2nd International Forum on Recent Developments of CCS Implementation
16th – 17th December 2015

Assessment of CO_2 Enhanced Oil Recovery Projects through Process Modelling

Adekola Lawal, Mario Calado, Alfredo Ramos and Andrew Green

PSE HISTORY: FROM RESEARCH TO INDUSTRY

1989 – 1997

Imperial College London

Centre for Process Systems Engineering

100s of person-years of R&D with industry

Simulation & modelling, optimization, numerical solutions techniques, supply chain

1997

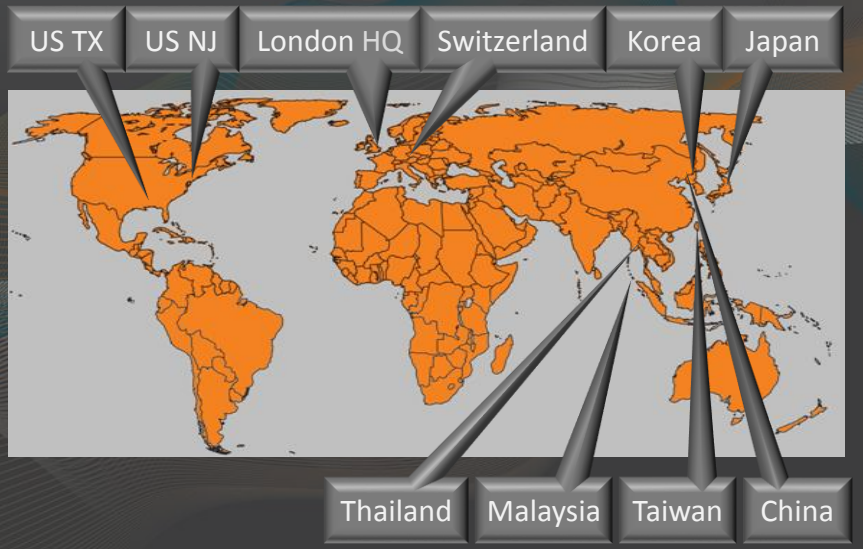
PSE

Company 'spun out'
Acquires technology

Private, independent company incorporated in UK

gPROMS

Now



Advanced Process Modelling

- Software and services (60:40)
- Major process industry focus – all sectors
- Strong R&D, strong commercials

Royal Academy MacRobert Award for Engineering Innovation

UK's highest engineering award

Previous winners include: Microsoft, IBM, Johnson Matthey, Rolls-Royce, BP

Global customer base (partial)

Americas

Air Products
BP Chemicals
Carus Corporation
CD Tech
C&I Engineering
ConocoPhillips
Dow Chemicals
DuPont
ExxonMobil
Ineos
Praxair

Eli Lilly
Energy Solutions
Folgers
Johns Manville
Minera EXAR
Procter & Gamble
Pfizer • SQM
Toyota Motor US
United Technologies RC
United Technologies Power

EMEA

Arkema • AstraZeneca
BP Chemicals
BP Exploration
BASF • CEPSA
E.On • EDF
Infineum • Indorama
Jacobs Engineering
Linde • Petrofac
Repsol • SABIC • SASOL
Shell • Siemens VAI -
Süd-Chemie • Sulzer
TOTAL • Wacker Chemie
Wolff Cellulosics

Anglo Platinum
AstraZeneca
Atomic Weapons Est.
Cadbury's • Ceres Power
det Norske Veritas
Energy Technologies Institute
FL Smidth • Friesland Campina
GSK • National Nuclear Labs
Nestlé • Purac
Veolia • Voith Paper

APAC

Idemitsu Petrochemicals
GS E&C • Hyosung
JGC • LG Chem
Mitsubishi Chemical
Posco •
Samnam Petrochemical
Samsung BP
SKC
SK Chemicals
SK Energy
SK Petrochemicals
Taiyo Nippon Sanso

Denso • KIER
Samsung Electronics
Samsung SDI
Sugar Australia
Toshiba Fuel Cell
Honda • Toyota CRDL
Toyota Motor Company

Background

gCCS

CO_2 Enhanced Oil Recovery

gCCS: The CCS System modelling Tool-kit Project

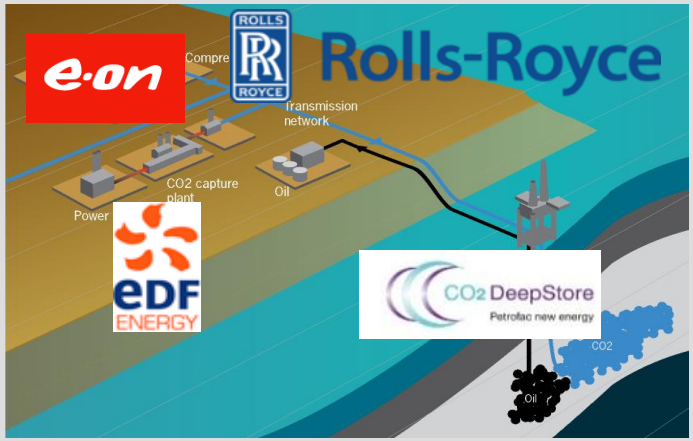
2011-2014

- **Energy Technologies Institute (ETI)**

corporate

public institutions

- ~$5m project commissioned & co-funded by the ETI
- Objective: **“end-to-end” CCS modelling tool**



gPROMS modelling platform & expertise

Project Management

gCCS current scope (ETI project deliverable)

- **Process models**
  - Power generation
    - Conventional: pulverised-coal, CCGT
    - Non-conventional: oxy-fuelled, IGCC
  - Solvent-based CO_2 capture
  - CO_2 compression & liquefaction
  - CO_2 transportation
  - CO_2 injection in sub-sea storage
  - CO_2 Enhanced oil recovery
- **Materials models**
  - cubic EoS (PR 78)
    - flue gas in power plant
  - Corresponding States Model
    - water/steam streams
  - SAFT-VR SW/ SAFT-γ Mie
    - solvent-containing streams in CO_2 capture
  - SAFT-γ Mie
    - near-pure post-capture CO_2 streams
- Cost estimation
  - Equipment CAPEX & OPEX

Open architecture allows incorporation of 3rd party models

gCCS current scope (ETI project deliverable)

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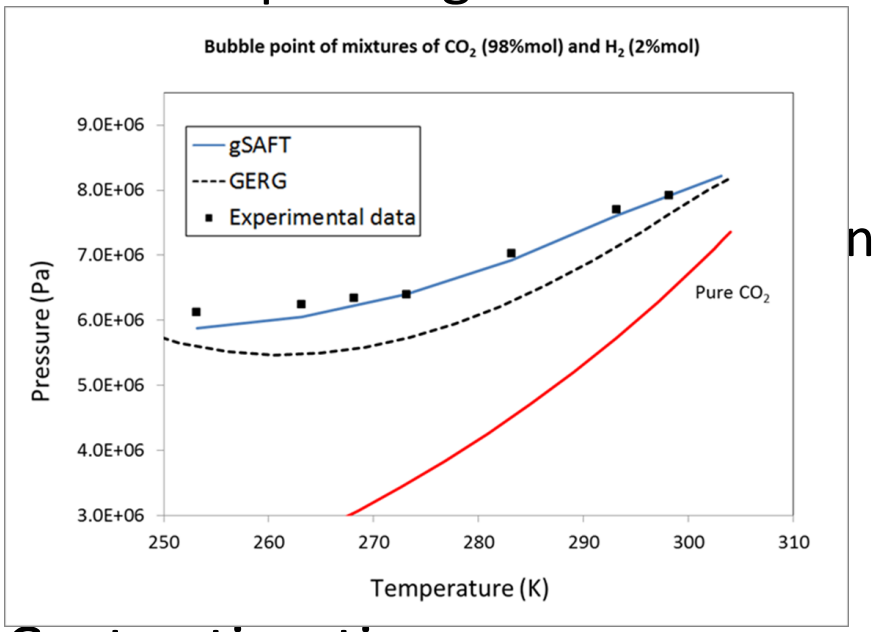

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CCSI™ Carbon Capture Simulation Initiative

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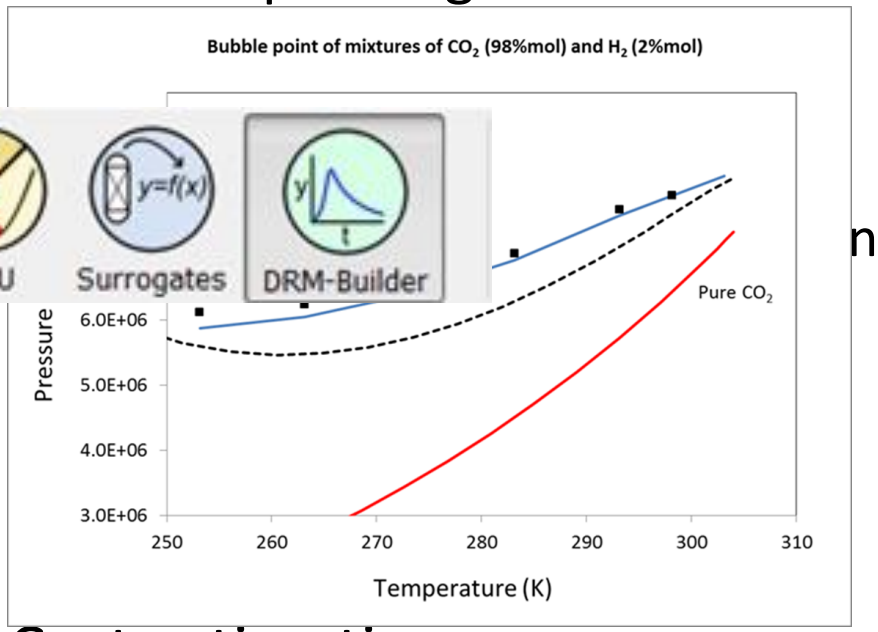

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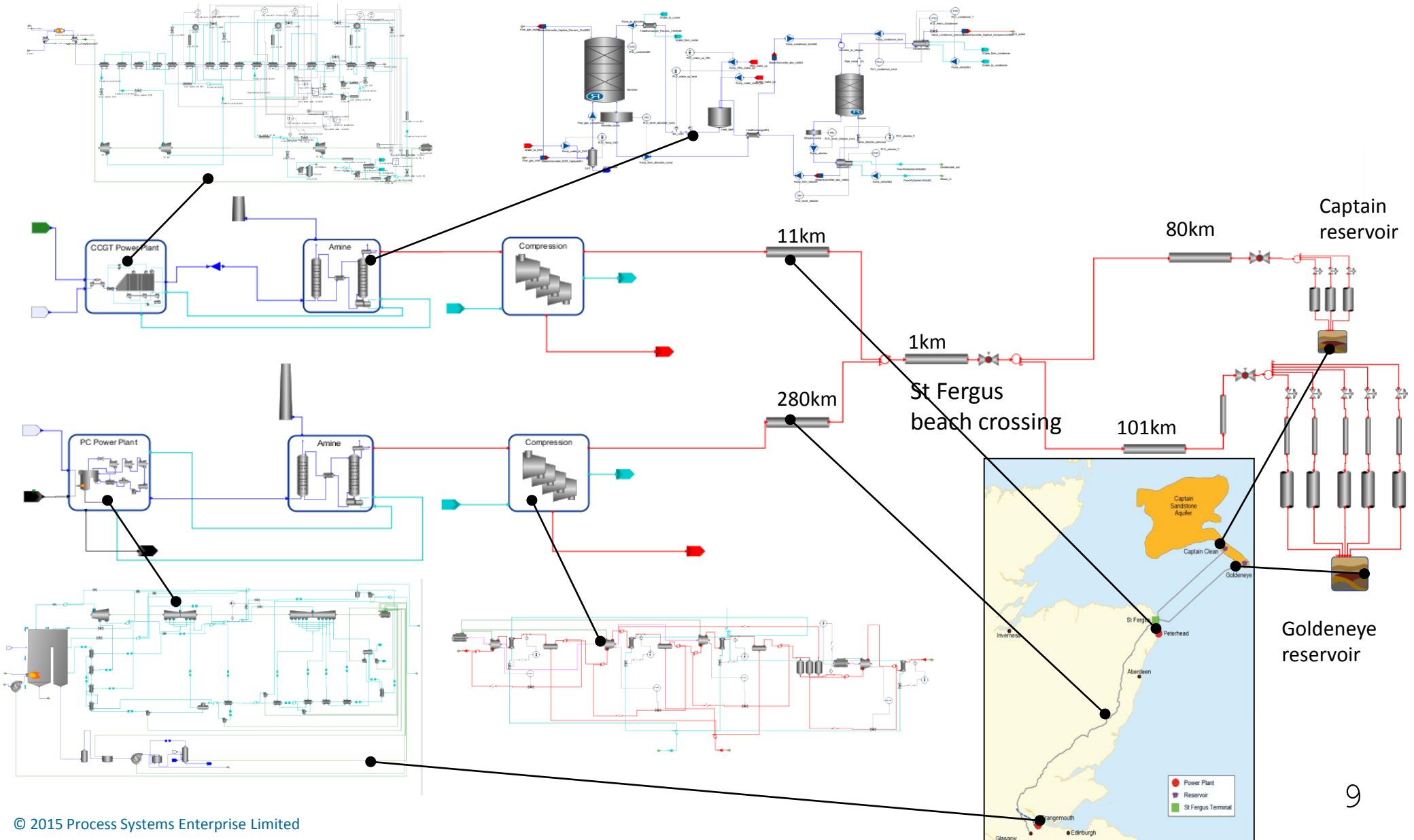
  - Equipment CAPEX & OPEX

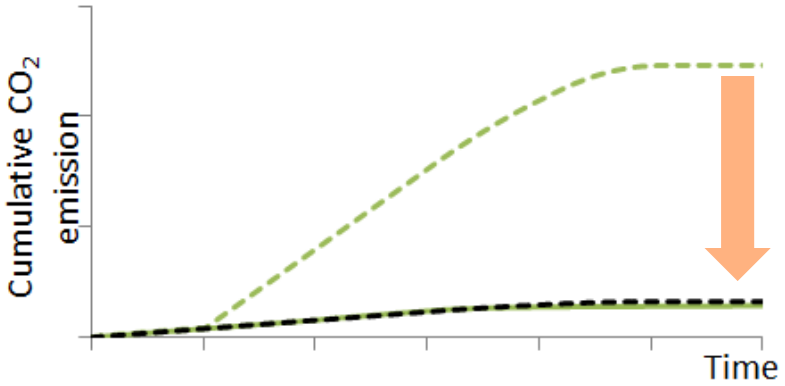
Open architecture allows incorporation of 3rd party models

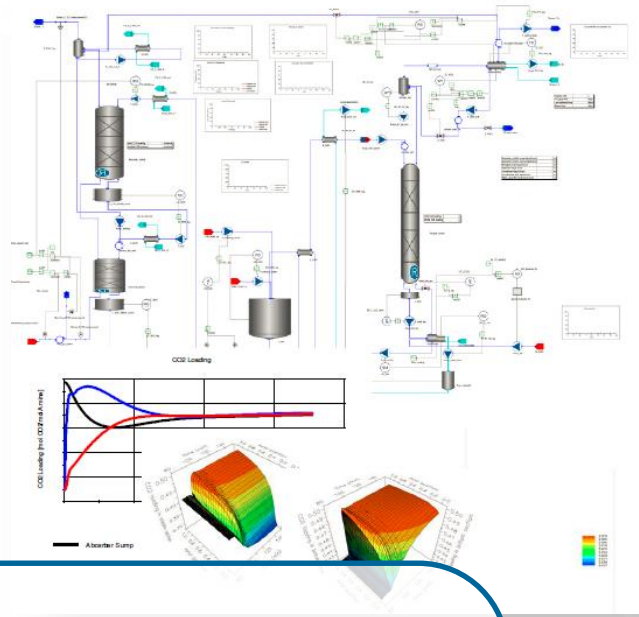
CCS network process simulation



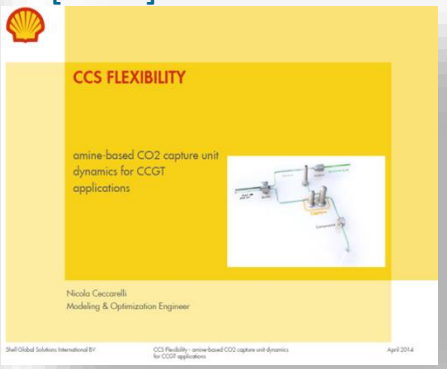
gCCS applications

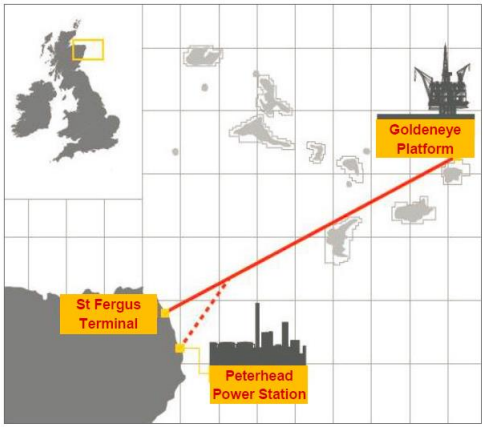
CCS Flexibility (Shell)



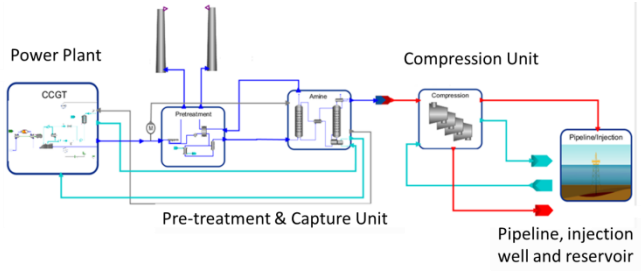


Optimizing start-up and shutdown procedures of gas treating plants [Shell]





CCS chain and network studies [Energy Technologies Institute] and [Shell]

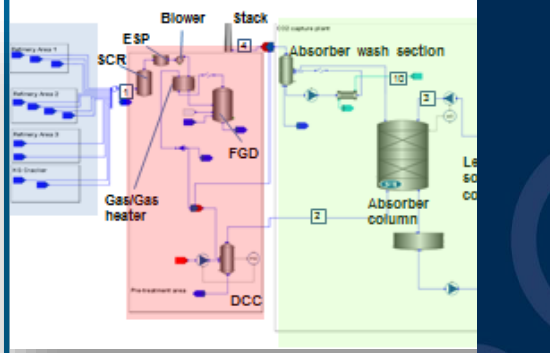


GCCSI Webinar:
"The Shell Peterhead CCS project: Understanding full-chain CCS operations"
June 2015

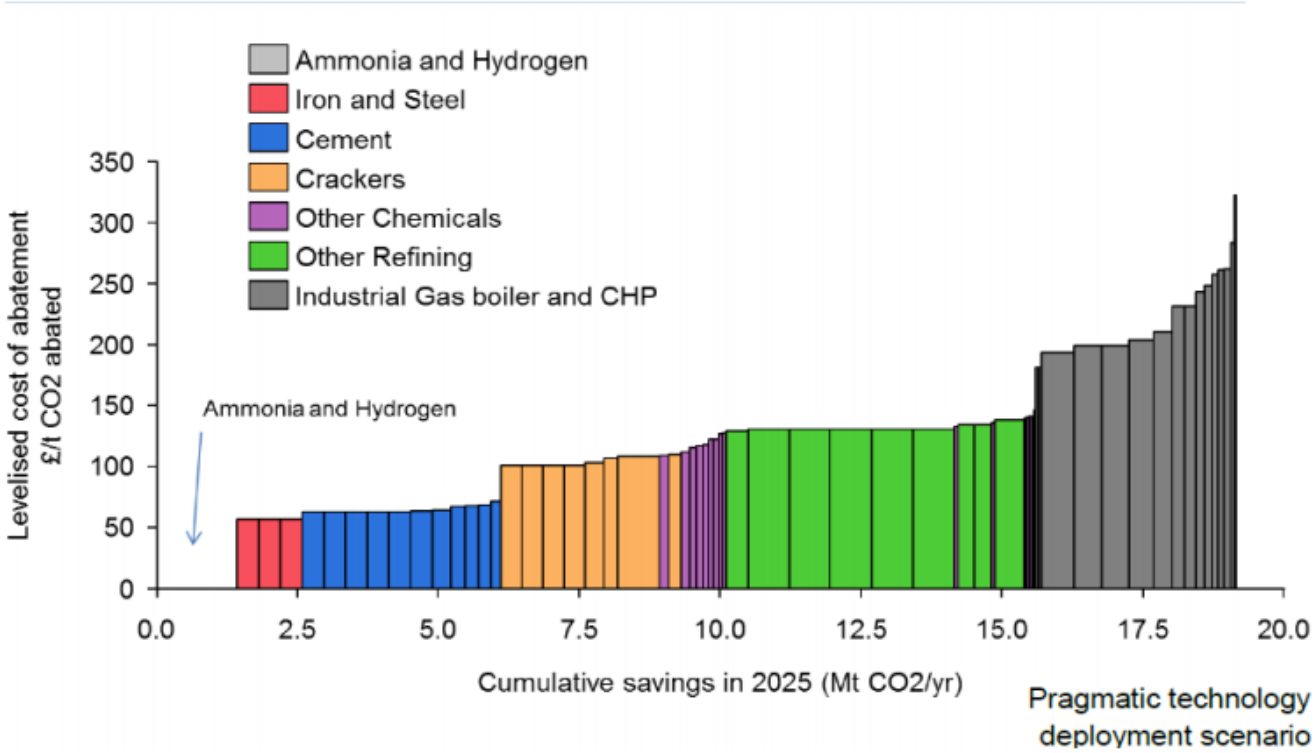
gCCS applications

Industrial CCS (DECC / Element Energy)

Techno-economic study of Industrial Carbon Capture and storage
[DECC and Element Energy]



MACC curve of capture technologies

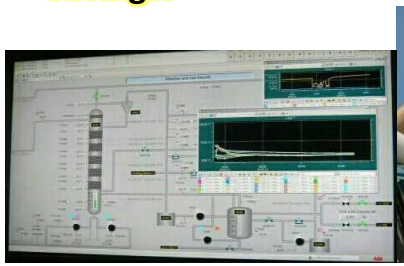


gCCS applications

CAPSULE (DECC / Carbon Clean Solutions)

Specific Project Objectives

- Reduce the solvent regeneration energy footprint by up to 40% as compared to a standard/current MEA process.
- Demonstrate zero solvent emissions from carbon capture plant.
- Reduce corrosion rates to migrate to inexpensive material of construction.
- Focus on process standardization, intensification and industrial scale up. Reduce the overall level of plant redundancy and overdesign to account for outage and performance risks in the future CO_2 capture systems.
- **Development of high-fidelity predictive models for optimising the design and operation of the full-scale plant in order to realise the full extent of these savings.**



Carbon Clean Solutions launches test campaign at pioneering Technology Centre Mongstad pilot

Test campaign intended to bring CCSL's patented technology to commercial readiness

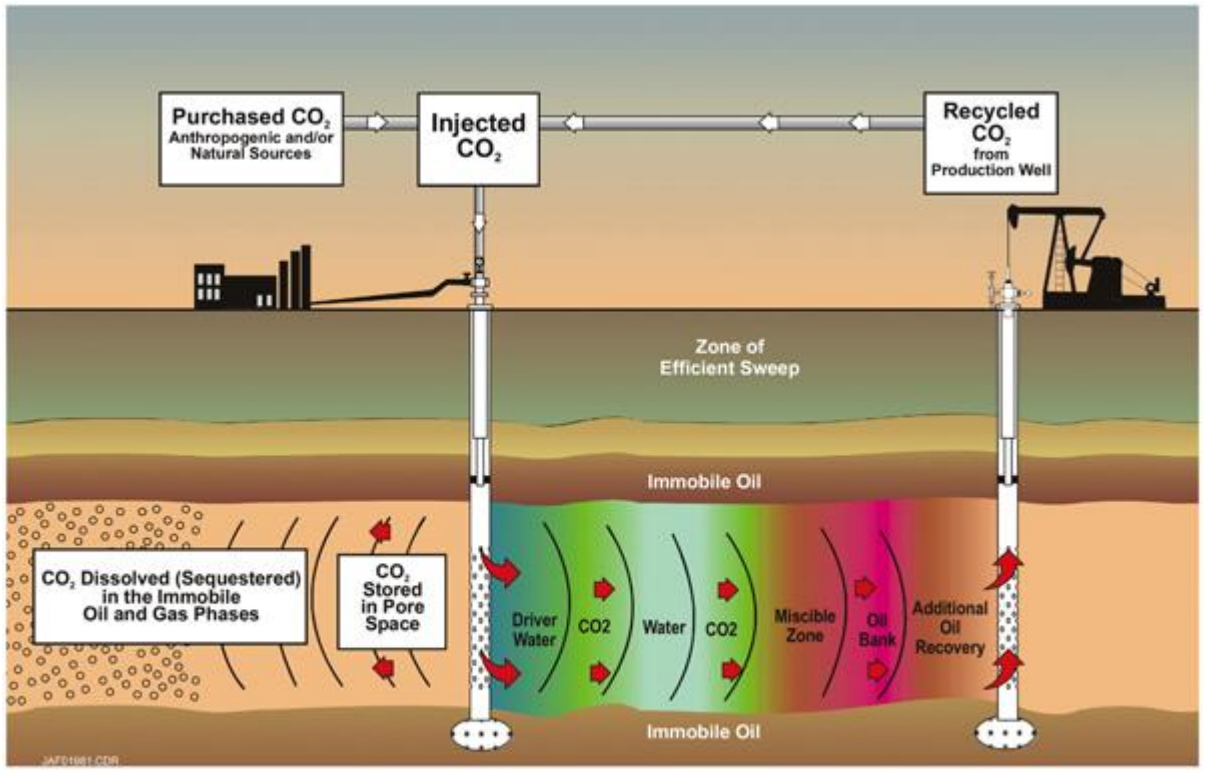
Department of Energy & Climate Change

Benefits

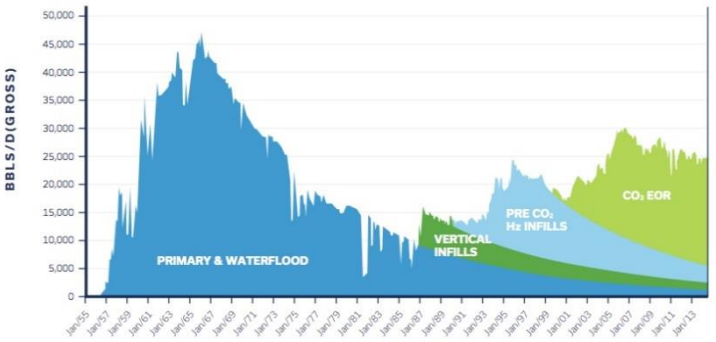
- The novel APBS solvents reduce the steam consumption by upto 40% which translates to an approximate 22% reduction in LCOE (levelised cost of electricity) for a CCS enabled power plant.
- Auxiliary electrical load, which consists mainly of pumps and fans, can be reduced by 50%.
- Improved process layout, which maximizes sharing of infrastructures and mitigation of expensive connections.
- Process standardization, better layouts and best metering technology selection will boost the confidence in future leading to savings realization between 5% - 7%. Also reduced redundancy and overdesign will reduce the risk premium leading to savings between 2% - 4%.

CO_2 Enhanced Oil Recovery

CO_2 Enhanced Oil Recovery: Key facts



Source: Advanced Resources International and Melzer Consulting, Optimization of CO_2 Storage in CO_2 Enhanced Oil Recovery Projects, prepared for UK Department of Energy & Climate Change, November 2010.

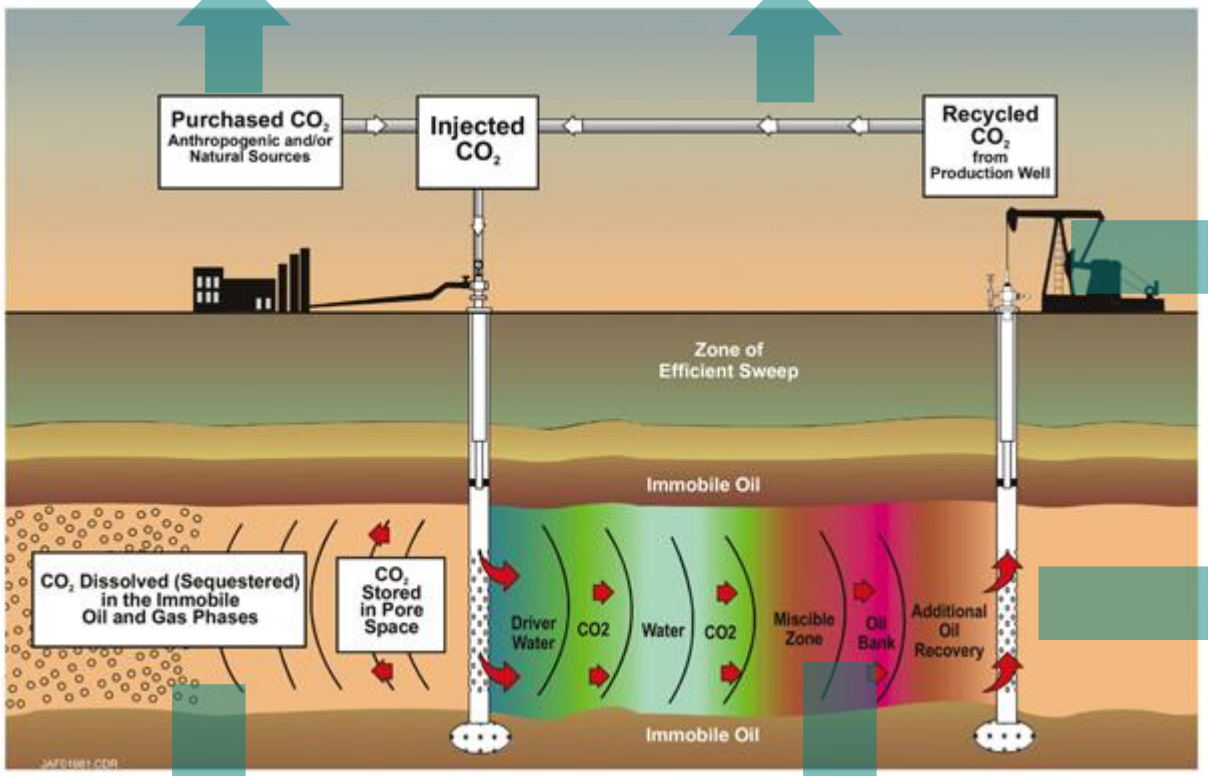


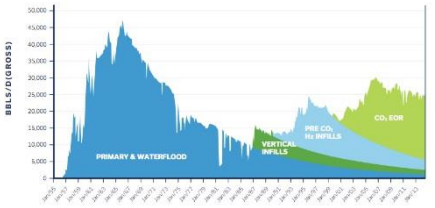
- CO_2 EOR is a typical tertiary oil recovery mechanism which can allow a further 5 – 30% Original oil in place (OOIP) of production
- Has been used extensively since 1970s especially onshore USA
- Some CO_2 remains trapped in reservoirs – can be used to reduce anthropogenic emissions

CO_2 Enhanced Oil Recovery: Challenges

Supply vs demand
- Constraints, Costs

Handling of recycled gas before and after breakthrough





How do I optimize field development schedules?

- Capacity/design/location of facilities?
- Design trade-offs?
- How long can we produce sales gas to spec?

What are the produced fluid composition changes before and after CO_2 breakthrough

How much CO_2 is stored?

- Reservoir dynamic performance?
  - How much oil, water, gas and CO_2 is produced with time?
  - Pressure maintenance requirements?

CO_2 Enhanced Oil Recovery: Challenges

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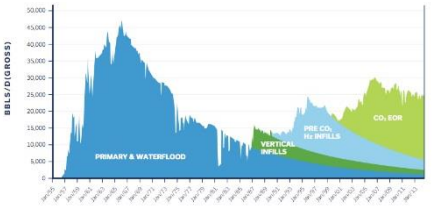

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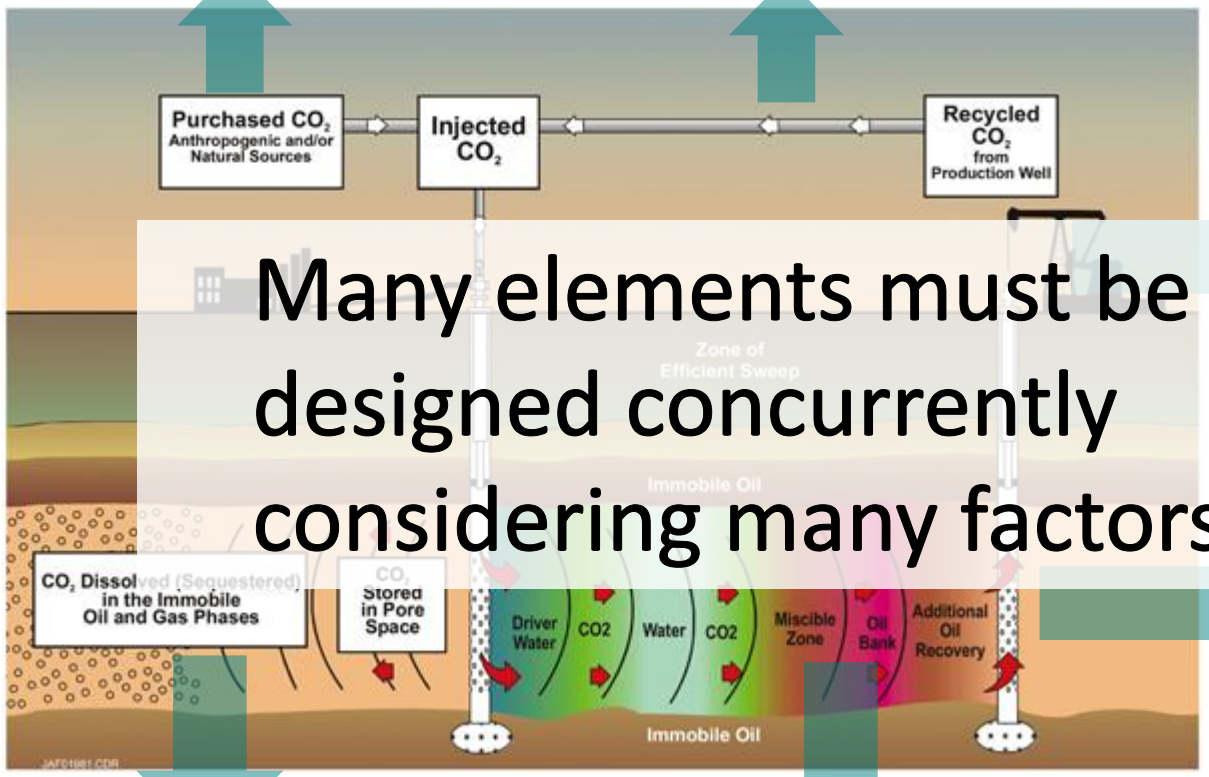

Many elements must be designed concurrently considering many factors

- Capacity/design/location of facilities?
- Design trade-offs?
- How long can we produce sales gas to spec?

What are the produced fluid composition changes before and after CO_2 breakthrough

How much CO_2 is stored?

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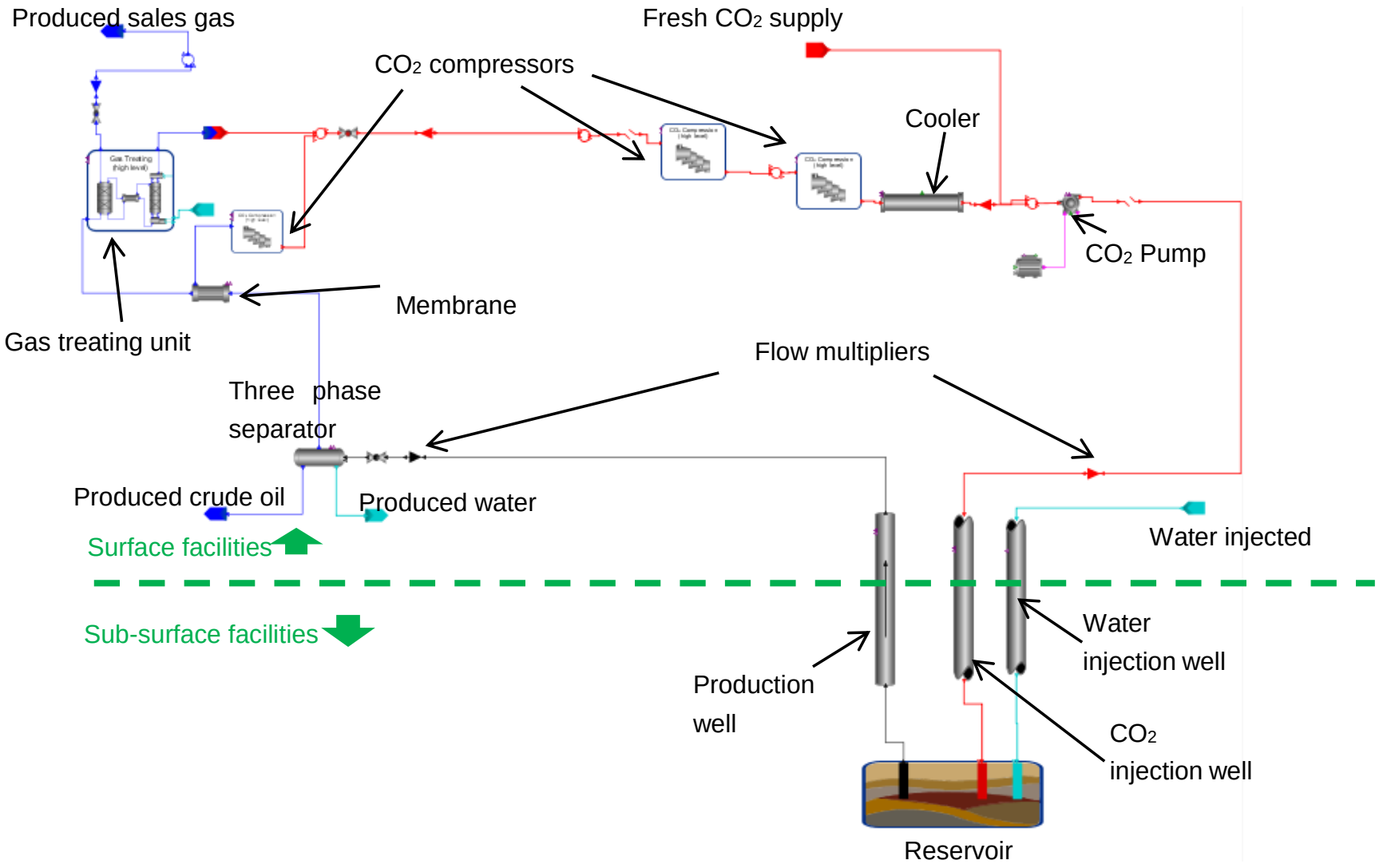
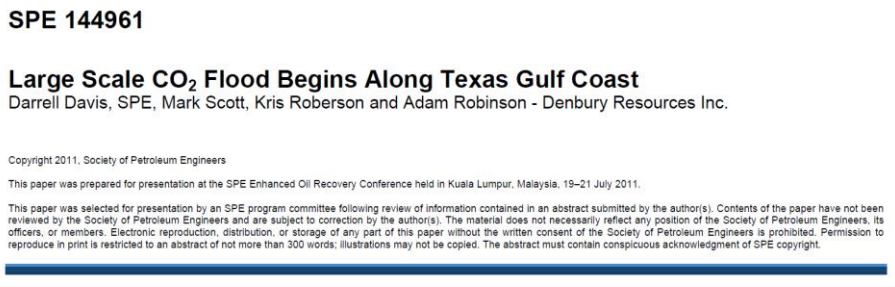
gCCS

CO_2 EOR Flowsheet in gCCS



Case Study basis

- 70 patterns
- 80 acres per pattern, 75ft thickness, 6000ft depth
- 31° API oil viscosity
- 1.2 RB/STB (oil);
- OOIP – 9.3MMSTB per pattern; HCPV – 11.2MMRB per pattern
- Current production: 1000BOPD; >99% water cut
- Absolute permeability: 1000mD
- Reservoir pressure: 3000psi
- GOR – 400 scf/stb

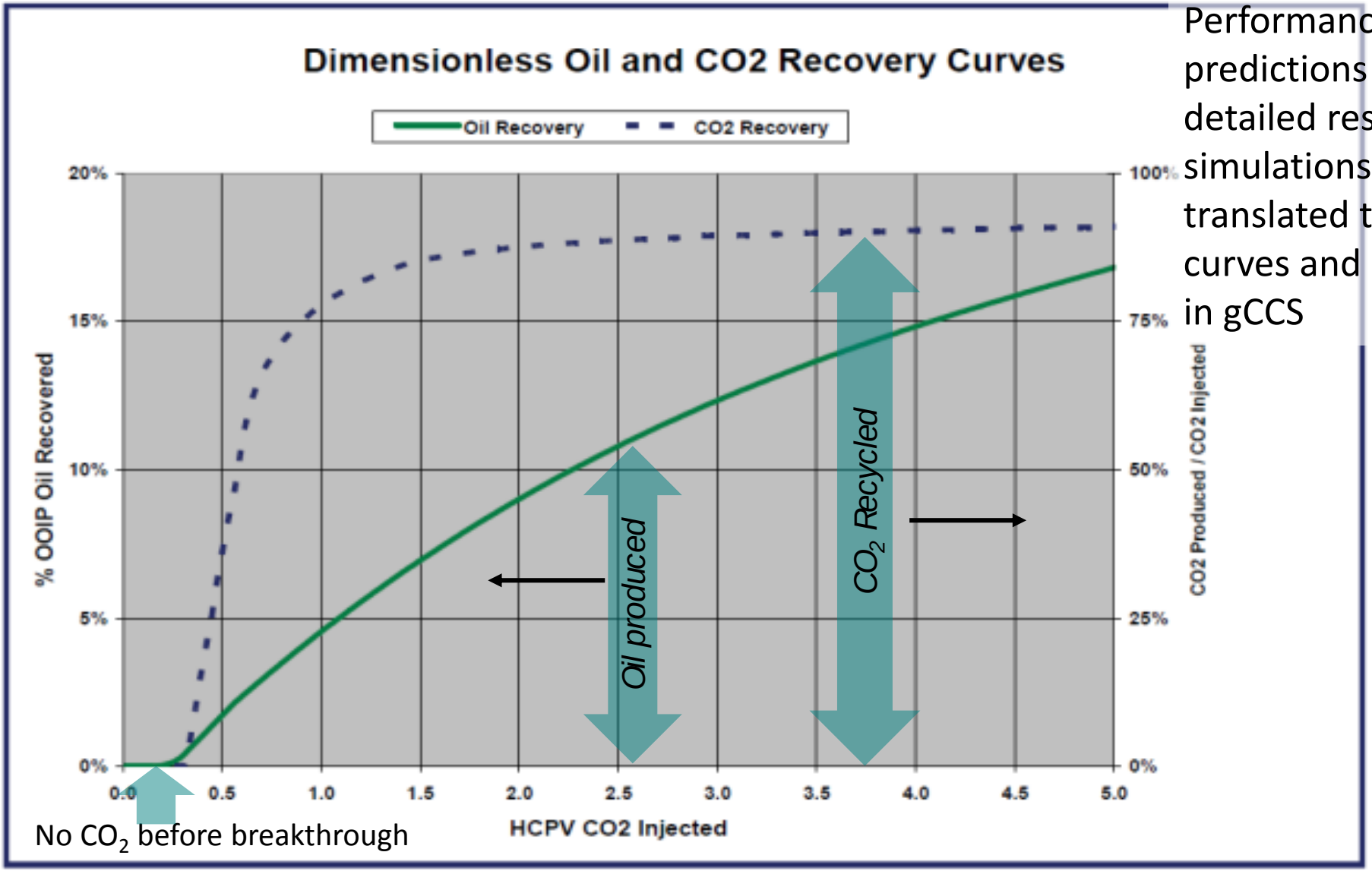


SPE 144961

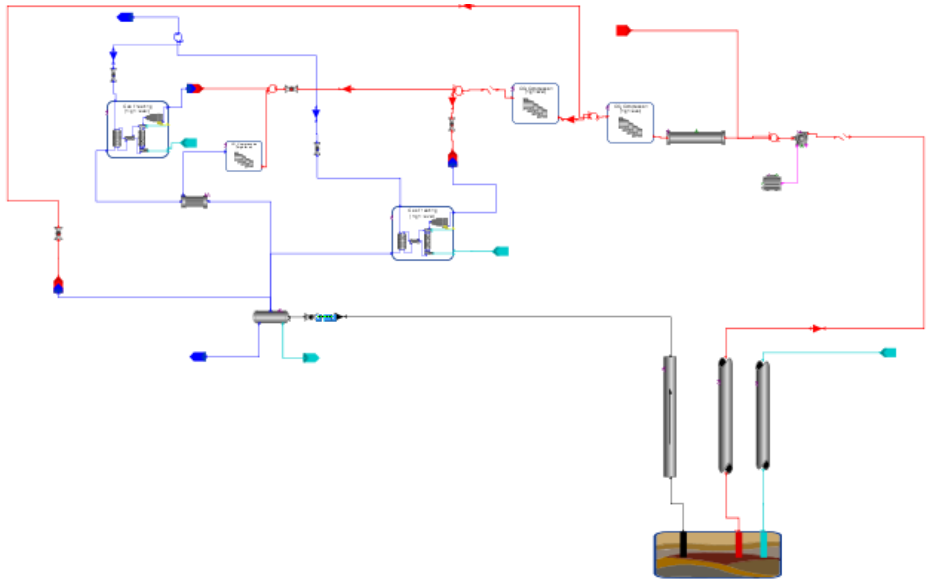
Large Scale CO_2 Flood Begins Along Texas Gulf Coast

Darrell Davis, SPE, Mark Scott, Kris Roberson and Adam Robinson - Denbury Resources Inc.

Reservoir type curves



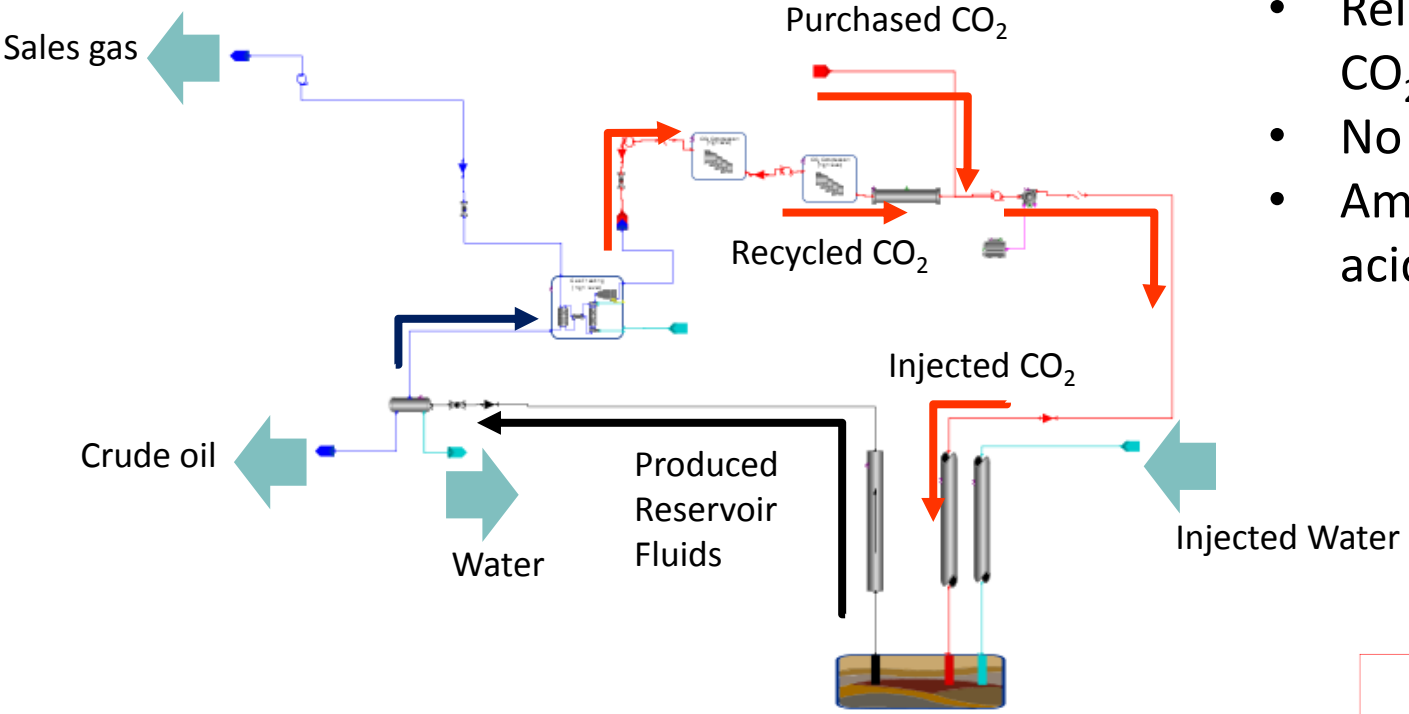
Performance predictions from detailed reservoir simulations can be translated to type curves and utilized in gCCS



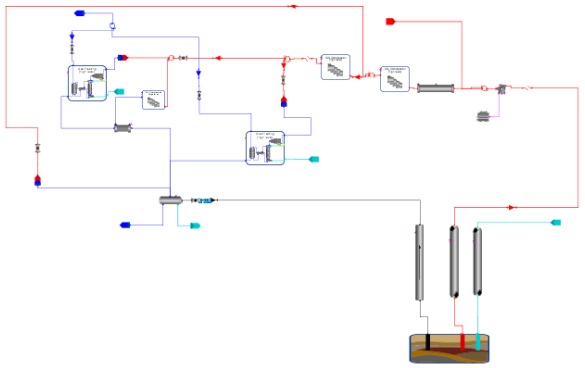
CO_2 EOR project lifecycle

Using super-structure models in gCCS to predict the phases of operation in a CO_2 EOR project

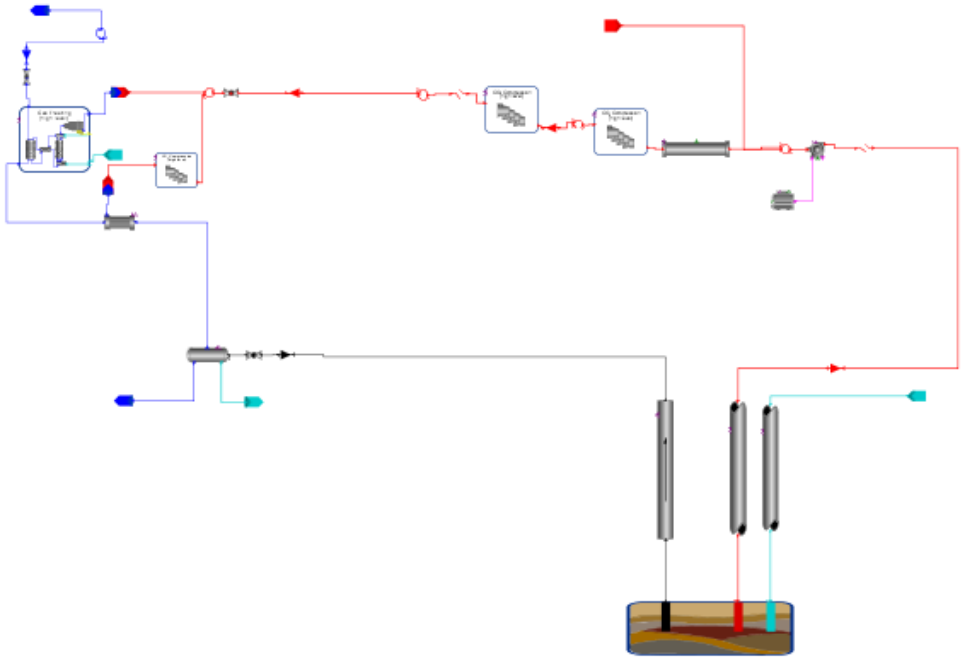
Phase 1 operations



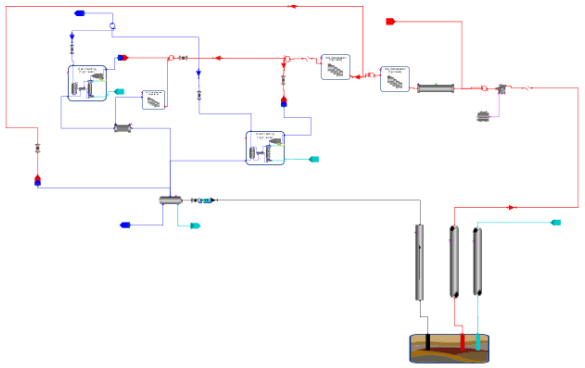
- Before CO_2 breakthrough
- Relatively small amount of CO_2 recycled
- No membrane units
- Amine gas treating removes acid gas to specifications



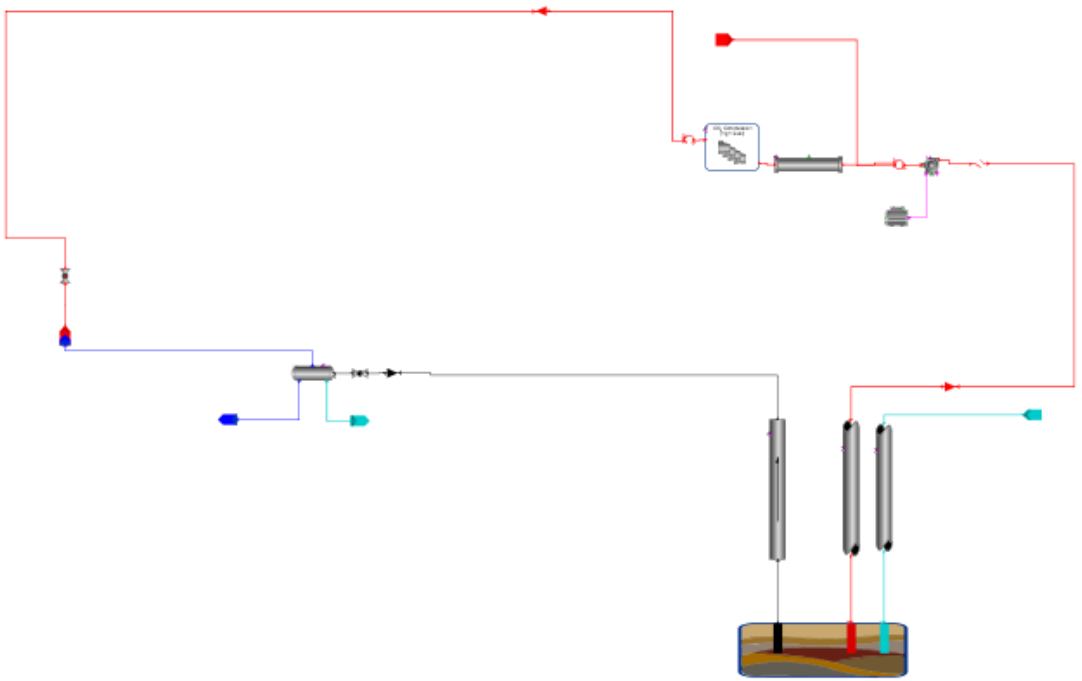
Phase 2 operations



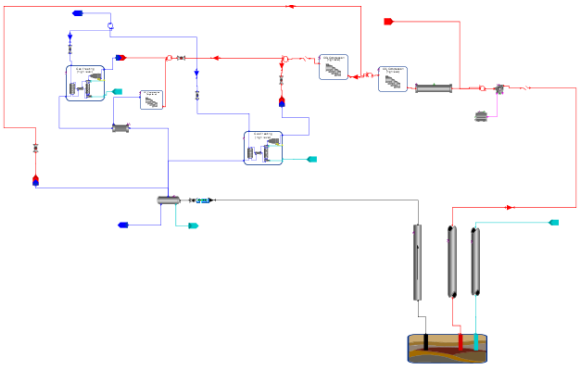
- Onset of CO_2 breakthrough.
- Larger amounts of CO_2 recycled
- Membrane units installed for additional capacity
- Amine gas treating removes acid gas to specifications



Phase 3 operations

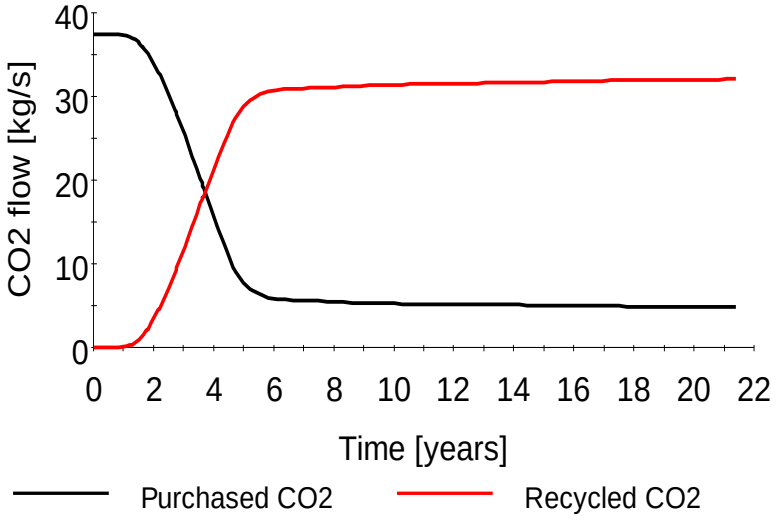


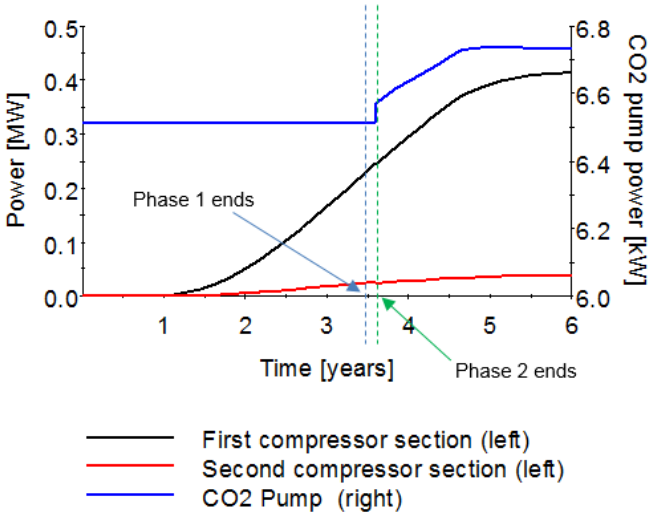
- After CO_2 breakthrough.
- Produced gas is mostly CO_2
- Capacity of gas treating units exceeded so a bypass is established
- CO_2 purity drops

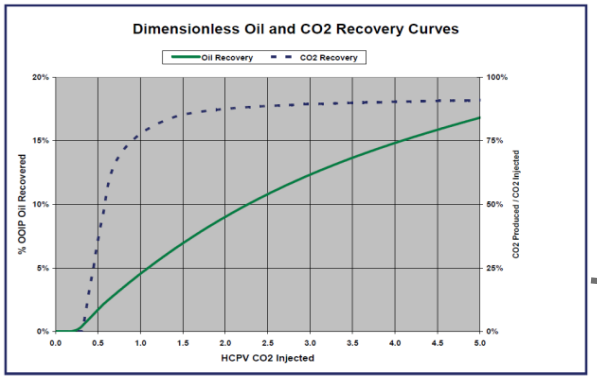


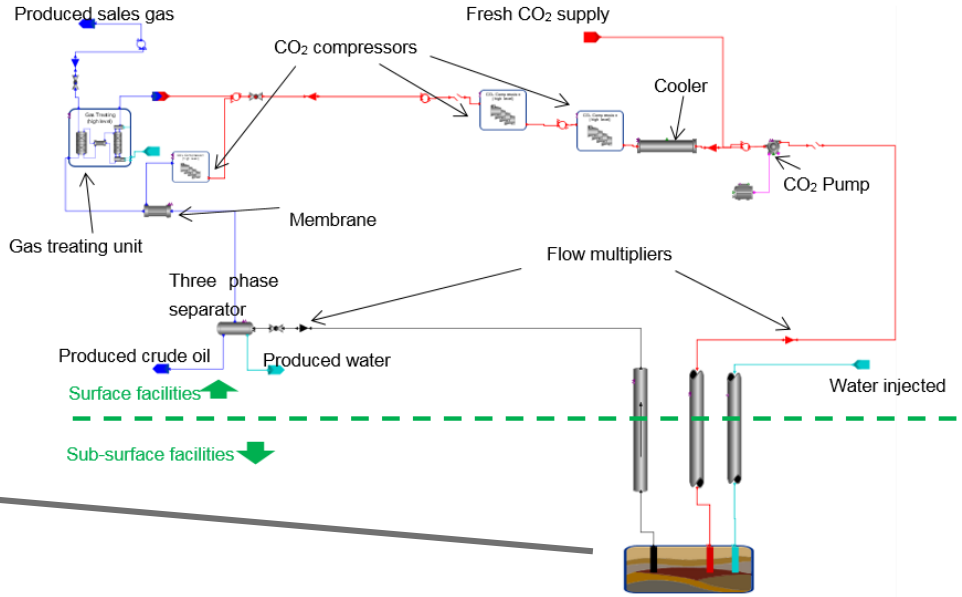
Case Study results – Simultaneous development

Source of injected CO_2









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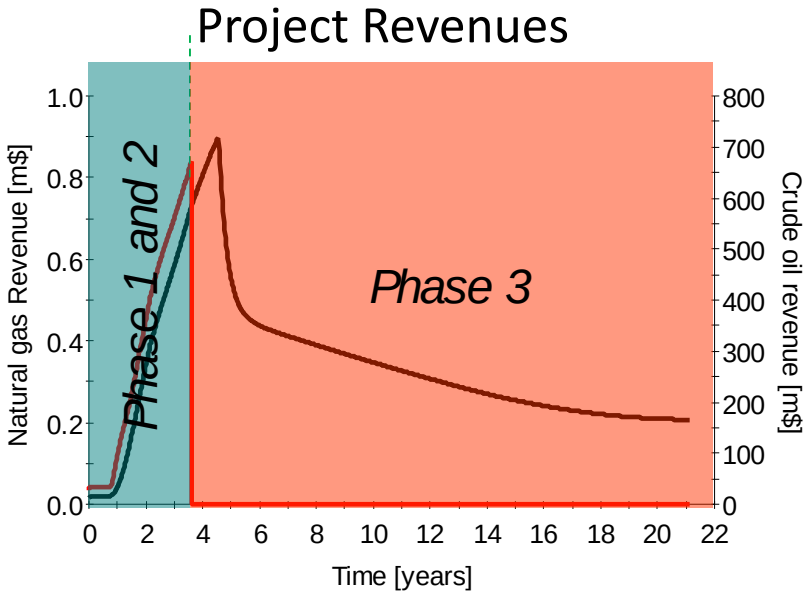
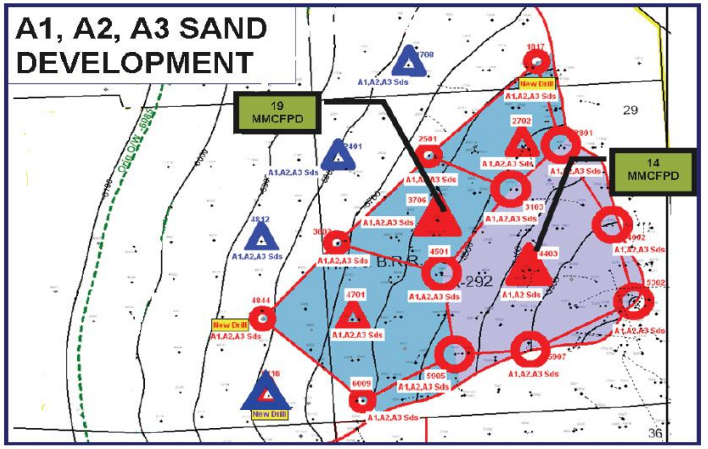
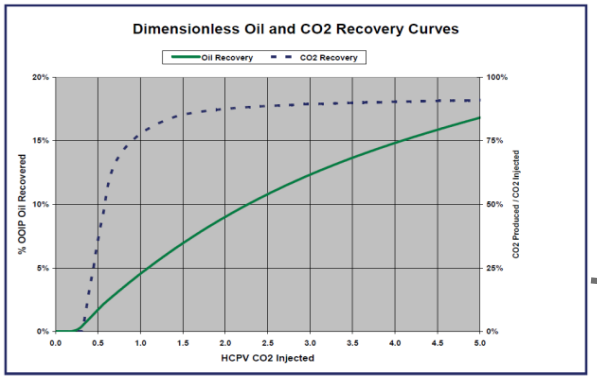
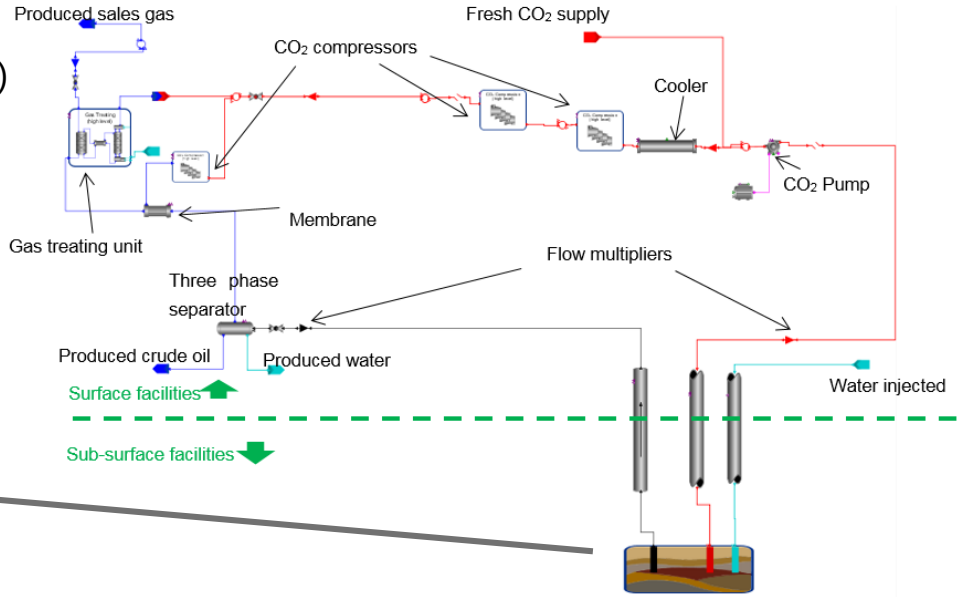




Natural gas Revenue (left)

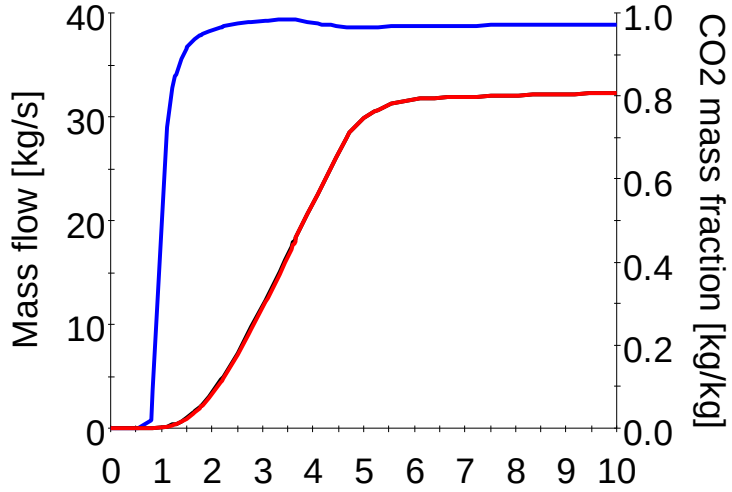
Crude oil revenue (right)



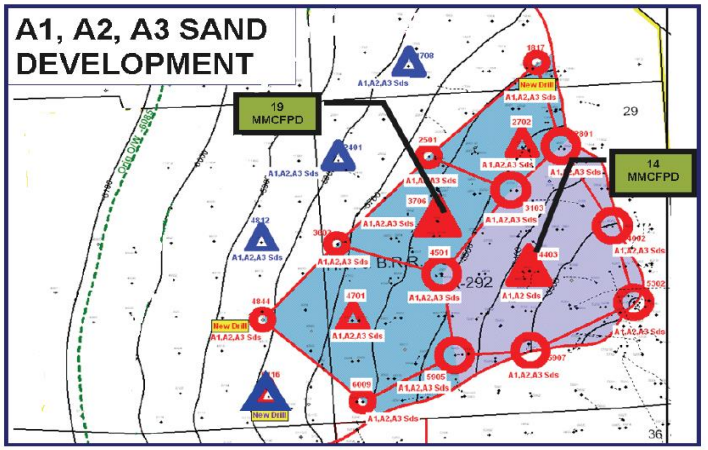


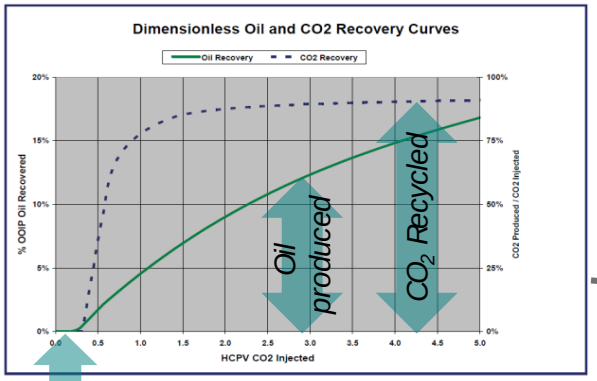
Case Study results

Produced gas flow and composition

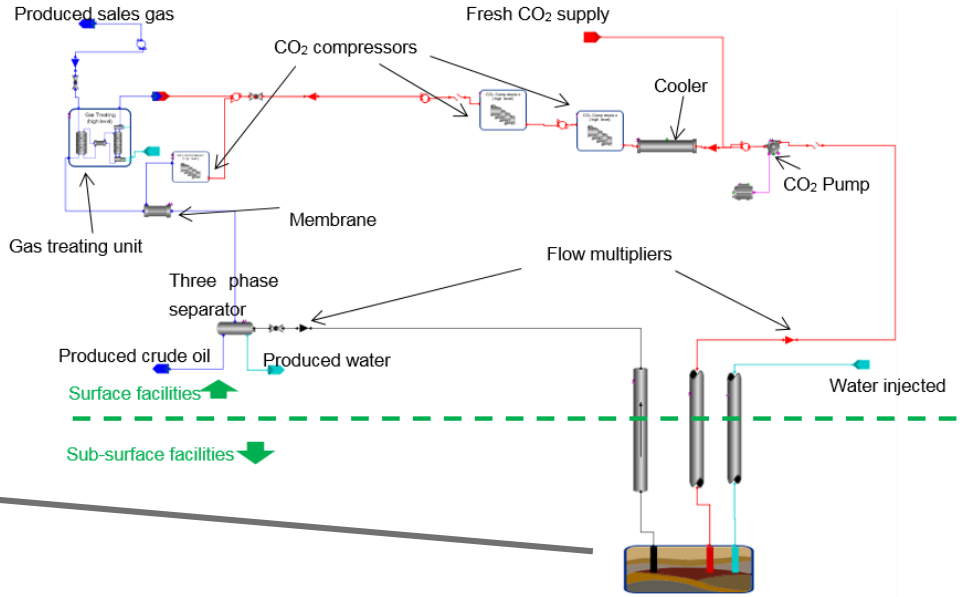


Gas flow at three-phase separator (left)
Recycled CO2 (left)
CO2 mass fraction (right)





No CO_2 before breakthrough

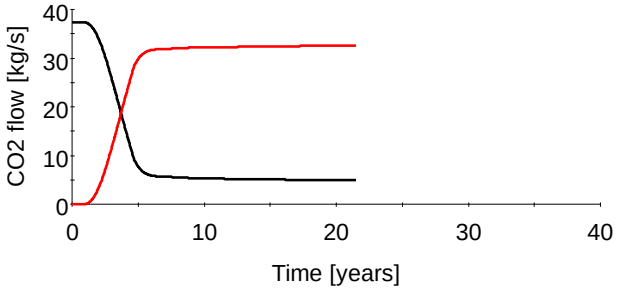


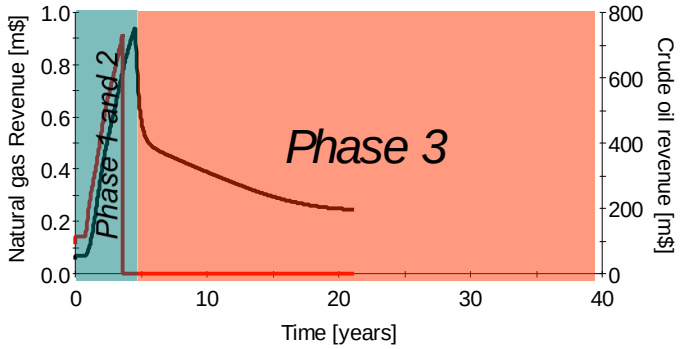
Field development strategies

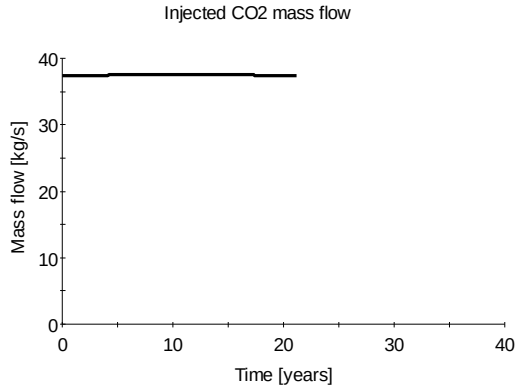
Comparing simultaneous field developments with staged developments

Case Study results – comparing with staged developments

Simultaneous development

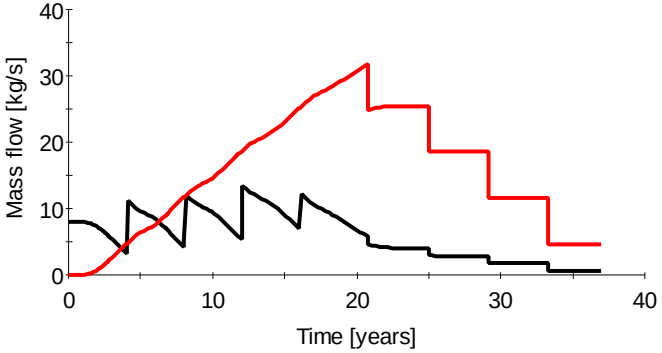


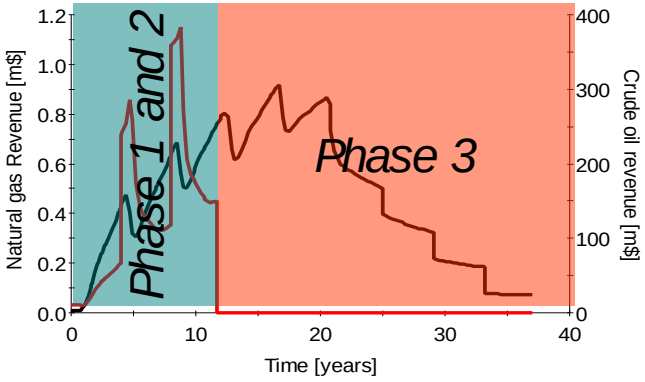


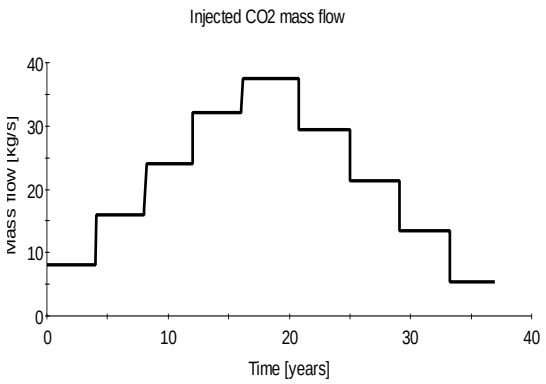


Purchased CO2 — Recycled CO2 — Natural gas Revenue (left) — Crude oil revenue (right)

Staged development







Purchased CO2 — Recycled CO2 — Natural gas Revenue (left) — Crude oil revenue (right)

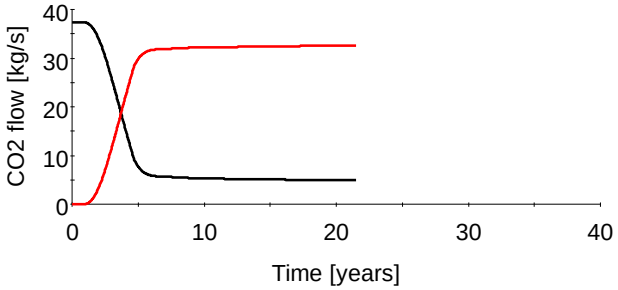
Longer project term

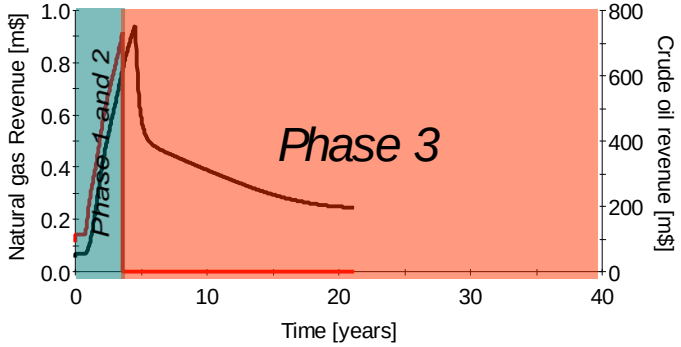
Field development strategies

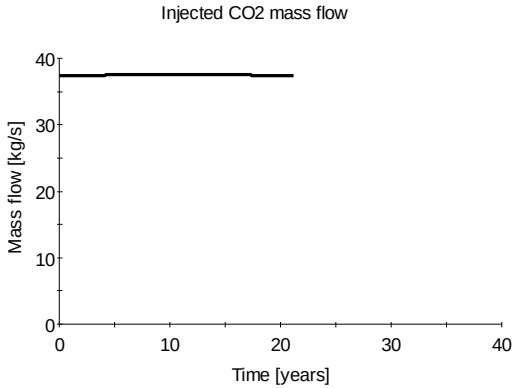
Considering CO_2 supply constraints

Case Study results – comparing with CO_2 supply constraints

Unconstrained supply

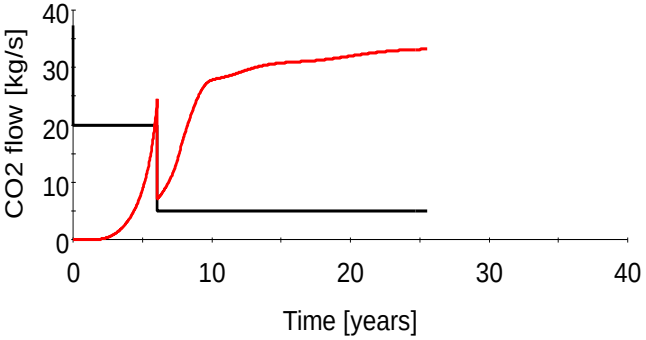


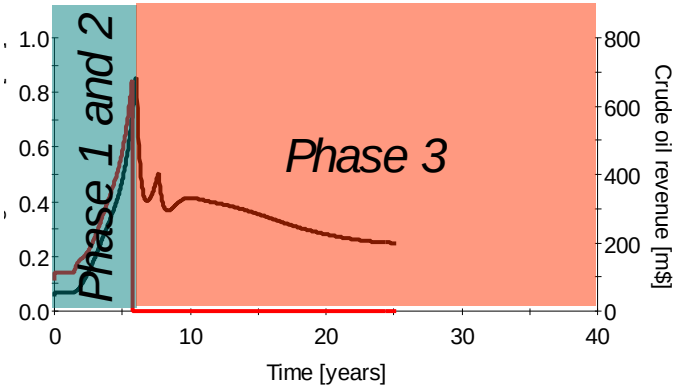


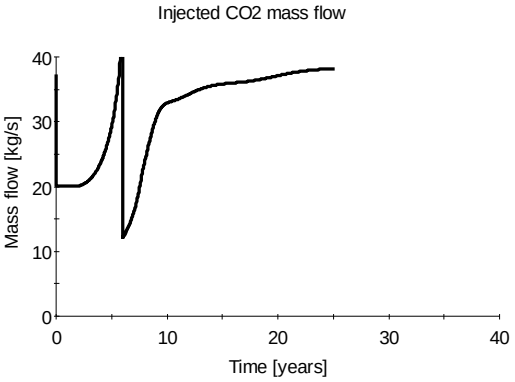


Purchased CO2 — Recycled CO2 — Natural gas Revenue (left) — Crude oil revenue (right)

Constrained supply



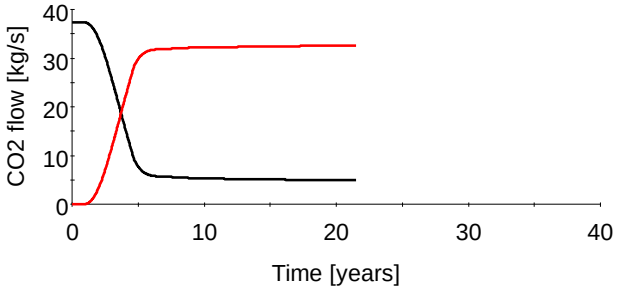


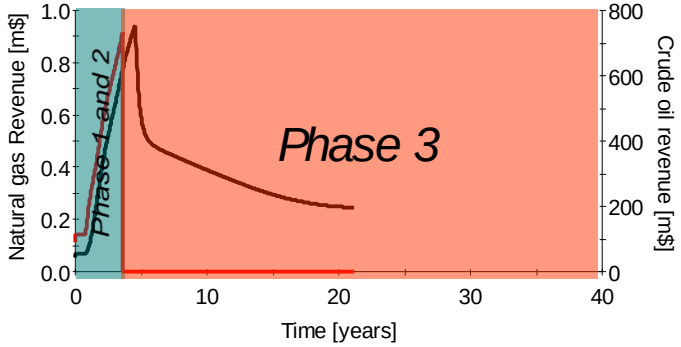


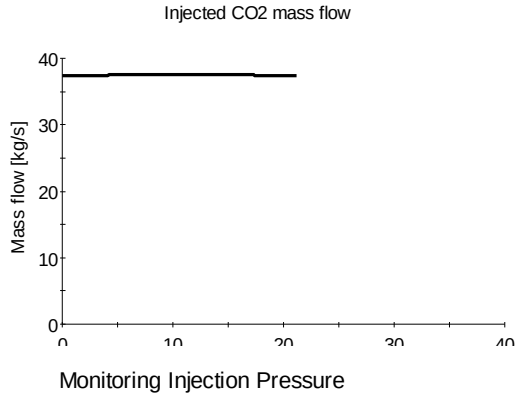
Purchased CO2 — Recycled CO2 — Natural gas Revenue (left) — Crude oil revenue (right)

Case Study results – comparing with CO_2 supply constraints

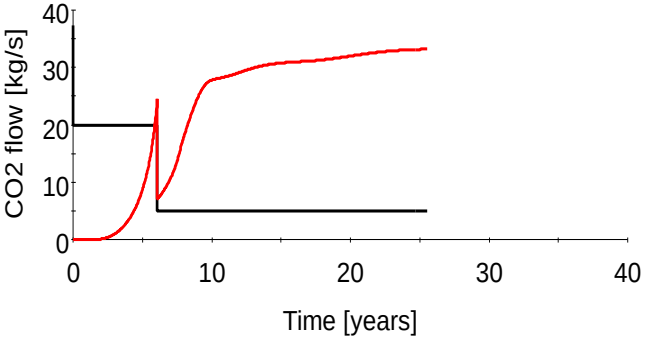
Unconstrained supply

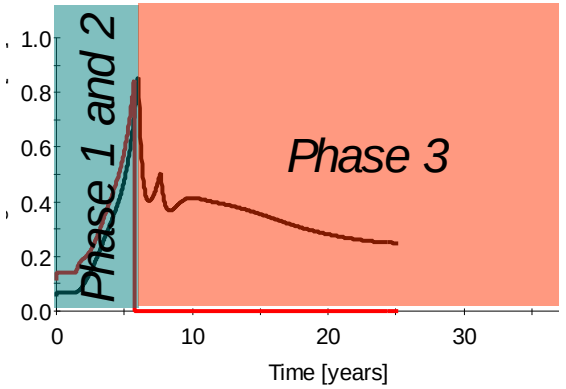


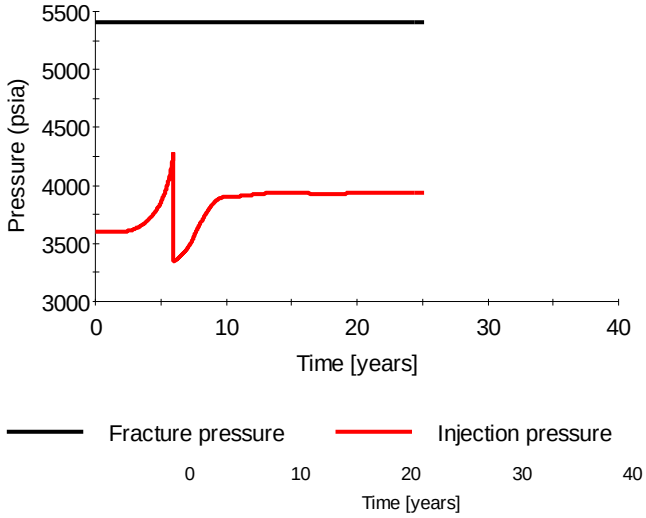




Constrained supply

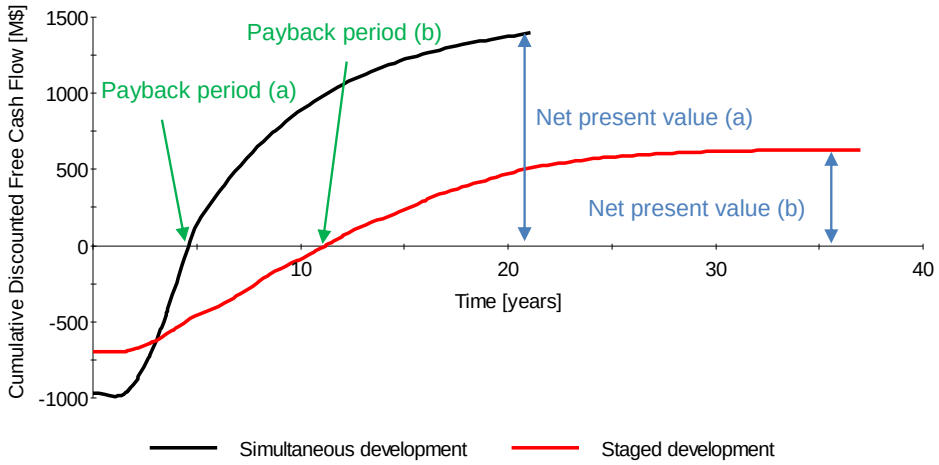


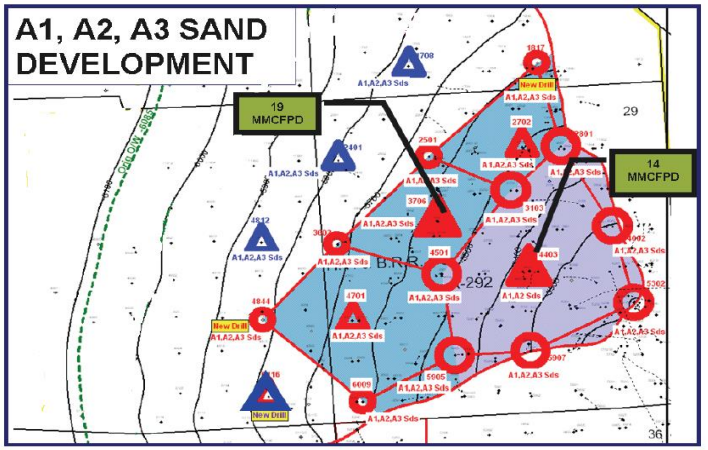


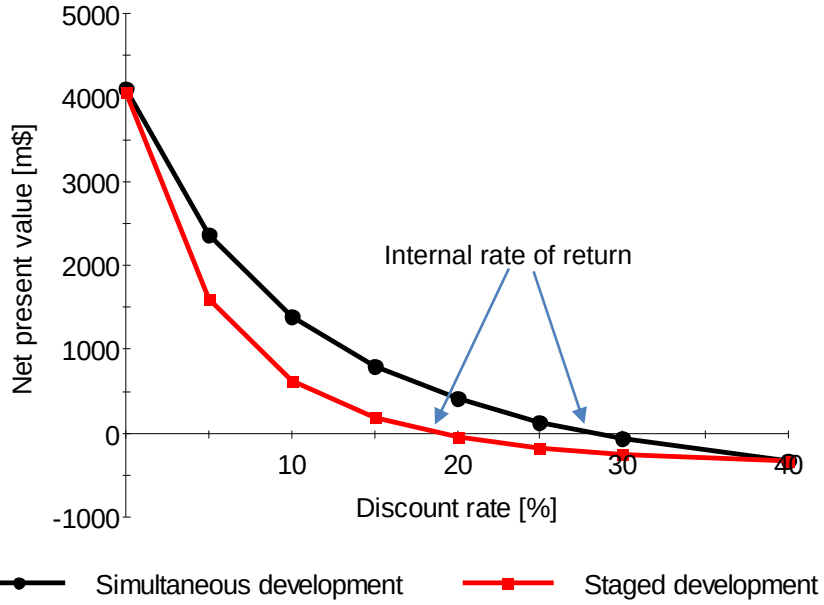


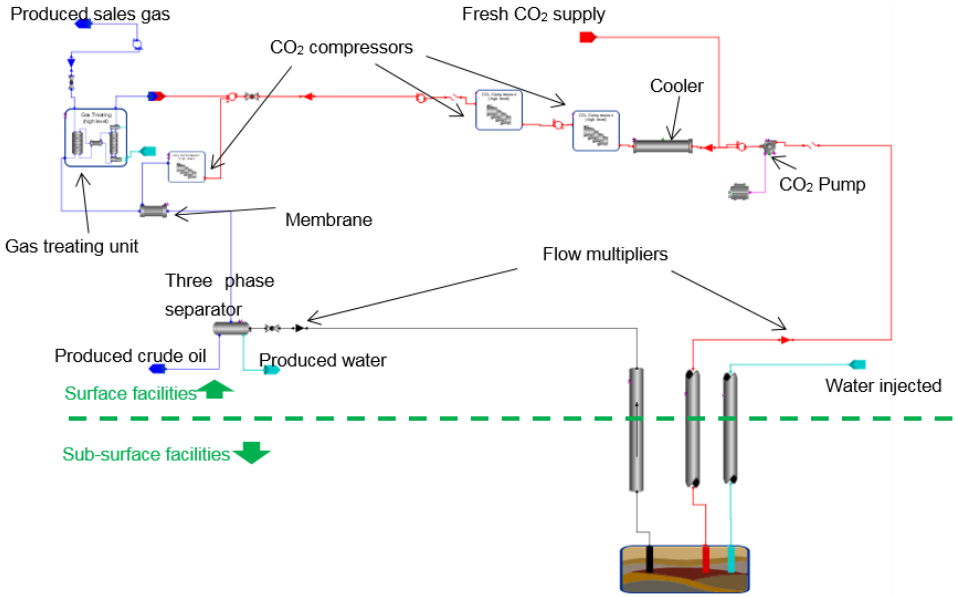
Project Economics

Case Study results - economics









Summary

- Process model library developed for CO_2 EOR studies
  - Design of CO_2 recycling facilities
  - Interface to detailed reservoir simulators (type curves)
  - Scheduling operations
  - Investigating constraints
  - Comparison of various strategies
- Economic analysis of CO_2 EOR operations
  - Pay back period
  - Internal rate of return estimation

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Thank you