Crosscutting Research & Rare Elements Portfolios Review
20 April 2016
FE0026307

Evaluation and Demonstration of Commercialization Potential of Carbon Capture Simulation Initiative Tools within gPROMS Advanced Simulation Platform

Alfredo Ramos, Vice President Energy & Environment

Outline

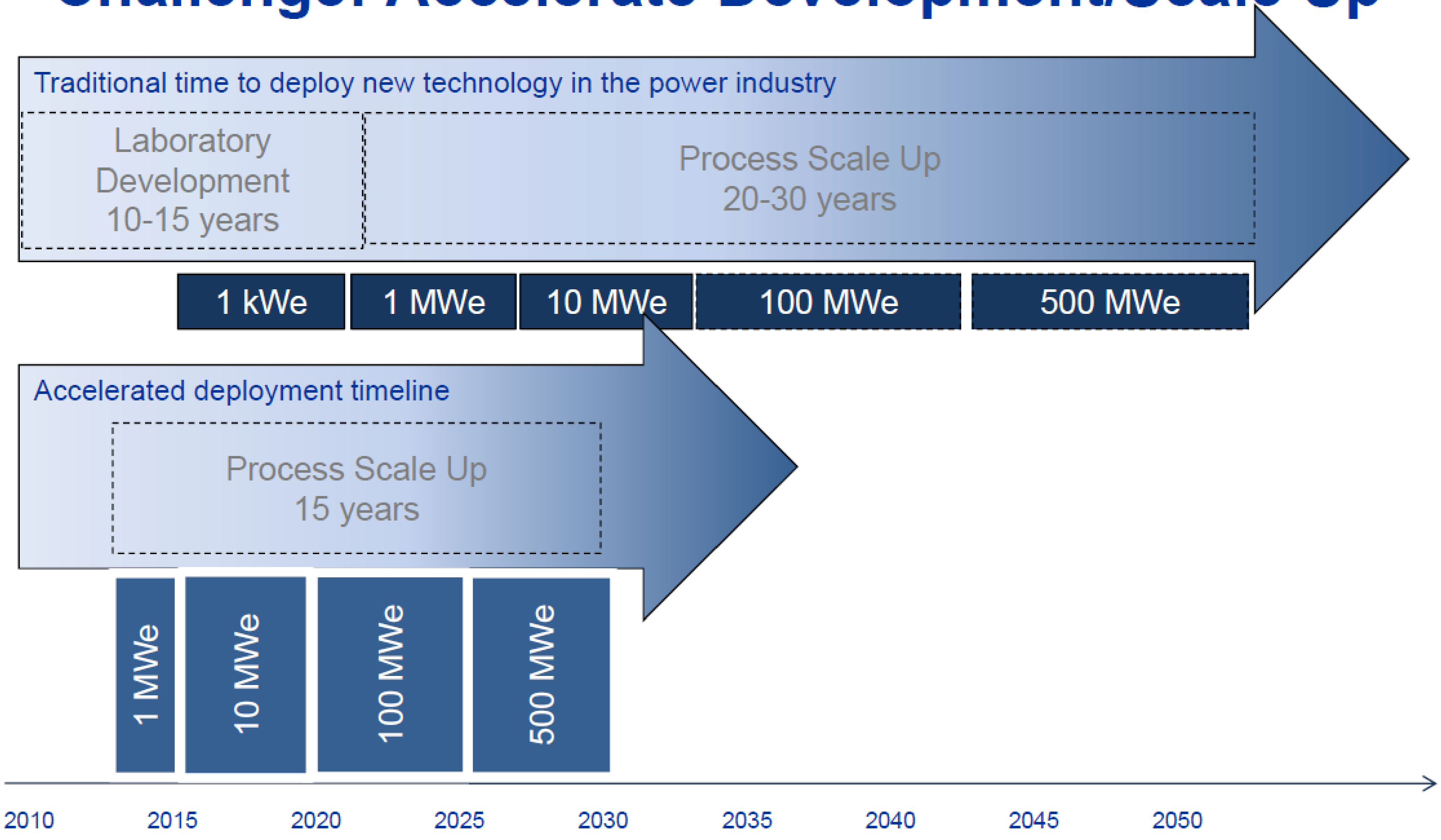
- Carbon Capture Simulation Initiative
- CCSI Commercialization Project (FE0026307)
- Role of advanced process/systems modelling
- PSE background – why us?
- Project status update
- Summary

Advanced Process Modelling initiatives aimed at CCS

2. Carbon Capture Simulation Initiative (CCSI)

U.S. Carbon Capture Simulation Initiative (CCSI)

Challenge: Accelerate Development/Scale Up



Traditional time to deploy new technology in the power industry

Laboratory Development 10-15 years

Process Scale Up 20-30 years

1 kWe | 1 MWe | 10 MWe | 100 MWe | 500 MWe

Accelerated deployment timeline

Process Scale Up 15 years

1 MWe | 10 MWe | 100 MWe | 500 MWe

CCSI Carbon Capture Simulation Initiative

NETL · Berkeley Lab · Lawrence Livermore National Laboratory · Los Alamos National Laboratory · Pacific Northwest National Laboratory · U.S. Department of Energy

Goals & Objectives of CCSI

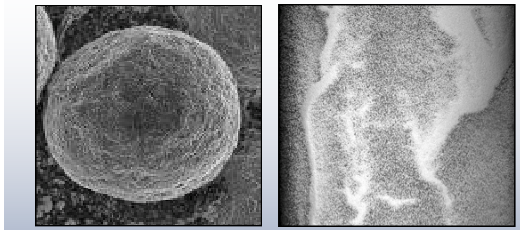
- **Develop** new computational tools and models to enable industry to more rapidly develop and deploy new advanced energy technologies
  - Base development on industry needs/constraints

- **Demonstrate** the capabilities of the CCSI Toolset on non-proprietary case studies
  - Examples of how new capabilities improve ability to develop capture technology

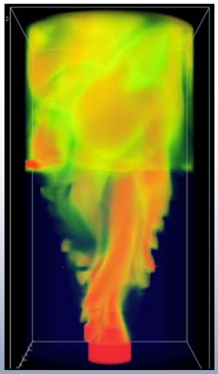
- **Deploy** the CCSI Toolset to industry
  - Initial licensees, CRADA

U.S. Carbon Capture Simulation Initiative (CCSI)

CCSI Carbon Capture Simulation Initiative | For Accelerating Technology Development



Rapidly synthesize optimized processes to identify promising concepts →



Better understand internal behavior to reduce time for troubleshooting →

Quantify sources and effects of uncertainty to guide testing & reach larger scales faster →

Stabilize the cost during commercial deployment

National Labs

Berkeley Lab
Pacific Northwest National Laboratory
NETL
Los Alamos National Laboratory EST.1943
Lawrence Livermore National Laboratory

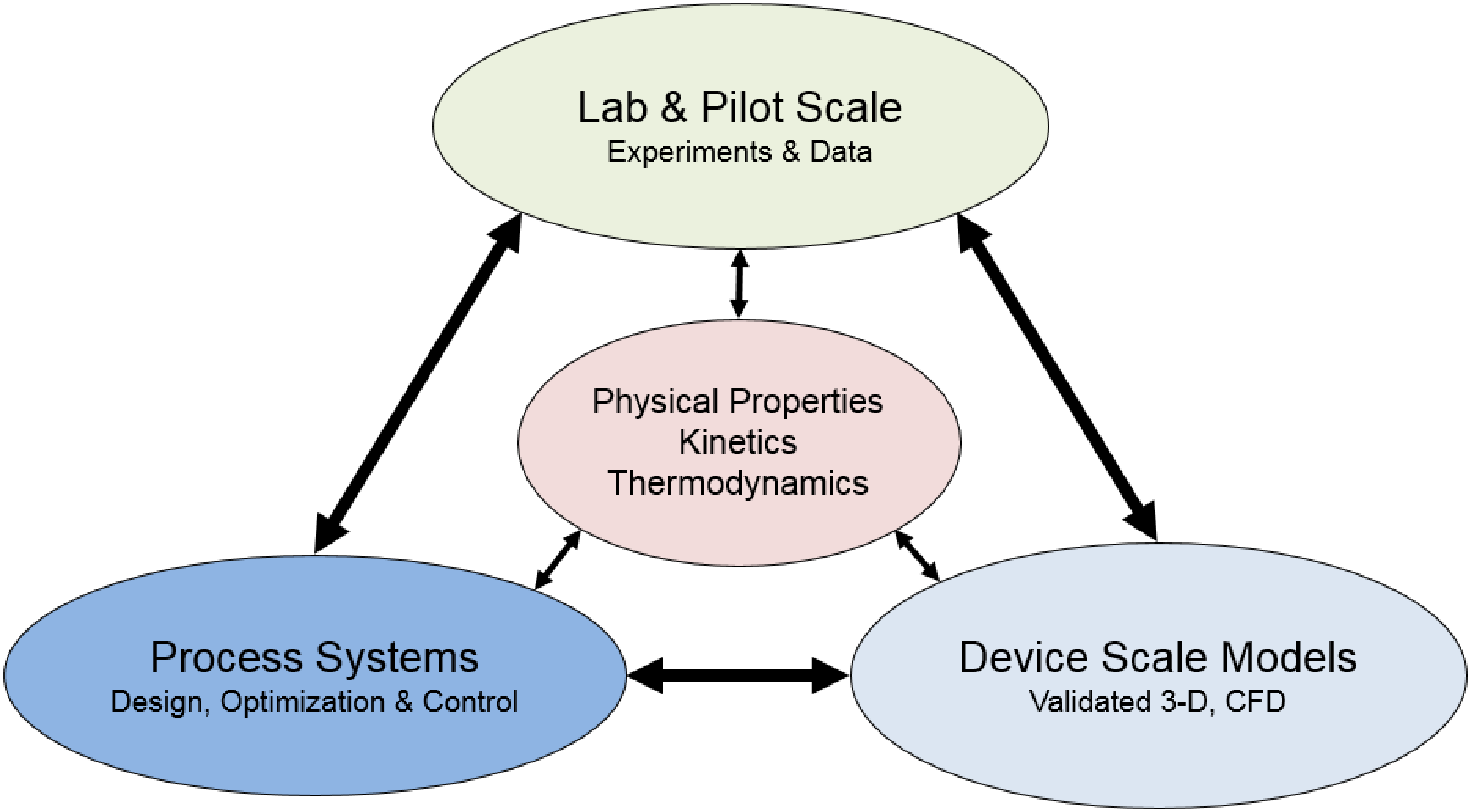
Academia

Carnegie Mellon
Princeton University
West Virginia University
Boston University
The University of Texas at Austin

Industry

ADA Environmental Solutions
Alstom
B&W the babcock&wilcox company
GE
EPRI Electric Power Research Institute
Fluor
Phillips 66
AEP American Electric Power
Southern California Edison An Edison International Company San Onofre Nuclear Generating Station
Southern Company
ExxonMobil
Chevron
URS
Air Products
Eastman
aspentech
ANSYS
Schneider Electric
PSE

Advanced Computational Tools to Accelerate Carbon Capture Technology Development



Lab & Pilot Scale
Experiments & Data

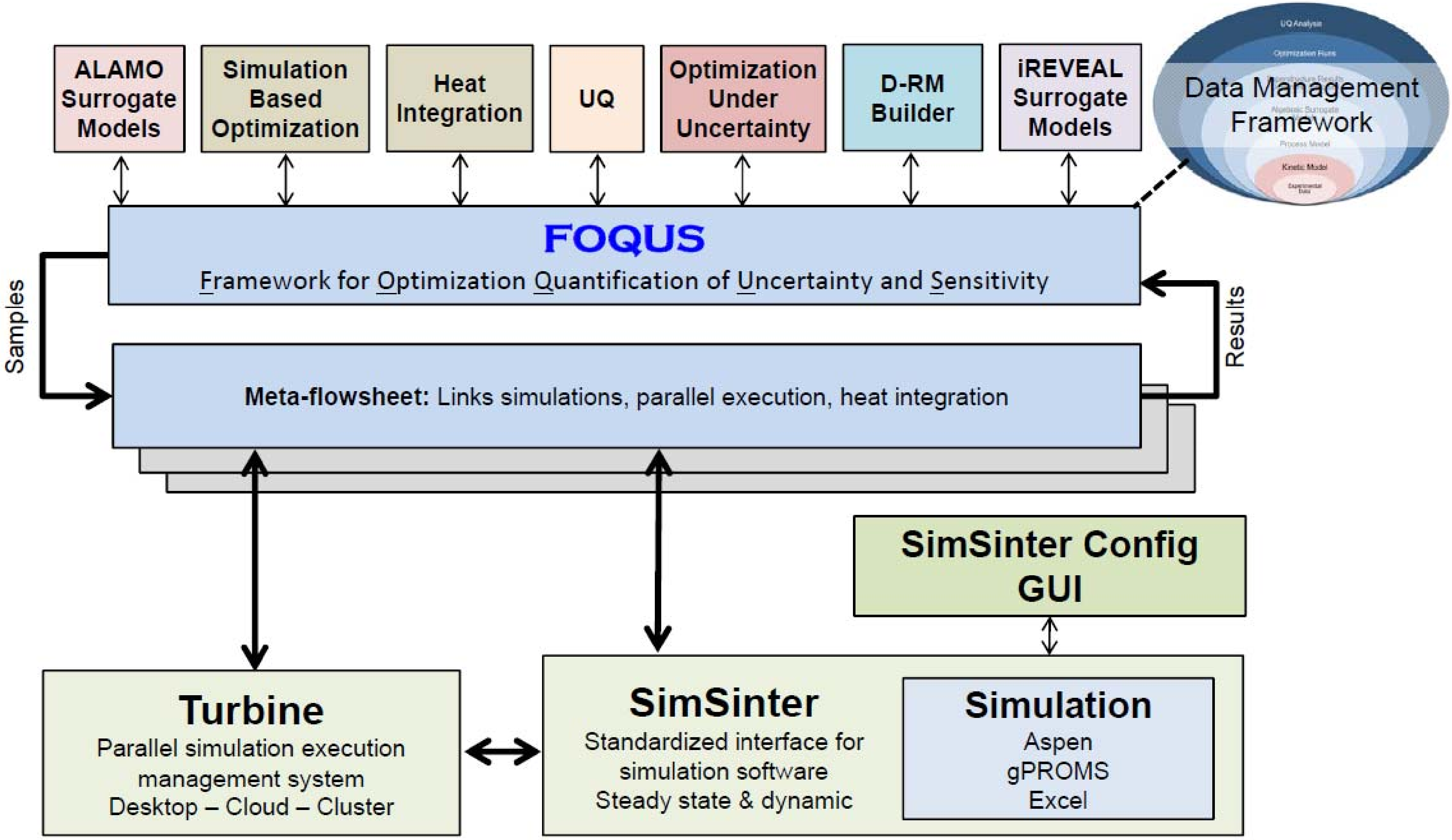
Physical Properties
Kinetics
Thermodynamics

Process Systems
Design, Optimization & Control

Device Scale Models
Validated 3-D, CFD

CCSI Carbon Capture Simulation Initiative · NETL · Berkeley Lab · Lawrence Livermore National Laboratory · Los Alamos National Laboratory · Pacific Northwest National Laboratory · U.S. Department of Energy

U.S. Carbon Capture Simulation Initiative (CCSI) Framework & technologies



ALAMO Surrogate Models

Simulation Based Optimization

Heat Integration

UQ

Optimization Under Uncertainty

D-RM Builder

iREVEAL Surrogate Models

Data Management Framework

FOQUS

Framework for Optimization Quantification of Uncertainty and Sensitivity

Samples

Results

Meta-flowsheet: Links simulations, parallel execution, heat integration

SimSinter Config GUI

Turbine
Parallel simulation execution management system
Desktop – Cloud – Cluster

SimSinter
Standardized interface for simulation software
Steady state & dynamic

Simulation
Aspen
gPROMS
Excel

D. C. Miller, B. Ng, J. C. Eslick, C. Tong and Y. Chen, 2014, Advanced Computational Tools for Optimization and Uncertainty Quantification of Carbon Capture Processes. In *Proceedings of the 8th Foundations of Computer Aided Process Design Conference – FOCAPD 2014.* M. R. Eden, J. D. Siirola and G. P. Towler Elsevier.

CCSI Carbon Capture Simulation Initiative

NETL

Berkeley Lab

Lawrence Livermore National Laboratory

Los Alamos National Laboratory

Pacific Northwest National Laboratory

U.S. DEPARTMENT OF ENERGY

CCSI Toolset Commercialization Project – DoE Award Number FE0026307

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Project objectives

- Identify opportunities for commercialising components of the CCSI toolkit within the gPROMS platform
  - Assessment and ranking of tools according to commercial and technical criteria
- Develop and demonstrate a clear technical delivery path towards achieving these opportunities
  - Devise implementation plans and build team for Phase 2

Motivation for PSE

- Expand Power & CCS offering
    - Enhancements to gCCS and gPOWER products
    - Supporting Advanced Energy Systems initiatives (Fuel Cells)

- Deploy CCSI tools and models beyond CCS applications
    - Chemicals and petrochemicals (energy management)
    - Life sciences
    - Oil & Gas

Project team/stakeholders

Project partners …and team

Alejandro Cano, PhD
Principal Investigator
Technical focal point

Alfredo Ramos, MBA, MSc
Co-Principal Investigator
Commercialization

Ade Lawal, PhD
Project Manager
Coordinator Process Modelling task

Pieter Schmal, PhD
Principal Applications Engineer
Coordinator ALAMO/FOQUS

West Virginia University

Debangsu Bhattacharyya, PhD
Co-Principal
Task leader Process Modelling

David Mebane, PhD
Co-Principal
Task leader Sorbentfit/SolventFit

CARNEGIE MELLON UNIVERSITY
PITTSBURGH PENNSYLVANIA 1900

Prof Nick Sahinidis
Co-Principal
Task leader ALAMO

Key external stakeholders

- Organisations

U.S. DEPARTMENT OF ENERGY

NETL

CCSI™ Carbon Capture Simulation Initiative

- People
  - Jason C. Hissam (NETL Project Officer)
  - Ashley Reichl (U.S. Contract Specialist)
  - David Miller as initial (introductory) point of contact for non-fast track tools

Key external stakeholders

- Industry advisory board members

ADA
ENVIRONMENTAL SOLUTIONS
ALSTOM
B&W
thebabcock&wilcoxcompany
GE
EPRI
ELECTRIC POWER
RESEARCH INSTITUTE
FLUOR
PHILLIPS 66
AEP
AMERICAN
ELECTRIC
POWER
SOUTHERN CALIFORNIA
EDISON
An EDISON INTERNATIONAL Company
San Onofre Nuclear Generating Station
SOUTHERN
COMPANY
ExxonMobil
Chevron
URS
AIR
PRODUCTS
EASTMAN
aspentech
ANSYS
Schneider
Electric
PSE

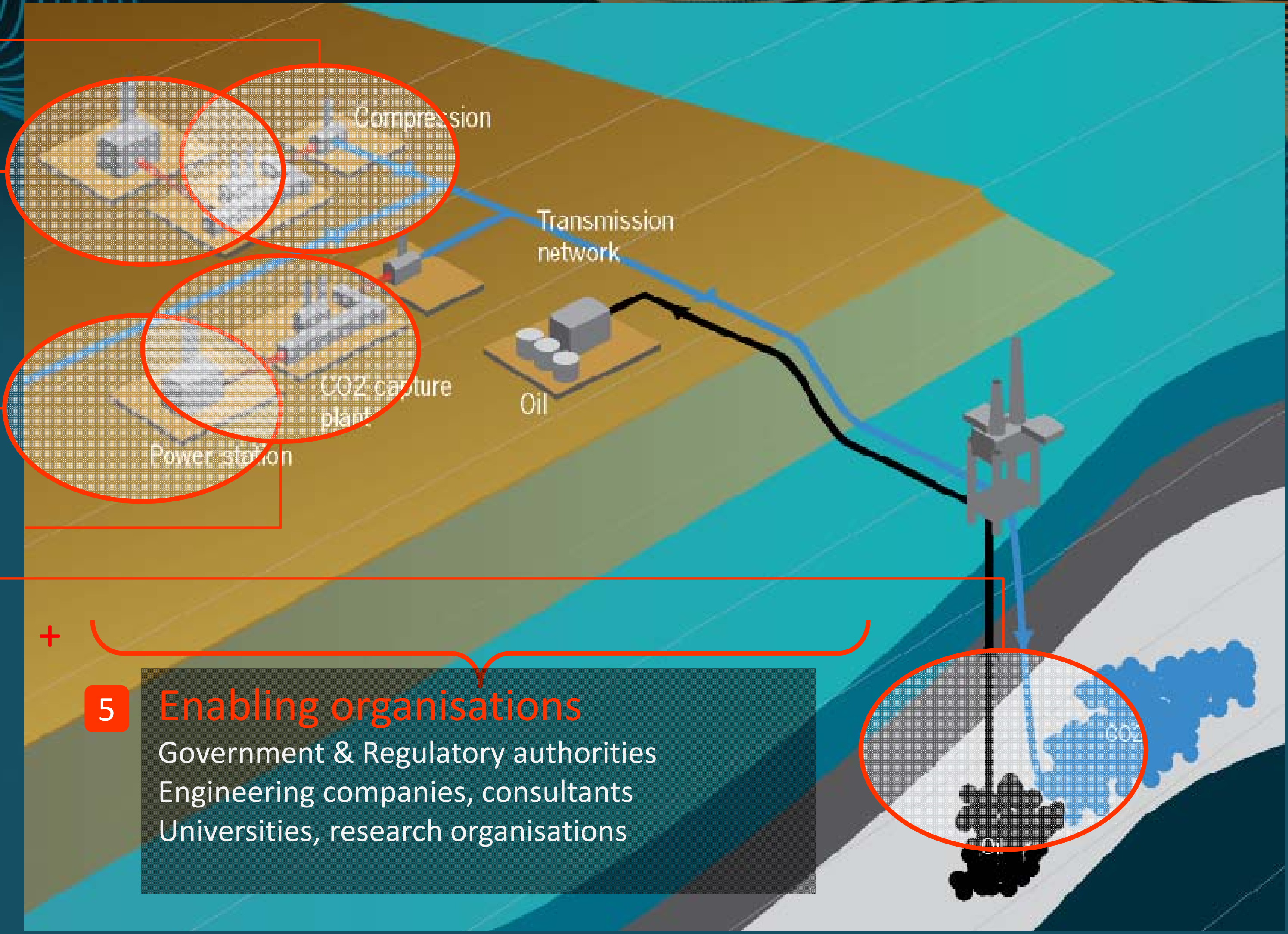
Desired outcomes & impact

- Uncertainty quantification approach essential in guiding R&D efforts to minimise cost of low-emission energy systems
  - Focus on what really matters

- Seamless integration of data-driven and first-principles models streamlines lifecycle of models/modelling tools
  - Extend range of application of model-based solutions
  - Accelerate deployment of innovative, low-carbon energy systems
  - Optimal design and operation of CCS and other advanced energy systems, reducing transition cost to low-carbon economy

Challenges to the roll-out of Carbon Capture Utilization and Storage (CCUS)

CCSU challenges – stakeholders



Compression & transmission 3

Industrial gas companies 2

Power generators 1

Process providers 2

CO_2 Users and Storage providers 4

\+

5 Enabling organisations

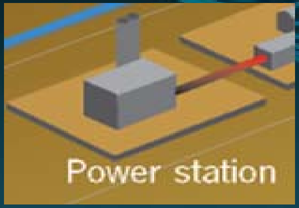
Government & Regulatory authorities

Engineering companies, consultants

Universities, research organisations

CCS challenges

Multiple stakeholders with different issues & challenges



- Grid demand
- Flexibility
- Efficiency
- Fuel mix
- Trip scenarios

- Sizing
- Flexibility
- Buffer storage
- Amine loading
- Capital cost optimization
- Energy sacrifice
- Heat integration
- Solvent issues

- Optimal operating point
- Efficiency
- New design
- Impurities
- Control
- Safety

- Composition effects
- Phase behavior
- Capacity
- Buffering / packing
- Routing
- Safety
- Depressurisation
- Control
- Leak detection

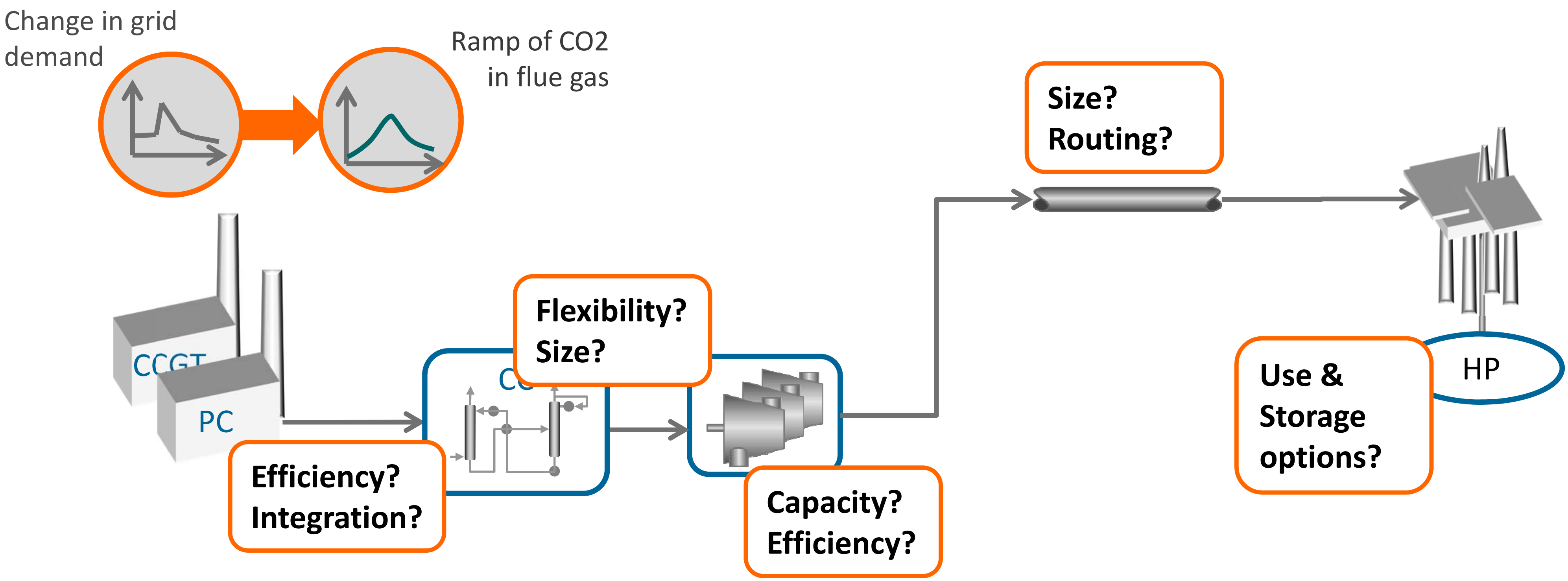
Government

- Policy
- Strategic
- Infrastructure development
- H&S

- Compression
- Supply variability
- Composition
- Thermodynamics
- Temperatures / hydrates
- Well performance
- Long-term storage dynamics
- Back-pressures

…currently being addressed by individual tools

Challenges – ‘interconnectedness’ (I)



Size?
Routing?

Flexibility?
Size?

Efficiency?
Integration?

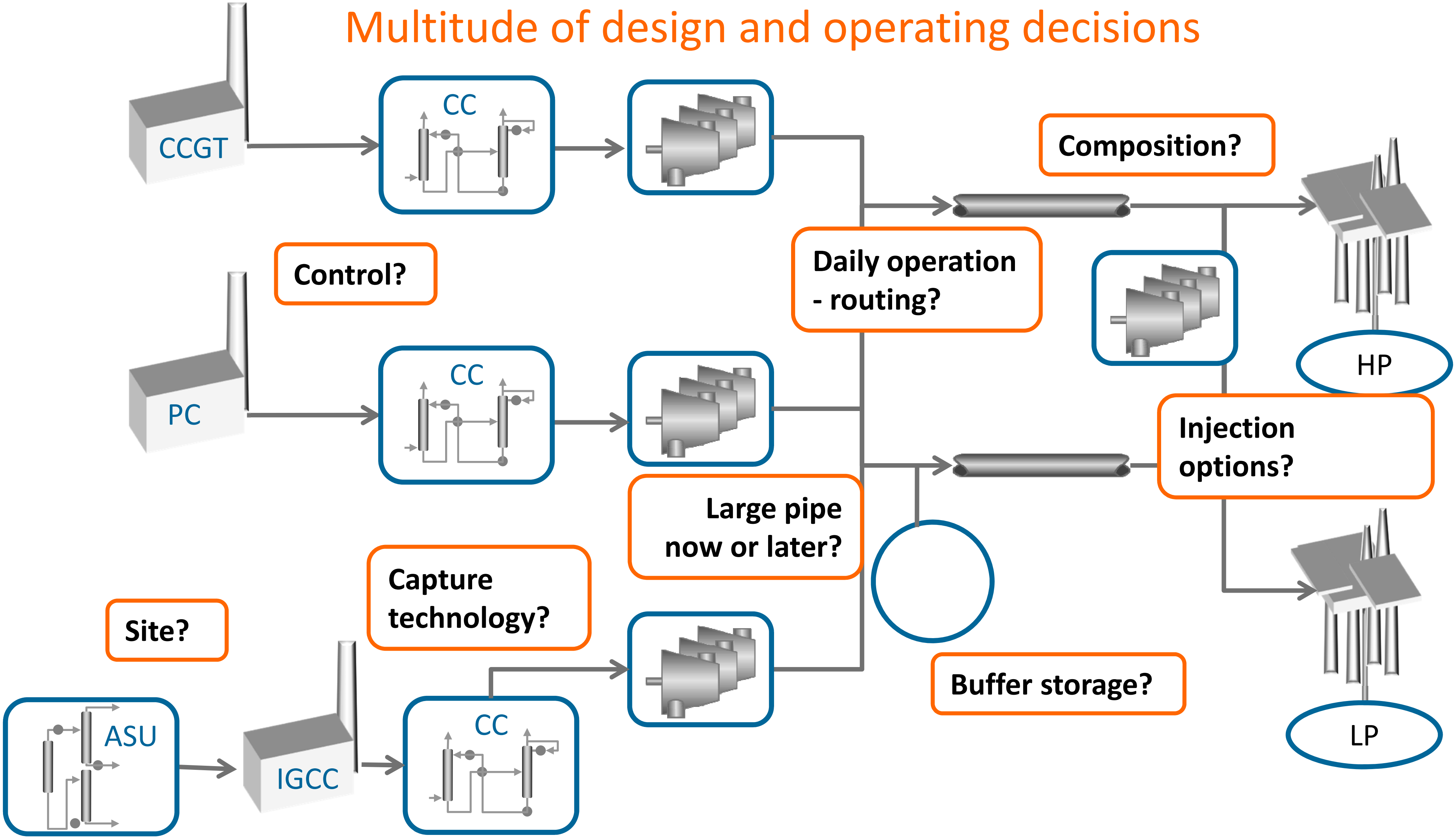
Capacity?
Efficiency?

Use & Storage options?

Now all connected CO2 network as well

Challenges – ‘interconnectedness’ (II)

Multitude of design and operating decisions



Composition?

Control?

Daily operation - routing?

Injection options?

Large pipe now or later?

Capture technology?

Site?

Buffer storage?

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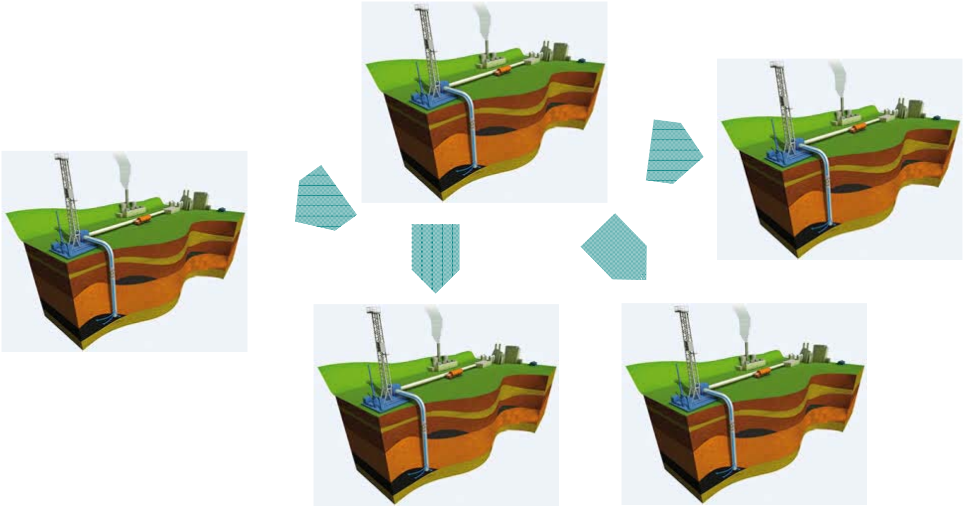
Challenges – ‘transferability of experience/expertise’ (I)

- Substantial challenges in moving from first-of-a-kind (FOAK) to Nth-of-a-kins (NOAK) owing to “uniqueness” of each CCS project
  - CO_2 sources
  - Topography / pipeline layout
  - CO_2 store’s geological characteristics
- Advanced process modelling is essential to translate experience from one large-scale integrated project to the next



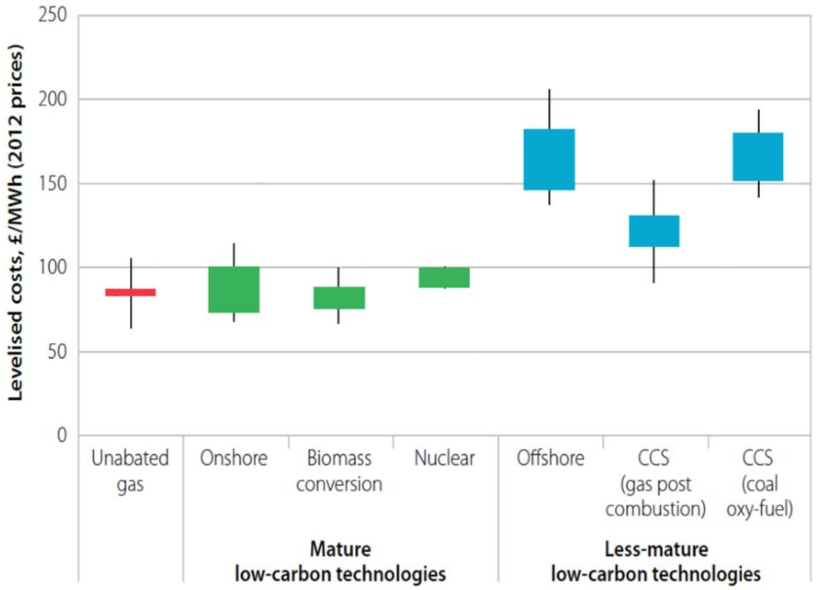
Challenges for CCS – ‘cost’ (I)

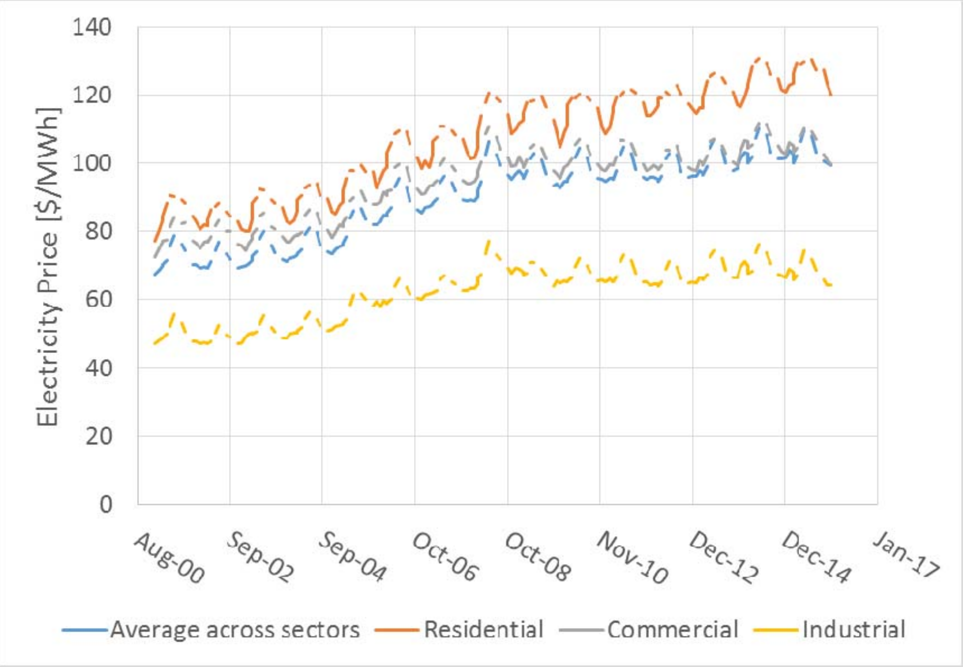
- Current cost of abatement of CCS too high with respect to other low-carbon technologies/ renewables
- …particularly when put in perspective with electricity price

Current cost

vs.

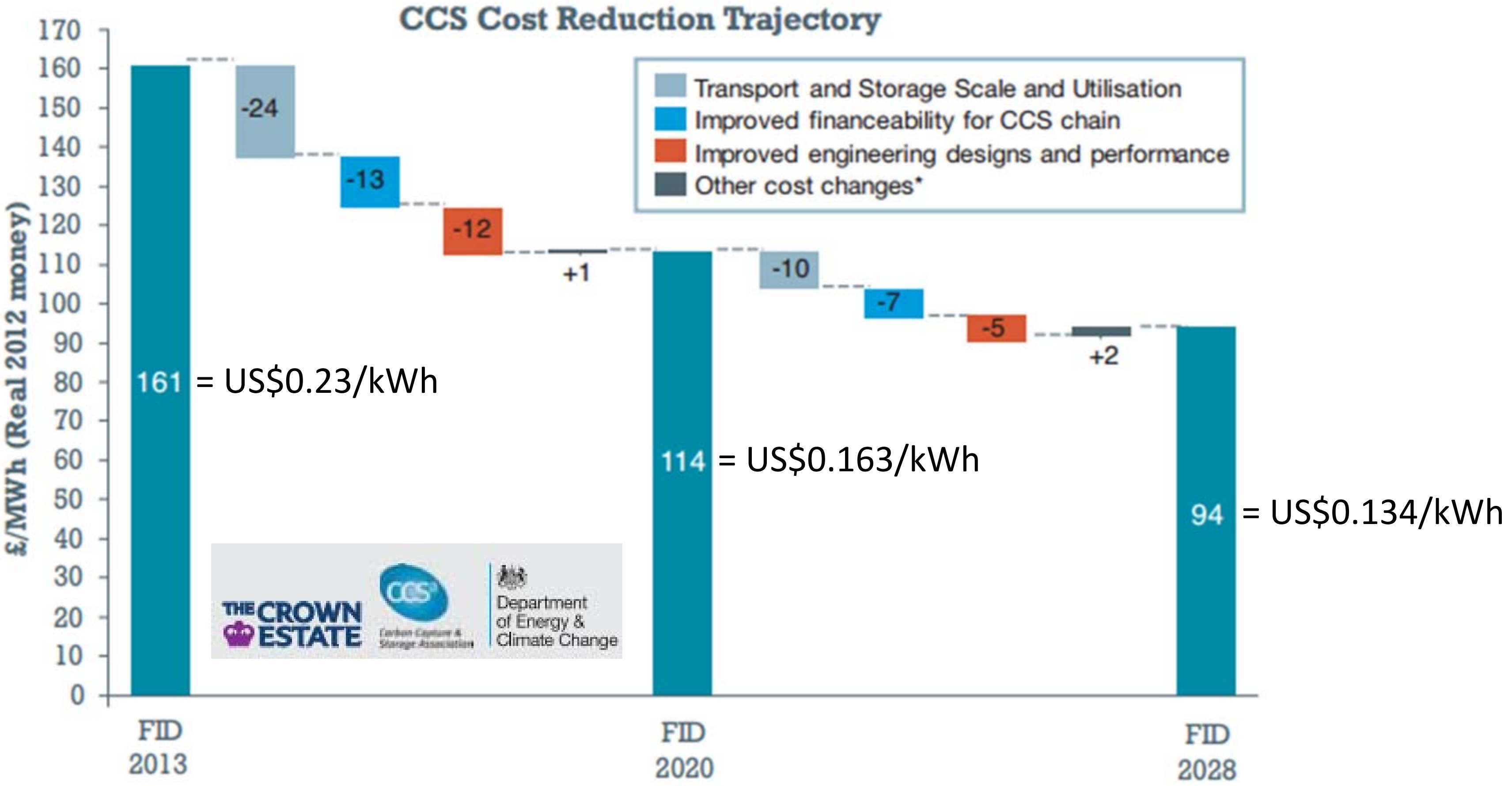
Electricity price





Challenges for CCS – ‘cost’ (II)

- Outlook 2030 – there is hope!
  - UK’s CCS Cost Reduction Taskforce identified potential for US$0.024/kWh* directly attributable to improved engineering designs and performance



161 = US$0.23/kWh

114 = US$0.163/kWh

94 = US$0.134/kWh

Source: UK Cost Reduction Taskforce Final Report – May 2013

* Exchange rate: USD/GBP = 0.7

Putting these all together …

System-wide modelling is a key technology for addressing these questions and investigating **whole-chain** or **partial-chain interaction**

… by providing **accurate quantification** for **decision support**

PSE BACKGROUND: FROM RESEARCH TO INDUSTRY

1997

Company 'spins out' off Imperial College
Private, independent company incorporated in UK

Acquires technology

2007

PSE wins Royal Academy MacRobert Award for Engineering Innovation. This is the UK's highest engineering award

2015

International company delivering software and services

Major process industry focus

Strong R&D

Established sectors

- Chemicals & PetroChemicals
- Oil & Gas
- Formulated Products

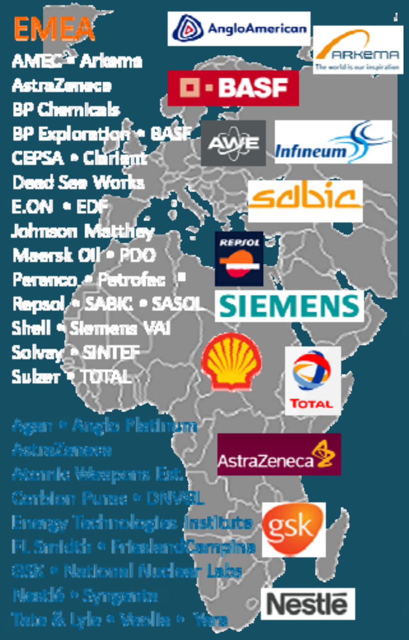
Strategic initiatives

- Energy & Environment

Americas

Air Products
Air Liquide
BP Chemicals
Carus Corporation
CB&I
ConocoPhillips
DuPont
ExxonMobil
Ineos • Infineum
KBR • Praxair

Argonne National Lab
Ballard
Boehringer Ingelheim
Eli Lilly • Energy Solutions
Folgers • Genentech
Johns Manville • Merck
Minera ESAR • NETL
Procter & Gamble
Pfizer • SQM
Smuckers
SQM
Vertex



EMEA

AMEC • Arkema
AstraZeneca
BP Chemicals
BP Exploration • BASF
CEPSA • Clariant
Dead Sea Works
E.ON • EDF
Johnson Matthey
Maersk Oil • PDO
Perenco • Petrofac •
Repsol • SABIC • SASOL
Shell • Siemens VAI
Solvay • SINTEF
Sulzer • TOTAL

Agan • Anglo Platinum
AstraZeneca
Atomic Weapons Est.
Cerblon Purac • DNVGL
Energy Technologies Institute
FL Smidth • FrieslandCampina
GSK • National Nuclear Labs
Nestlé • Syngenta
Tate & Lyle • Veolia • Yara

APAC

GS E&C
Hanwha Chemical • Hyosung
Hyundai HI
JGC • KIOST
KRICT • LG Chem
Lotte Chemical
Mitsubishi Chemical
Posco Energy • RIST
Samnam Petrochemical
Samsung BP • SCG • SKC
SK Chemicals
SK Innovation
SK Petrochemicals
Synfuels China
Taiyo Nippon Sanso

Ajinomoto
DSF • Denso
Honda • KIER
Samsung Electronics
Samsung SDI
Toshiba Fuel Cell
Toyota CRDL
Toyota Motor Company

Sectors (verticals) and products

General mathematical modelling

Oil & Gas

Chemicals & Petrochemicals

Formulated Products

Energy & Environment

g|MODEL g|FLARE g|PROCESS g|CRYSTAL g|SOLIDS g|COAS g|POWER g|FUELCELL g|CCS g|WATER

gPROMS ModelBuilder Advanced process modelling

Flare networks & depressurisation

Oil major

gPROMS ProcessBuilder Advanced process simulation

Solids process optimisation

Crystallization process optimisation

Procter & Gamble

Oral absorption modelling

Pfizer

Power plant modelling

Fuel cell stack & system design

Toyota

Carbon capture & storage

ETI

Water systems optimisation

EPFL

gPROMS THE WORLD'S LEADING ADVANCED PROCESS MODELLING PLATFORM

gSAFT

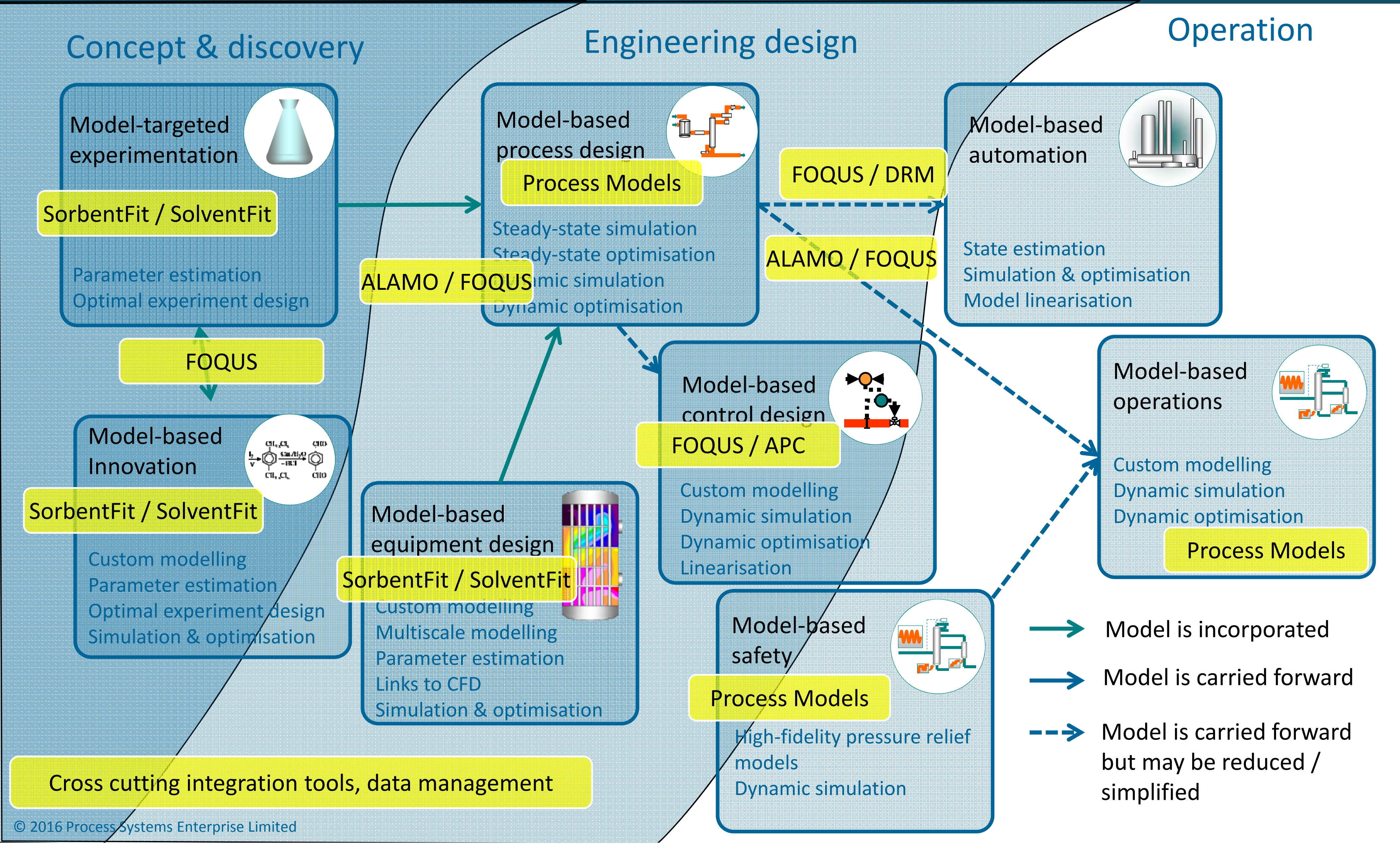
Molecular Systems Engineering @Imperial College

High-fidelity modelling and optimisation tools for R&D, Engineering & Operations

Accelerate innovation • Optimise process design & operations • Improve R&D efficiency • Manage technology risk

Model-based Engineering

Technologies & workflows across the process lifecycle



Concept & discovery

Model-targeted experimentation

SorbentFit / SolventFit

Parameter estimation
Optimal experiment design

FOQUS

Model-based Innovation

SorbentFit / SolventFit

Custom modelling
Parameter estimation
Optimal experiment design
Simulation & optimisation

Engineering design

Model-based process design

Process Models

Steady-state simulation
Steady-state optimisation
Dynamic simulation
Dynamic optimisation

ALAMO / FOQUS

Model-based equipment design

SorbentFit / SolventFit

Custom modelling
Multiscale modelling
Parameter estimation
Links to CFD
Simulation & optimisation

Model-based control design

FOQUS / APC

Custom modelling
Dynamic simulation
Dynamic optimisation
Linearisation

Model-based safety

Process Models

High-fidelity pressure relief models
Dynamic simulation

FOQUS / DRM

ALAMO / FOQUS

Operation

Model-based automation

State estimation
Simulation & optimisation
Model linearisation

Model-based operations

Custom modelling
Dynamic simulation
Dynamic optimisation

Process Models

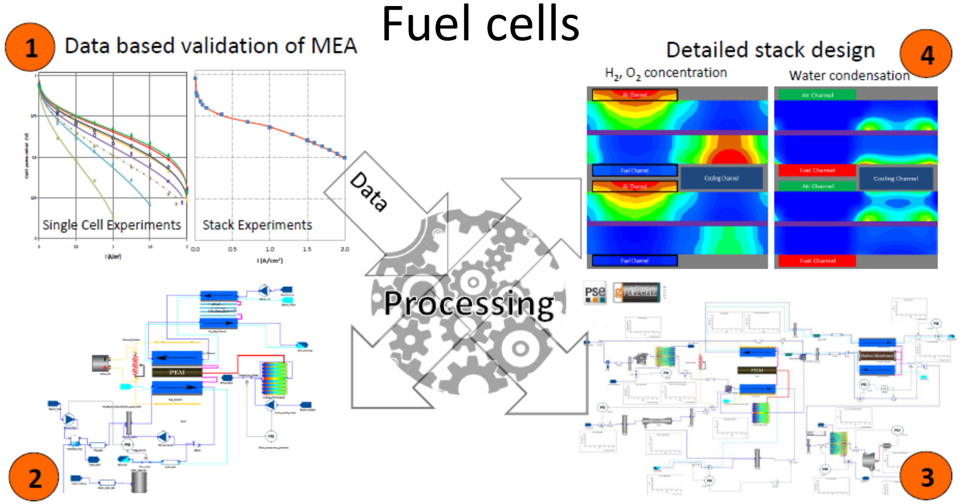
Cross cutting integration tools, data management

→ Model is incorporated
→ Model is carried forward
- - → Model is carried forward but may be reduced / simplified

Applications

- Accelerate rate of cost reductions for low-emission technologies through deployment of models across the entire development lifecycle

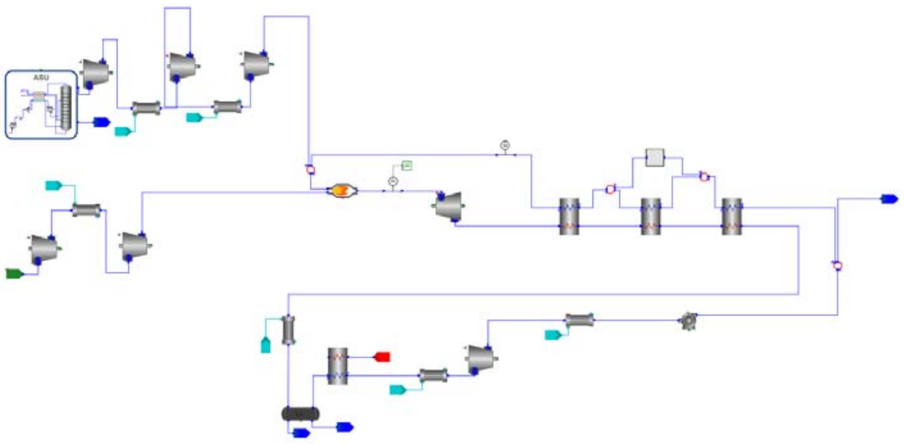
Fuel cells



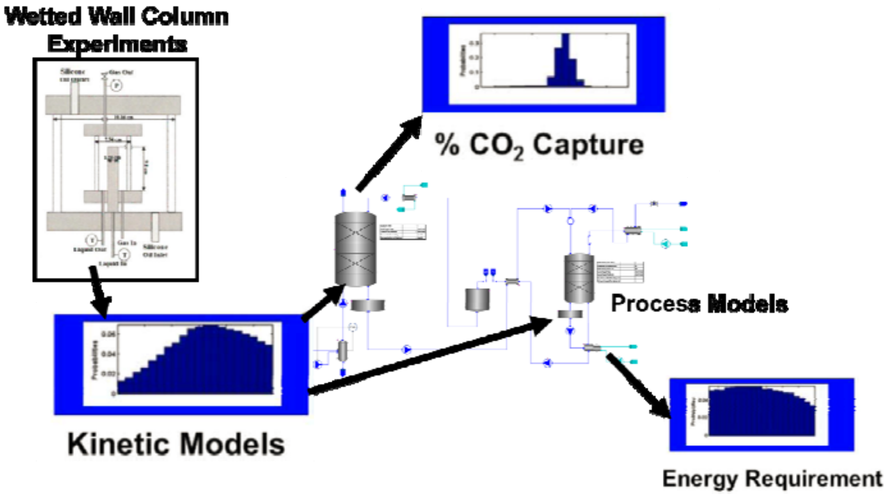
Stack performance in a simple system, water management, deactivation, design decisions

Design and optimisation of complete system for commercial applications, dynamic simulation of drive cycles

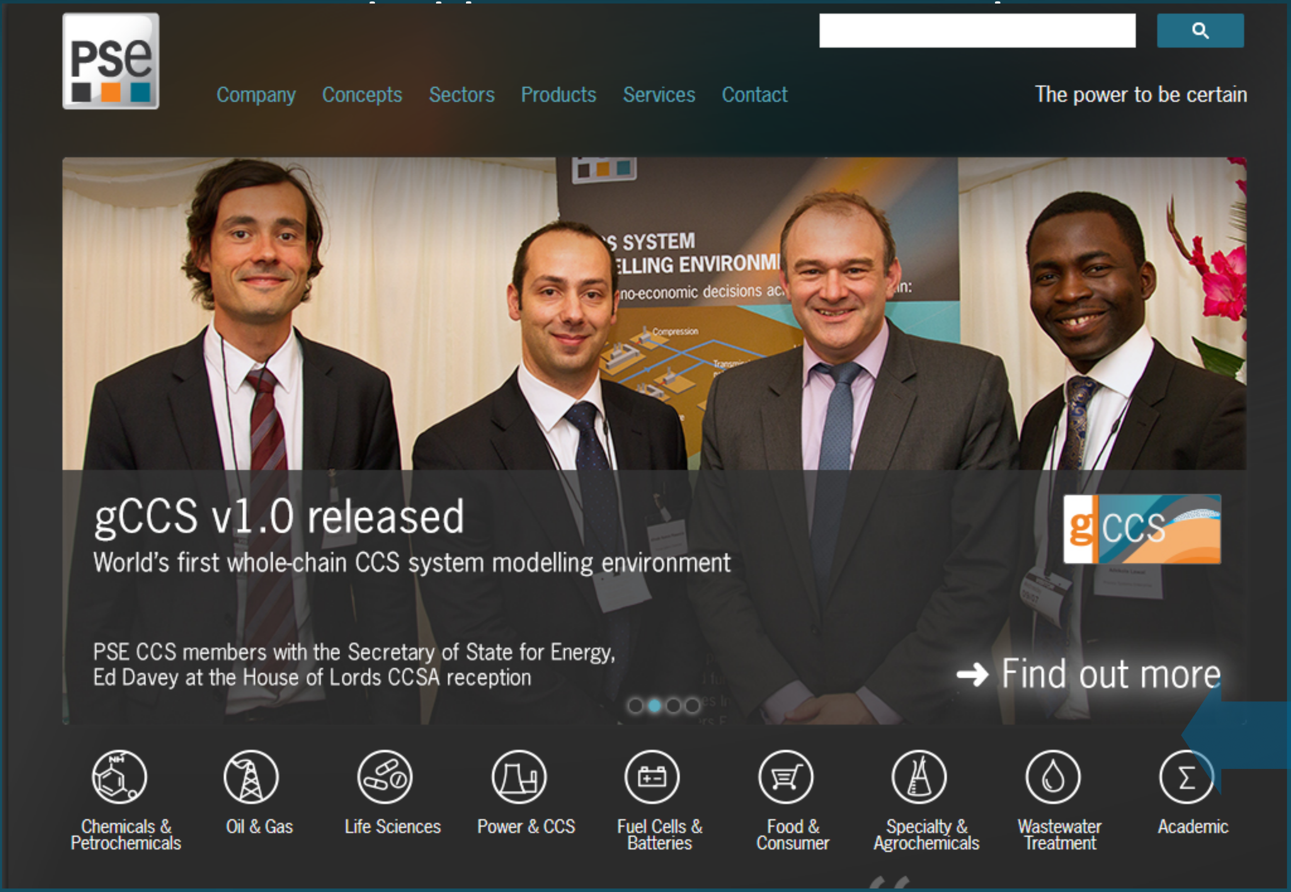
Advanced Thermodynamic Cycles
(e.g. Allam)



- Uncertainty Quantification extension of gCCS CO2 Capture library (Morgan et al., 2015)



- **CCS Advanced Process Modelling Tool-kit Project**
  - $5.5m project
  - 3 year development (2011-2014)
  - Tool tested using several case studies



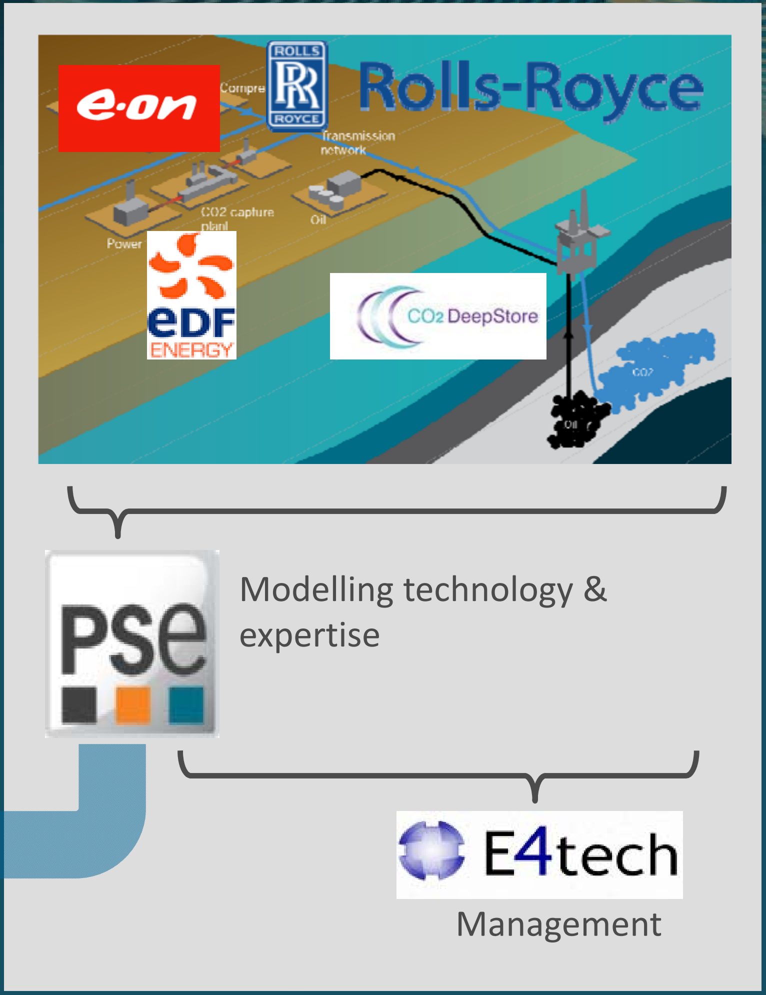
The power to be certain

gCCS v1.0 released

World's first whole-chain CCS system modelling environment

PSE CCS members with the Secretary of State for Energy, Ed Davey at the House of Lords CCSA reception

→ Find out more



Modelling technology & expertise

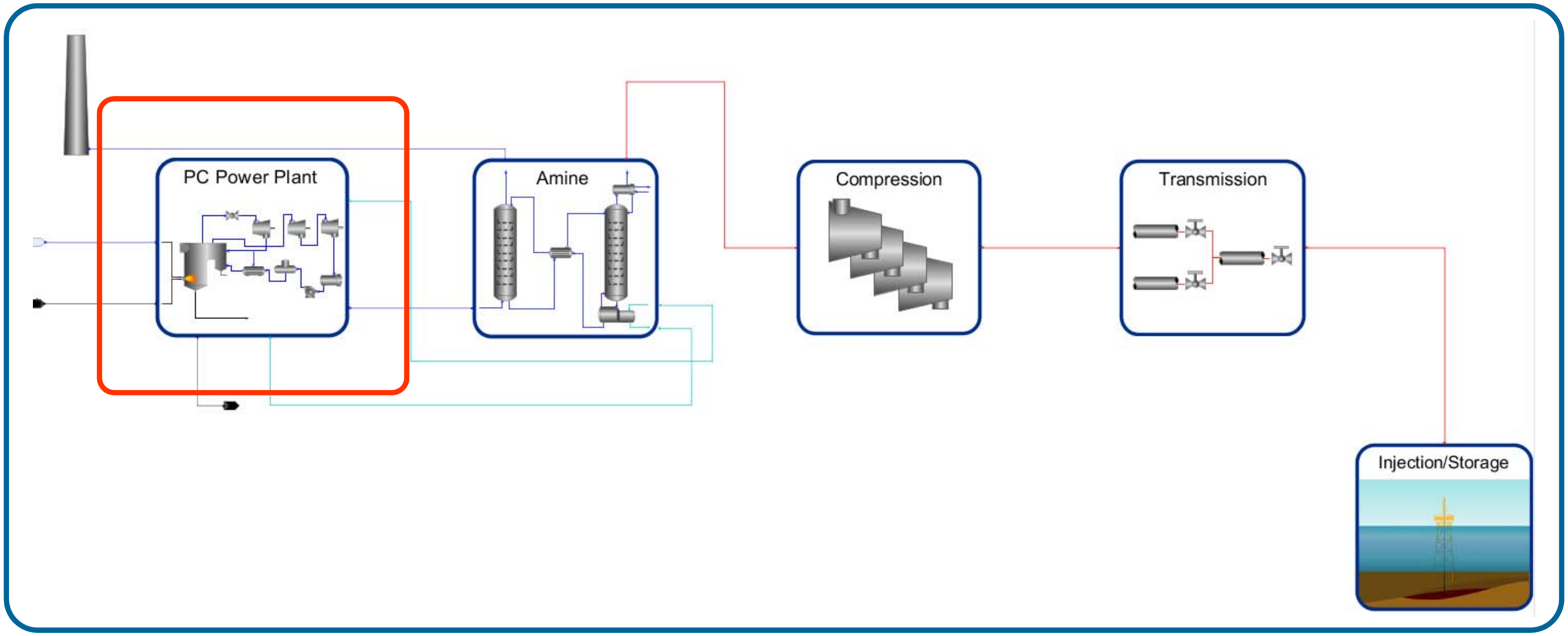
Management

gCCS v1.1 scope

- **Process models**
  - Power generation
    - Conventional: PC, NGCC
    - 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
- **Costing models**
  - Equipment CapEx & OpeX
- **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

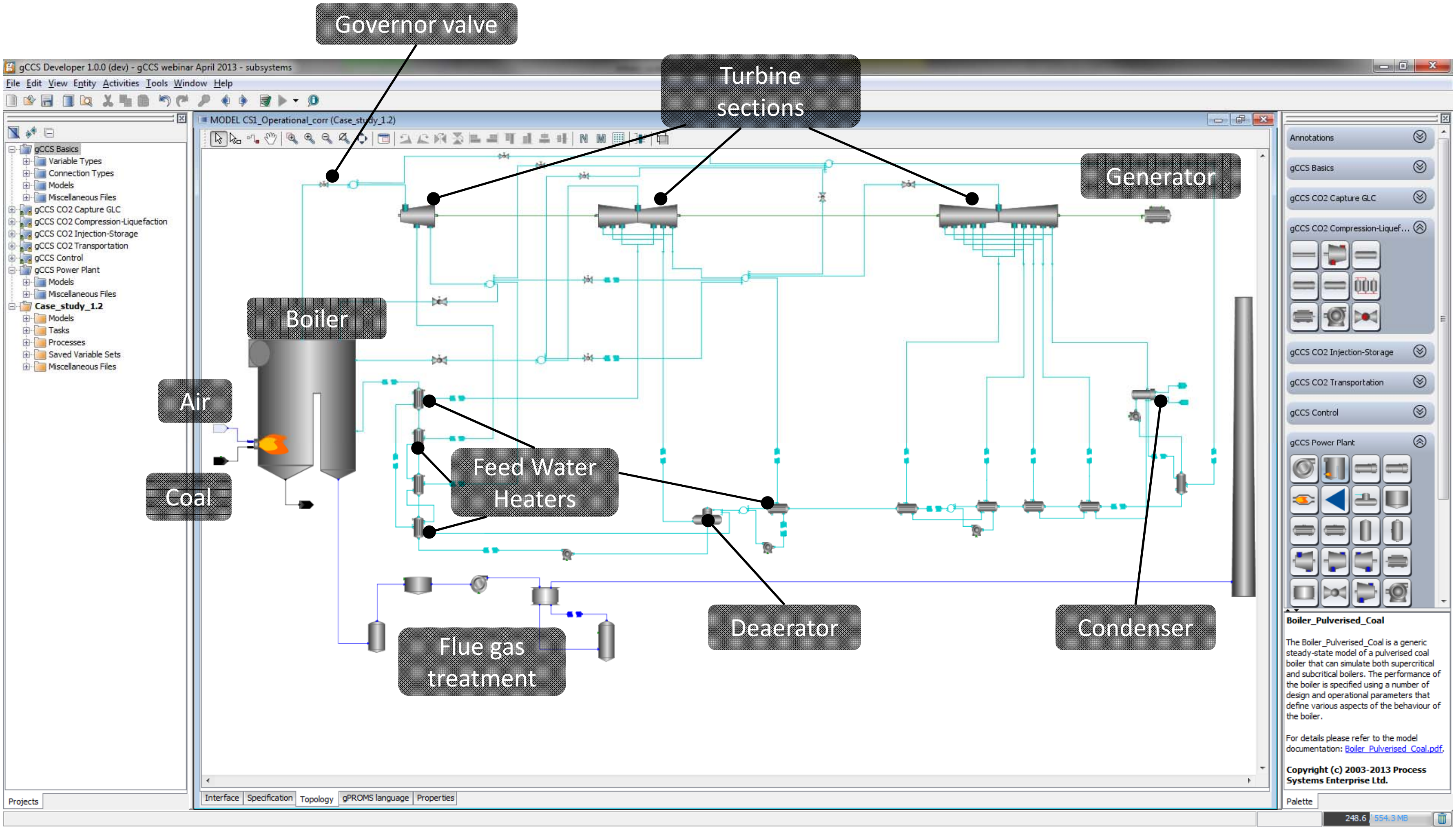
Open architecture allows incorporation of 3rd party models

Power generation



gCCS Power Plant Library – conventional power generation

Supercritical pulverized coal power plant



Boiler_Pulverised_Coal

The Boiler_Pulverised_Coal is a generic steady-state model of a pulverised coal boiler that can simulate both supercritical and subcritical boilers. The performance of the boiler is specified using a number of design and operational parameters that define various aspects of the behaviour of the boiler.

For details please refer to the model documentation: Boiler_Pulverised_Coal.pdf.

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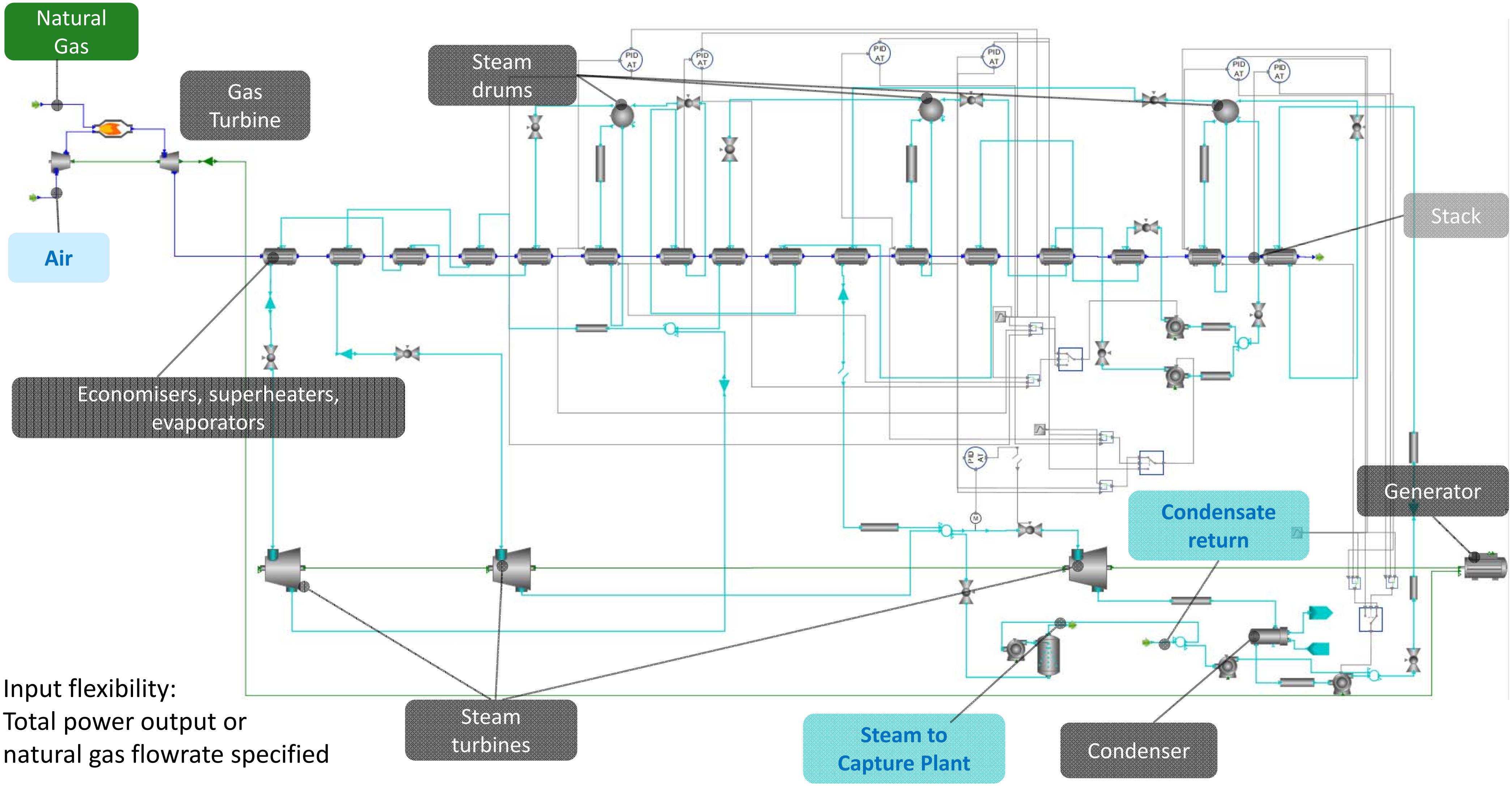
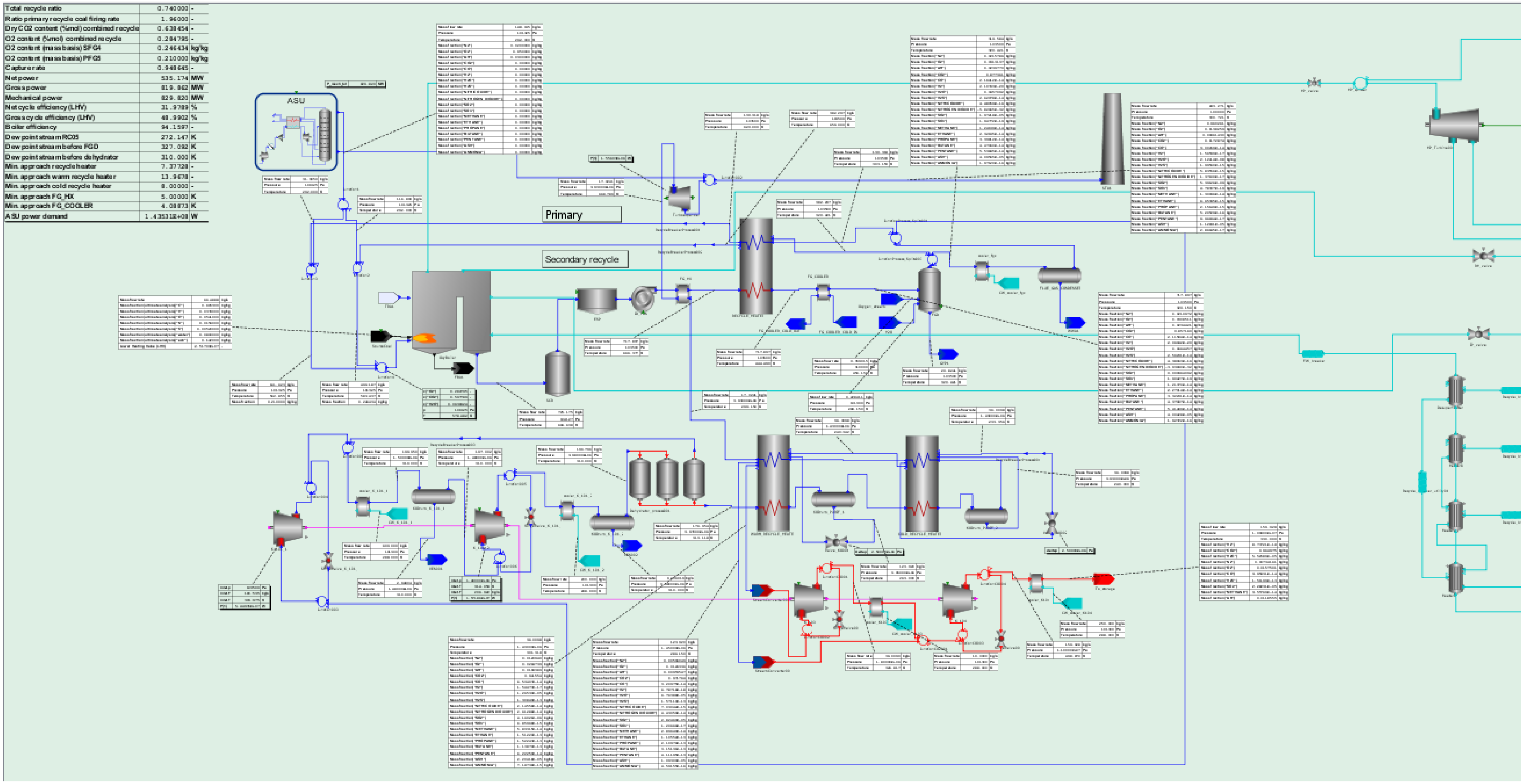
gCCS Power Plant library – conventional power generation

NGCC power plant



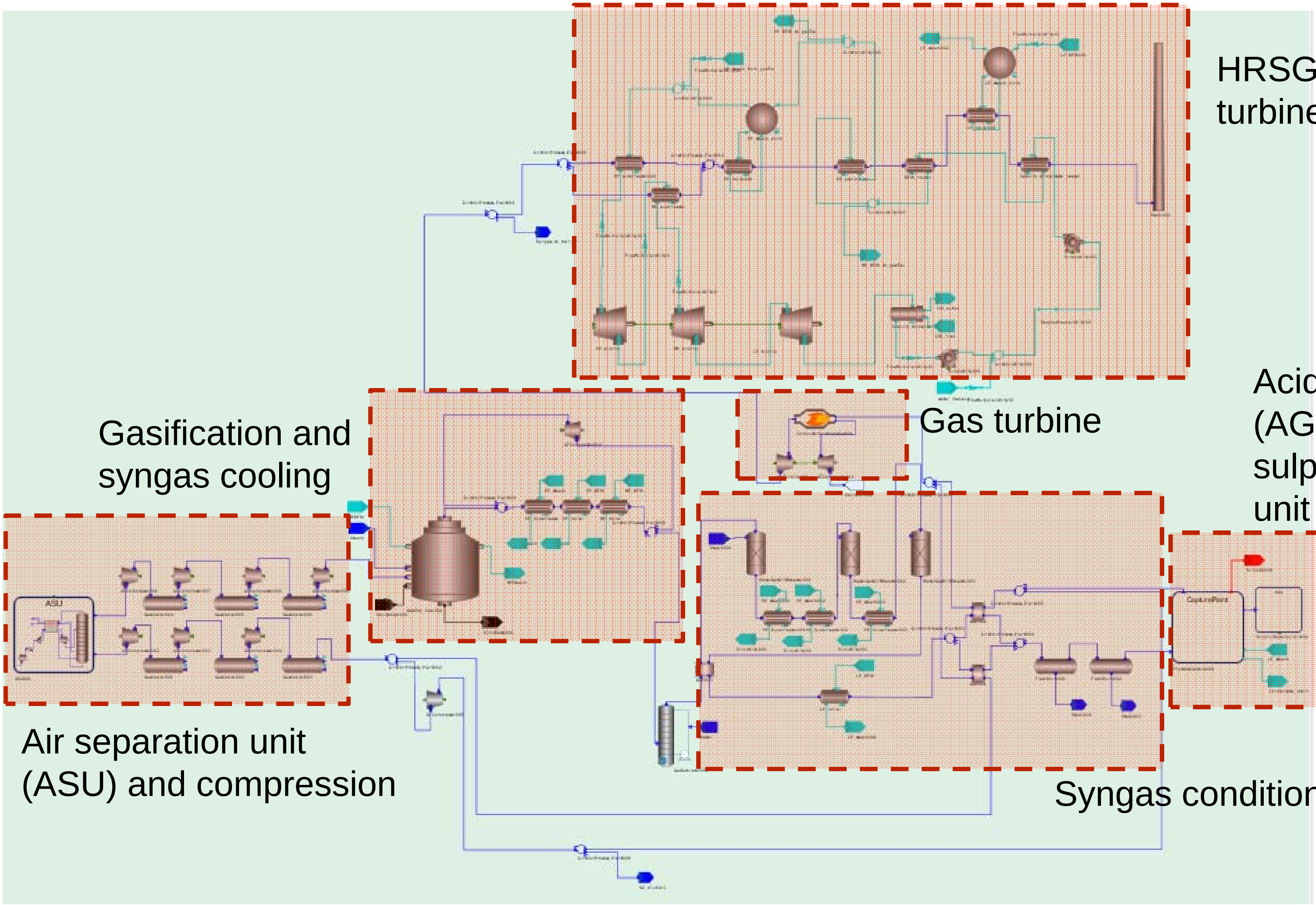
Input flexibility:
Total power output or natural gas flowrate specified

Oxyfuel system



Total recycle ratio	0.740000	-
Ratio primary recycle coal firing rate	1.96000	-
Dry CO2 content (%mol) combined recycle	0.638454	-
O2 content (%mol) combined recycle	0.284795	-
O2 content (mass basis) SFG4	0.246434	kg/kg
O2 content (mass basis) PFG5	0.210000	kg/kg
Capture rate	0.948645	-
Net power	535.174	MW
Gross power	819.862	MW
Mechanical power	829.820	MW
Net cycle efficiency (LHV)	31.9789	%
Gross cycle efficiency (LHV)	48.9902	%
Boiler efficiency	94.1597	-
Dew point stream RC05	272.147	K
Dew point stream before FGD	327.082	K
Dew point stream before dehydrator	310.000	K
Min. approach recycle heater	7.37728	-
Min. approach warm recycle heater	13.9678	-
Min. approach cold recycle heater	8.00000	-
Min. approach FG_HX	5.00000	K
Min. approach FG_COOLER	4.08873	K
ASU power demand	1.43531E+08	W

Integrated Gasification Combined Cycle (IGCC)



HRSG and steam turbines

Gas turbine

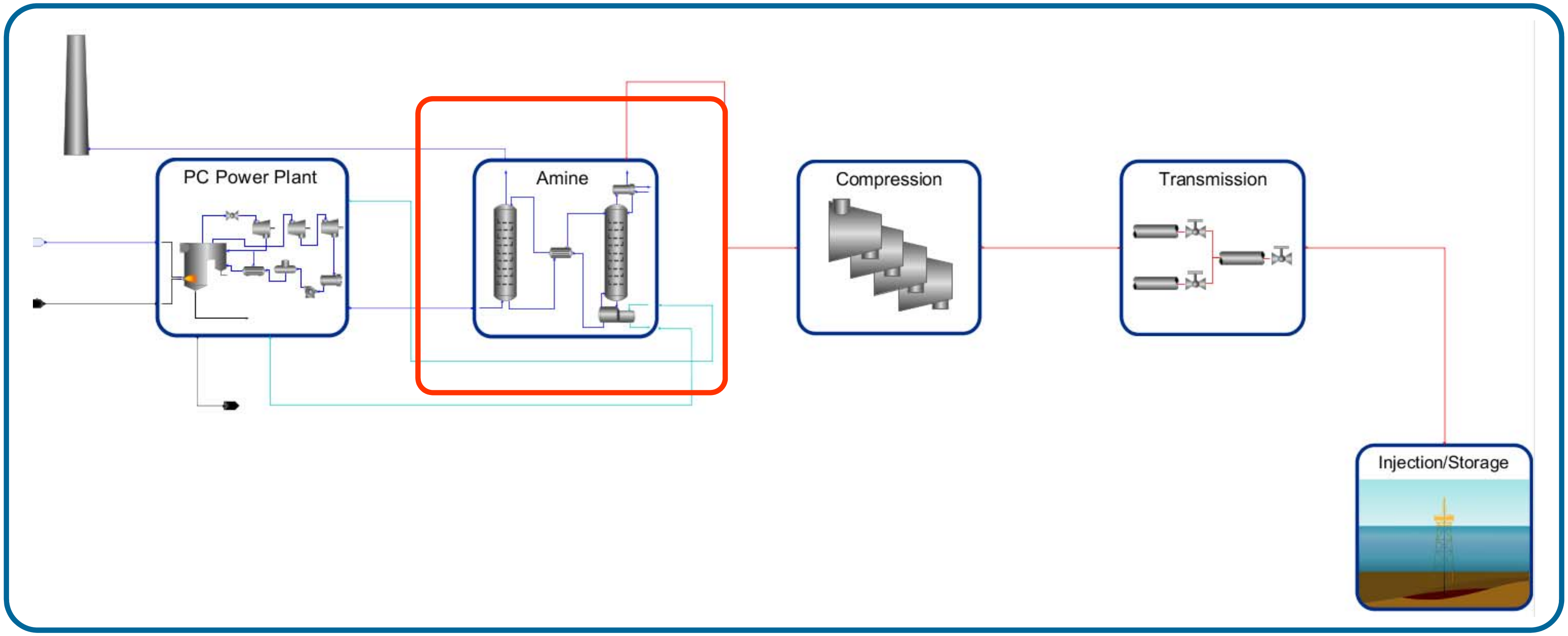
Acid gas removal (AGR) and sulphur recovery unit (SRU)

Gasification and syngas cooling

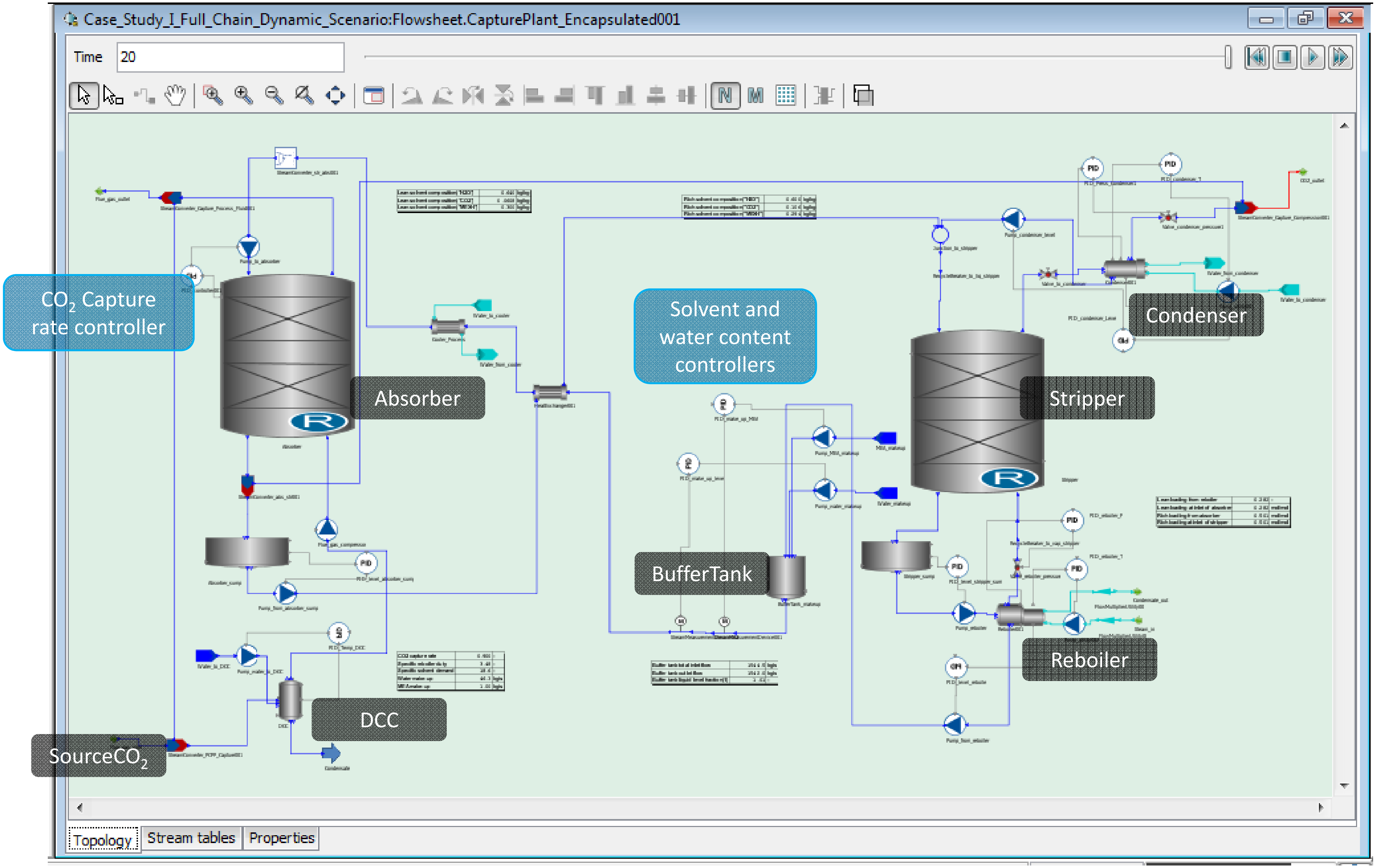
Air separation unit (ASU) and compression

Syngas conditioning

CO_2 Capture


PC Power Plant
Amine
Compression
Transmission
Injection/Storage

Chemical Absorption



Case_Study_I_Full_Chain_Dynamic_Scenario:Flowsheet.CapturePlant_Encapsulated001

Time: 20

CO_2 Capture rate controller

Absorber

Solvent and water content controllers

Condenser

Stripper

BufferTank

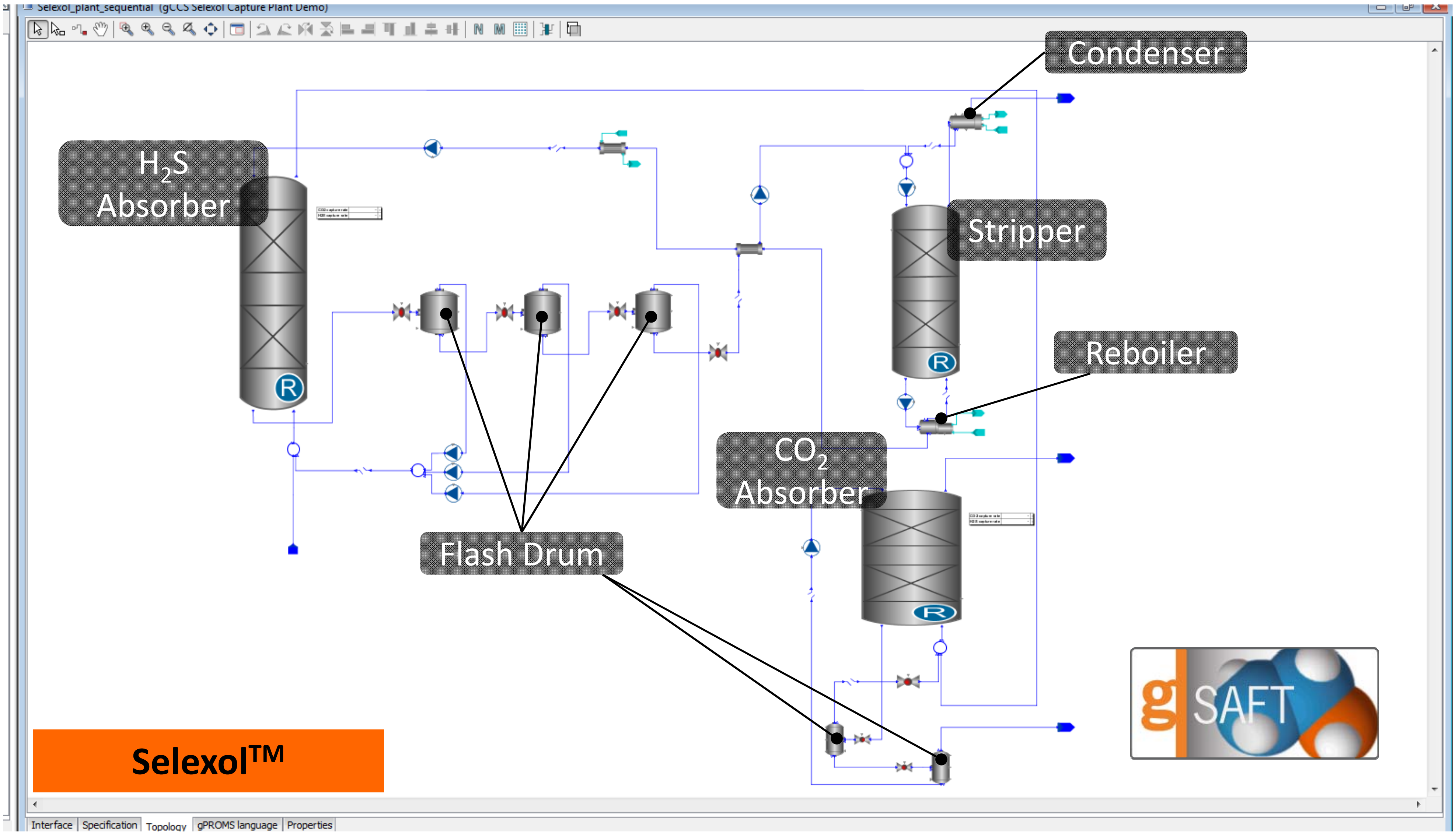
Reboiler

DCC

SourceCO$_2$

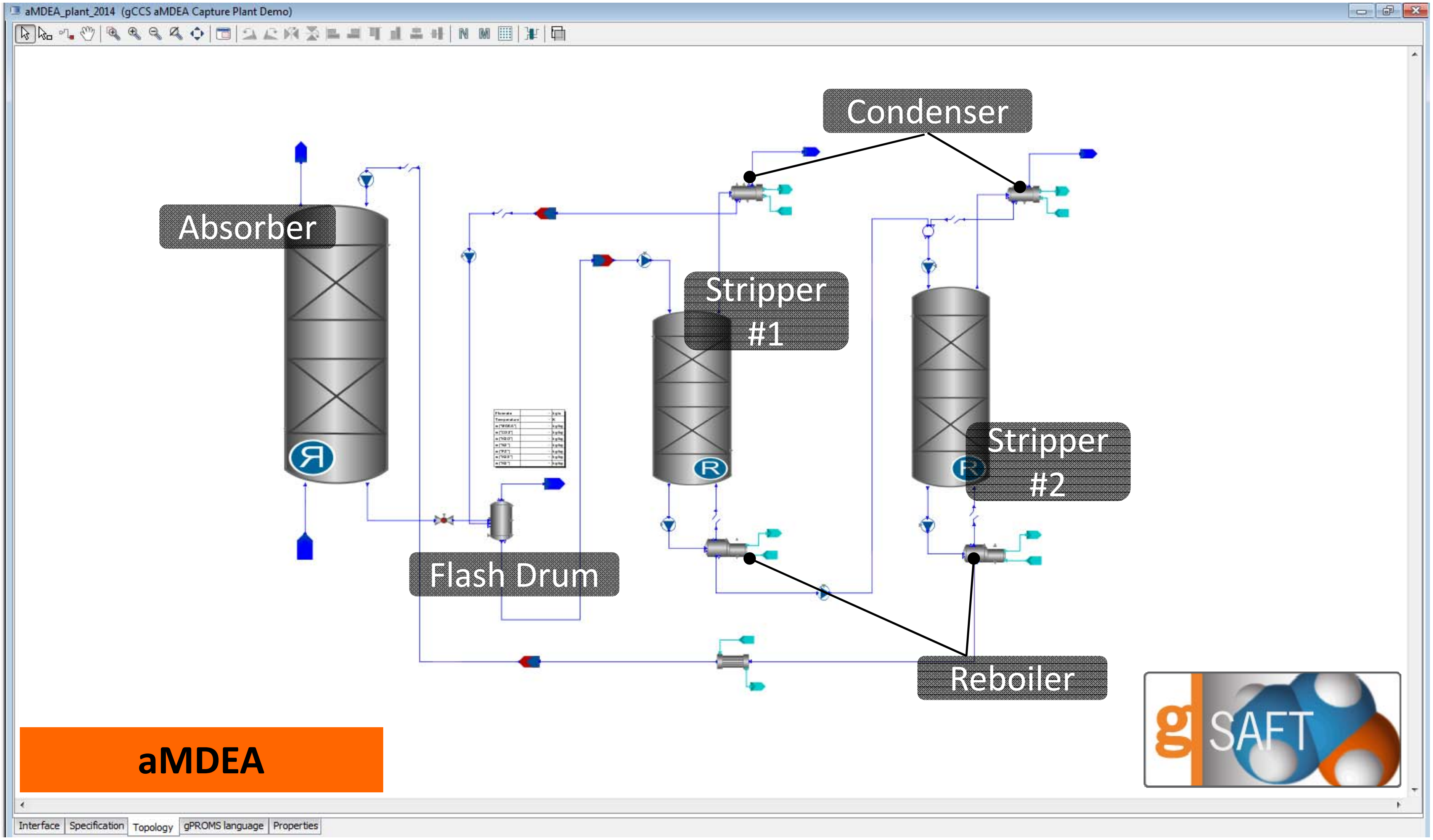
gCCS CO_2 Capture Library

Physical absorption capture plant model

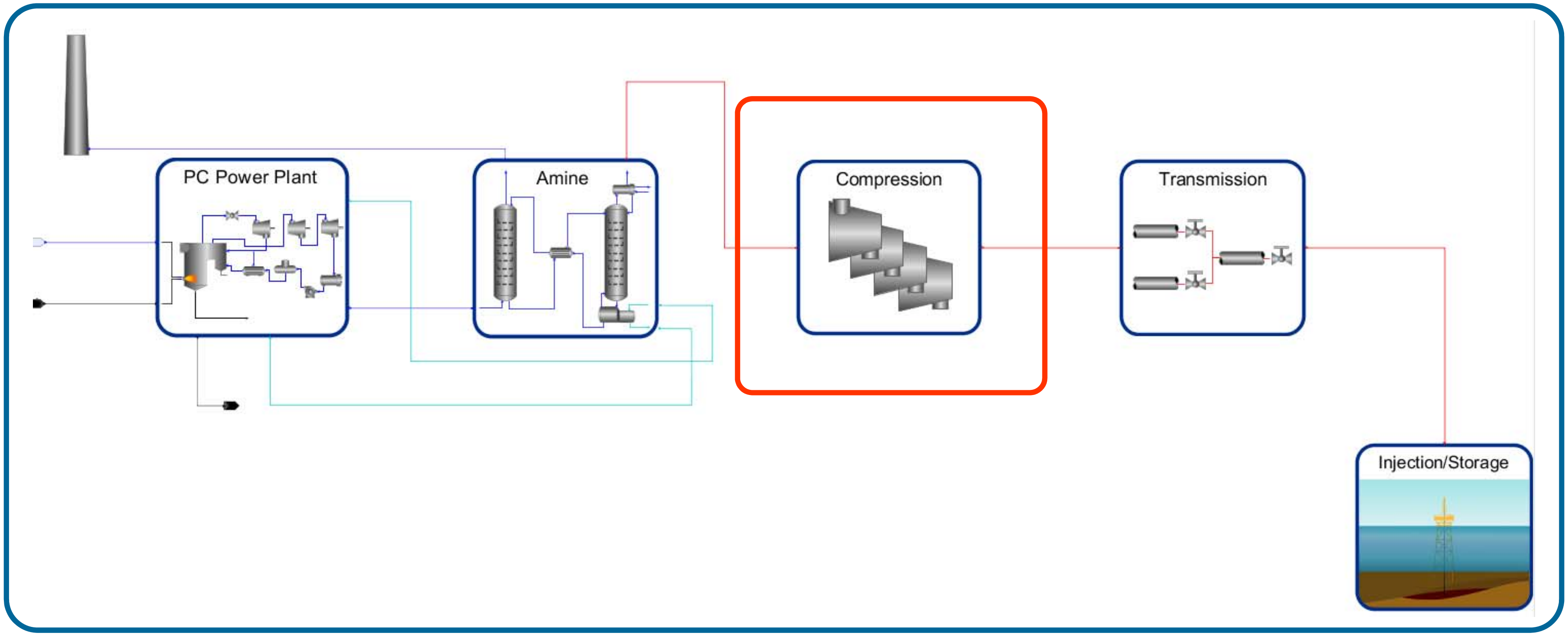


gCCS CO_2 Capture Library

Custom models: Activated amine capture plant

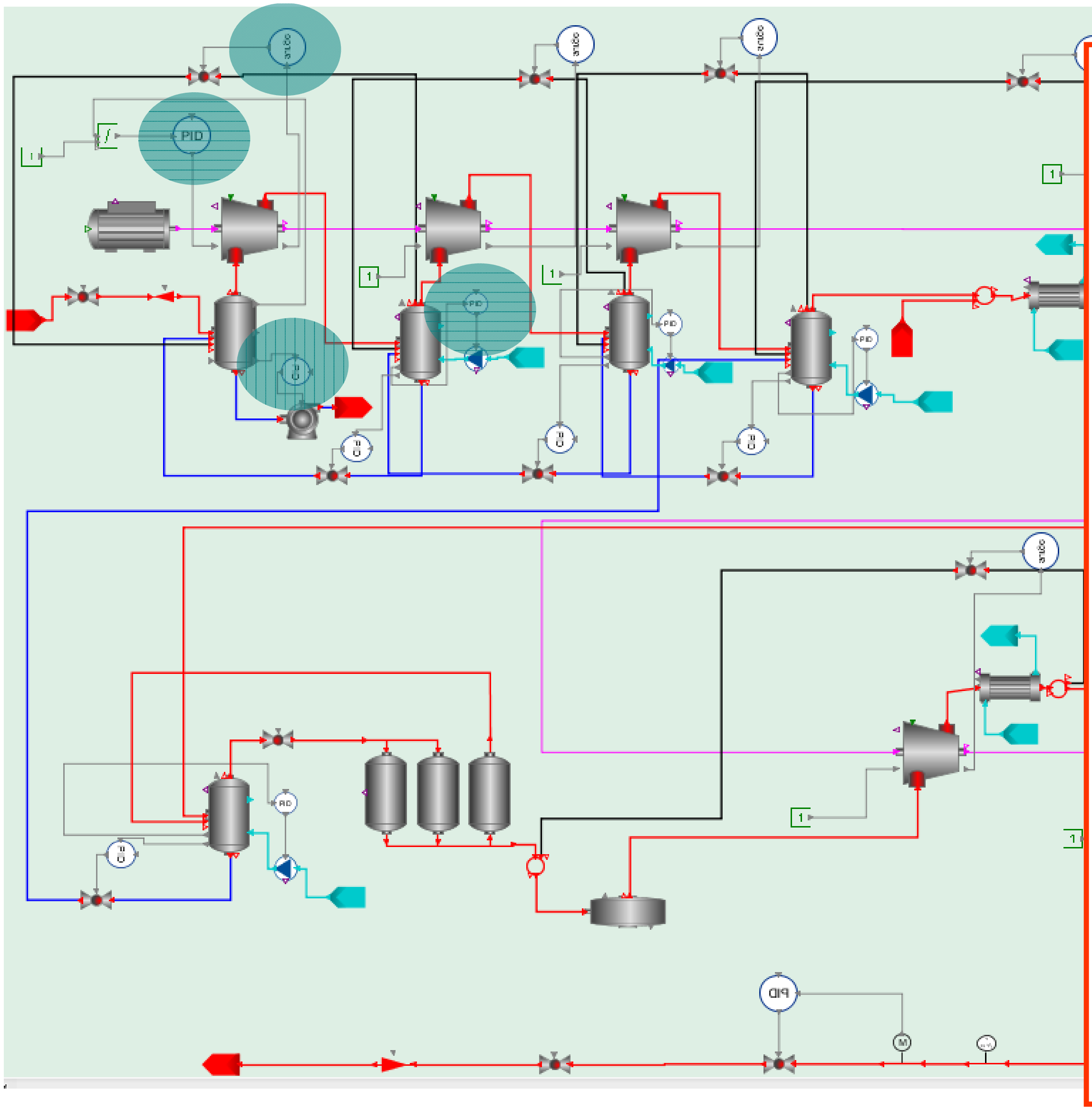


Compression



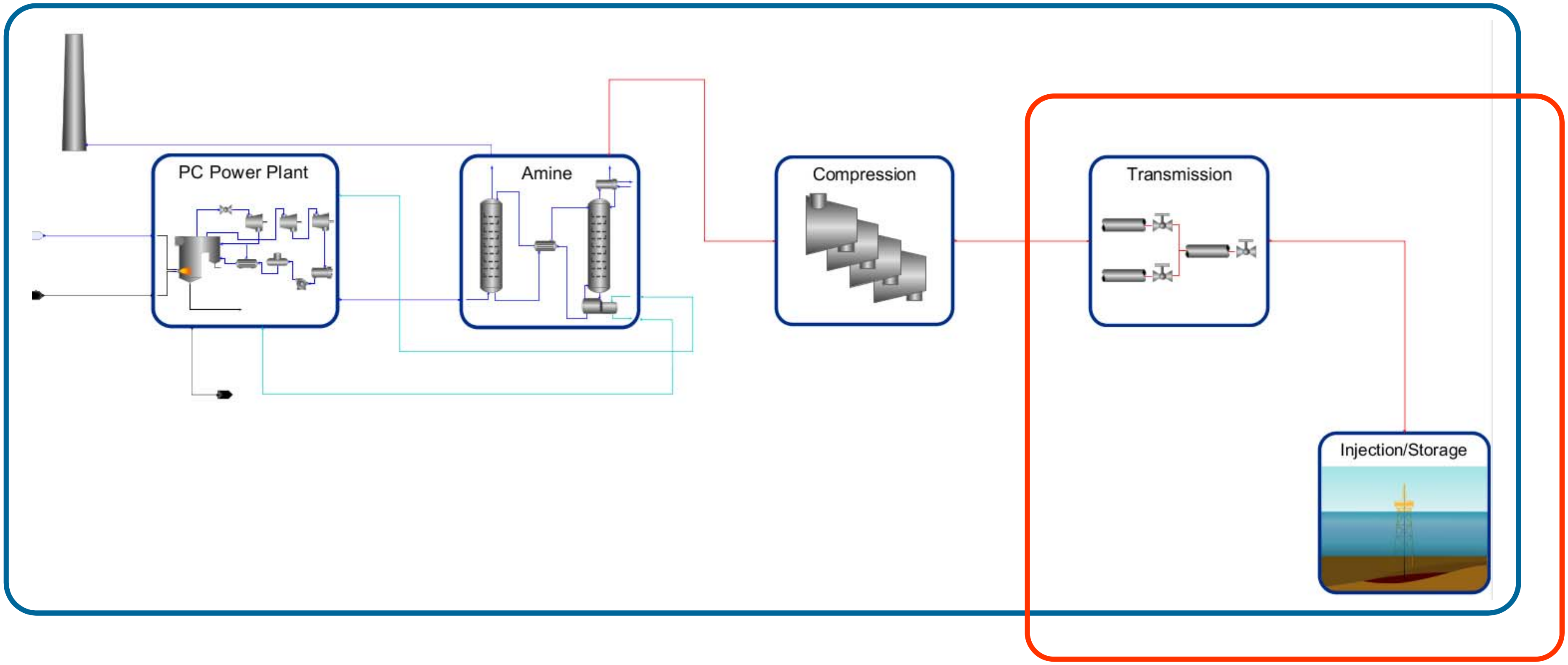
Multi-section compressor train

Including Control System

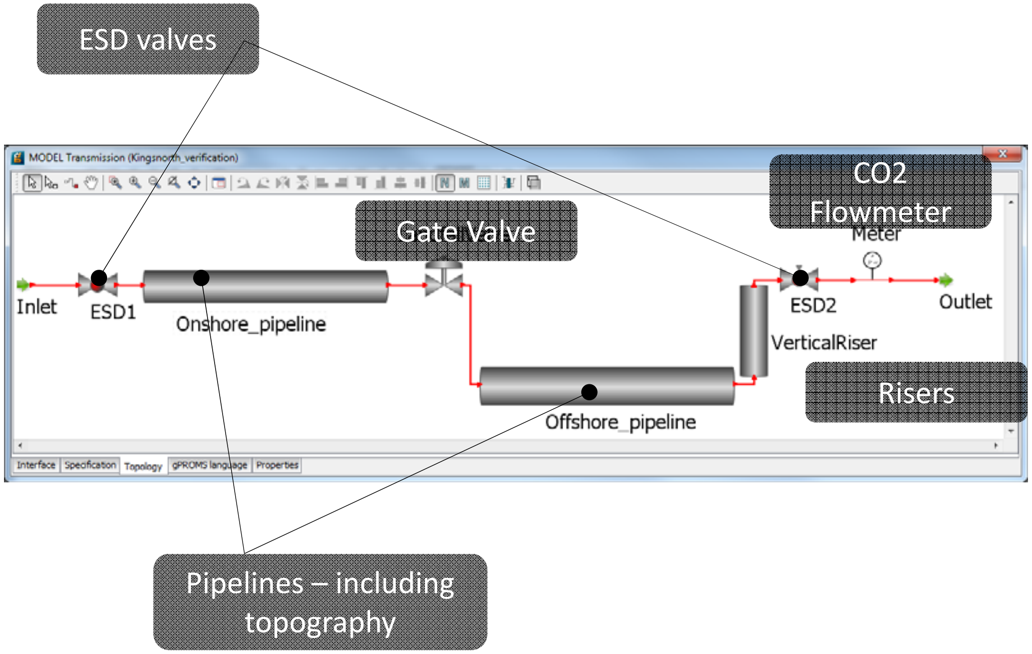


- Dynamics accounted for
  - KO-Drum mass/energy holdup
  - Shaft and compressor inertia
  - Valve dynamics
    - Opening time
    - Closing time
  - Controller parameters
- Suction pressure
  - IGV control
  - VFD control
- For every compression stage
  - Anti-surge control
  - Discharge temperature control
  - KO-Drum level control
- All safety valves
  - ESD valve
  - Check valve

Transmission & injection



Transmission and Injection



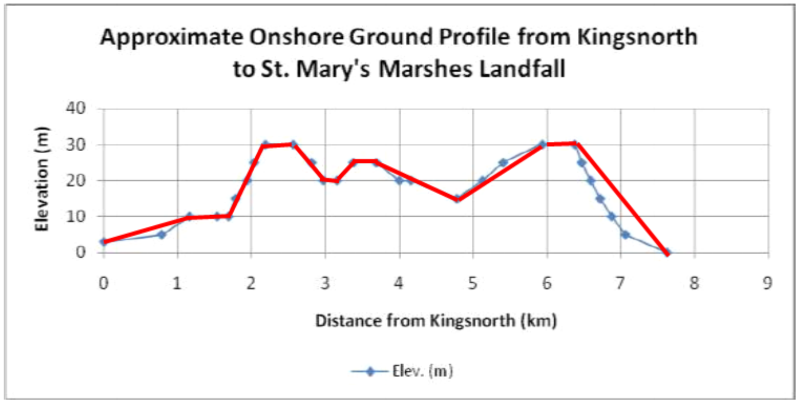
ESD valves

CO2 Flowmeter

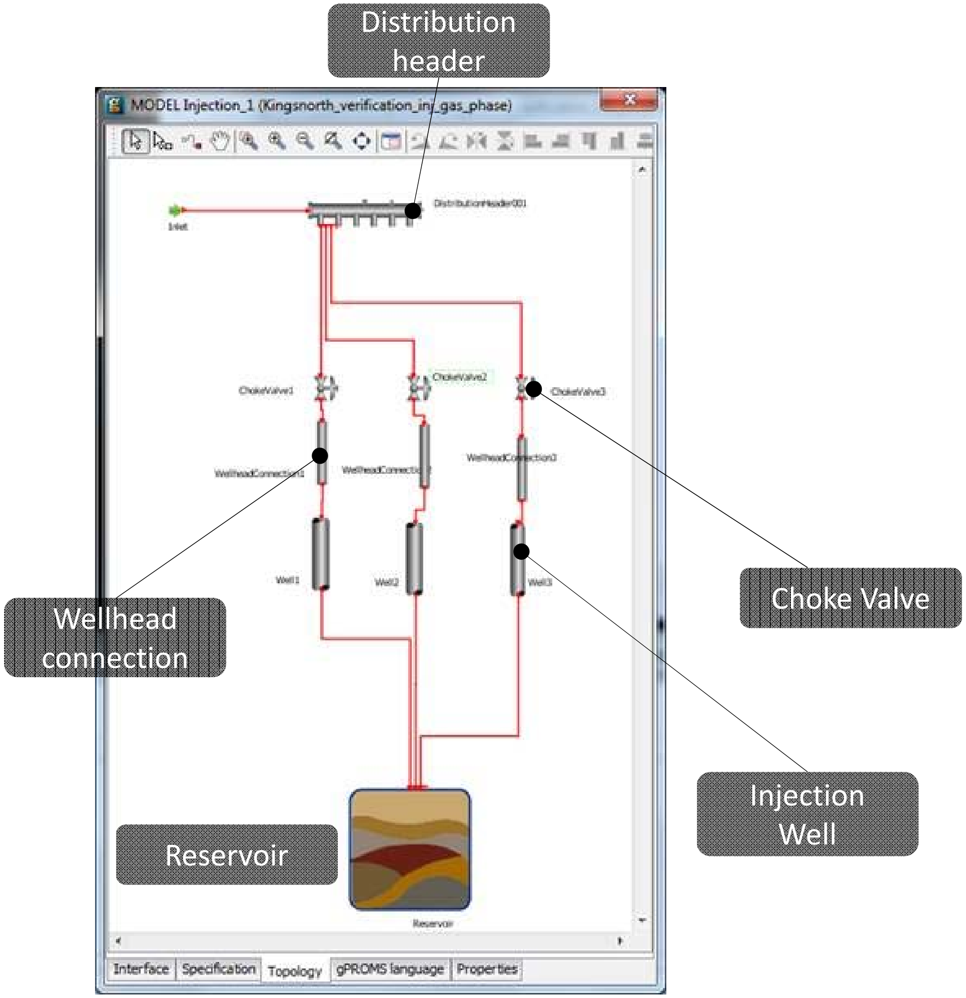
Gate Valve

Risers

Pipelines – including topography



Approximate Onshore Ground Profile from Kingsnorth to St. Mary's Marshes Landfall



Distribution header

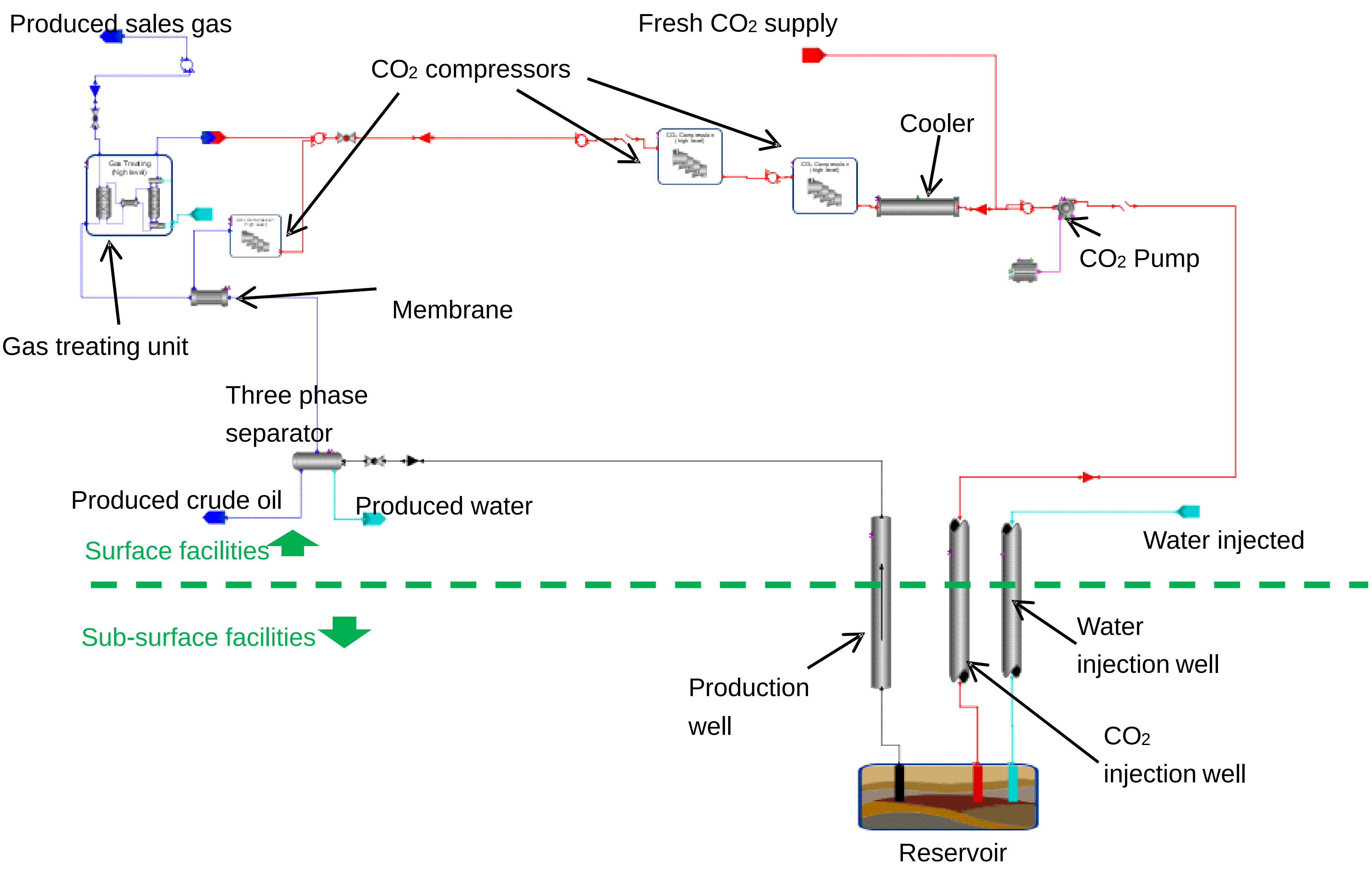
Wellhead connection

Choke Valve

Injection Well

Reservoir

CO$_2$ Enhanced Oil Recovery



Produced sales gas

Fresh CO$_2$ supply

CO$_2$ compressors

Cooler

CO$_2$ Pump

Membrane

Gas treating unit

Three phase separator

Produced crude oil

Produced water

Surface facilities

Sub-surface facilities

Water injected

Water injection well

Production well

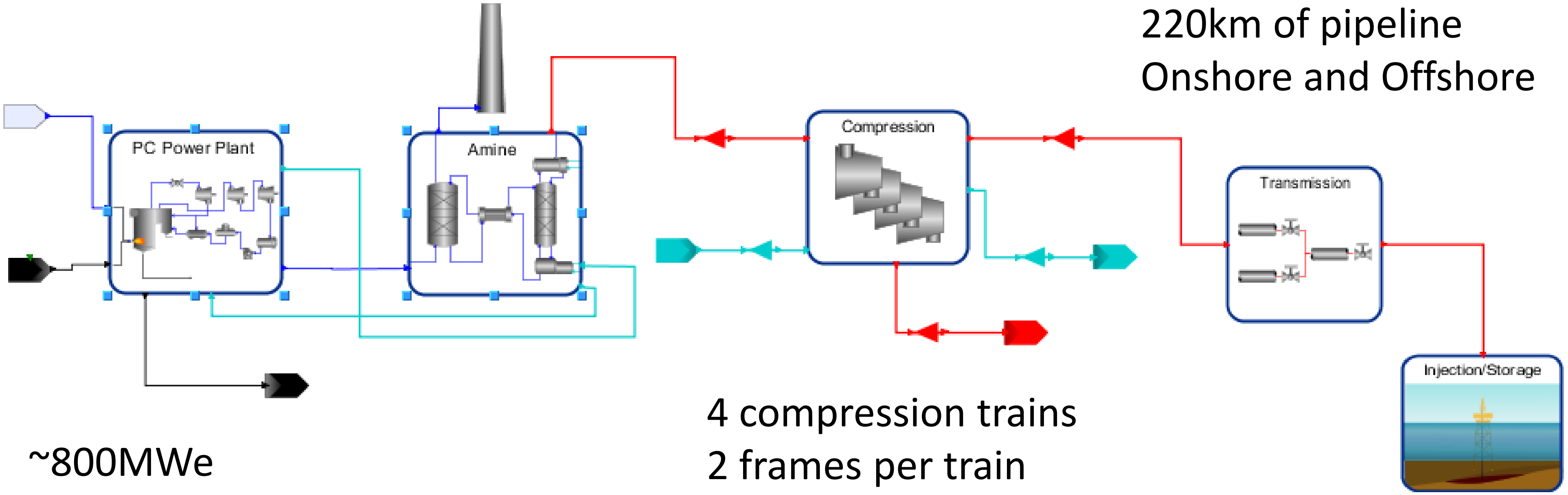
CO$_2$ injection well

Reservoir

Applications of gCCS: Case Studies

1. Process integration in CCS chains and networks

CCS Chain model developed in gCCS



Chemical absorption
MEA solvent
90% CO_2 capture

220km of pipeline
Onshore and Offshore

~800MWe
Supercritical
Pulverized coal
(acknowledgement: E.ON)

4 compression trains
2 frames per train
Surge control
(acknowledgement:
Rolls-Royce)

Offshore dense-phase
injection; 4 injection wells
~2km reservoir depth
(acknowledgement:
CO2DeepStore)

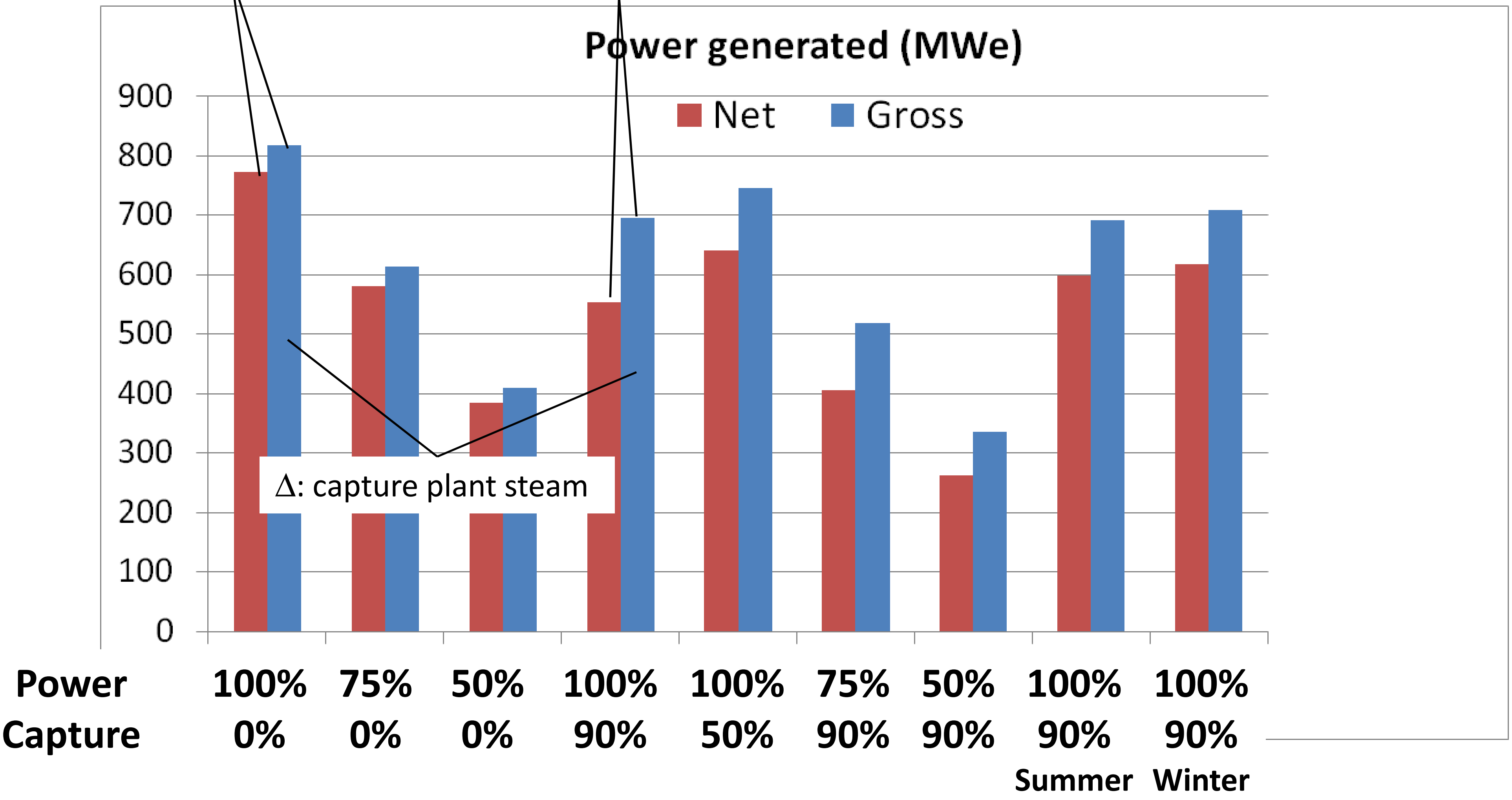
Steady-state scenarios

Scenario	Description	Power plant operation (% of nominal load)	Capture plant operation (CO2 % captured)
SS1.1 (a,b,c)	Base Load Power Plant	(a) 100%; (b) 75%; (c) 50%	0% (no capture)
SS1.2 (a, b)	Base load CCS Chain	100%	(a) 90%; (b) 50%
SS1.3 (a, b)	Part Load Analysis	(a) 75%; (b) 50%	90%
SS1.4	Extreme Weather: Max Summer	100%	90%
SS1.5	Extreme Weather: Min Winter	100%	90%

Temperatures (°C)	Affected sub-systems	Base Case	Extreme Summer	Extreme Winter
Cooling water	Power, Capture, Compression	18	22	7
Air	Power, Transmission, Injection	15	30	-15
Sea water	Transmission, Injection	9	14	4
NB. Geothermal gradient of +27.5°C / km				

Steady-state analysis

Power generation



Δ: coal milling
+ power plant auxiliaries

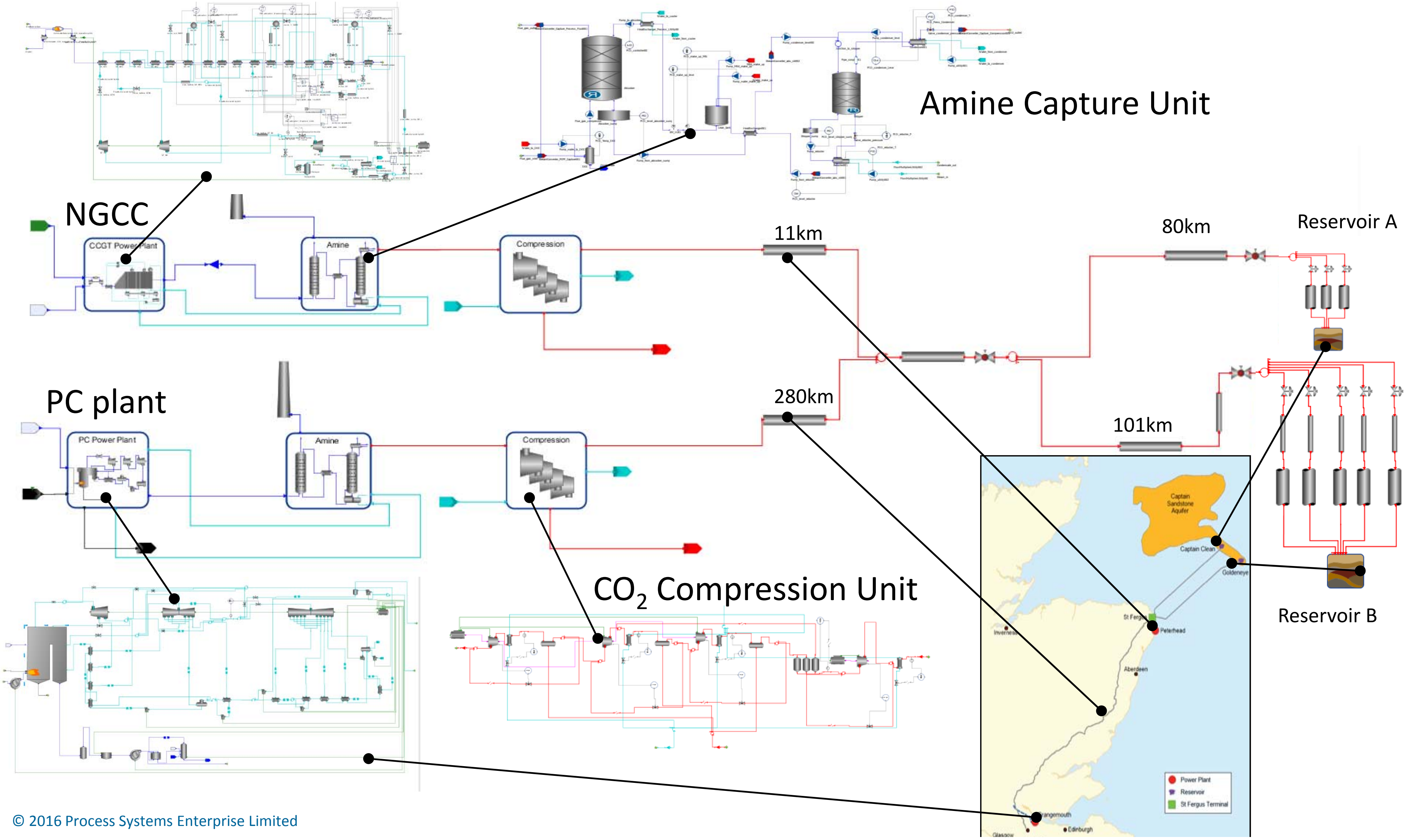
Δ: coal milling
+ power plant auxiliaries
+ CO_2 compression

Δ: capture plant steam

Applications of gCCS: Case Studies

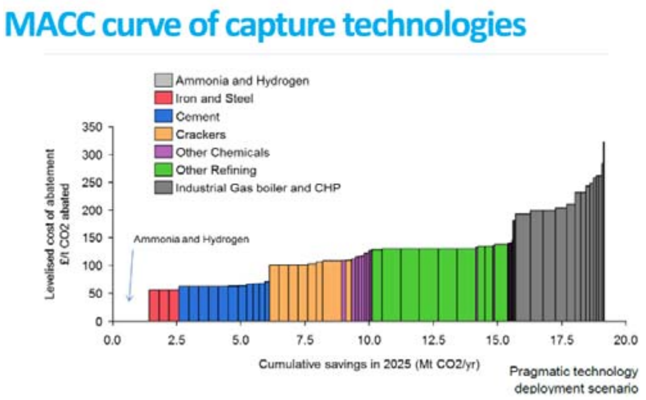
2. Dynamics in CCS Networks

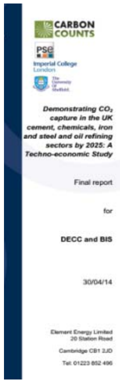
CCS network modelling in gCCS



Industrial projects

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




CARBON COUNTS

Imperial College London

The University Of Sheffield

Demonstrating CO_2 capture in the UK cement, chemicals, iron and steel and oil refining sectors by 2025: A Techno-economic Study

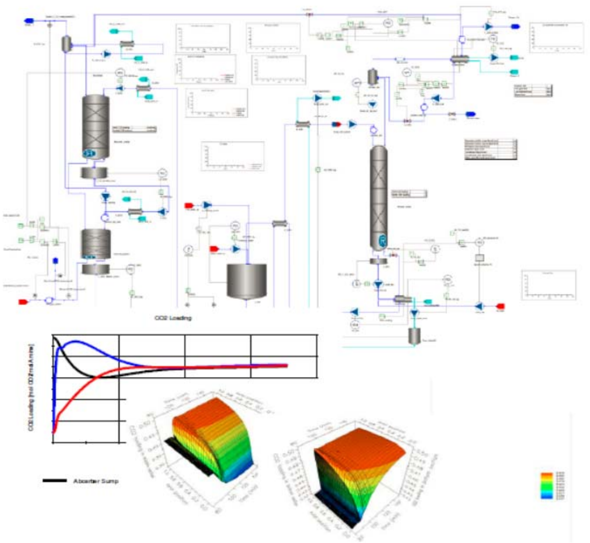
Final report

for

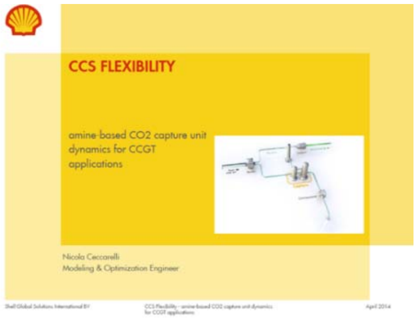
DECC and BIS

30/04/14

Element Energy Limited
20 Station Road
Cambridge CB1 2JD
Tel: 01223 852 496



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


CCS FLEXIBILITY

amine-based CO2 capture unit dynamics for CCGT applications

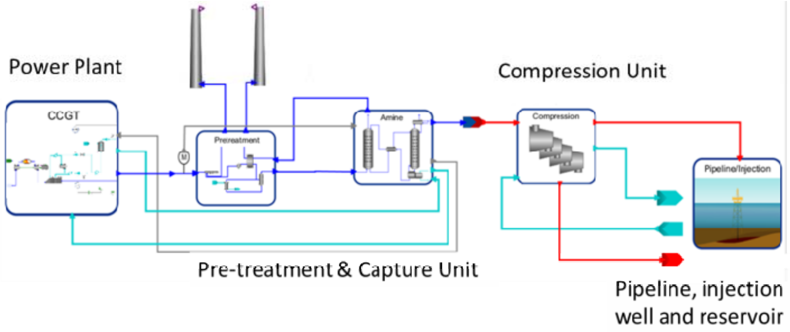
Nicola Ceccarelli
Modeling & Optimization Engineer

Shell Global Solutions International BV

CCS Flexibility - amine-based CO2 capture unit dynamics for CCGT applications

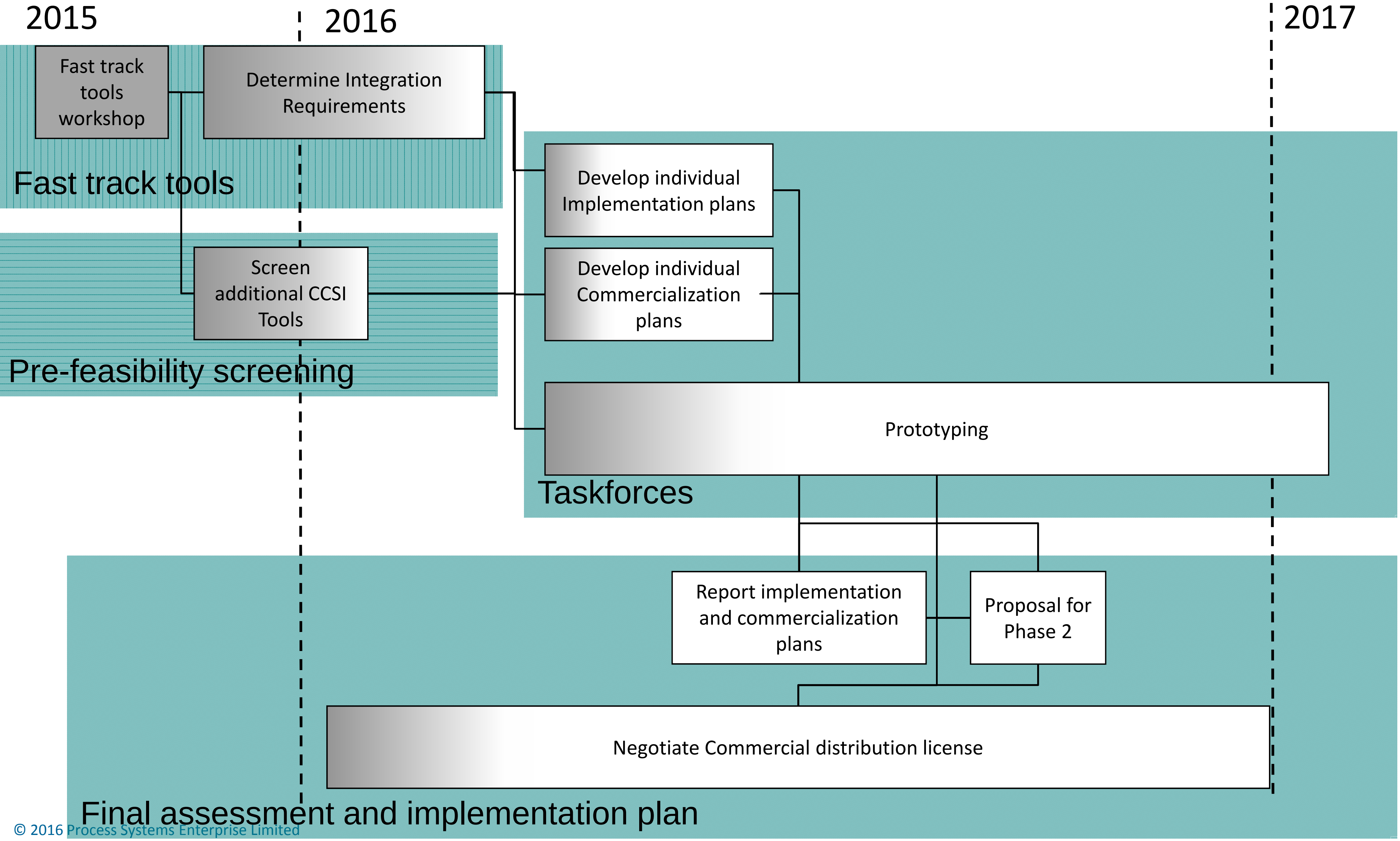
April 2014

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



Status update and next steps

Project structure



2015

2016

2017

Fast track tools workshop

Determine Integration Requirements

Fast track tools

Screen additional CCSI Tools

Pre-feasibility screening

Develop individual Implementation plans

Develop individual Commercialization plans

Prototyping

Taskforces

Report implementation and commercialization plans

Proposal for Phase 2

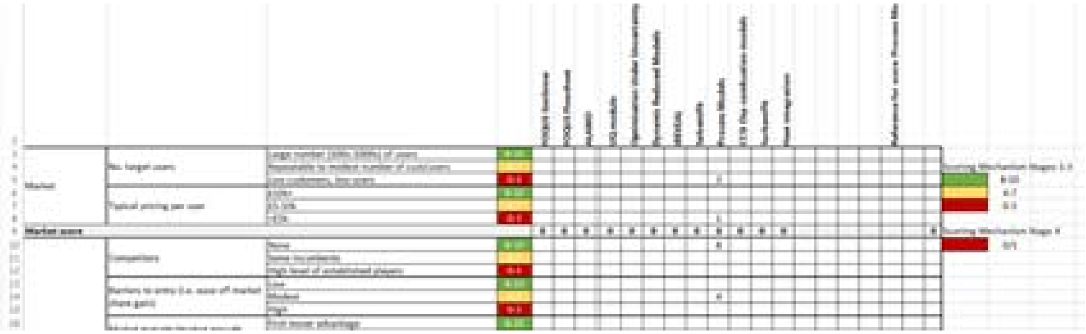
Negotiate Commercial distribution license

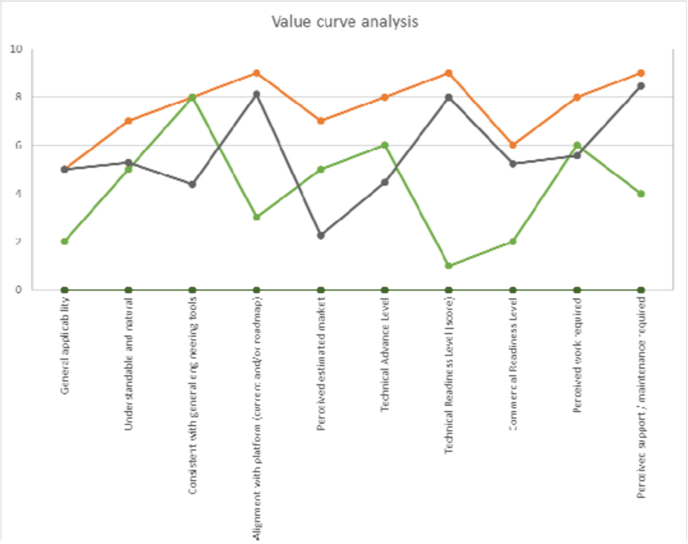
Final assessment and implementation plan

Current status

- Completed recruitment of new resources
- Completed Workshops for fast-tracked CCSI tools
- Defined sub-projects for WVU and CMU
- Developed screening criteria and commenced with screening other CCSI tools
- Ongoing negotiations of commercial licenses
- Ongoing familiarization exercises with CCSI toolkit

Screening spreadsheet



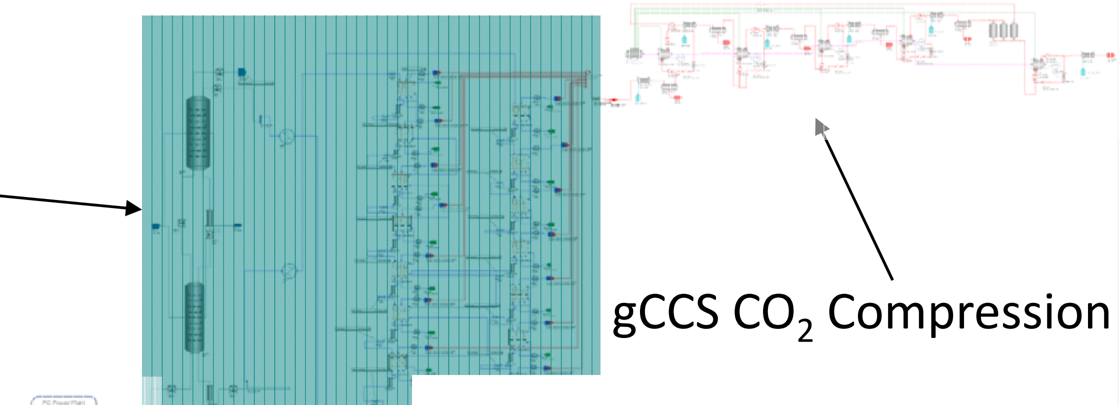


ALAMO

- ALAMO being used to generate a property method model from property model data
- Prototype interfaces between ALAMO and gPROMS in development
- ALAMO brochure developed describing
  - Workflow
  - Potential applications
  - Competitors
  - SWOT Analysis
- Market research carried out

Process Models

- CCSI tools consist of flowsheets with Bubbling fluidized bed (BFB) and Moving bed (MB) models
- This was integrated with other gCCS models

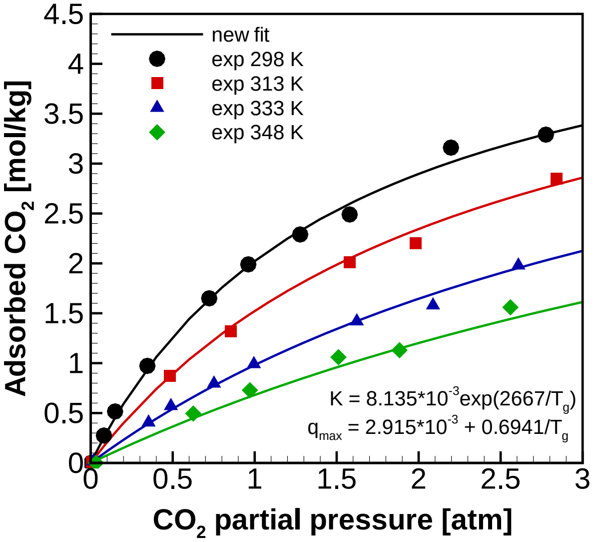


CCSI BFB and MB models

gCCS Power plant

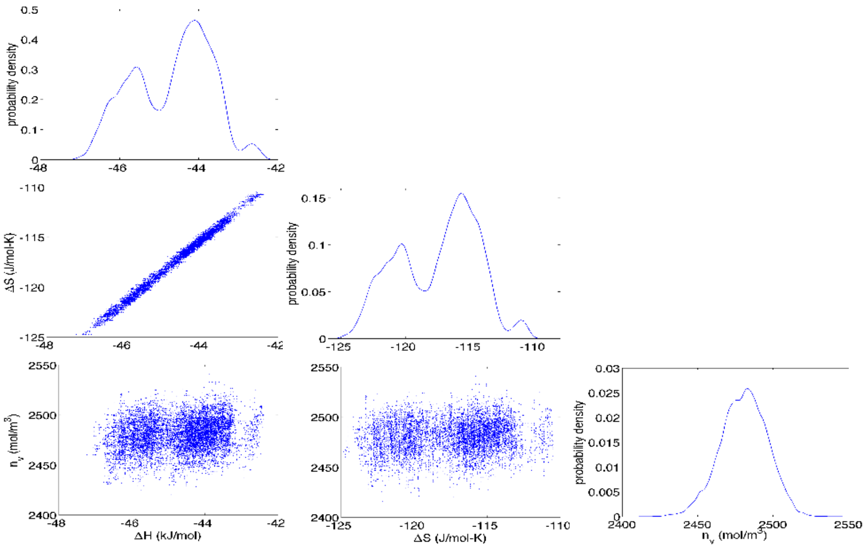
gCCS CO_2 Compression

- A fixed bed adsorber model was developed to extend the model library
- Market research activities carried out
- Brochure developed



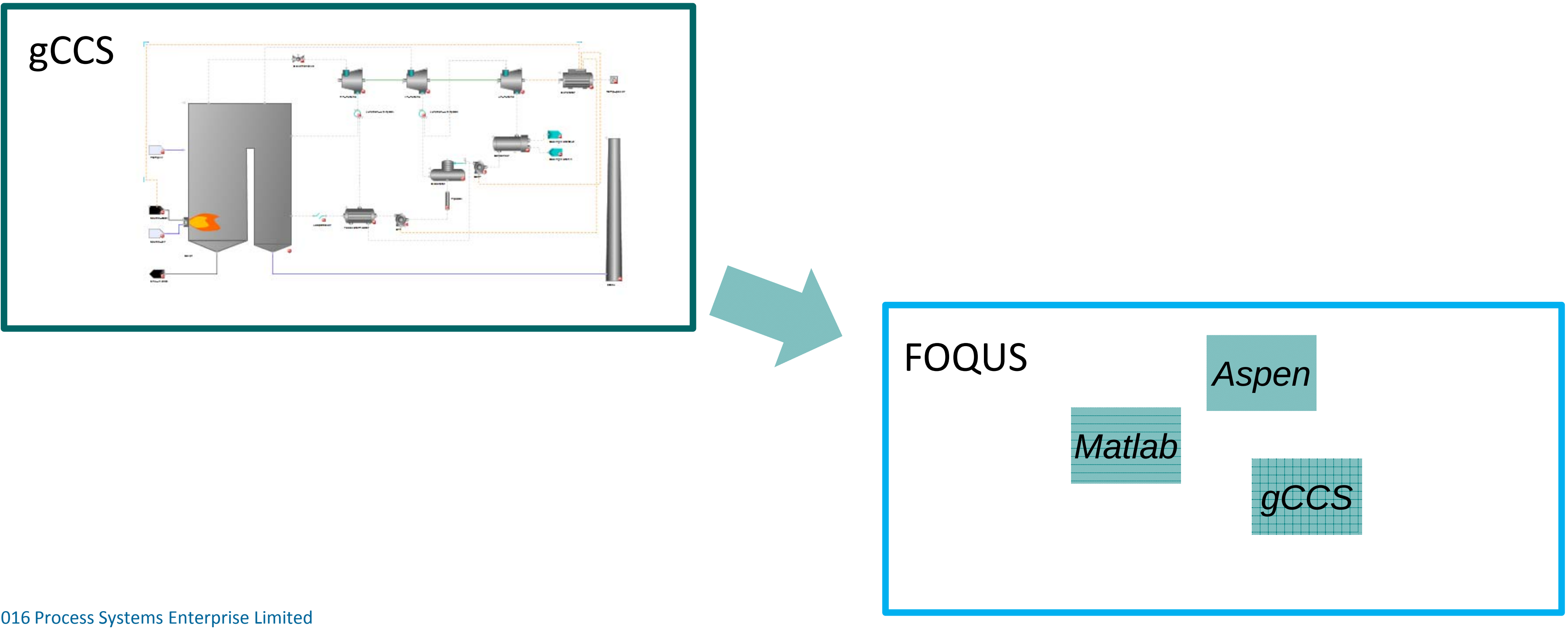
SorbentFit / SolventFit

- Fits combined thermodynamic and kinetic models of amine-based CO_2 solid sorbents to lab/bench-scale data
- Demonstrated the uncertainty quantification features of the tool
- Prototype interfaces between SorbentFit and gPROMS in development
- Brochure in development



FOQUS Flowsheet + SimSinter

- SimSinter provides a wrapper to enable models created in process simulators to be linked into a FOQUS Flowsheet
- Brochure in development



Summary

Conclusions

- Advanced process modelling is an essential tool
  - inform and aid the **design** of CCS systems and network and **reduce capital expenditure** of large-scale integrated CCS projects
  - Minimise **operating expenditure** by integrating **dynamic operation** and considering **scale** aspects
  - **Evaluate technology** – benchmarking existing and provide a basis to **assess** buddying **next-generation technology**

- **Transfer** experience and best-practice between demonstration and large-scale integrated CCS projects

- **Integrating platform** for working with other stakeholders in chain collaborative R&D, working with academia

Next steps for the next period

- Complete screening for non-fast-track tools
- Set up discussions with members of Industrial Advisory Board to help prioritise screening process
- Assess of integration requirements for fast-track tools

Improving commercial viability and reducing technology risk

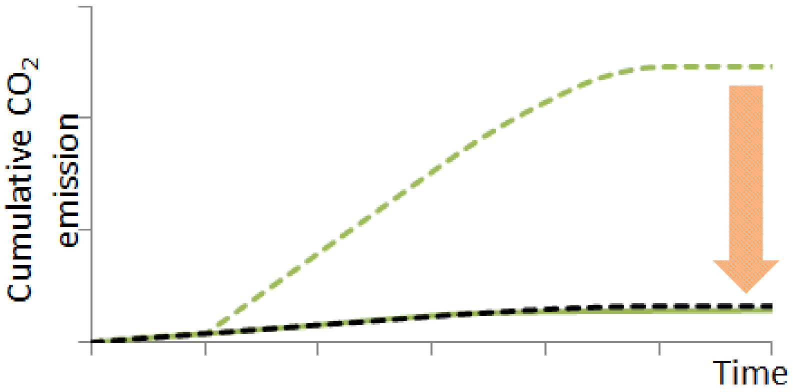
- Business case
  - Reduce cost (particularly CapEx)
  - Understand financial risk to investors
  - Support negotiations between emitters and ‘carbon uptakers’
  - Assess impact of various trip scenarios on generated ‘clean electricity’ (and thus, price of electricity)
- Flexibility of CCS Systems
  - Start-up/shut-down sequences
  - How fast can the capture unit be ramped down with load?
- Safety analysis
  - Assess impact of turbine/compressor/injection trips
  - Quantify reaction time available along the CCS chain depending on a specific trip scenario

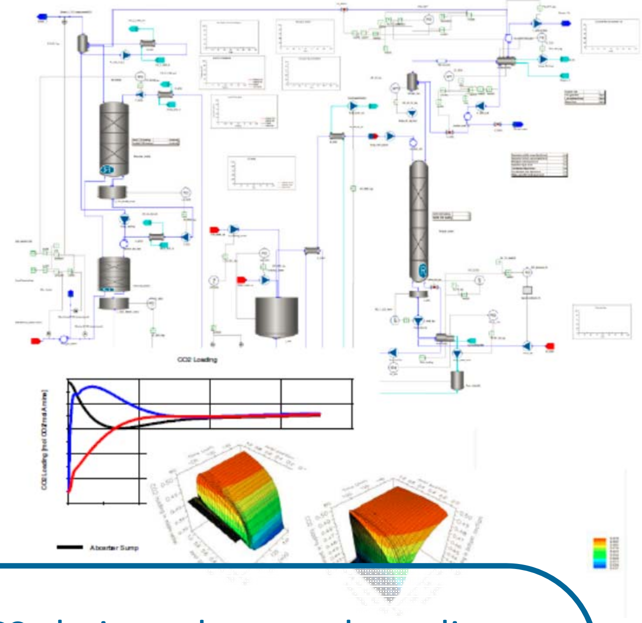
Thank you

Industrial and UK Government-funded projects

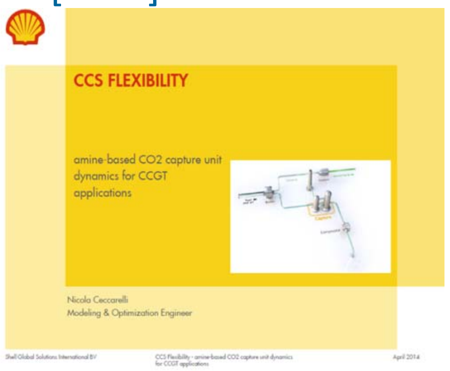
CCS

Projects: CCS Flexibility (Shell)





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



CCS FLEXIBILITY

amine-based CO2 capture unit dynamics for CCGT applications

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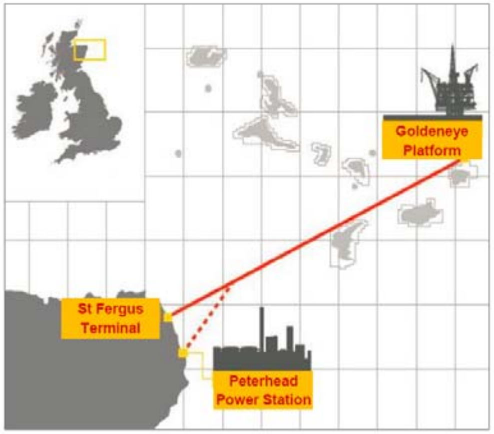
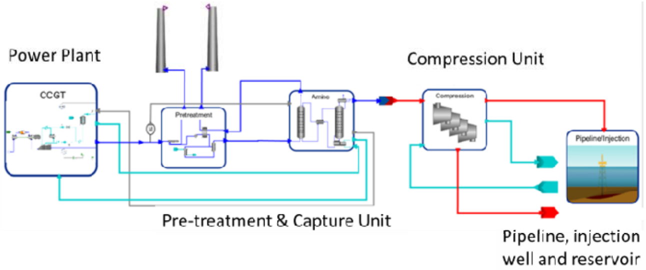
CCS Flexibility - amine-based CO2 capture unit dynamics for CCGT applications

April 2014



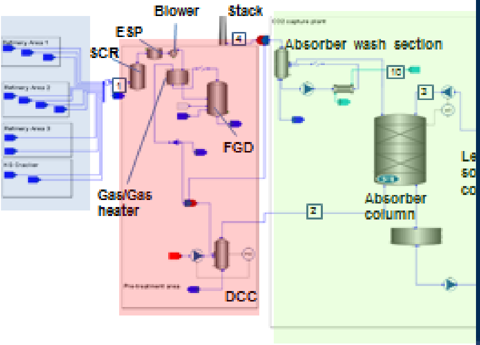
CCS chain and network studies [Energy Technologies Institute] and [Shell]

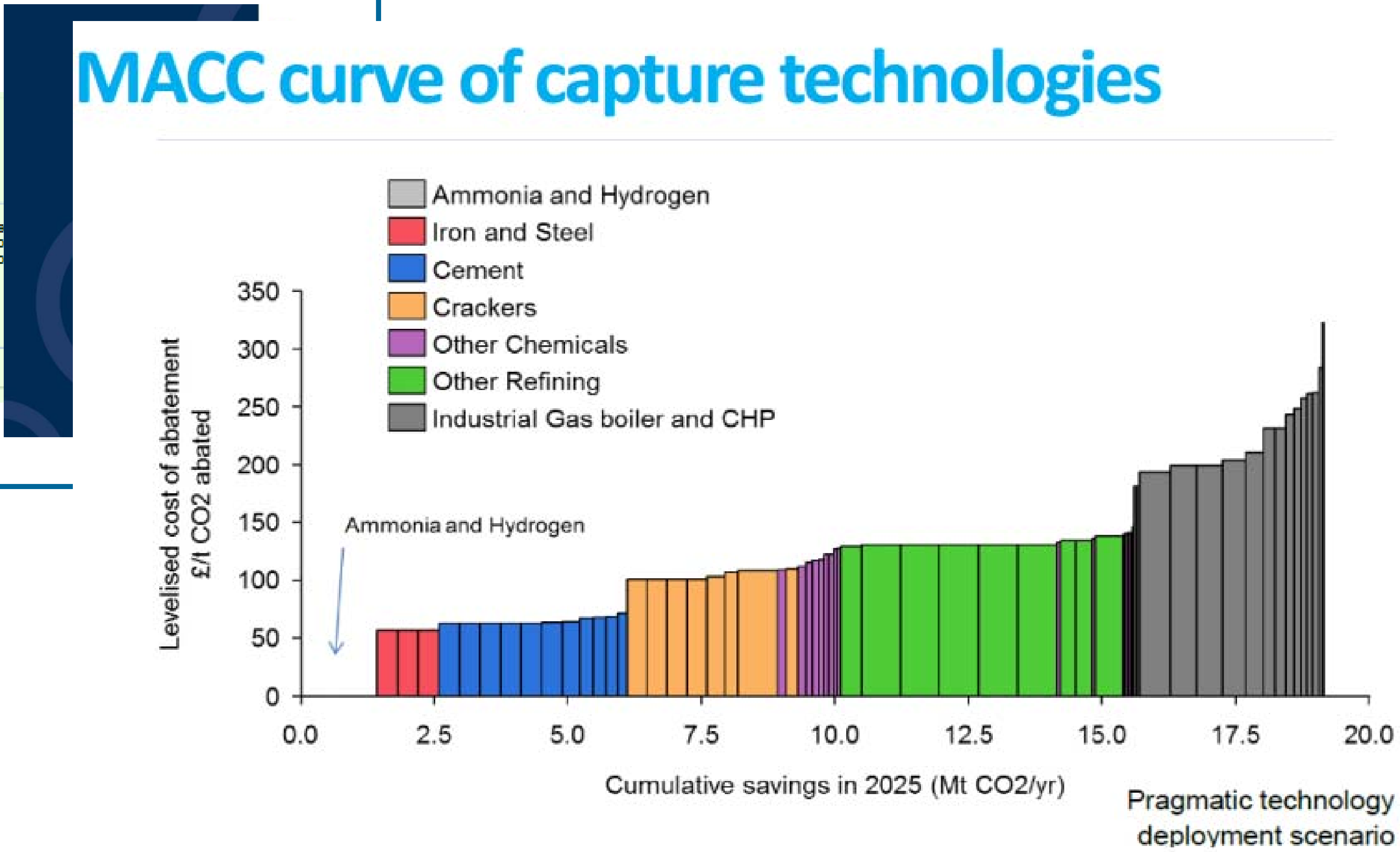


CCS

Projects: Industrial CCS (DECC / Element Energy)

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





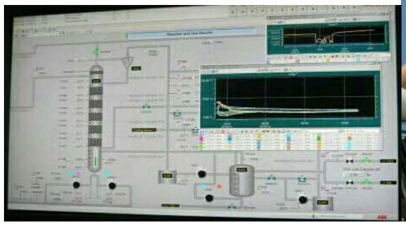
MACC curve of capture technologies

Pragmatic technology deployment scenario

CAPSULE (UK Government/ 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.**



Department
of Energy &
Climate Change

Benefits

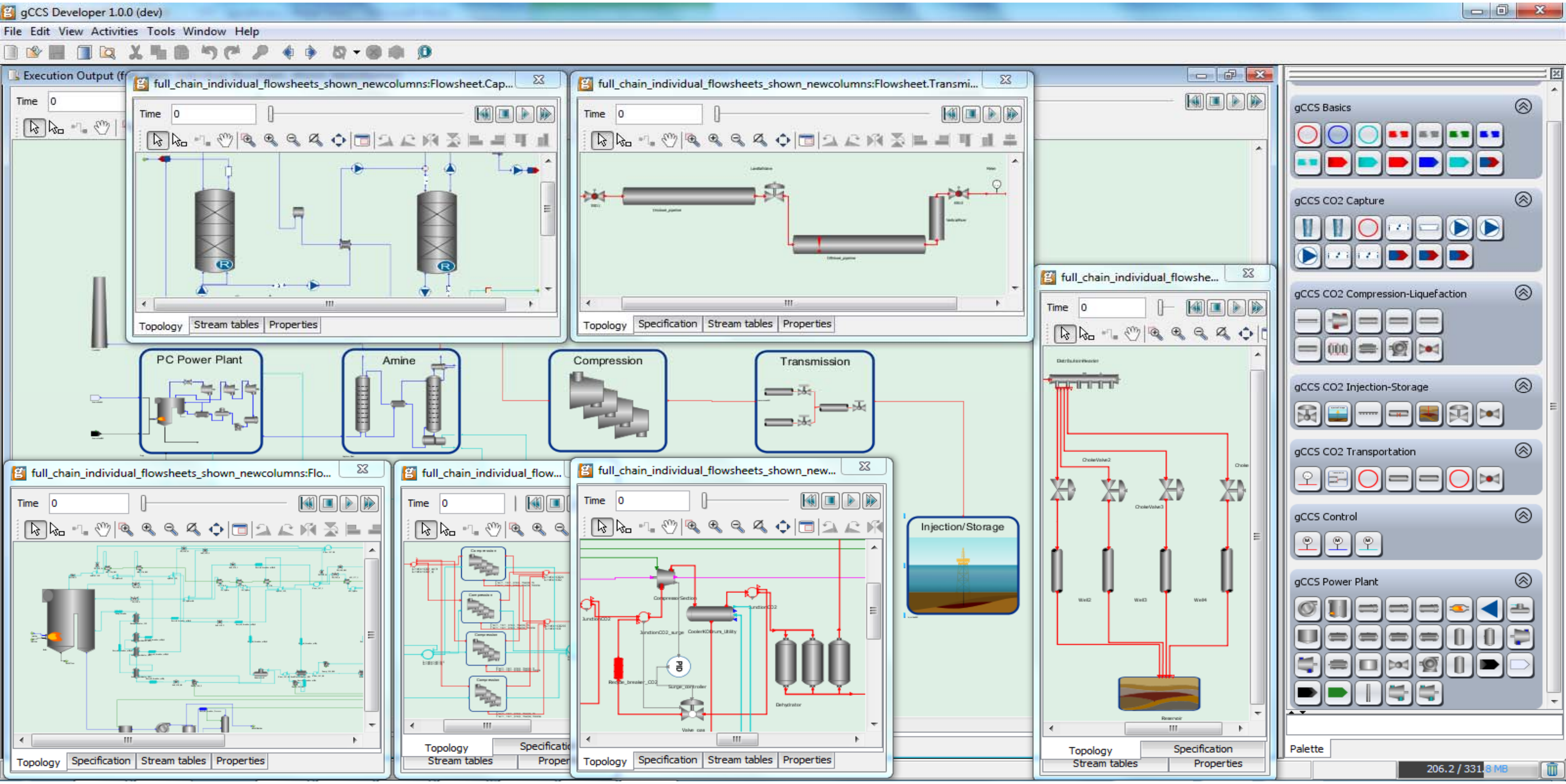
- The novel APBS solvents reduce the steam consumption by upto 40% which translates to an approximate 22% reduction in LCOE (levelised cost of electricity) for a CCS enabled power plant.
- Auxiliary electrical load, which consists mainly of pumps and fans, can be reduced by 50%.
- Improved process layout, 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%.

gCCS Current scope

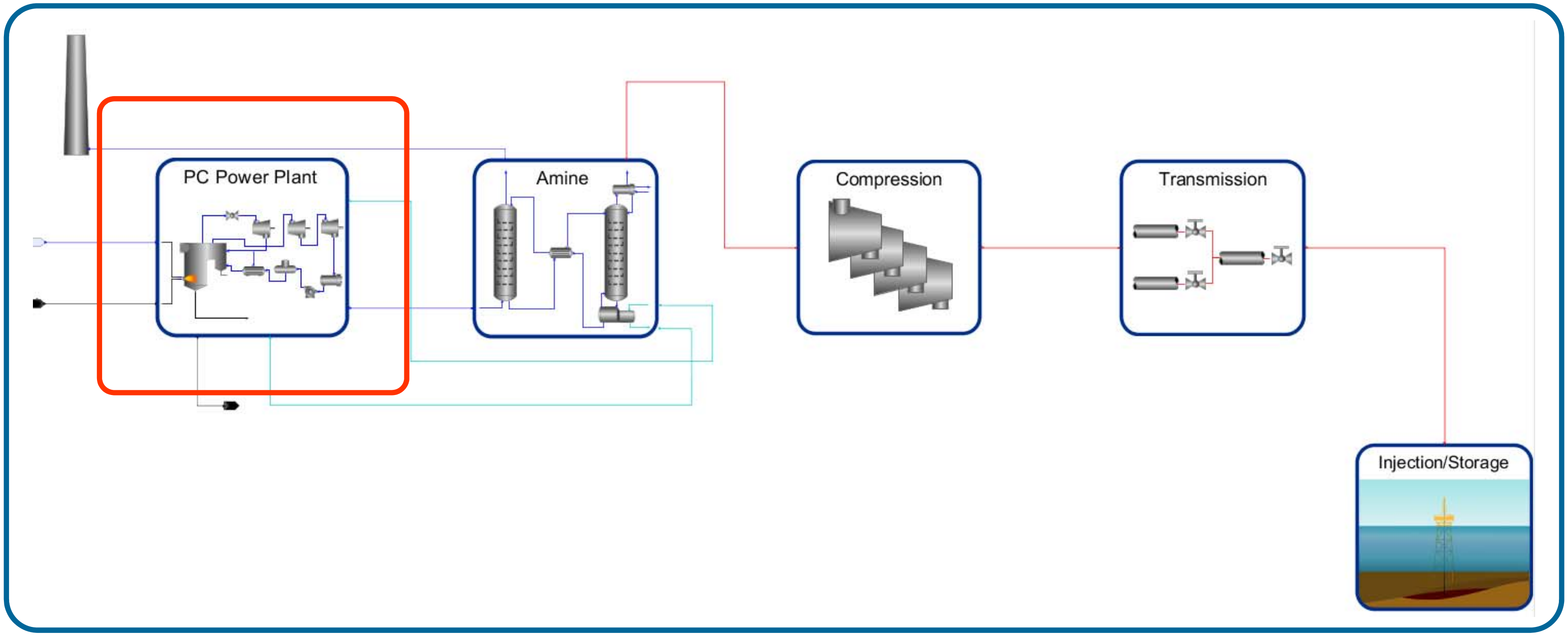
- **Process models**
  - Power generation
    - Conventional: pulverised-coal, CCGT
    - Non-conventional: oxy-fuelled, IGCC
  - Solvent-based CO_2 capture
  - CO_2 compression & liquefaction
  - CO_2 transportation
  - CO_2 injection in sub-sea storage

- **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

Toolkit Graphical User Interface

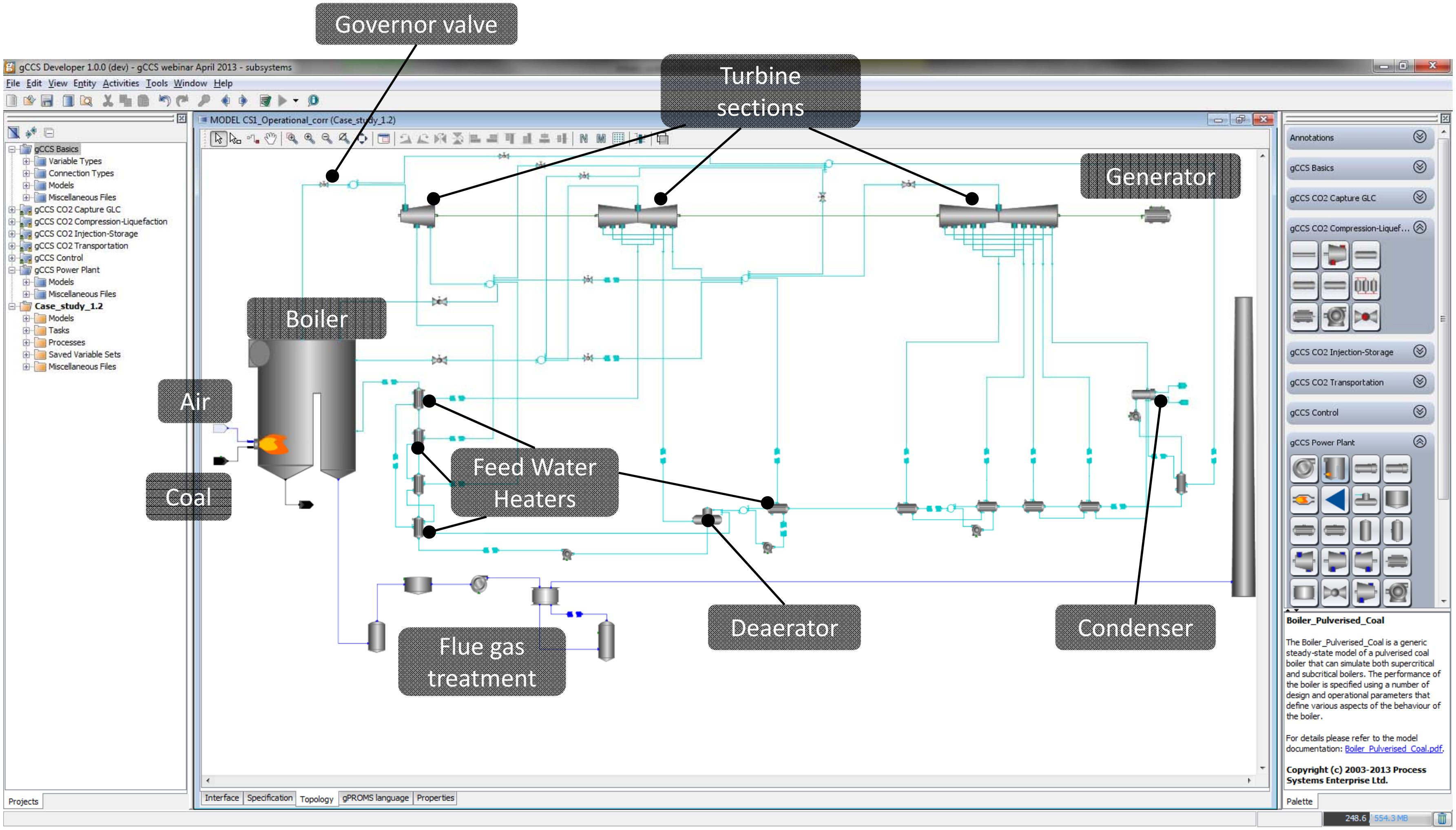


Power generation



gCCS Power Plant Library – conventional power generation

Supercritical pulverized coal power plant



Governor valve

Turbine sections

Generator

Boiler

Air

Coal

Feed Water Heaters

Flue gas treatment

Deaerator

Condenser

Boiler_Pulverised_Coal

The Boiler_Pulverised_Coal is a generic steady-state model of a pulverised coal boiler that can simulate both supercritical and subcritical boilers. The performance of the boiler is specified using a number of design and operational parameters that define various aspects of the behaviour of the boiler.

For details please refer to the model documentation: Boiler_Pulverised_Coal.pdf.

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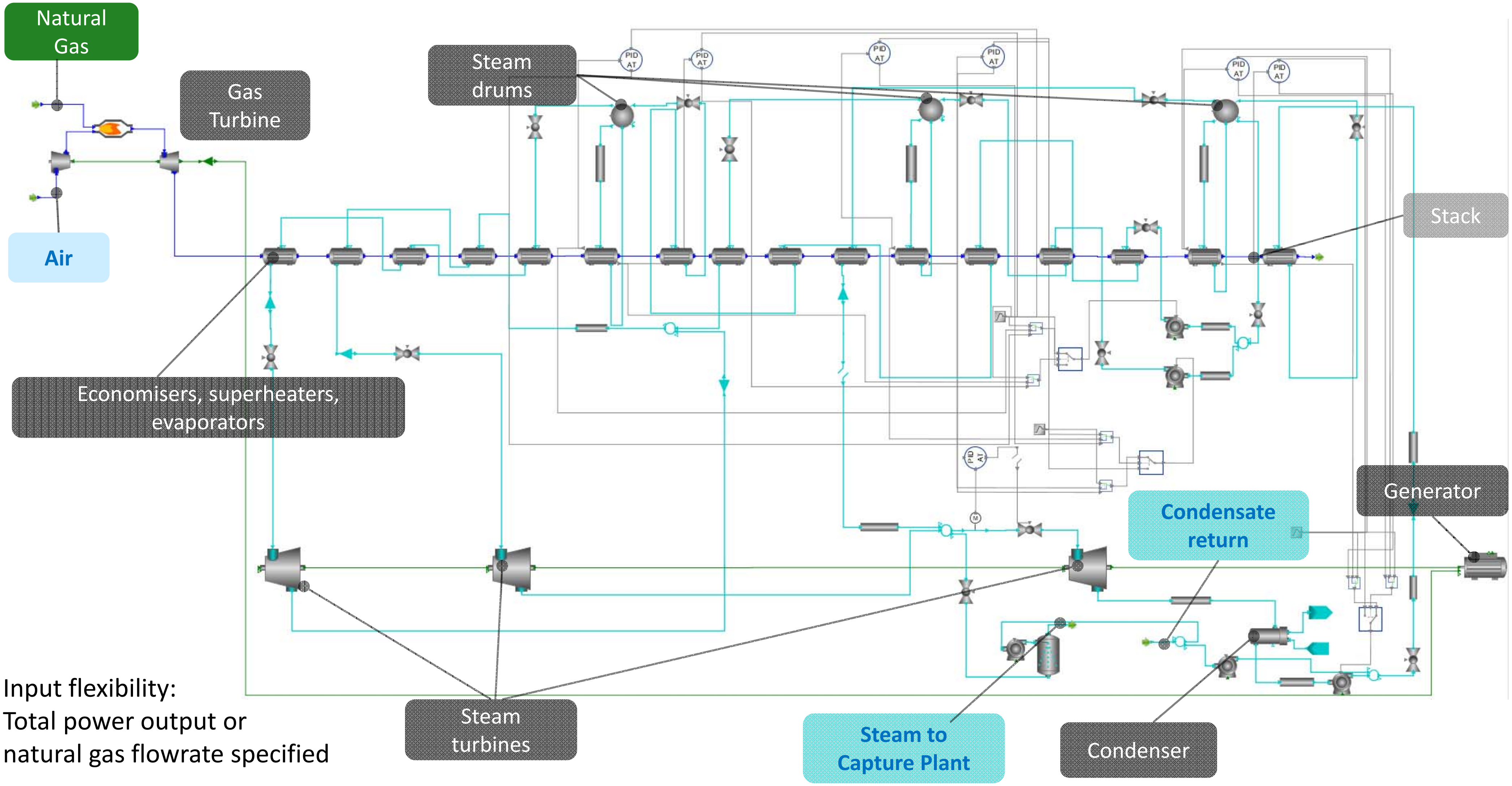
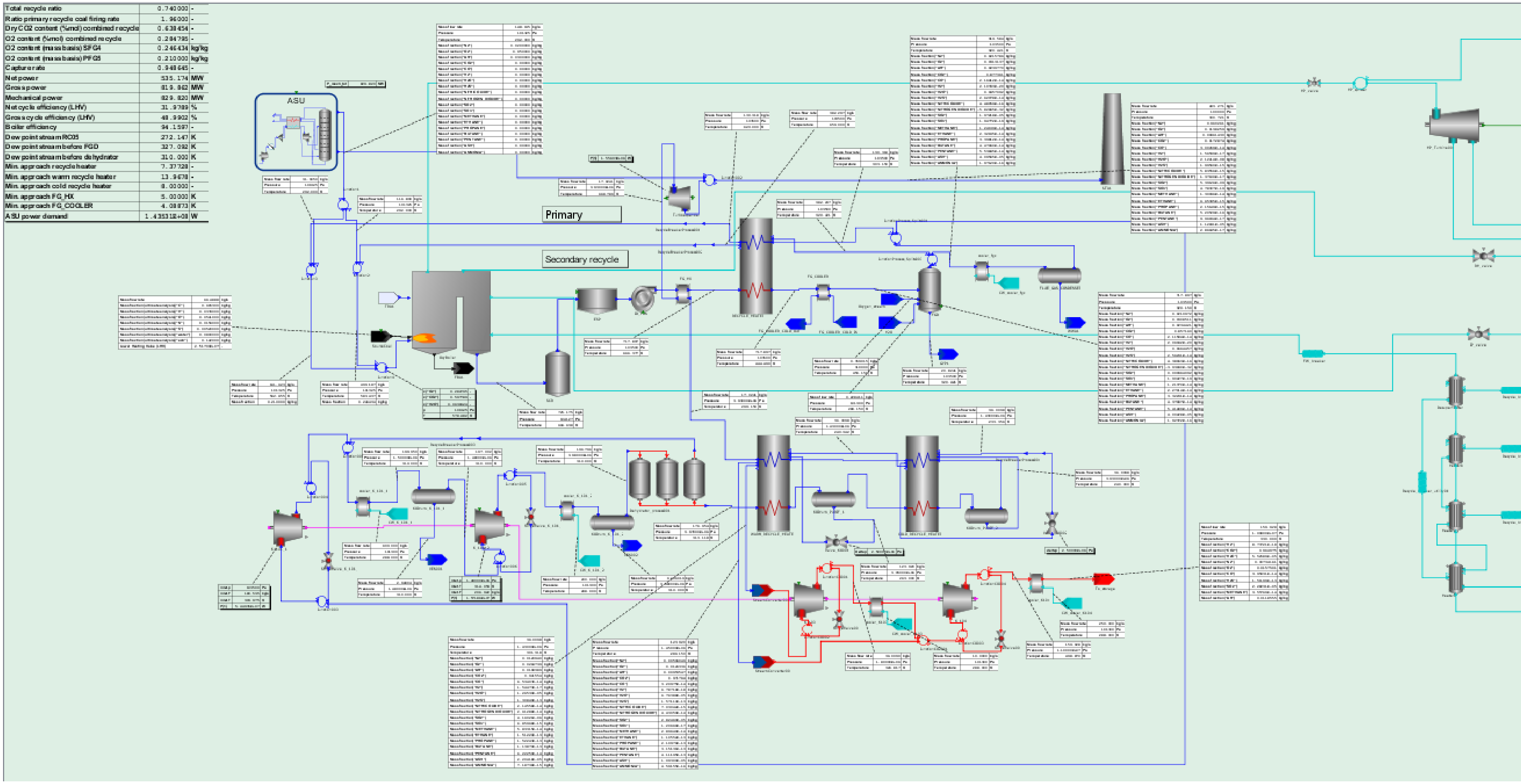
gCCS Power Plant library – conventional power generation

CCGT power plant



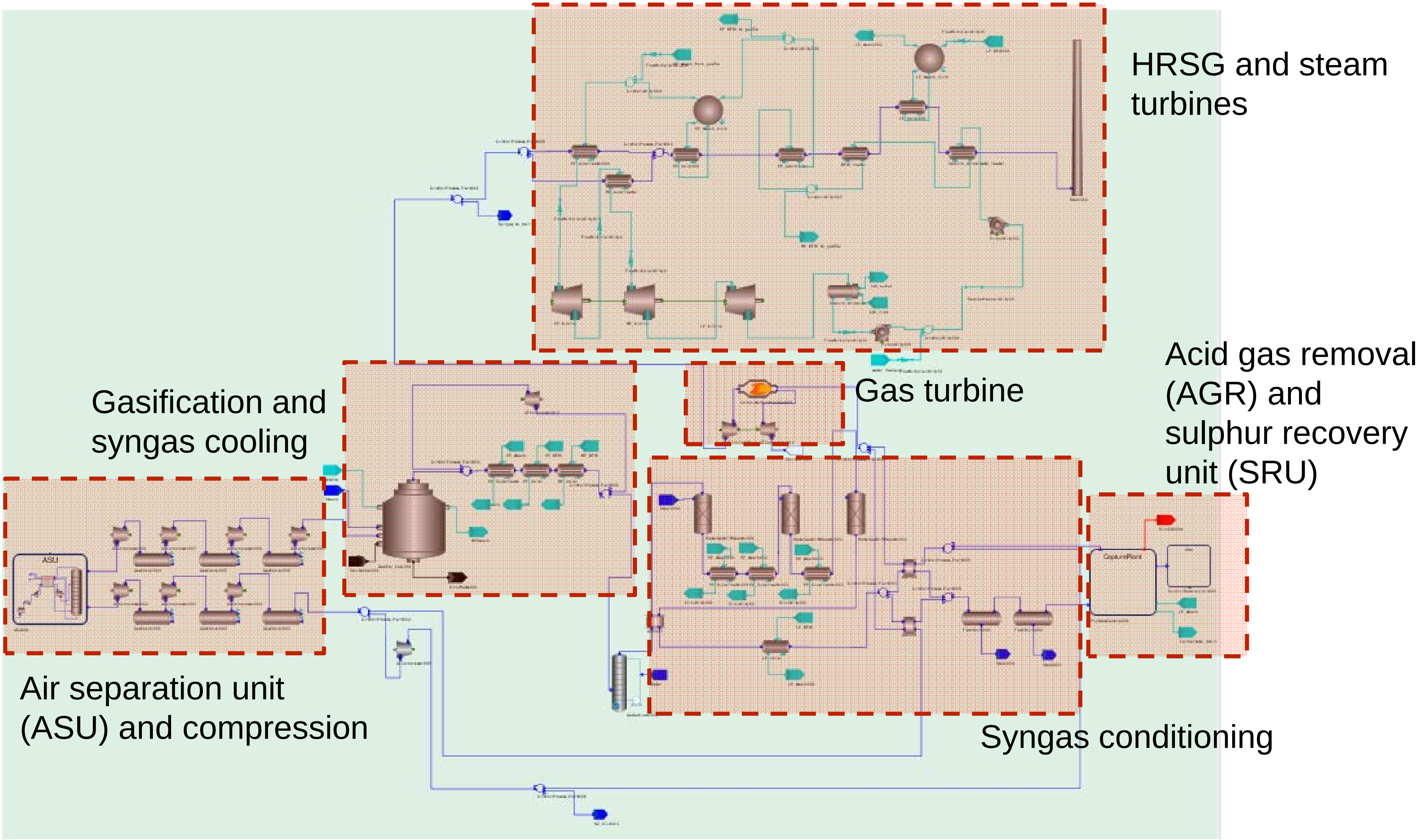
Input flexibility:
Total power output or
natural gas flowrate specified

Oxyfuel system



Total recycle ratio	0.740000	-
Ratio primary recycle coal firing rate	1.96000	-
Dry CO2 content (%mol) combined recycle	0.638454	-
O2 content (%mol) combined recycle	0.284795	-
O2 content (mass basis) SFG4	0.246434	kg/kg
O2 content (mass basis) PFG5	0.210000	kg/kg
Capture ratio	0.948645	-
Net power	535.174	MW
Gross power	819.862	MW
Mechanical power	829.820	MW
Net cycle efficiency (LHV)	31.9789	%
Gross cycle efficiency (LHV)	48.9902	%
Boiler efficiency	94.1597	-
Dew point stream RC05	272.147	K
Dew point stream before FGD	327.092	K
Dew point stream before dehydrator	310.000	K
Min. approach recycle heater	7.37728	-
Min. approach warm recycle heater	13.9678	-
Min. approach cold recycle heater	8.00000	-
Min. approach FG_HX	5.00000	K
Min. approach FG_COOLER	4.08873	K
ASU power demand	1.43531E+08	W

IGCC



HRSG and steam turbines

Gas turbine

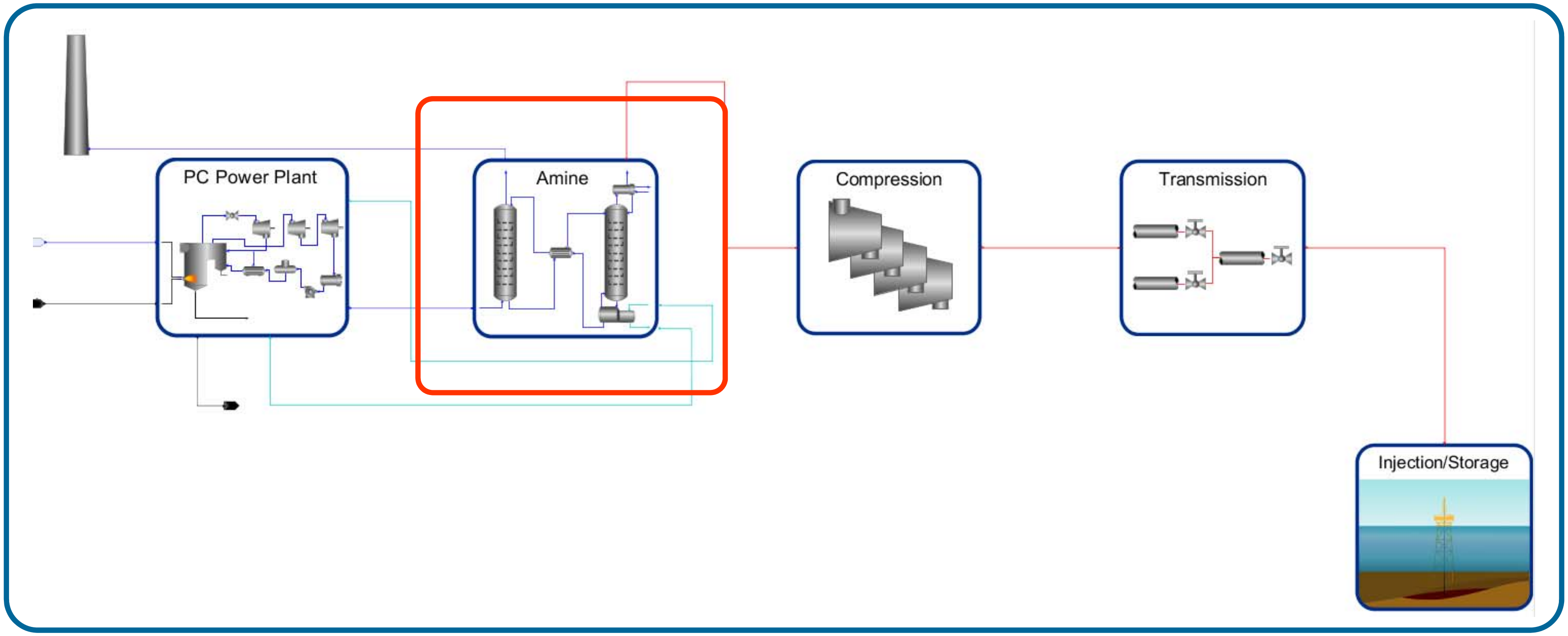
Acid gas removal (AGR) and sulphur recovery unit (SRU)

Gasification and syngas cooling

Air separation unit (ASU) and compression

Syngas conditioning

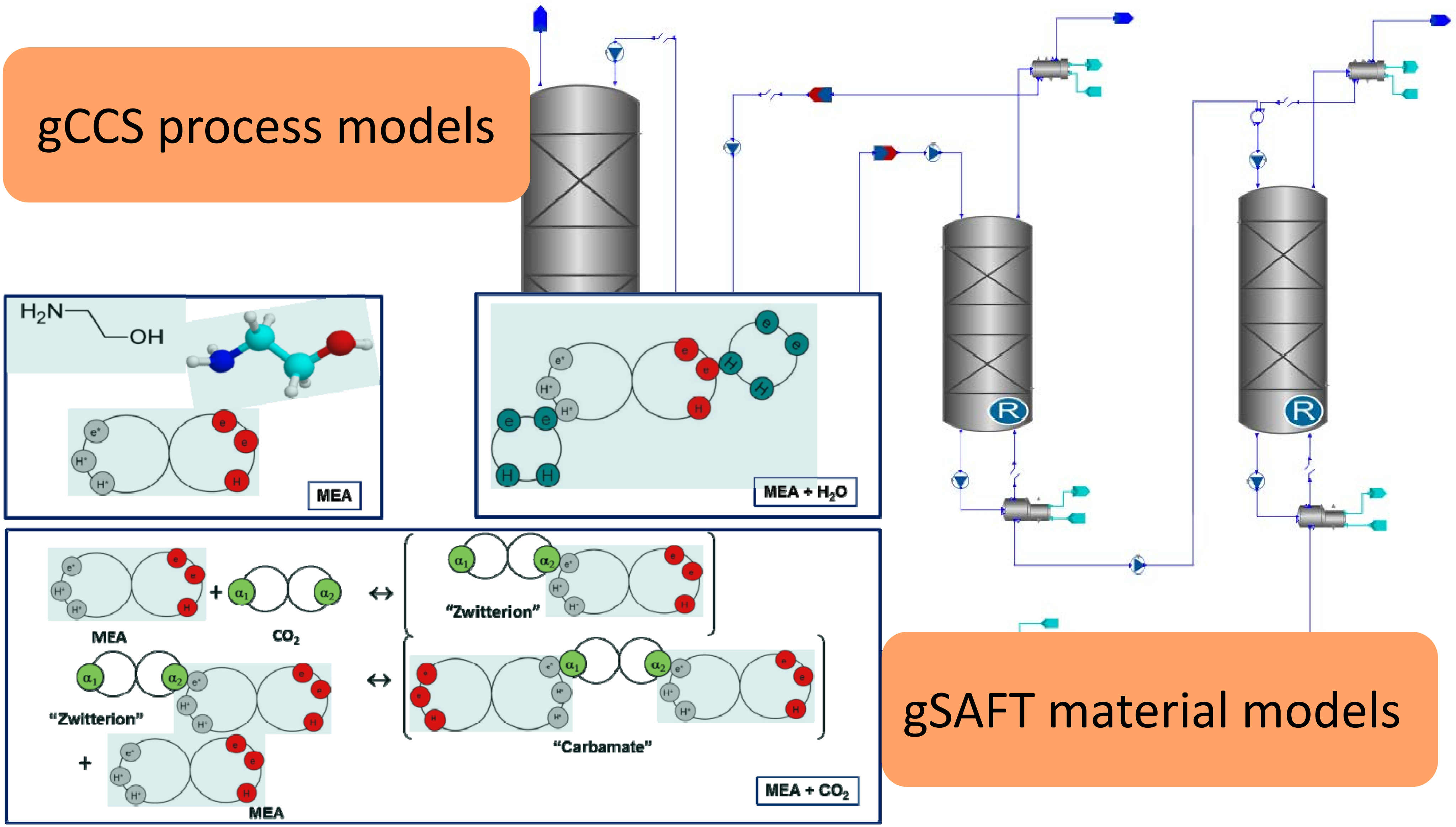
CO_2 Capture


PC Power Plant
Amine
Compression
Transmission
Injection/Storage

gCCS solvent-based CO_2 capture modelling framework

Process and material models

gCCS process models

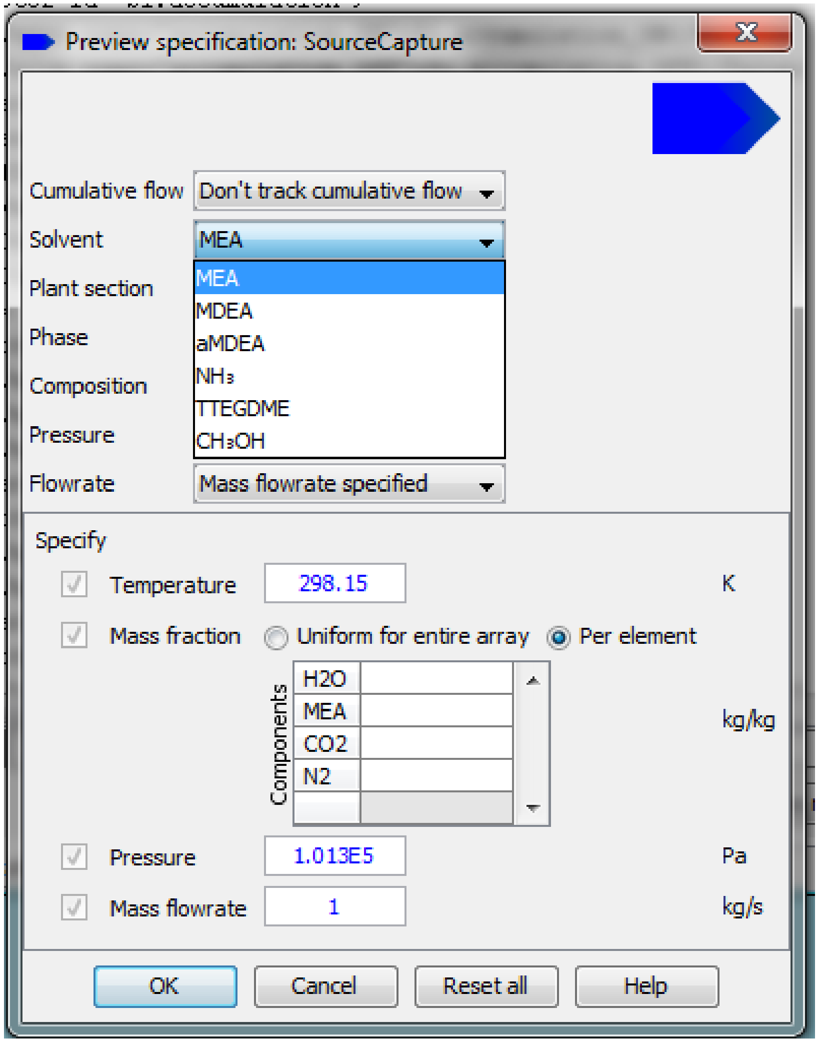


gSAFT material models

gCCS solvent-based CO_2 capture modelling framework

Current status

- Chemical absorption
  - MEA, MDEA activated with piperazine, NH_3
- Physical absorption
  - Mixtures of PEGDME (as those employed in the Selexol^{TM} process) and methanol (Rectisol^{TM} process)



Preview specification: SourceCapture

Cumulative flow: Don't track cumulative flow

Solvent: MEA

MEA
MDEA
aMDEA
NH_3
TTEGDME
CH_3OH

Plant section

Phase

Composition

Pressure

Flowrate: Mass flowrate specified

Specify

☑ Temperature 298.15 K

☑ Mass fraction ○ Uniform for entire array ● Per element

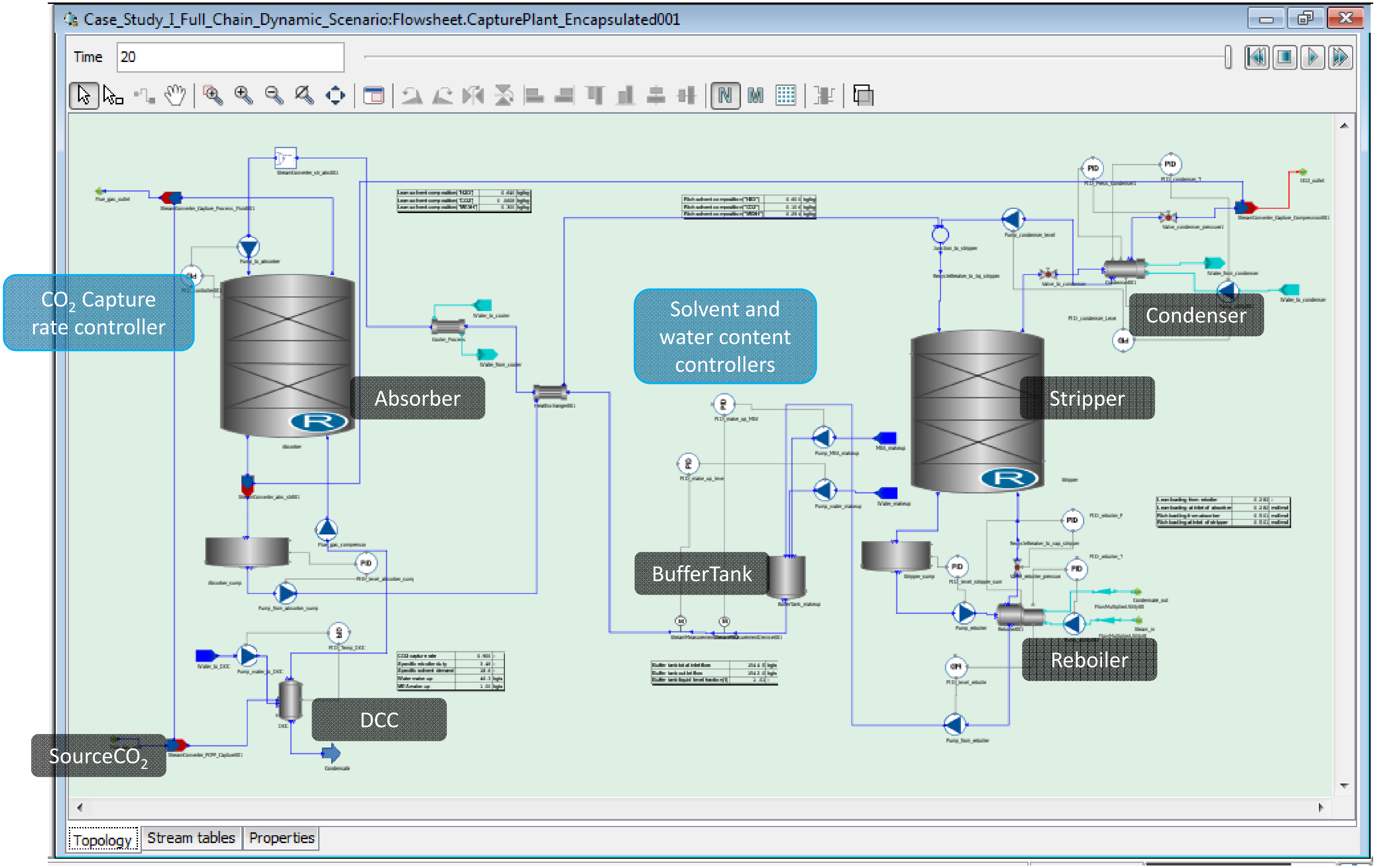
Components	
H2O	
MEA	
CO2	
N2	

kg/kg

☑ Pressure 1.013E5 Pa

☑ Mass flowrate 1 kg/s

Chemical Absorption



Case_Study_I_Full_Chain_Dynamic_Scenario:Flowsheet.CapturePlant_Encapsulated001

Time 20

CO$_2$ Capture rate controller

Absorber

Solvent and water content controllers

Condenser

Stripper

BufferTank

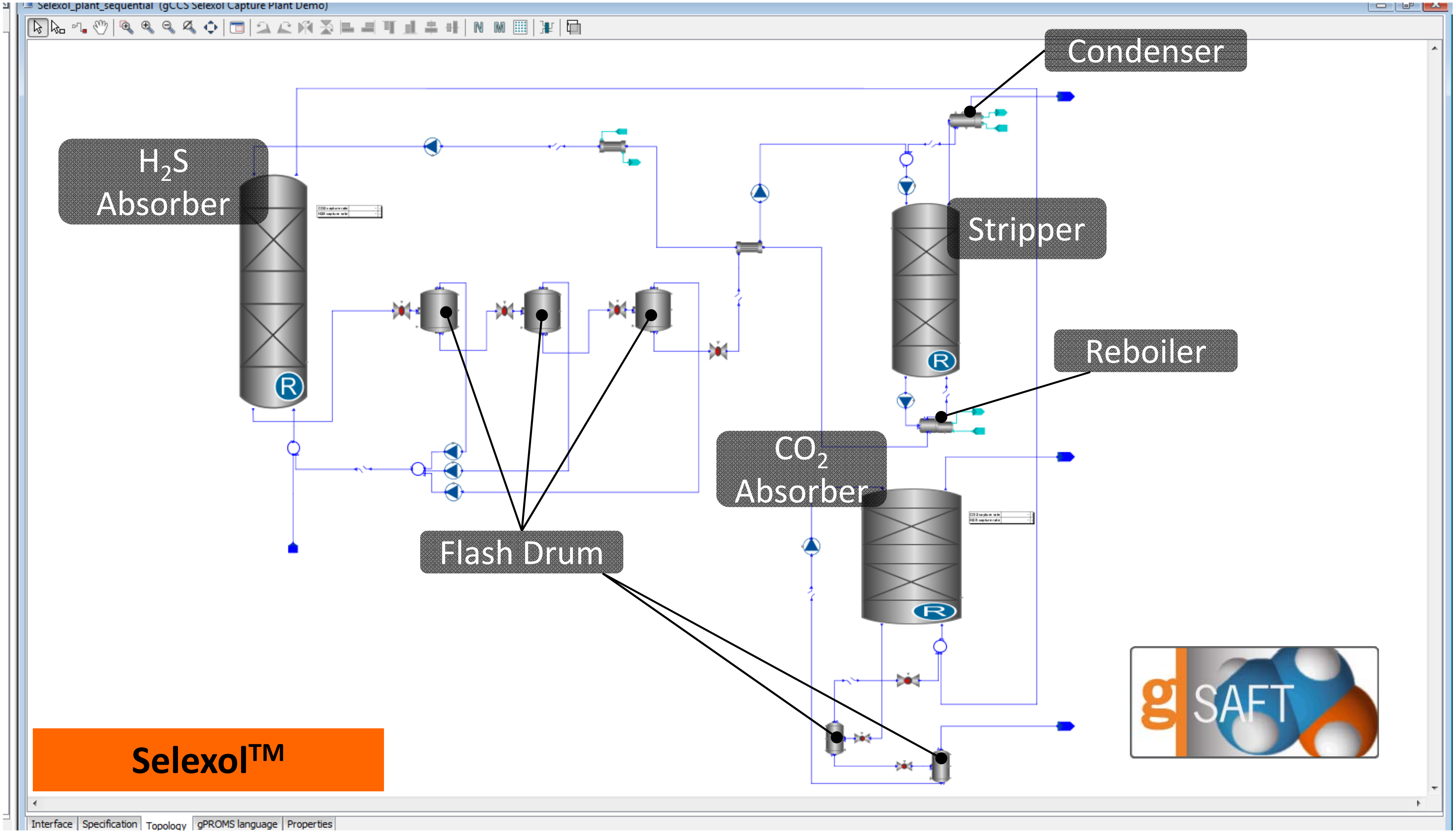
DCC

Reboiler

SourceCO$_2$

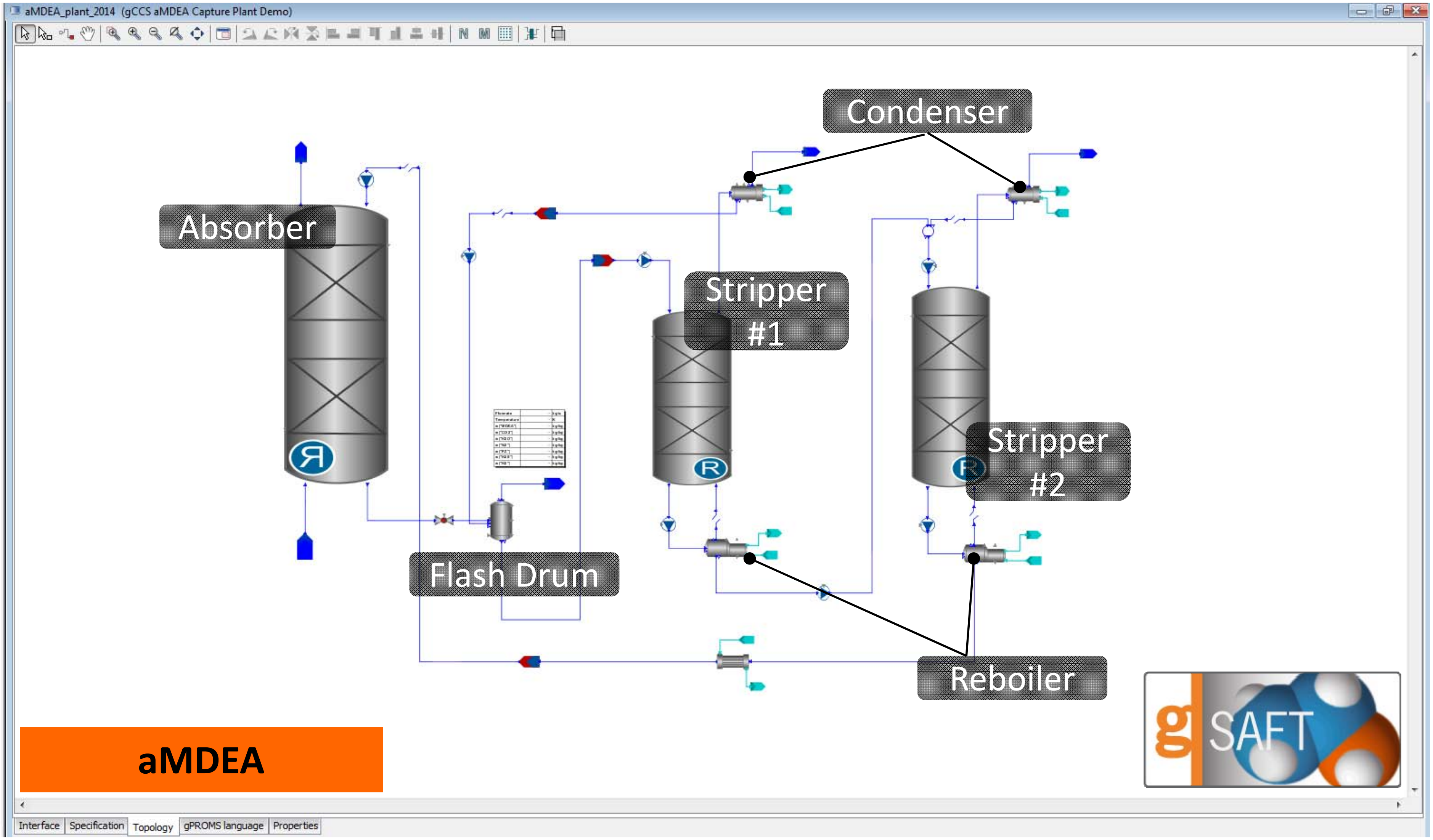
gCCS CO_2 Capture Library

Physical absorption capture plant model

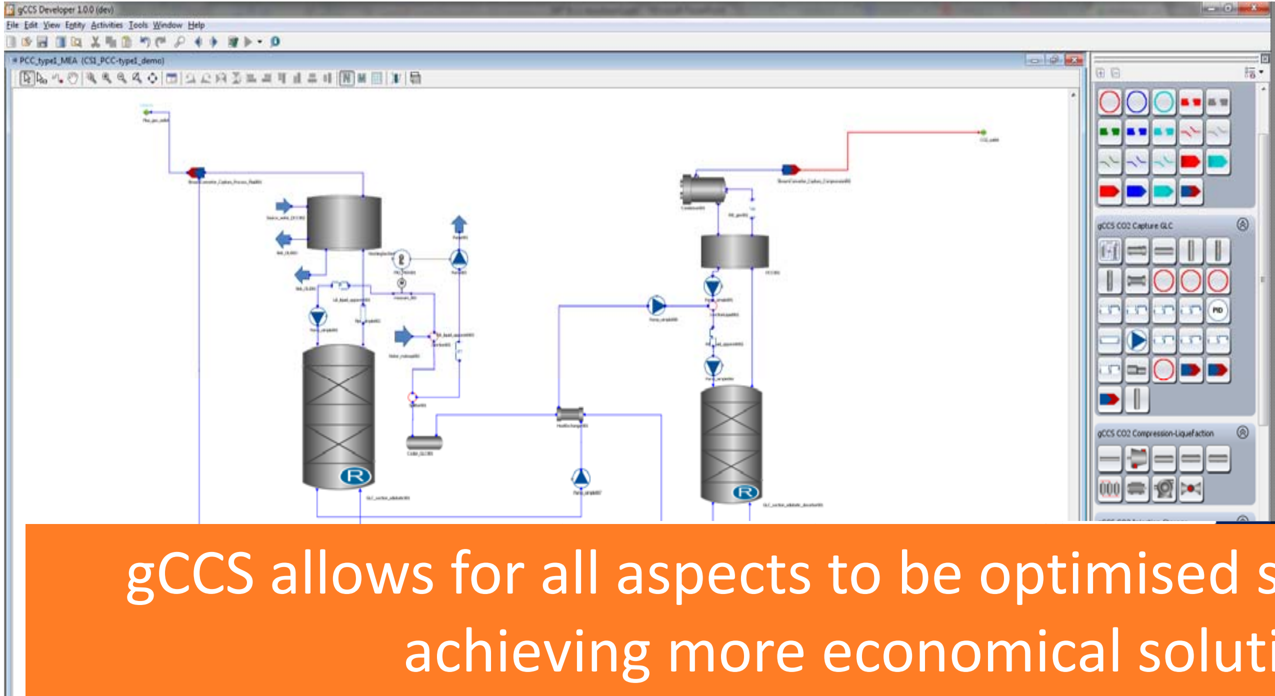


gCCS CO_2 Capture Library

Custom models: Activated amine capture plant



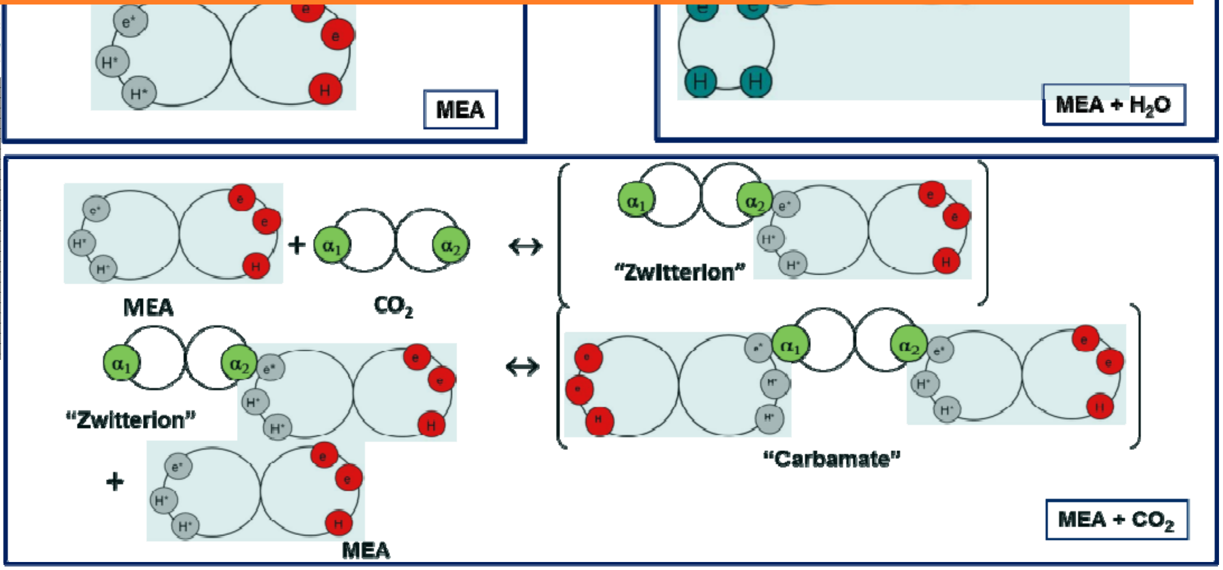
Solvent-based CO_2 capture optimisation



<u>Process design</u>
Configuration
Equipment size
Heat integration
…
<u>Process operation</u>
Solvent loading
Flowrates
Pressures, temperatures
…

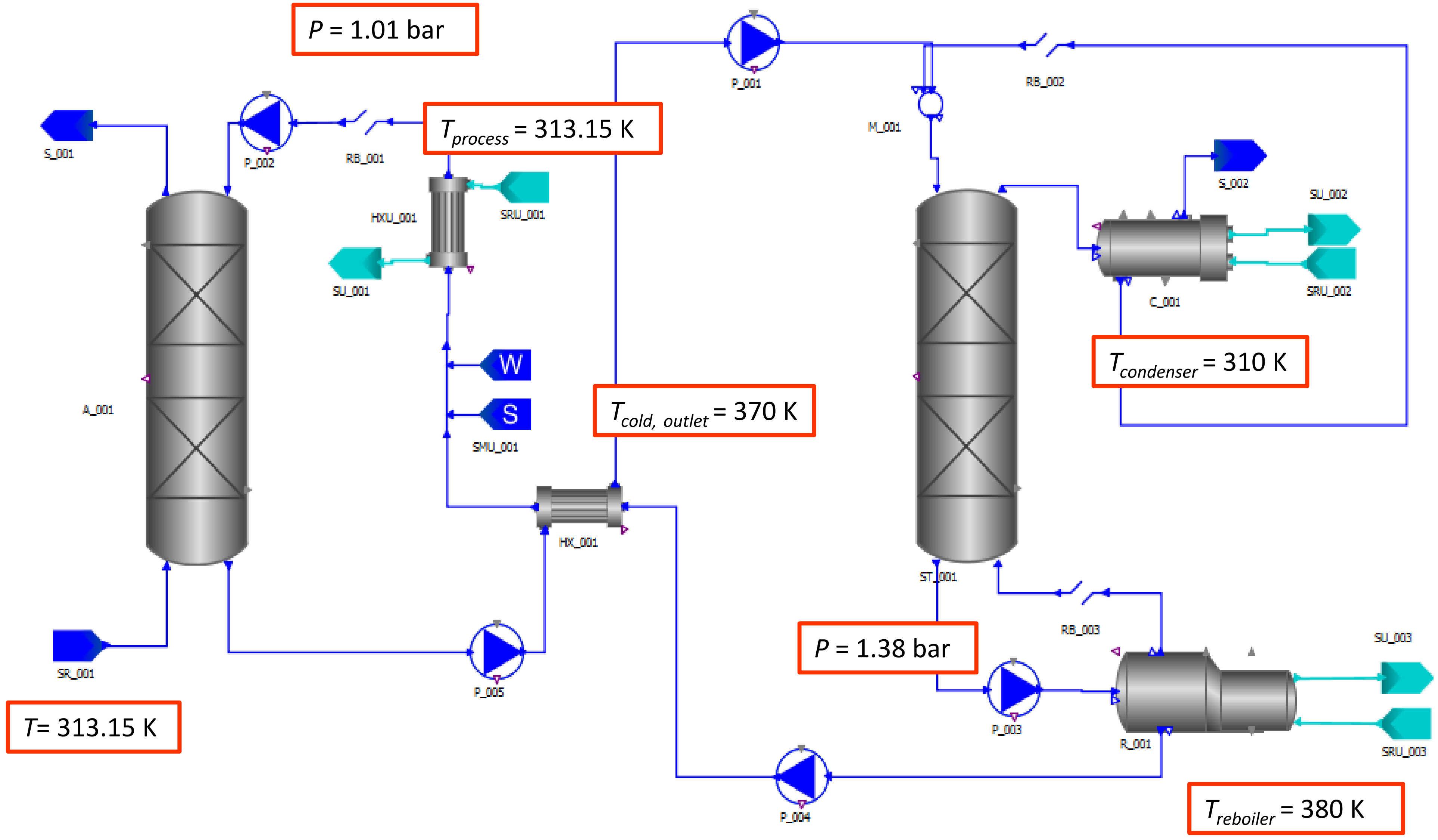
gCCS allows for all aspects to be optimised simultaneously achieving more economical solutions

<u>Solvent design/ development</u>
Screening of candidates
New molecules (group contribution method)
New mixtures



Optimization example

Simple absorber and simple stripper configuration



$P = 1.01$ bar

$T_{process} = 313.15$ K

$T_{condenser} = 310$ K

$T_{cold,\ outlet} = 370$ K

$P = 1.38$ bar

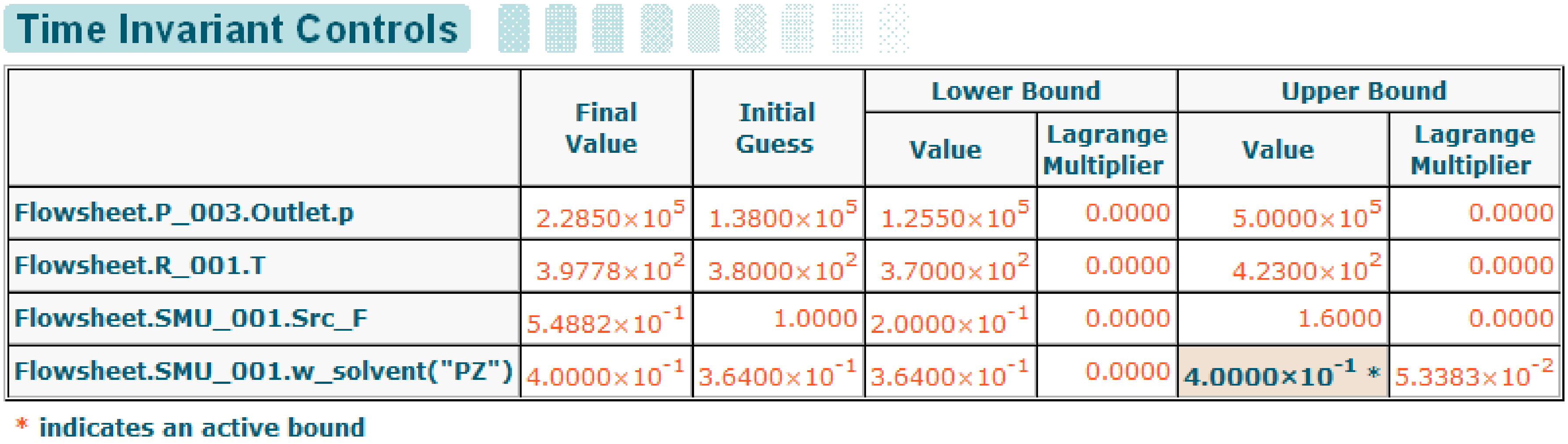
$T = 313.15$ K

$T_{reboiler} = 380$ K

Optimization example

Simple absorber and simple stripper configuration

- Objective function: reboiler heat duty
- Constraint: CO_2 capture > 90 %



Time Invariant Controls

	Final Value	Initial Guess	Lower Bound		Upper Bound	
			Value	Lagrange Multiplier	Value	Lagrange Multiplier
Flowsheet.P_003.Outlet.p	2.2850×10^{5}	1.3800×10^{5}	1.2550×10^{5}	0.0000	5.0000×10^{5}	0.0000
Flowsheet.R_001.T	3.9778×10^{2}	3.8000×10^{2}	3.7000×10^{2}	0.0000	4.2300×10^{2}	0.0000
Flowsheet.SMU_001.Src_F	5.4882×10^{-1}	1.0000	2.0000×10^{-1}	0.0000	1.6000	0.0000
Flowsheet.SMU_001.w_solvent("PZ")	4.0000×10^{-1}	3.6400×10^{-1}	3.6400×10^{-1}	0.0000	4.0000×10^{-1} *	5.3383×10^{-2}

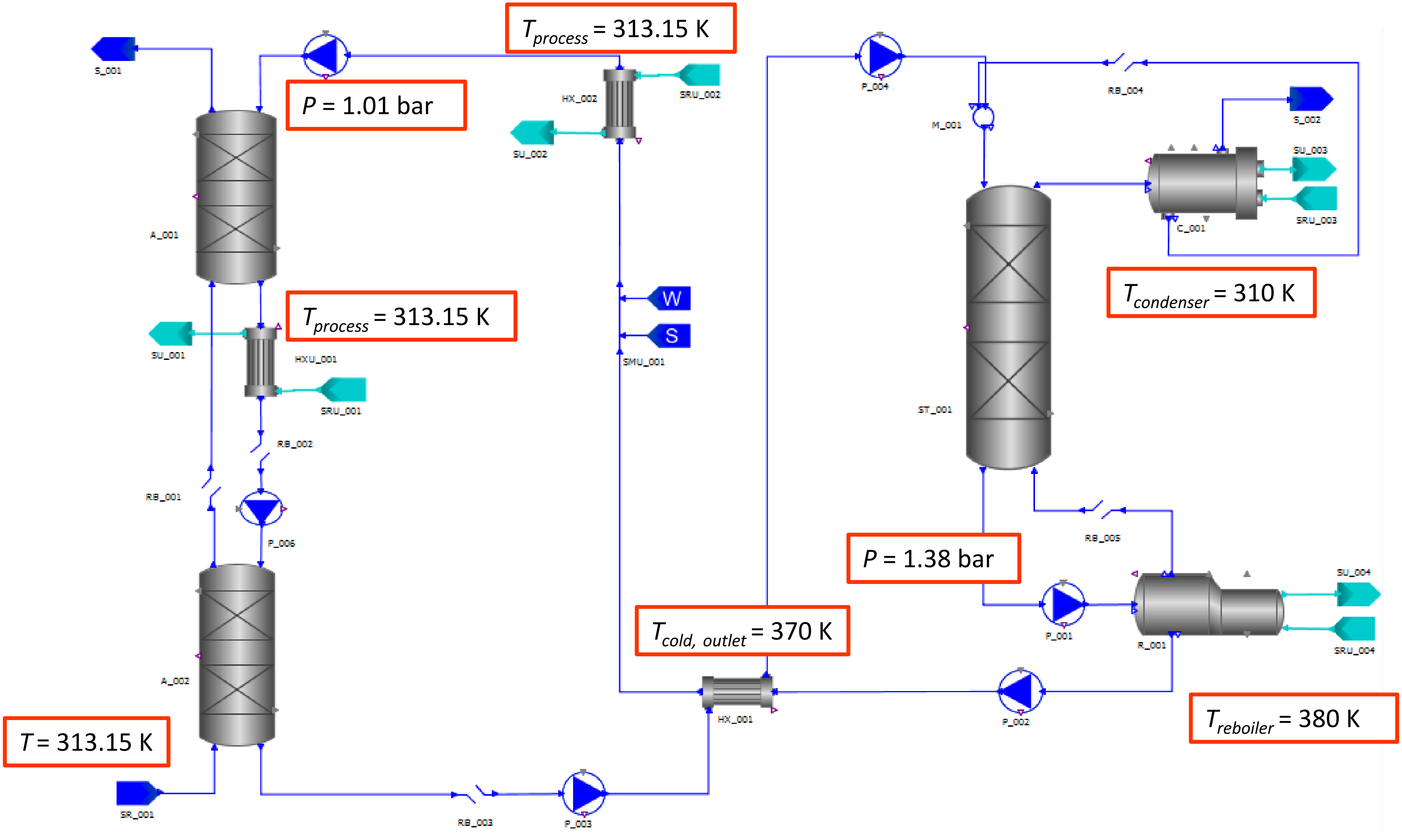
* indicates an active bound

Variable	Initial value	Lower bound	Upper bound	Optimisation value
CO_2 capture (%)	88.8	90.0	100	90.5
(kJ/kg CO_2)	5229	-	-	4230

- 11 %

Optimization example

Intercooled absorber and simple stripper configuration



$T_{process}$ = 313.15 K

P = 1.01 bar

$T_{process}$ = 313.15 K

T = 313.15 K

$T_{cold,\ outlet}$ = 370 K

$T_{condenser}$ = 310 K

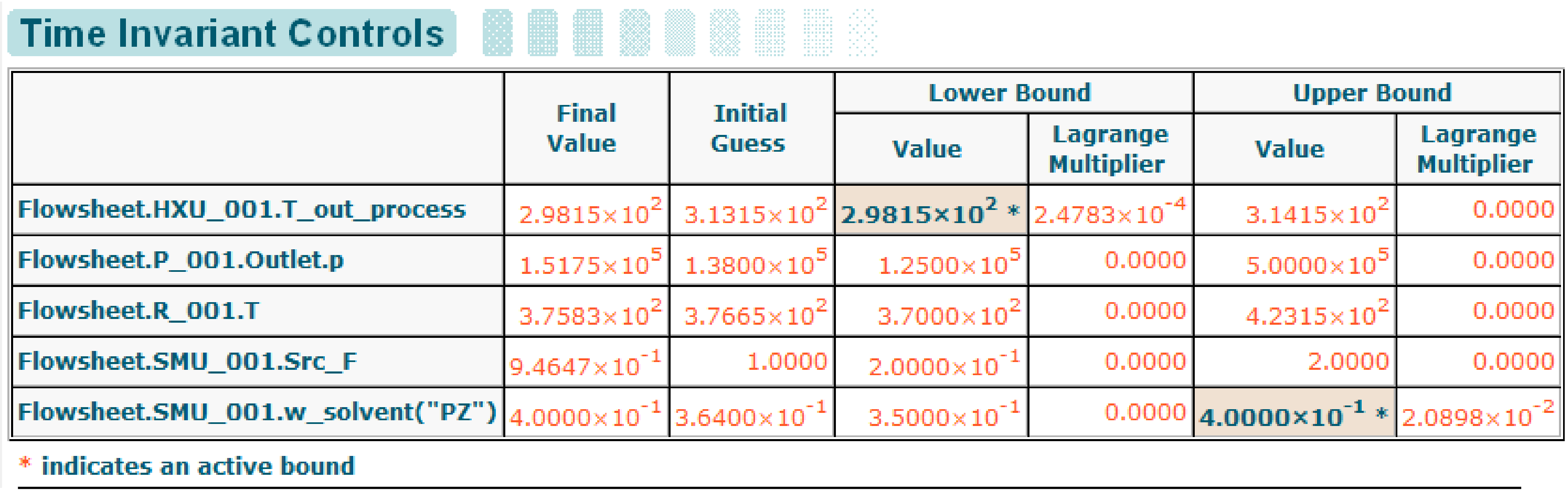
P = 1.38 bar

$T_{reboiler}$ = 380 K

Optimization example

Intercooled absorber and simple stripper configuration

- Objective function: reboiler heat duty
- Constraint: CO_2 capture > 90 %

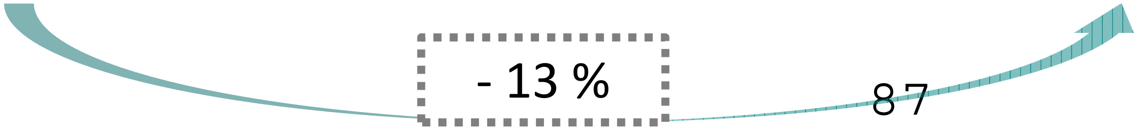


Time Invariant Controls

	Final Value	Initial Guess	Lower Bound		Upper Bound	
			Value	Lagrange Multiplier	Value	Lagrange Multiplier
Flowsheet.HXU_001.T_out_process	2.9815×10^{2}	3.1315×10^{2}	2.9815×10^{2} *	2.4783×10^{-4}	3.1415×10^{2}	0.0000
Flowsheet.P_001.Outlet.p	1.5175×10^{5}	1.3800×10^{5}	1.2500×10^{5}	0.0000	5.0000×10^{5}	0.0000
Flowsheet.R_001.T	3.7583×10^{2}	3.7665×10^{2}	3.7000×10^{2}	0.0000	4.2315×10^{2}	0.0000
Flowsheet.SMU_001.Src_F	9.4647×10^{-1}	1.0000	2.0000×10^{-1}	0.0000	2.0000	0.0000
Flowsheet.SMU_001.w_solvent("PZ")	4.0000×10^{-1}	3.6400×10^{-1}	3.5000×10^{-1}	0.0000	4.0000×10^{-1} *	2.0898×10^{-2}

* indicates an active bound

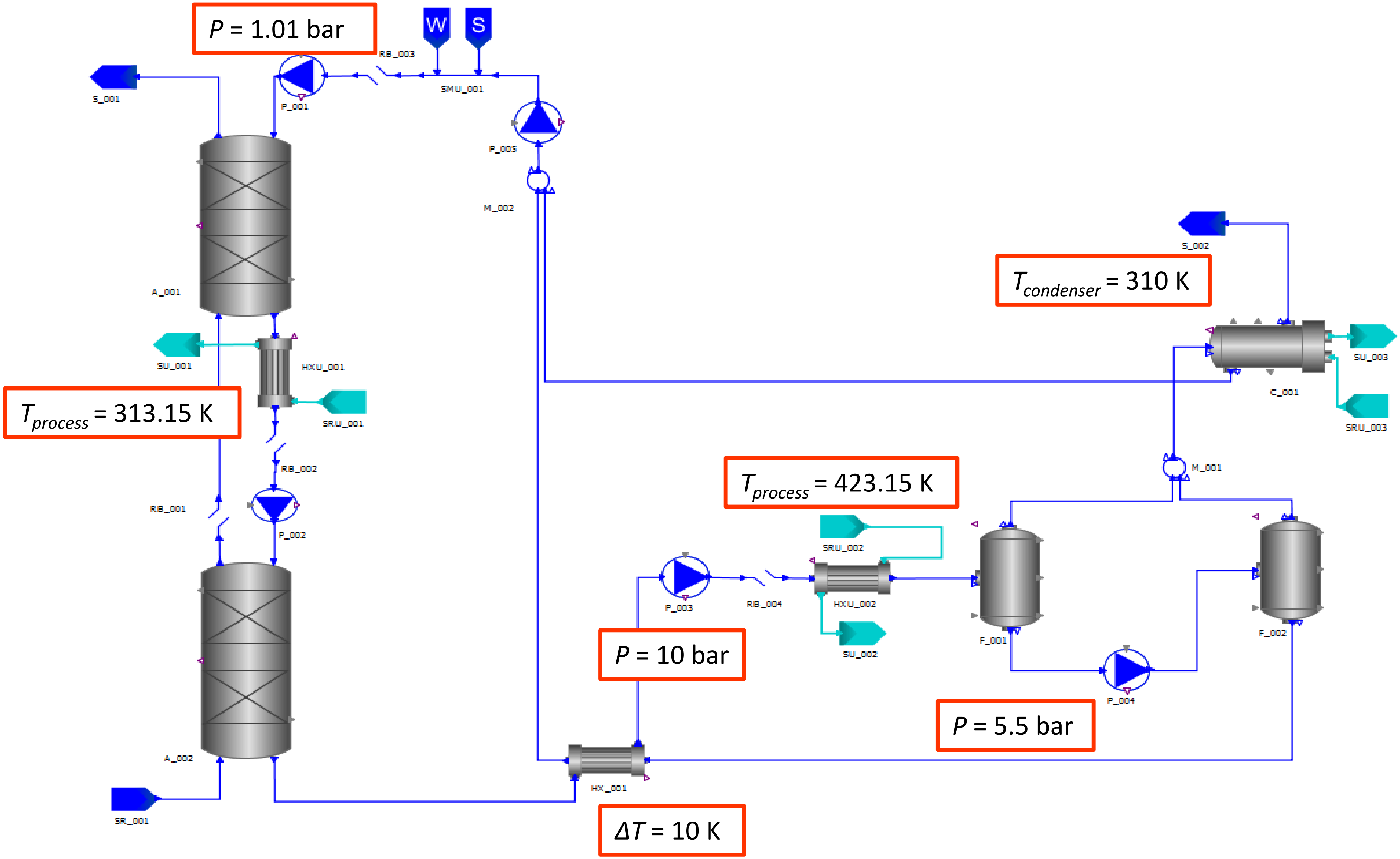
Variable	Initial value	Lower bound	Upper bound	Optimised value
CO_2 capture (%)	98.6	90.0	100	90.4
(kJ/kg CO_2)	4924	-	-	4239



- 13 %

Optimization Example:

Intercooled absorber with two flashes



P = 1.01 bar

$T_{process}$ = 313.15 K

$T_{condenser}$ = 310 K

$T_{process}$ = 423.15 K

P = 10 bar

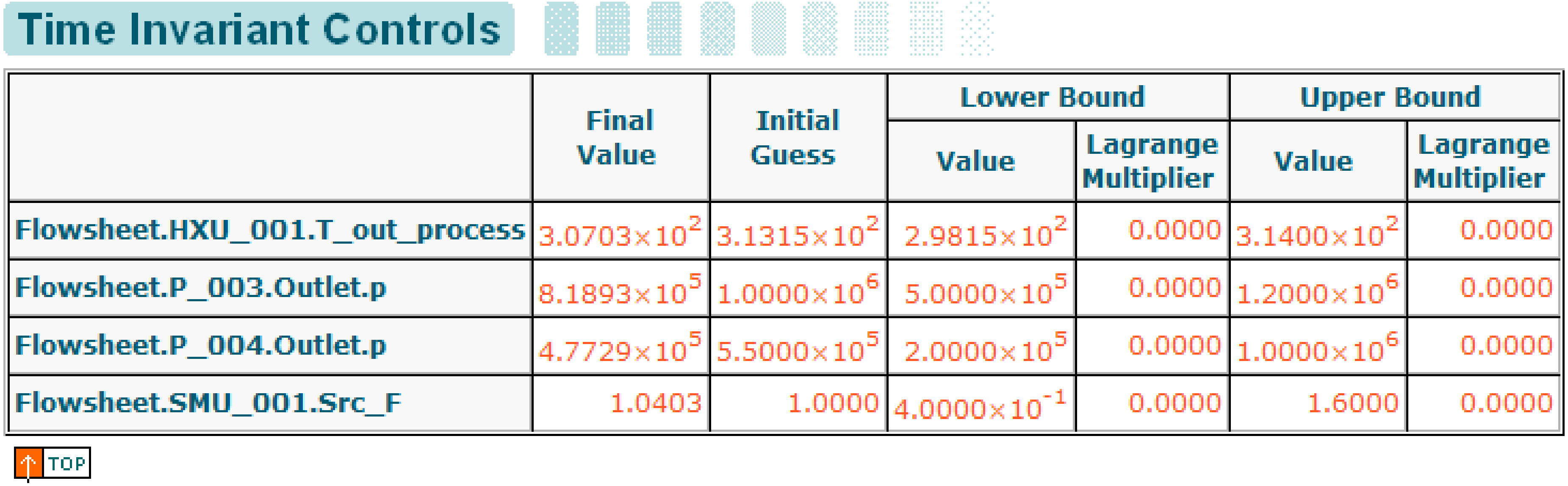
P = 5.5 bar

ΔT = 10 K

Optimization Example:

Intercooled absorber with two flashes

- Objective function: CO_2 capture



Time Invariant Controls

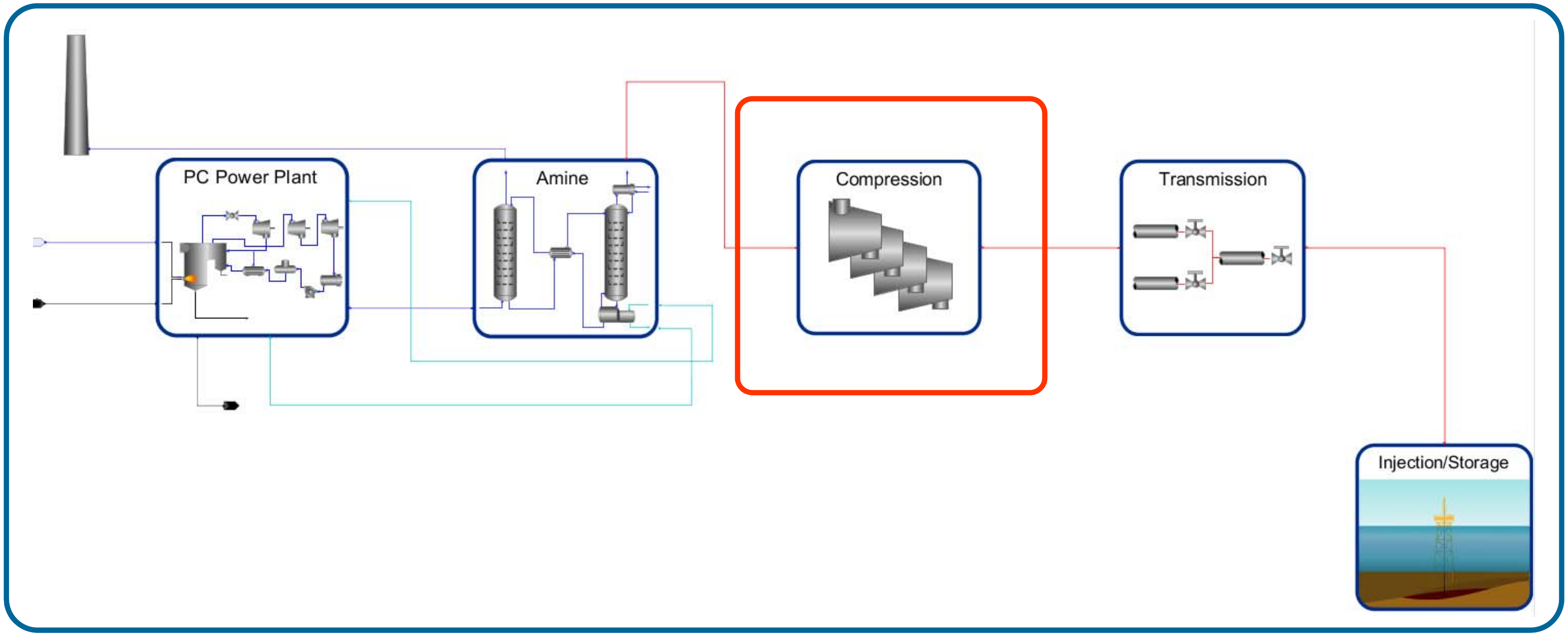
	Final Value	Initial Guess	Lower Bound		Upper Bound	
			Value	Lagrange Multiplier	Value	Lagrange Multiplier
Flowsheet.HXU_001.T_out_process	3.0703×10^{2}	3.1315×10^{2}	2.9815×10^{2}	0.0000	3.1400×10^{2}	0.0000
Flowsheet.P_003.Outlet.p	8.1893×10^{5}	1.0000×10^{6}	5.0000×10^{5}	0.0000	1.2000×10^{6}	0.0000
Flowsheet.P_004.Outlet.p	4.7729×10^{5}	5.5000×10^{5}	2.0000×10^{5}	0.0000	1.0000×10^{6}	0.0000
Flowsheet.SMU_001.Src_F	1.0403	1.0000	4.0000×10^{-1}	0.0000	1.6000	0.0000

Variable	Initial value	Lower bound	Upper bound	Optimised value
CO_2 capture (%)	63.2	-	-	77.0
(kJ/kg CO_2)	4372	-	-	4119

+ 22%

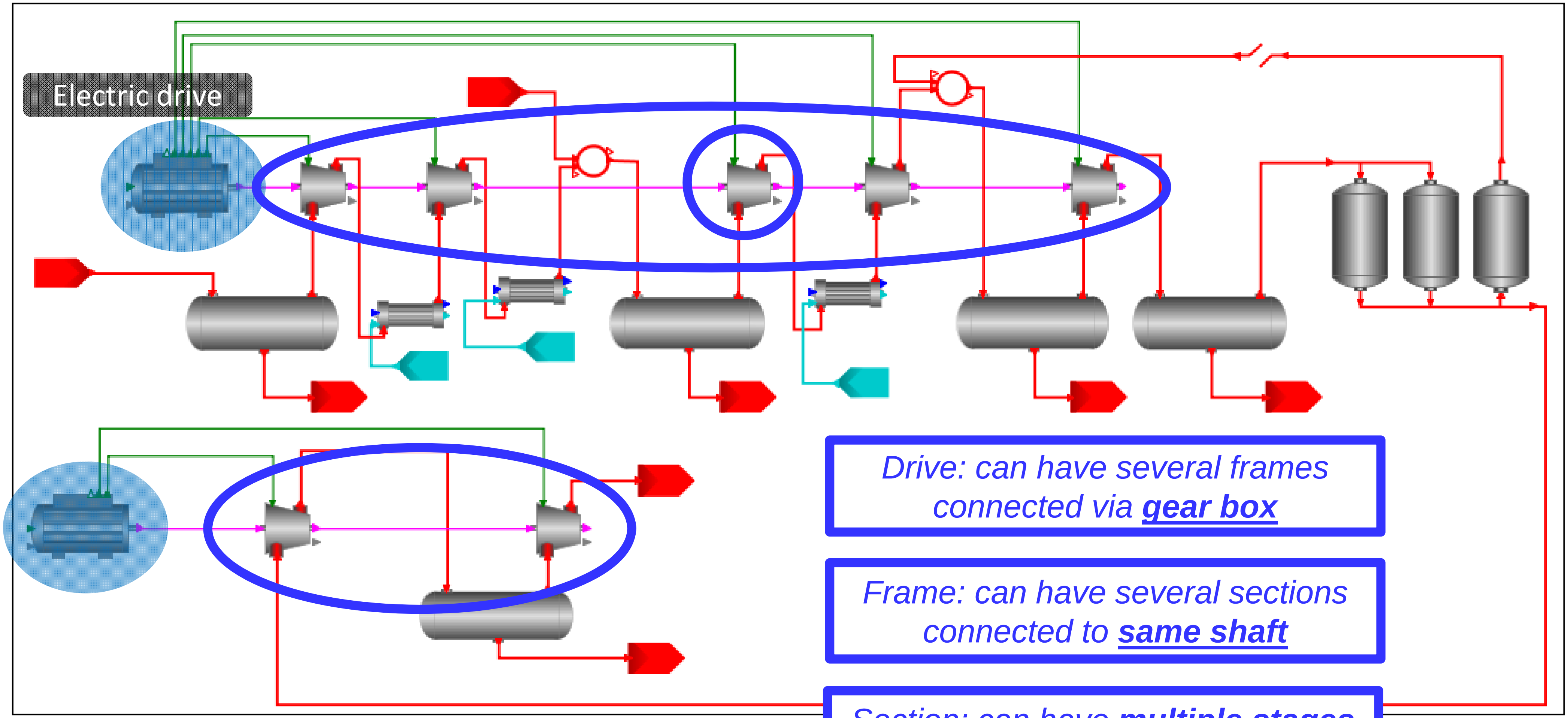
- 6 %

Compression



Multi-section compressor train

Basic concepts

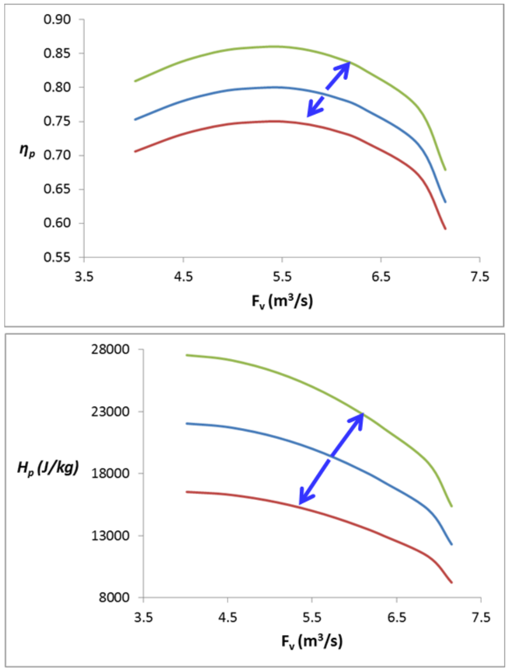


Drive: can have several frames connected via **gear box**

Frame: can have several sections connected to **same shaft**

Section: can have **multiple stages** within the same casing

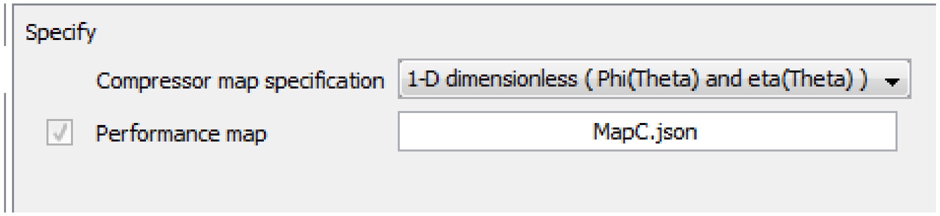
Compressor model – performance maps



Performance map data (flow/head and flow/eff)

```
],
 "Diameter" : 1.066864516,
 "DesignSpeed" : 69.95,
 "Map" :
 [
  {
   "Curve" :
   [
    [0.10847,  2.387901, 0.850614],
    [0.112603, 2.373763, 0.860395],
    [0.116736, 2.351798, 0.868467],
    [0.120868, 2.321925, 0.874854],
    [0.125001, 2.282775, 0.879213],
    [0.129134, 2.230553, 0.880363],
    [0.133266, 2.164399, 0.877854],
    [0.137399, 2.085194, 0.87204 ],
    [0.141531, 1.986933, 0.860782],
    [0.145664, 1.84251,  0.834881],
    [0.149797, 1.610725, 0.778101]
```

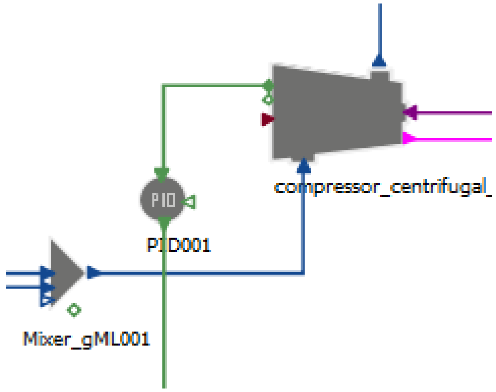
Converted to txt file format in ProcessBuilder
(including multiple stages)



Specify

Compressor map specification: 1-D dimensionless (Phi(Theta) and eta(Theta))

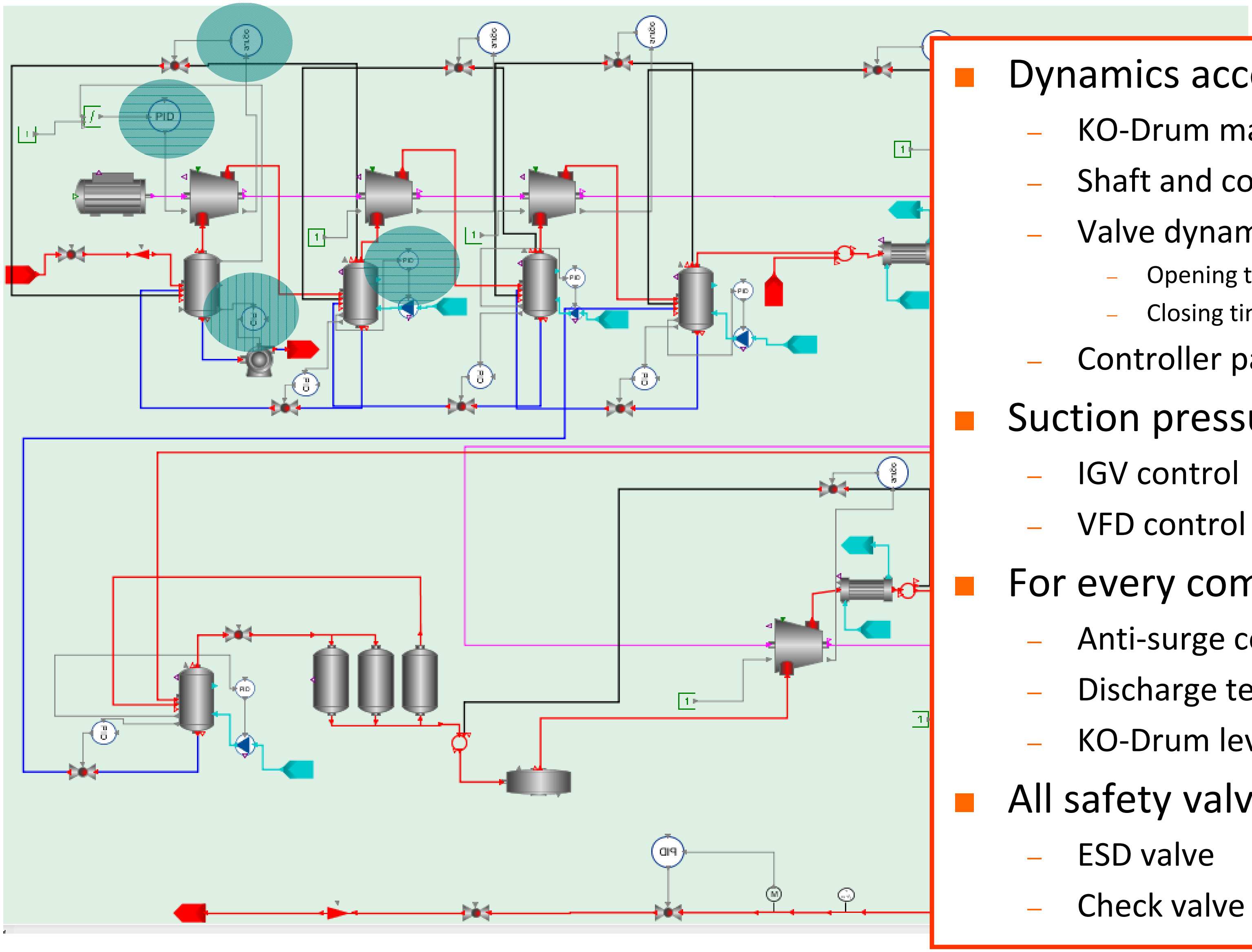
☑ Performance map: MapC.json



Compressor model reads performance map file

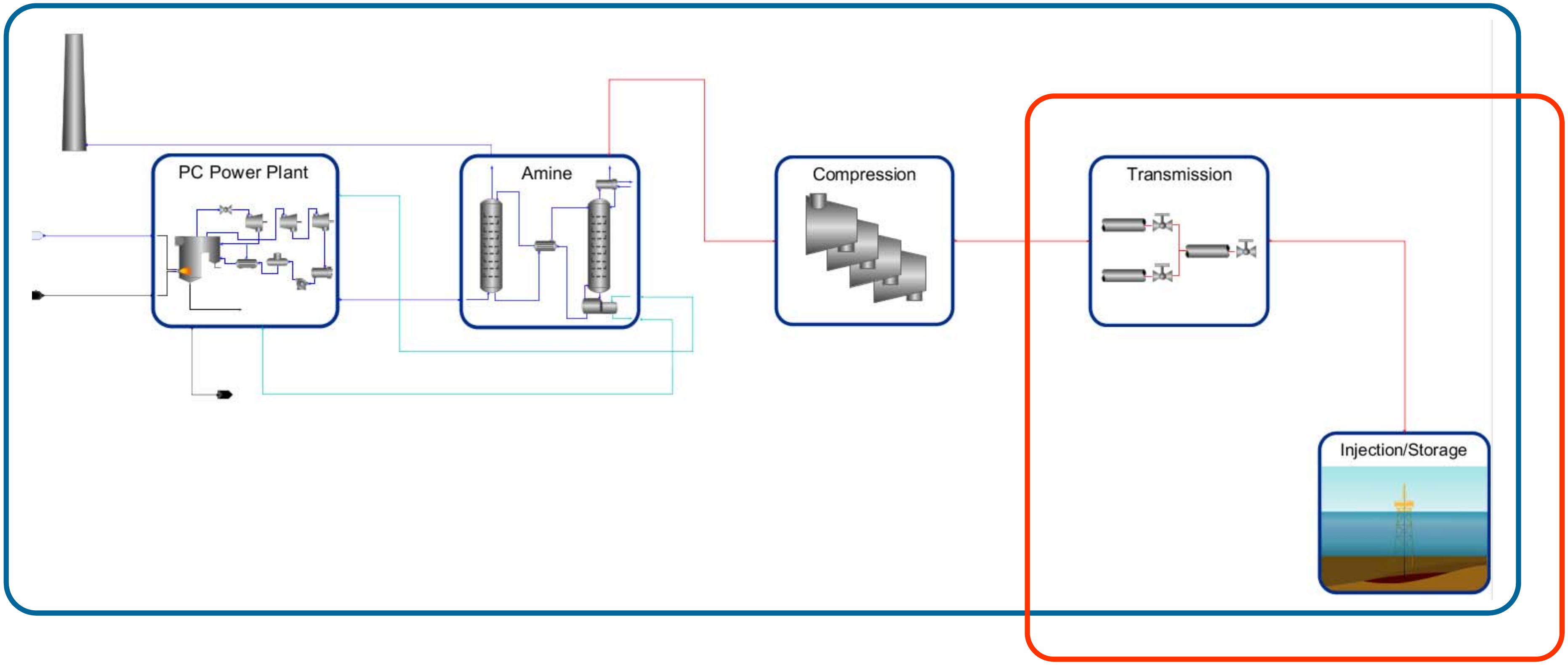
Multi-section compressor train

Control system - Demo



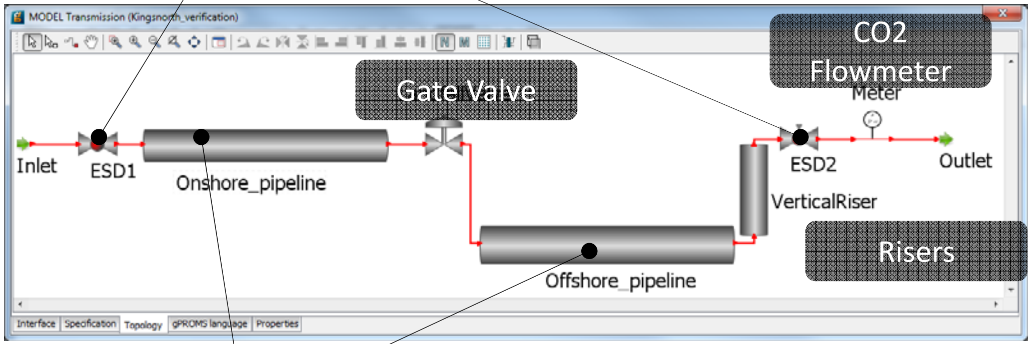
- Dynamics accounted for
  - KO-Drum mass/energy holdup
  - Shaft and compressor inertia
  - Valve dynamics
    - Opening time
    - Closing time
  - Controller parameters
- Suction pressure
  - IGV control
  - VFD control
- For every compression stage
  - Anti-surge control
  - Discharge temperature control
  - KO-Drum level control
- All safety valves
  - ESD valve
  - Check valve

Transmission & injection



Transmission and Injection

ESD valves

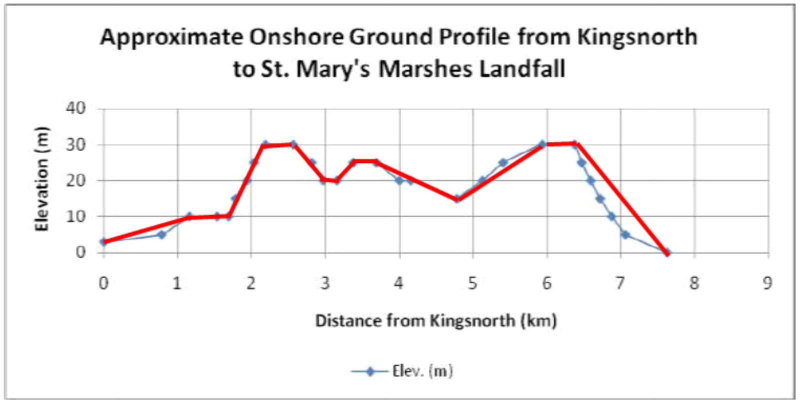


CO2 Flowmeter

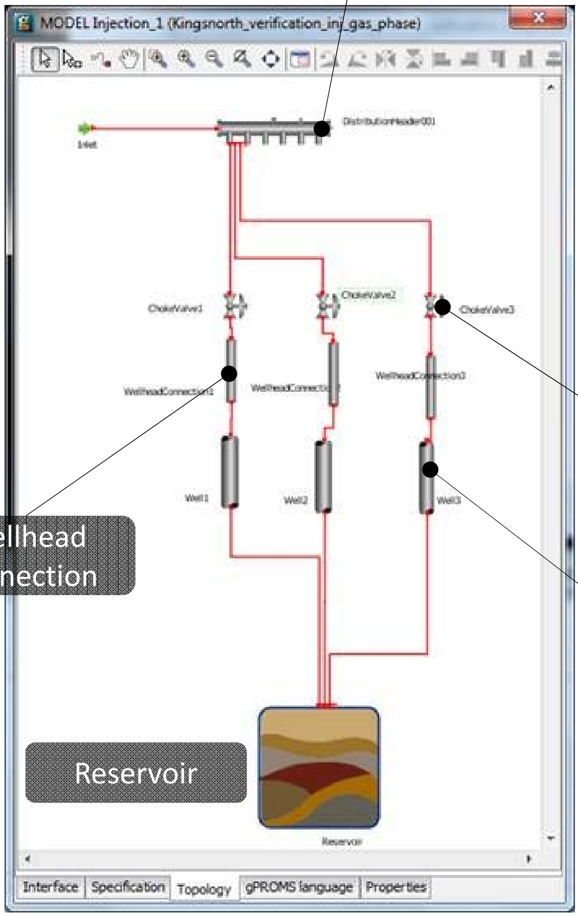
Gate Valve

Risers

Pipelines – including topography


Approximate Onshore Ground Profile from Kingsnorth to St. Mary's Marshes Landfall

Distribution header



Wellhead connection

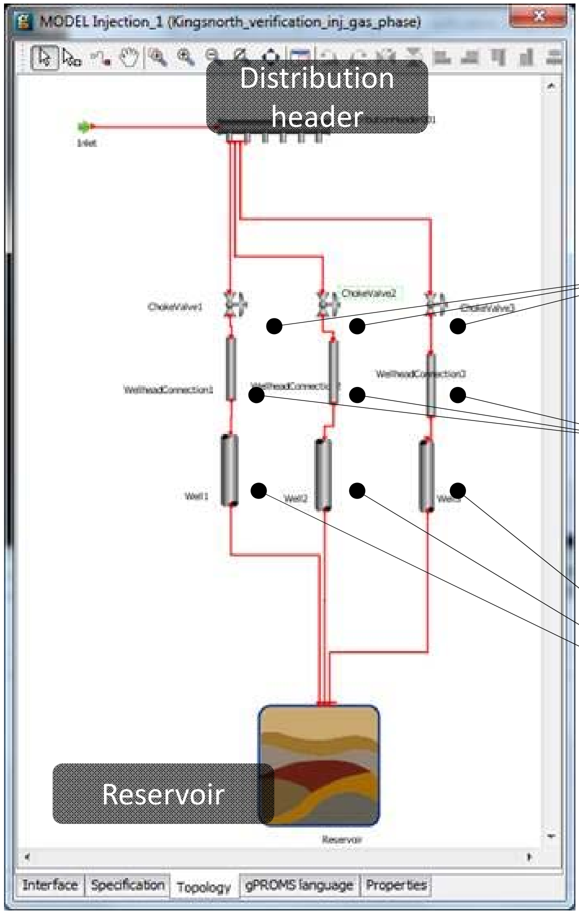
Choke Valve

Injection Well

Reservoir

Transmission and Injection

Model verification: e.g. Kingsnorth FEED - Injection/storage



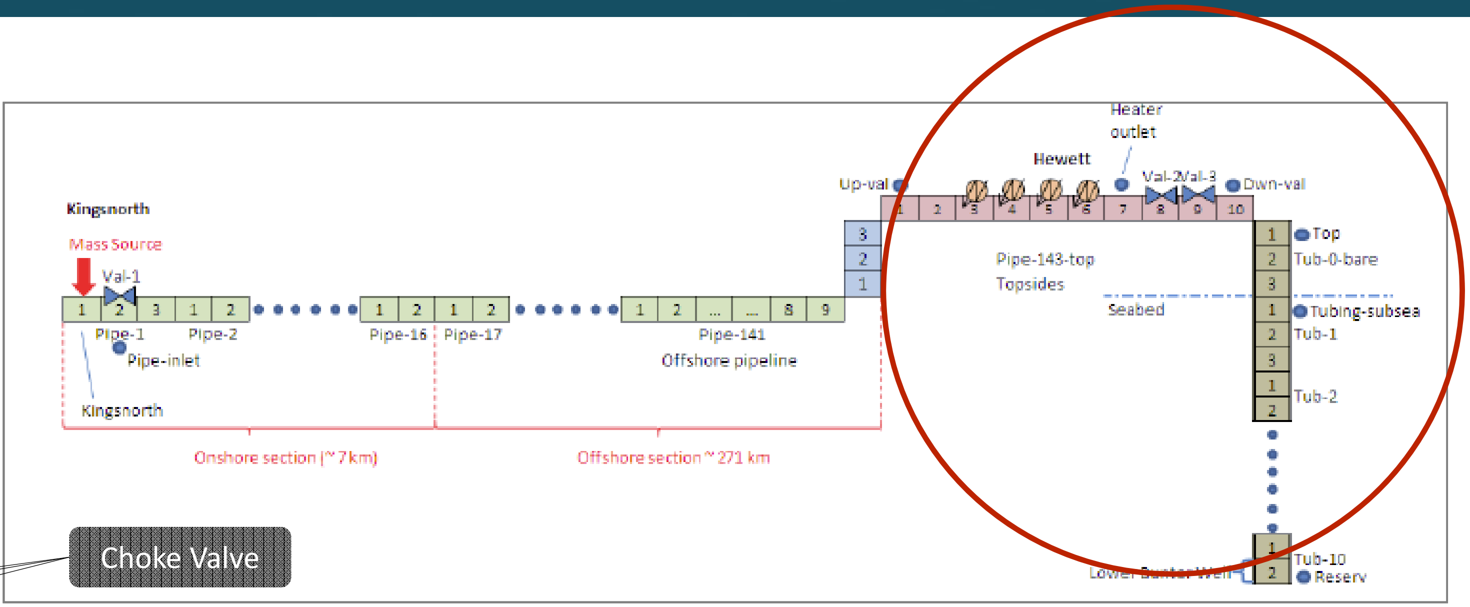
Distribution header

Choke Valve

Wellhead connection

Well

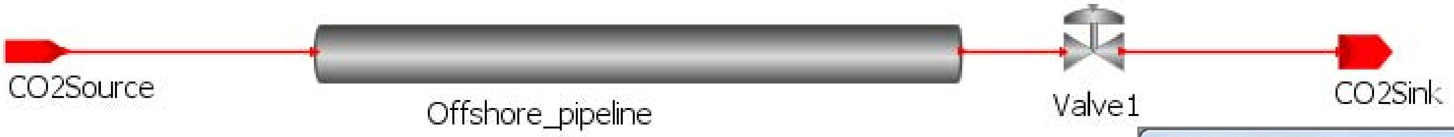
Reservoir

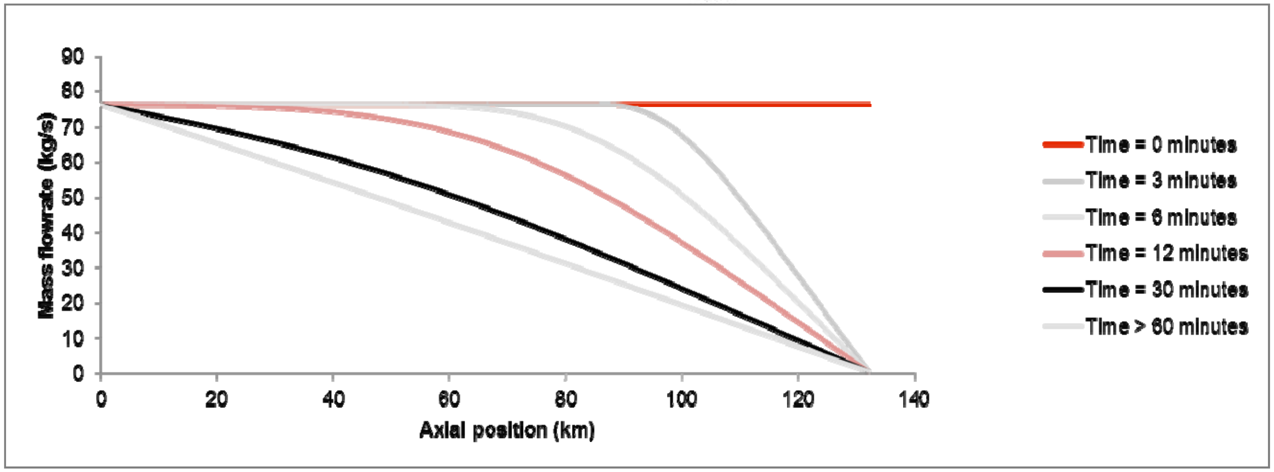


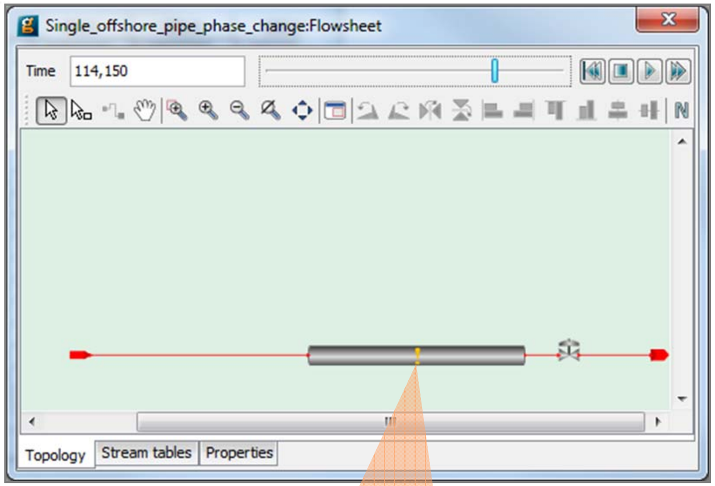
For gas phase operation (reservoir pressure 2.1barg)	Kingsnorth	gCCS	% Error (abs K for temps)
ΔP between Reservoir and Bottomhole (bar)	5.4	5.36	~0.6
ΔP between Bottomhole and downstream the choke valve (bar)	13.3	13.3	~0
Fluid temperature at Bottomhole (K)	279.05	280.9	-1.85

Example – line packing

- System dynamics following downstream valve closure

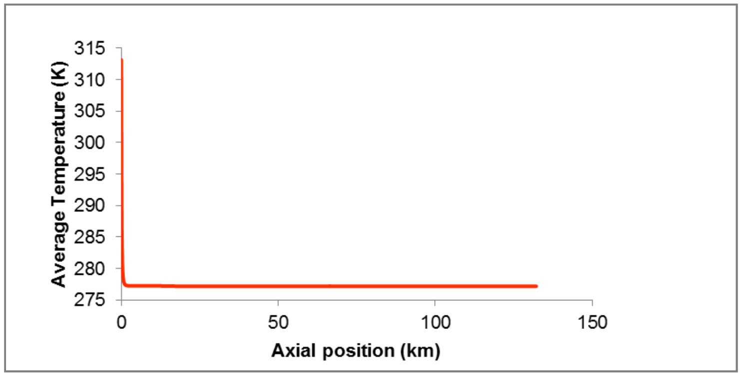


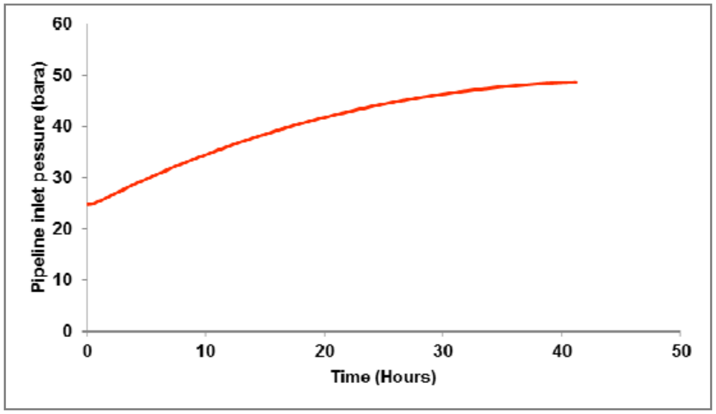




Single_offshore_pipe_phase_change:Flowsheet

Time 114,150



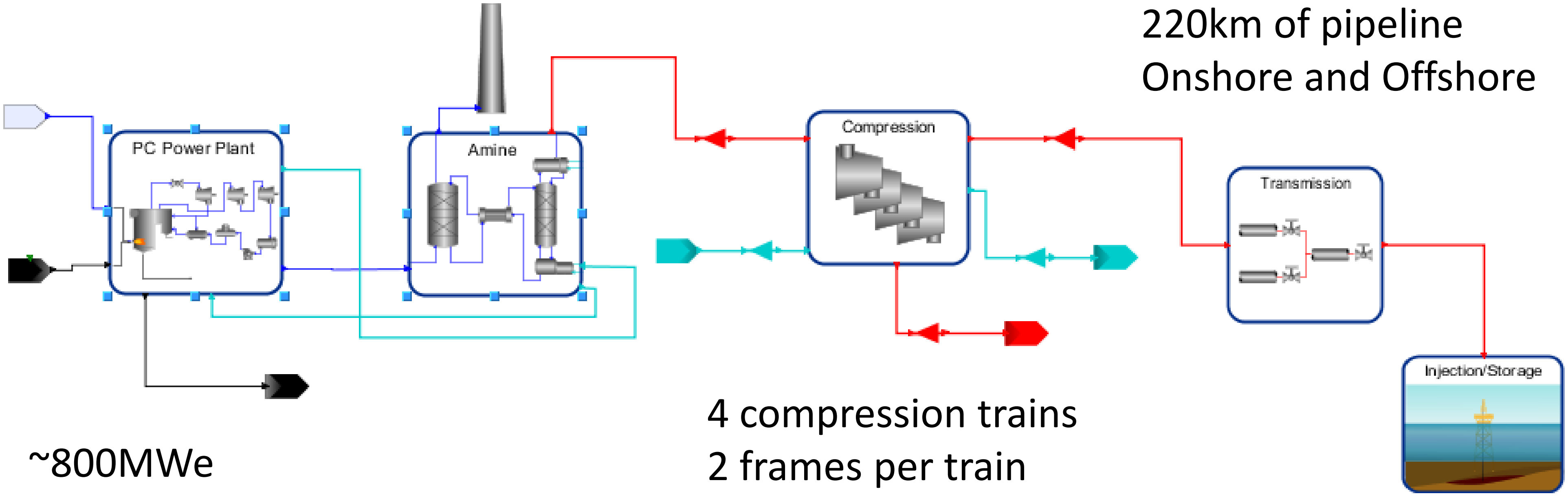


***Warning**: Phase change identified!*

Applications of gCCS: Case Studies

1. Process integration in CCS chains and networks

CCS Chain model developed in gCCS



Chemical absorption
MEA solvent
90% CO_2 capture

220km of pipeline
Onshore and Offshore

~800MWe
Supercritical
Pulverized coal
(acknowledgement: E.ON)

4 compression trains
2 frames per train
Surge control
(acknowledgement:
Rolls-Royce)

Offshore dense-phase
injection; 4 injection wells
~2km reservoir depth
(acknowledgement:
CO2DeepStore)

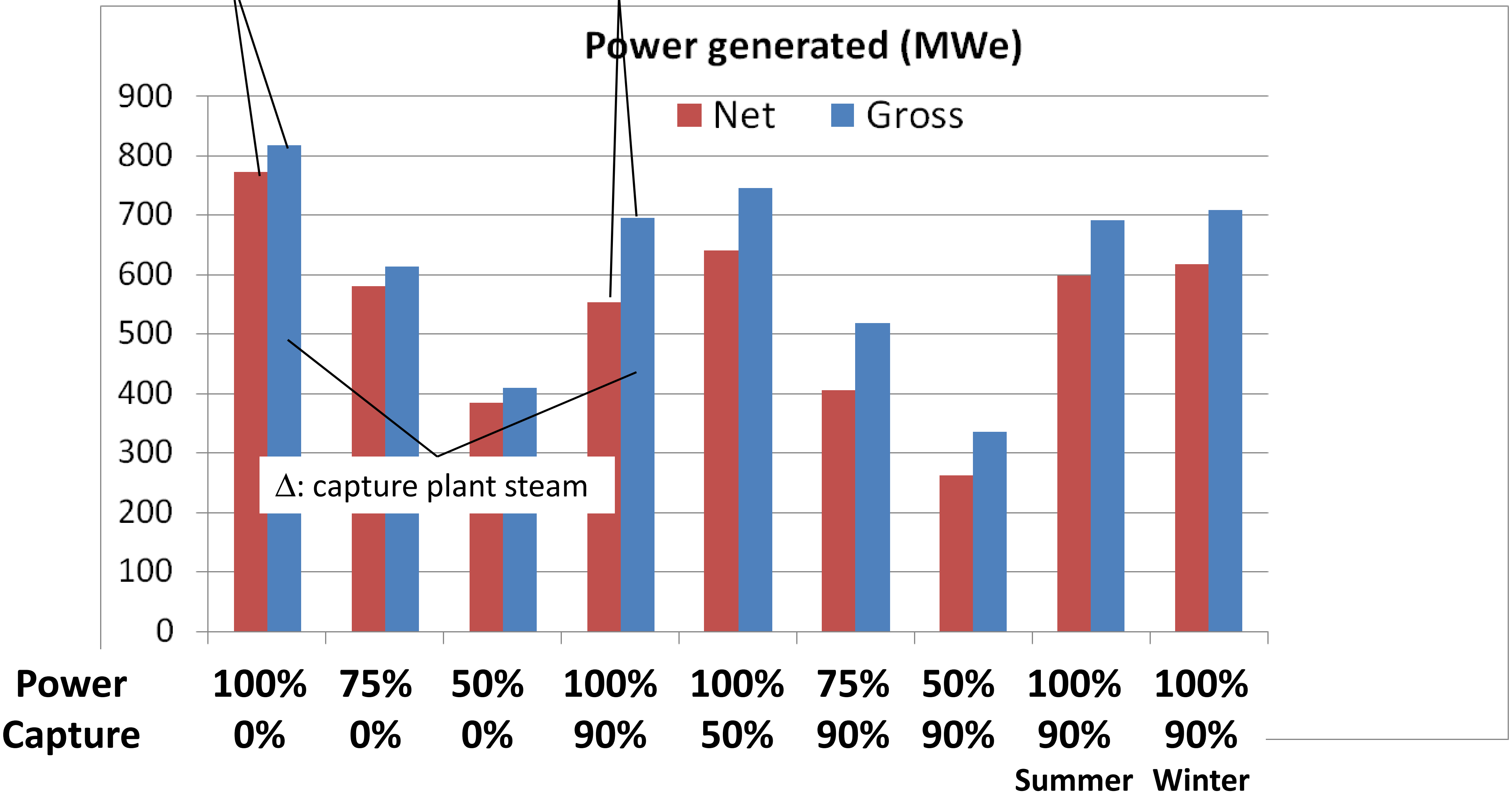
Steady-state scenarios

Scenario	Description	Power plant operation (% of nominal load)	Capture plant operation (CO2 % captured)
SS1.1 (a,b,c)	Base Load Power Plant	(a) 100%; (b) 75%; (c) 50%	0% (no capture)
SS1.2 (a, b)	Base load CCS Chain	100%	(a) 90%; (b) 50%
SS1.3 (a, b)	Part Load Analysis	(a) 75%; (b) 50%	90%
SS1.4	Extreme Weather: Max Summer	100%	90%
SS1.5	Extreme Weather: Min Winter	100%	90%

Temperatures (°C)	Affected sub-systems	Base Case	Extreme Summer	Extreme Winter
Cooling water	Power, Capture, Compression	18	22	7
Air	Power, Transmission, Injection	15	30	-15
Sea water	Transmission, Injection	9	14	4
NB. Geothermal gradient of +27.5°C / km				

Steady-state analysis

Power generation



Δ: coal milling
+ power plant auxiliaries

Δ: coal milling
+ power plant auxiliaries
+ CO_2 compression

Δ: capture plant steam

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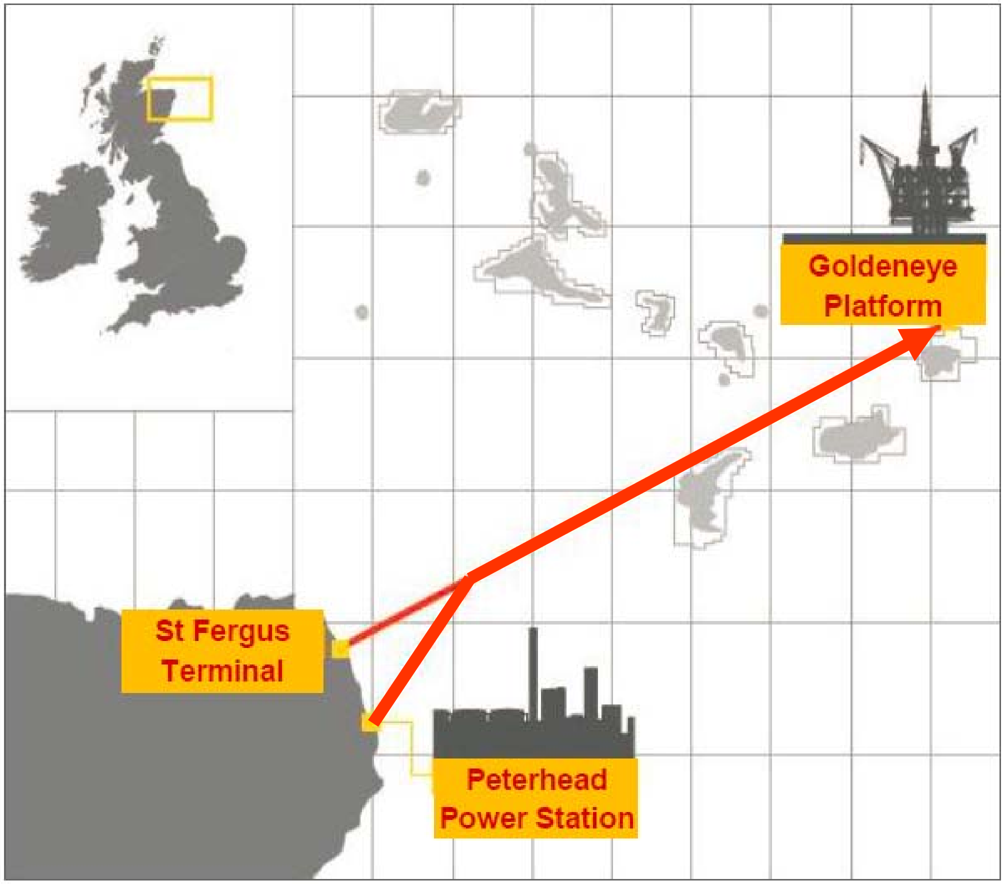
Applications of gCCS: Case Studies

2. Shell Peterhead CCS project

The Shell Peterhead CCS project

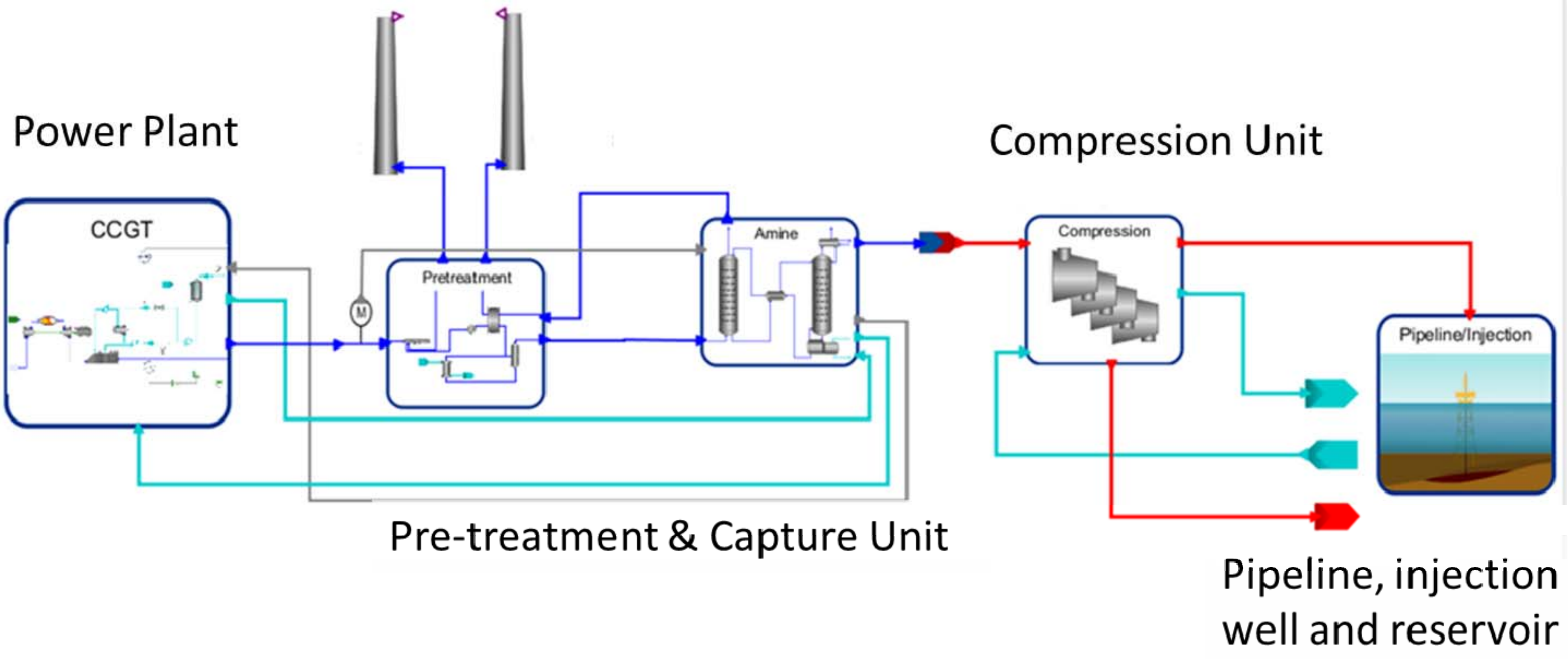
- **World First** – first planned full-scale CCS project on a gas-fired power station
- **Where** – capture at Peterhead Power Station; storage in depleted Goldeneye gas reservoir (100 km off shore)
- **Technology** – post-combustion capture using amines.
- **Impact** – 10 to 15 million tonnes of CO_2 over a 10- to 15-year period (90% CO_2 capture from one turbine)



Modelling Project Objectives

- Develop full chain model from FEED deliverables
- High level verification of the overall CCS plant control philosophy
- Simulate dynamic operation scenarios including start-up, shut-down and various failure modes
- Analyse the simulation results to identify improvements to the existing operating procedures, which need to be followed up in detailed engineering studies.

Full chain flowsheet screenshot


Power Plant

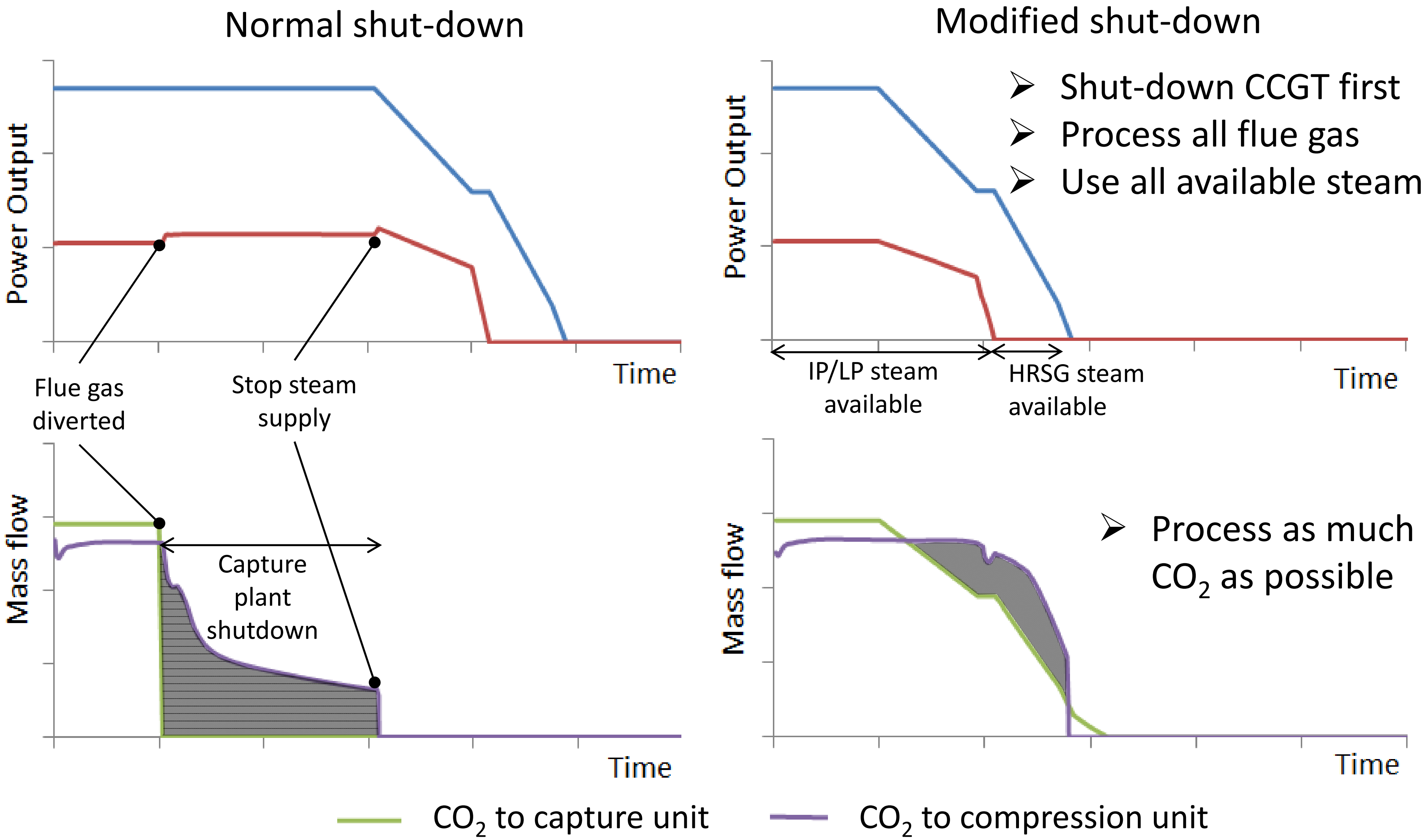
Compression Unit

Pre-treatment & Capture Unit

Pipeline, injection well and reservoir

- 18,700 equations/variables
  - 17,800 algebraic
  - 900 differential
- Computation time (on laptop computer)
  - ~14h for whole CCS chain start-up

Example: Optimization of shut-down procedure



Normal shut-down

Modified shut-down

- ➢ Shut-down CCGT first
- ➢ Process all flue gas
- ➢ Use all available steam

Flue gas diverted

Stop steam supply

Capture plant shutdown

IP/LP steam available

HRSG steam available

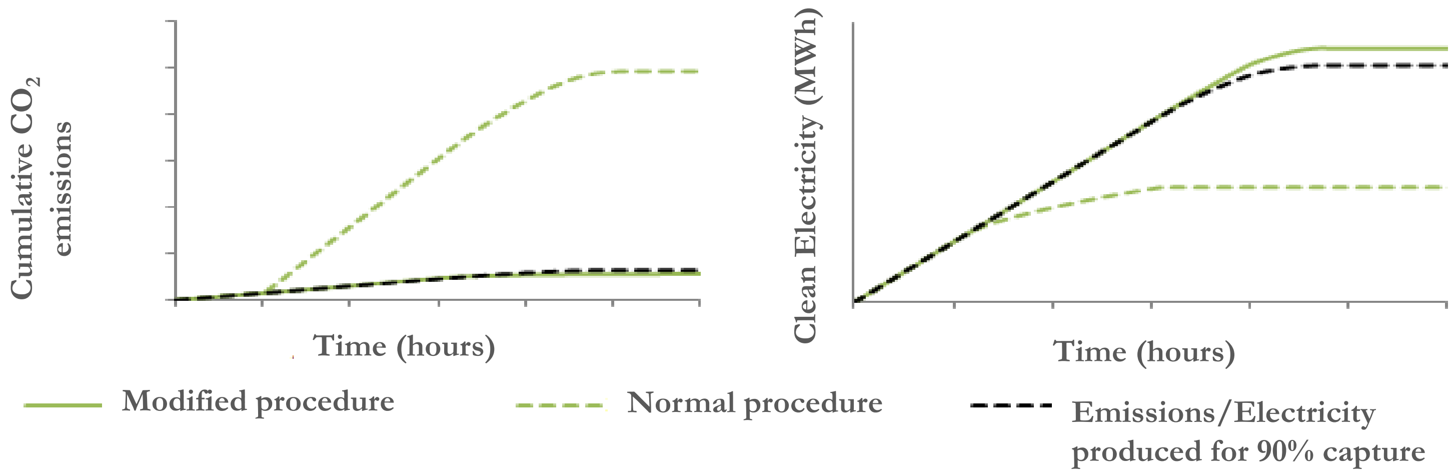
- ➢ Process as much CO_2 as possible

CO_2 to capture unit

CO_2 to compression unit

Shut-down summary

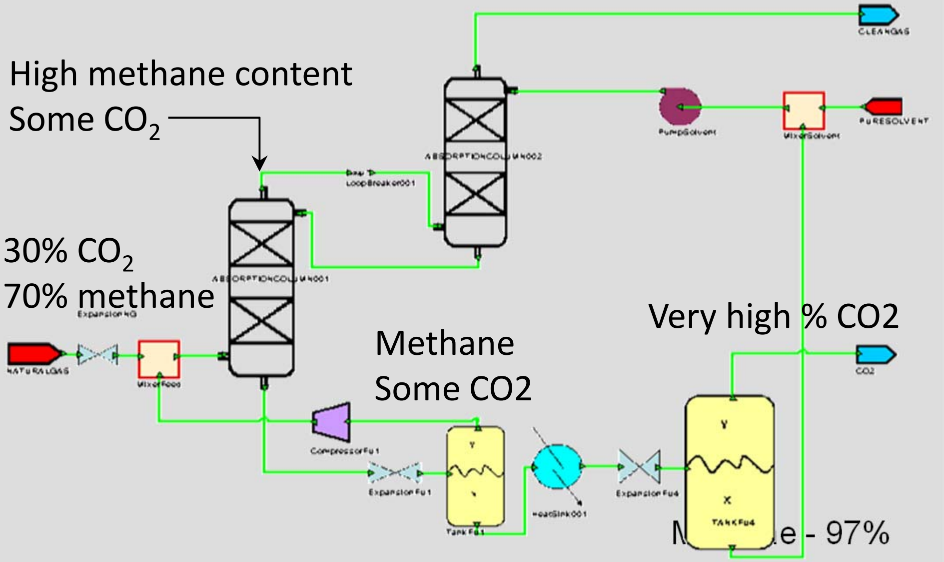
- It is not necessary to shut down the capture plant before shutting down the power plant
- Modified procedure leads to lower emissions and more clean electricity produced



R&D projects

New processes & solvents for carbon capture
(Imperial College London, Schlumberger)

- Study:
  - <u>multiple scenarios</u> with various compositions
  - <u>single design</u> that works under all scenarios and conditions
- <u>Simultaneous optimisation</u> of process design and solvent molecular design
- Technologies
  - gPROMS mixed integer optimisation
  - SAFT equation of state


High methane content
Some CO_2

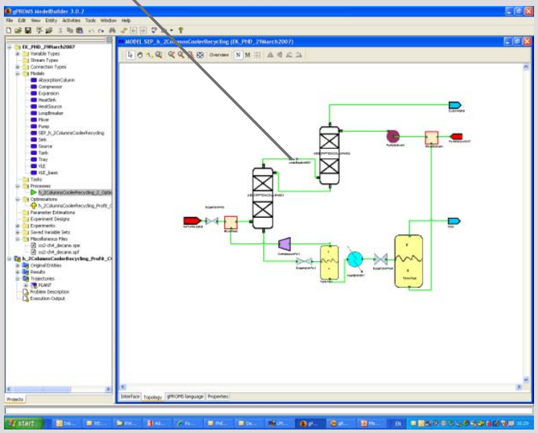
30% CO_2
70% methane

Methane
Some CO2

Very high % CO2

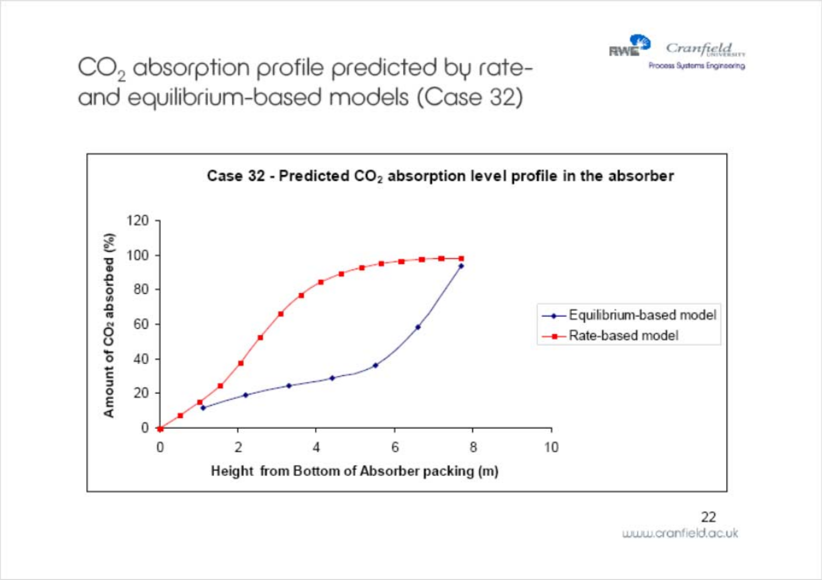
M e - 97%

Simultaneous optimisation
of **process design** and
solvent molecular design

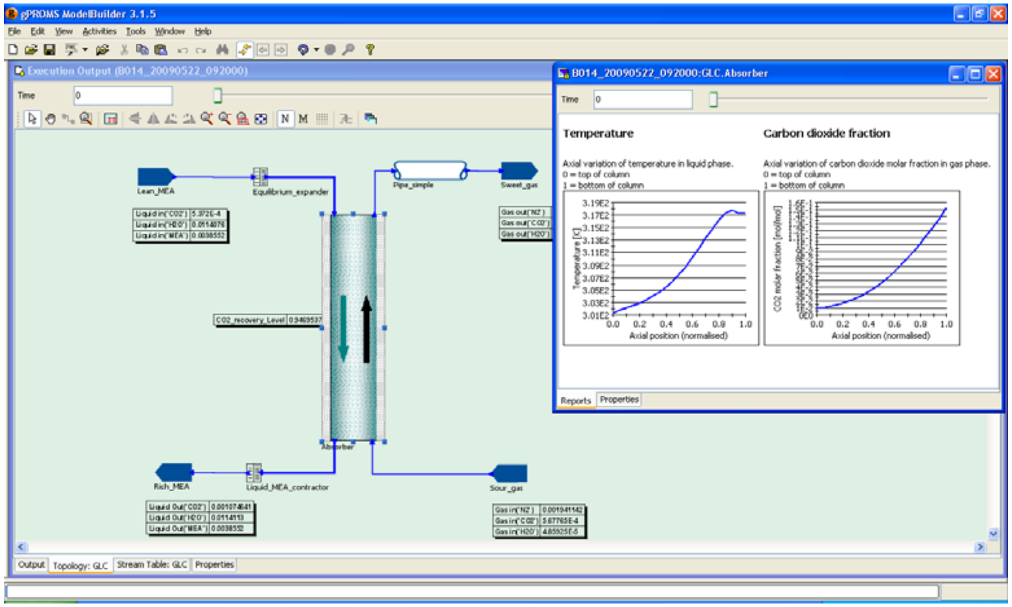


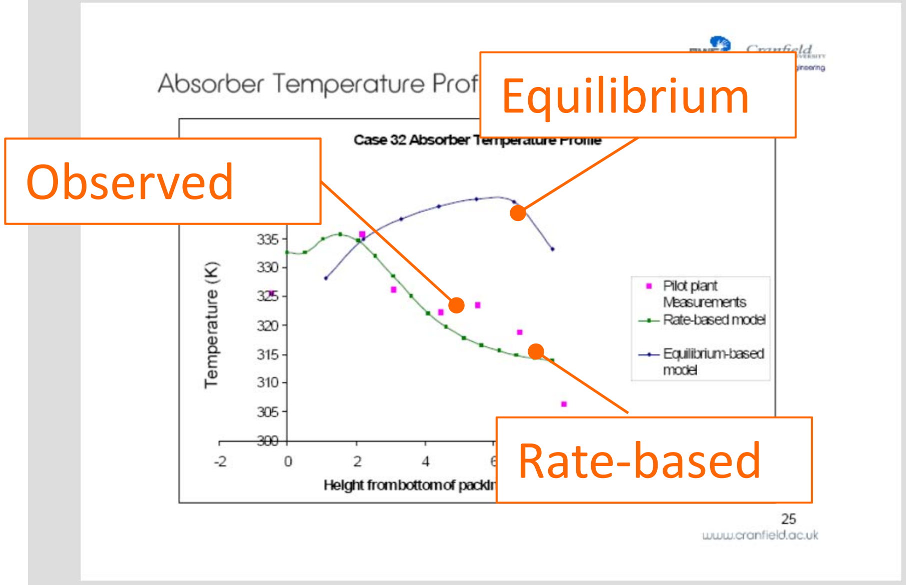
Amine process design (Cranfield, RWE)

- Importance of **high-fidelity** modelling
  - Rate-based vs. equilibrium methods
  - Completely different results



CO$_2$ absorption profile predicted by rate- and equilibrium-based models (Case 32)





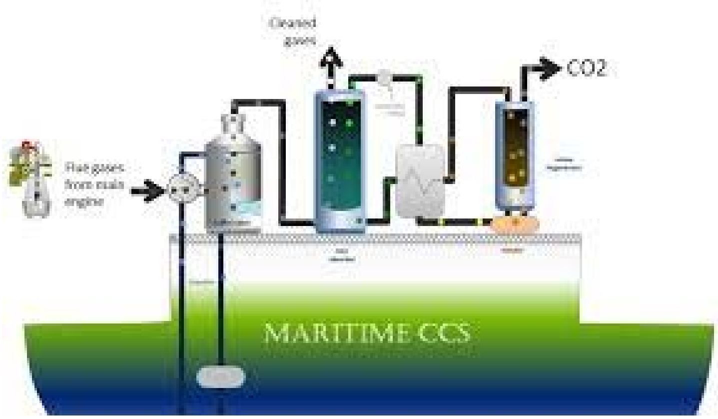
Absorber Temperature Prof

Equilibrium

Observed

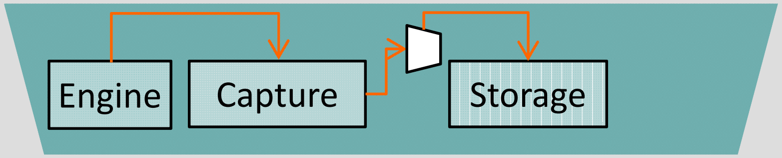
Rate-based

Maritime CCS capture



- Significant % of world CO_2 generation is maritime
  - large single-point emissions
- Eurostars project
  - PSE & DNV
  - investigate optimal capture routes
  - process design blueprints
  - safety & operability issues

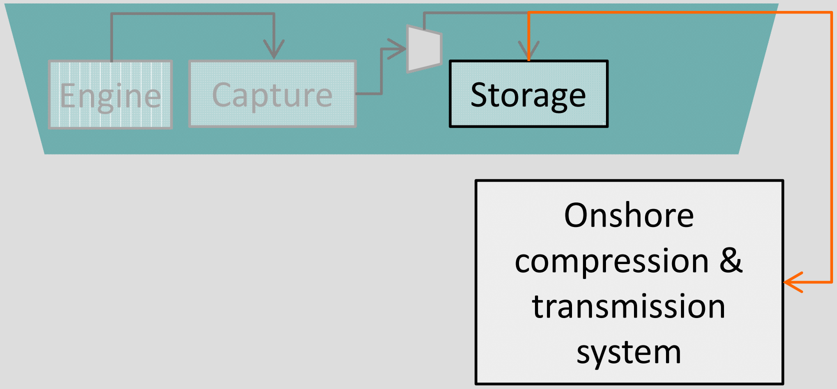
1. In transit


Engine

Capture

Storage

2. Dock


Engine

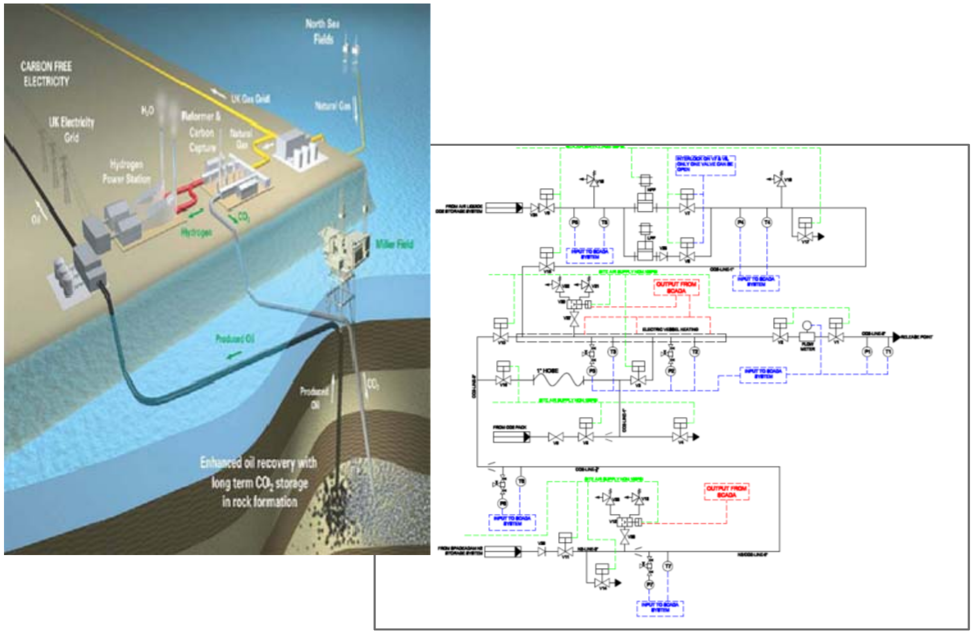
Capture

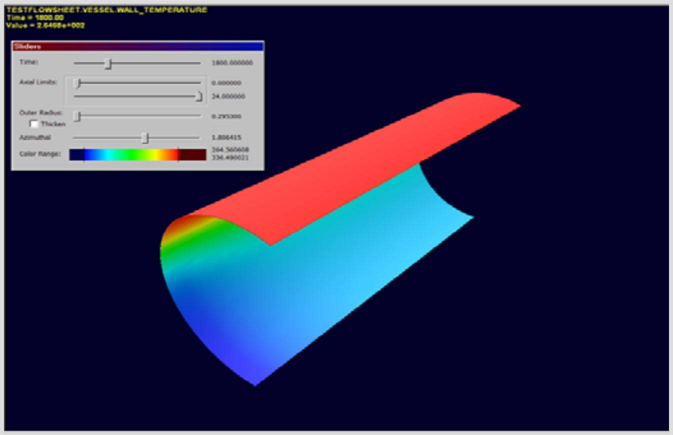
Storage

Onshore compression & transmission system

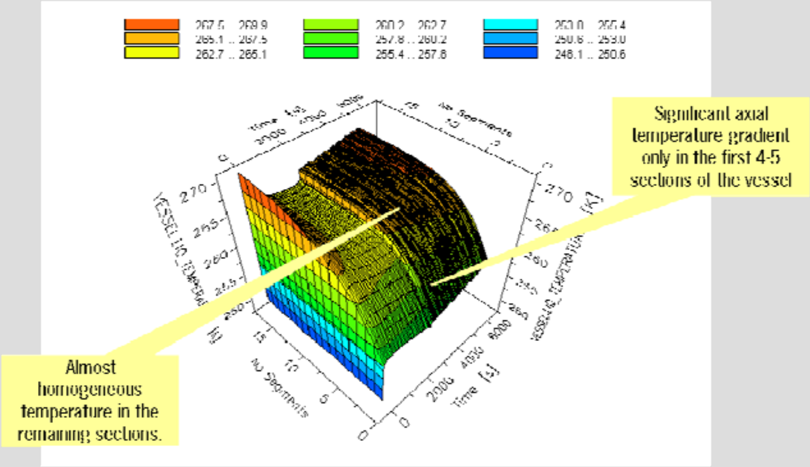
CO_2 compression & transmission (BP, SSE)

- BP DF1 project:
  - support understanding of different handling scenarios
  - example: pipeline temperatures during rapid depressurisation




TESTFLOWSHEET.VESSEL.WALL_TEMPERATURE
Time = 1800.00
Value = 2.6468e+002

Time: 1800.000000
Axial Limits: 0.000000 24.000000
Outer Radius: 0.295300
☐ Thicken
Azimuthal 1.806415
Color Range: 264.560608 336.490021



Significant axial temperature gradient only in the first 4-5 sections of the vessel

Almost homogeneous temperature in the remaining sections.

Applications of gCCS: Case Studies

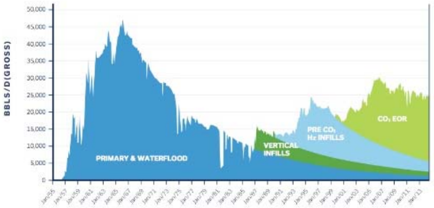
3. CO_2 Enhanced Oil Recovery Studies (CO_2 EOR)

CO_2 Enhanced Oil Recovery: Challenges

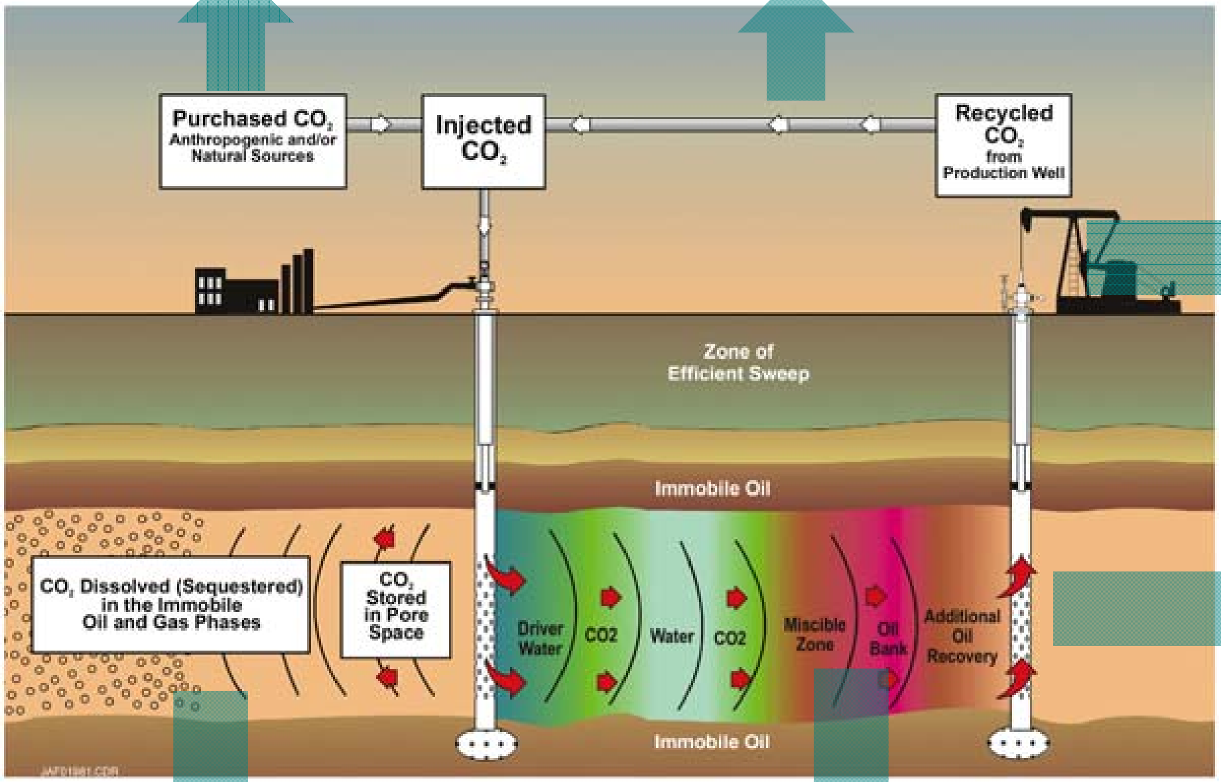
Supply vs demand

- Constraints, Costs

Handling of recycled gas before and after breakthrough



How do I optimize field development schedules?



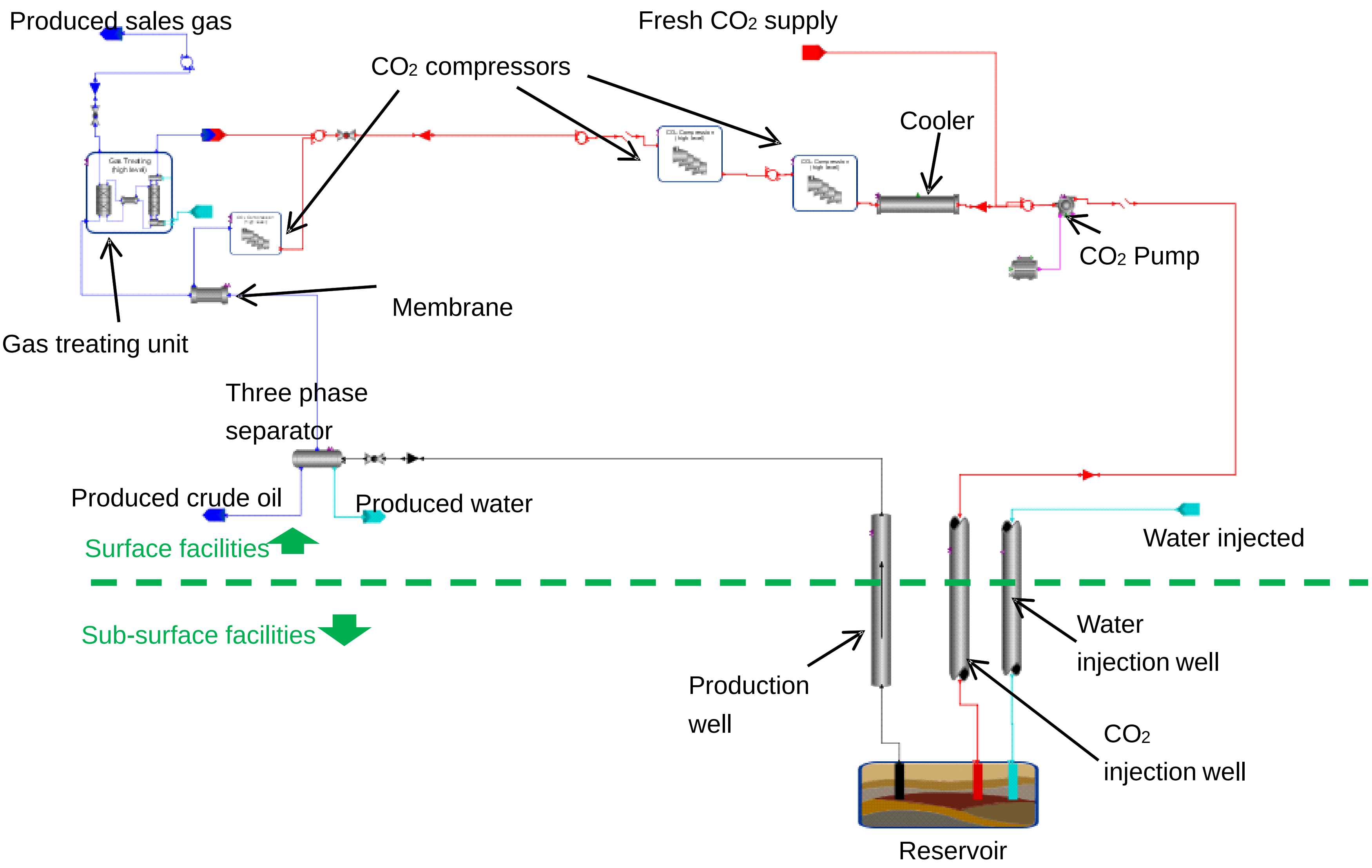
- Capacity/design/location of facilities?
- Design trade-offs?
- How long can we produce sales gas to spec?

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

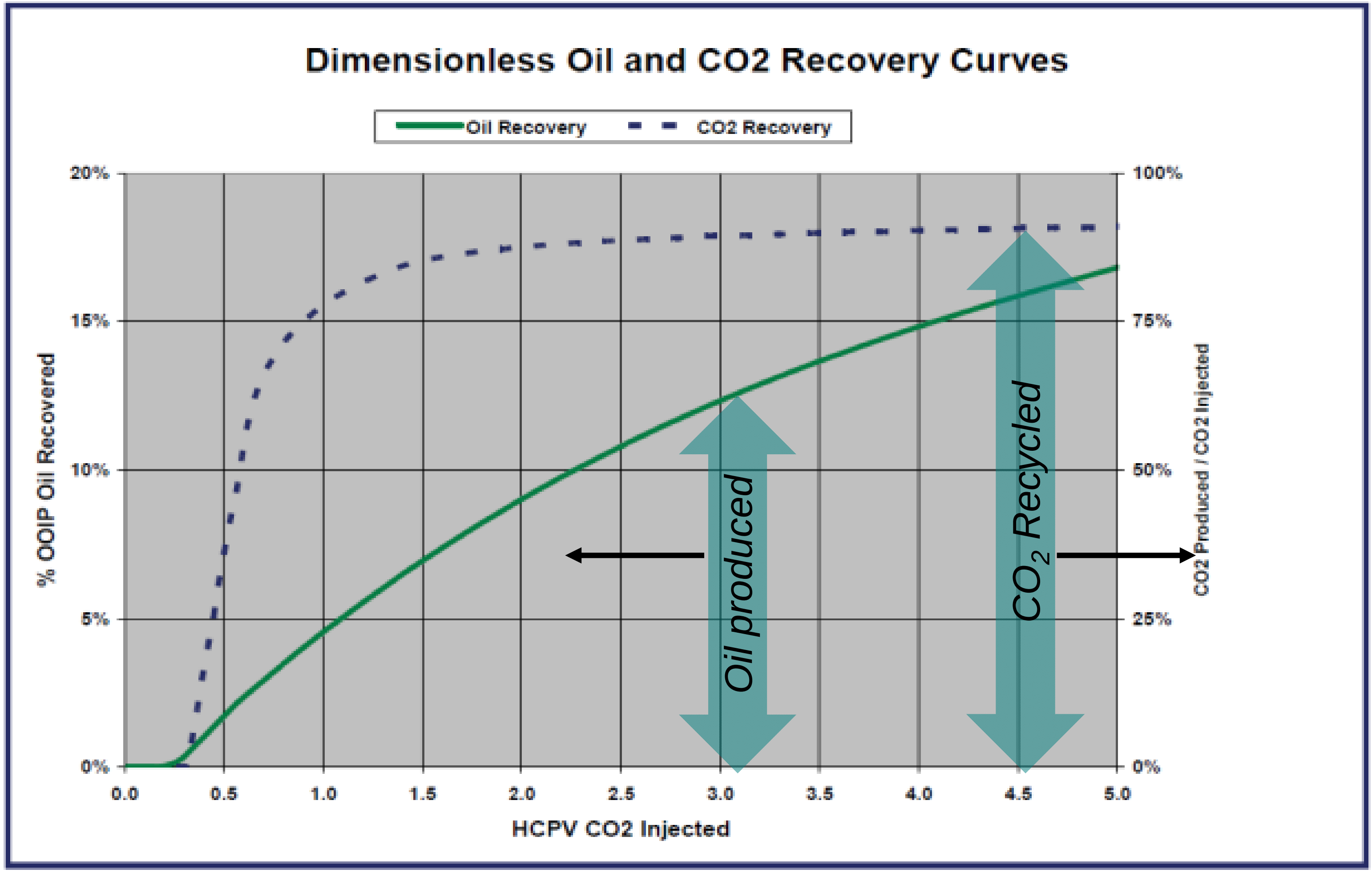
How much CO_2 is stored?

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

CO_2 EOR Flowsheet in gCCS

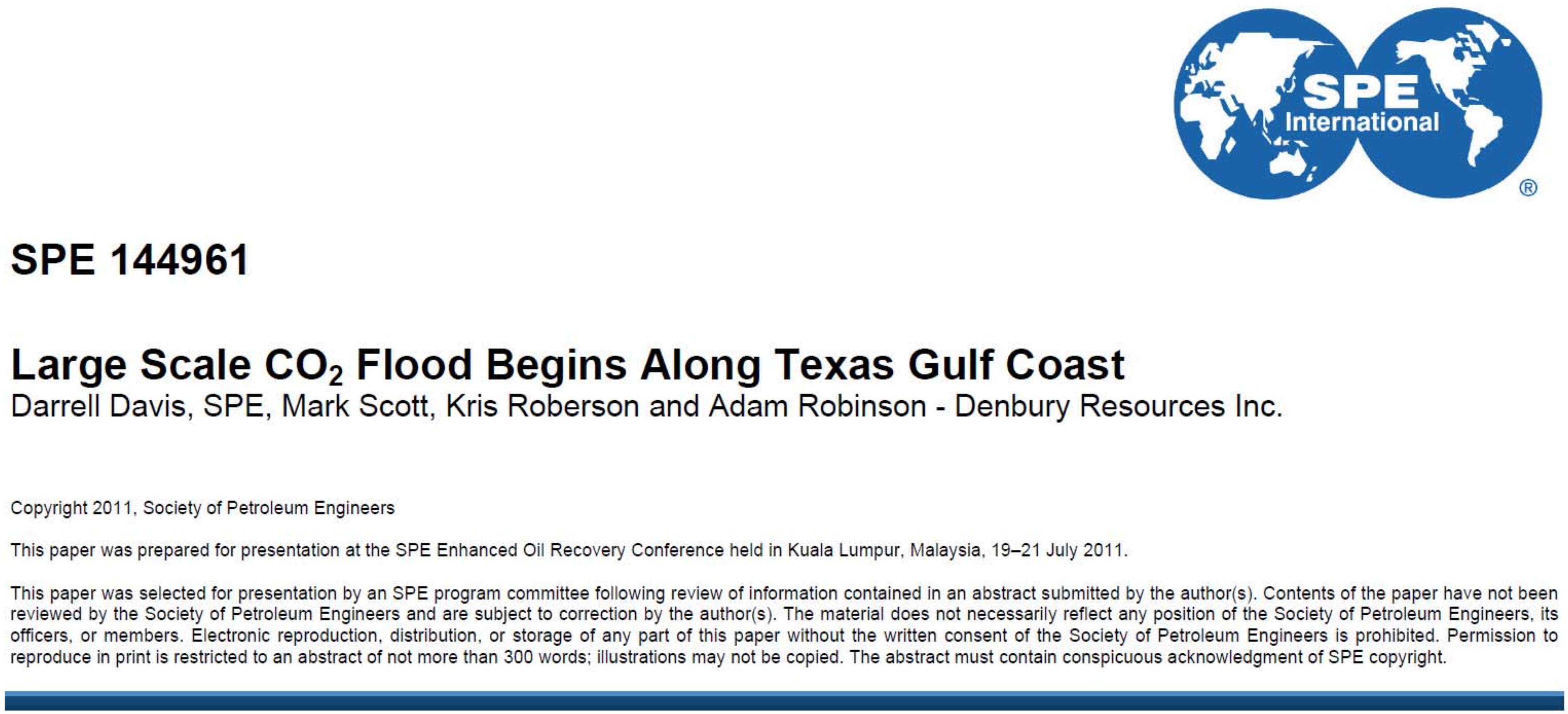


Reservoir type curves



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

Case Study



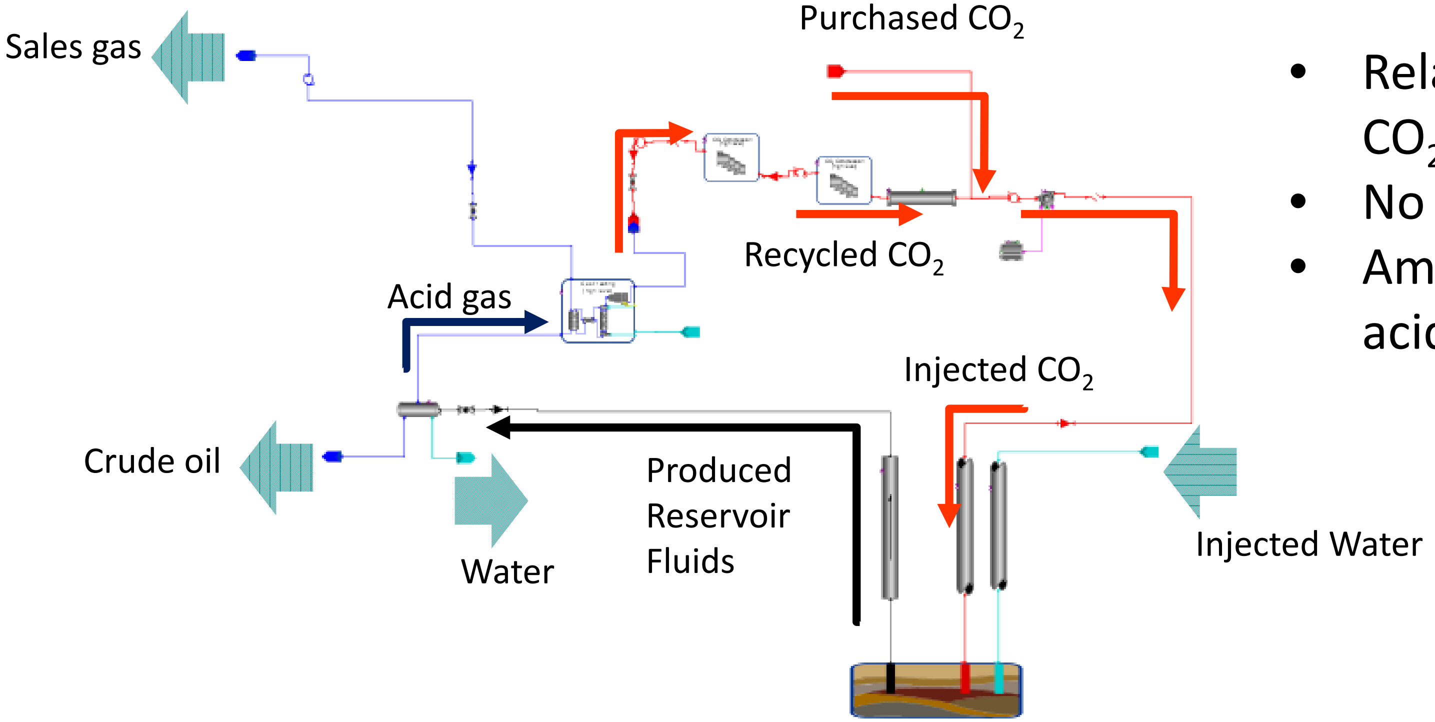
SPE 144961

Large Scale CO_2 Flood Begins Along Texas Gulf Coast

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

This paper was prepared for presentation at the SPE Enhanced Oil Recovery Conference held in Kuala Lumpur, Malaysia, 19–21 July 2011.

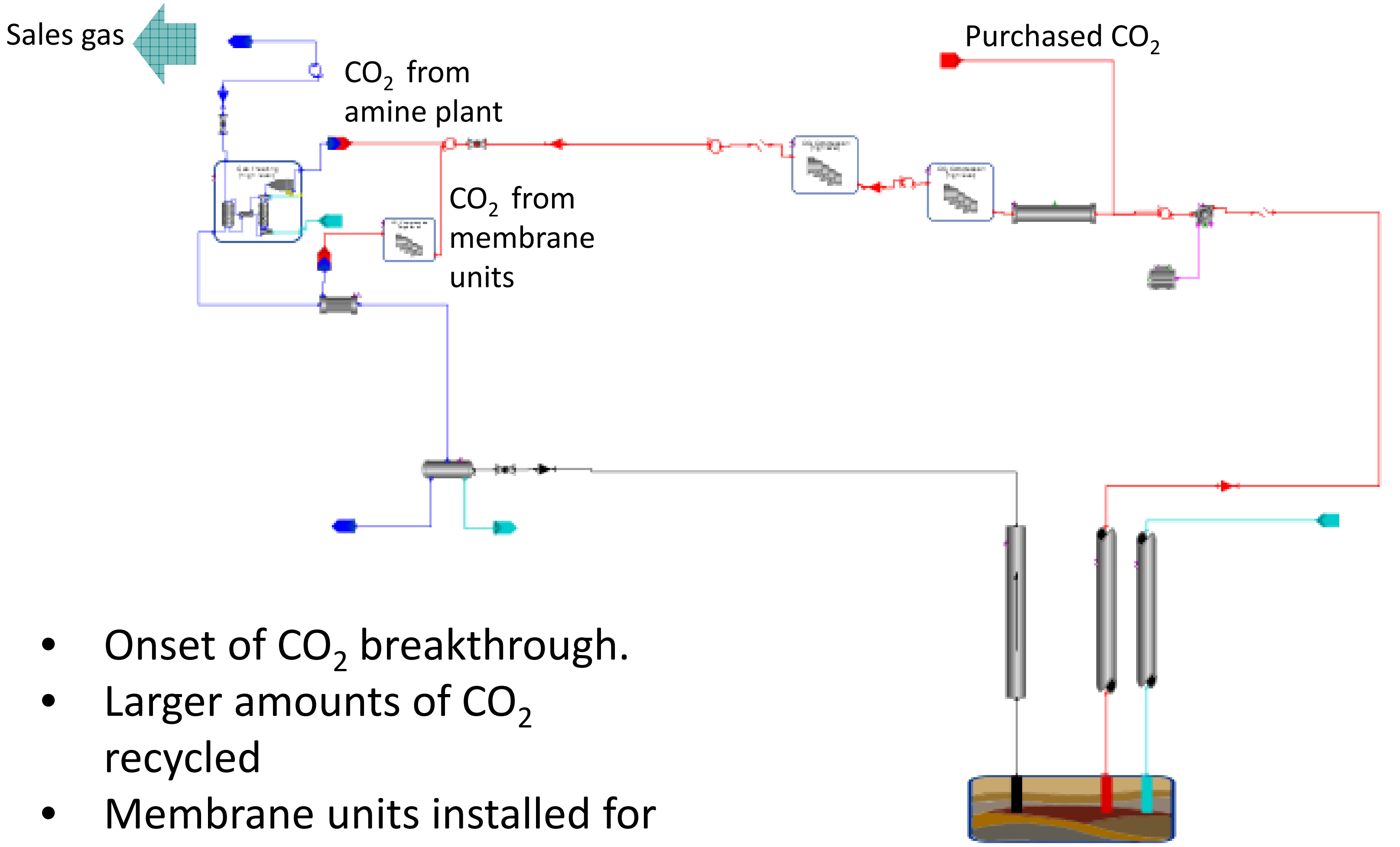
Phase 1 operations



- 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



Sales gas

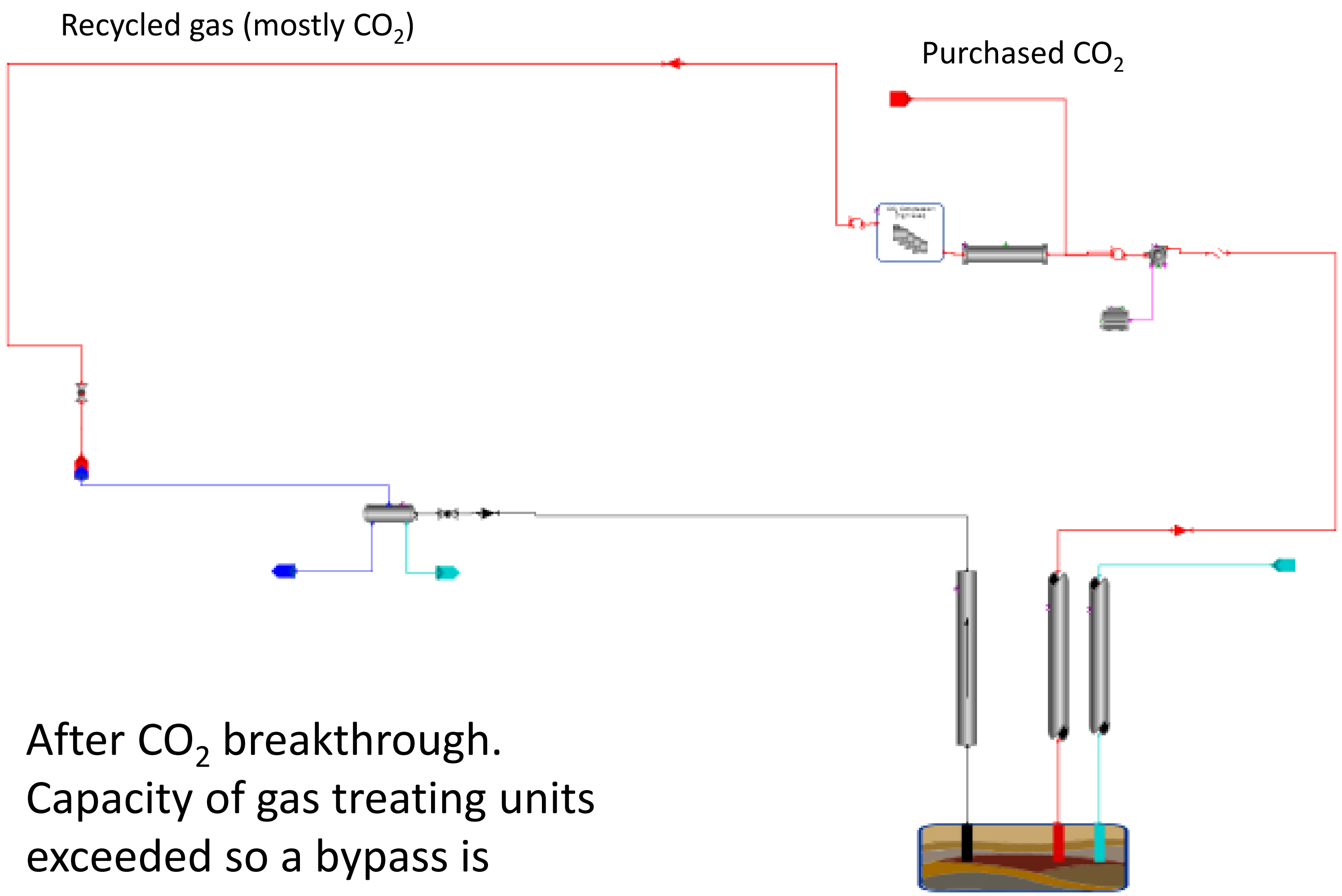
CO_2 from amine plant

CO_2 from membrane units

Purchased CO_2

- 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

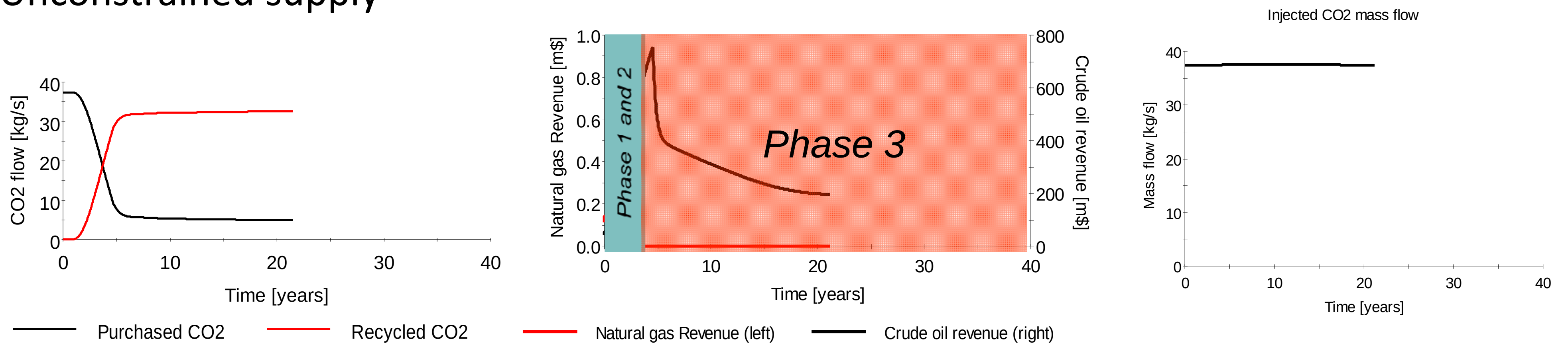
Phase 3 operations



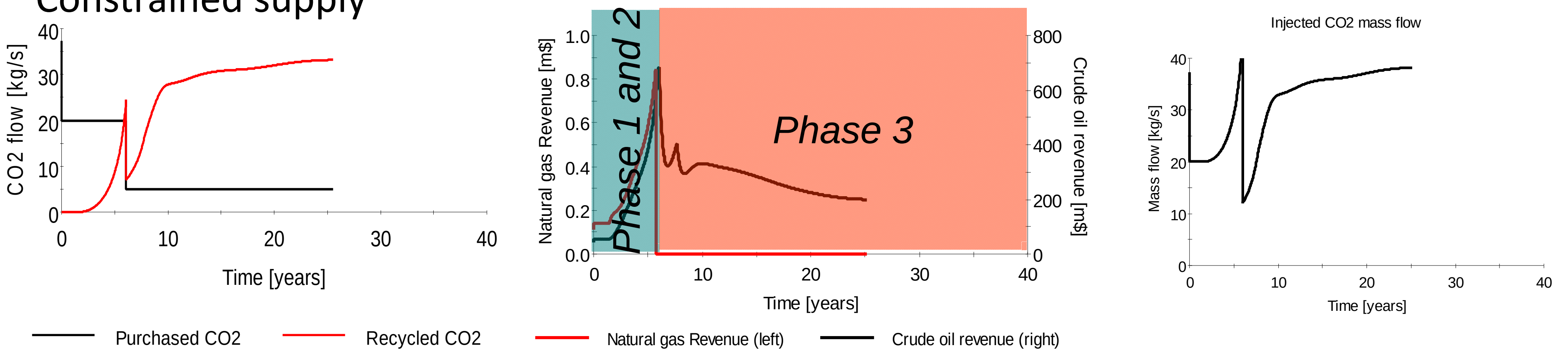
- After CO_2 breakthrough.
- Capacity of gas treating units exceeded so a bypass is established
- CO_2 purity of injected gas drops

Case Study results – comparing with CO_2 supply constraints

Unconstrained supply



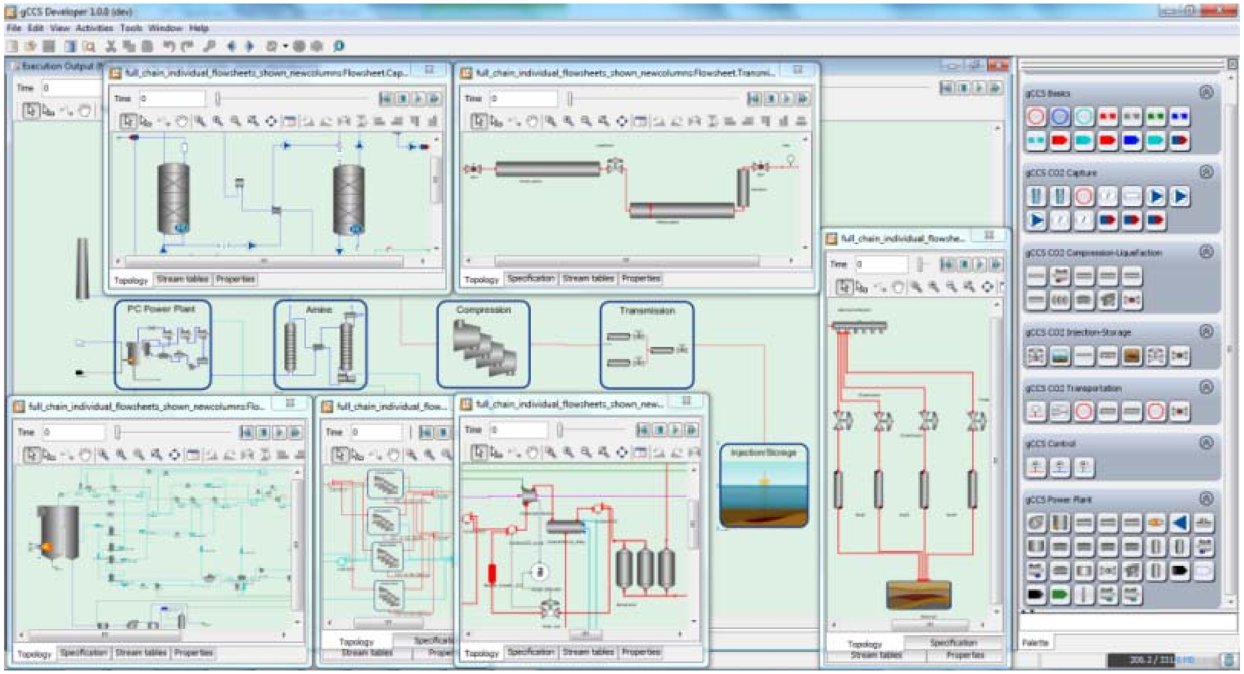
Constrained supply



Improving commercial viability

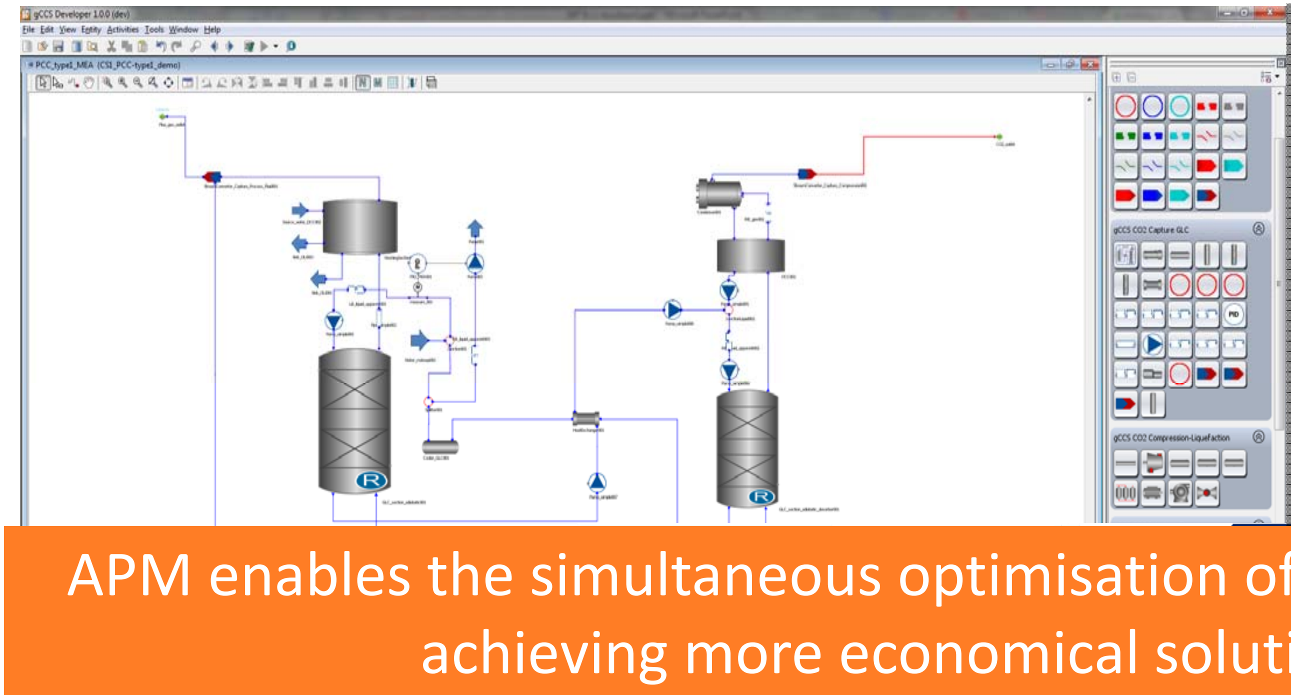
Cost reductions

- **System integration** is crucial
  - Assess heat integration options to reduce parasitic load
  - Identify opportunities to reduce cost of capture, e.g. use of let-down steam in post-combustion capture
  - Test alternative capture technologies and assess their suitability for retrofitting existing plants



Improving commercial viability

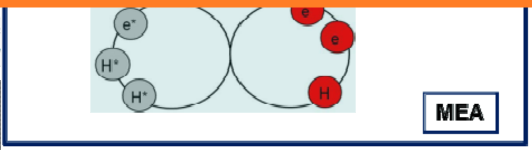
Cost reductions

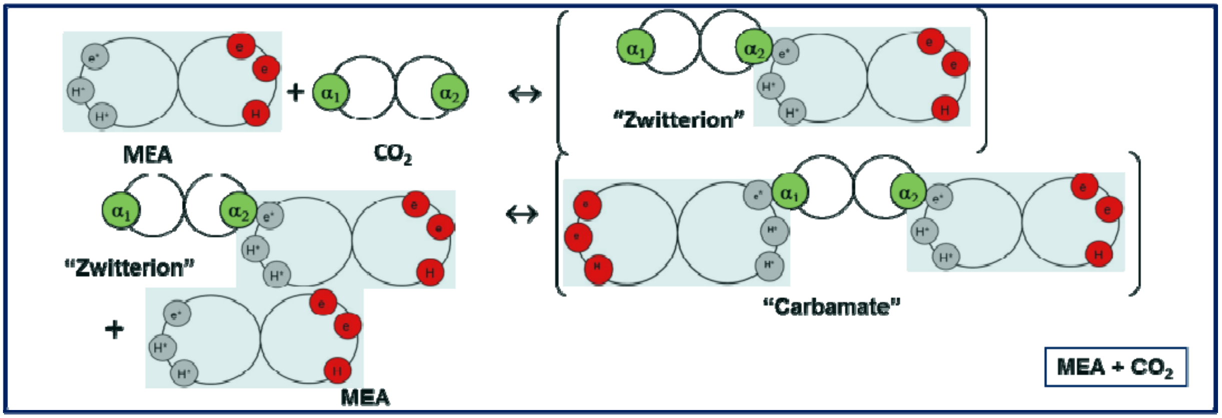


Process design
Configuration
Equipment size
Heat integration
…
Process operation
Solvent loading
Flowrates
Pressures, temperatures
…

APM enables the simultaneous optimisation of all these aspects achieving more economical solutions

Solvent design/ development
Screening of candidates
New molecules (group contribution method)
New mixtures

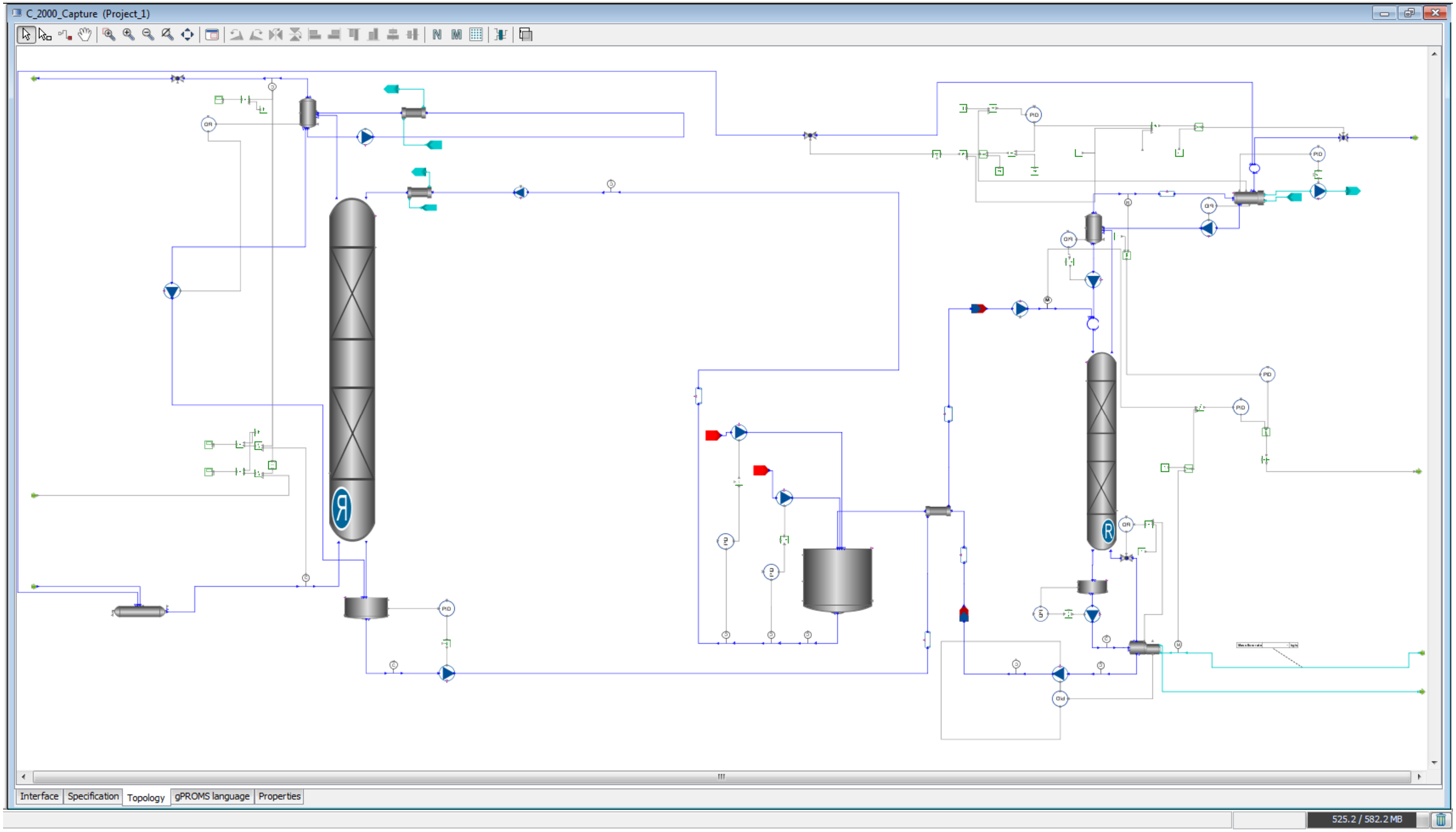




Improving commercial viability

Cost reductions

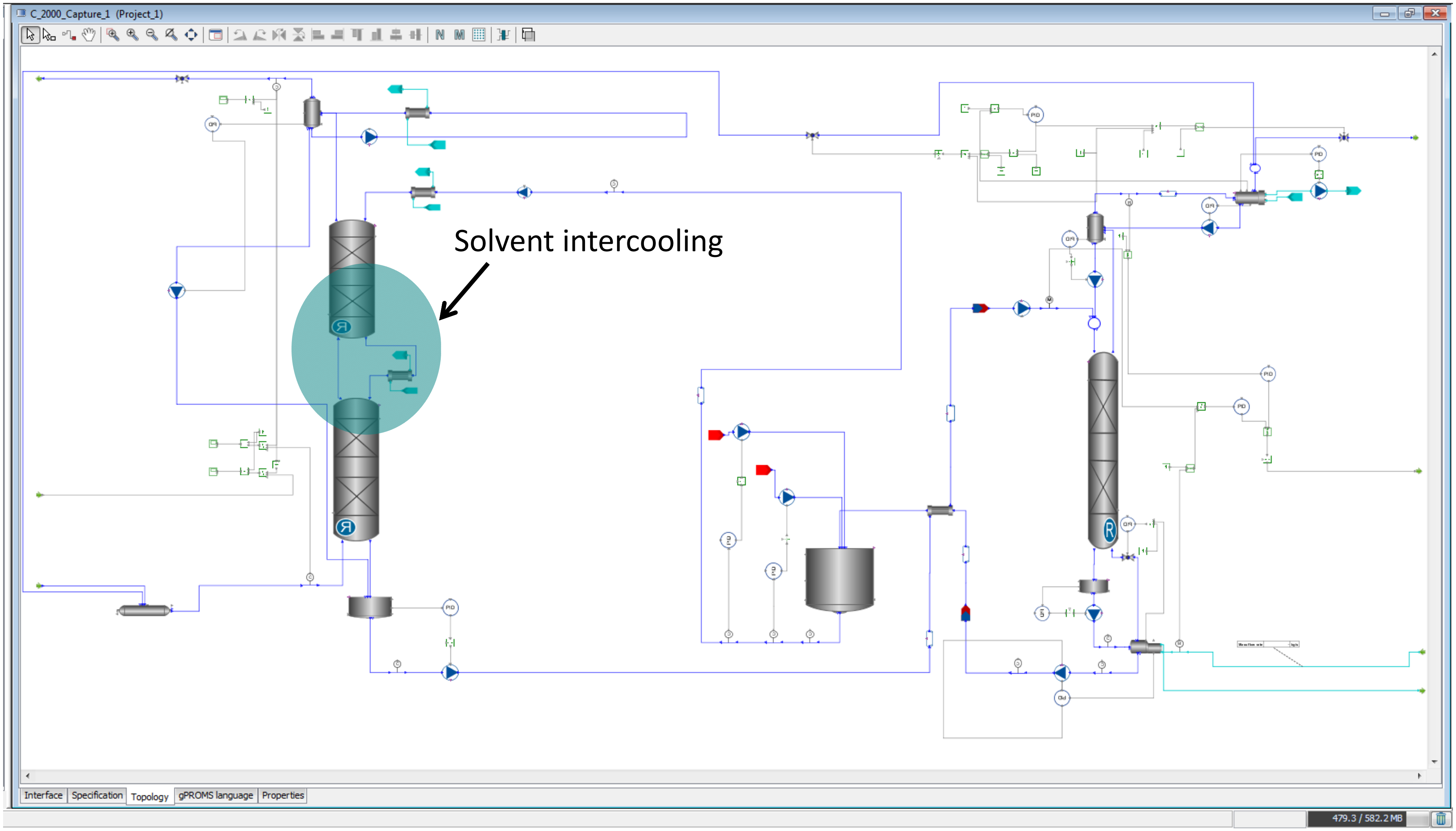
- Process design – alternative solvent-based PCC configurations



Improving commercial viability

Cost reductions

- Process design – alternative solvent-based PCC configurations

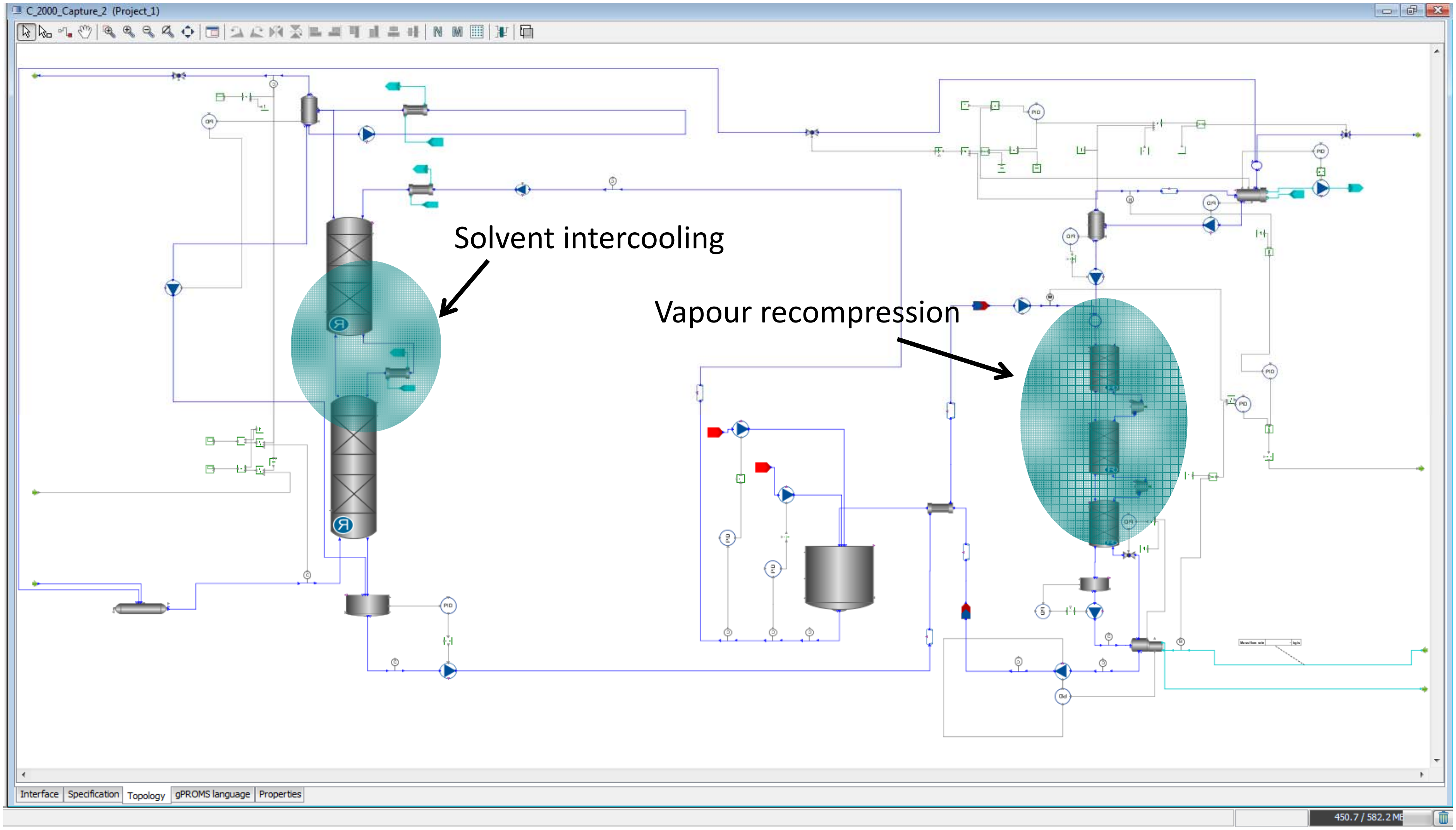


Solvent intercooling

Improving commercial viability

Cost reductions

- Process design – alternative solvent-based PCC configurations



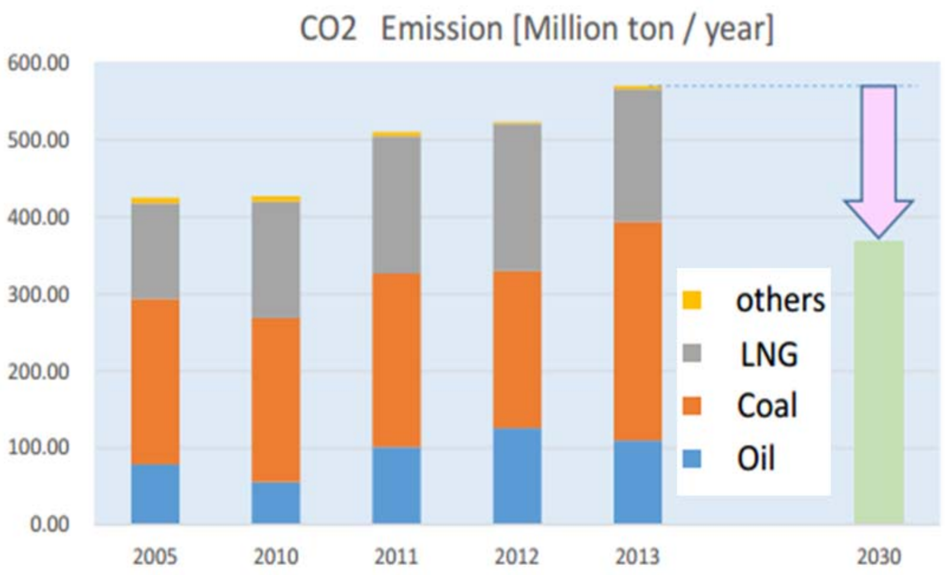
Solvent intercooling

Vapour recompression

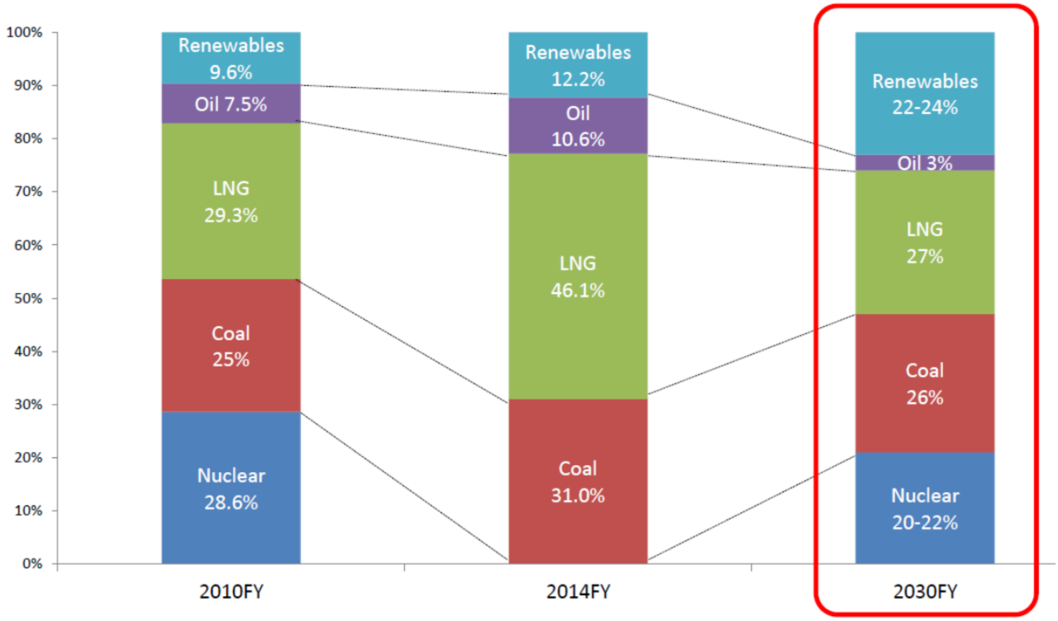
CCS in Japan

Plan for emissions reduction in Japan (I)

- 26% Total Emission Reduction from 2013 level
- Translates for the Power Generation sector to a reduction of 35% from 2013 level
- Reductions achieved primarily by switching from LNG/Oil/Coal plants to Nuclear & Renewables generation



quoted from materials of the Federation of
Electric Power Companies of Japan, issued in July 2015

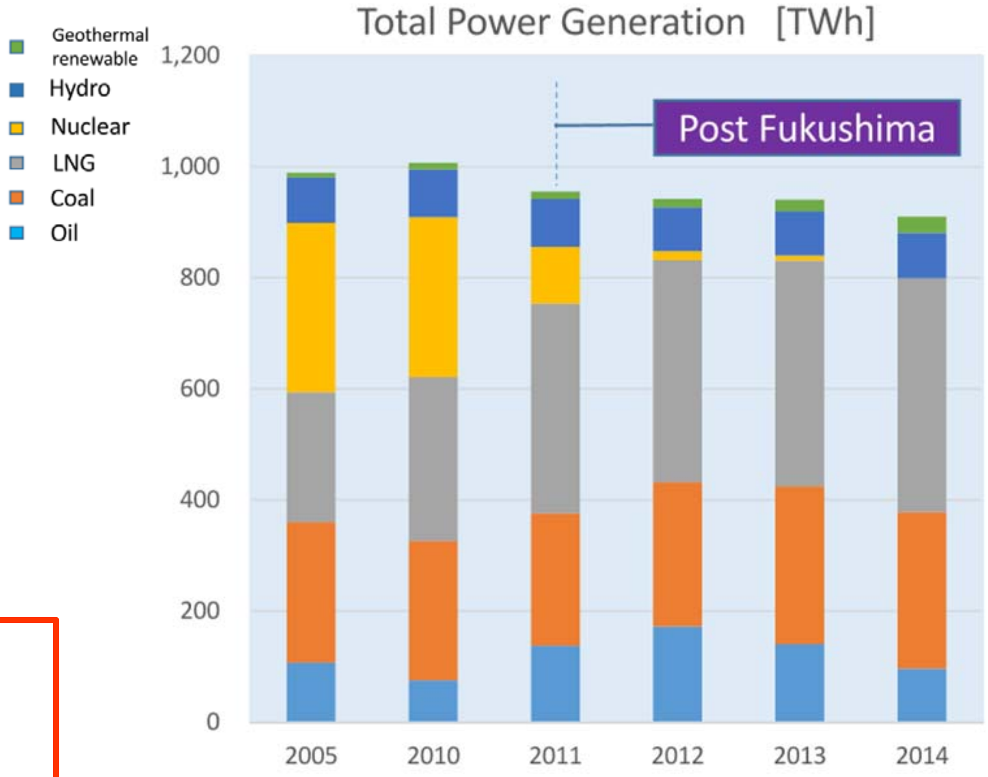


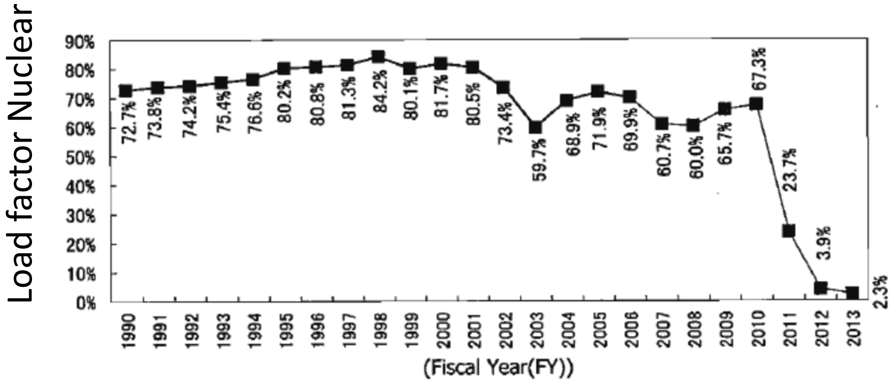
Source: Yamazaki, T., Director for Electricity Market Reform,
Ministry of Economy, Trade and Industry, July 2015

Uncertainty affecting the targeted reductions

- Public acceptance of nuclear power post-Fukushima
  - One nuclear power unit out of 44 restarted in Aug 2015
  - 8.75GW of coal-fired power plants planned

- Development of low-carbon fossil generation technologies
  - Efficiency increases in fossil fuel generation
  - Carbon Capture & Storage

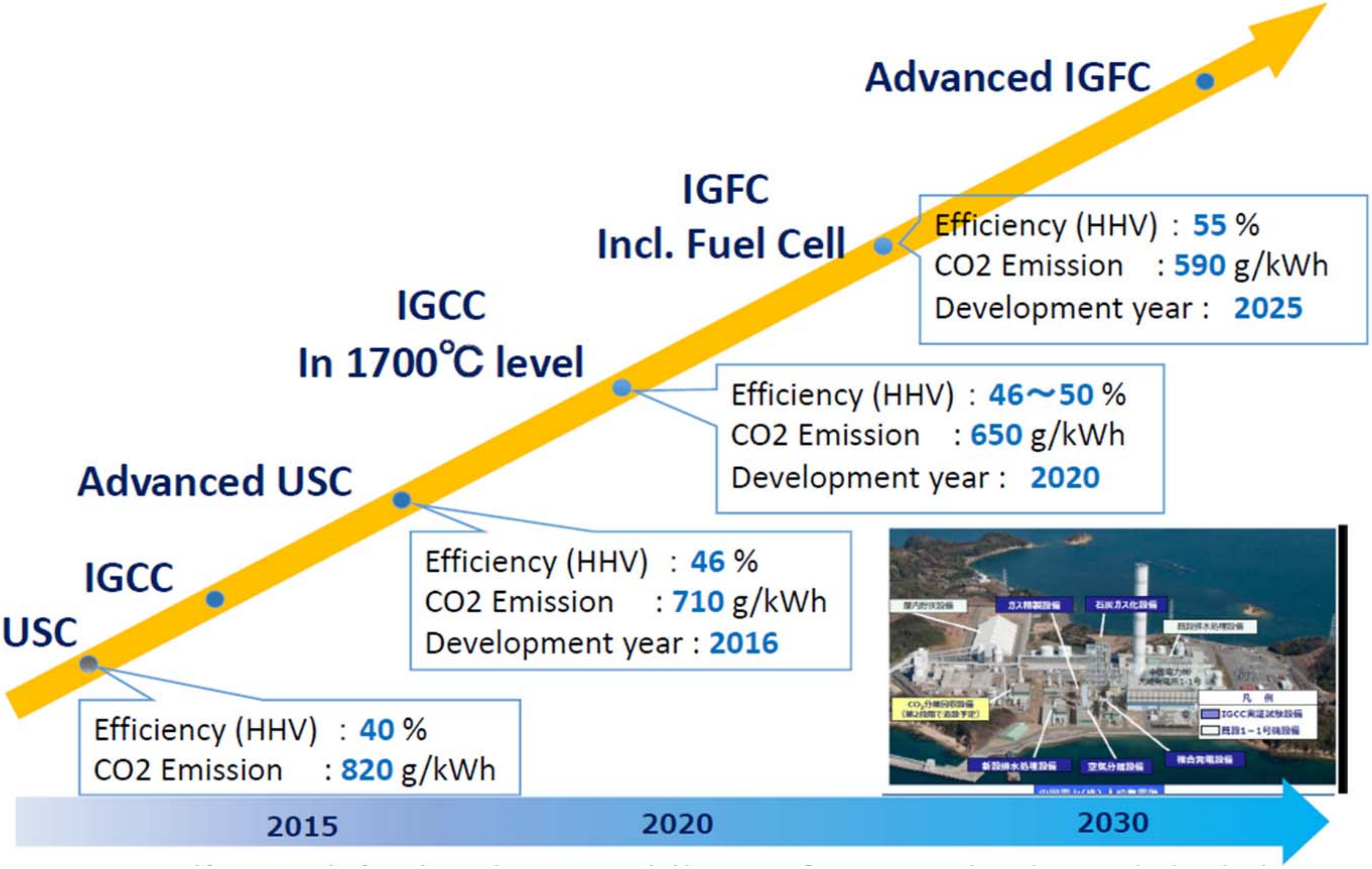




(Source) The Federation of Electric Power Companies of Japan

Plan for emissions reduction in Japan (II)

- Drive for higher efficiency in coal-fired power generation



Advanced IGFC

IGFC
Incl. Fuel Cell

Efficiency (HHV) : **55** %
CO2 Emission : **590** g/kWh
Development year : **2025**

IGCC
In 1700℃ level

Efficiency (HHV) : **46～50** %
CO2 Emission : **650** g/kWh
Development year : **2020**

Advanced USC

Efficiency (HHV) : **46** %
CO2 Emission : **710** g/kWh
Development year : **2016**

IGCC

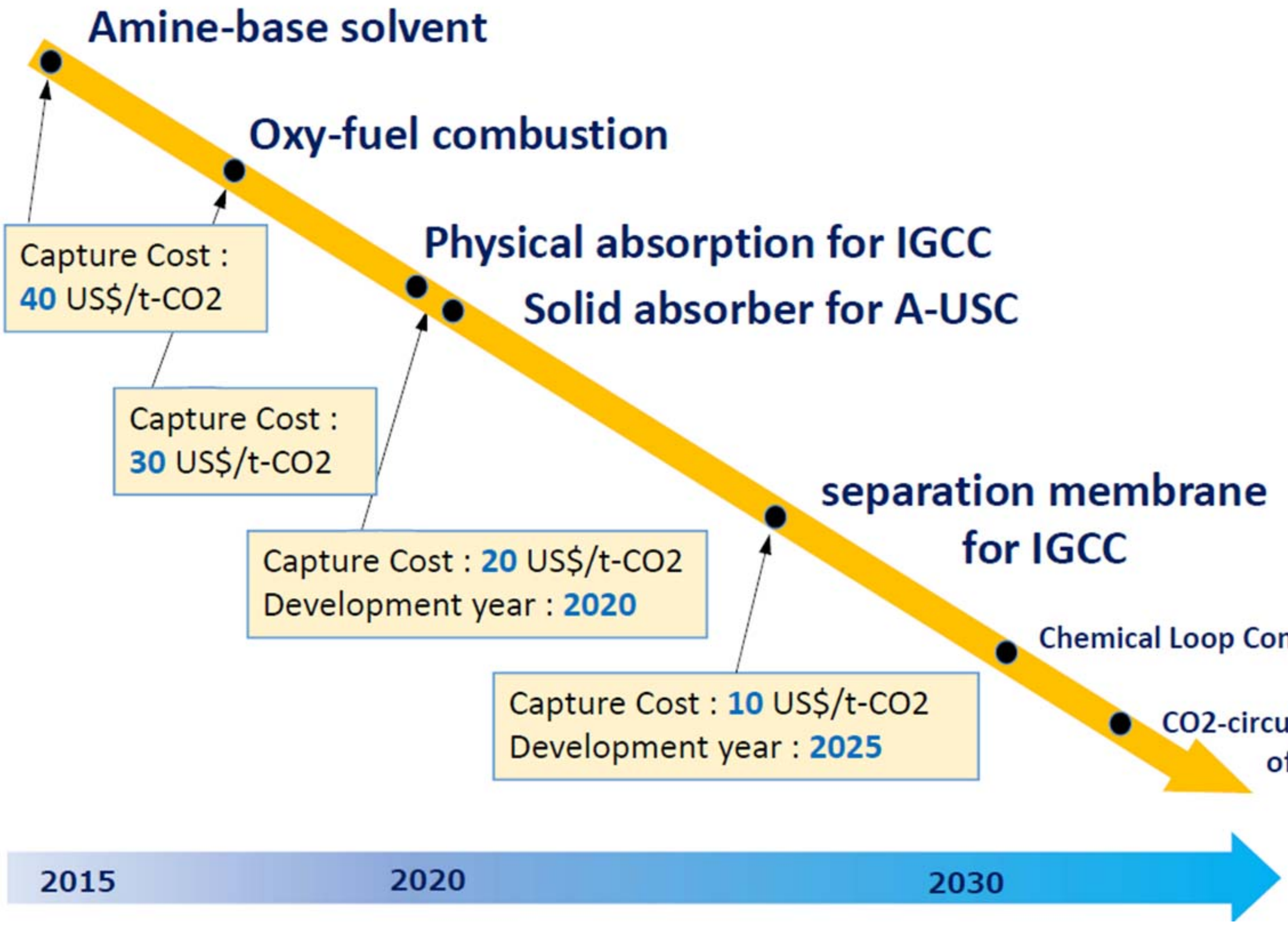
USC

Efficiency (HHV) : **40** %
CO2 Emission : **820** g/kWh

Source: Kawasaki, T. & Harada, M., Japan Coal Center, Sep 2015

Plan for emissions reduction in Japan (IV)

- Roadmap for CCS in Japan



Amine-base solvent

Oxy-fuel combustion

Physical absorption for IGCC

Solid absorber for A-USC

separation membrane for IGCC

Chemical Loop Combustion

CO2-circulated type of IGCC

Capture Cost : 40 US$/t-CO2

Capture Cost : 30 US$/t-CO2

Capture Cost : 20 US$/t-CO2
Development year : 2020

Capture Cost : 10 US$/t-CO2
Development year : 2025

Source: Kawasaki, T. & Harada, M., Japan Coal Center, Sep 2015

Plan for emissions reduction in Japan (VI)
Challenges for CCS: Cost

- Outlook 2030 – there is hope!
  - Figures from Ministry of the Environment in Japan are equally optimistic

				Electricity Cost [US$/kWh]		
Type	**Generating Capacity [MW]**	**Transport Distance [km]**	**CCS Cost [US$/t-$CO_2$]**	**Generation**	**CCS**	**Total**
Super Critical Pressure Coal-Fired (SC)	750	185	90	0.085	0.086	0.172
		600	97		0.093	0.179
		970	103		0.099	0.185
Ultra Super Critical Pressure Coal-Fired (USC)	750	185	91	0.079	0.075	0.154
		600	99		0.080	0.160
		970	105		0.086	0.165
Integrated Gasification Combined Cycle (IGCC)	750	185	78	0.099	0.073	0.172
		600	85		0.079	0.179
		970	91		0.085	0.184
Natural Gas Combined Cycle (NGCC)	750	185	124	0.092	0.045	0.138
		600	131		0.047	0.140
		970	137		0.050	0.142

Source: Sekiya, T., Director Low-Carbon Society Promotion Office,
Ministry of the Environment (MOE), Jan 2016
* Exchange rate: USD/JPY = 100

Challenges for CCS: Cost

- How to achieve those cost reductions…
  - with only limited experience of large-scale integrated projects?
    (so far only SaskPower's Boundary Dam)
  - while making the most efficient use of technology development funds?
    (e.g. by supporting most promising technologies)

System- and process modelling is one of the key ingredients for success