fired Power Plants
Ash/Dust	Cement & Lime Kilns, Post Combustion Power Plants
Na	Lime Kilns
K	Lime Kilns
Mg	Pre & Post Combustion IGCC Fired Power Plants, Waste Incinerators
Cr	Waste Incinerators
Ni	Pre & Post Combustion IGCC Fired Power Plants, Waste Incinerators

Impurity	Potential Sources of Impurity
Cd	Waste Incinerators
Hg	Pre & Post Combustion Coal, IGCC Power Plants, Refinery Stacks and Cement Kilns, Waste Incinerators
Tl	Waste Incinerators
Pb	Pre & Post Combustion IGCC Fired Power Plants, Waste Incinerators
As	Pre & Post Combustion Coal, IGCC Power Plants, Refinery Stacks and Cement Kilns, Waste Incinerators
Se	Pre & Post Combustion Coal, IGCC Power Plants, Refinery Stacks and Cement Kilns, Waste Incinerators
Napthalene	Pre & Post Combustion IGCC Fired Power Plants
VOCs	Waste Incinerators, degradation products
Formaldehyde	Biomass Power Plants
Acetaldehyde	Biomass Power Plants
Dimethyl Sulfide	Biomass Power Plants
Ethanol	Biomass power plants
Cl_2	Pulverised Coal, Refineries, Cement, Lime and Coke
HCl	Biomass Power Plants, Waste Incinerators, Pulverised Coal, Refineries, Cement, Lime and Coke
HF	Biomass Power Plants, Waste Incinerators, Cement and Lime Kilns
HCN	Natural Gas and Syngas processing
Glycol (TEG/DEG/MEG)	Glycols based dehydration of CO2
Dioxins and Furans (PCDD/PCDF)	Cement, Waste Incinerators
selexol (Polyethylene glycol dimethyl ether)	Pre-combustion solvent
Nitrosamines and Nitramines	degradation products from amines

Pace CCS Corrosion Solution software

Comprehensive review of all corrosion risks for CCS

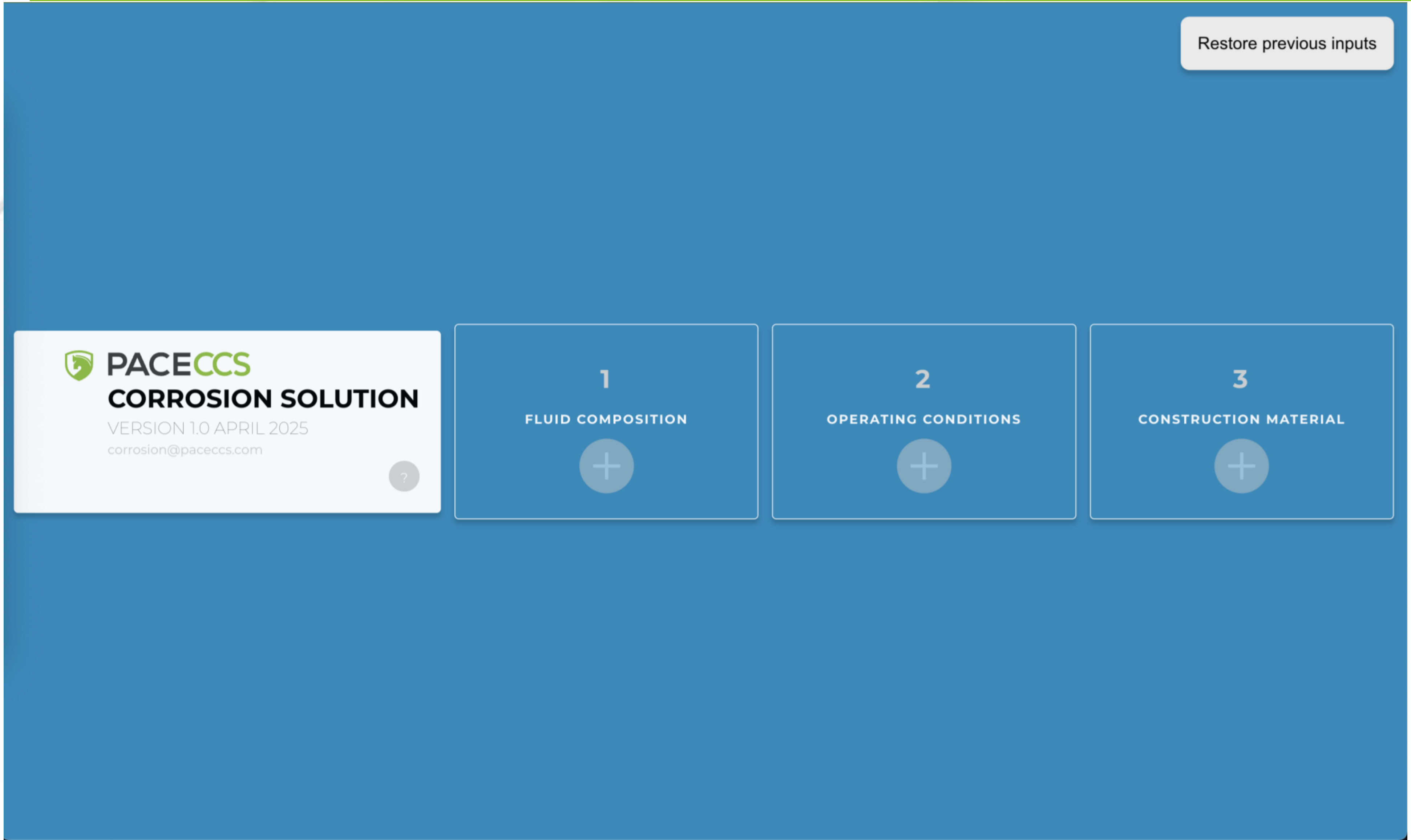
- Sulphuric acid & nitric acid
- Water condensation
- Induced aqueous phases
- Erosion from organic salts & elemental sulphur



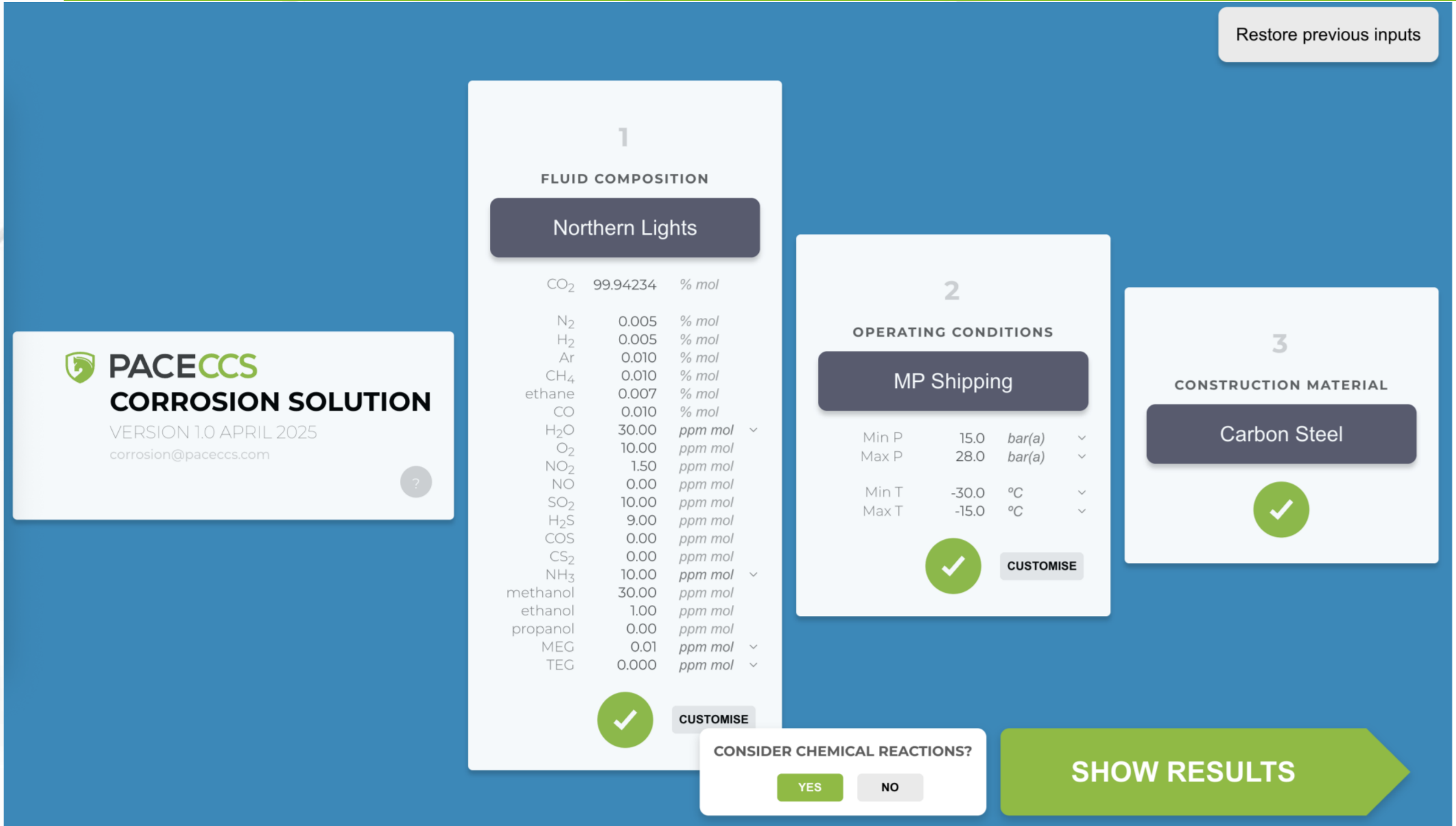
Complete technical basis

- Pace CCS polar and non-polar CCS thermodynamic model
- Laboratory testing to improve predictions of aqueous phase composition and solubility in CO_2 (Germany, France)
- Comprehensive database of all likely and possible chemical reaction pathways (with Oxford University)
- Laboratory testing to improve understanding of chemical reaction pathways (Taiwan)
- Acid solubility predictions as per IFE
- Evolutionary algorithm to predict worst case induced aqueous phase risk
- Secure web-based software app deployment

paceccs.com/corrosion



paceccs.com/corrosion



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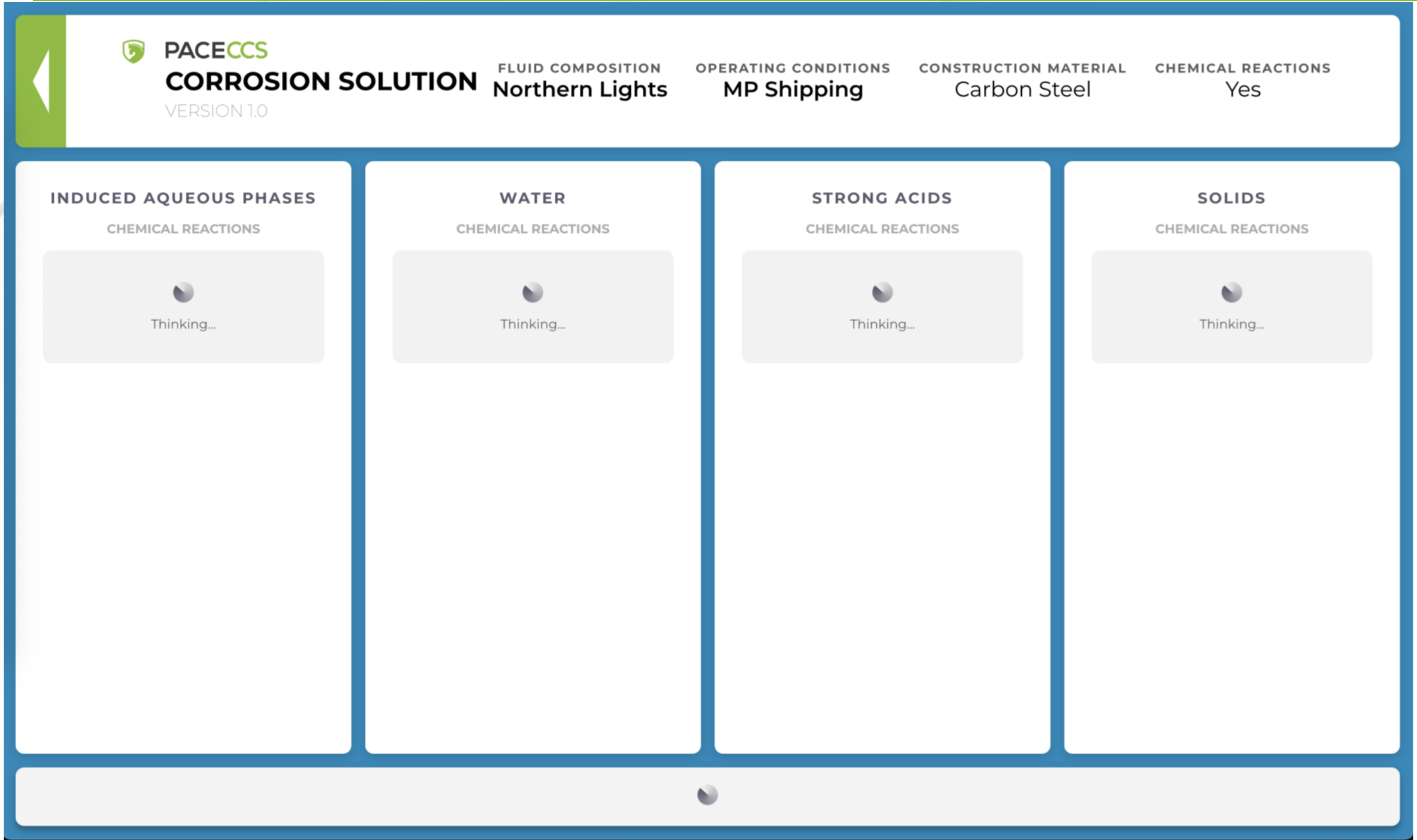


paceccs.com/corrosion

INDUCED AQUEOUS PHASES

CHEMICAL REACTIONS

2. $H_2S + O_2$	→	2. H_2O + 2. S

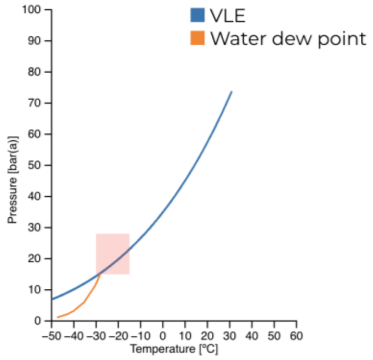
EVOLUTIONARY ALGORITHM

Worst Case Identified

Generations **209**
Time to solution **7m10s**

WORST CASE COMPOSITION WITH REACTIONS

PHASE ENVELOPE



RESULTS

>10 % mol water fraction found in aqueous phase

Key Impurity	MEG
Risk of corrosion	YES

WATER

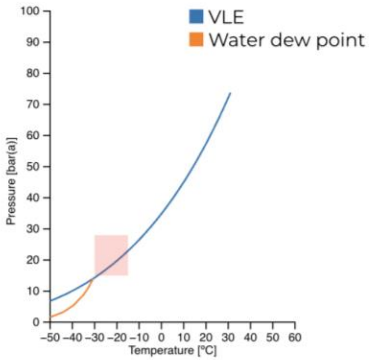
CHEMICAL REACTIONS

2. $H_2S + O_2$	→	2. H_2O + 2. S

WORST CASE COMPOSITION AFTER REACTIONS

	Final	Change	
CO_2	99.9423495		% mol
H_2O	39.00	+9.00	ppm mol

PHASE ENVELOPE



RESULTS

Risk of corrosion	NO

STRONG ACIDS

CHEMICAL REACTIONS

$SO_2 + NO_2 + H_2O$	→	H_2SO_4 + NO
2. NO + O_2	→	2. NO_2
H_2S + 2. NO_2 + O_2	→	H_2SO_4 + 2. NO
H_2S + 2. NO_2	→	H_2SO_4 + N_2

WORST CASE COMPOSITION

	Final	Change	
CO_2	99.9423495		% mol
N_2	0.005	+TRACE	% mol
H_2	0.005		% mol
Ar	0.010		% mol
CH_4	0.010		% mol
ethane	0.007		% mol
CO	0.010		% mol
H_2O	20.00	-10.00	ppm m
O_2	0.00	-10.00	ppm m
NO_2	0.00	-1.50	ppm m
NO	1.00	+1.00	ppm m
SO_2	0.00	-10.00	ppm m
H_2S	6.00	-3.00	ppm m
COS	0.00		ppm m
CS_2	0.00		ppm m
NH_3	10.00		ppm m
methanol	30.00		ppm m
ethanol	1.00		ppm m
propanol	0.00		ppm m
MEG	0.01		ppm m
TEG	0.000		ppm m
H_2SO_4	13.00	+13.00	ppm m
HNO_3	0.00		ppm m

RESULTS

Sulfuric acid phase condensation possible	YES
Nitric acid formation possible	NO

Risk of corrosion

SOLIDS

CHEMICAL REACTIONS

CO_2 + 2. NH_3	→	$[NH_4]NH_2CO_2$
2. $H_2S + O_2$	→	2. H_2O + 2. S

COMPOSITION

$[NH_4]NH_2CO_2$	8.9	mg/kg
S	6.6	mg/kg

RESULTS

Solid formation possible	YES

Scavenging to prevent chemical reactions

Chemical scavengers can be added to a CCS fluid via chemical injection.

A CCS chemical scavenger injection skid would include:

- measurement of impurities via gas chromatography or similar method
- injection of chemical scavenger from a storage tank into CCS pipeline
- application of mature technology in the semiconductor industry

Current status:

- Pace CCS – Foxconn partnership
- Feasibility study complete and successful
- Proof of Concept underway
- Laboratory under construction (Taiwan)

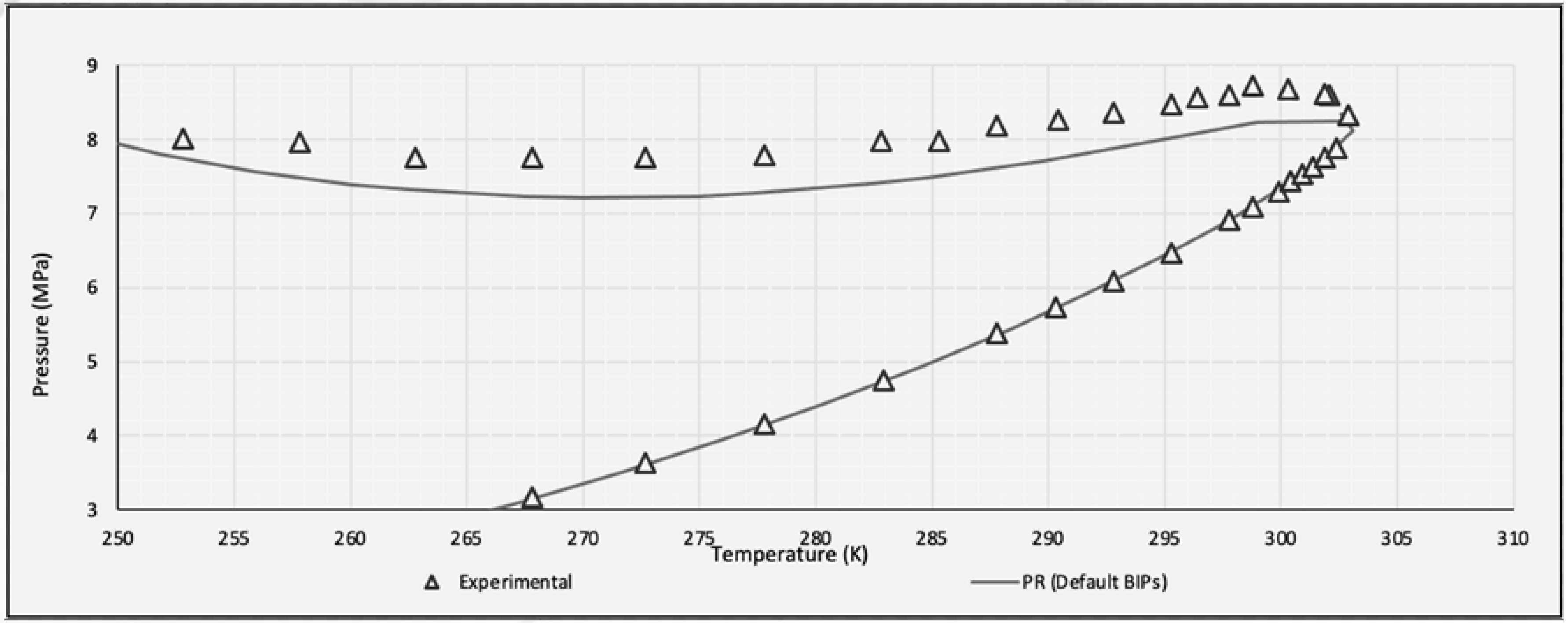
PACECCS

Thank You

Matt Healey
matt@paceccs.com

Bulk VLE – data sources

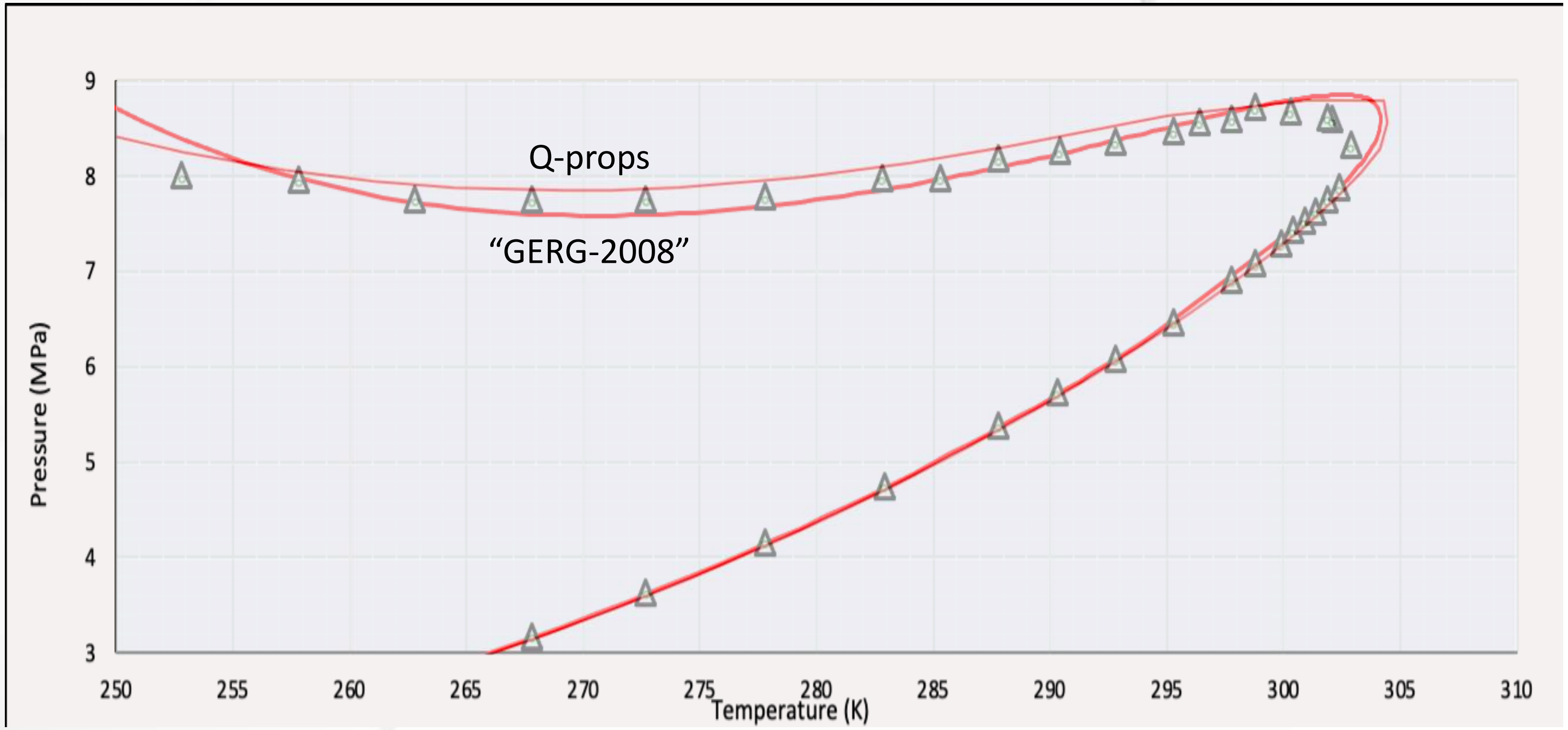
Public domain data of CO2 with impurities.



Bulk VLE – data sources

Synthetic data of CO2 with impurities, Q-Props method

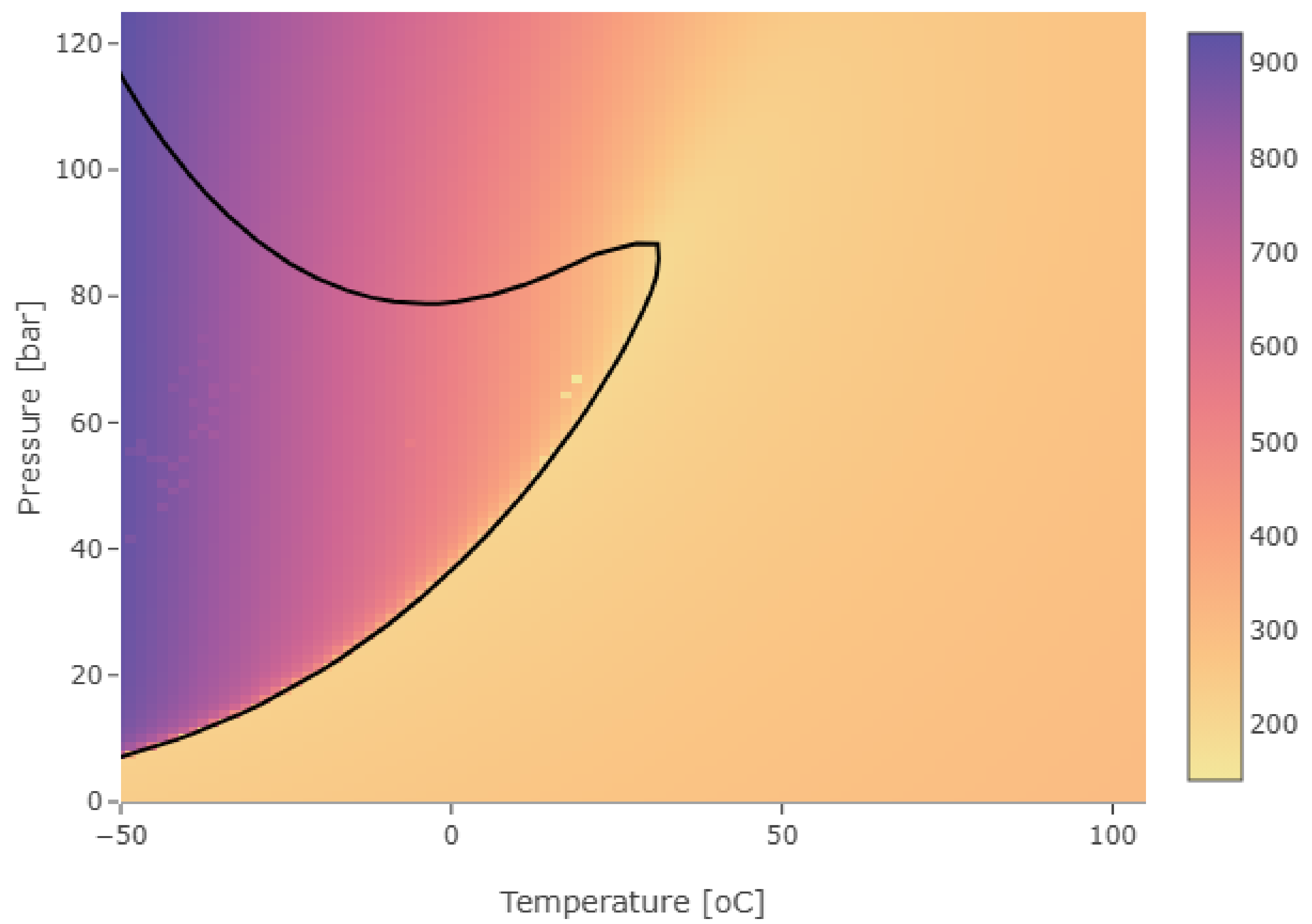
State-of-the-art models such as quantum chemistry and molecular simulation in a fully automated, intelligent and transparent way.



Bulk VLE – data sources

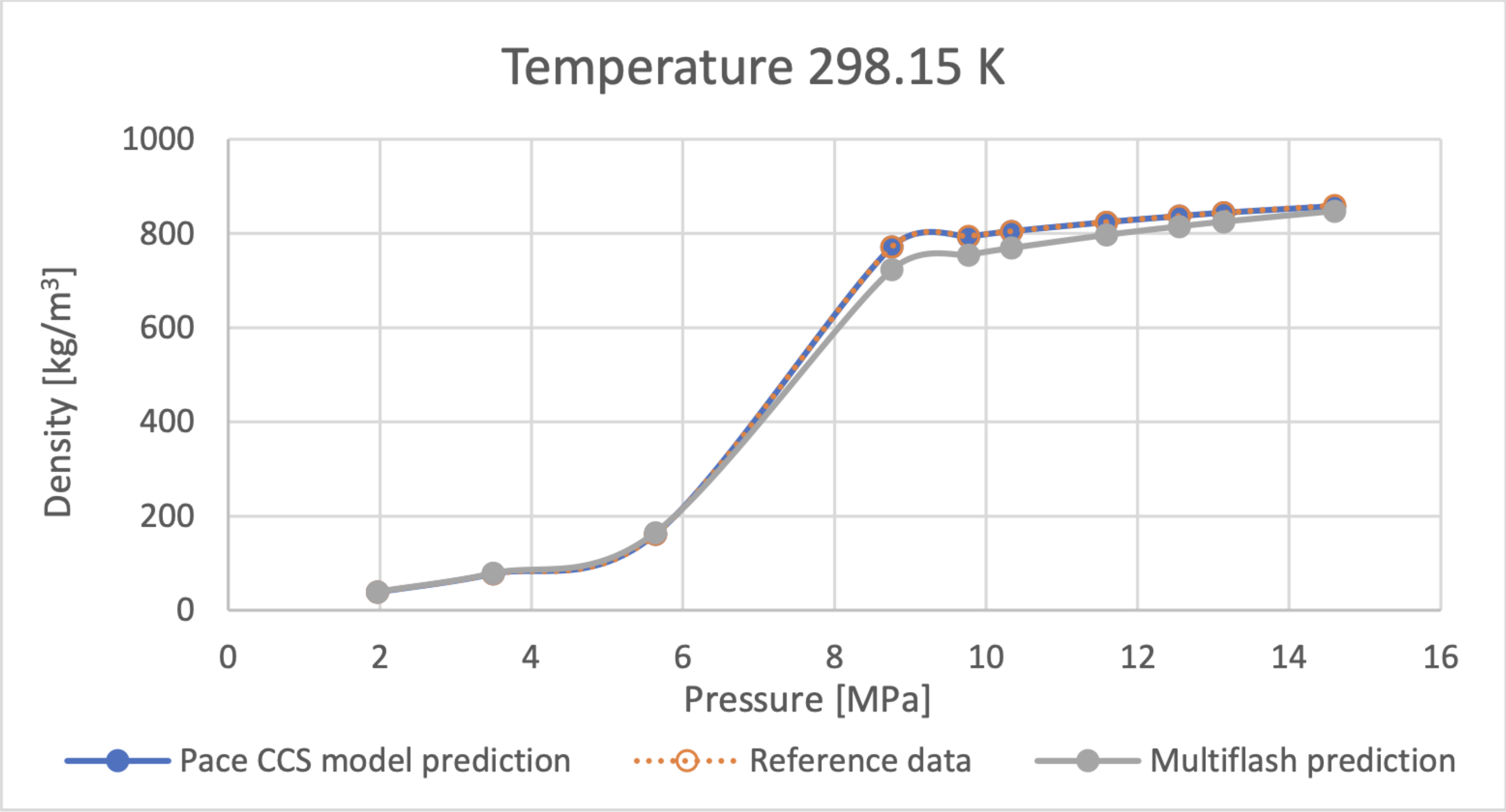
Synthetic data of CO2 with impurities, Q-Props method

(Speed of sound)



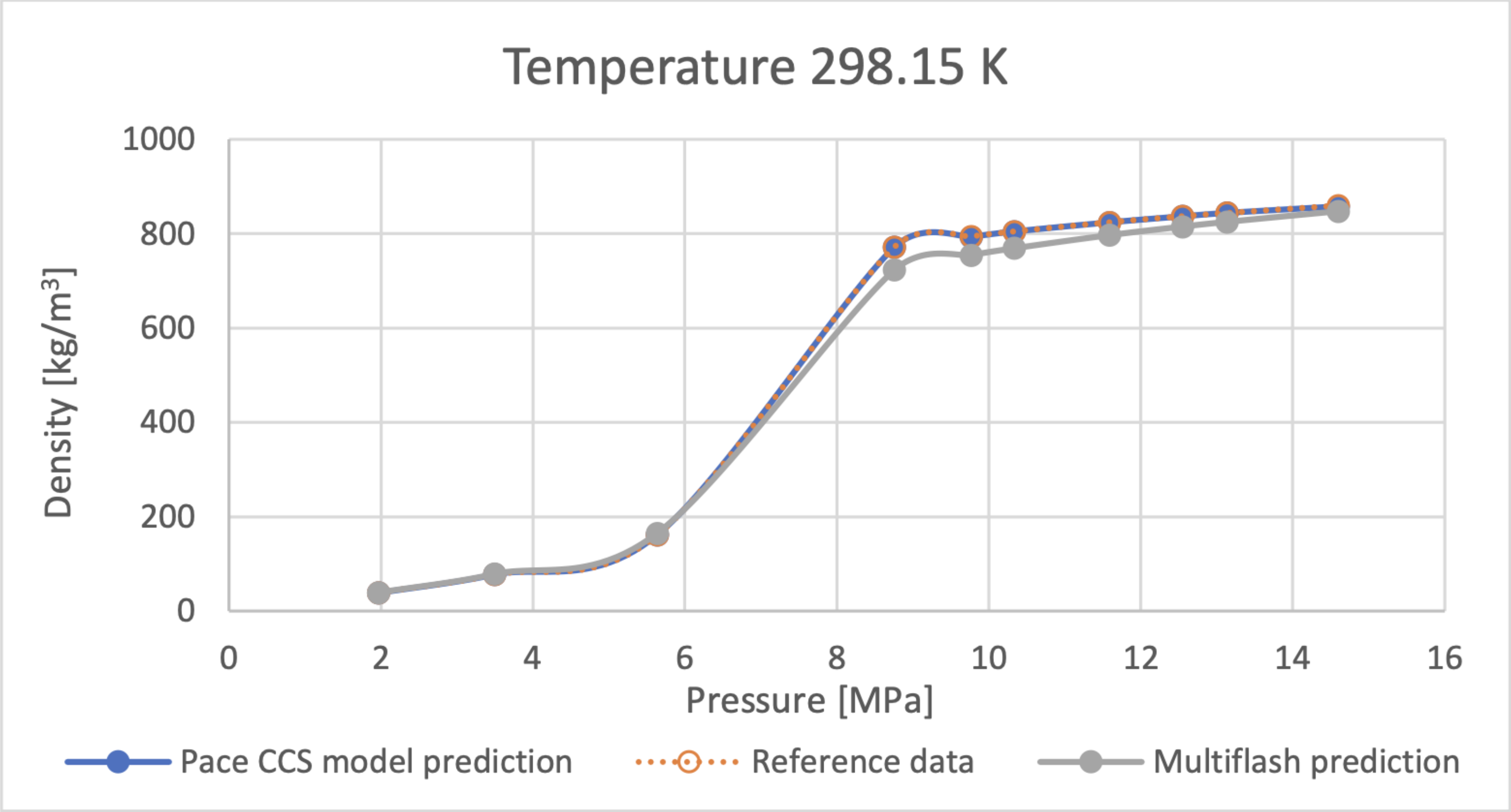
Bulk VLE – benchmarking

With 1% N2



Bulk VLE – benchmarking

With 1% H2



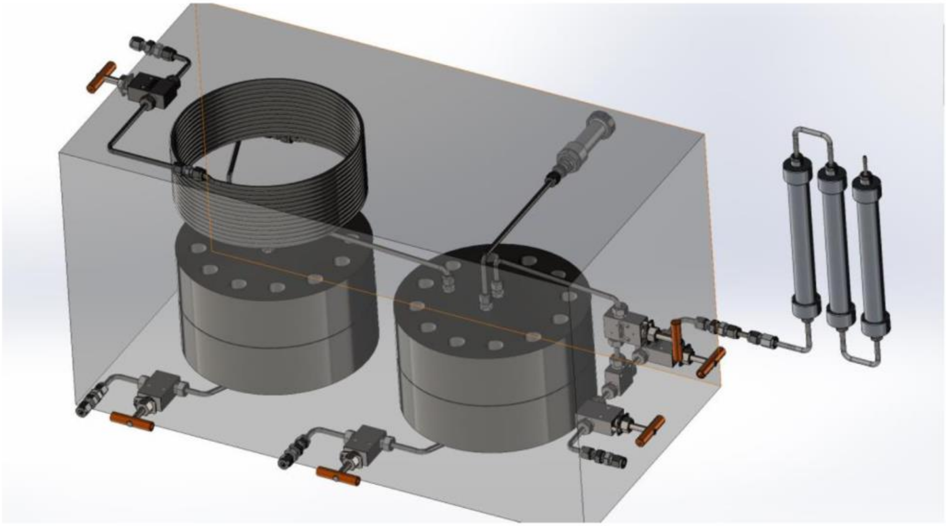
Water VLE – data sources

Laboratory testing to improve predictions of aqueous phase dewpoint and composition, with alcohols & glycols present.

- Saturation of CO_2 gas with TEG/Methanol/Water using HPHT Saturation Unit

- Specifications
  - Pressure: from 1 to 700 bar
  - Temperature: from -20 to 200 °C

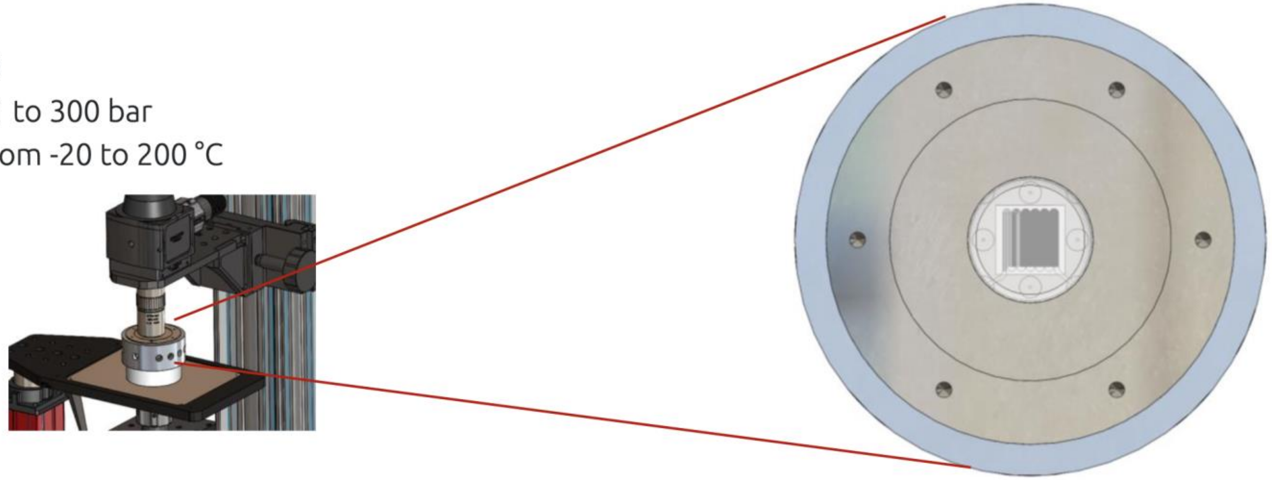
- Accuracy
  - Pressure: +/- 0.1% FS
  - Temperature: +/- 0.1 K



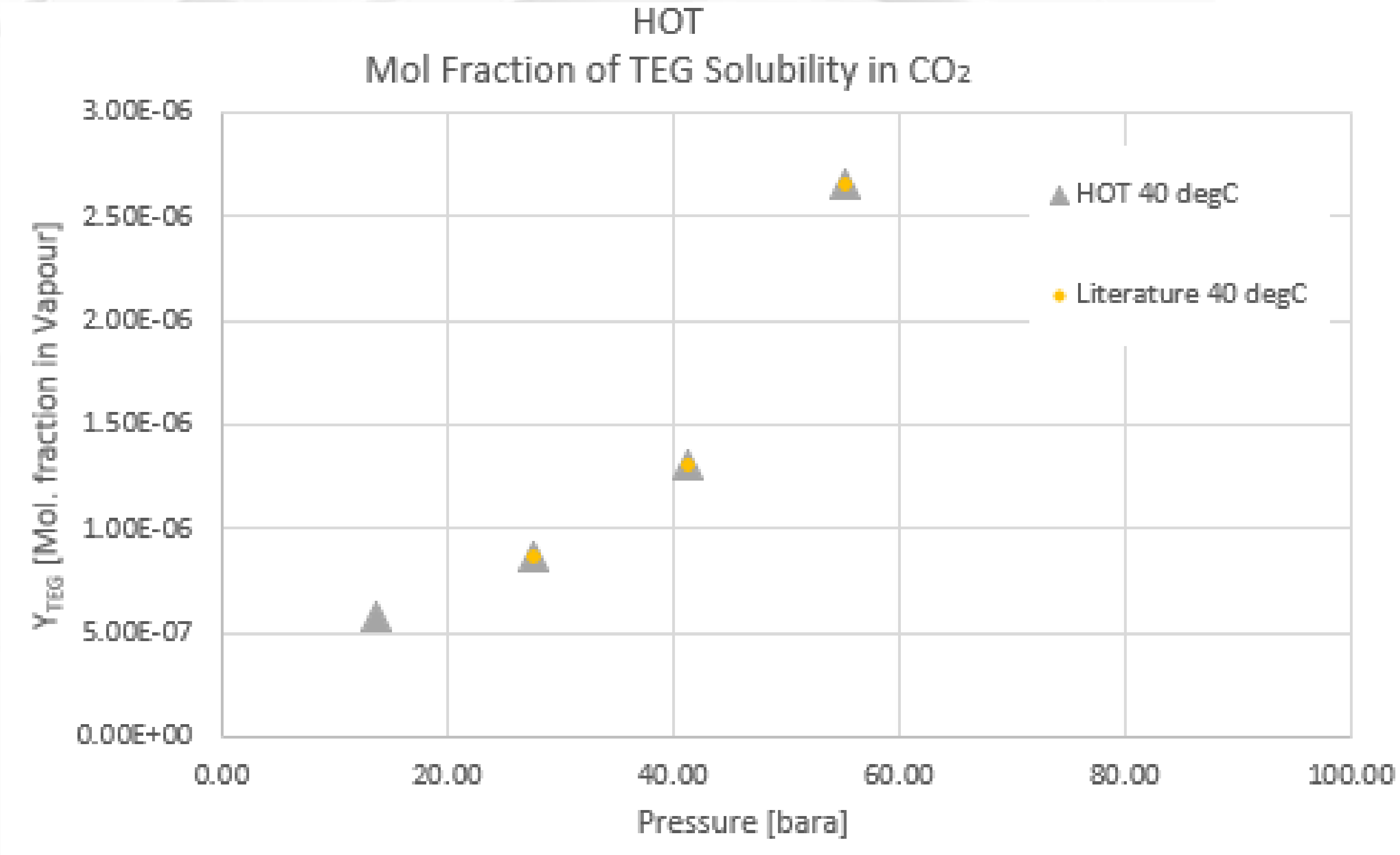
Water VLE – data sources

Laboratory testing to improve predictions of aqueous phase dewpoint and composition, with alcohols & glycols present.

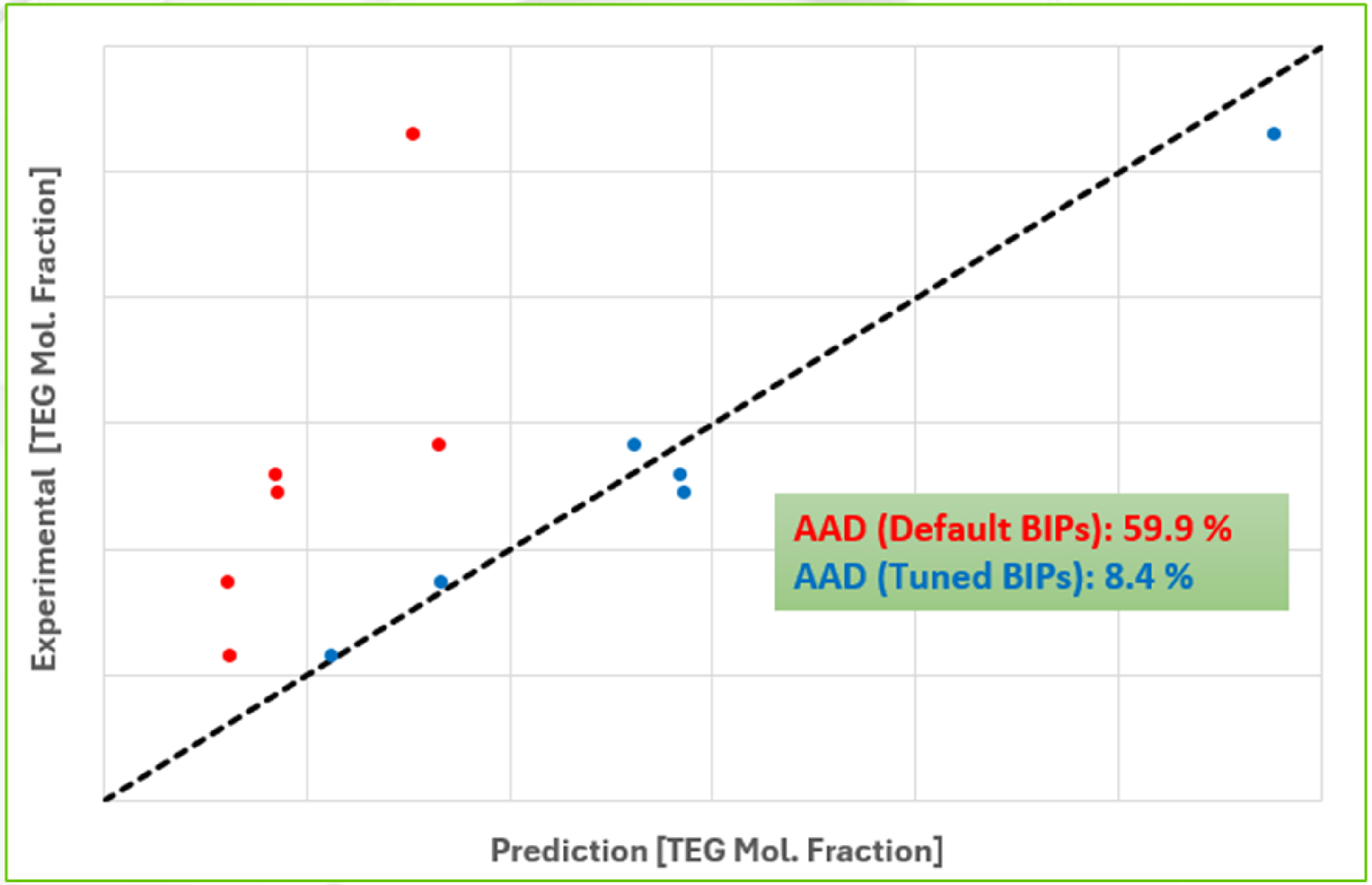
- Visual detection of dew point using HPHT microfluidic platform with a microscope
- Specifications
  - Pressure: from 1 to 300 bar
  - Temperature: from -20 to 200 °C



Water VLE – benchmarking



Water VLE – benchmarking



Chemical reactions

Problem statement

There are about 4000 "thermodynamically likely" chemical reactions that can take place between impurities in a typical CCS industrial hub.

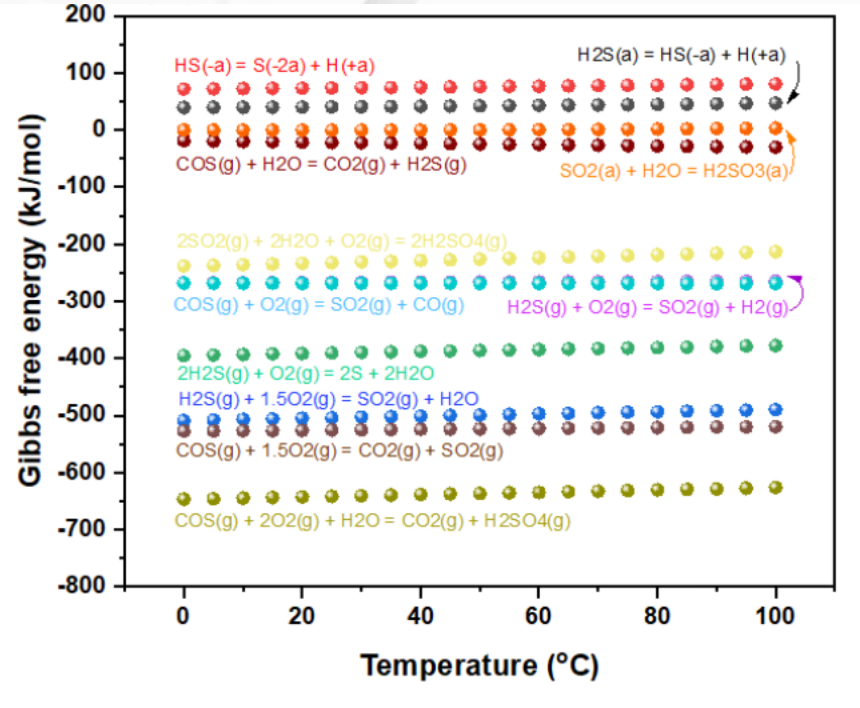
- Most have never been considered in a lab
- Some relevant to sulphuric acid are shown

:

Chemical reaction	$\Delta G°_{298}$, kJ
$H_2S(g) + 2.NO_2(g) \rightarrow H_2SO_4(g) + N_2(g)$	-725
$H_2S(g) + 2.NO_2(g) + O_2(g) \rightarrow H_2SO_4(g) + 2NO(g)$	-543
$H_2S(g) + 3.NO_2(g) \rightarrow SO_2(g) + 3.NO(g) + H_2O(g)$	-398
$SO_2(g) + ½.O_2(g) + H_2O(g) \rightarrow H_2SO_4\ (g)$	-124
$SO_2(g) + NO_2(g) + H_2O(g) \rightarrow NO(g) + H_2SO_4(g)$	-89
$NO(g) + ½.O_2(g) \rightarrow NO_2(g)$	-35

Chemical reactions – source data

Pace CCS and Oxford University joint project



Thermodynamic analysis of reactions between NH_3 and other impurities

Reactions of NH_3 with CO_2 and CO

Reactions of NH_3 with S-containing impurities (H_2S/COS and SO_2)

Reactions of NH_3 and light hydrocarbons (CH_4, C_2H_6 and C_3H_8) and aromatics (BTEX)

Reactions of NH_3 with CH_3OH (and C_2H_5OH)

Reactions of NH_3 with NO_x (NO, NO_2) and N_2O

Reactions of NH_3 with H_2O/O_2

Reactions of NH_3 with acid impurities

Thermodynamic analysis of reactions between S-containing impurities (H_2S/CO, SO_2) and other impurities

Reactions among S-containing impurities (H_2S/CO, SO_2)

Reactions of S-containing impurities (H_2S/CO, SO_2) and CO

Reactions of S-containing impurities (H_2S/CO, SO_2) and methanol (CH_3OH)

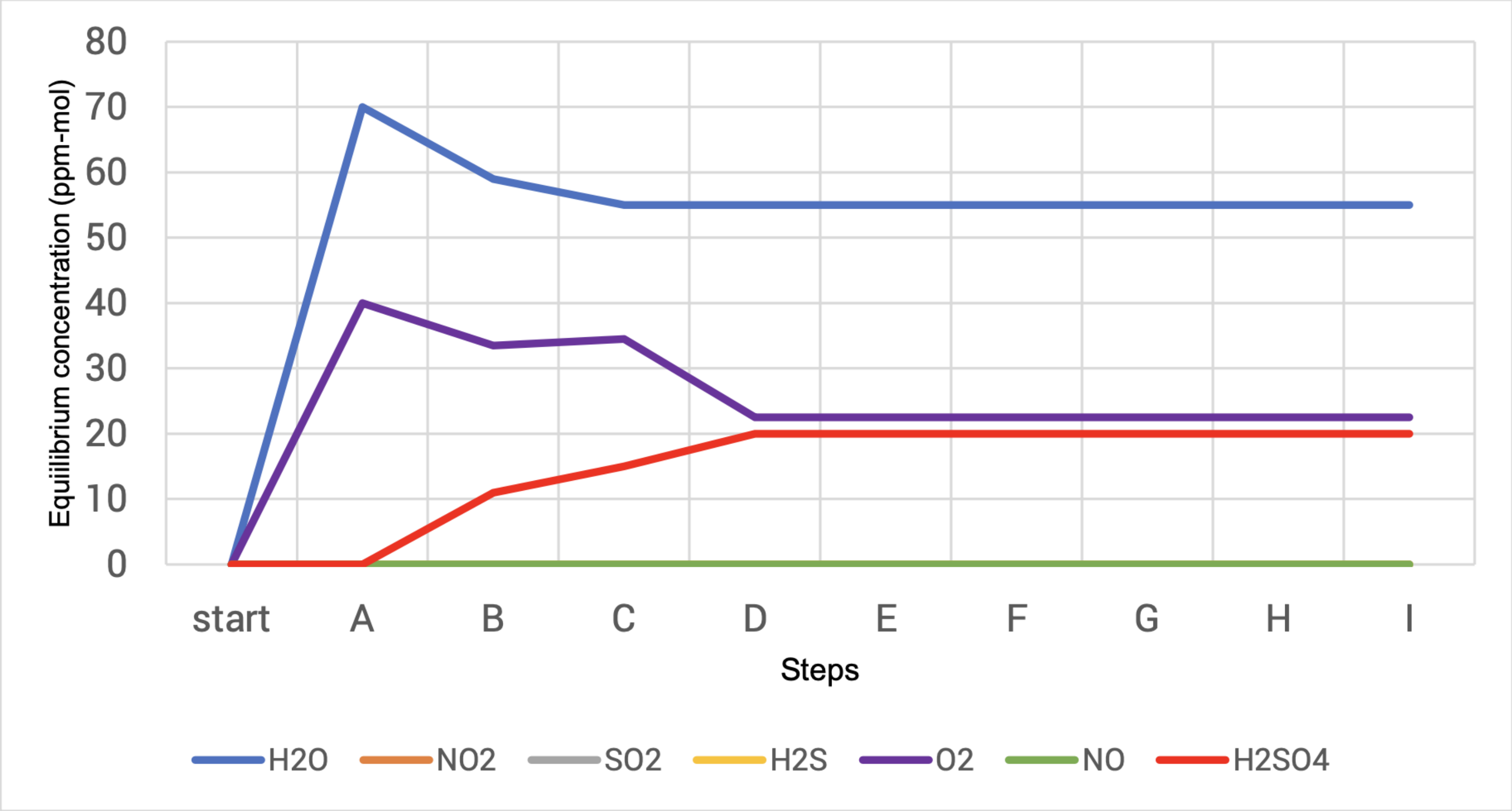
Reactions of S-containing impurities (H_2S/CO, SO_2) with alkanes (CH_4, C_2H_6 and C_3H_8) or aromatics (BTEX)

Reactions of S-containing impurities (H_2S/CO, SO_2) with NO_x (NO, NO_2)

Reactions of S-containing impurities (H_2S/CO, SO_2) with H_2O/O_2

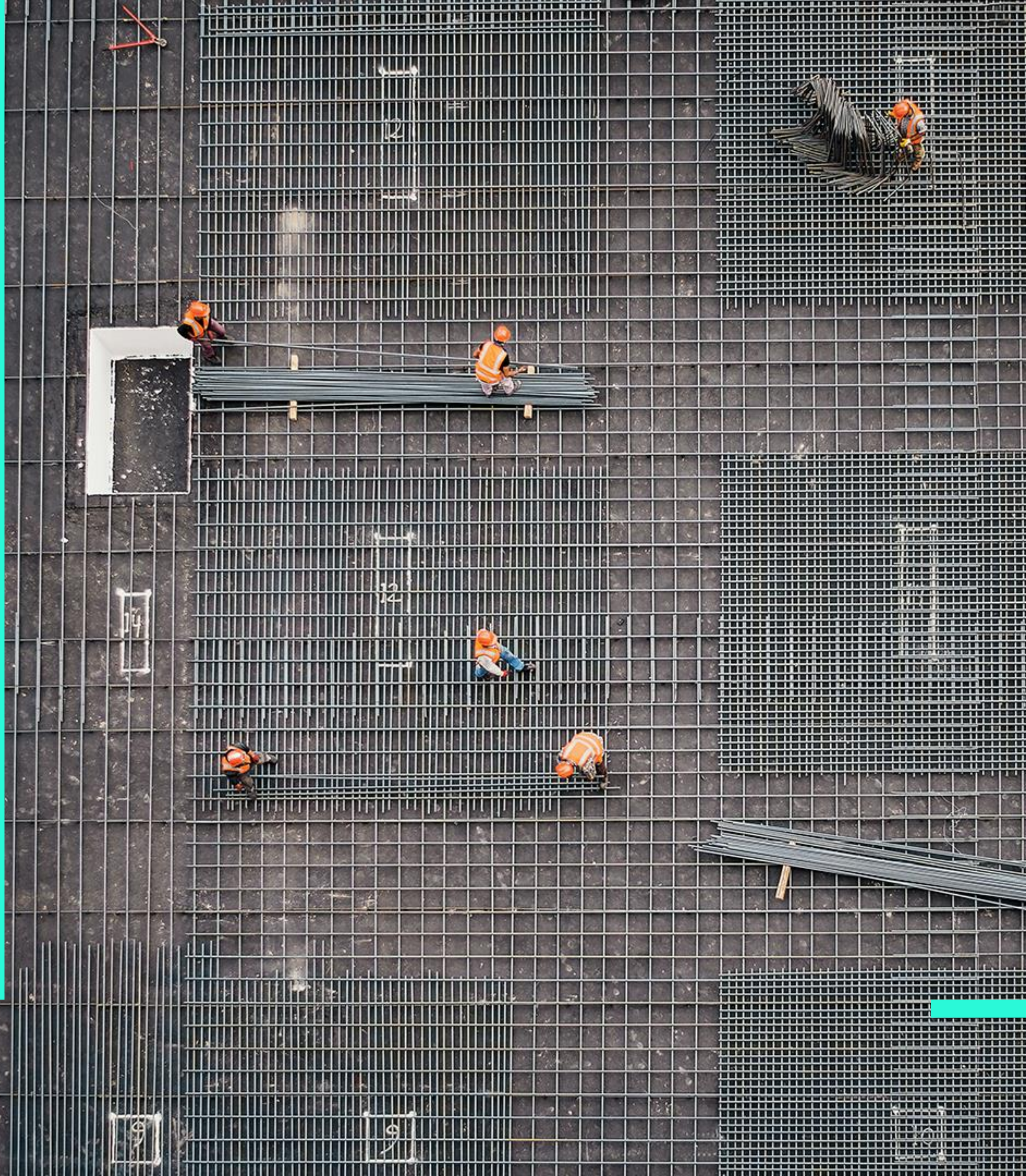
Chemical reactions – benchmarking

Comparison of Pace CCS predictions with IFE/lab data



Presentation:

CarbonX Programme – Funding opportunities and innovation for CCUS projects



CCSA

CarbonX

CarbonX Program 2.0

/ Info Session

April 2025

CarbonX provides tens of millions USD in catalytic grant funding. For more information and to apply, please visit:

https://carbonxprogram.com/en

CarbonX 2.0 focuses on cutting-edge CDR, CCUS, CCU, and long-duration energy storage technologies, and solicits proposals from early-stage teams around the world

CarbonX

CarbonX 2.0
Global Call for Proposal

CarbonX 1.0

Point-source CCUS | DAC CS

CCUS

CDR

Point-source CCUS

CCU

LDES

CCUS

The CarbonX Program was initiated by Tencent, together with industry, investment and ecosystem partners.

It is dedicated to supporting emerging low-carbon technologies with substantial catalytic funding and resources.

It aims to **support building first-of-its kind pilot projects in real industrial settings, incubate high-potential startups, and support capacity building projects.**

The CarbonX Program will solicit proposals globally with tens of millions USD in grant funding pool

CarbonX

Collaborate with global partners to design the tech demonstration scenarios

First round: select the top 10–20 teams in each application track

Second round: 1–3 final winning teams in each track will be selected; the CarbonX Program will support them in constructing first-of-its-kind pilots with millions of USD in funding; estimated total budget is tens of millions USD

Main Support

- For: Universities, research institutes, and other non-profit organizations
- **Grants**: Direct grant support for demonstration pilot projects

- For: Startups
- **Grants + future investment terms**: grant support for pilot demonstration projects and future equity investment rights through warrants

Application Tracks

Carbon Dioxide Removal

CCUS for the Steel Industry

CarbonXmade

CO_2 Utilization in Consumer Products

Long-duration Energy Storage

CarbonX Program Partners

CarbonX

Industry Partners

CONCH · 華潤電力 CR POWER · Great Carbon Valley · HBIS · sasol · SCG · SINOPEC

Investment Partners

Africa Climate Ventures · 中科创星 CASSTAR · 招商局创投 CHINA MERCHANTS VENTURE · COPEC WIND VENTURES · HAPPINESS CAPITAL · HONGSHAN · Lightspeed CHINA PARTNERS · MPCi 经纬创投

Consumer Goods Partners

HAY · McDonald's · PEPSICO · POP MART · Unilever

Ecosystem Partners

ADB ASIAN DEVELOPMENT BANK · AFRICAN DEVELOPMENT BANK GROUP · GLOBAL CCS INSTITUTE · CDR.fyi · IMPACT HUB · TERRA CARTA Sustainable Markets Initiative · XPRIZE

* Sort in alphabetical order

Expert Committee of the CarbonX Program

CarbonX

Co-Chairs of the Expert Committee

Hongguang JIN
Academician, Chinese Academy of Sciences

Peixue JIANG
Academician, Chinese Academy of Sciences
Vice President, Tsinghua University

Jinyue YAN
Academician, European Academy of Sciences and Arts

Jing HUANG
Expert Member, National Climate Change Expert Committee

Tianshou ZHAO
Academician, Chinese Academy of Sciences,

Klaus Lackner
Founding Director, Center for Negative Carbon Emissions,
Arizona State University

Members of the Expert Committee

Lin GAO
Researcher, Huairou Laboratory

Xiaochun LI
Researcher, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences

Bin LIANG
Professor, Sichuan University

Qianguo LIN
Vice-Dean, Research Institute of Carbon Neutrality, Shanghai Jiao Tong University

Haizhong LUO
Director, Environmental Protection Center, China Energy Engineering Group Guangdong Electric Power Design Institute CO., LTD.

Xinbin MA
Vice-President, Xinjiang University

Wei WEI
Vice-Dean, Shanghai Advanced Research Institute, Chinese Academy of Sciences

Ruina XU
Professor, Department of Energy and Power Engineering, Tsinghua University

Xiaoliang YANG
China Country Manager, Global CCS Institute

Jiutian ZHANG
Executive Director, Green Development Institute, Beijing Normal University

Liang ZHAO
Vice-Dean, School of Sustainable Energy and Resources, Nanjing University

Huamin ZHANG
Chief Researcher, Dalian Institute of Chemical Physics, Chinese Academy of Sciences

Jarad Daniels
CEO,
Global CCS Institute

Niall Mac Dowell
Professor in Energy Systems Engineering,
Imperial College London

Wolfgang Heidug
Senior Visiting Research Fellow at KAPSARC

David Reiner
Professor of Technology Policy,
University of Cambridge

Priyantha Wijayatunga
Chief of Energy Sector Group, Asian Development Bank (ADB)

Roland Span
Chair of Thermodynamics,
Ruhr University Bochum

Olufunso Somorin
Regional Climate Head East Africa, Climate Change and Green Growth Program, African Development Bank

Juan Carlos Abanades
Professor, Institute of Carbon Science and Technology (INCAR)
Spanish National Research Council (CSIC)

More experts to join...

Conveners of the Expert Committee

Yongping ZHAI
Tencent
Senior Advisor for Carbon Neutrality

Xuedu LYU
Tencent
Senior Advisor for Carbon Neutrality

Secretary-General of the Expert Committee

Xian ZHANG
Director, Administrative Center for China's Agenda 21, Ministry of Science and Technology

Timeline and Selection Process

CarbonX

December 3rd, 2024
CarbonX 2.0 Launch

- Official website & application portal go live at the same time
- 3-4 Open Day events

May 2025
Deadline of submitting proposals

- Preliminary screening by written application materials
- First round of online presentation and selection: this round will focus on evaluating **technical innovation and competitive advantage**

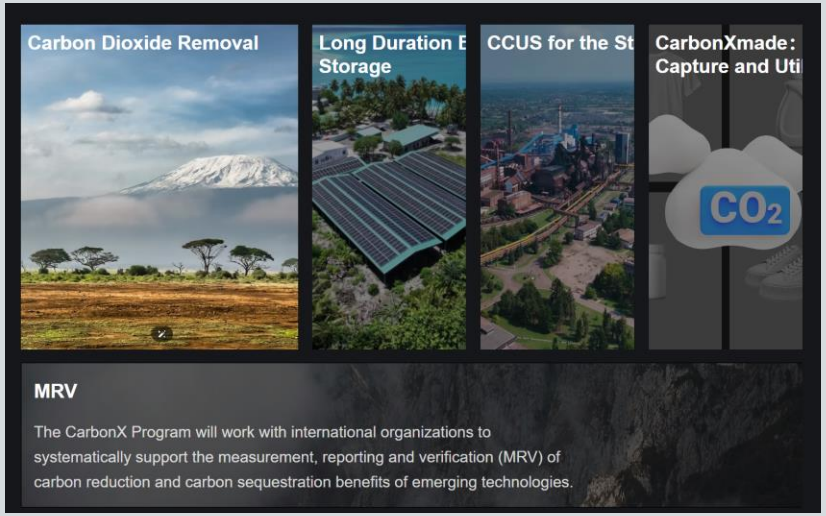
September 2025
Announce Top 50-80

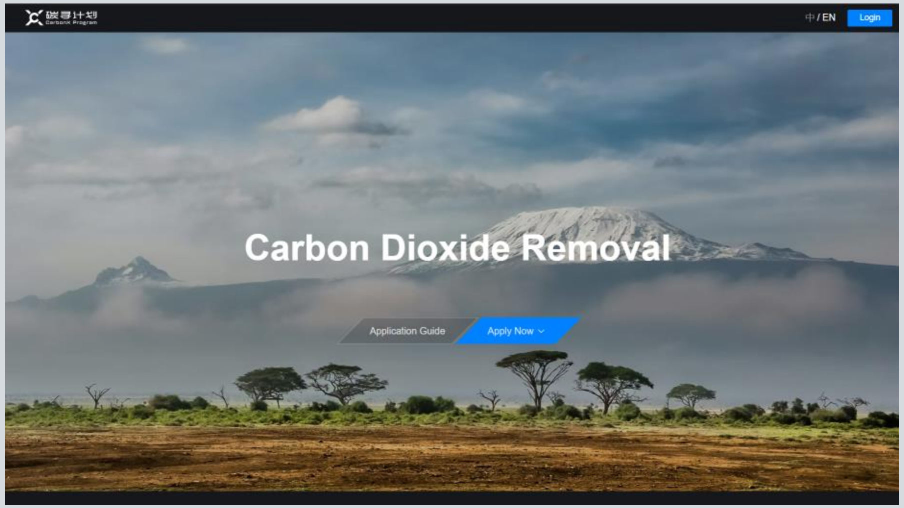
- Shortlisted teams need to submit further materials for next round screening
- Final round of offline roadshow presentation and defense

~ February 2026
Announce final winning teams for each application track

- Visit of demonstration sites and project kick-off meetings

Official website, application guide, and Q&A channels





Official Website: https://carbonxprogram.com/

Email: info@carbonxprogram.com

CarbonX

CarbonX Program 2.0 Application Guide

March 2025 Edition

The CarbonX Program, initiated by Tencent and a global alliance of industry, investment, and ecosystem partners, aims to accelerate the large-scale deployment of cutting-edge low-carbon technologies. Leveraging tens of millions of USD of catalytic grant funding, CarbonX Program 2.0 focuses on pioneering advancements in Carbon Capture, Utilization, and Storage (CCUS), Carbon Dioxide Removal (CDR), and Long-Duration Energy Storage (LDES). Now open for proposals from visionary technology teams worldwide, the program will drive impactful demonstration projects, support startups with high economic potential, and strengthen foundational capabilities to enable transformative low-carbon innovations.

This document serves as the program's application guide. For more background on the initiative, please visit the official website: https://carbonxprogram.com/.

1. Program Overview and Application Tracks

1.1 Program Overview

碳寻计划 CarbonX Program

Global partners provide tech demonstration scenarios and collaborate to explore cutting-edge technological solutions

First round: Select the top 10-20 teams in each track to build the global influence of the CarbonX Program

Main Support

Final round: 1-3 final winning teams in each track will be selected; the CarbonX Program will support them in constructing first-of-its-kind pilots with millions to tens of millions USD in funding

(WhatsApp)

Scan the QR code above to connect with the "CarbonX Assistant" for consultation.

Application Track 1: Carbon Dioxide Removal (CDR)

CarbonX

Why choose Kenya?

Close to 100% renewable power supply

Abundant basalt provides ideal conditions for CO2 geological storage

Goals / Requirements

- Hundred-tonne Scale
- Permanent Carbon Removal
- Next Generation Technology

Future Challenges and Opportunities

~100,000 times

Growth at scale

- The current technology-based permanent removal volume, which is only tens of thousands of tons per year, will need to increase 100,000 times to one billion tonnes per year in the future.

~30-40 years

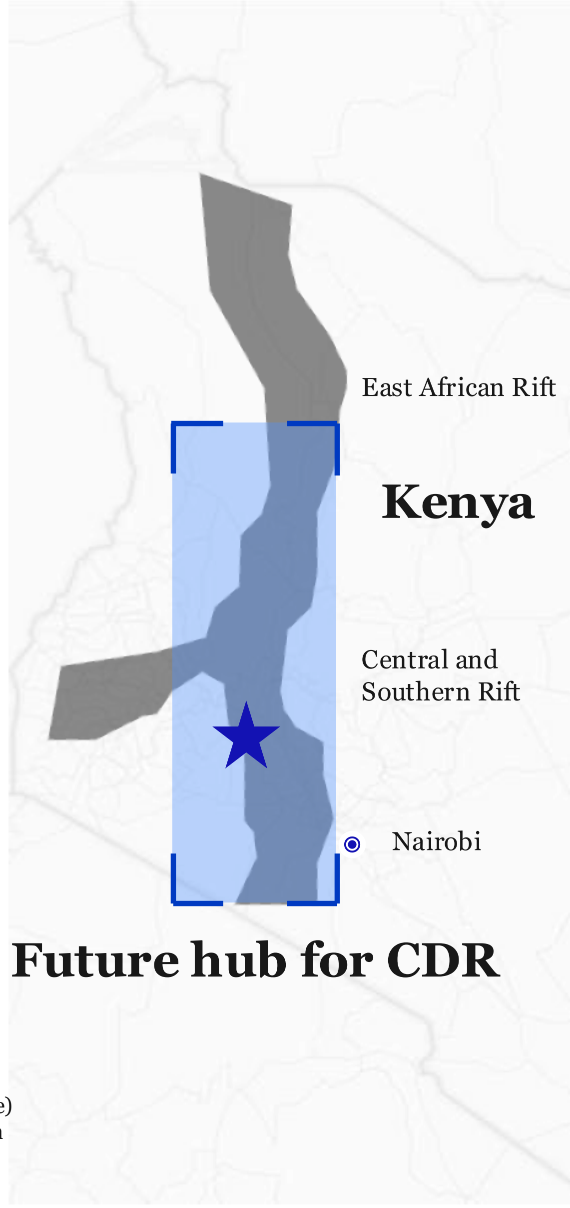
Limited time window

- To meet the 1.5°C climate target, carbon removal needs to reach a gigaton-per-year scale within a 30-40 year window.

~90%

Cost reduction

- At present, carbon removal (especially direct air carbon capture) is expensive, and the cost reduction potential can be up to 90%.



Application Track 2: Point-source CCUS

CarbonX

Why choose HBIS Serbia?

A typical long-process steel plant with good implementation conditions and strong technical applicability

Traditional steel plants have entered the low-carbon transformation window period and are in urgent need of reducing carbon emissions

Goals / Requirements

- Thousand-tonne Scale
- Focus on blast furnace ironmaking process
- Closed-loop Solution

Future Challenges and Opportunities

Million tonnes

Large-scale single project

- The annual carbon emissions of large steel plants generally exceed one million tonnes, and CCUS technology needs to match the corresponding scale.

CO / Solid waste

Economic potential

- Steelmaking exhaust gas features a high concentration of CO_2 at elevated temperatures and pressures, and it contains economically valuable components—offering significant potential for multi-stage cyclic or coupled utilization.

50%-90%

Cost reduction

- CCUS for steel industry requires breakthrough innovation to significantly reduce energy consumption and material costs.

Application Track 3: CarbonXmade-CCU

CarbonX

Why support CO2-Chemicals-Product?

Using first principles to identify the green carbon feedstock for a future net-zero world.

High possibility: the application scenarios are very wide, and downstream products have the potential to replace food, clothing, housing and transportation materials

Extensive technology: The sources of carbon dioxide are distributed, and the conversion paths and technologies are extensive

Goals / Requirements

- At least tonne-scale CCU production
- Economic viability and large-scale emission reduction potential
- Next generation technology

Future Challenges and Opportunities

1-1-1

Long value chain

- From technology innovators to end users, there are usually multiple levels in the value chain, each involving various stakeholders.

60%+

Cost reduction

- Need to be economically competitive compared with alternatives by 2030.

?

Emission reductions are unclear

- At present, there is a lack of judgment data on the unit emission reduction and total emission reduction of most CCU paths and products.

CarbonXmade Consortium

- Emerging Technology Providers
- Industry Partners
- Consumer Product Companies

中国石化 SINOPEC, sasol

Unilever, POP MART, HAY, PEPSICO

Application Track 4: Long Duration Energy Storage

CarbonX

Why choose an inhabited island in the Maldives?

Himandhoo Island's energy load is sized to enable a swift increase in renewables, creating an ideal scenario for LDES applications

At present, the island relies heavily on imported diesel. Renewable energy + storage can significantly reduce energy costs and carbon emissions

The Asian Development Bank has led energy transition projects in the Maldives for many years, providing a solid basis for collaboration

Goals / Requirements

~100 kW scale for more than 6 hours of storage	Non-lithium battery power	Next generation technology

Future Challenges and Opportunities

50%-80%

Renewables penetration rises significantly

- As grid fluctuation is increasing, large-scale development of LDES technology becomes vital to the energy transition.

N+ Technologies

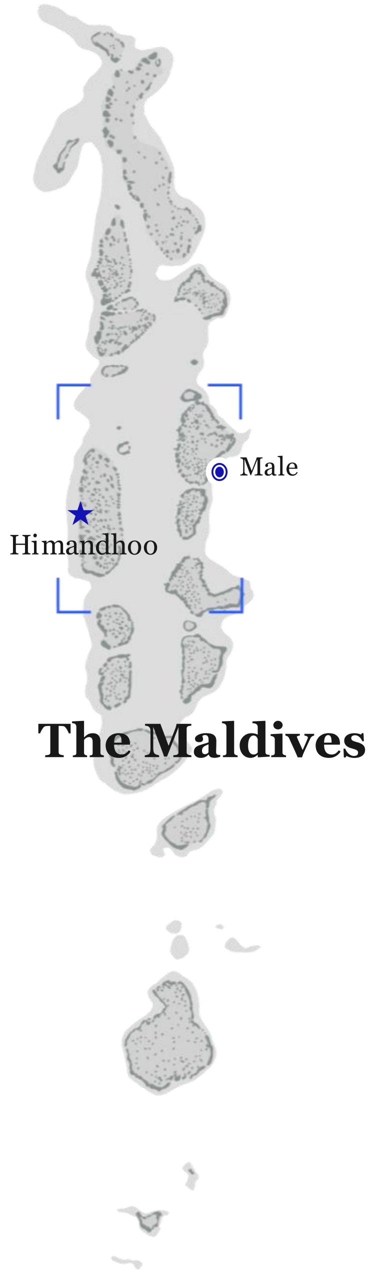
Uncertain technical pathways

- No single "go-to" solution exists for diverse scenarios, making it difficult to develop a supporting supply chain.

~90%

Huge potential for system cost reduction

- At present, the cost of LDES systems is high, and there is room for cost reduction of up to 90%.



AOB & Conclusions

- Review actions arising from meeting
- Next Working Group Meeting: **September 2025** (date TBC)
- AOB