INTERNATIONAL FORUM ON RECENT DEVELOPMENTS OF CCS IMPLEMENTATION

Session 3: Process Optimisation and Techno-economic Considerations

26st March, 2015

Authors:

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CCS System Modelling

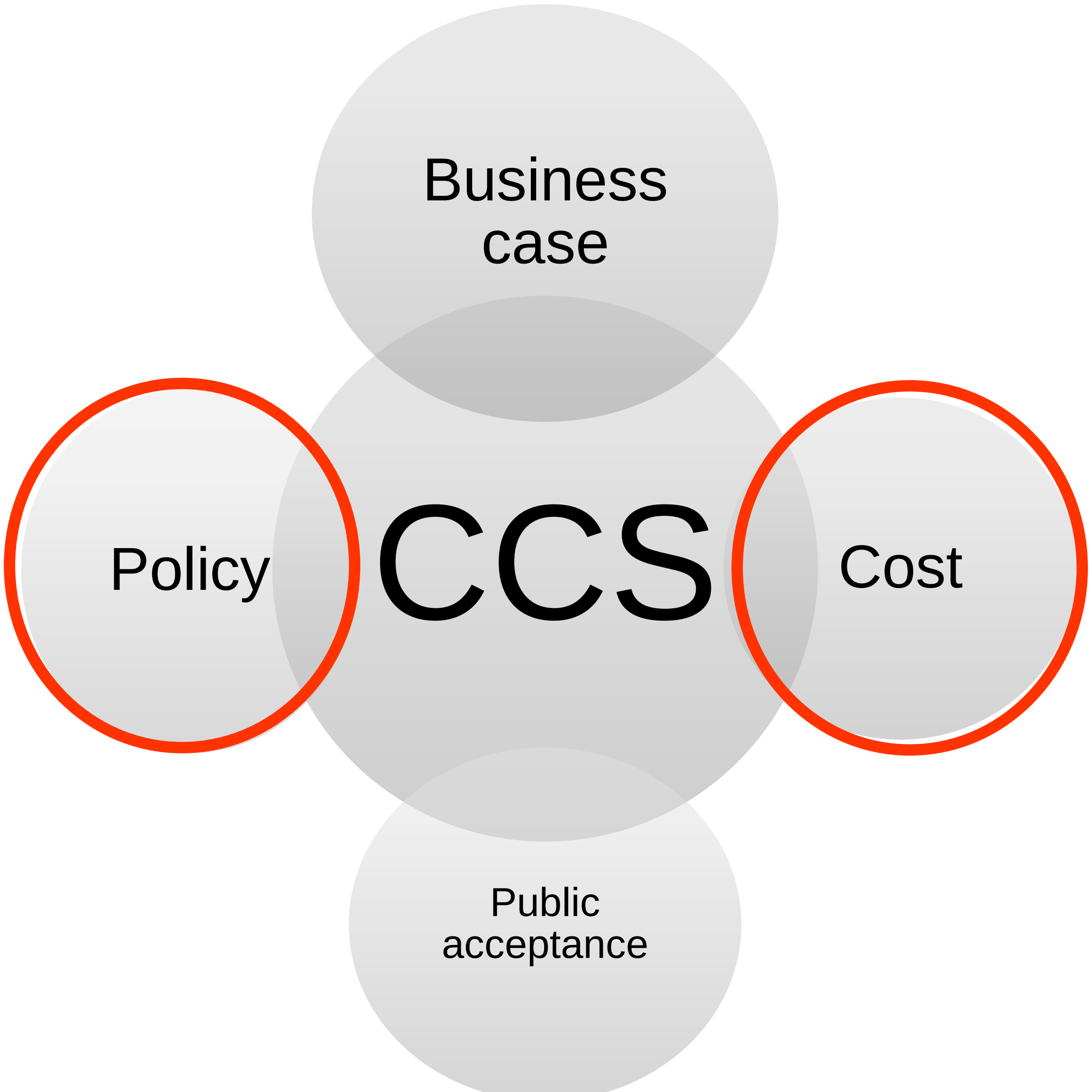
Impact of power plant flexibility on CCS networks

Mario Calado – Consultant Engineer

Overview

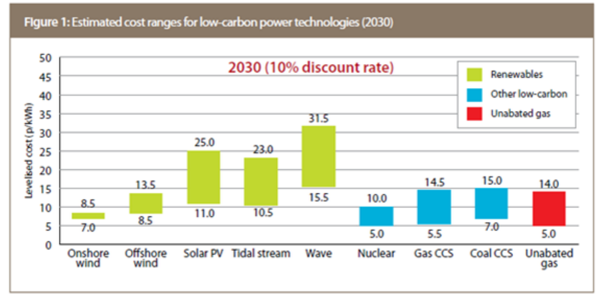
- Challenges to the commercial viability of CCS
- Systems modelling for CCS
- Case Study – CCS networks
  - Why CCS networks?
- Conclusions

Challenges to the commercial viability of CCS



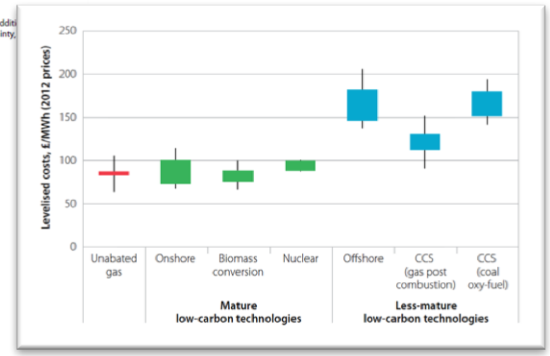
Cost

- Current cost of abatement of CCS too high with respect to other low-carbon technologies/ renewables

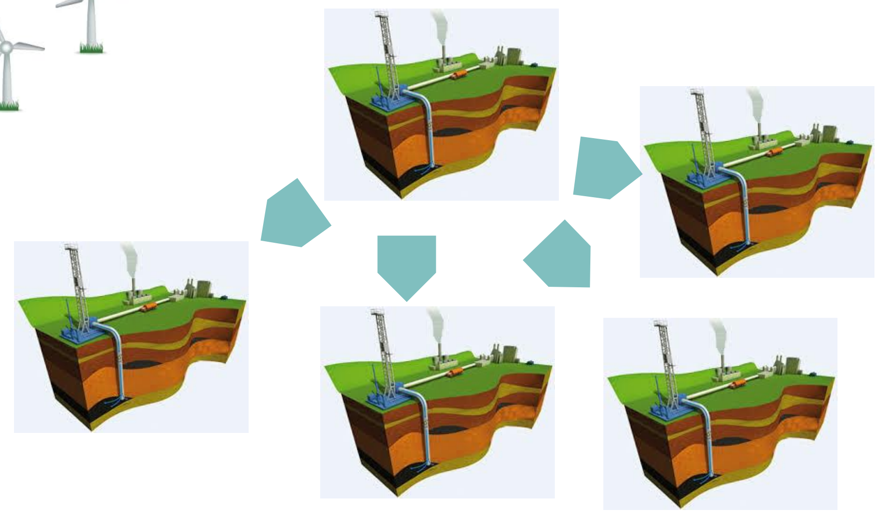


Source: CCC calculations, based on Mott MacDonald (2011) *Costs of low-carbon generation technologies.*

Note(s): 2010 prices, using 10% discount rate, for a project starting construction in 2030. Unabated gas includes a carbon price. Excludes additi system costs due to intermittency, e.g. back-up, interconnection. These ranges take into account capital cost and fuel/carbon price uncertainty, do not cover all possible eventualities (e.g. they assume that CCS is successfully demonstrated).

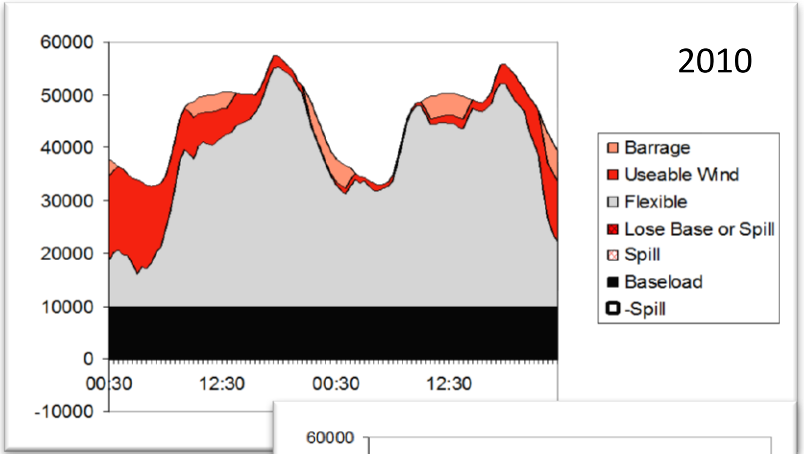


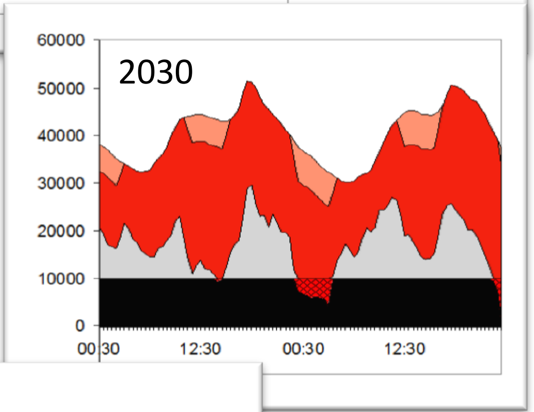
- Substantial challenges in moving from FOAK to NOAK owing to "uniqueness" of each CCS project
  - CO_2 sources
  - Topography / pipeline layout
  - CO_2 stores

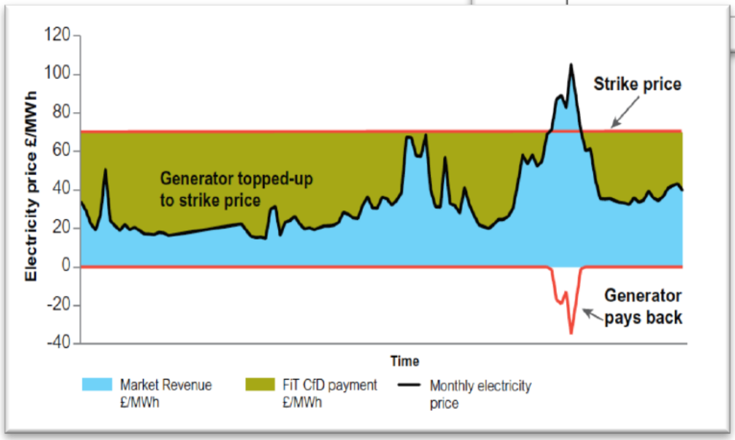


Policy – creating an "even playfield"

- Intermittency of renewables needs to be balanced
- Benefits of flexibility in generation of 'clean electricity' through CCS
- How to 'reward' this flexibility in generation?







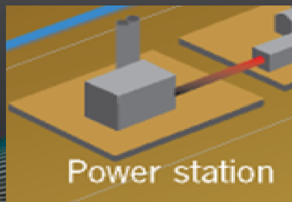
Why is dynamic simulation of CCS important?

- To achieve carbon reduction targets in the UK, electricity must be effectively decarbonised by ~2030
- Therefore to meet these targets fossil plants must have CO_2 capture and sequestration to eliminate their emissions
- Fossil plant currently provides the on-demand flexible generation to meet changes in demand over the day
- Inflexible intermittent generation (e.g. wind & solar) means fossil plant will be required to change load around less predictable changes in green supply

Source: e·on

CCS chains

Existing technology in a new configuration



Grid demand
Flexibility
Efficiency
Fuel mix
Trip scenarios

Tools
PROATES
GTPro
Ebsilon
Dymola
Aspen Plus
…

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

Tools
gPROMS
PROMAX
Aspen Plus
…

Optimal operating point
Efficiency
New design
Impurities
Control
Safety

Tools
Various in-house

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

Tools
OLGA
PIPESIM
…

Government
Policy
Strategic
Infrastructure development
H&S

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

Tools
OLGA
Prosper/Gap
…

…new technology required to address the new challenges posed by integrated CCS system

The CCS System modelling Tool-kit Project

2011-2014

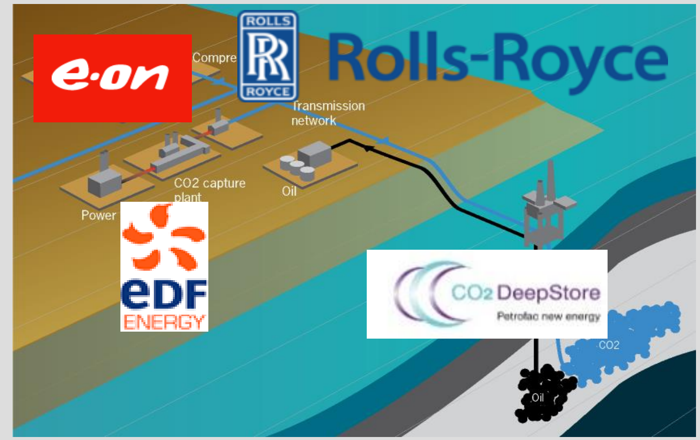
- **Energy Technologies Institute (ETI)**

Shell, CATERPILLAR, e·on, Rolls-Royce, EDF ENERGY, bp — corporate

BIS, Department of Energy & Climate Change, EPSRC, Technology Strategy Board — public institutions

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

gCCS



PSE — **gPROMS modelling platform & expertise**

E4tech — Project Management

System-wide modelling
Key enabling technology for CCS

- Explore **complex decision space** rapidly based on high-fidelity, technically realistic models
  - resolve own technical and economic issues
  - take into account upstream & downstream behaviour
  - Manage **interactions** and **trade-offs**
- **Evaluate technology** – existing and next-generation
  - judge relative merits of emerging technologies
  - support consistent, future-proof choices
- **Integrating platform** for
  - working with other stakeholders in chain
  - collaborative R&D, working with academia

Case Study: CCS network

Why is CCS networks?

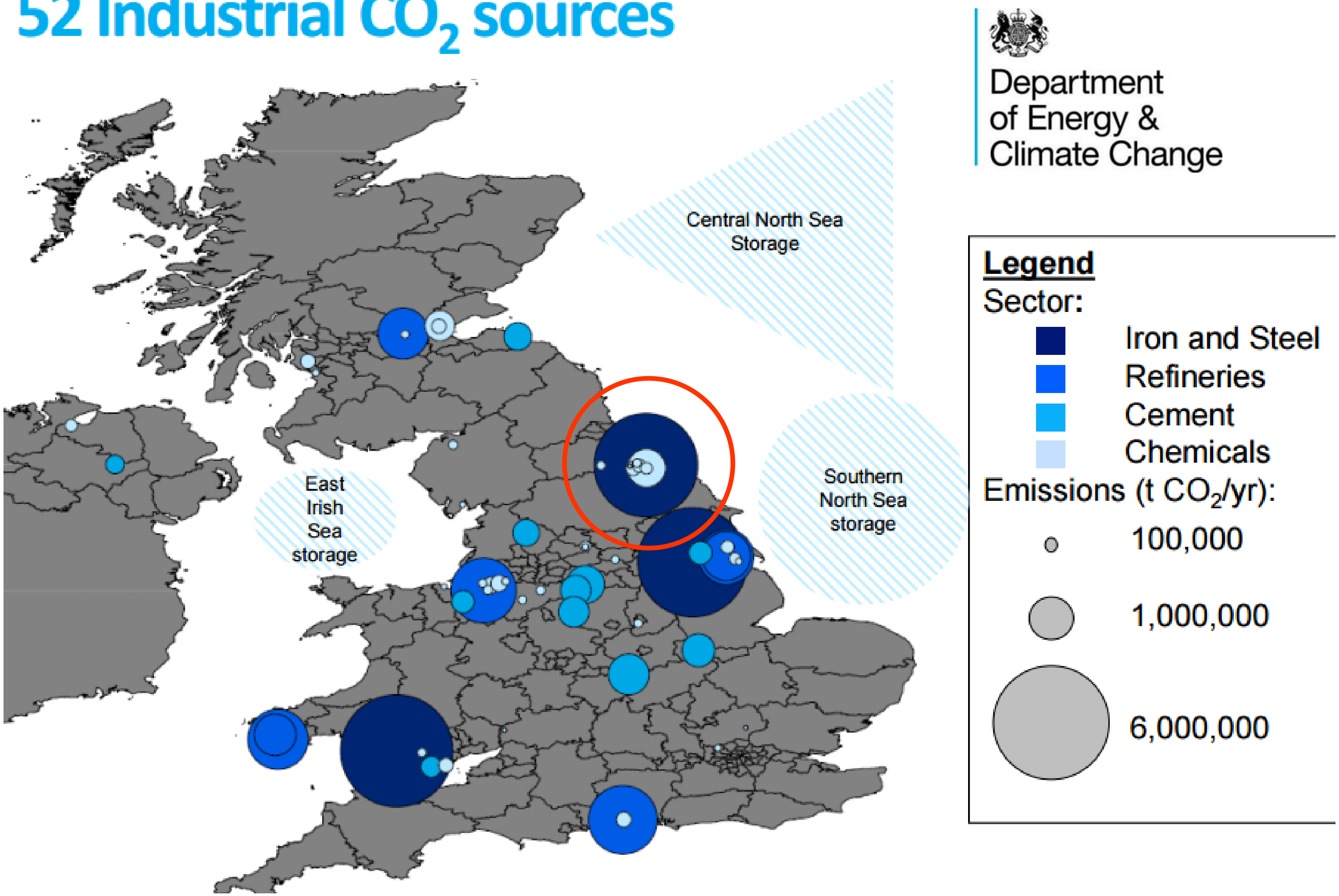
CCS in Process Industries- State-of- the-Art and Future Opportunities

A Joint Workshop organized by IEA Greenhouse Gas R&D Programme (IEAGHG) and IEA Industrial Energy-related Technologies and Systems (IETS)

10th – 11th March, 2015
Lisbon, Portugal

Why is CCS networks?

52 Industrial CO_2 sources

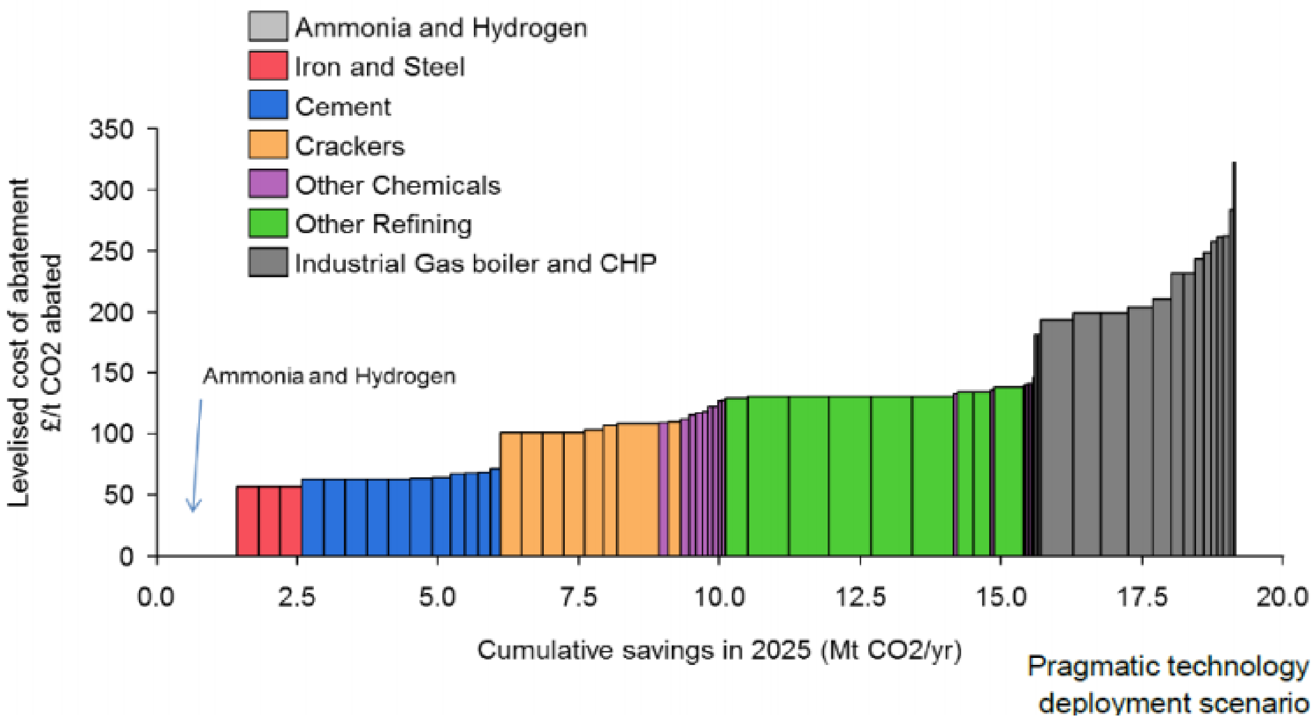


- Industrial sources typically too small for dedicated pipeline for CO_2 transport
- Need for pipeline network for industrial clusters, like Tees Valley

Source: "Industrial CCS & CCU - View from the UK": IEAGHG workshop in "CCS in Process Industries State-of- the-Art and Future Opportunities" – 10/03/2015 Lisbon (Portugal)

Why is CCS networks?

MACC curve of capture technologies

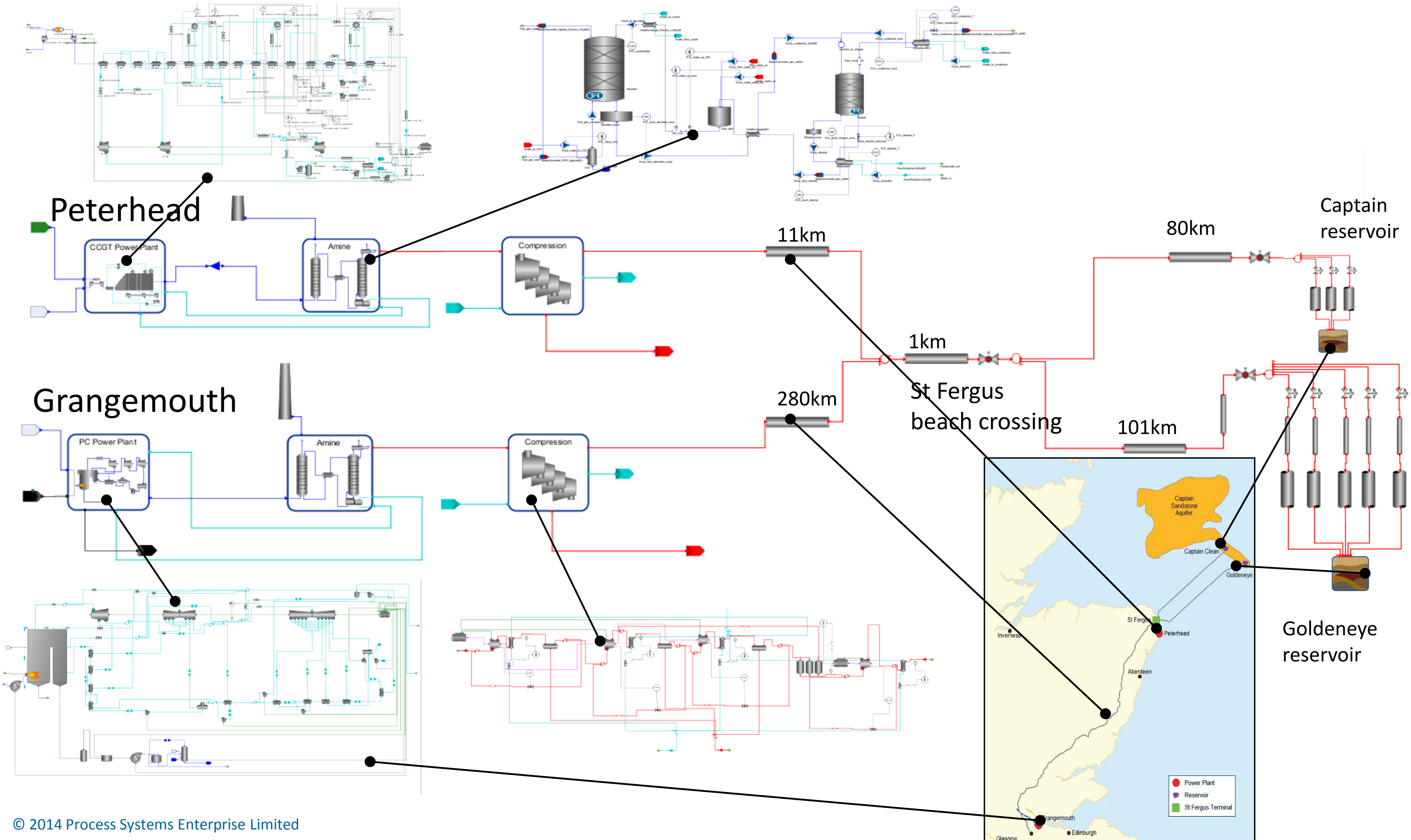


Department of Energy & Climate Change

- Capture cost significantly varies with CO_2 source
- Greatest cost reduction potential relies in CO_2 transport network optimisation

Source: "Industrial CCS & CCU - View from the UK": IEAGHG workshop in "CCS in Process Industries State-of- the-Art and Future Opportunities" – 10/03/2015 Lisbon (Portugal)

CCS network configuration



System overview

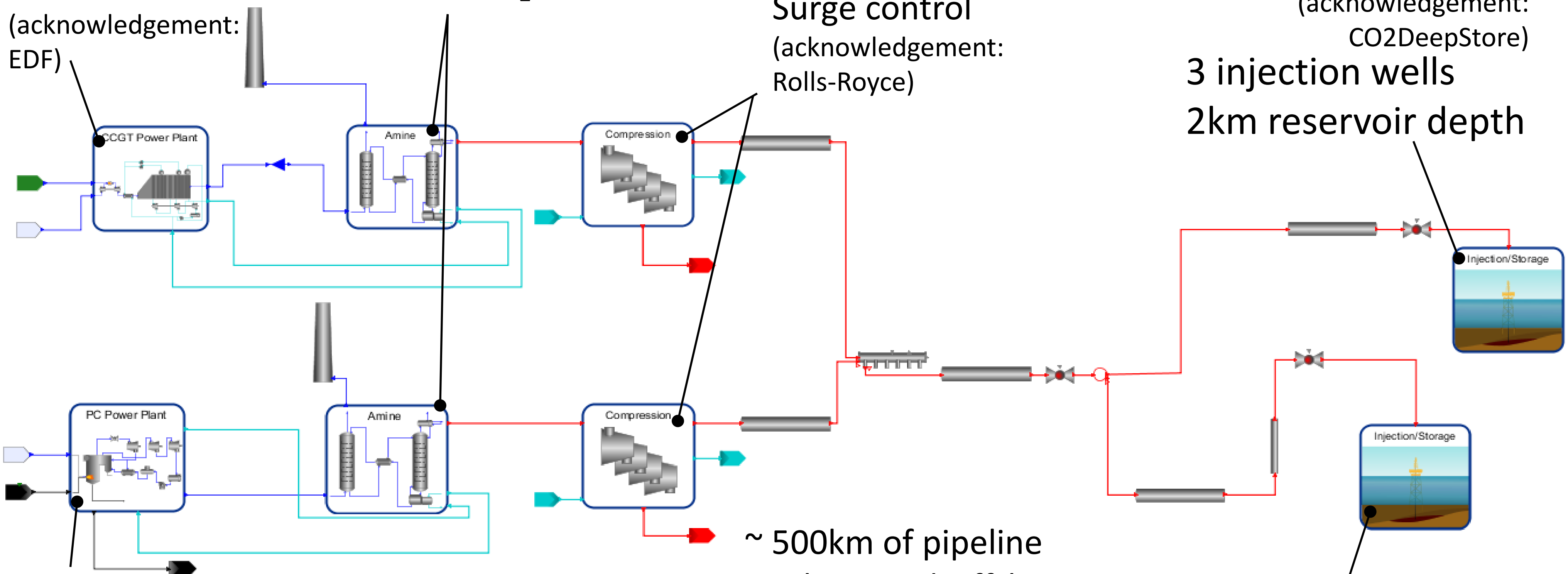
~740MWe
Combined Cycle
Gas Turbine
(acknowledgement: EDF)

Chemical absorption
MEA solvent
90% CO_2 capture

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

Offshore dense-phase injection
(acknowledgement: CO2DeepStore)

3 injection wells
2km reservoir depth



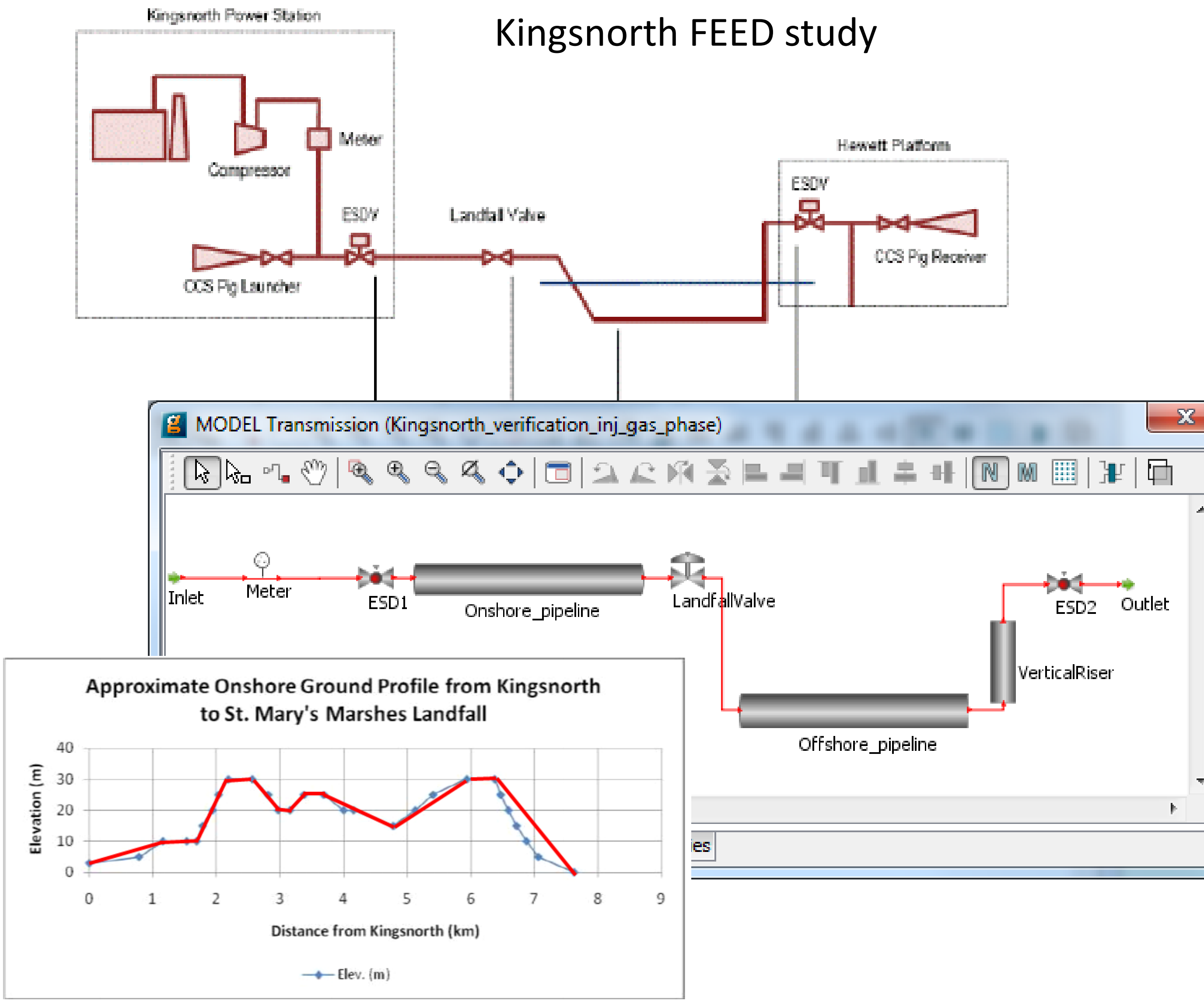
~ 500km of pipeline
Onshore and Offshore

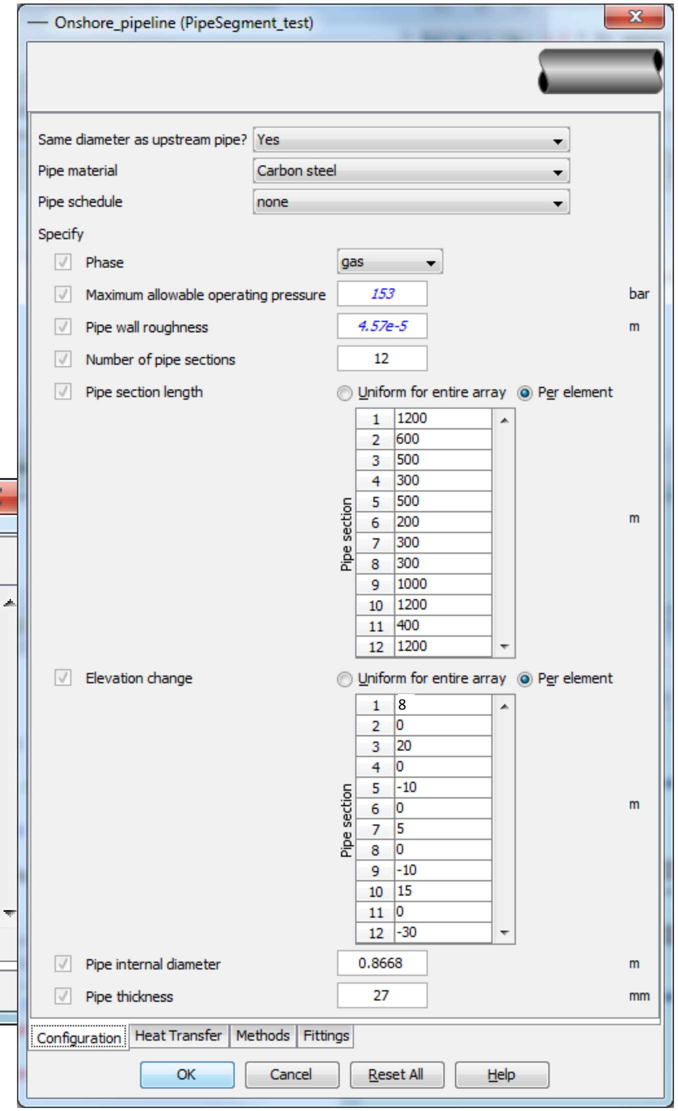
5 injection wells
2.6km reservoir depth

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

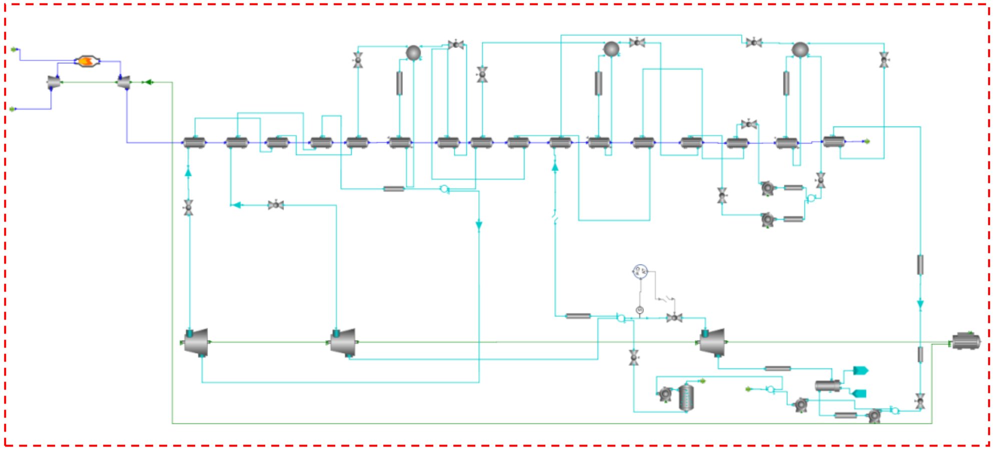
CCS network configuration – Pipeline topography

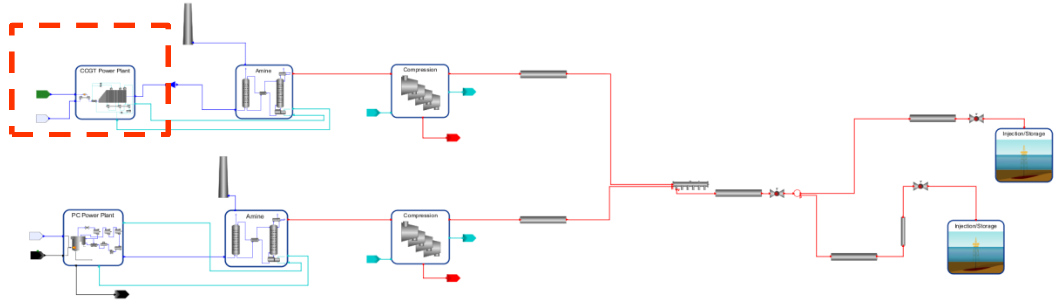
Kingsnorth FEED study

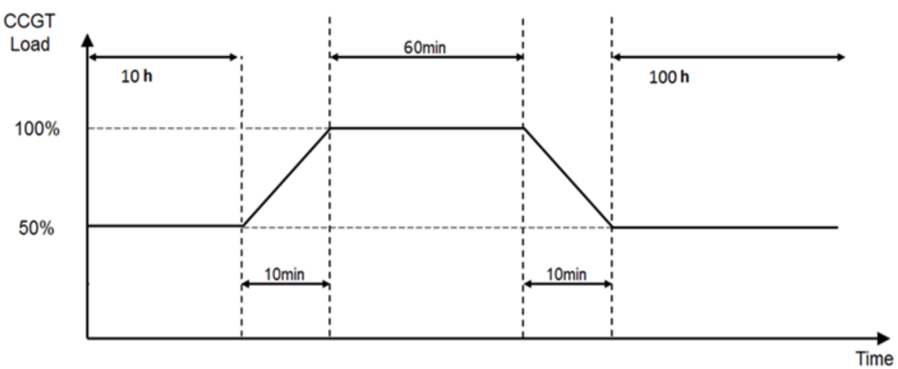


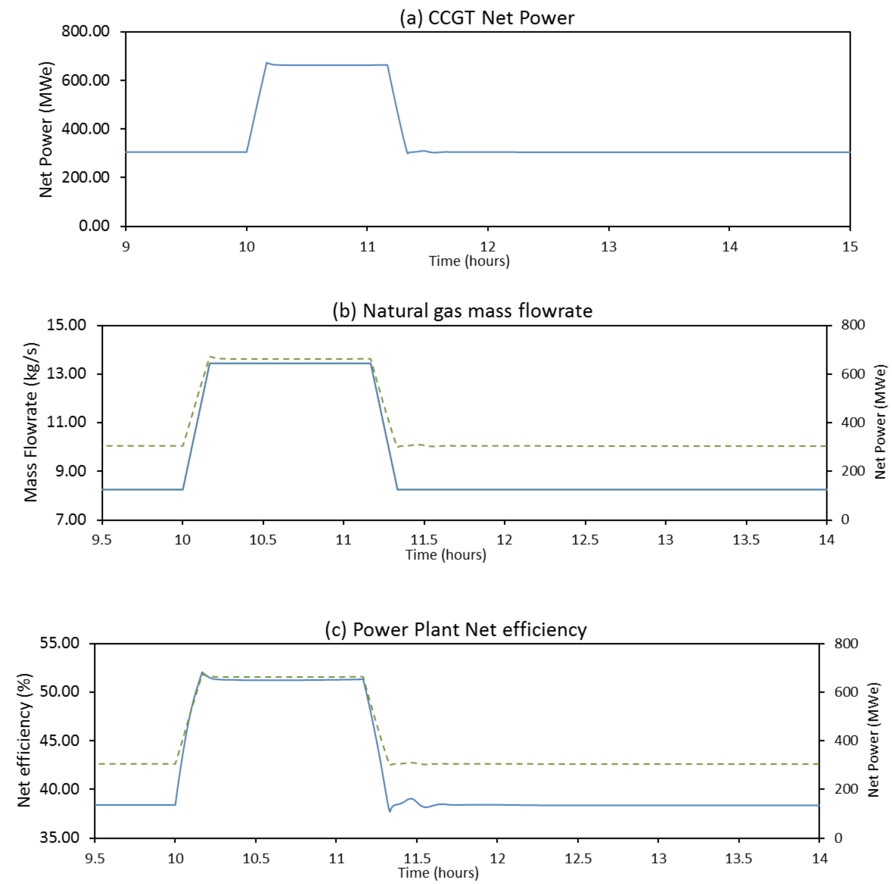


Load disturbance in CCGT

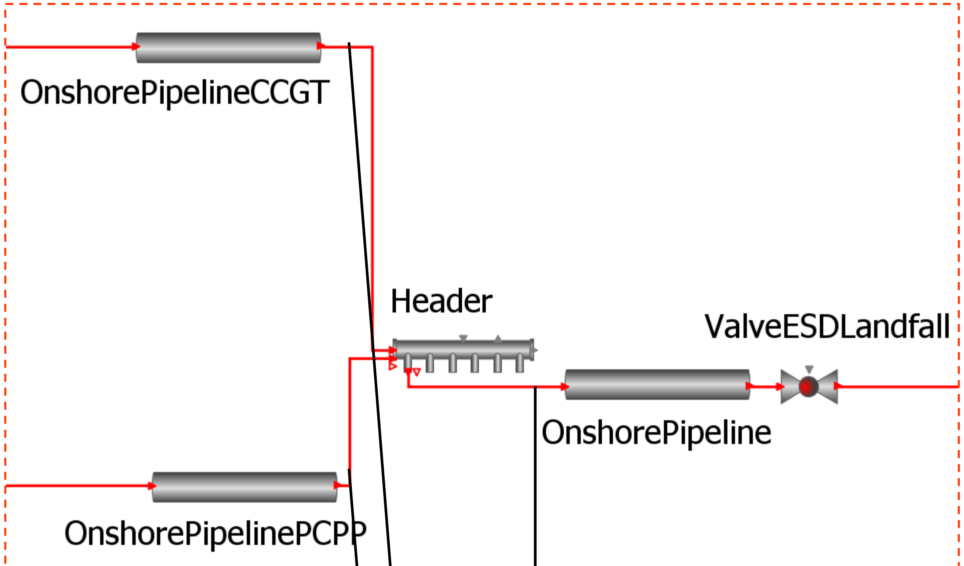


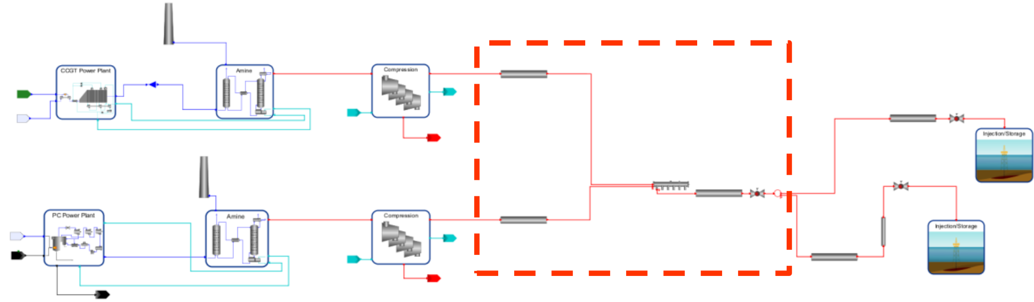






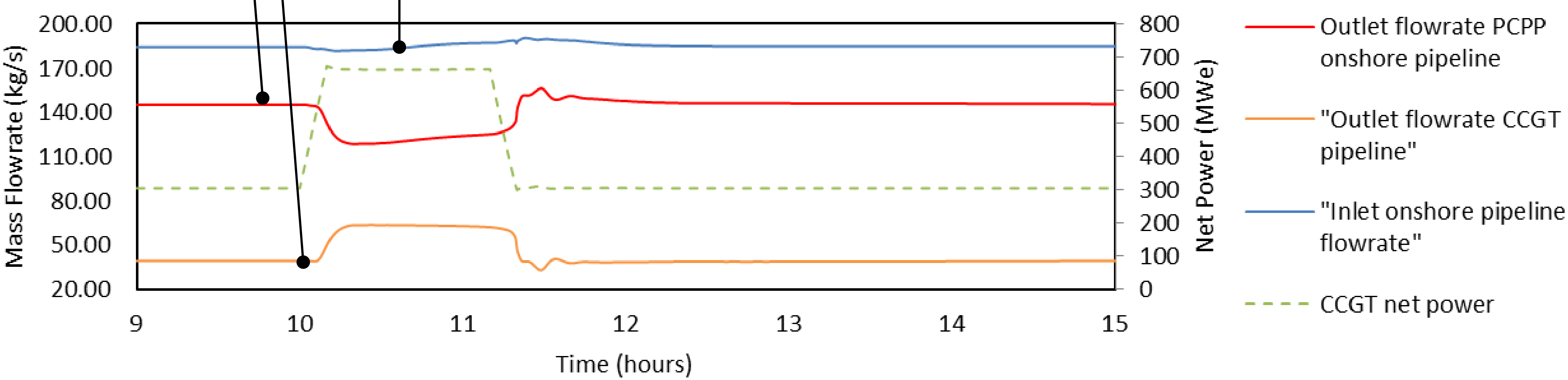
Load change effects



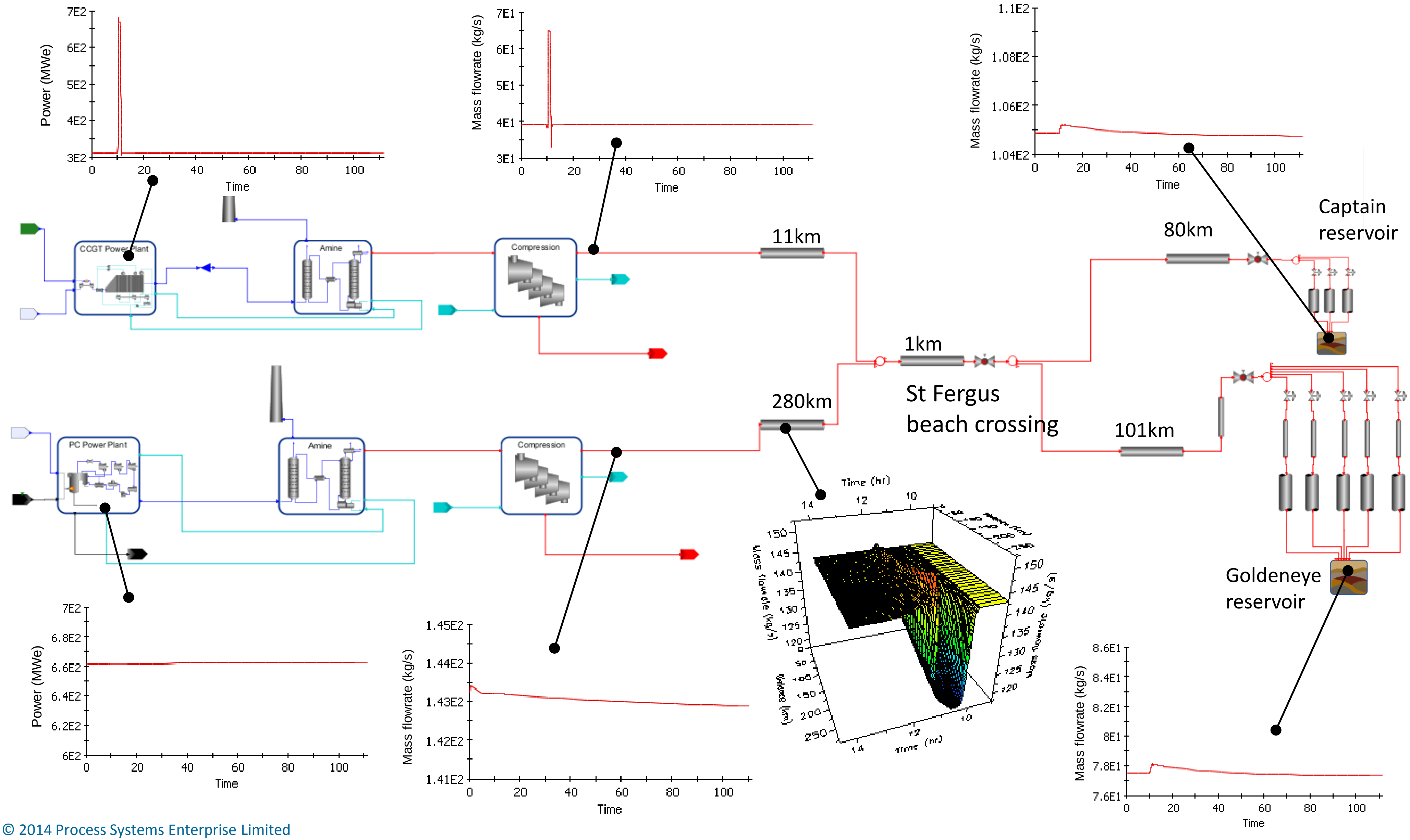


An increase of about 62% in the CCGT onshore pipe flowrate only increases 1.8% the inlet flowrate of the onshore pipe

(e) Onshore pipeline flowrate



Dynamic analysis of CCS Networks



Other commercial applications

Carbon Capture Journal

News | Events | Magazine | Social Network | Videos

gCCS system modelling technology used for Shell Peterhead project

Aug 10 2014

Shell Peterhead CCS project will be the first commercial UK user of PSE's gCCS systems modelling environment for whole-chain CCS design and operation.

gCCS is the world's first process modelling environment for support of design and operating decisions across the full CCS chain, from power generation through CO2 capture, compression and transport to injection. It is specifically designed to allow developers across the chain to address issues of interaction and interoperability between different chain components.

The gCCS software will be used during the Front-End Engineering Design (FEED) study phase of Shell's Peterhead CCS demonstration project to provide insight into the transient behaviour of the amine-based capture unit, and its effect on operations when integrated within the full system. In particular it will help to demonstrate the flexibility of the capture process design within the wider CCS chain through simulation of normal and off-design operational scenarios, and thus help reduce technology risks in this first-of-a-kind CCS project.

Alfredo Ramos, PSE's head of Power & CCS and leader of the development, said, "this is precisely the type of large-scale CCS application that gCCS was developed to support. For the first UK commercial use, we are very pleased to see it being used on such an important development."

element energy

CARBON COUNTS

PSE

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

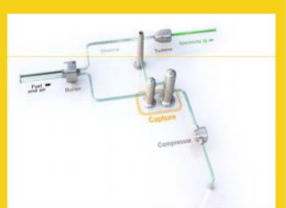
Element Energy Limited
20 Station Road

Cambridge CB1 2JD

Tel: 01223 852 496

CCS FLEXIBILITY

amine-based CO2 capture unit dynamics for CCGT applications



Nicola Ceccarelli
Modeling & Optimization Engineer

ELSEVIER

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GHGT-12

Flexibility of low-CO_2 gas power plants: Integration of the CO_2 capture unit with CCGT operation

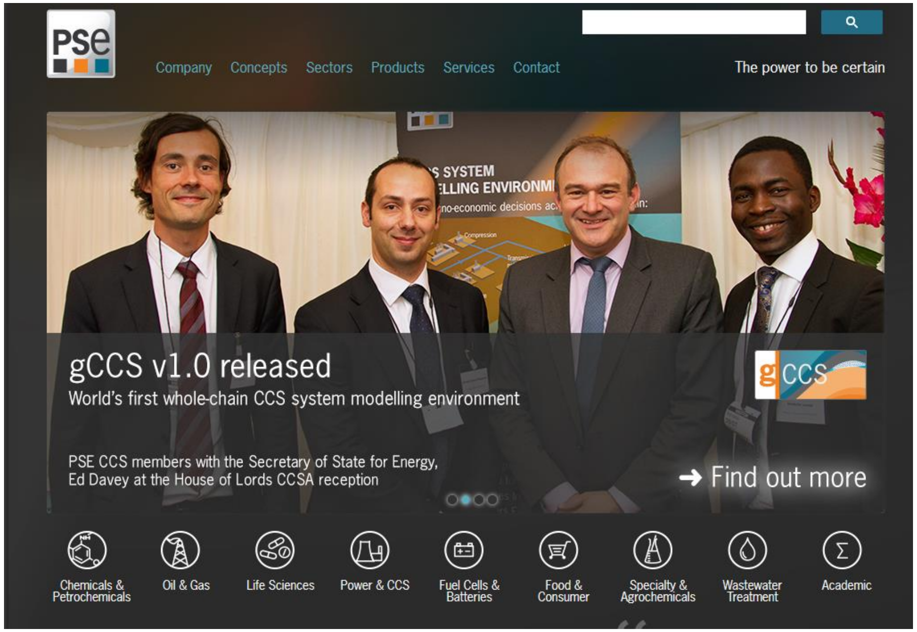
Nicola Ceccarelli, Monica van Leeuwen, Tanja Wolf, Peter van Leeuwen, Rick van der Vaart, Wilfried Maas[a], Alfredo Ramos[b]

[a]Shell Global Solutions, Carel van Bylandtlaan 23, 2596 HP The Hague, The Netherlands
[b]Process Systems Enterprise, 26-28 Hammersmith Gr, London W6 7HA, United Kingdom

Conclusions

Conclusions

- **System modelling is an essential tool**
  - explore **complex decision space** resolve own technical and economic issues
  - inform and aid the **design** of safe control systems and operating procedures
  - identify areas requiring additional attention when designing for **dynamic operation**
  - **Evaluate technology** – existing and next-generation
- **Integrating platform** for working with other stakeholders in chain collaborative R&D, working with academia



- **gCCS - an integrated Advanced Process Modelling tool**
  - Capture, formalise & deploy existing knowledge on CCS technology
  - Common language for communication
  - Open architecture➔ allow incorporation of future technology

Thank you

Contact: m.calado@psenterprise.com

gCCS initial scope (2014/Q2)

- **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
    - amine-containing streams in CO_2 capture
  - SAFT-γ Mie
    - near-pure post-capture CO_2 streams

Open architecture allows incorporation of 3rd party models (e.g. E.ON's PROATES)

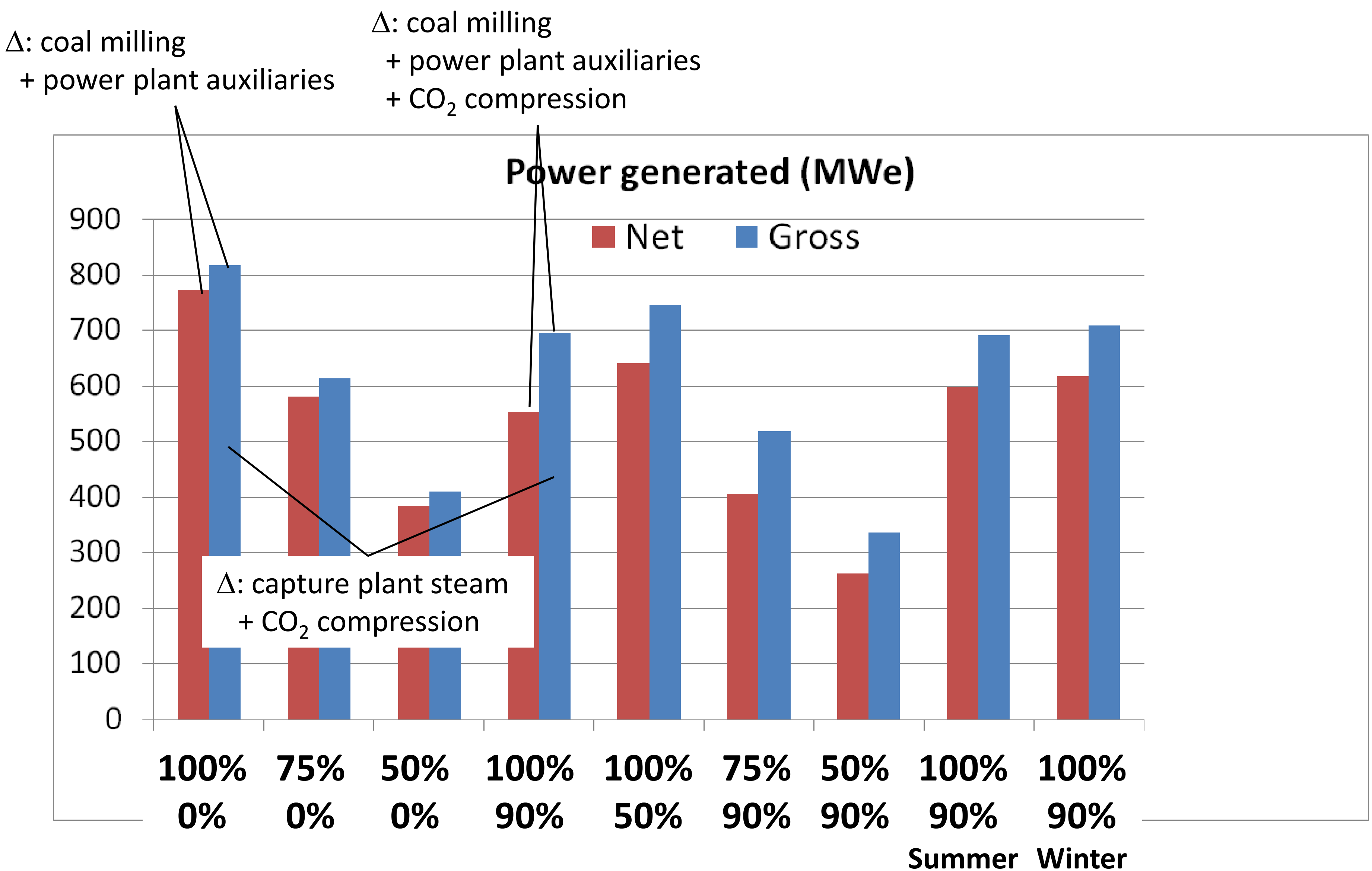
Back-up slides (case study 1)

Steady-state scenarios

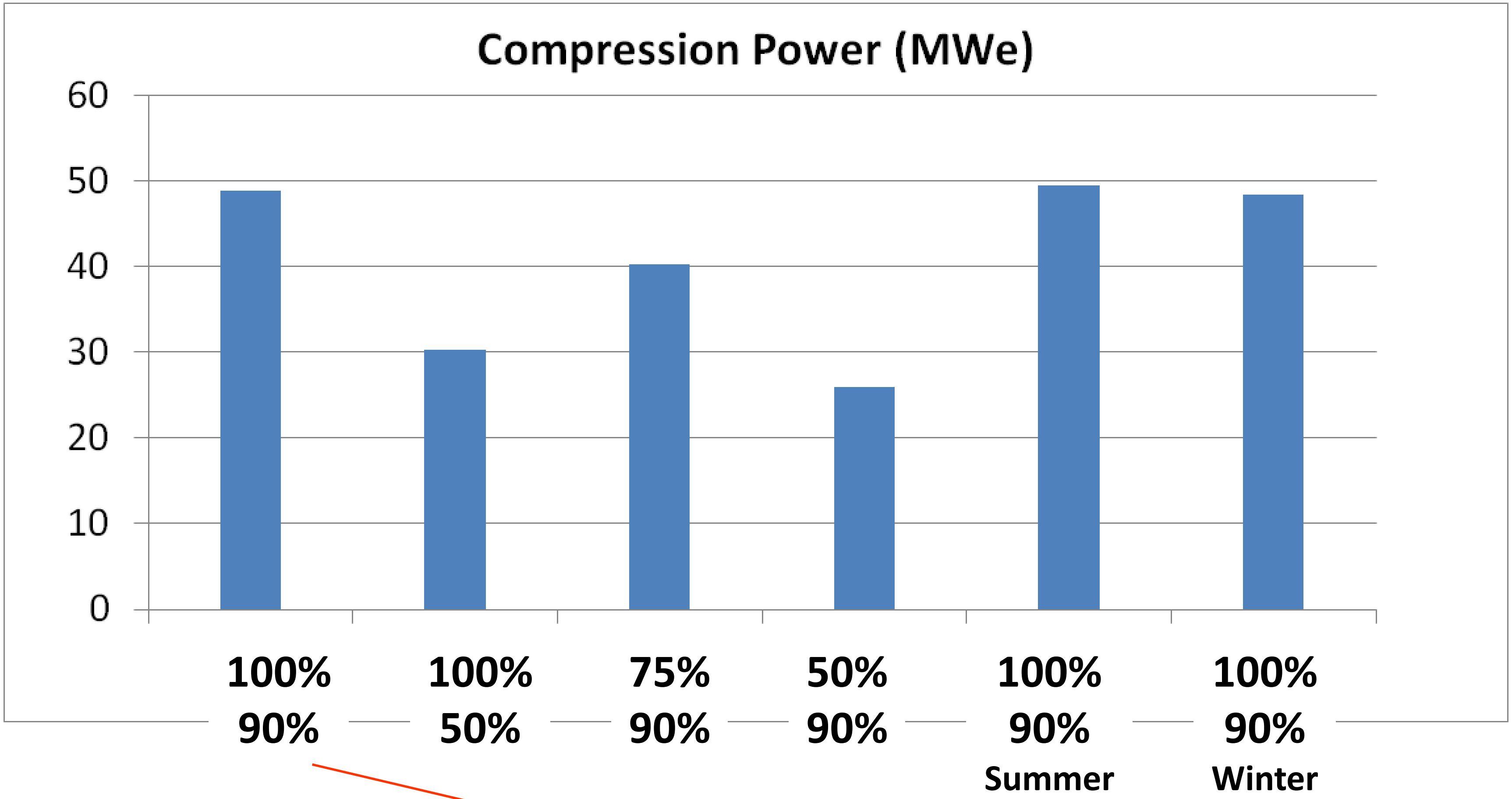
Scenario	Description	Power plant operation (% of nominal load)	Capture plant operation (CO2 % captured)
SS1.1 (a,b,c)	Base Load Power Plant	(a) 100%; (b) 75%; (c) 50%	0% (no capture)
SS1.2 (a, b)	Base load CCS Chain	100%	(a) 90%; (b) 50%
SS1.3 (a, b)	Part Load Analysis	(a) 75%; (b) 50%	90%
SS1.4	Extreme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

Power generation

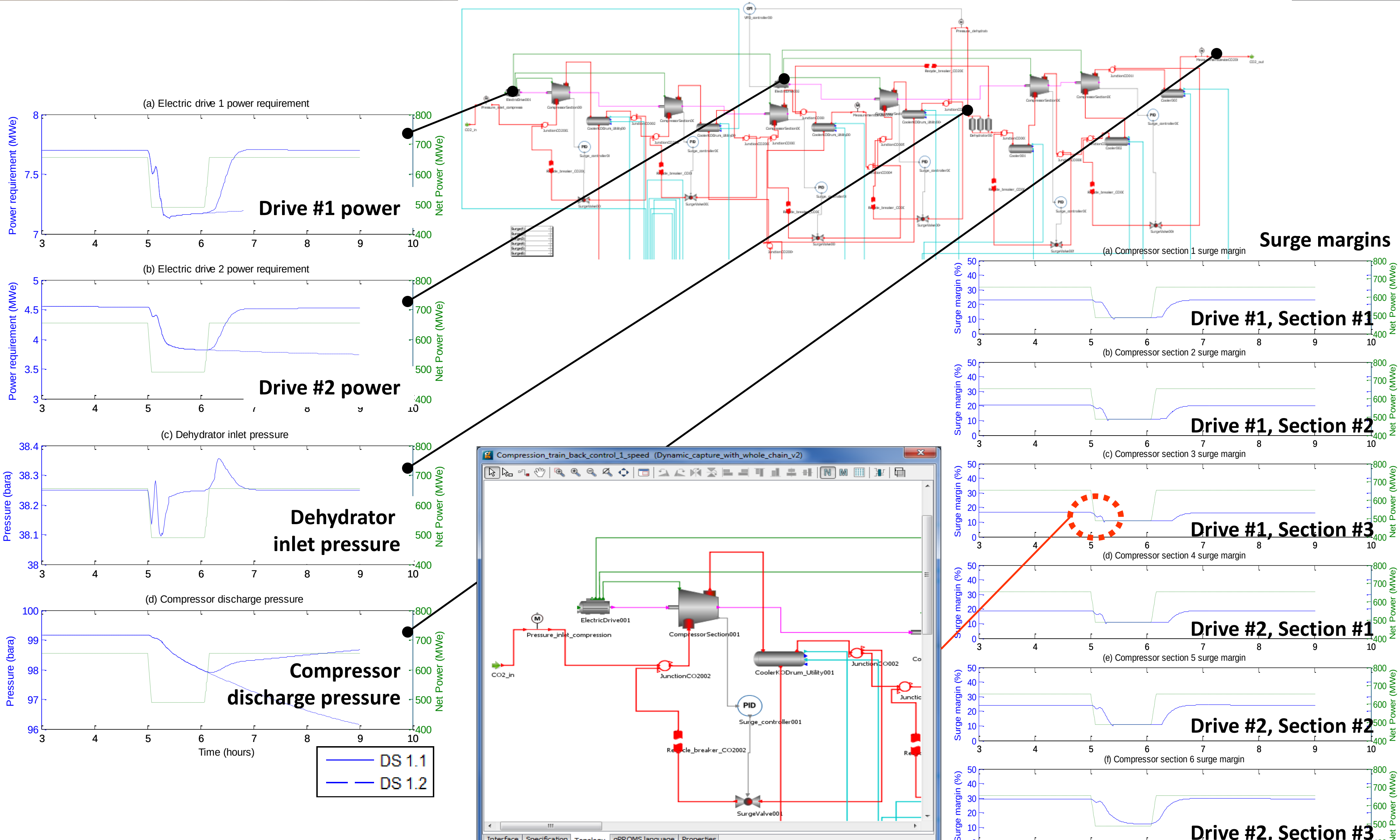


CO_2 compression power



Differences primarily due to changes in viscosity of fluid in pipeline

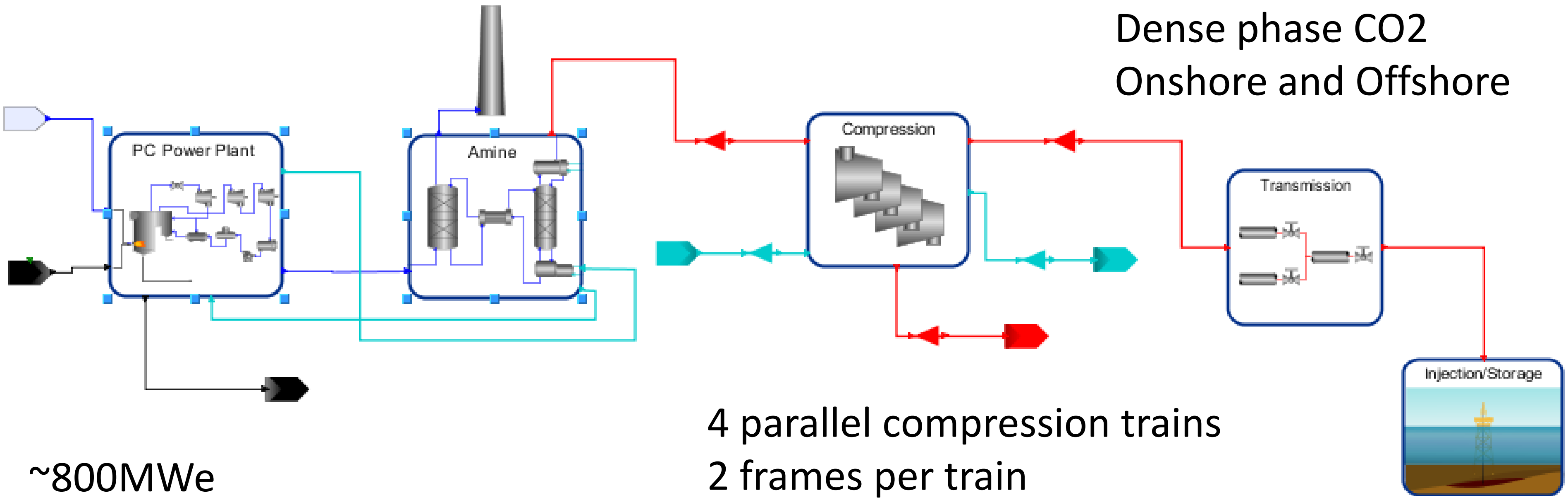
Dynamic analysis
CO_2 compression plant



System overview

Chemical absorption
MEA solvent
90% CO_2 capture

220km pipeline
Dense phase CO2
Onshore and Offshore



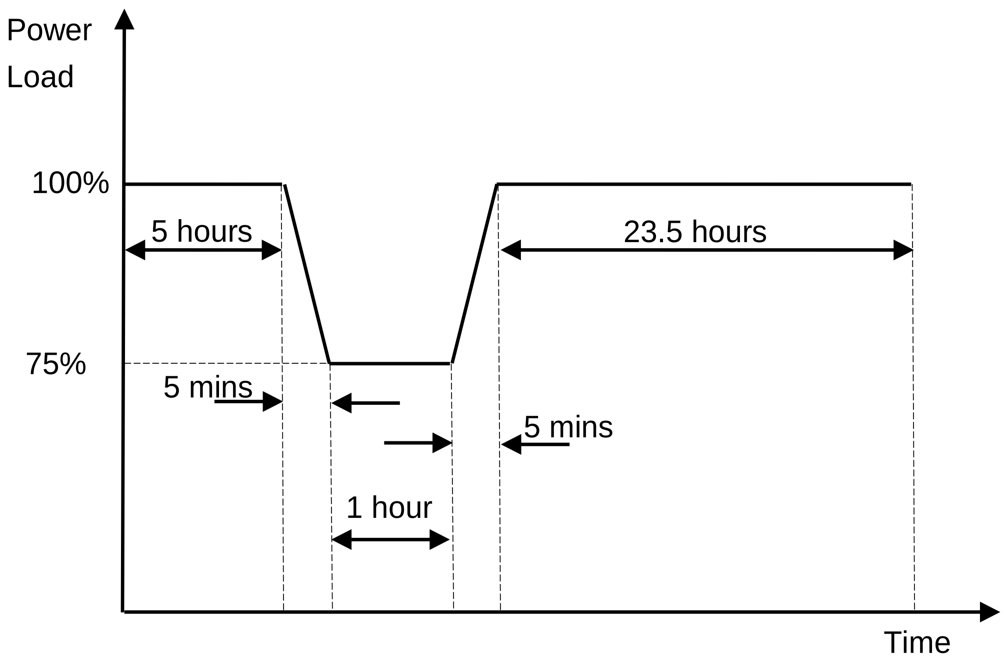
~800MWe
Supercritical
Pulverized coal
(acknowledgement: E.ON)

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

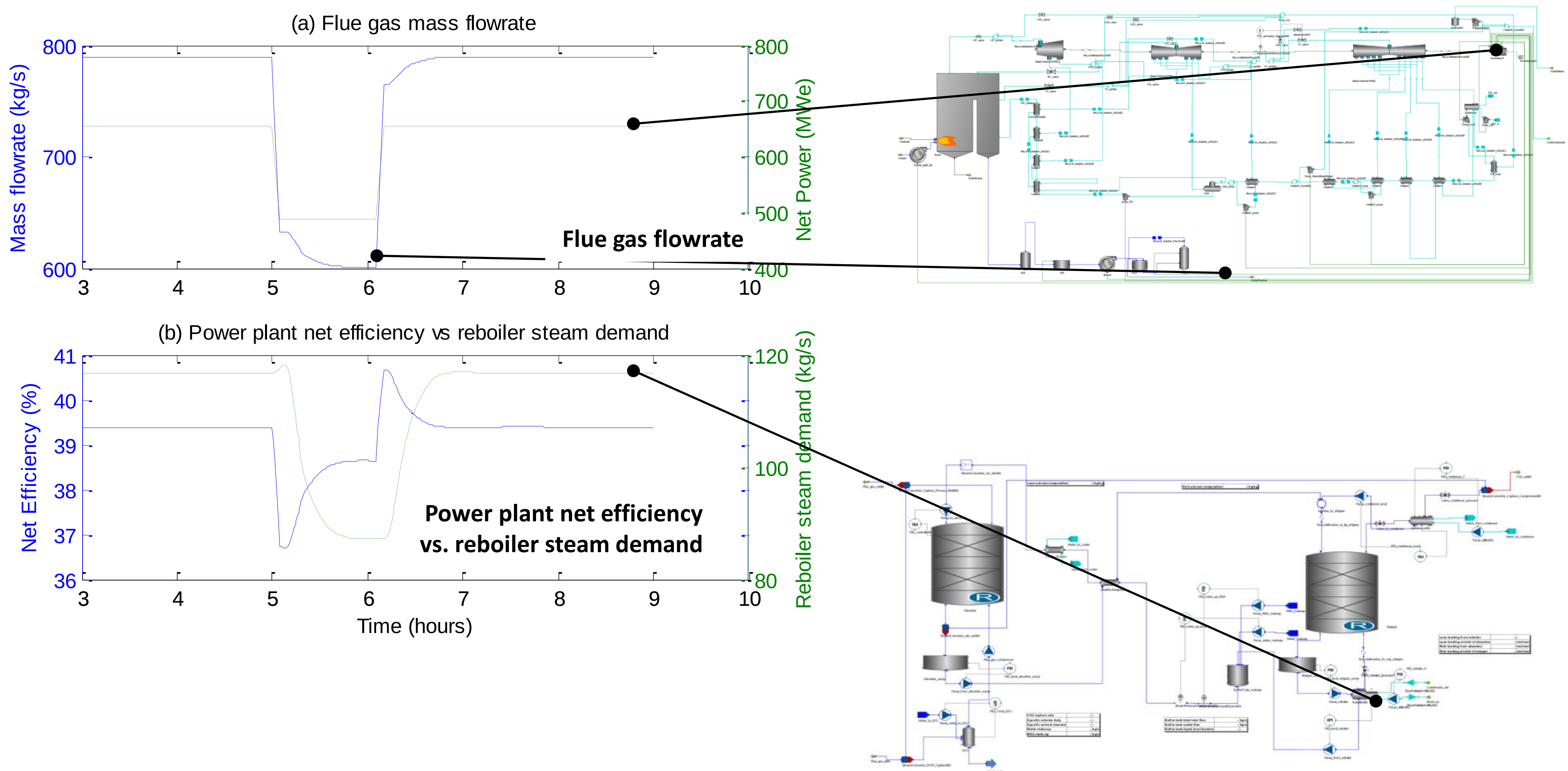
Offshore dense-phase injection; 4 injection wells
~2km reservoir depth
(acknowledgement: CO2DeepStore)

Scheduled changes in power plant load

- Scenario DS1.1

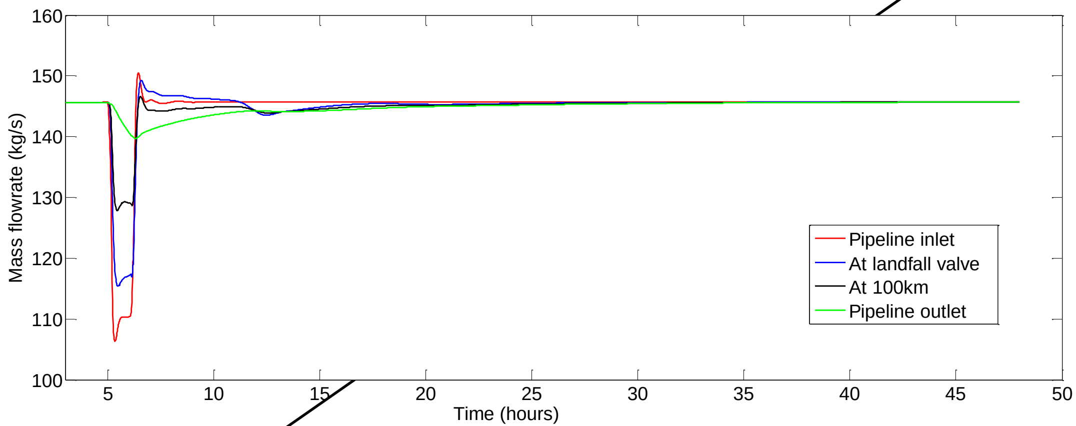


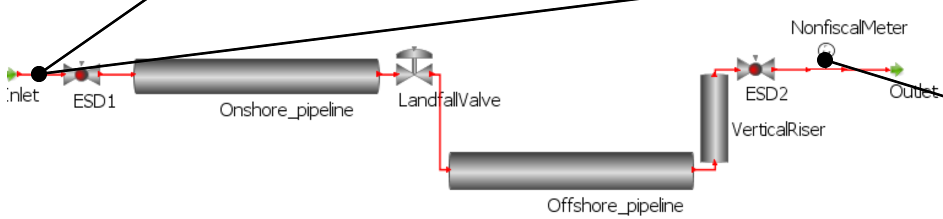
Power/CO_2 capture two-way coupling

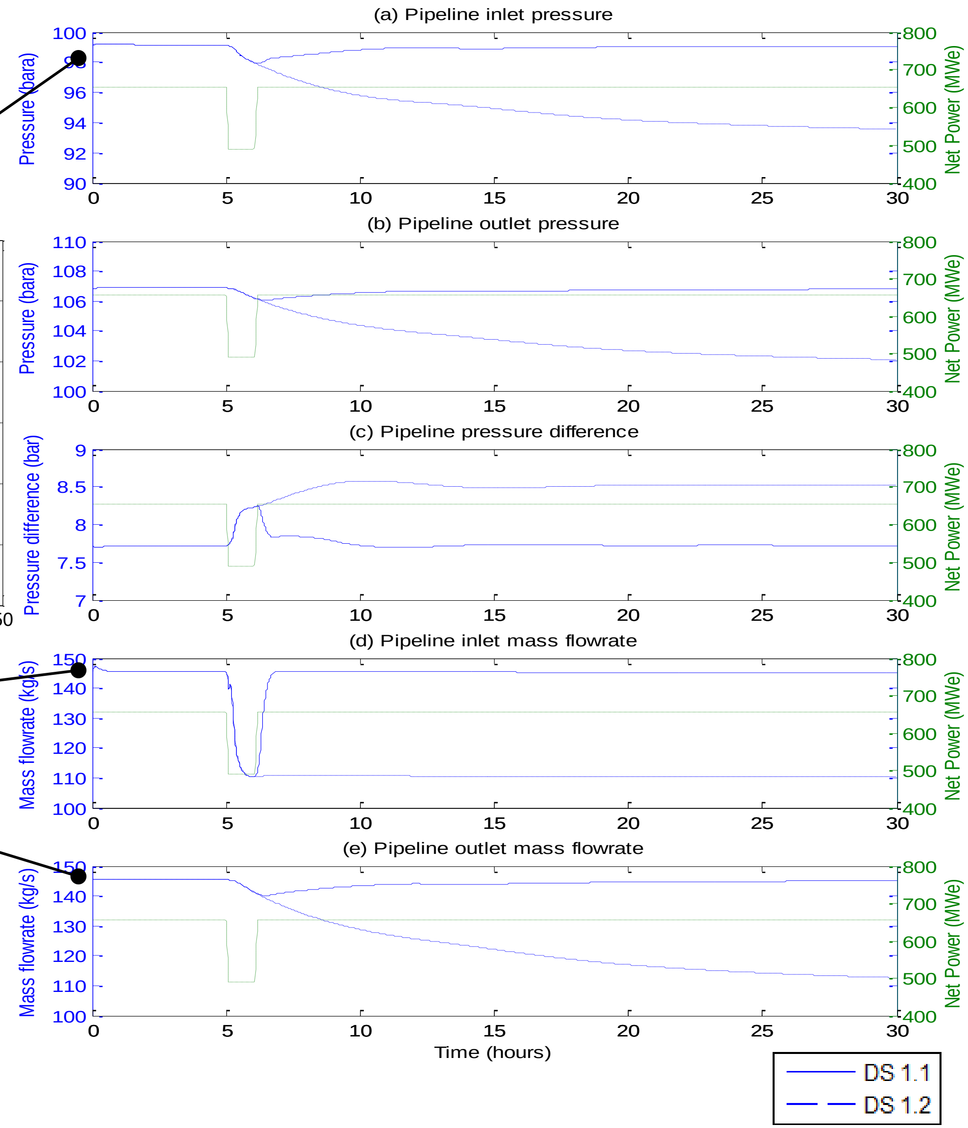


CO_2 transmission pipelines

- Buffer potential for flexible operation



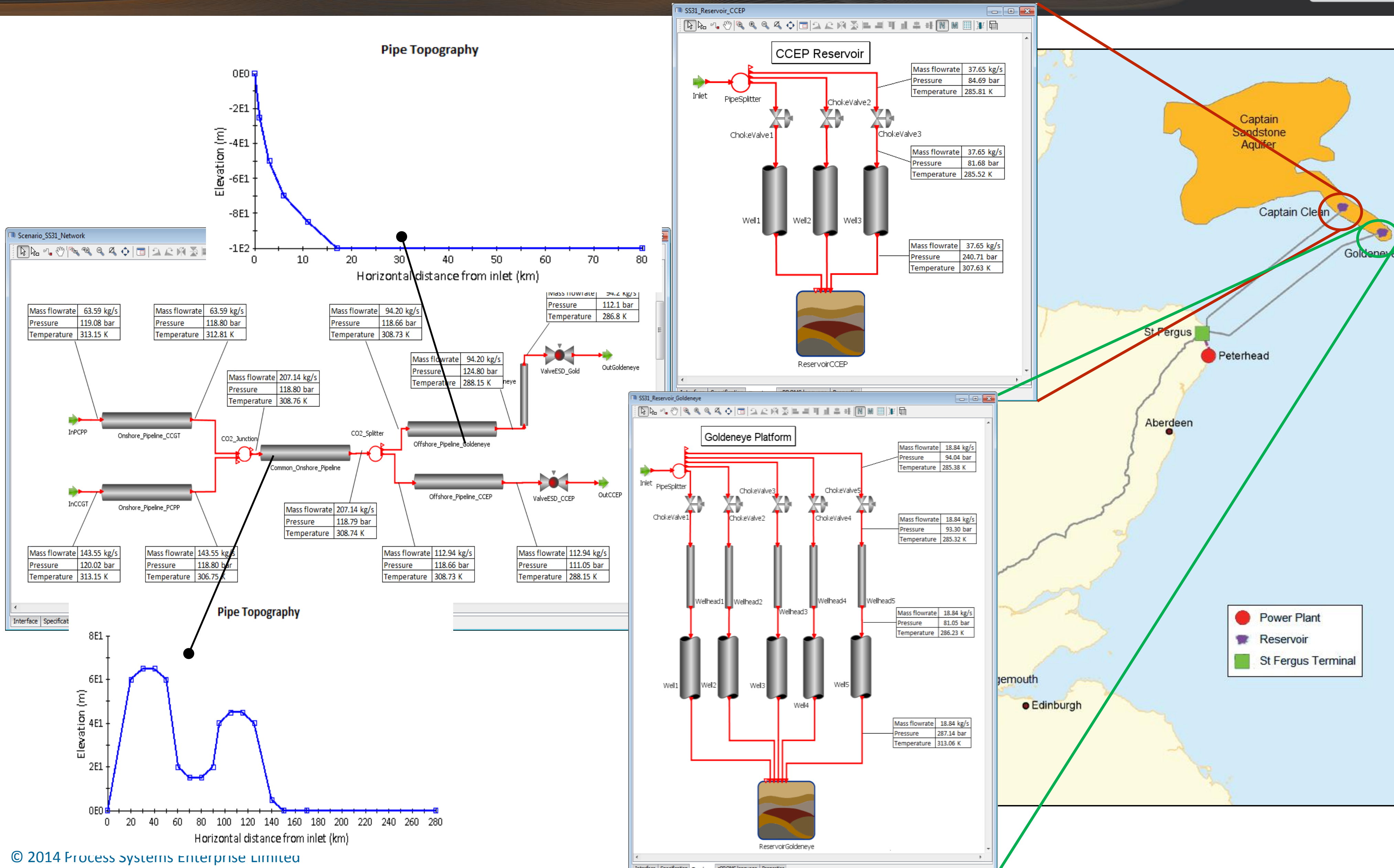




Back-up slides (case study 2)

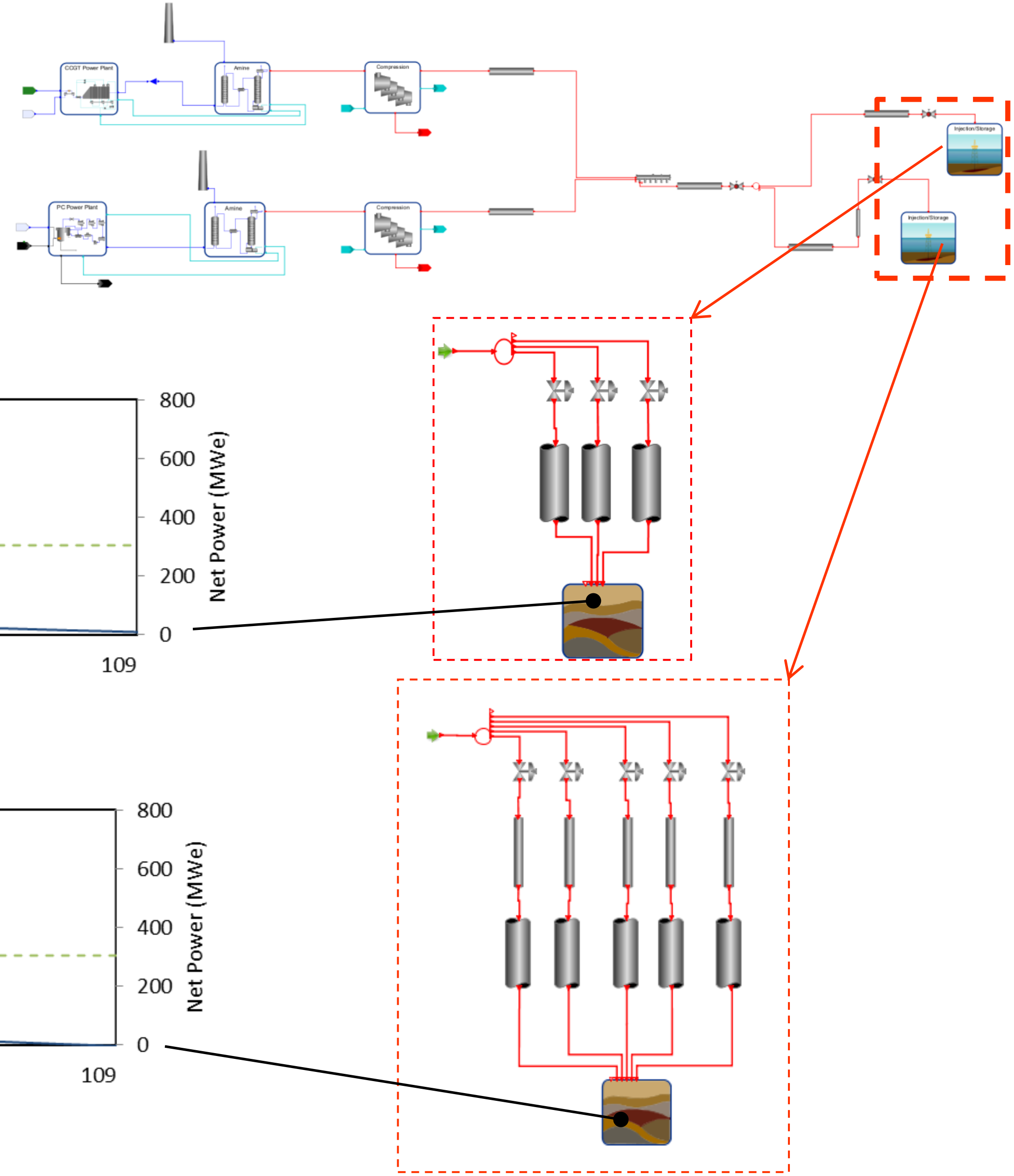
gCCS Transmission & Injection Library

CO_2 transmission networks

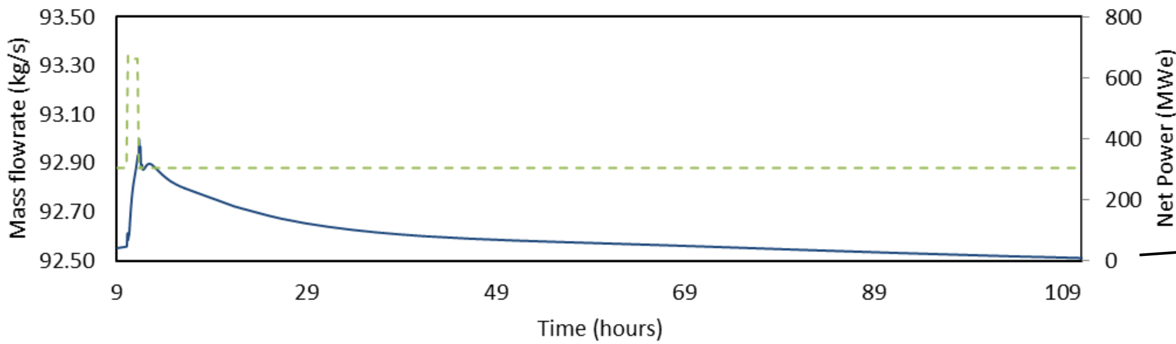


Load change effects

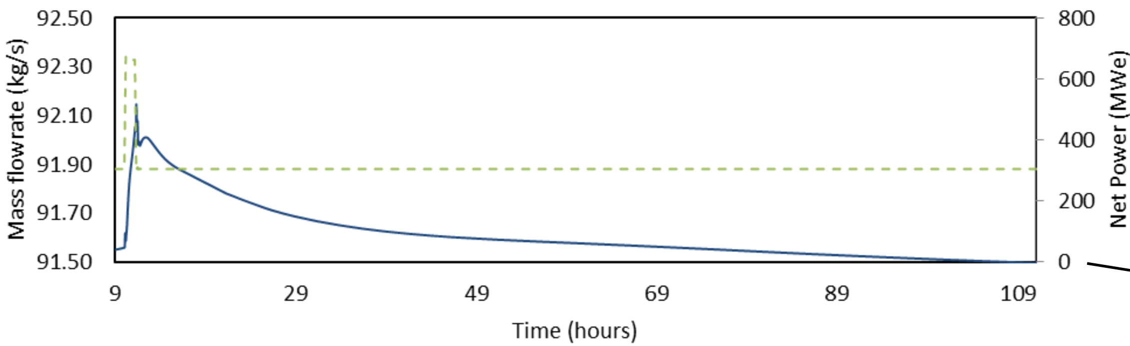
Load disturbance increases the CO_2 injected flowrate by only 0.5%



(a) Injected flowrate - CCEP reservoir



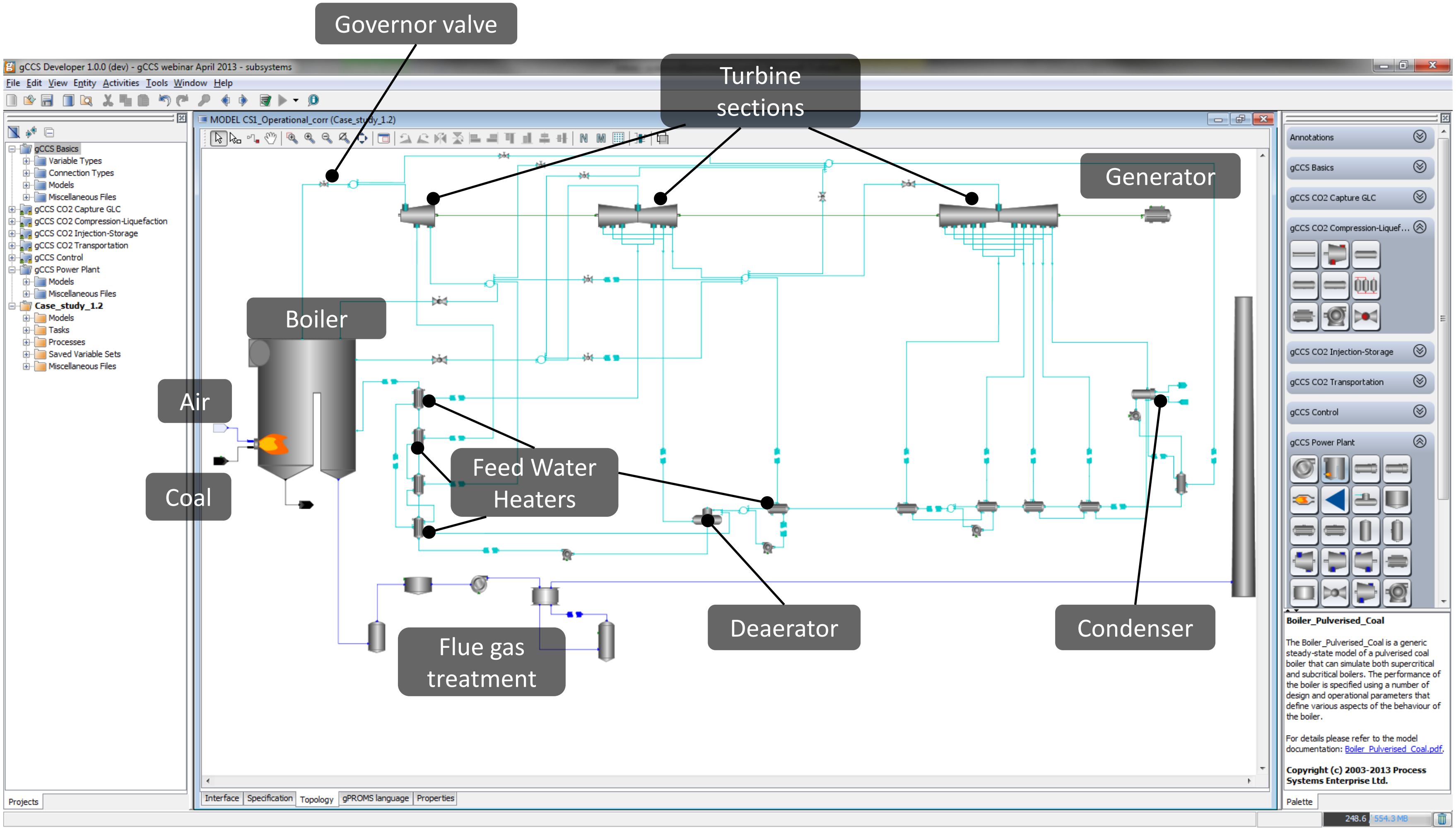
(b) Injected flowrate - Goldeneye reservoir



Back-up slides (power generation)

Sub-system #1

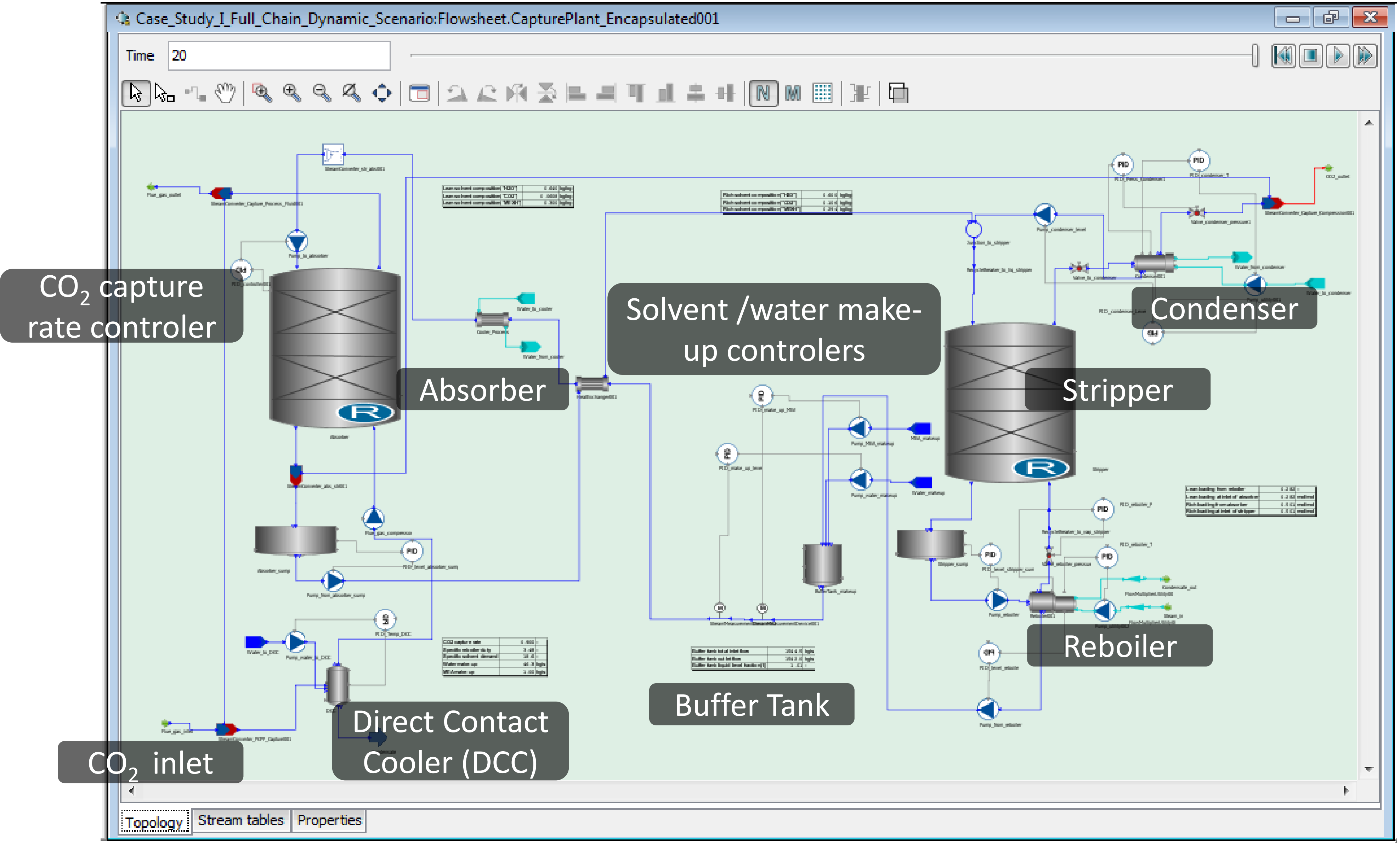
Supercritical pulverized coal power plant



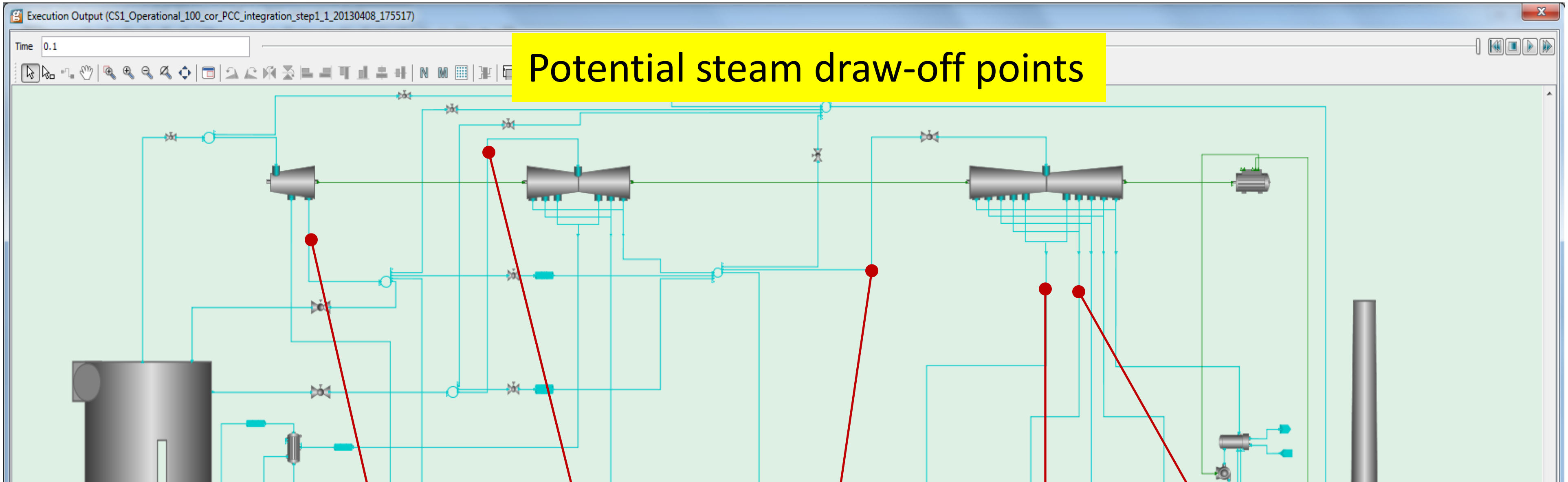
> 10 recycles & closed water/steam loop

Sub-system #2

CO_2 capture plant



Steam draw-off for amine regeneration



Context : Flowsheet

0 : Utility... Time 0.1

	HP_Turbine001.Outlet HP2_splitter.Inlet(1)	IP_Turbine001.Inlet IP_splitter.Outlet(1)	JunctionUtility001.Outlet(2) LP_valve.inlet	LP_Turbine001.OutletBleed1 Recycle_breaker_utility010.inlet	LP_Turbine001.OutletBleed2 Recycle_breaker_utility006.inlet
Mass flow rate [kg/s]	562.5	492	435	23.47	10.43
Pressure [Pa]	6.390E6	6.029E6	8.986E5	4.975E5	2.033E5
Temperature [K]	634.7	893.1	601.5	531.8	439

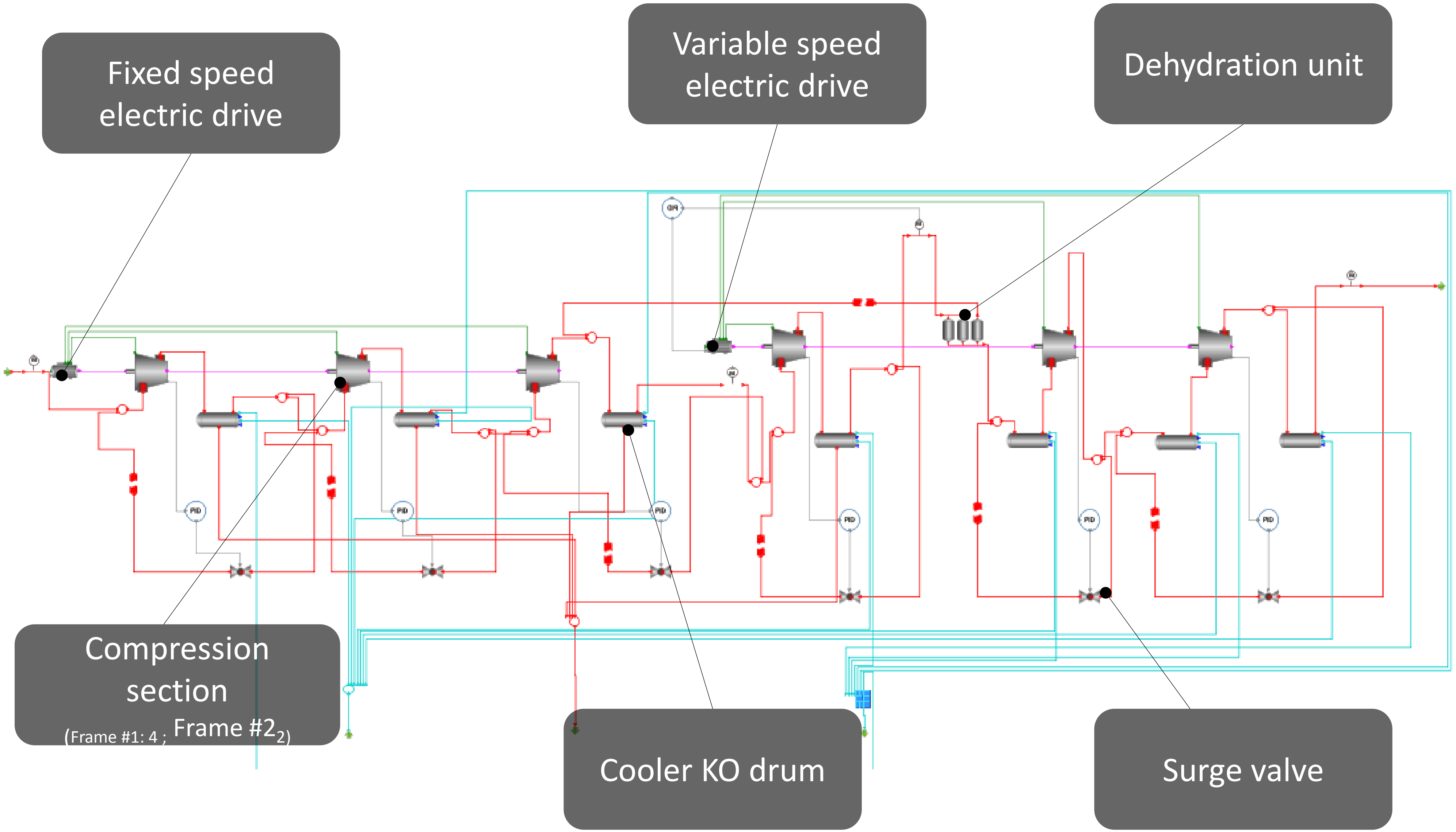
Pressure too high ➔ efficiency penalty

Optimal draw-off point

Pressure potentially too low at minimum plant loads

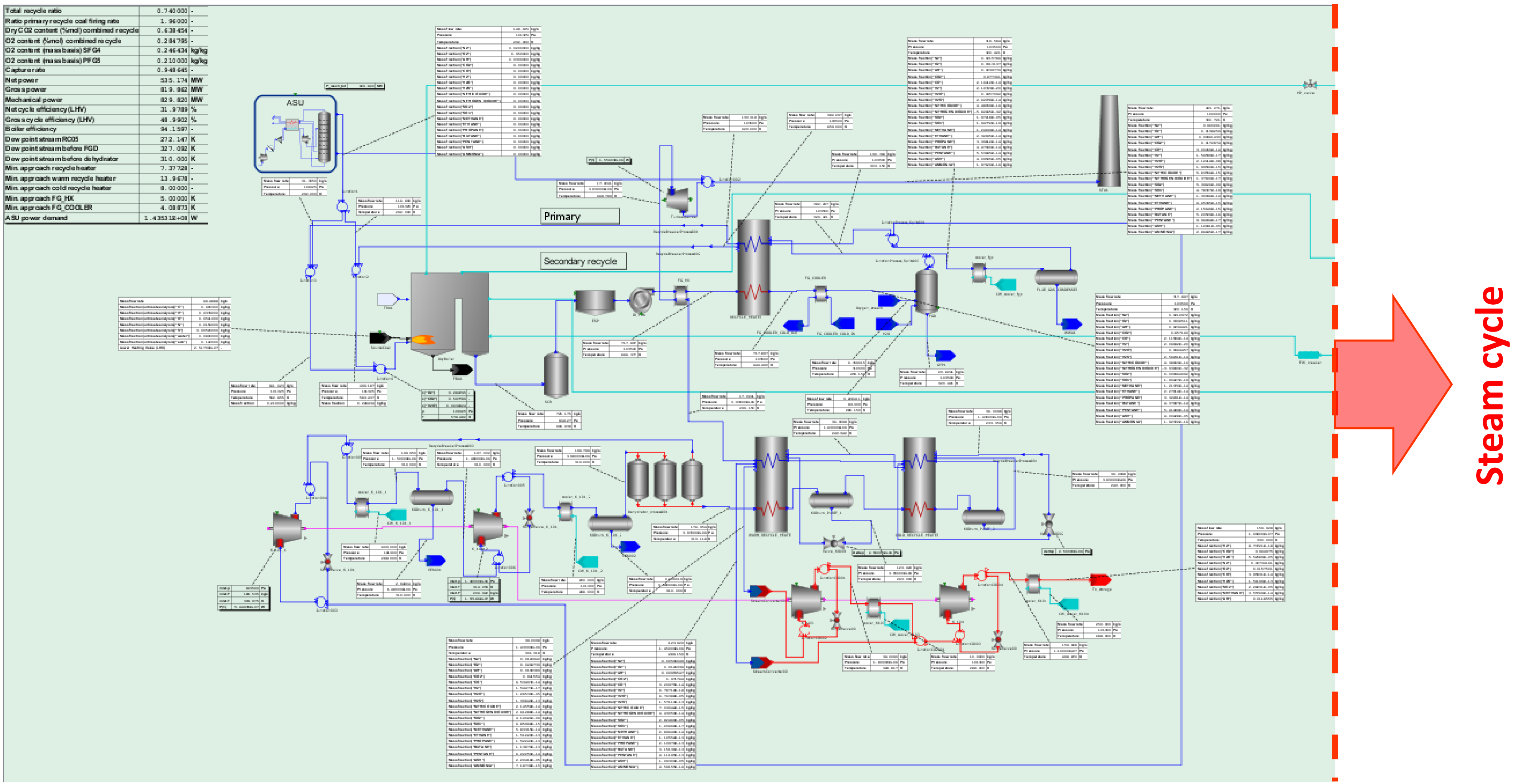
Pressure too low

Sub-system #3
CO_2 compression plant



Oxyfuel power plant

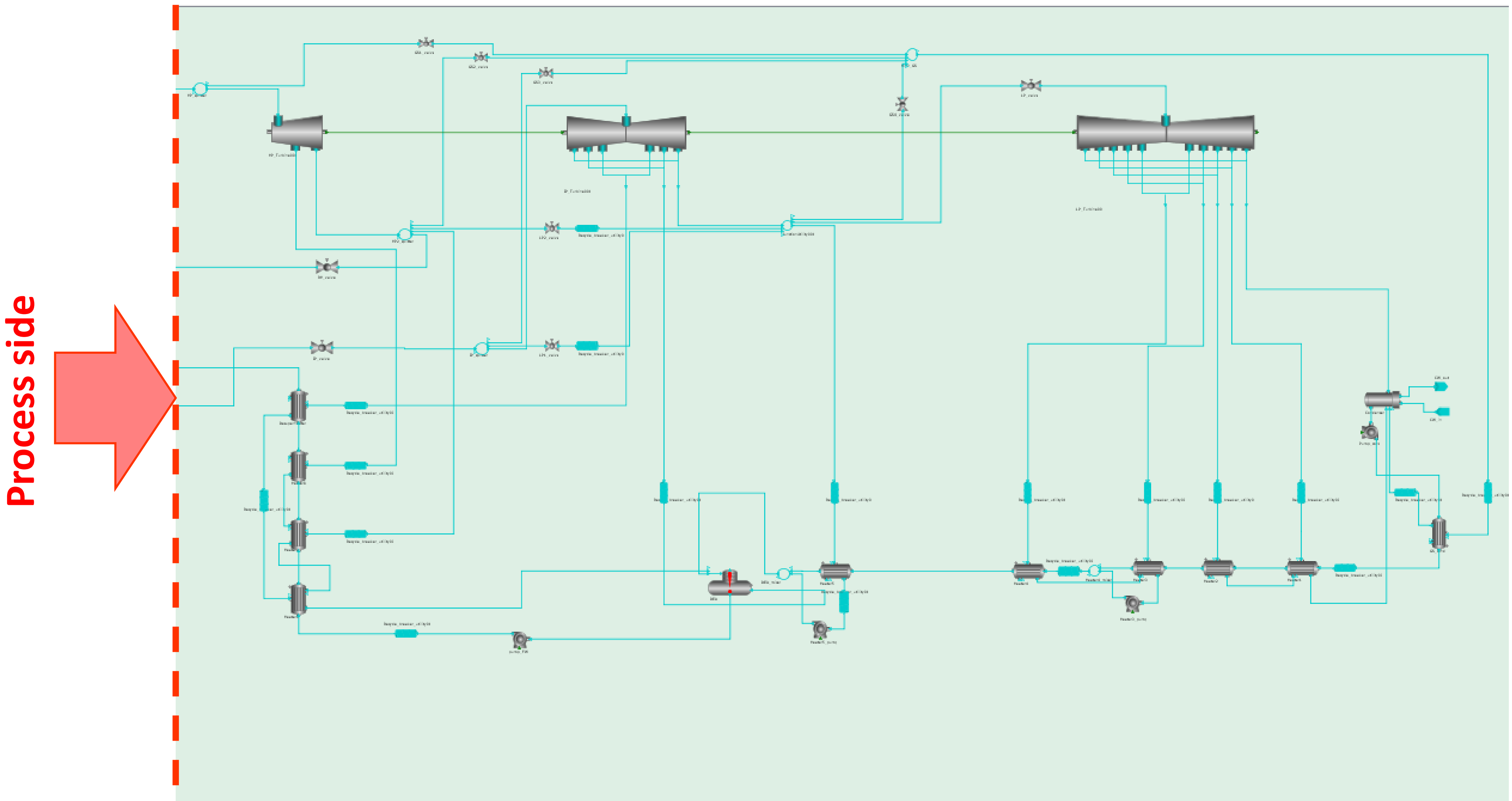
- Process side



Sub-system #1 – other power technologies considered

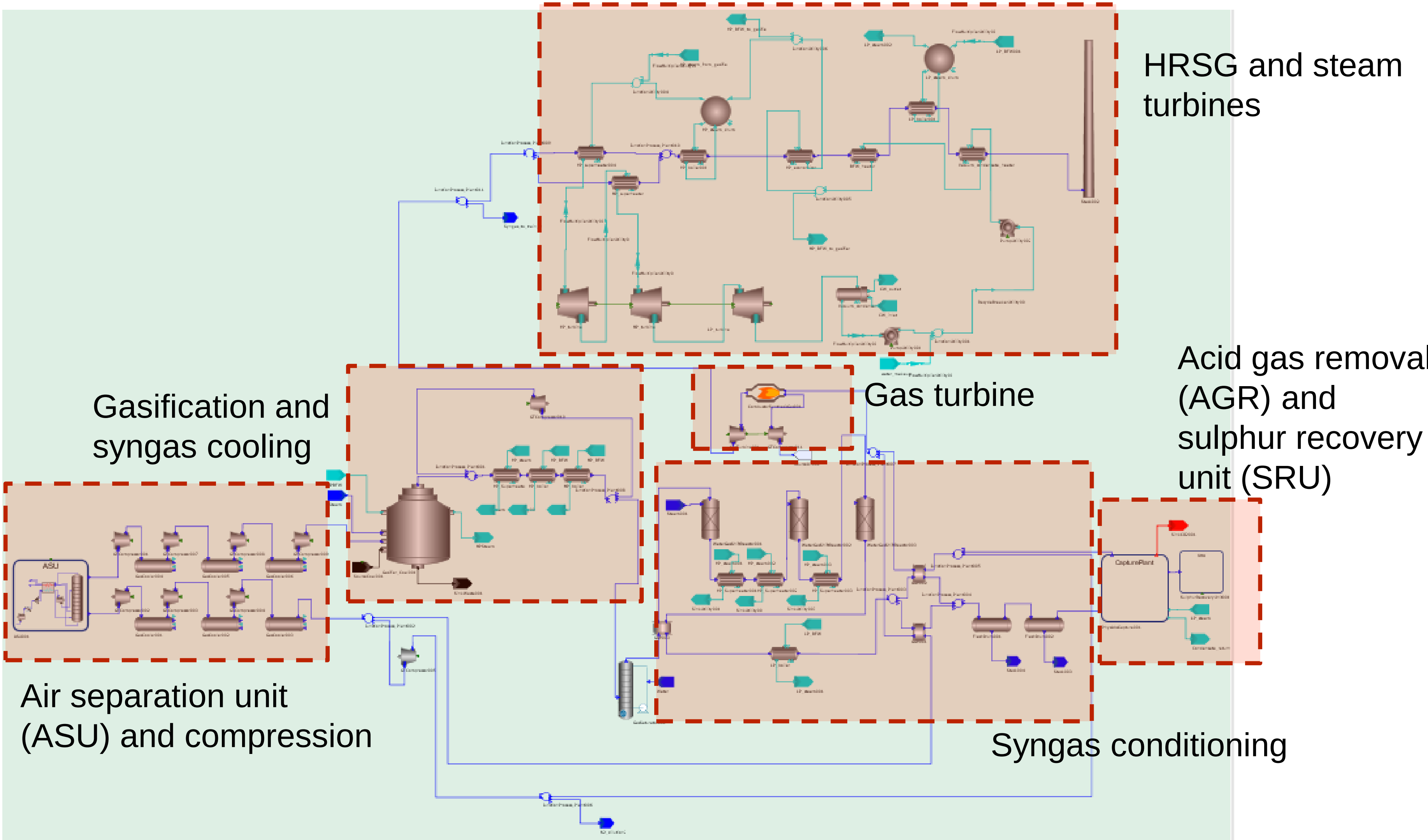
Oxyfuel power plant

- Steam Cycle

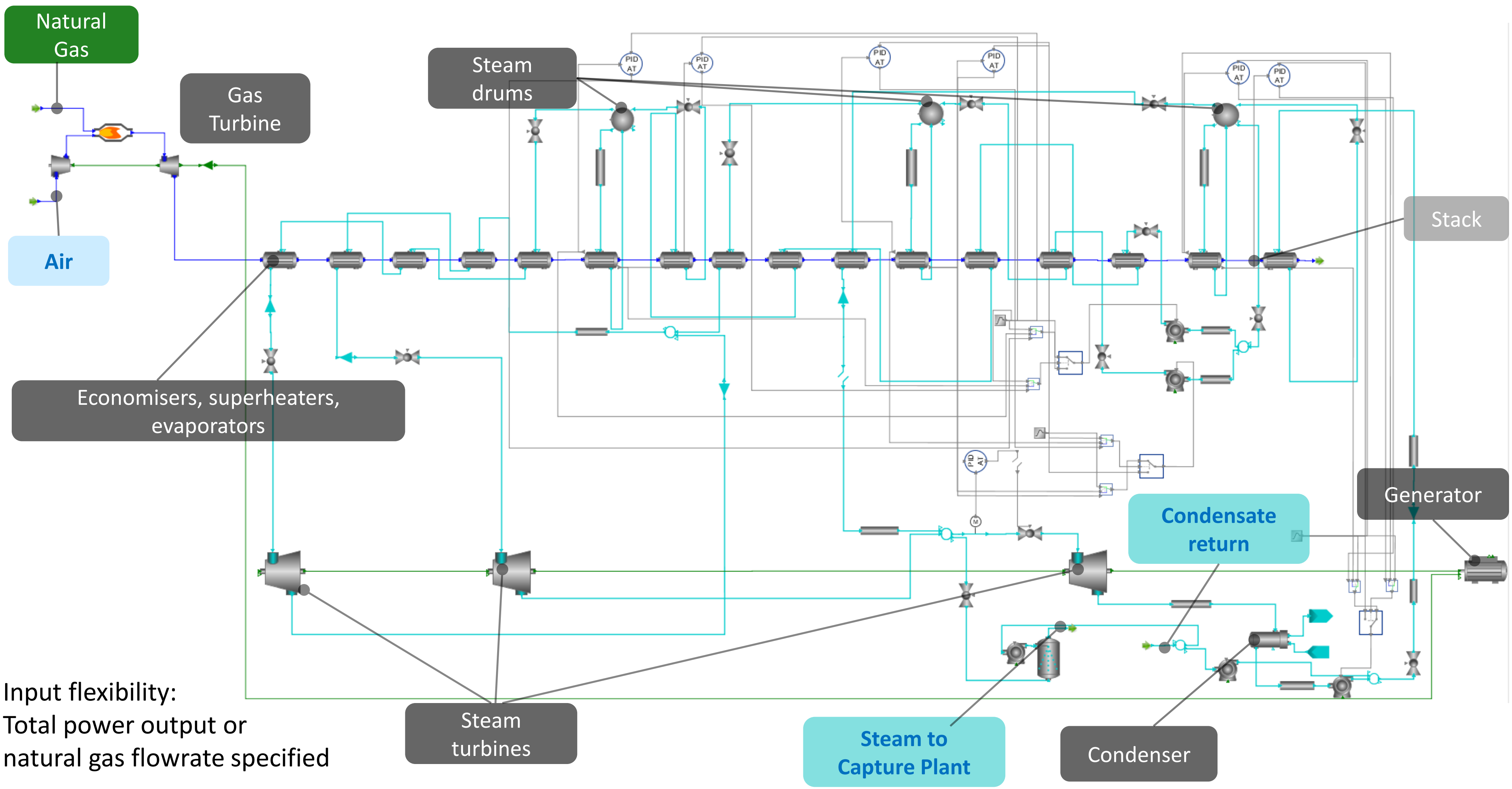


IGCC power plant

- Integrated Gasification Combined Cycle power plant (IGCC)



CCGT power plant



Input flexibility:
Total power output or
natural gas flowrate specified

Back-up slides (Interfaces)

Tool-kit components

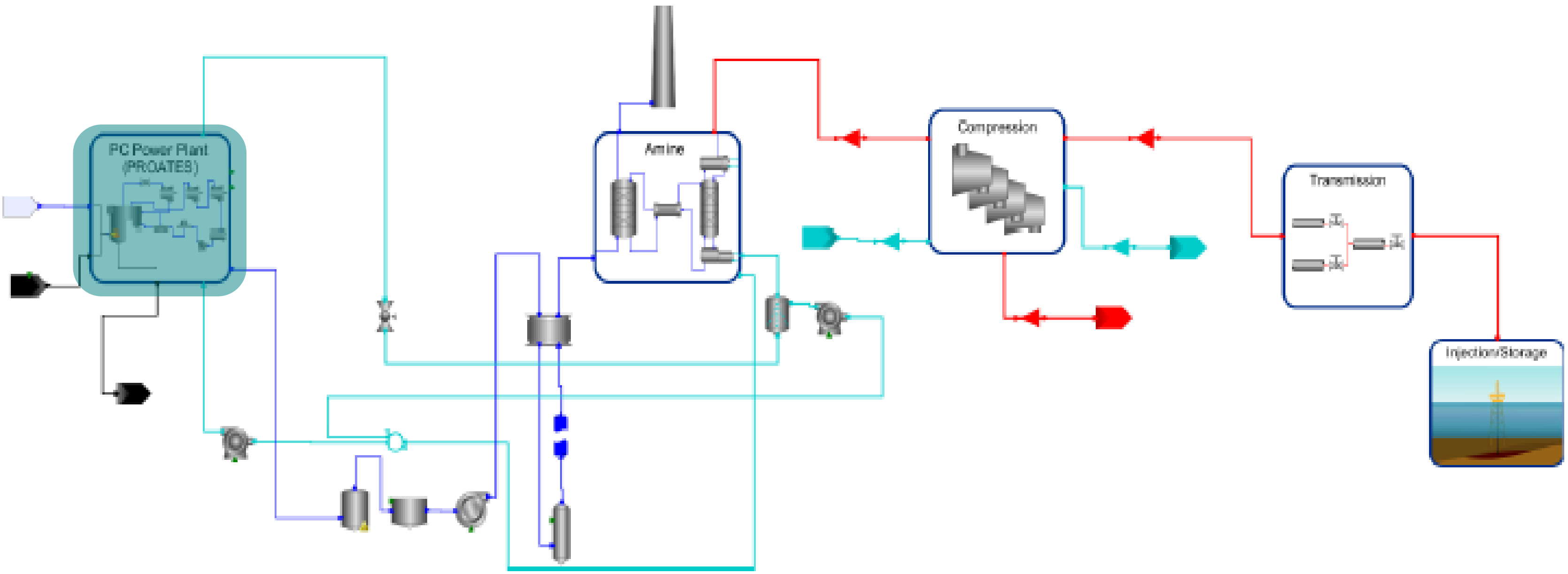
Interfaces to 3rd party modelling tools

- Direct interfacing / co-simulation – based on gPROMS's Foreign Object (FO) interface
  - Steady-state modelling and simulation packages (E.ON's PROATES)
  - Equipment design tools (Rolls-Royce's CompPerform/CompSelect)

- Model fitting
  - Incorporate reduced-order models of high-fidelity equipment models

Deployment of 3rd party models

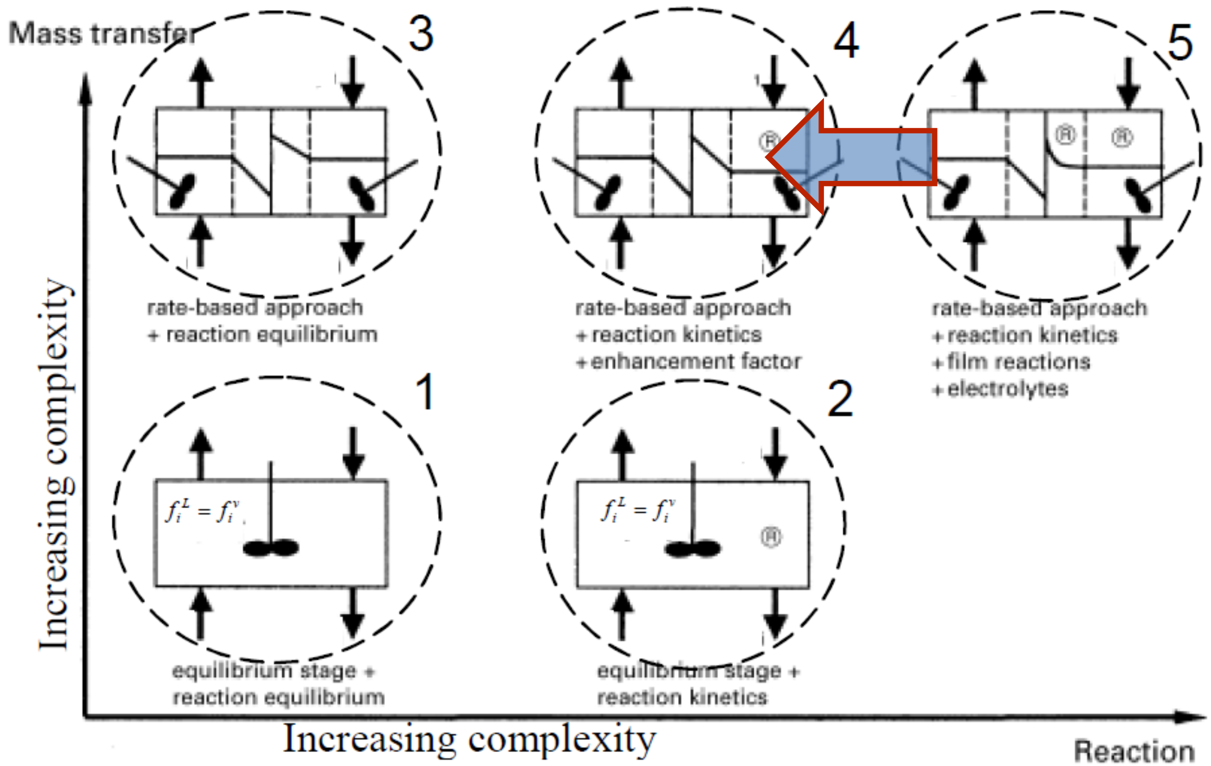
- Integration of PROATES power plant model in gCCS for whole chain studies



Back-up slides (solvent-based CO_2 Capture)

Tool-kit components

Model libraries – CO_2 Capture (chemical and physical absorption)

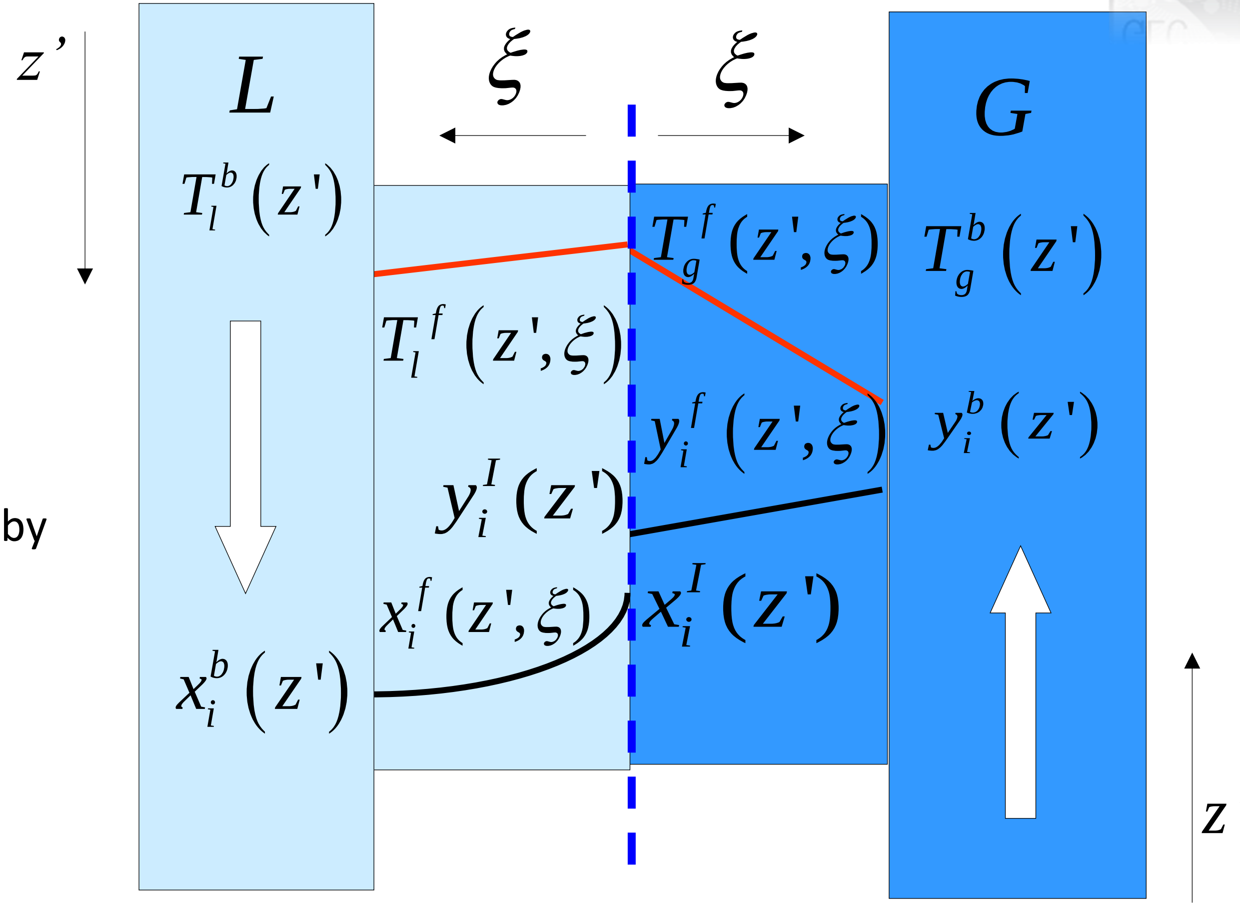


Rate-based Approach

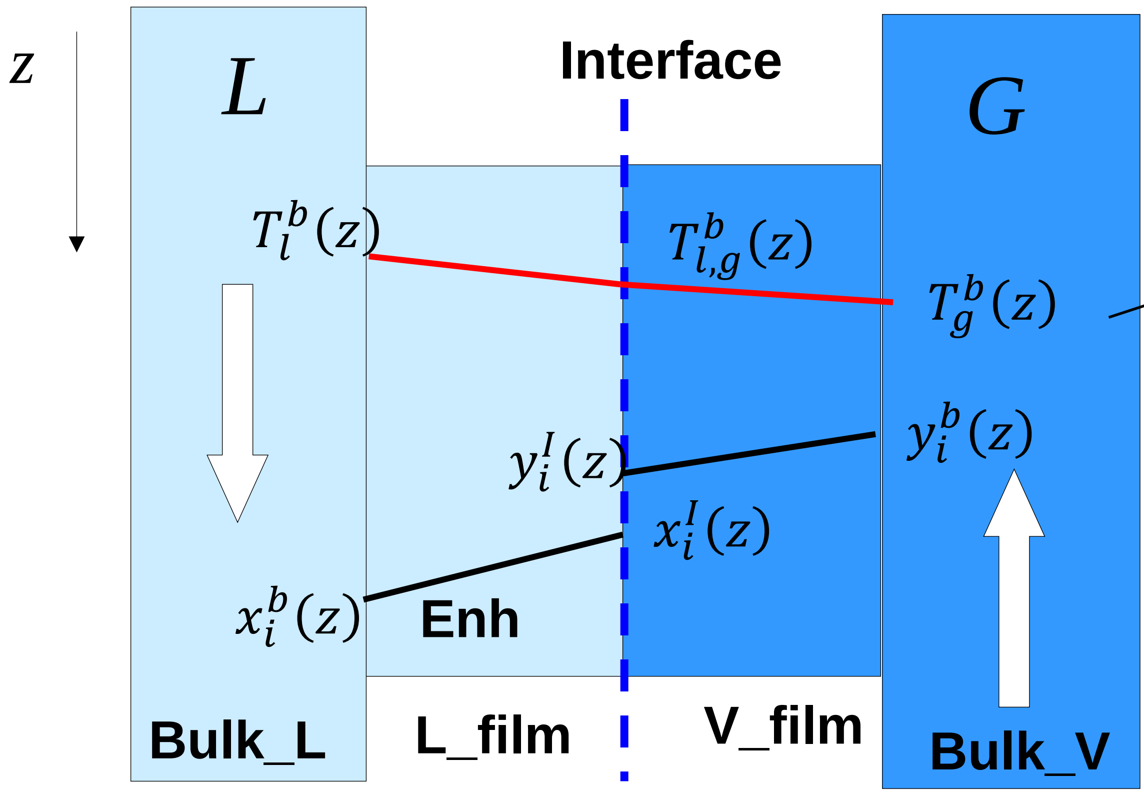
Equilibrium-based Approach

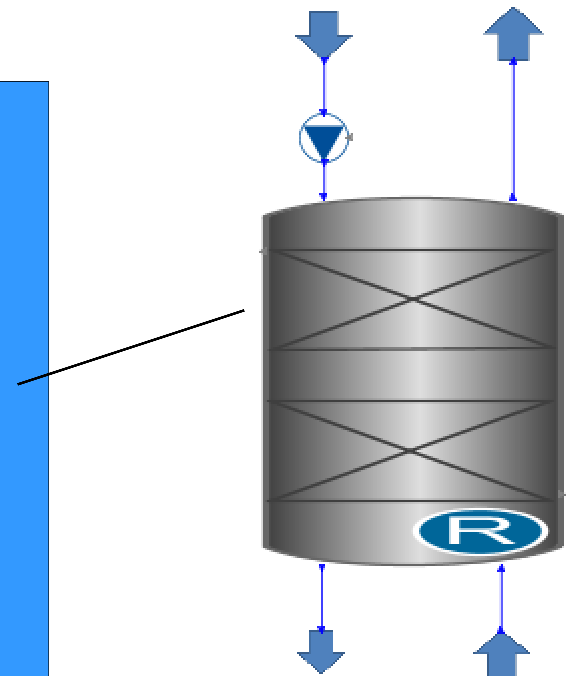
High-fidelity column model

- Non-equilibrium models
- Models distributed in axial direction and in the direction of the liquid and vapour films
- Energy balance and V/L equilibrium at the interface
- Phase behaviour and chemical equilibrium <u>currently</u> calculated by OLI thermodynamic package
  - to be replaced by gSAFT
- Transport properties
  - Obtained from correlations and Multiflash

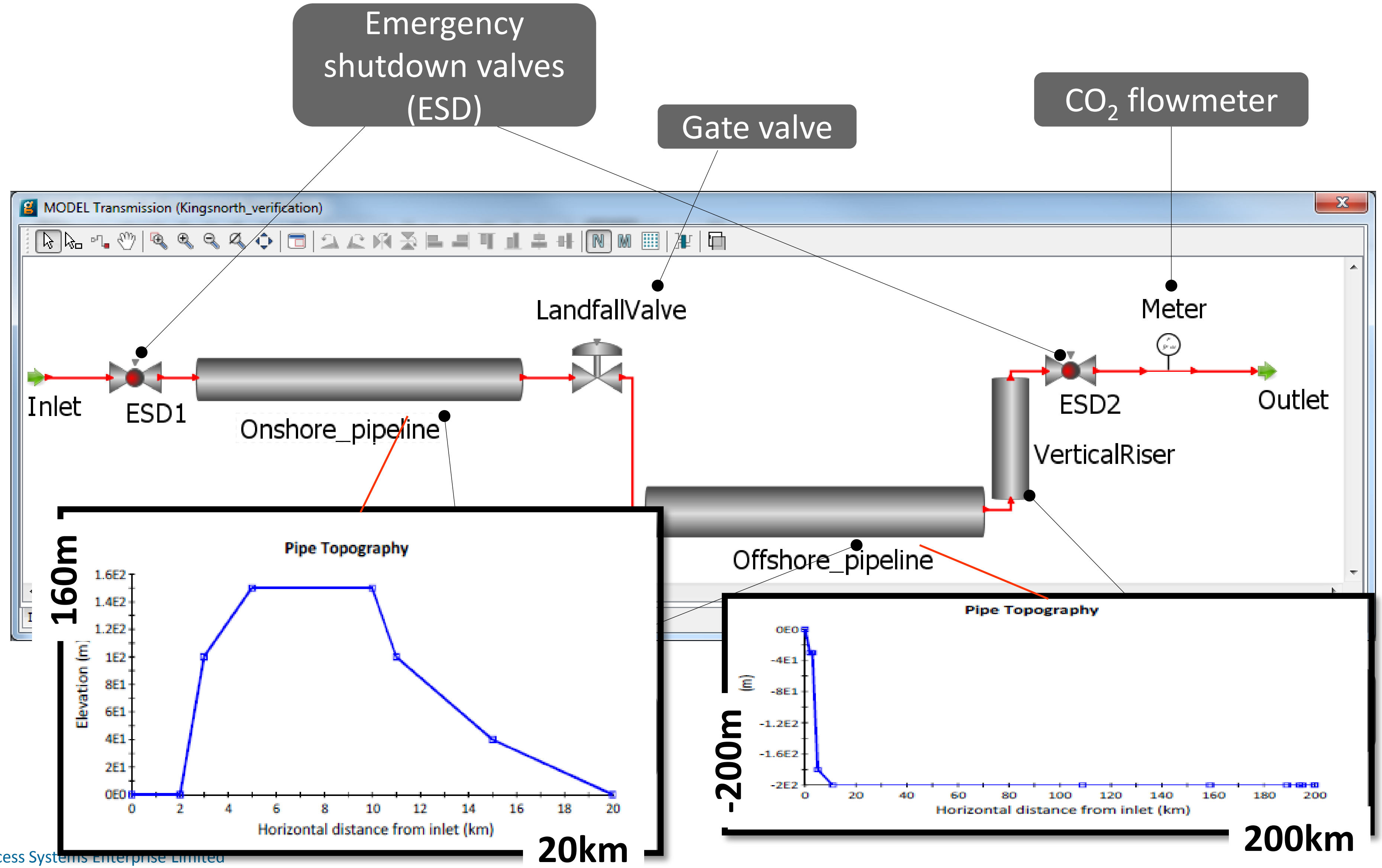


- Medium-fidelity column model
  - Based on two-film theory
  - Enhancement factors account for effect of reactions
  - Vapour/Liquid equilibrium at interface



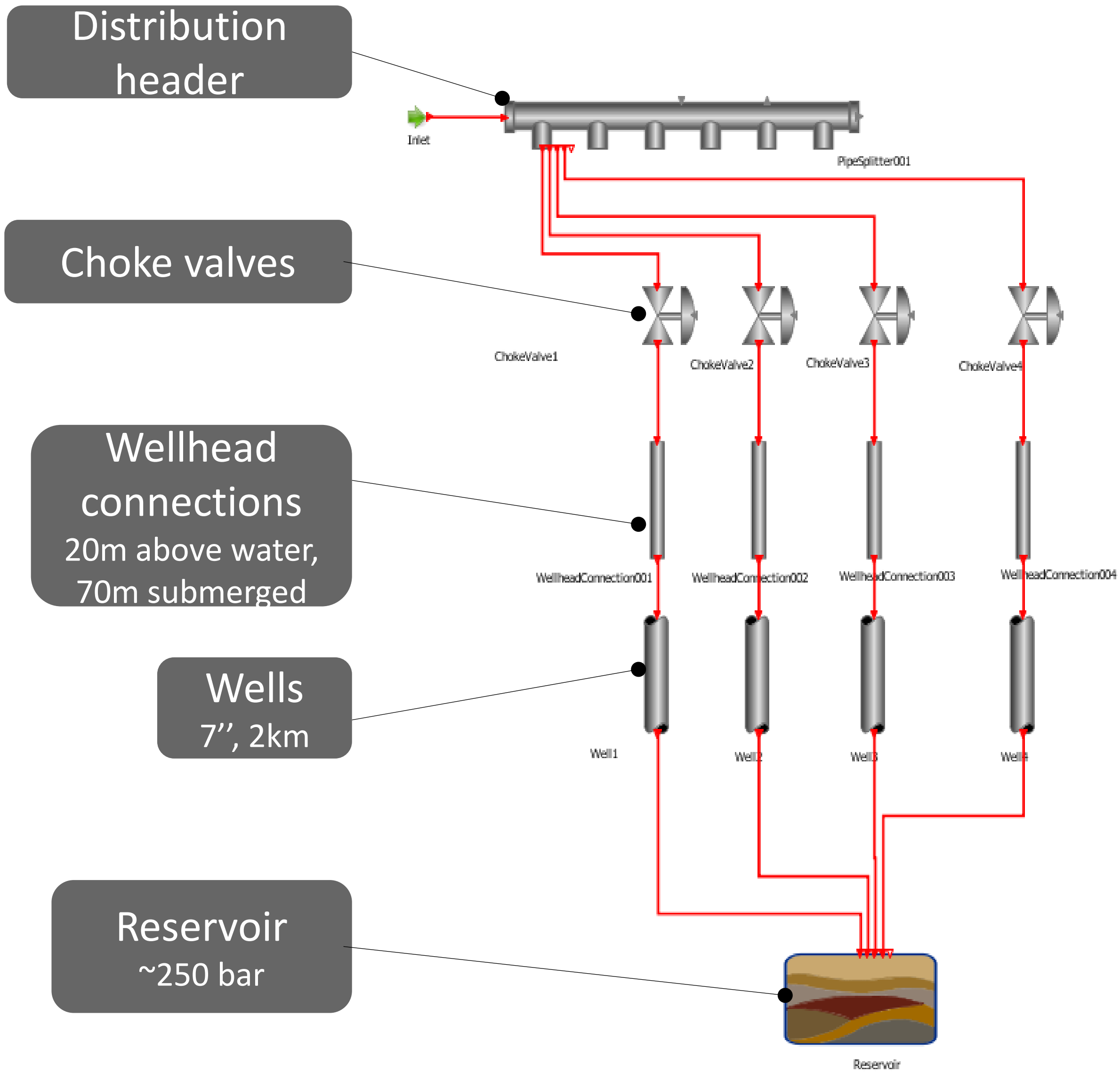


Sub-system #4
CO_2 transmission pipelines



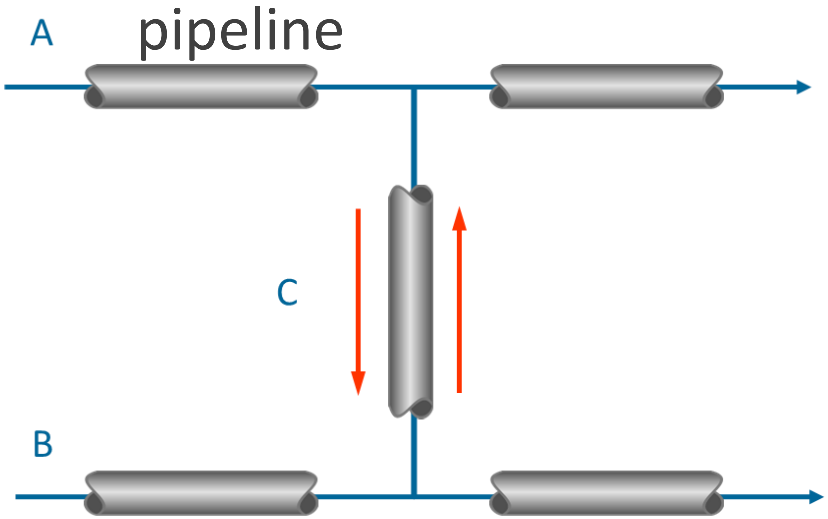
Sub-system #5

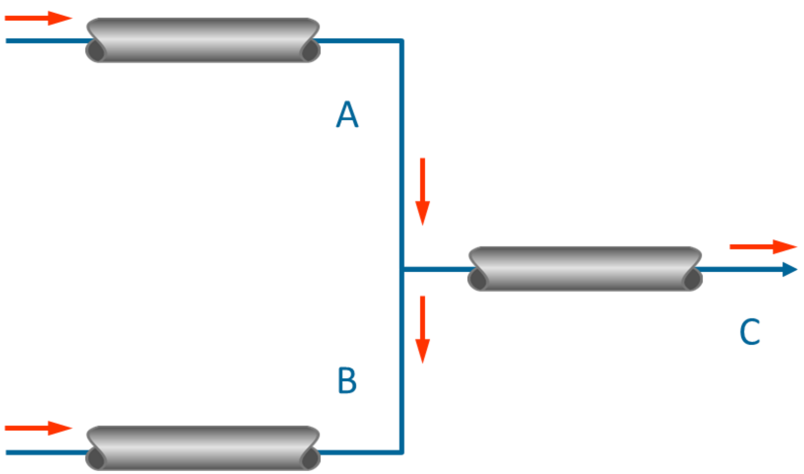
CO_2 injection & storage in reservoir



Reversible flow in CO_2 transmission networks

- Reversible flow scenarios
  - Normal: pipe expected to allow flow in either direction depending on the operation of the connected networks
  - Abnormal: unexpected transient event upstream or downstream causes temporary flow reversal in part of one pipeline





Back-up slides (Physical Properties)

Tool-kit components

Physical properties

- Different material/species within the same sub-system
  - e.g. in power plant: coal, water, flue gas
- Different materials/species in different sub-systems
  - e.g. MEA in CO_2 capture plant
- Need different thermodynamic models for different materials, e.g.
  - cubic EoS (PR 78) for flue gas in power plant
  - Corresponding States (Steam Tables) for pure water

  gPROMS Properties (Multiflash®)

  - SAFT for amine-containing streams in CO_2 capture
  - SAFT for near-pure post-capture CO_2 streams

  gSAFT
- Transport properties obtained from gPROMS Properties
  - models/ correlations

Physical properties for compression/transmission in CCS

Challenges

- Impurities
- Wide range of conditions
- Limited experimental data

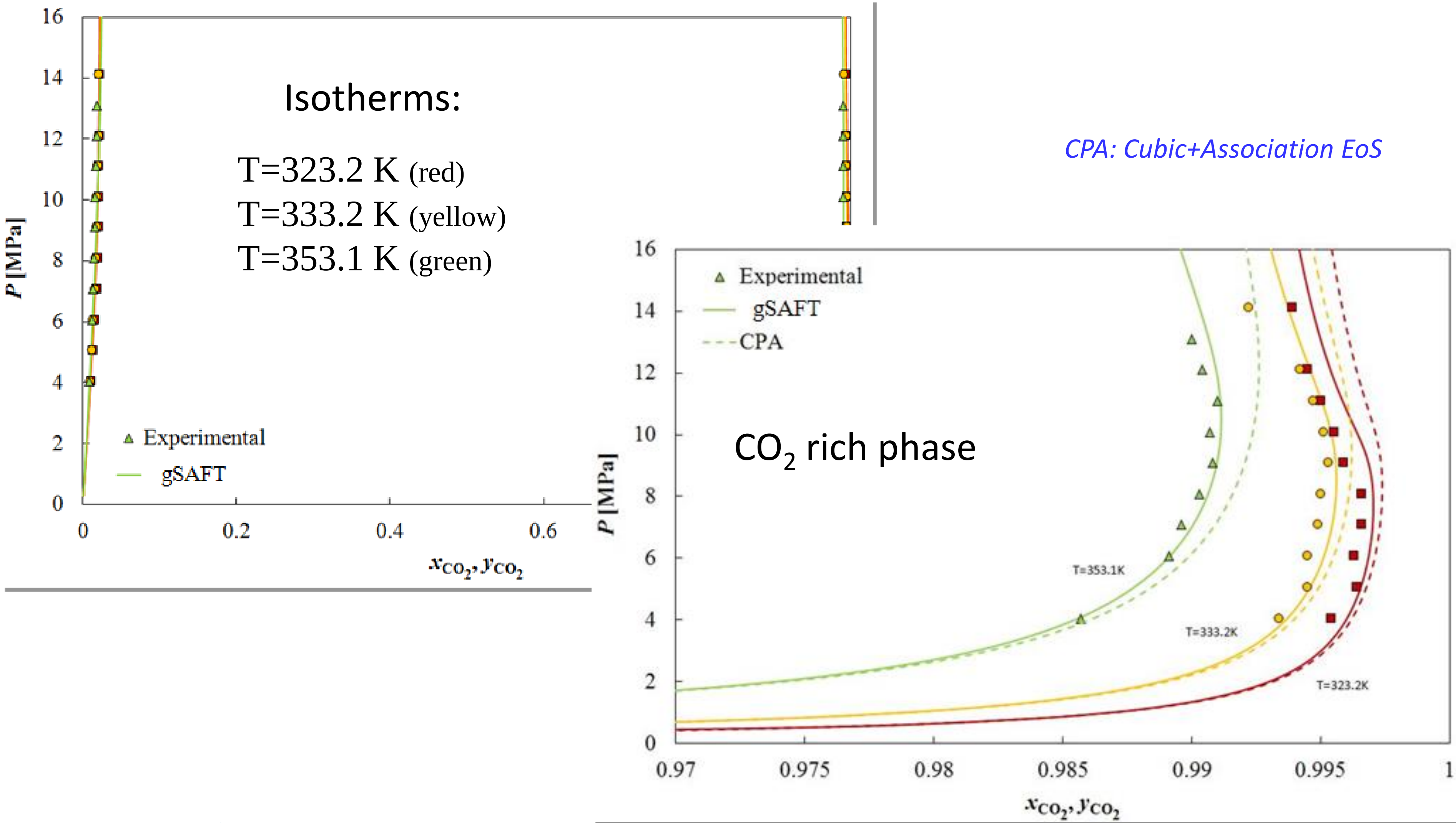
→ A predictive equation of state is required

- applied to mixtures of CO_2, CO, H_2O, Ar.....
- small molecules → single group each

gSAFT for compression/transmission in CCS

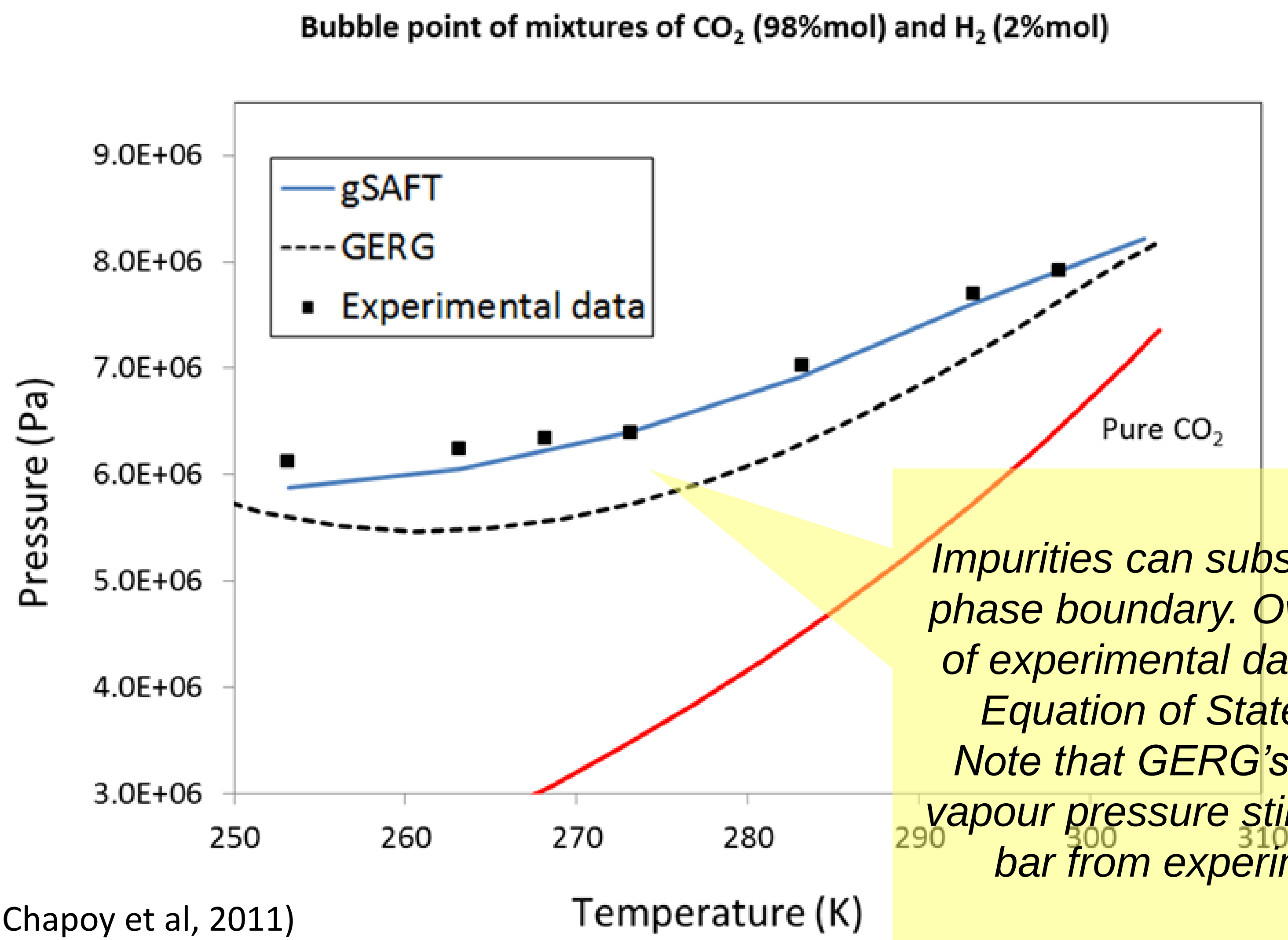
Comparisons: Binary mixture H_2O + CO_2

CPA: Cubic+Association EoS



Why gSAFT?

Accurate prediction of phase envelope for near-pure CO_2 mixtures



(Chapoy et al, 2011)

Impurities can substantially impact phase boundary. Owing to the lack of experimental data, a predictive Equation of State is required. Note that GERG's predictions of vapour pressure still deviate by 4-5 bar from experimental data.

gPROMS product family

PSE

General mathematical modelling

gMODEL

gPROMS ModelBuilder
Advanced process modelling environment

Sector-focused modelling tools

Chemicals & Petrochemicals

gPROCESS

gPROMS ProcessBuilder
Advanced process simulation

AML: GLC
AML: FBCR
AML: FT
AML: BCR
AML: TBR

Advanced model libraries for reaction & separation

Life Sciences, Consumer, Food, Spec & Agrochem

gSOLIDS

Solids process optimisation

gCRYSTAL

Crystallization process optimisation

gCOAS

Oral absorption

Power & CCS

gCCS

CCS system modelling

Fuel Cells & Batteries

gFUELCELL

Fuel cell stack & system design

Oil & Gas

gFLARE

Flare networks & depressurisation

Wastewater Treatment

gWATER

Wastewater systems optimisation

gPROMS — The gPROMS platform

Equation-oriented modelling & solution engine

Materials modelling

gSAFT
INFOCHEM Multiflash
OLI

Model deployment tools

Enterprise: gE:Web

Objects: gO:Run, gO:MATLAB, gO:CAPE-OPEN, gO:CFD

Deploy models in common engineering software

Corporate

PSE

Products

gPROMS

gPROMS

gMODEL

gPROCESS

gSAFT

AML: FBCR

AML: GLC

gFLARE

gFUELCELL

gCRYSTAL

gSOLIDS

gCCS

gCOAS

gWATER

Sector icons

gPROMS Objects

MATLAB Enabled

gO:MATLAB

gO:CFD

gO:CAPE-OPEN

gO:Run

Enterprise

APM Forum

APM

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