CCUS数值模拟研发历史及应用
CO2 History and its Disposal Problems

Computer Modelling Group Ltd.

CMG

It all started with – CO2 EOR

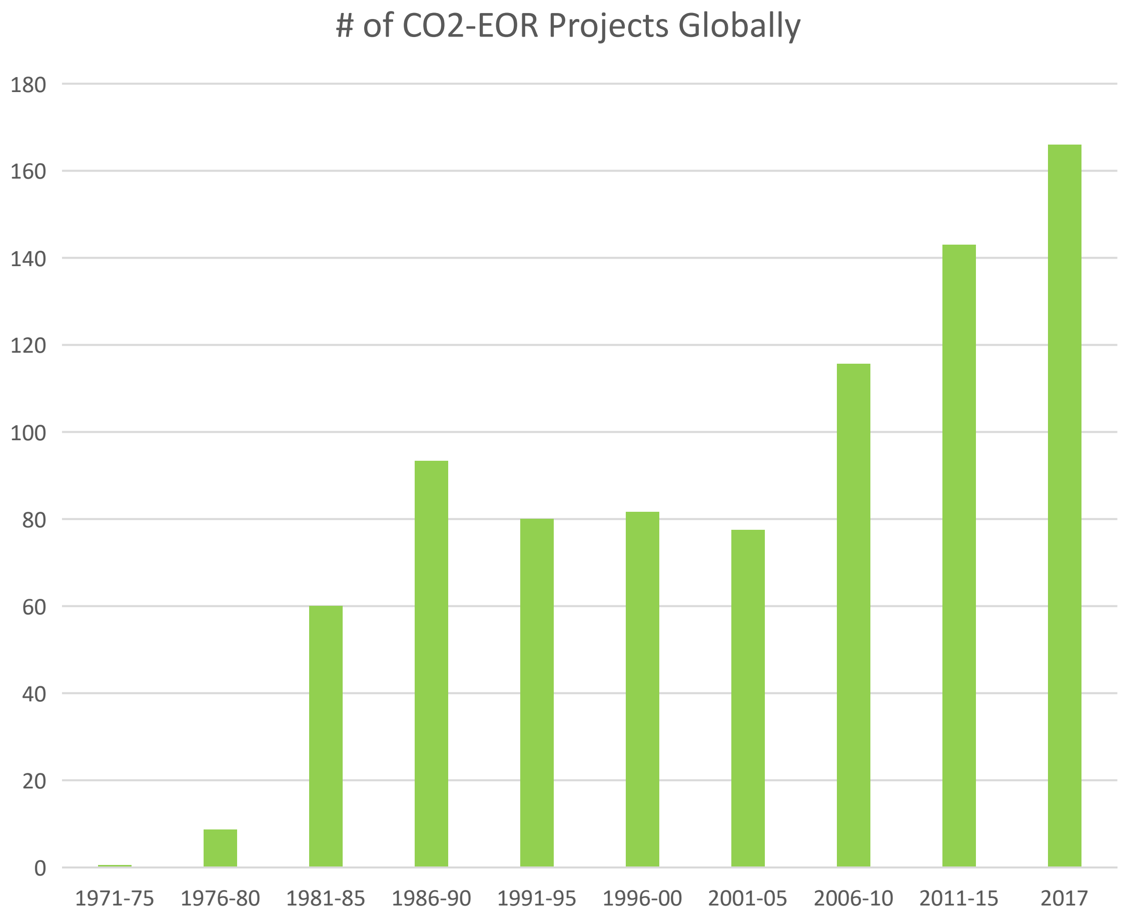
CO2 EOR has been around a long time!

1952 - First Patent for CO2 EOR

1964 - First Field test

1972 - First commercial CO2 EOR project SACROC (West Texas)

CMG started modelling in 1990’s



IEA, Number of EOR projects in operation globally, 1971-2017, IEA, Paris https://www.iea.org/data-and-statistics/charts/number-of-eor-projects-in-operation-globally-1971-2017

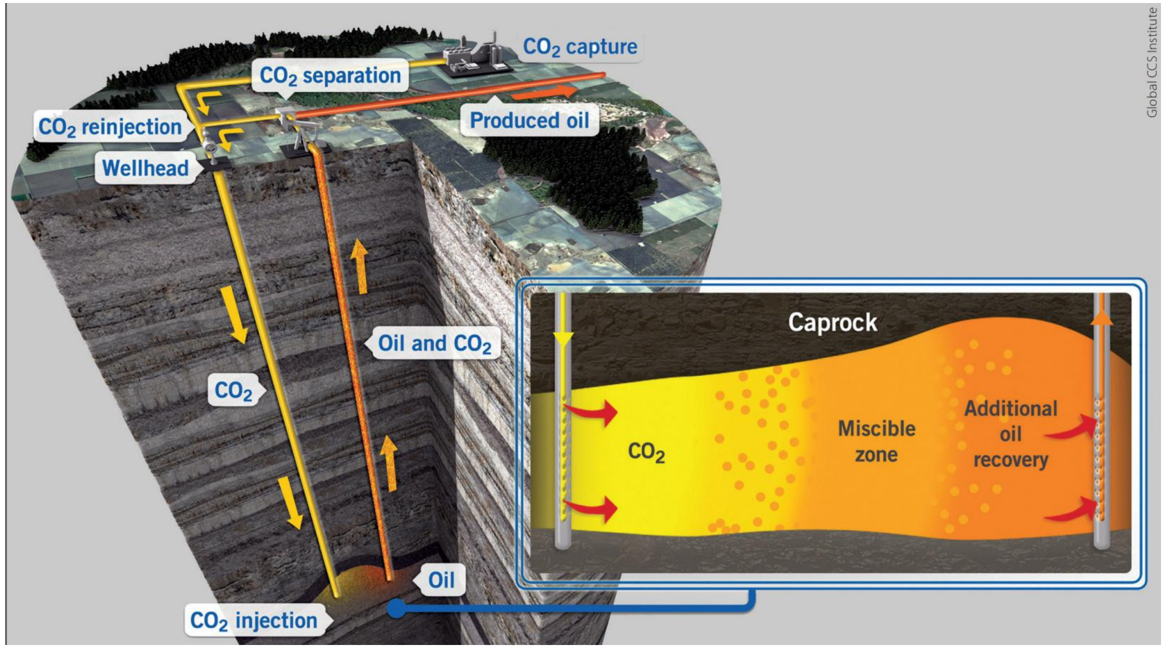
CO_2 EOR

CO_2 EOR all about miscibility

- Creating Single phase flow
- Reducing Sor
- Sweeping new parts of the reservoir

Popular where there is sufficient CO_2 supply

- Usually high reservoir P&T
- E.g. 4,000psi & 100C
- In USA <15% of CO_2 EOR is sourced from CO_2 emitters. Rest is produced from CO_2 reservoirs!

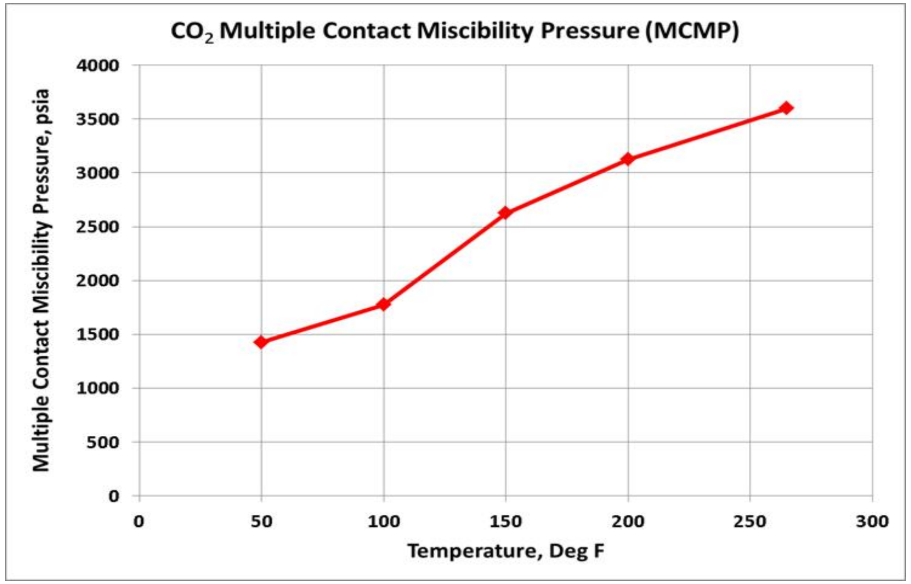


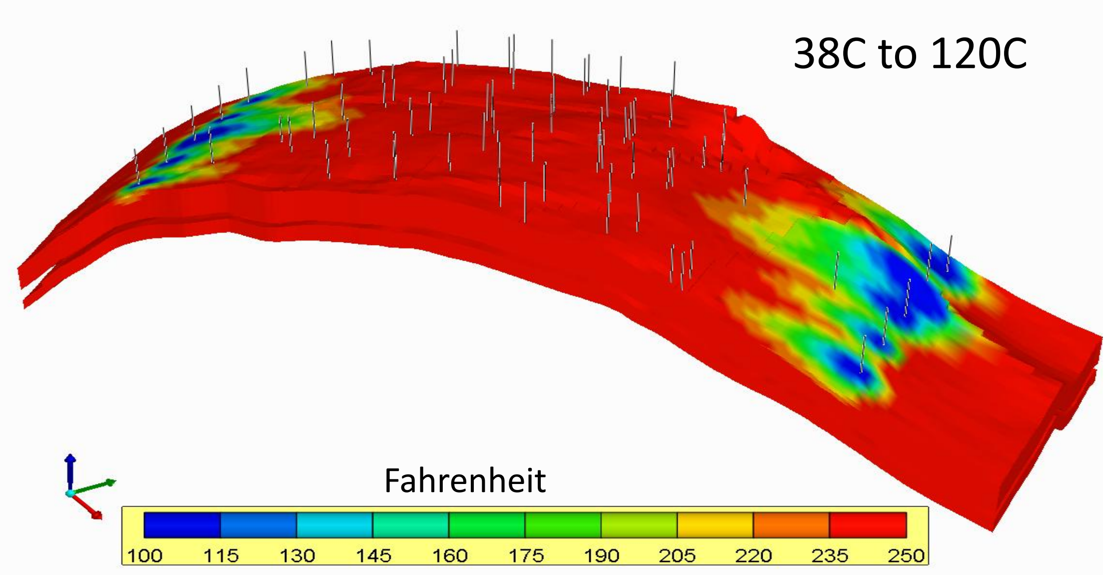
CO2 EOR and Temperature

Many CO2 processes are sensitive to Temperature

- CO2 solubility in water (changes ρ_w)
  - Solubility increases as P increases
  - Typically decreases as T increases
- Asphaltene deposition and plugging
- Matrix dissolution in a carbonate reservoir

Cold Water Injection lowers CO2 miscibility pressure





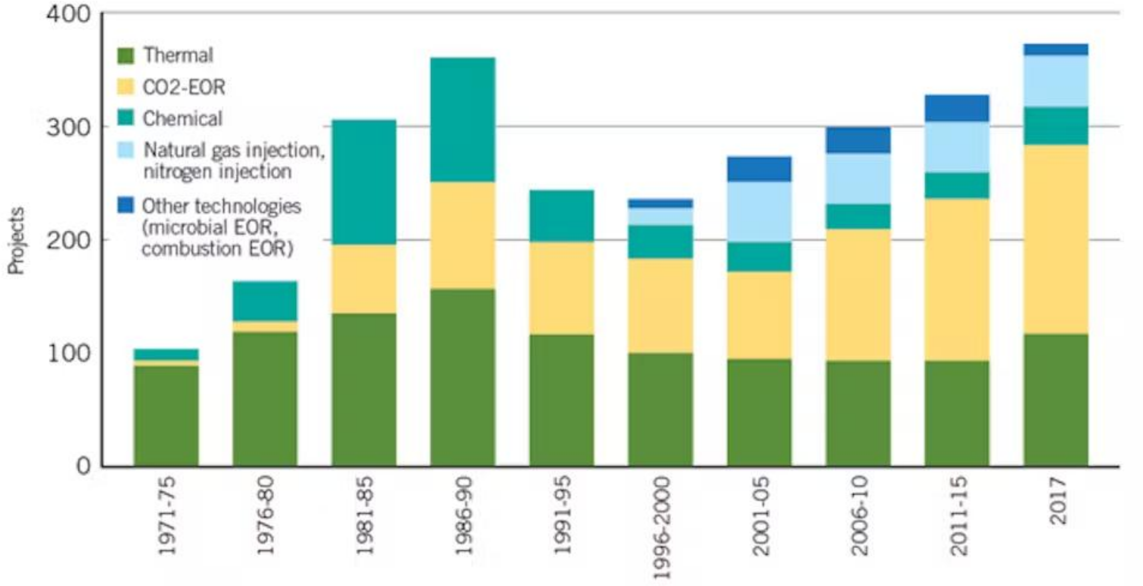
GEM is fully thermal

How CO2 EOR became CO2 Sequestration

Most CO2 disposal projects in USA are CO2 EOR

- Economics purely based on incremental oil production
- 45Q has enhanced those revenues through a tax credit
  - Direct Air Capture numbers!
    - Occidental’s big investment in this process!

EOR PROJECTS OPERATING WORLDWIDE FIG. 1



Source: IEA World Energy Outlook

45Q Enhancements in the Inflation Reduction Act

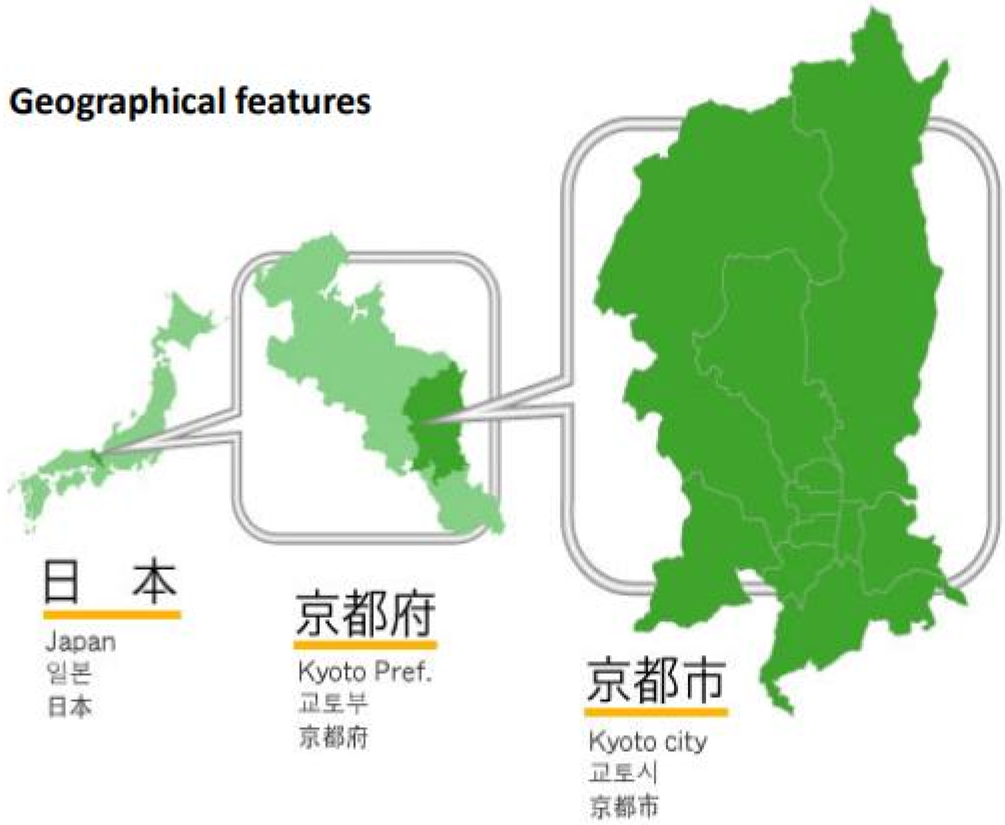
$

The IRA increased credit values across the board, with full value realized only if prevailing wage and apprenticeship requirements are met:

- 45Q incentives increase from $50 to $85/tonne for storage in saline geologic formations from carbon capture on industrial and power generation facilities.
- 45Q incentives increase from $35 to $60/tonne for utilization from industrial and power generation carbon capture.
- 45Q incentives increase from $50 to $180/tonne for storage in saline geologic formations from DAC.
- 45Q incentives increase from $50 to $130/tonne for utilization from DAC.
- The credit can be realized for 12 years after the carbon capture equipment is placed in service and will be inflation-adjusted beginning in 2027 and indexed to base year 2025.

COP3 Kickstarts CO2 Storage Initiatives

Kyoto Protocol adopted on 11th December 1997 at COP3

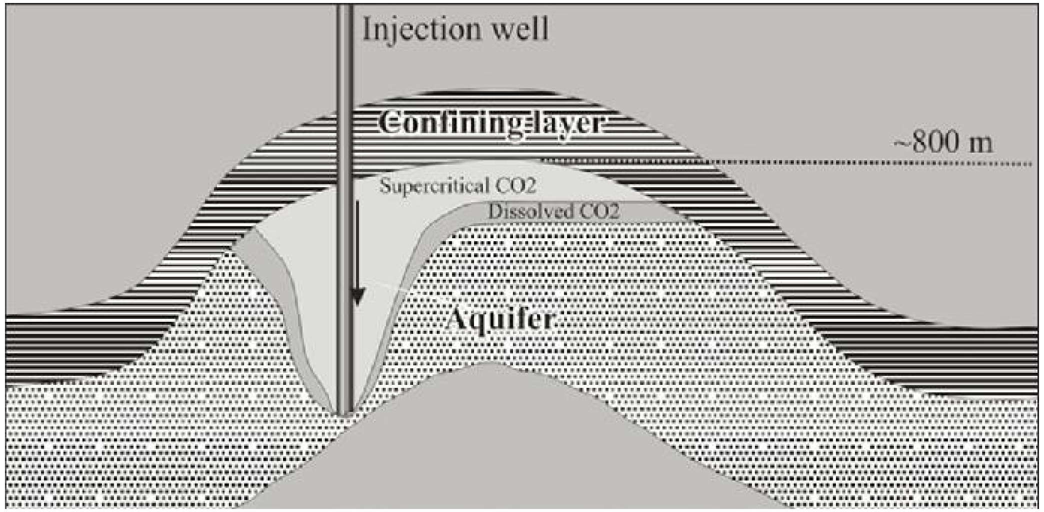


COP28 being held in Abu Dhabi later this year

Storage Capacity

Major interest in Saline aquifer disposal at this time until about 2010

- Main efforts towards looking for Storage sites; their capacity; and their long term storage potential
- Tools were built to analyse and understand the storage issue
  - CMG project for CO_2 sequestration: Jan 2001 until April 2005 to produce GEM-GHG
  - CMG and our partners produced ~100 technical papers during this time



CMG – GEM is the only simulator that has:

- Flow
- Full OWG flash
- Temperature
- Geochemistry
- Geomechanics

All fully coupled

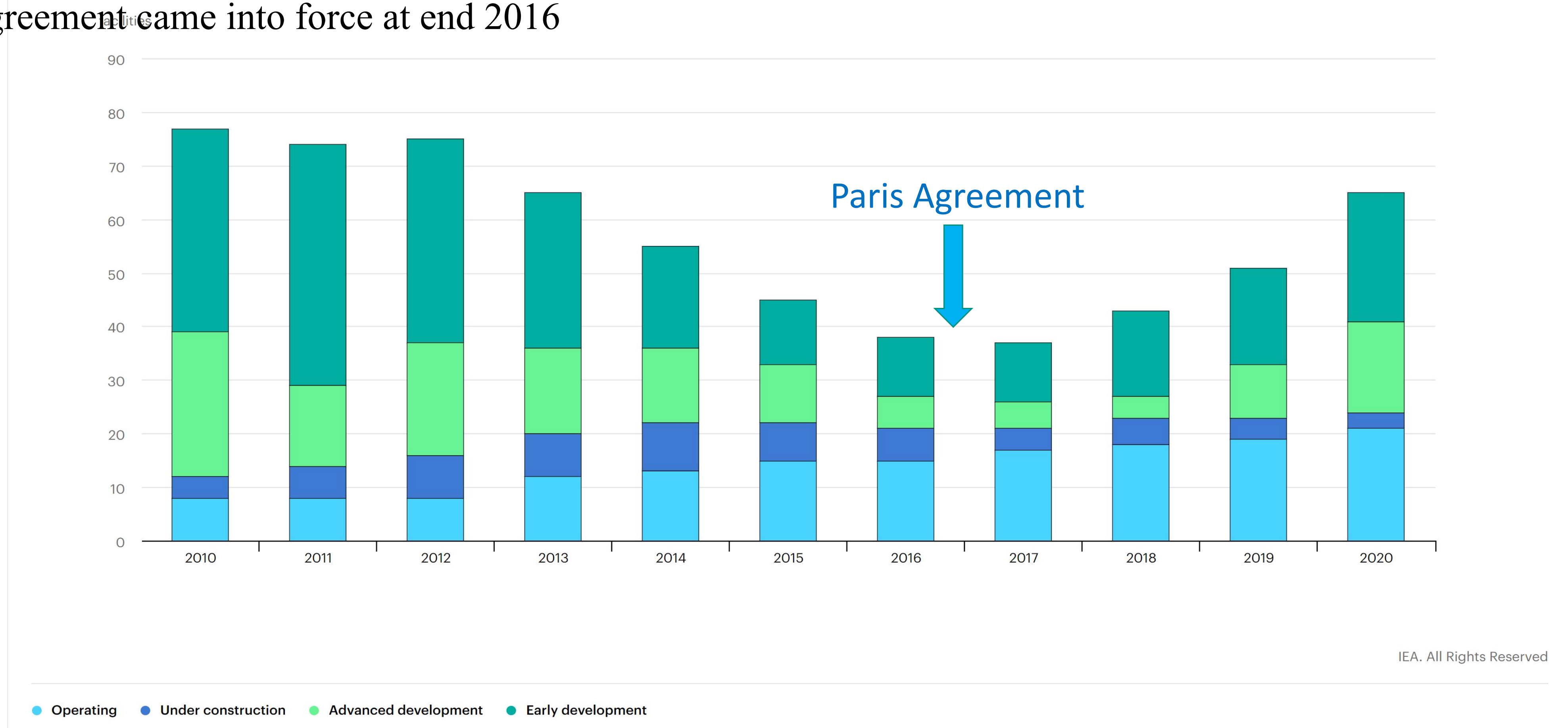
CMG and Carbon Sequestration

However, after 2010 things seemed to go very quiet…….

CO2 Storage

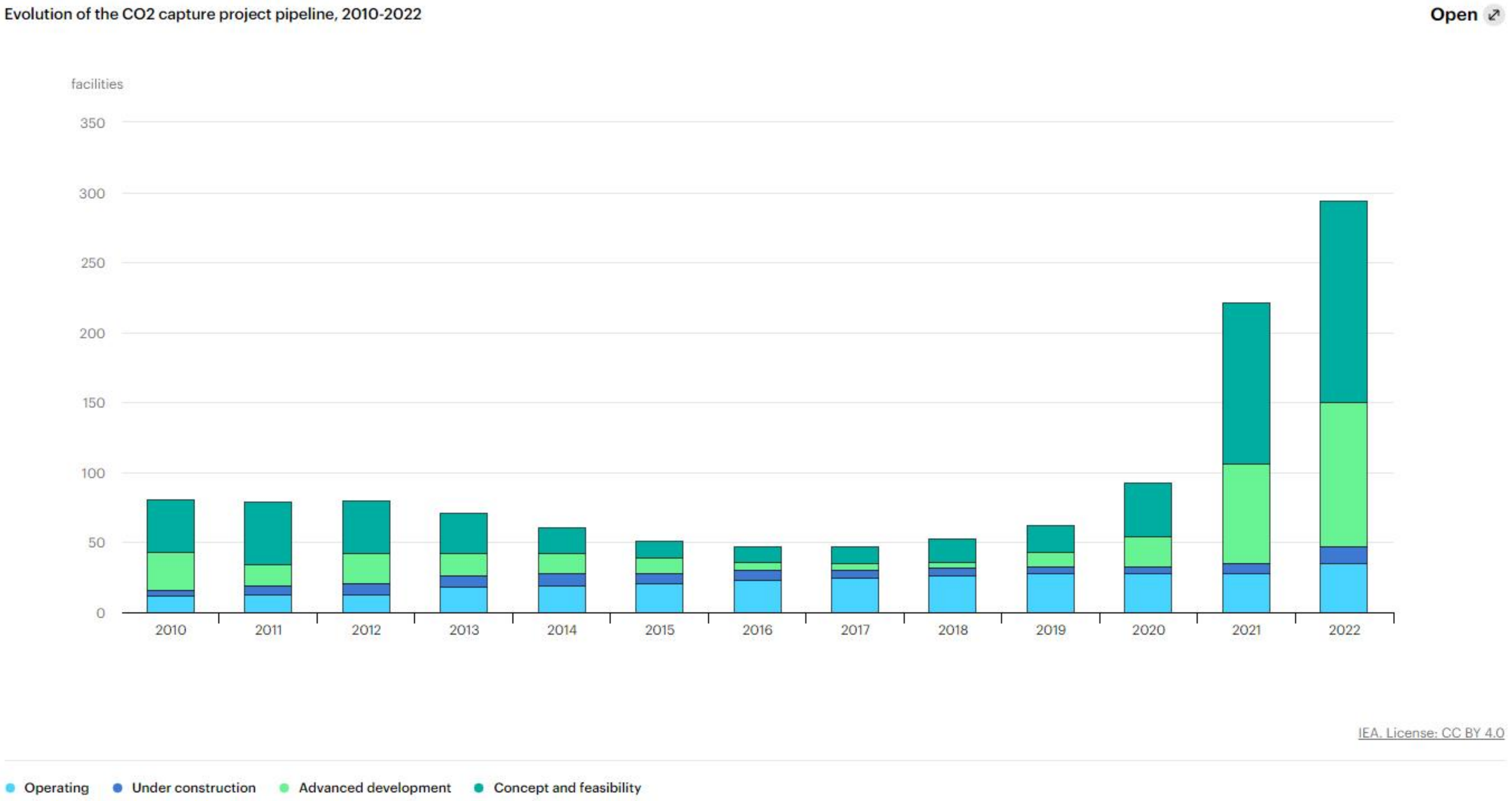
Then in 2016 things started to change again

Paris Agreement came into force at end 2016



IEA, *World large-scale CCUS facilities operating and in development, 2010-2020*, IEA, Paris https://www.iea.org/data-and-statistics/charts/world-large-scale-ccus-facilities-operating-and-in-development-2010-2020

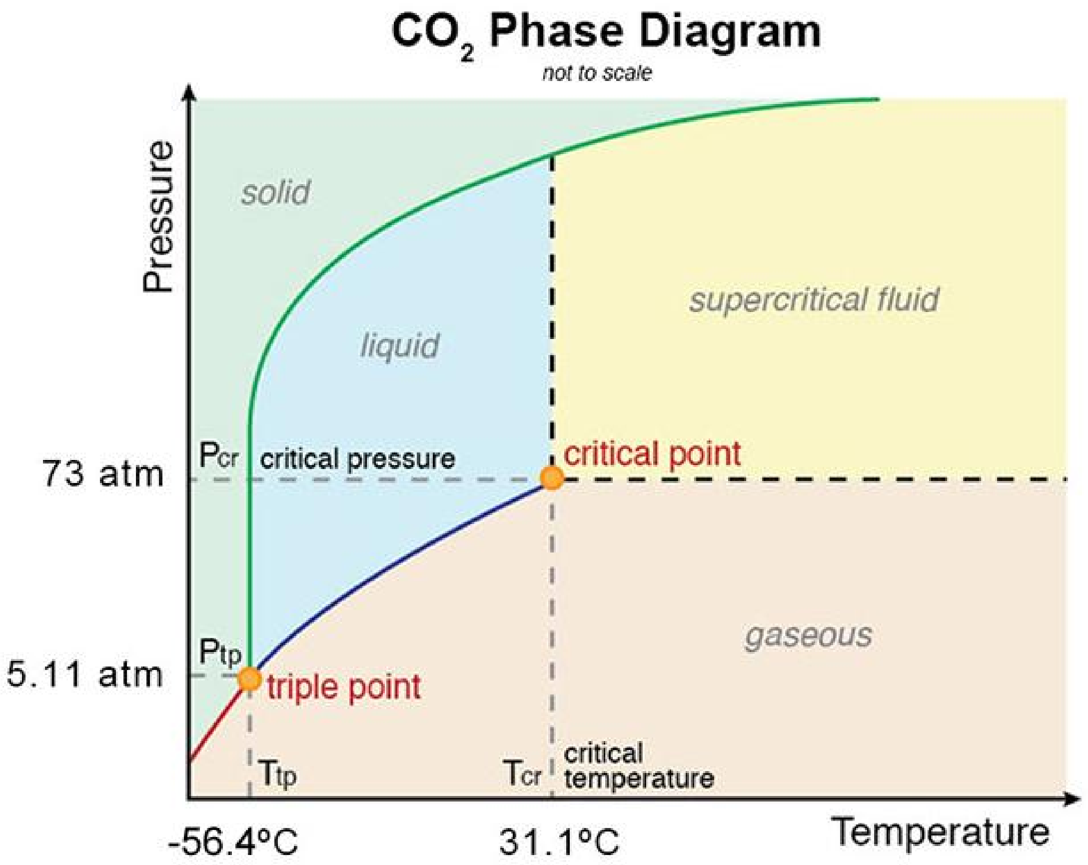
IEA Update


Evolution of the CO2 capture project pipeline, 2010-2022
Open
facilities
350
300
250
200
150
100
50
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
IEA. License: CC BY 4.0
Operating
Under construction
Advanced development
Concept and feasibility

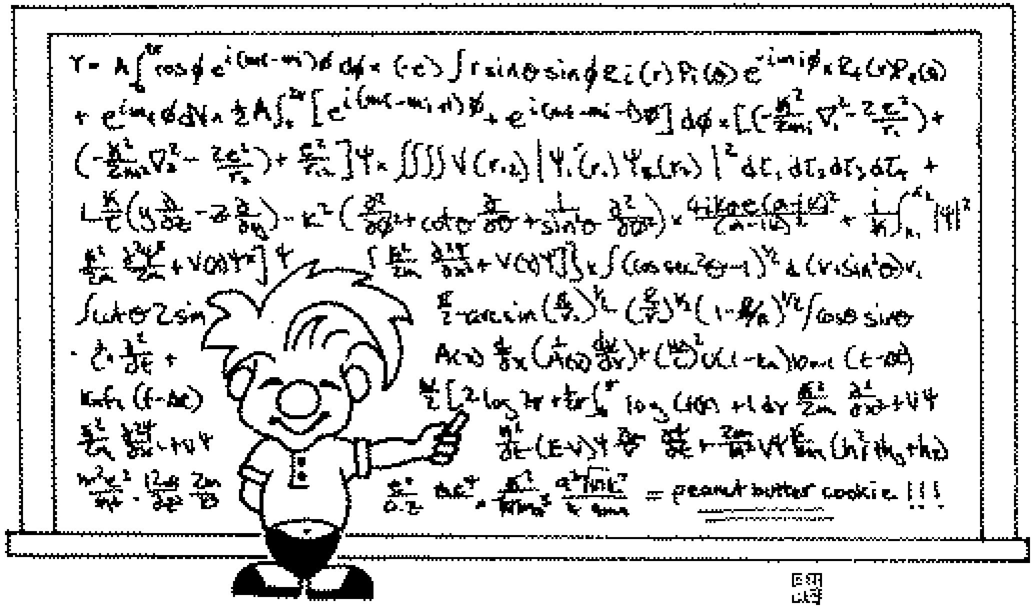
After Paris

Companies looking at 2 main types of disposal

- Deep Saline Aquifers
  - CO_2 solubility; long term mineralization; gas trapping; seal geomechanics
- Depleted Oil/Gas Reservoirs
  - Offshore as Politics prevents Onshore
    - Sea floor T = 4-10C; 285K
    - Reservoir P ~400psi; 28bar
    - CO_2 phase behaviour
      - Tc 304K; 31C; 88F
      - Pc 7.4MPa; 72.8atm; 1,070psi



Things Become a Lot More Complicated



Pure CO2 Behaviour

Depleted systems tend to operate around CO2 critical point

- Causes problems for property calculations e.g. density and viscosity and phase identification in simulators

Typically looking to inject high purity CO2

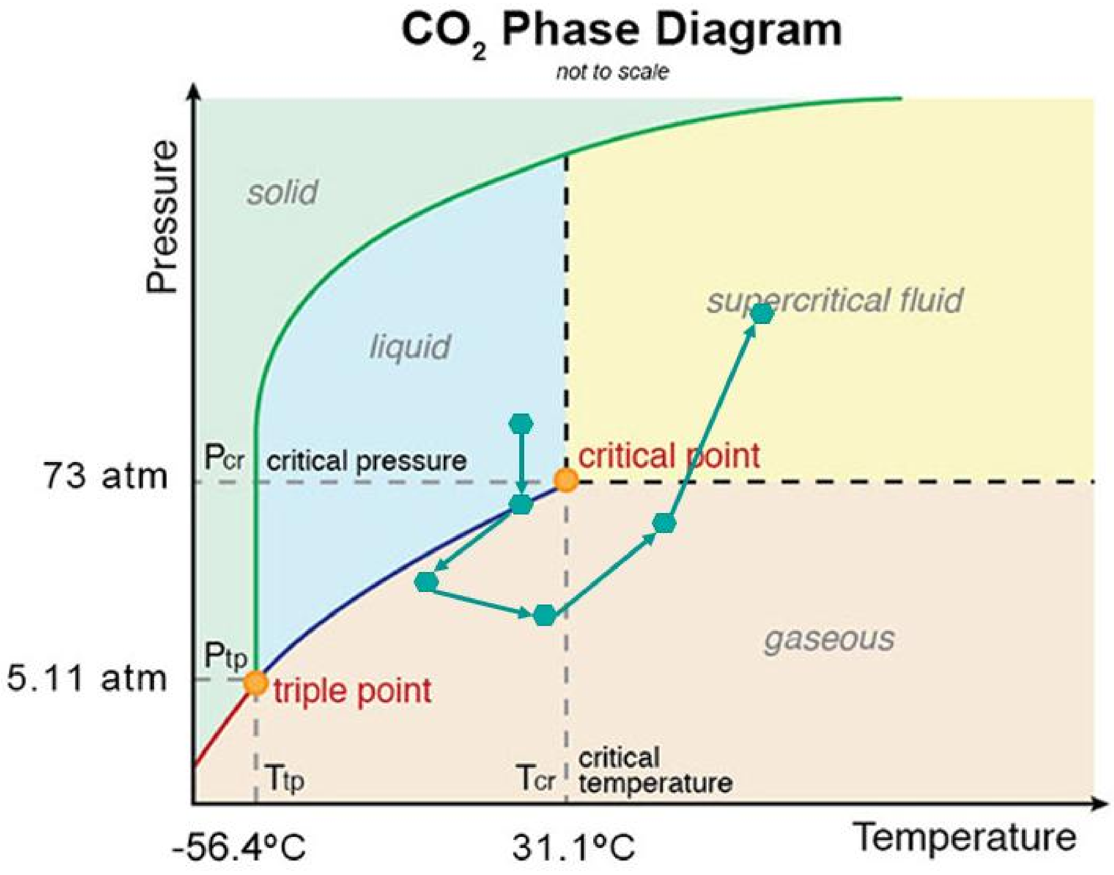
- Standard simulator PT based calculation becomes a problem need PH for single component CO2
- Impurities actually make things easier

CO2 is a refrigerant

- Change from liquid to gas causes severe cooling
- Reports of -30C at near well conditions

For release in 2024:

- **GEM has added the capability to deal with pure CO2 by using enthalpy and not temperature**
- **GEM allows T<0C**
- **GEM allows stable transition through the critical point**



Hydrates

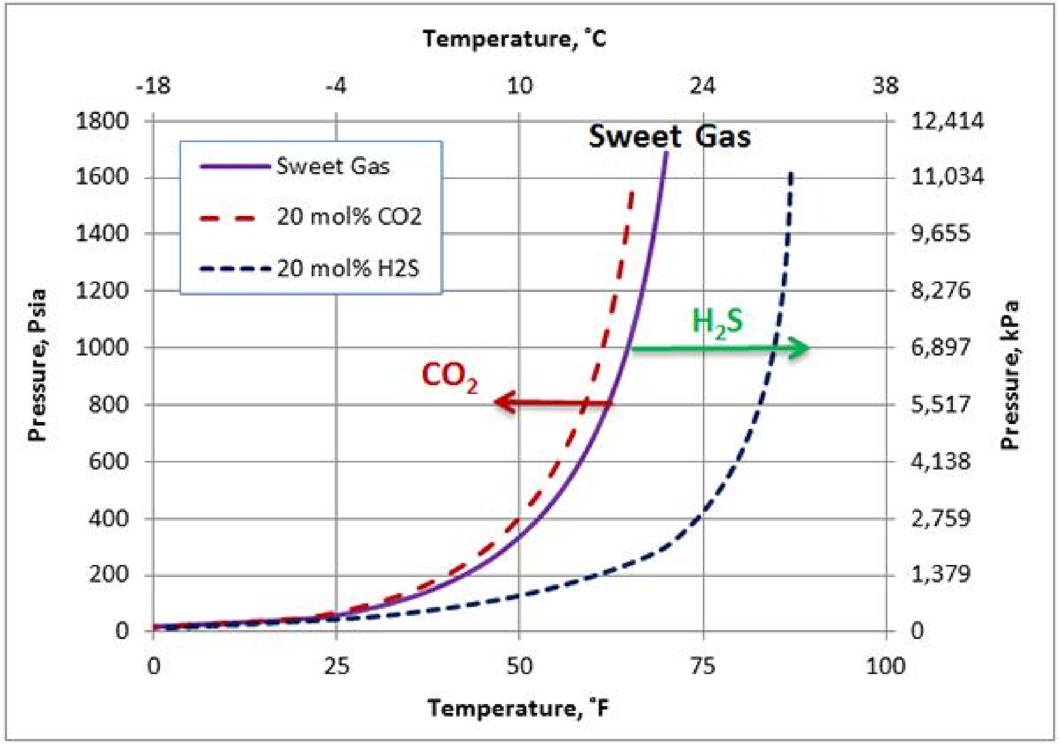
Hydrates tend to form when:

- Water present and T drops below hydrate formation T
  - BUT CO2 will dry out the near well region
    - Salt deposits form!
    - Fresh water flush to remove – but hydrates!
  - Well shutin allows water to flow back into the well region
- Sudden pressure drop due to expansion e.g. chokes; perfs

Low near well T can easily form

- Methane Hydrate
- CO2 Hydrate

GEM connects to hydrate simulator via our Python capabilities



Structural problems - Geomechanics

Pressure related stress

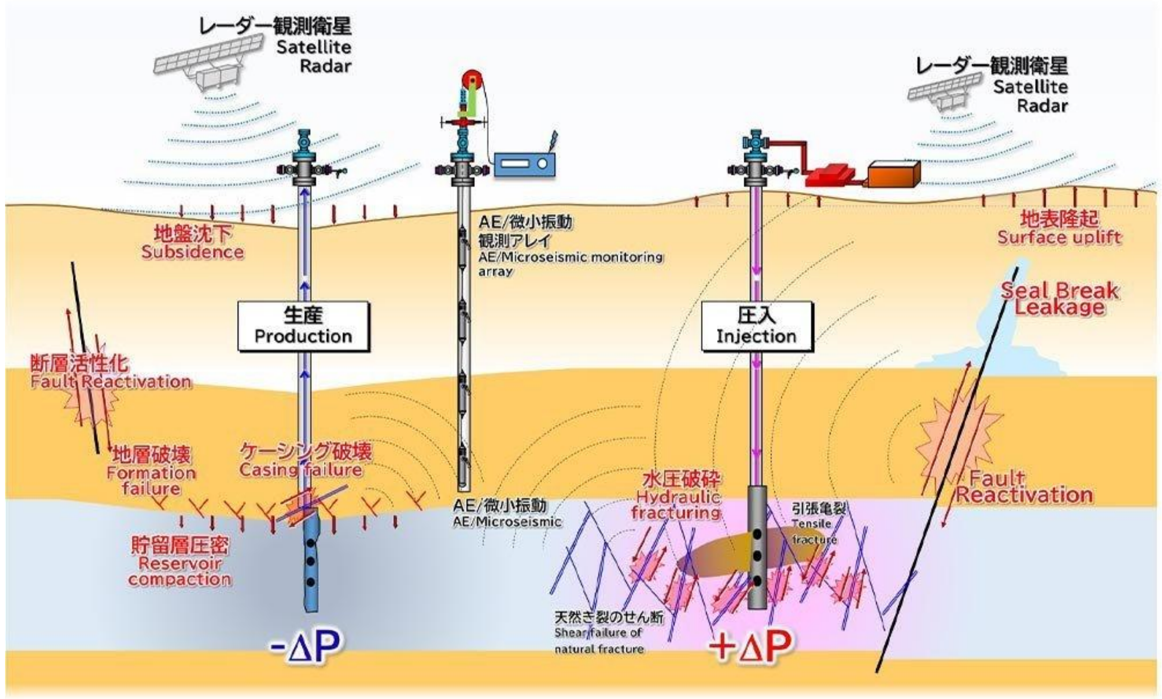
- Cap rock and Fault

Also near well thermal stresses!

- Differential thermal expansion
  - Rock
  - Casing
  - Cement

Can lead to localized injectivity improvement but containment problems.

GEM has fully coupled geomechanics including fault reactivation



Structural problems - Geochemistry

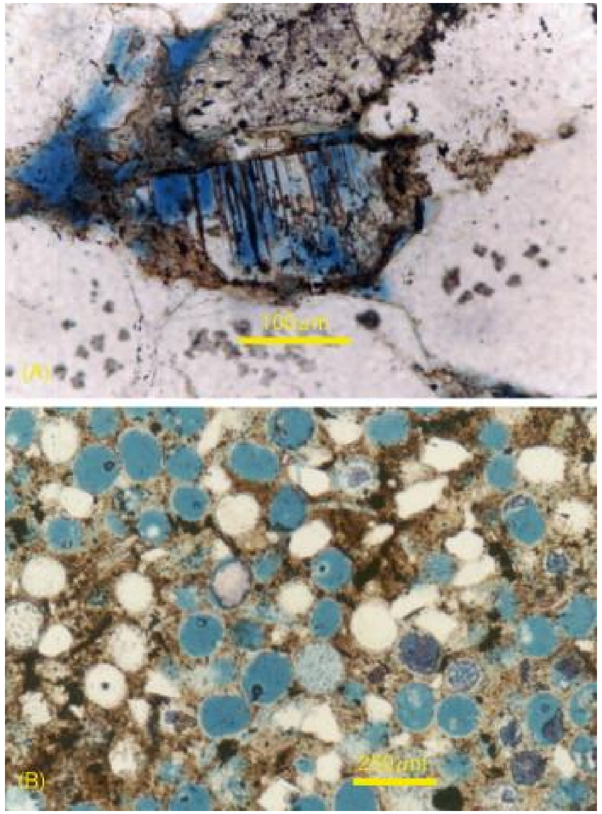
Water vapourization as CO_2 dries out the near well area

- Salt deposition and permeability reduction
- Although now have improvement due to single phase flow!

Potential for dissolution of reservoir cement by carbonic acid

- Depends on how fast you think that reaction is
- Potential rock matrix integrity problems around the well

GEM has full geochemical capability since 2004



Regular Fluid Flow Problems

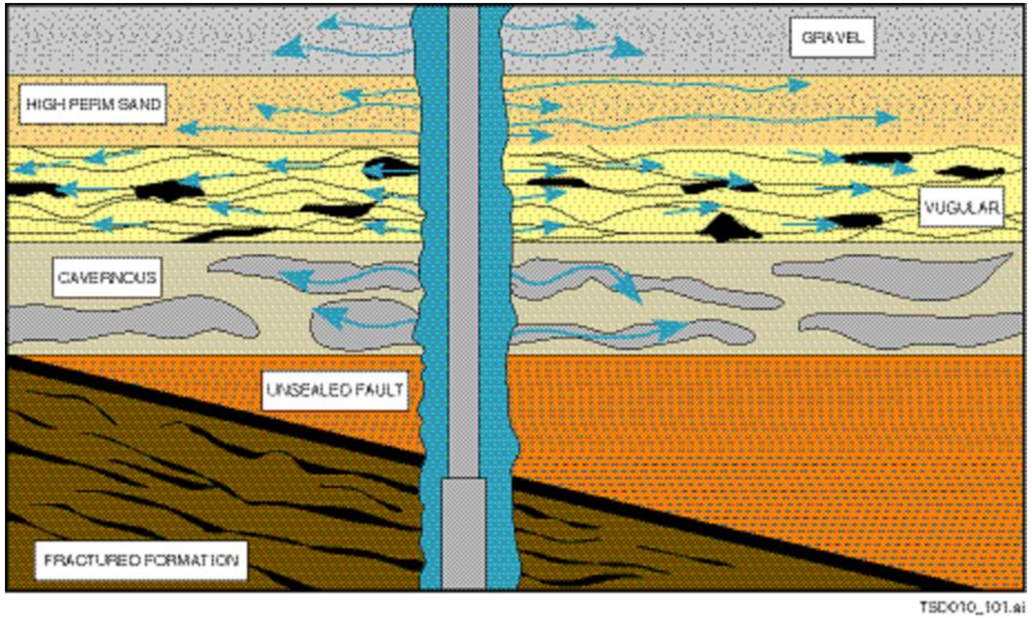
General reservoir structure / heterogeneity / layering

Fluid Flow

- Changes in relative permeability; viscosity; hysteresis effects; and phase trapping

Propagation of pressure, temperature and fluid fronts, and their resultant back pressure on the well

GEM is a fully compositional and thermal reservoir simulator



Problem changes from Storage, to Injectivity and Well operation

Discussion now changed from storage capacity to ability to inject!

- Can I consistently meet my contracted CO_2 disposal amounts?

The goal is risk, and hence cost, reduction

- Optimizing well and facilities design
- Optimization of well numbers
- Avoiding 'dangerous' operating conditions

What is the impact of my CO_2 deliverability model?

- Varying rates, pressures, temperatures and compositions of supply

How to safely operate my wells?

Detailed reservoir-well simulation can answer those questions

Do I need to consider heaters?

- In my well or at wellhead?

What size of wellbore is optimal and lowest risk

- How does that impact the number of required wells?

What size and type of compression/pump is required?

If well injectivity is degraded, does it drop injection rates below a commercial threshold?

- Do I need to drill a back up well(s)?

How frequently will wells need to be shut-in for treatment, if at all?

What treatments are effective?

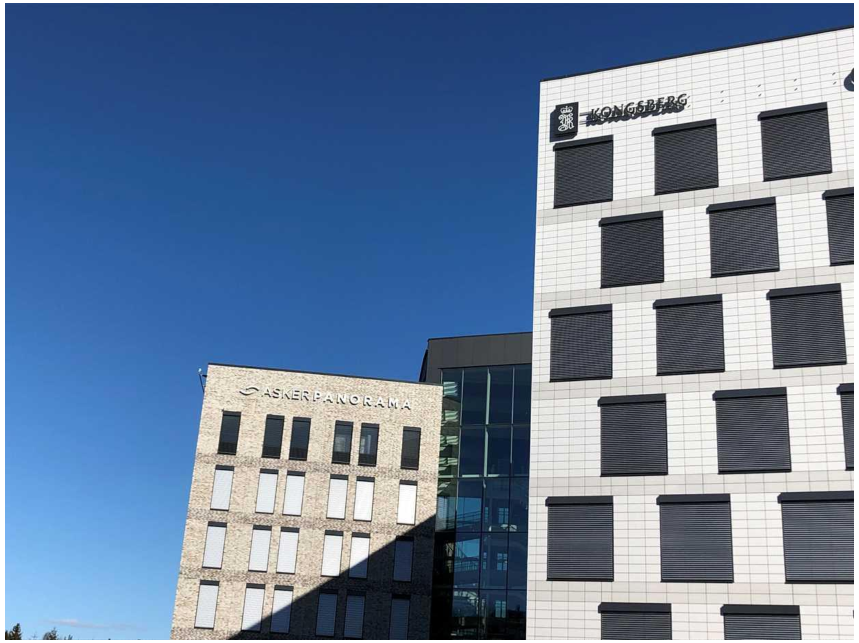
- How long will each treatment take?
- How long can the treatment take before other problems are induced?

Emergency shut down and restart?

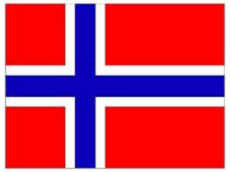
Overall system optimization

- Pipeline – Well - Reservoir

GEM – LedaFlow Coupling for CO2 Injection



GELECO2



Purpose of the JIP

Primarily to create a Controller to connect a Flow Assurance pipe flow simulator with an appropriate Reservoir Simulator to improve the ability to understand well performance when injecting CO_2 into low P and T reservoirs and deep saline aquifers.

- This will also build knowledge on how to couple the different timescales; discretization levels; transfer of data related to P, T and fluid properties

Secondarily to add capabilities to the simulators to allow better and more accurate representation of the expected CO_2 system behaviour in a variety of use case scenarios.

- E.g. Pure CO_2 phase behaviour and $T<0C$

Project Kick-off meeting happened on 14th February 2022 (2 year project)

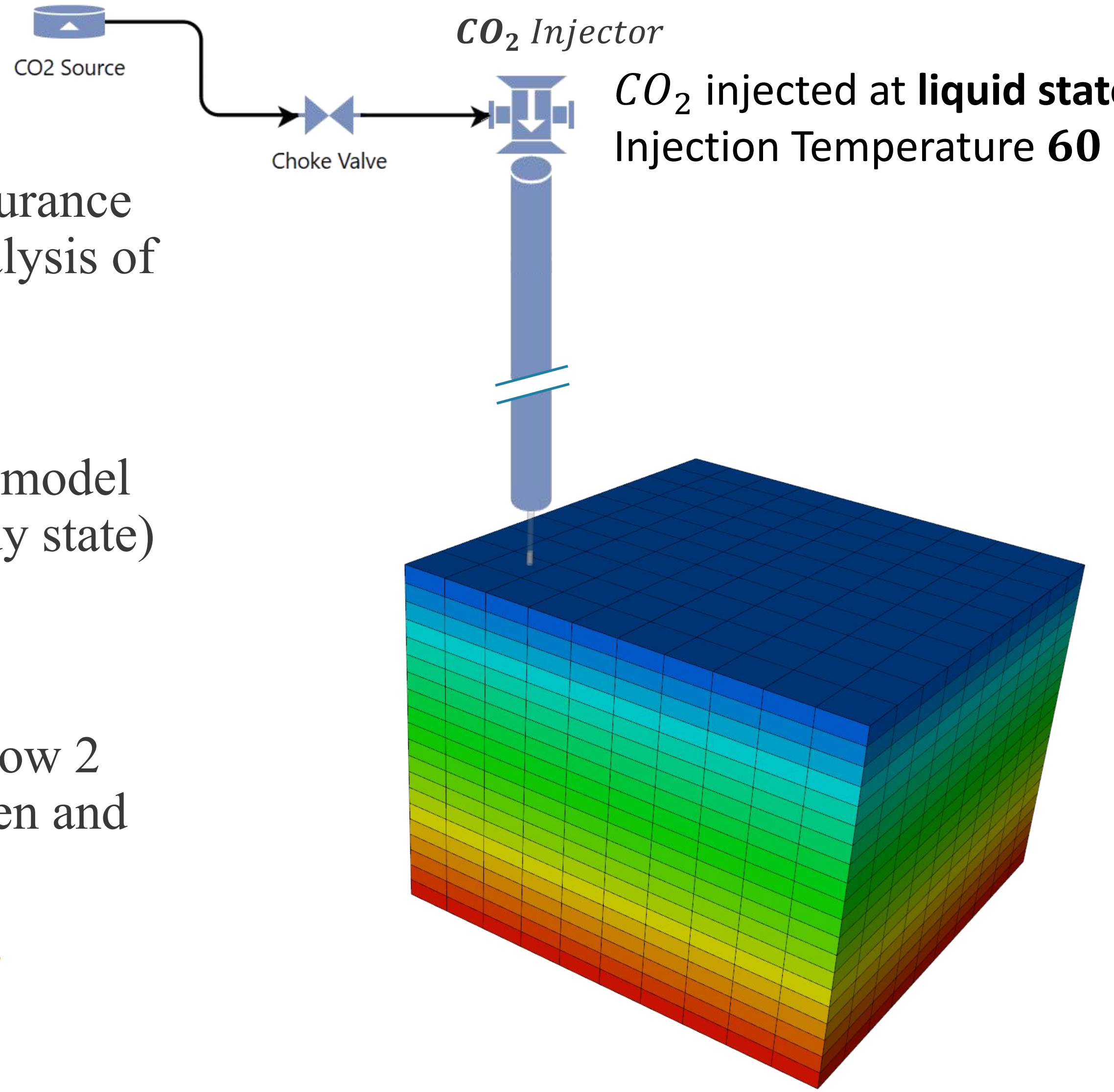
- Participants
  - **Total; Wintershall; Neptune; EBN; JX Nippon; Pale Blue Dot; ENI; Repsol; BP; Pertamina**
- Additional funding from CLIMIT (linked to Norwegian government)

Surface and Wells

- **Kongsberg's Ledaflow** Transient flow assurance well and pipe simulator allows detailed analysis of short term flow considerations

- **CMG's CoFlow** well and surface network model allows detailed analysis of long term (steady state) flow considerations

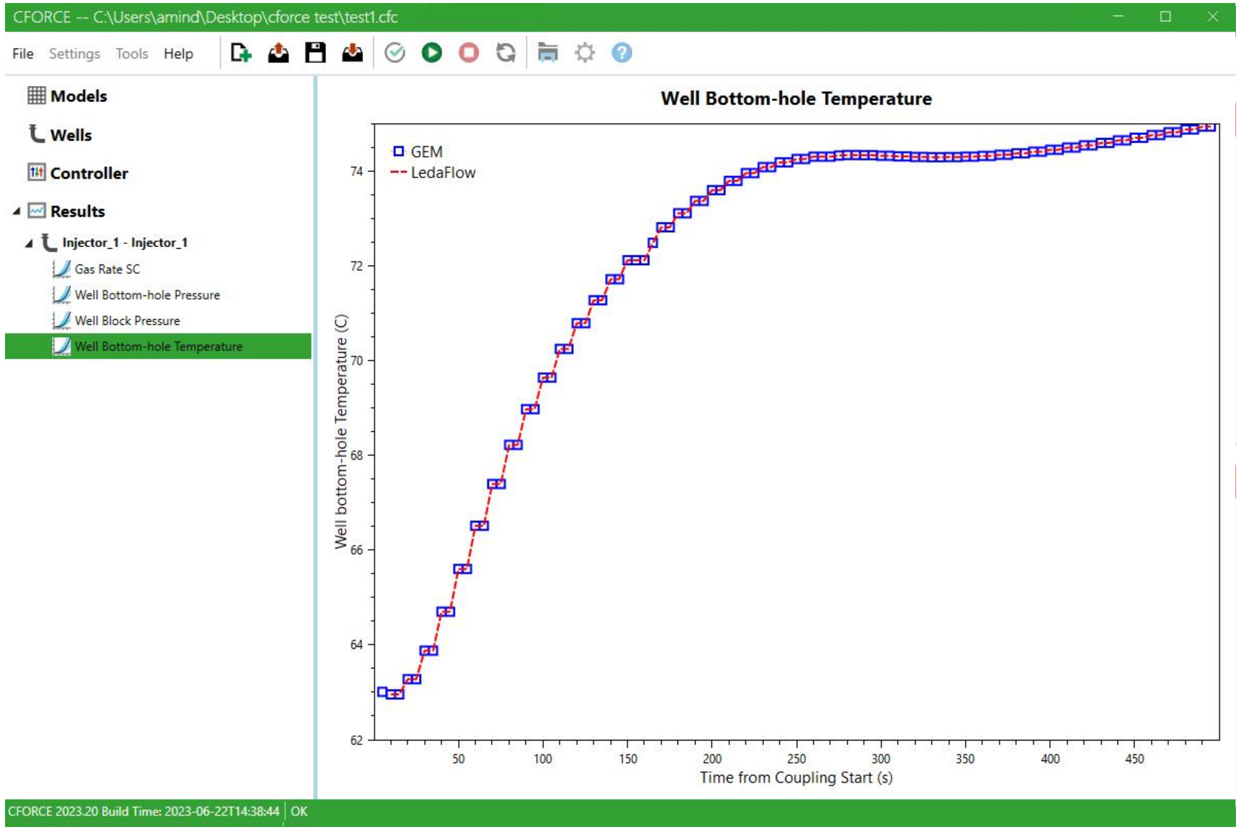
- CMG has an excellent YouTube video on how 2 phase flow of CO2 in the well system is seen and understood from a steady state perspective:
  - https://www.youtube.com/watch?v=prE0z-lxmeo&t=469s

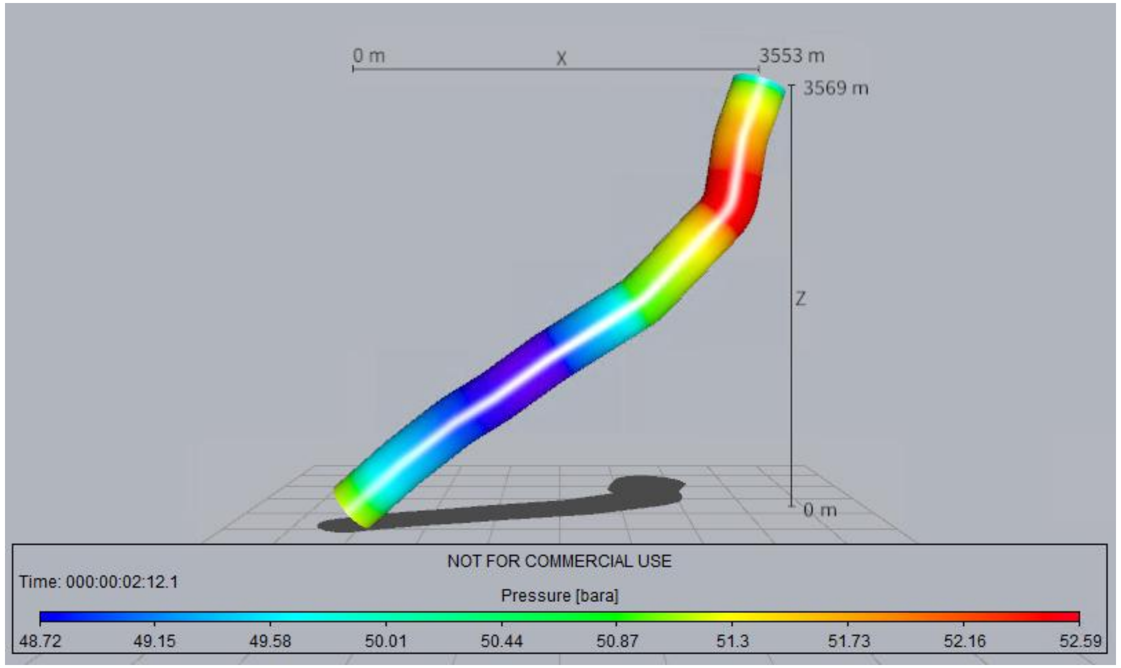


CO_2 injected at **liquid state** (at surface)
Injection Temperature **60** °F

CForce

1. Links Ledaflow transient pipe and well model to GEM for CO_2 injection
2. First ever link between such a transient well model and a reservoir simulator
3. Will become commercially available in March 2024





So where are we today?

CO_2 EOR works economically, especially in the USA

There are many potential storage sites available

- The current problem is how to gather the CO_2 and inject it safely and continuously

Saline aquifer disposal is simpler

- But a higher amount of uncertainty is associated with the storage site and overall trapping of the CO_2
- May or may not be close to existing infrastructure

Depleted reservoir disposal is complex

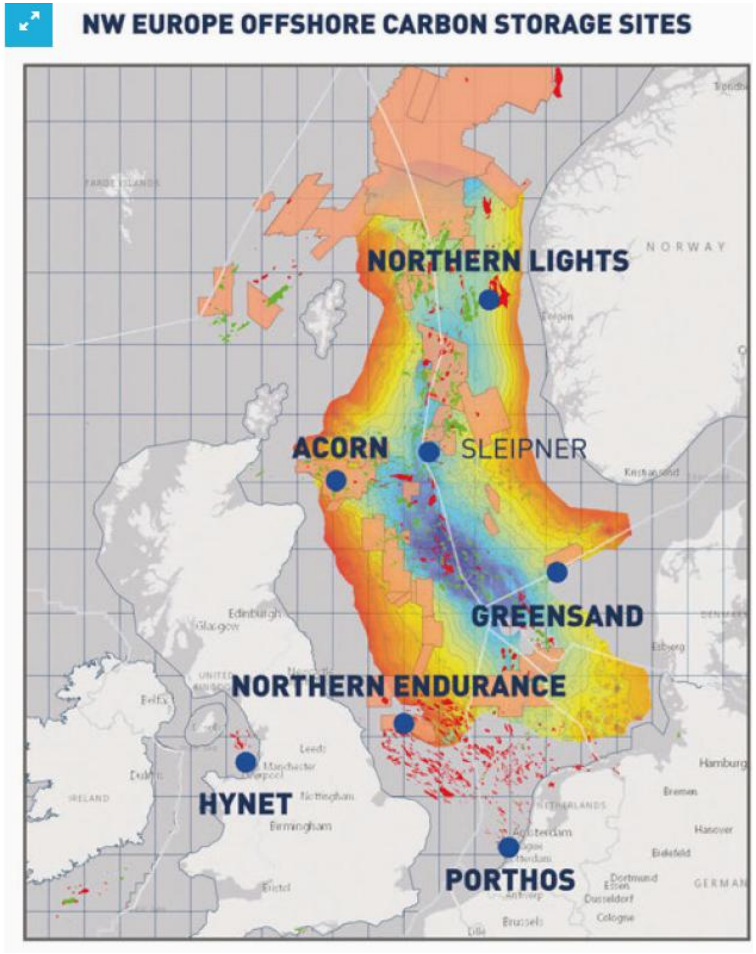
- But we know a lot about the storage site itself
- There is typically existing infrastructure
- Safe operational ranges for wells becomes more important

CMG with our GEM reservoir simulator is the leader in CO_2 based processes

CMG’s Work in Europe

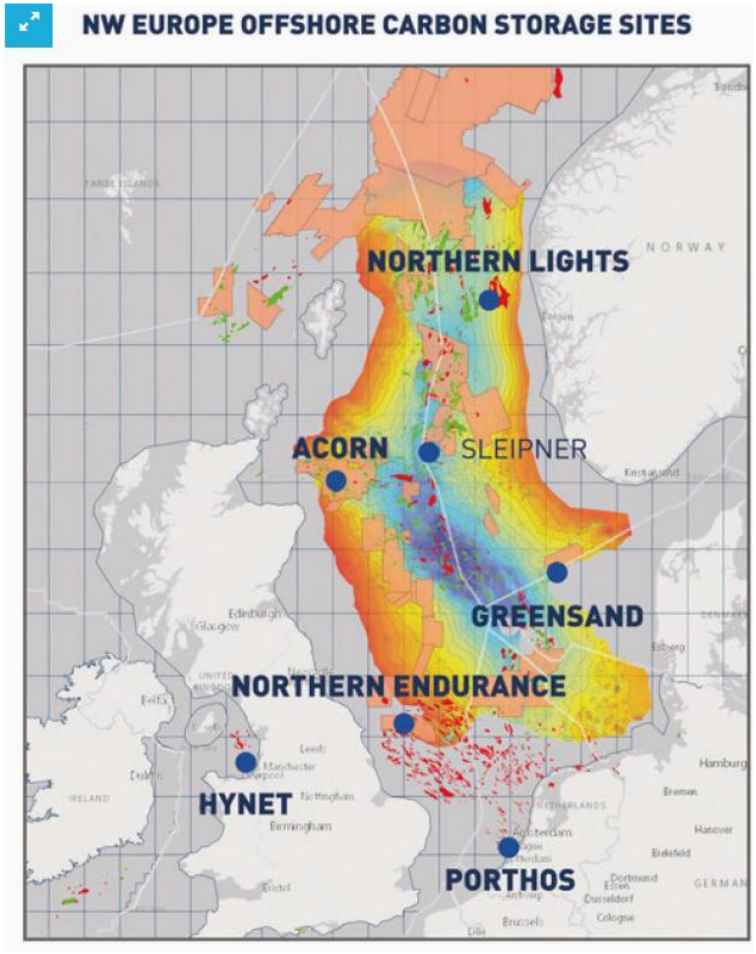
CMG GEM in Europe : Major CCS projects

1. Hynet (Depleted gas field)
   - ENI operated Liverpool Bay fields. ENI are using CMG GEM for all their CCS simulation, following extensive benchmarking. Track 1 cluster – scheduled to start injecting CO2 by 2025
2. Endurance (Saline aquifer)
   - The Northern Endurance Partnership operated by OGCI, and managed by BP. BP have standardized on GEM for CCS. Track 1 cluster - scheduled to start injecting CO2 by 2025
3. VNZ Fields (Depleted gas field)
   - Southern North Sea Basin – Operated by Harbour Energy who are also a partner in the Acorn Project. CMG completed a CCS consulting project for Harbour Energy last year. Track 2 cluster - scheduled to start injecting CO2 by 2030
4. Acorn (Saline aquifer)
   - Operated by Pale Blue Dot Energy. Simulation being performed in GEM by Shell, with the Pale Blue Dot engineers reviewing and monitoring in B/R with some GEM CLOUD simulations.



CMG GEM in Europe : Major CCS projects

5. DelpHYnus Project (Saline aquifer)
   - Southern North Sea - Neptune Energy operated. Hypersaline aquifer. Also interested in depleted gas fields. GEM used in the planning, and will be used going forward.
6. Greensand Project (Depleted gas field)
   - Offshore Denmark – consortium lead by WintershallDEA. Using GEM/CoFlow for CCS simulation, in particular salt deposition around the well. Depleted gas field with added complication of tanker delivery.
7. Port of Rotterdam (Depleted gas field)
   - Operated by EBN/Taqa. CMG GEM successfully benchmarked and used for all CCS simulation.
8. Icelandic 'Carbfix'
   - Novel process by which CO2 is injected into hot basaltic rock and is mineralized and thus trapped deep underground in the Earth's crust.



CCS @ CMG (70 companies and regulators)

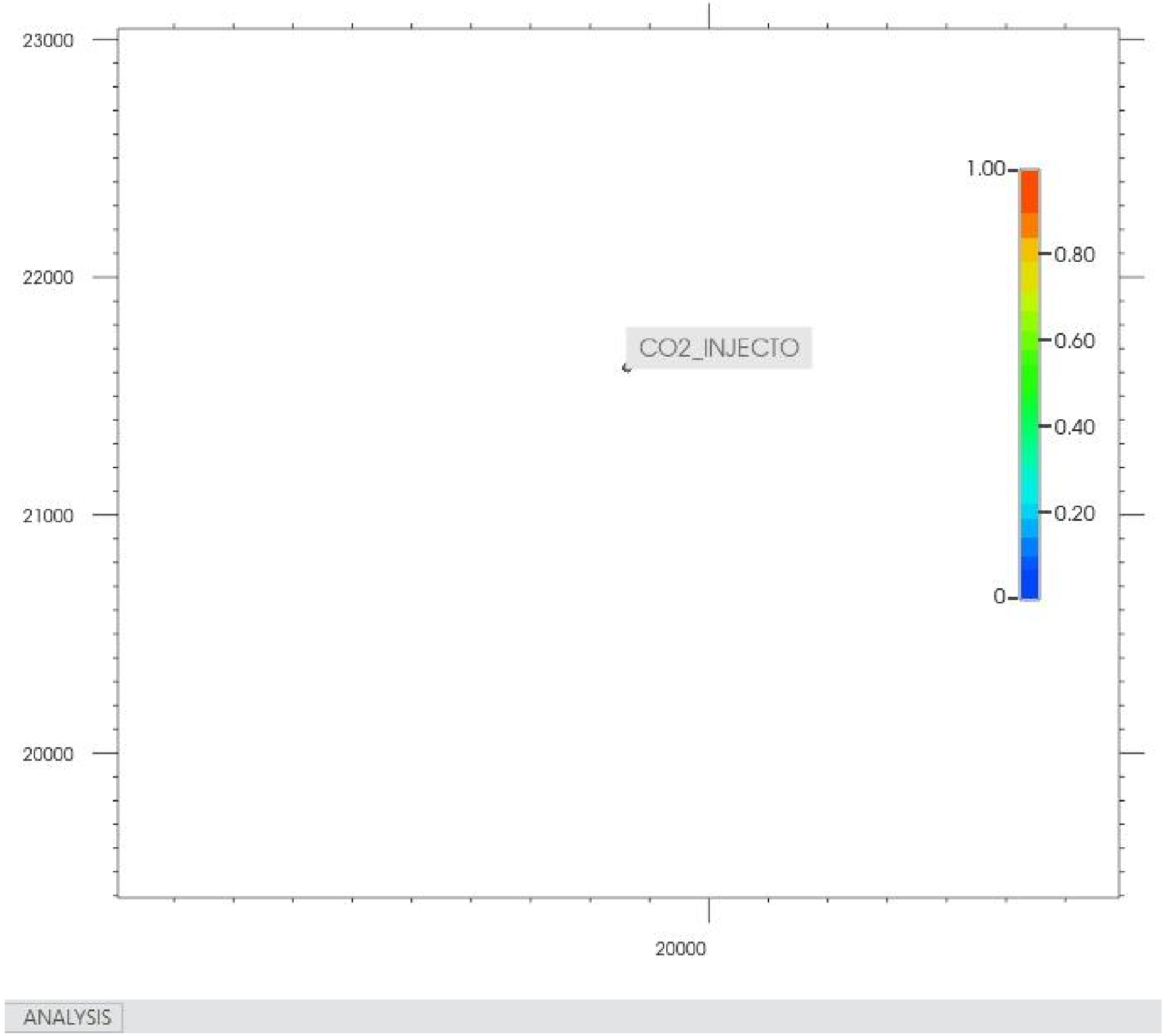
1. Europe
   - BP; ENI; Repsol; Wintershall; Total; Shell; Neptune Energy; Harbour Energy; Pale Blue Dot; Storegga; GEUS;
2. Asia
   - Petronas; Pertamina; JX Nippon; Japex; INPEX; Toho Earth Sciences; Taisei; Japan Oil Engineering; KIGAM
3. Middle East
   - 44.01 (drilling well with ADNOC)
4. Canada
   - Shell; CNRL; Saskatchewan Power; Enbridge; Pembina; TC Energy; Suncor; Entropy; Vault; Moraine; Heartland Power; Wolf Carbon Solutions; North River Midstream; Kiwetinohk; Pathways Alliance; West Lake Energy; AltaGas; Tourmaline Oil Corp
   - Alberta Energy Regulator
   - Natural Resources Canada

4. USA
   - ExxonMobil; Talos Energy; Denbury; Devon; Occidental; AERA Energy; CRC; Shell; BP; Repsol
   - Baker Hughes; Longquist; RESPEC; GHD; Next Decade; Ryder Scott; Vault 44.01; Elysian; Blue Sky International; Storegga; Milestone; Air Products; Carbon America
5. US Government Institutions
   - North Dakota Industrial Commission
   - Wyoming Department of Environmental Quality
   - Louisiana Department of Natural Resources
   - Alaska Department of Natural Resources
   - West Virginia Department of Environmental Protection
   - Battelle National Laboratory
6. Collaborations with:
   - WOOD; Hatch; McDaniel; ABB

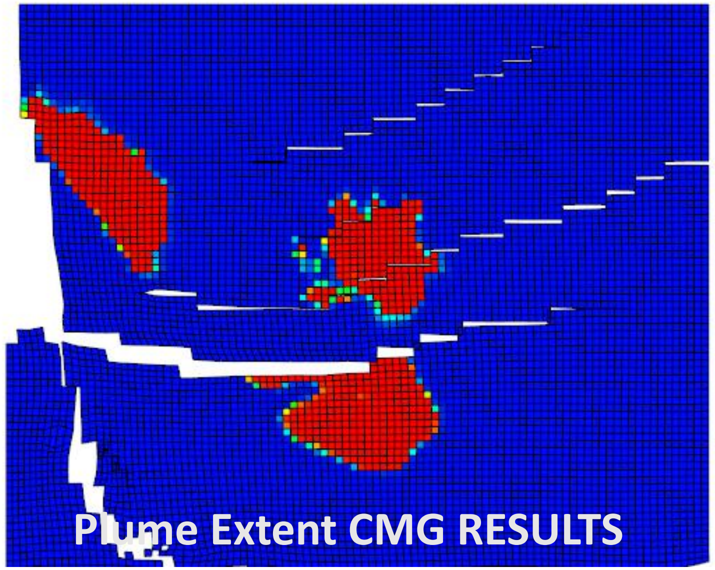
Useful Additions

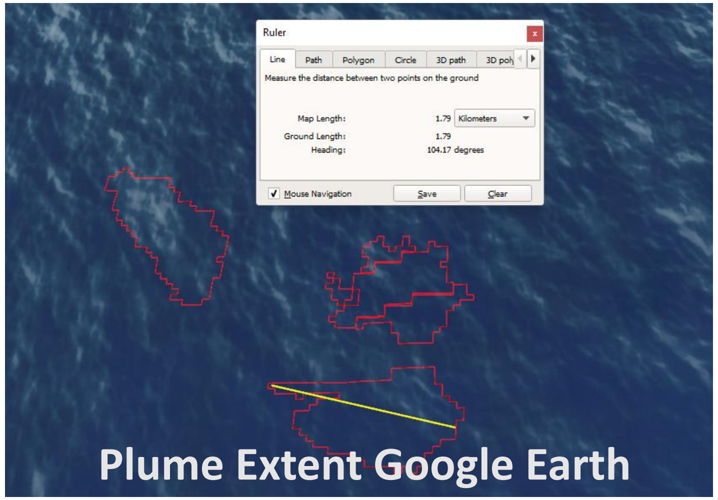
Boundary Polygons and Export of Shapefiles

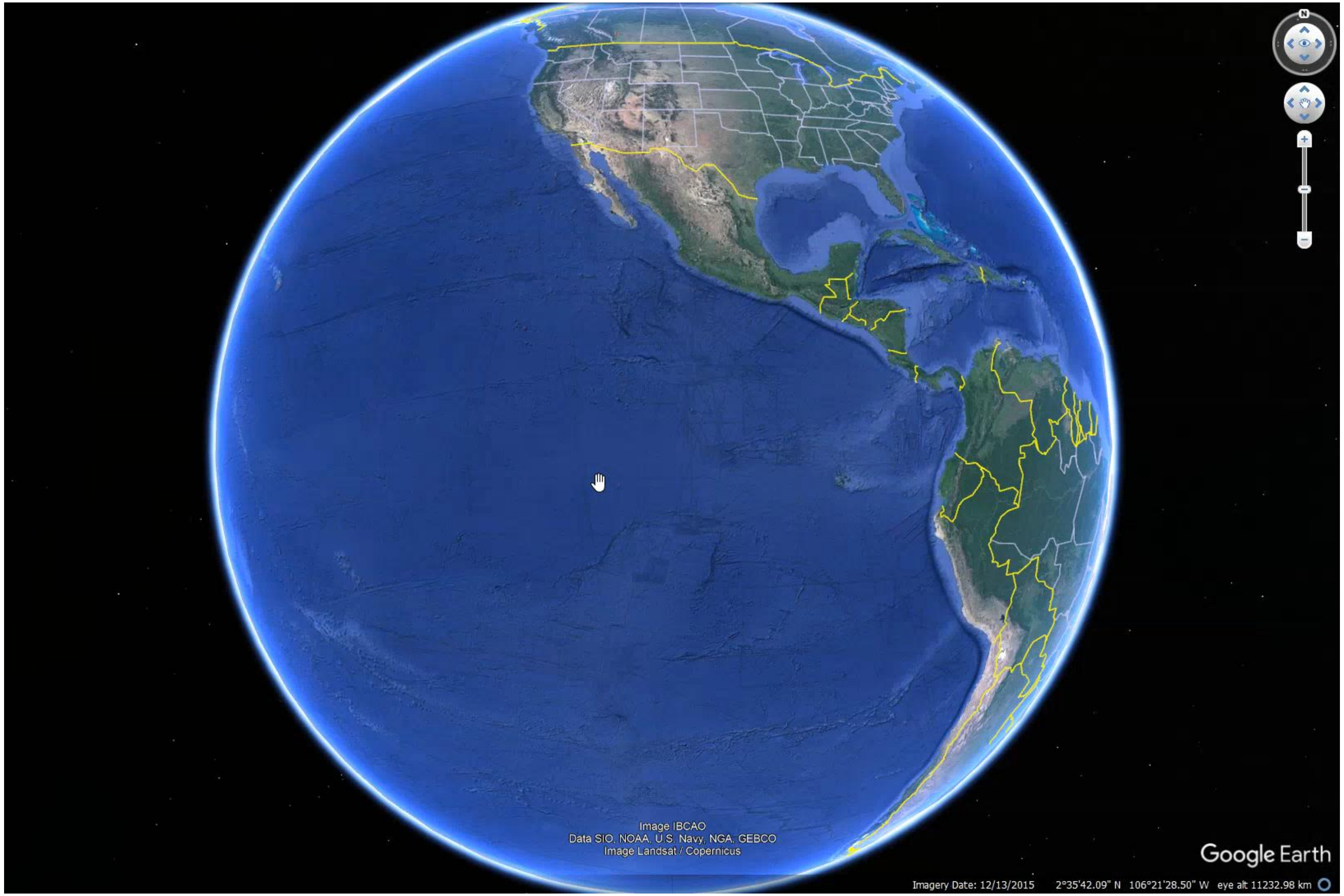
- Can highlight aerial areas of interest based on active filters
- Highlighted areas at specified time intervals can be exported to shapefiles for further analysis in a GIS application
- Examples:
  - Horizontal plume extent of CO_2 injection
  - Aerial extent of a SAGD steam chamber
  - Polymer injection flood pattern at a specified interval
  - Subsurface fluid migration across lease planes



Boundary Polygons and Export of Shapefiles







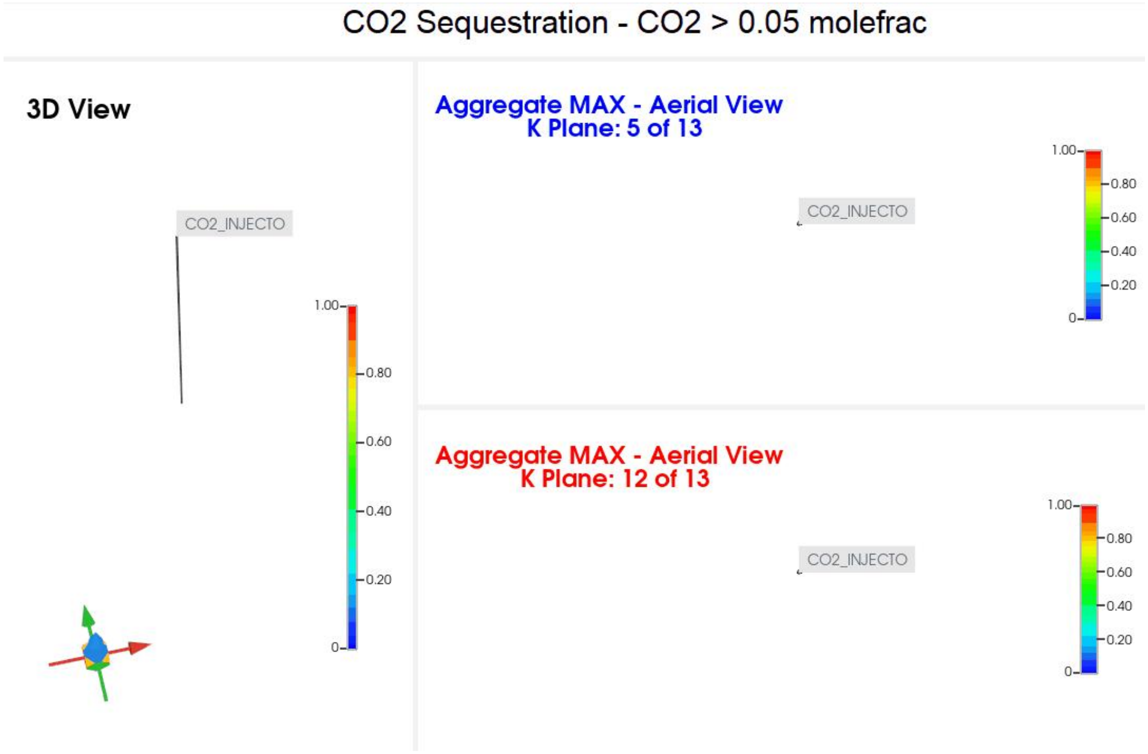
Vertical Column Property Aggregation

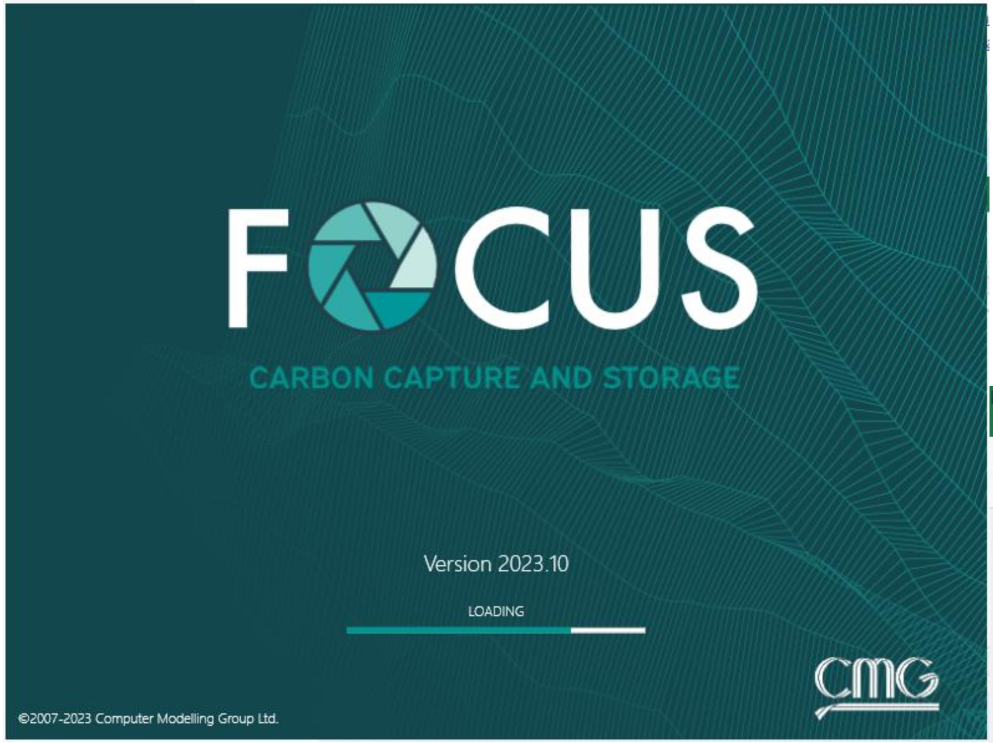
Challenge

Quickly capturing and understand the horizontal extent of fluid or pressure migration over an operating area can give important insights into the recovery process and assessing uncertainty. However, this can be especially tedious in models with many vertical layers.

Solution

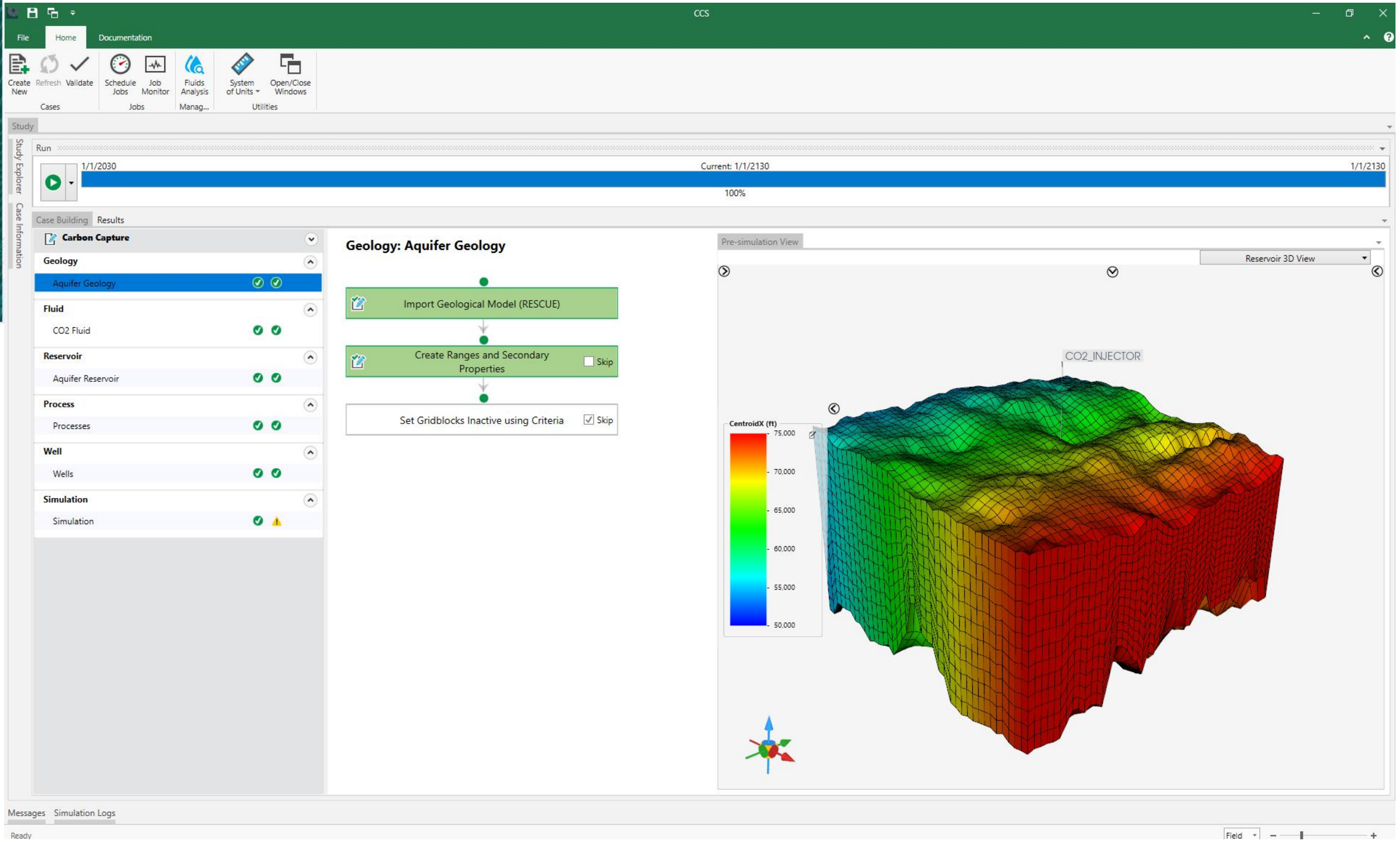
- Aggregate property values in the same vertical column
- Aggregate based on Max, Min, or Average values
- Quickly identify fluid horizonal migration irrespective of the current vertical layer displayed
- Combine with Boundary Polygons to highlight and export areas of interest





New product to launch in 2024

- Focused on building and analysing CO2 storage models
- Initial aim for Aquifer storage
- Will add depleted oil/gas; H2; geothermal later



Winprop to support CO2 in STARS

WinProp updates for fluid modelling and PVT creation

Isenthalpic Flash Improvements

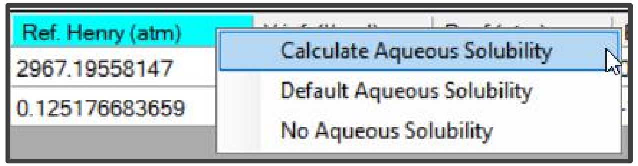
- Perform and plot a series of isenthalpic flashes for a range of pressures
- Obtain the enthalpy value based on the given pressure and temperature (in addition to the existing user input option)
- Important in understanding thermal operation conditions (e.g. thermal EOR and Geothermal)

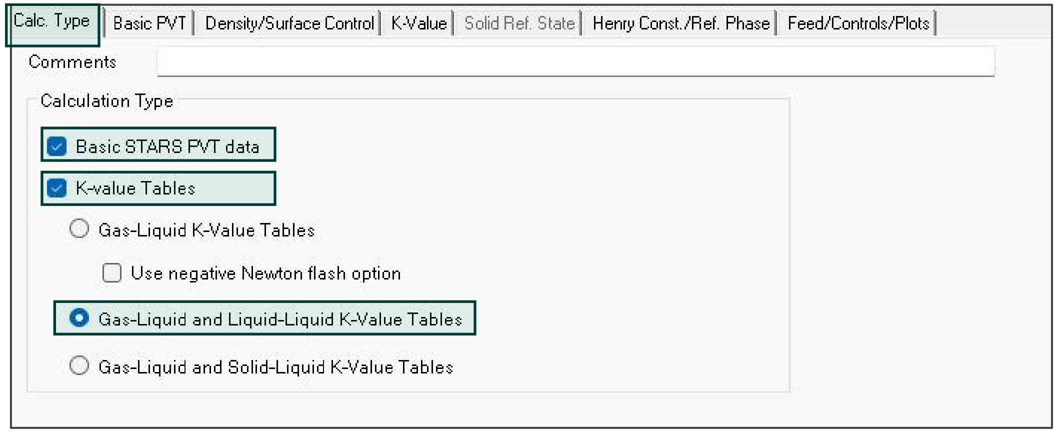
Enhancements to Fluid Model Creation- defining solubility of pure gases

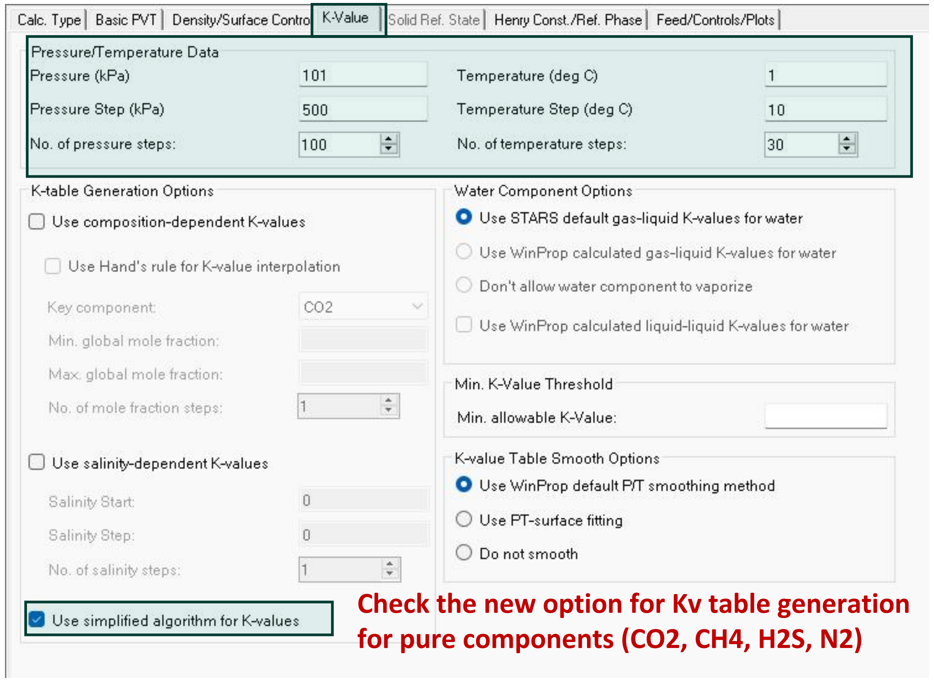
- Automated K-Value outputs for pure gaseous components when solubility needs to be considered (such as for CO_2, H_2S, CH_4, and N_2). Important for CCS, Aquathermolysis, Solvent and NCG, EOR, etc.

STARS CO_2 K_v Generation in WINPROP (2022.30 +)

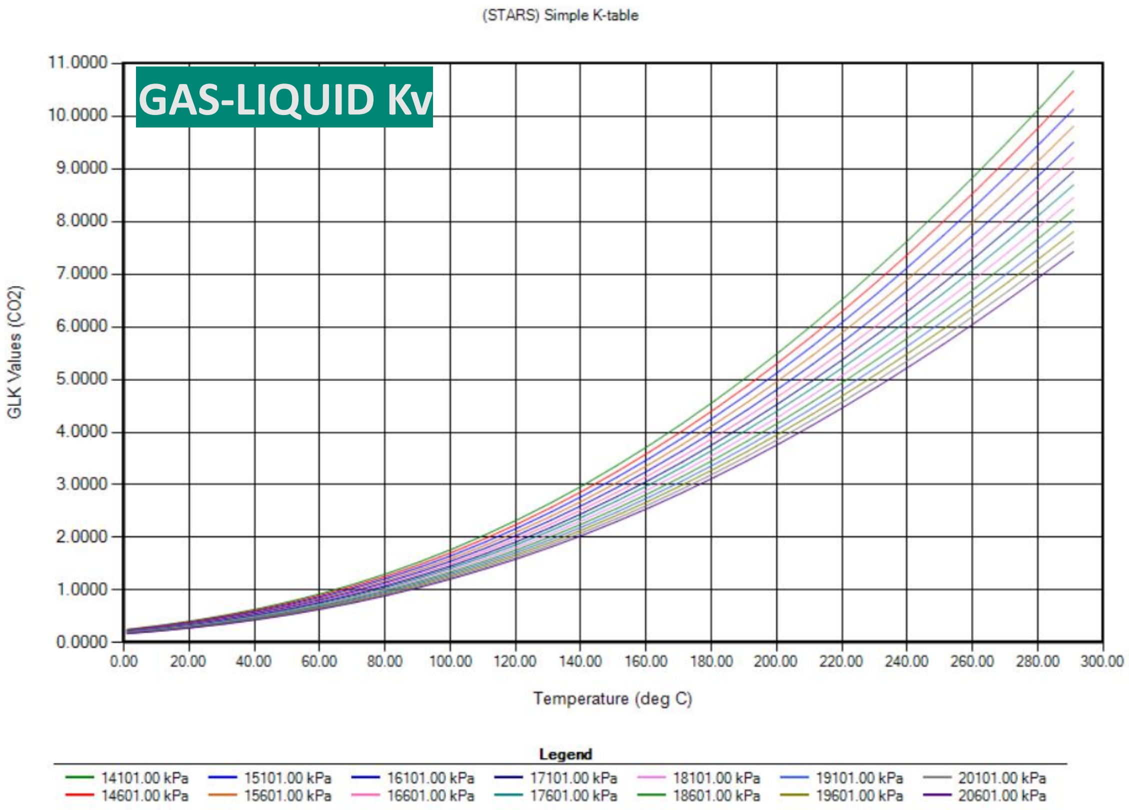
1. Add **CO2** and **H2O** as components
2. Use the **''Calculate Aqueous Solubility''** tool to compute the Henry Constant at desired (p,T) conditions
3. Set the Primary mole fraction to be **100% CO2**
4. Enable a **CMG STARS PVT data** calculation form

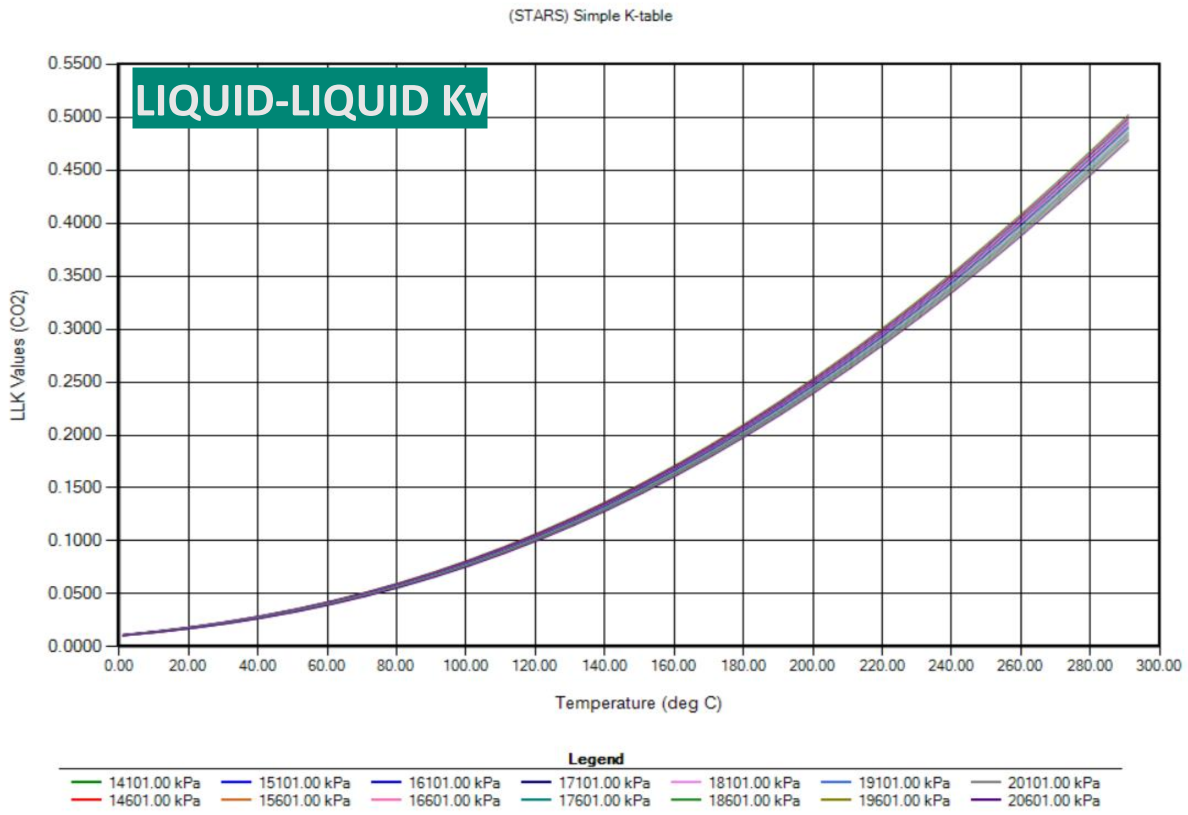






STARS CO_2 K_v Generation in WINPROP (2022.30 +)





Summary

1. GEM is our primary simulator for all CO_2 related processes
   - Used extensively in Europe; USA; Japan; SE Asia
2. Links to Ledaflow for detailed wellbore transient analysis
3. Links to CoFlow for detailed steady state wellbore and pipeline analysis
4. STARS Flexwell can also be used to provide a transient well model for pure CO_2 etc using new output capabilities in Winprop
5. IMEX is being modified to allow CO_2 so it can be used for super fast plume migration analysis
6. Focus will be our Energy Transition platform to allow companies to move away from using oil and gas simulators and their interfaces to a CO_2, H_2, geothermal specific environment
   - The relevant simulators will be packaged into this product to provide the level of detail required for each process

CMG is the world leader in CO_2 storage