Evaluation of the impact of post-combustion CO_2 capture on power plant performance

Dynamic model of a 725 MW combined cycle gas turbine power plant with a CO_2 post-combustion capture unit

Baligh El Hefni
Eric Joos
Anatole Weill
EDF/R&D
baligh.el-hefni@edf.fr ; eric.joos@edf.fr

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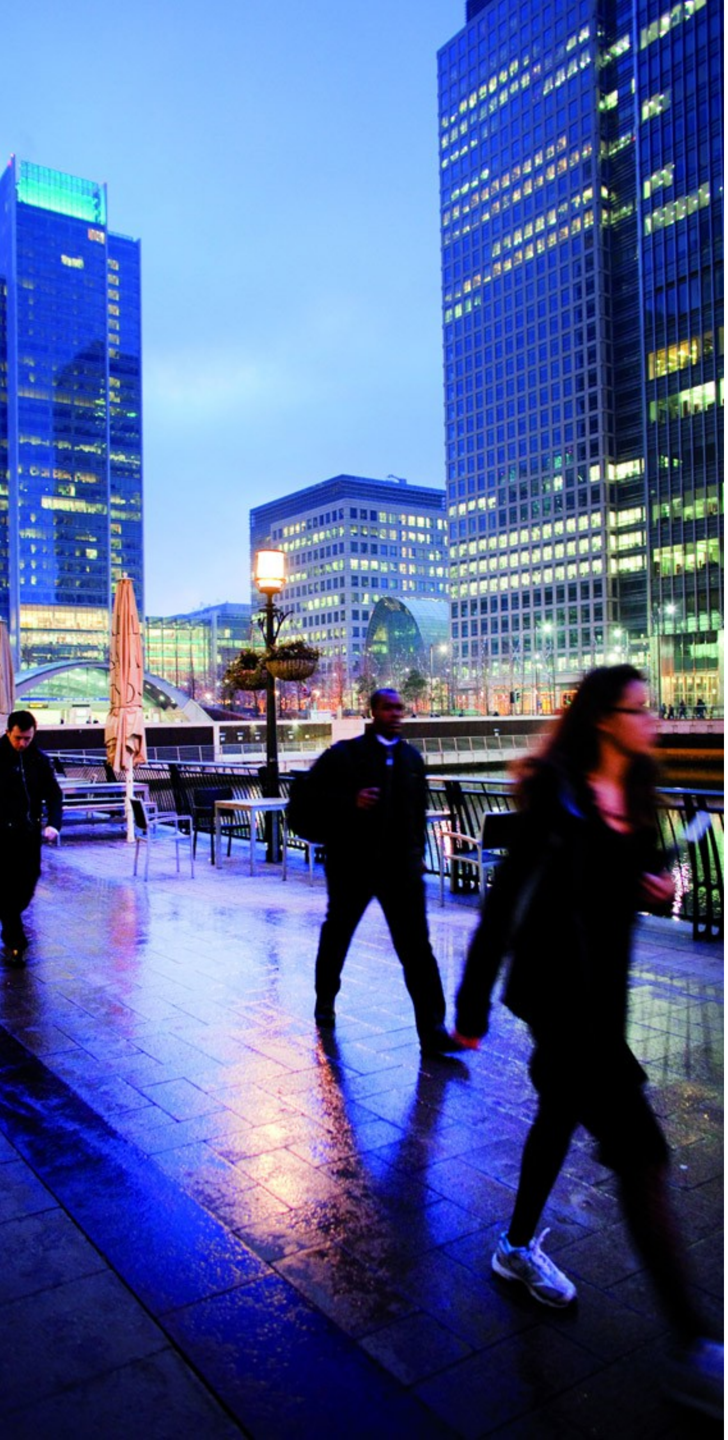
Overview

- Introduction to ThermoSysPro
- Dynamic model of the Combined-Cycle Power Plant with CO_2 capture unit
- Simulation scenario and results
- Conclusion



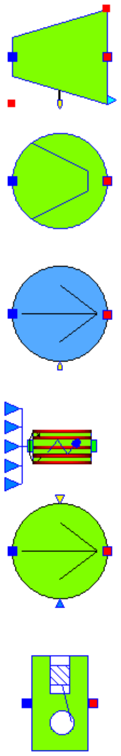
Introduction to ThermoSysPro

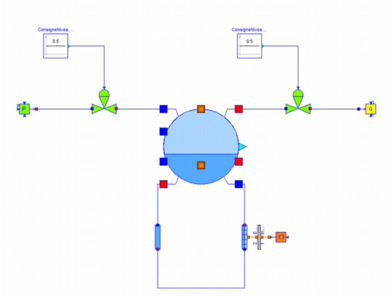
EDF Modelica Library

ThermoSysPro: General principles

ThermoSysPro is a generic library for the modeling and simulation of power plants and other kinds of energy systems.

- Multi-domain modelling: thermal-hydraulics (water/steam and flue gases), combustion, solar, neutronic, control, …
- The level of detail of the models is flexible
- Steady-state and dynamic modelling
- Based on first physical principles: mass, energy, and momentum conservation equations
- One and two-phase flow
- State-of-the-art correlations for two-phase flow
- Incompressible and compressible flow
- Handling of flow reversal

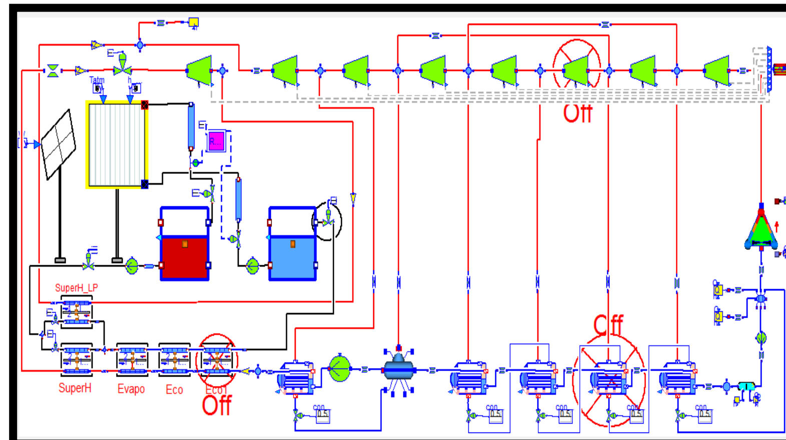


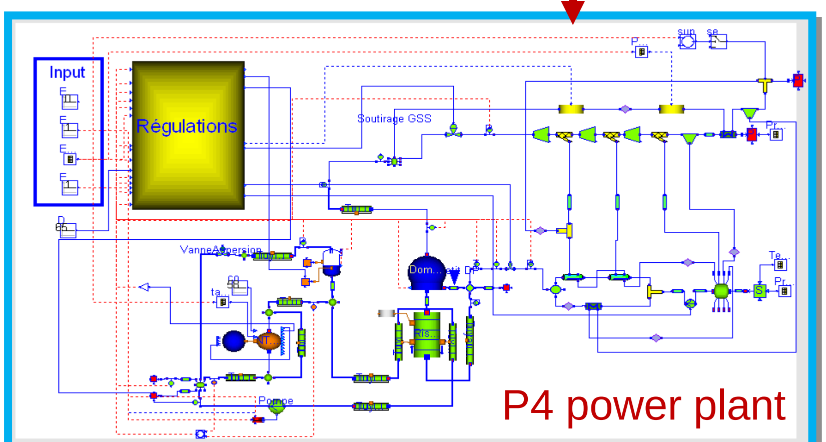


ThermoSysPro: General principles

- Open source released under **Modelica** 2 license
- Designed to be tool independent
  - Current reference tool: Dymola
  - Can be used with SimulationX and OpenModelica
- Designed to be easily understood and modifiable
- Validated against real applications:
  - Concentrated solar power plants
  - Fossil fuel fired power plants
  - Biomass power plants
  - Nuclear power plants
  - etc.

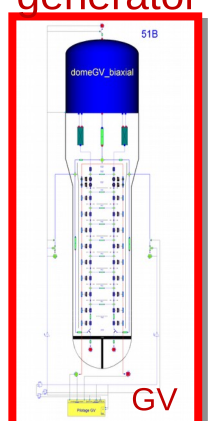
Concentrated solar power plant
Tower receiver, molten salt storage





P4 power plant

Steam generator



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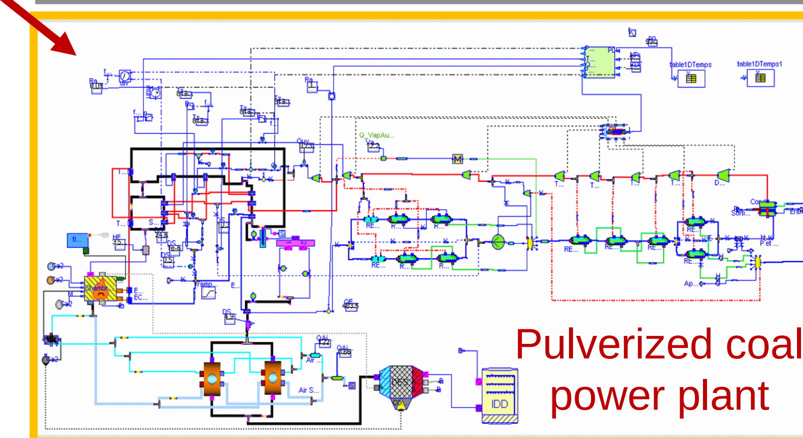
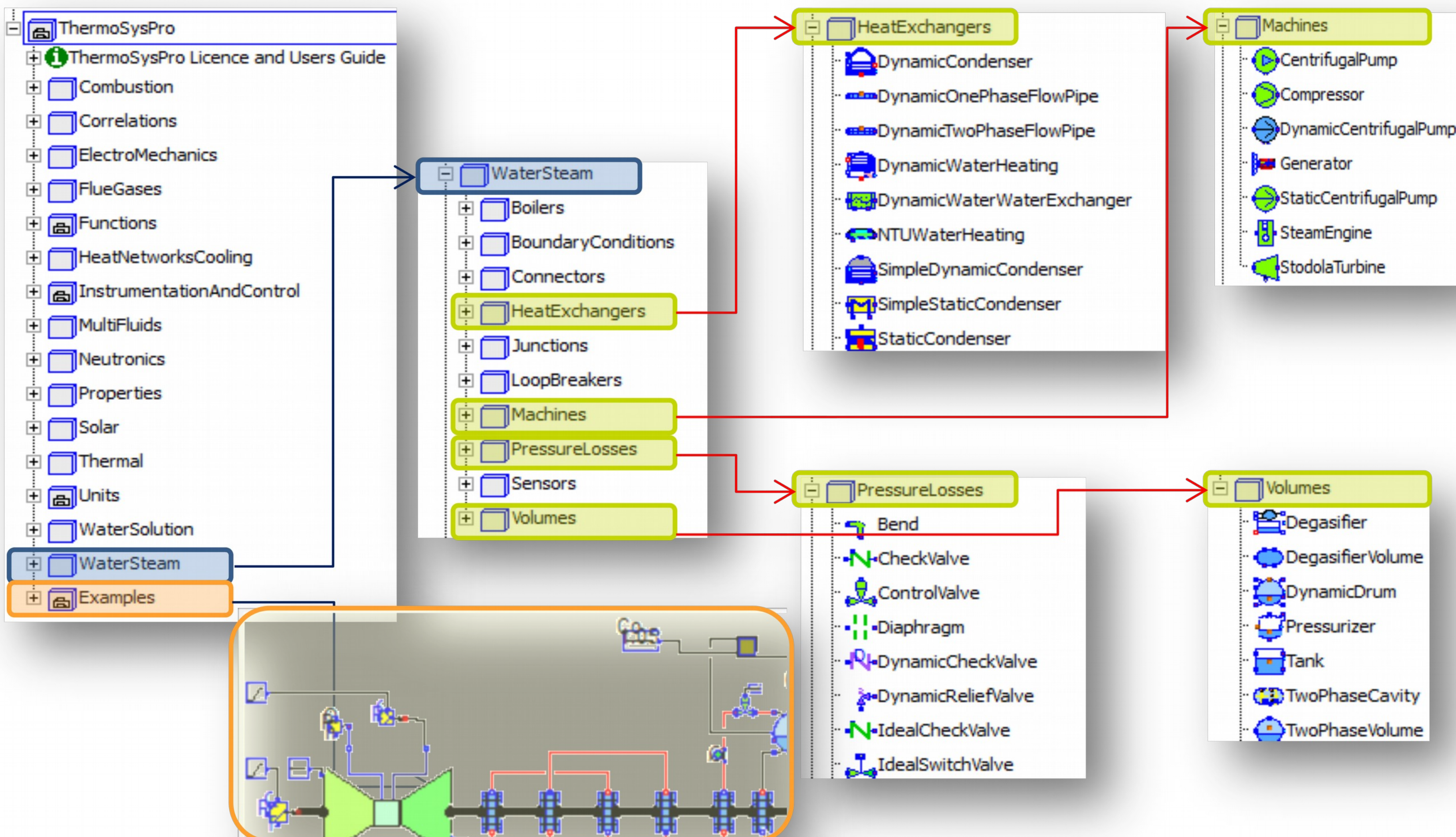


Pulverized coal power plant

ThermoSysPro: The library organization



Contains about 200
model components

ThermoSysPro: Carbon Capture Package

The components of the CO_2 post-combustion capture unit has been developed within the framework of a project funded by the Energy Technologies Institute (ETI) .

Column model: the transport model is based on mass and energy balance equations for liquid and gas phases, in order to represent the dynamic of the different fluids flowing vertically through the absorption and desorption columns. The model take into account other phenomena such:

- The mass transfer at the interphase gas-liquid as well as diffusion limitation in gas and liquid phases,
- The heat transfer between the two phases,

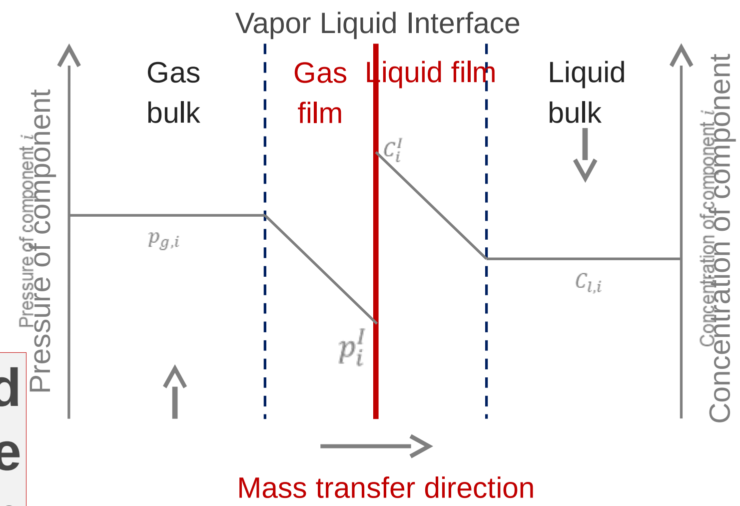
Column model: Assumptions

- Capture process based on MEA solvent (30 wt %),
- The equilibrium is reached, between the liquid and gas streams at each stage of the absorber (using performance correction factors),

ThermoSysPro: Carbon Capture Package

Column model: Assumptions

- The two film theory model has been used, for the mass transfer models with the generalized Fick's law equation (the reactions in the film were taken into account with, the use of the enhancement factor model for a pseudo-first order reaction with respect to the concentration of CO_2),
- No accumulation takes place in the film between the two phases, that chemical reactions only take place in the liquid bulk, and that the bulks of both phases are well mixed,



The key performance indicators provided by this model were compared to the experimental indicators and Aspen software.

This absorption column model is detailed in ETI report: Anatole Weill, "Milestone 20 WP5 Internal Deliverables 5.3.5b, Modelica post-combustion CO_2 capture models description and validation", March 2014".

Dynamic model of the Combined-Cycle Power Plant with CO_2 capture unit

Dynamic model of the Combined-Cycle Power Plant with CO_2 capture unit: objectives

The objectives of this study are:

- Developing a detailed dynamic model of a GCC power plant with CO_2 capture unit, in order to simulate the power plant performance,
- Evaluate the impact of the addition of a CO_2 capture unit, on the GCC power plant dynamic behavior, at full load and at load reduction,
- Quantify the power plant performance at the part load (plant efficiency).
- Compare the performance provided by the ThermoSysPro model, with the performance provided by some projects and software,

Dynamic model of the Combined-Cycle Power Plant with CO_2 capture unit : nominal data

Technical characteristics of the Combined-Cycle Power plant:

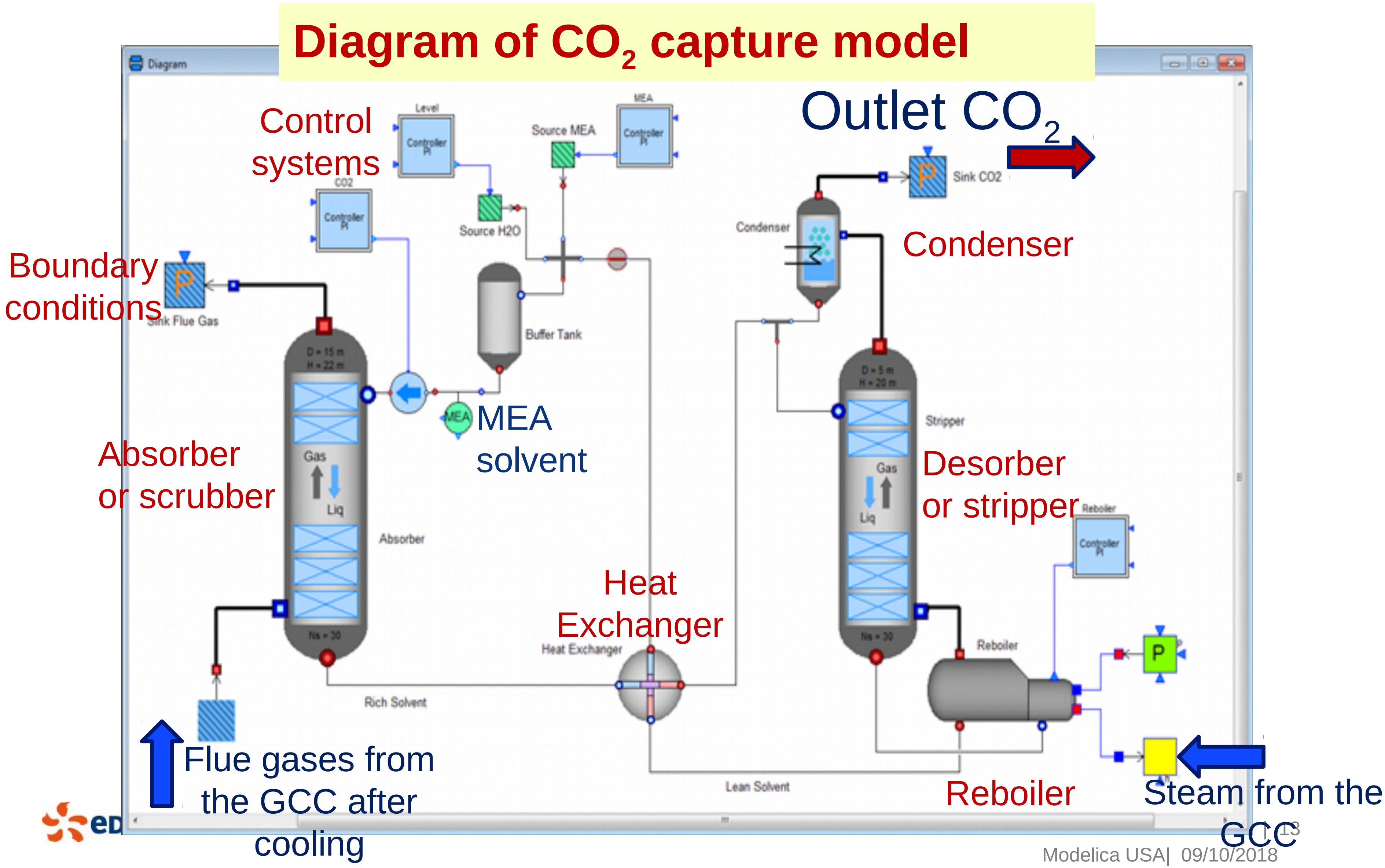
Configuration	Characteristics
Gas Turbine: Nominal power	2*230 MW (Two Gas Turbine)
Steam Turbine: Nominal power	265 MW (Two HRSG "two trains")
High pressure circuit at nominal power	127 bar, 567°C
Intermediate pressure circuit at nominal power	27 bar, 568°C
Low pressure circuit at nominal power	4.9 bar, 259°C,
Condenser: Thermal power	423 MW
Condenser: Steam mass flow rate	193.4 kg/s
Condenser: Vacuum pressure:	6100 Pa
Compressor: Compression rate	13,8

Dynamic model of the Combined-Cycle Power Plant with CO_2 capture unit: data

Technical characteristics of the capture unit

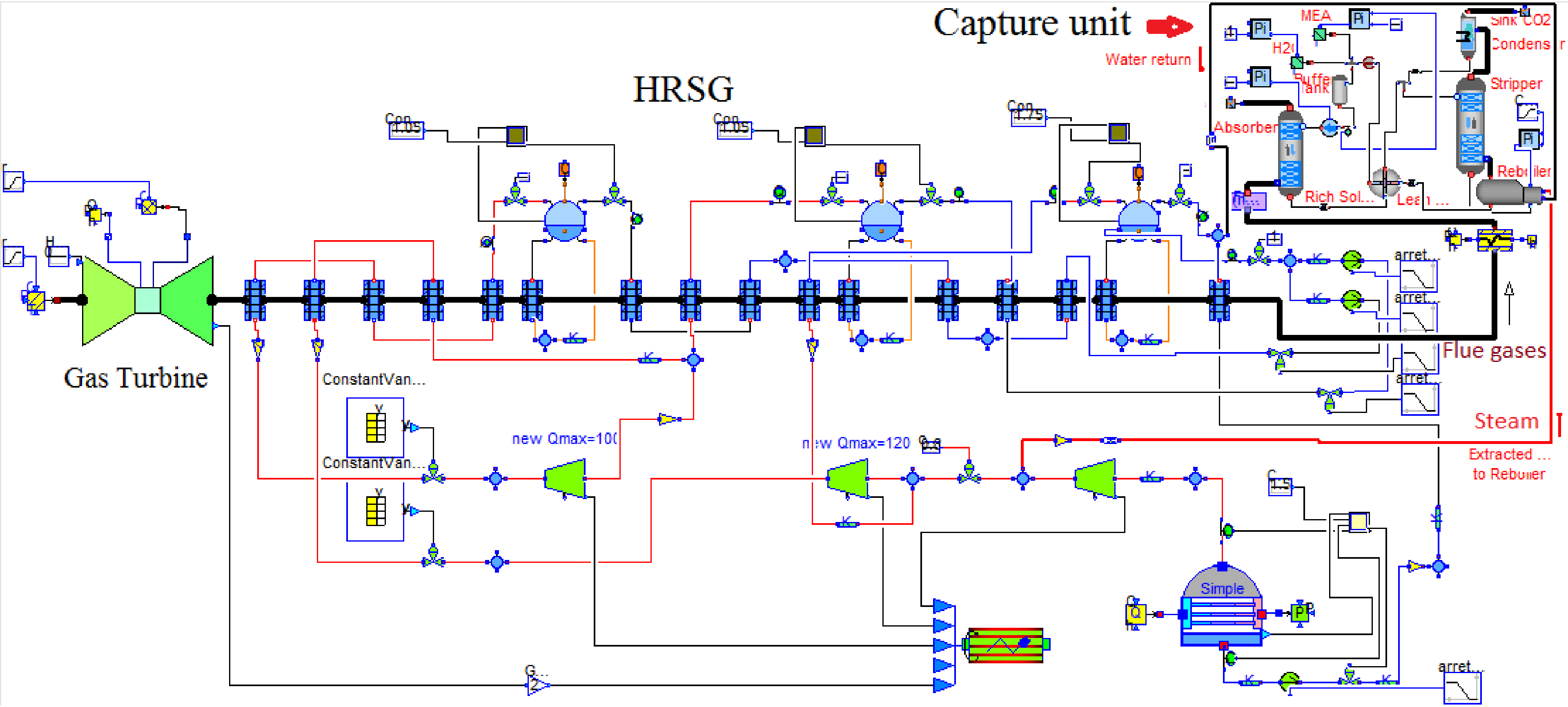
Configuration	Characteristics
Absorber: Diameter	15 m
Packing Height	15 m
Packing Type	Mellapak 250Y
Inlet Cold Solvent Temperature	40 °C
Desorber: Diameter	5 m
Packing Height	20 m
Packing Type	Mellapak 250Y
Inlet Cold Solvent Temperature	100 °C
Reboiler: Pressure	1,86 bar
Temperature	117,9 °C
Solvent Tank: Diameter	5 m

Dynamic model of the Combined-Cycle Power Plant with CO_2 capture unit: CO_2 capture unit model



Dynamic model of the Combined-Cycle Power Plant with CO_2 capture unit: (one train model)

Detailed dynamic model of the Combined-Cycle Power Plant, with a CO_2 capture unit.



Statistics:	1771	Components,	21683	Variables,
	11586	Equations,	700	Differentiated variables

Hydraulic loop is closed via condenser

Dynamic model of the Combined-Cycle Power Plant with CO_2 capture unit: calibration

A preliminary calibration of the model was made against measurement or design data at 100% load.

Variables imposed in the model	Parameters computed by the model
Pressure at the outlet of the pumps	Characteristics of the pumps
Pressure at the inlet of the steam turbines	Ellipse law coefficients of the steam turbines
Liquid level in drums and in condenser and pressure	CV of the valves (characteristics) and the valves positions (openings)
Overall heat exchangers coefficients	Heat exchangers fouling coefficients
Isentropic efficiency of the compressor	Nominal isentropic efficiency of the compressor
Exhaust temperature of the gas turbine	Nominal isentropic efficiency of the turbine

Simulation Scenario and Results

Dynamic model of the Combined-Cycle Power Plant with CO_2 capture unit: simulation scenario

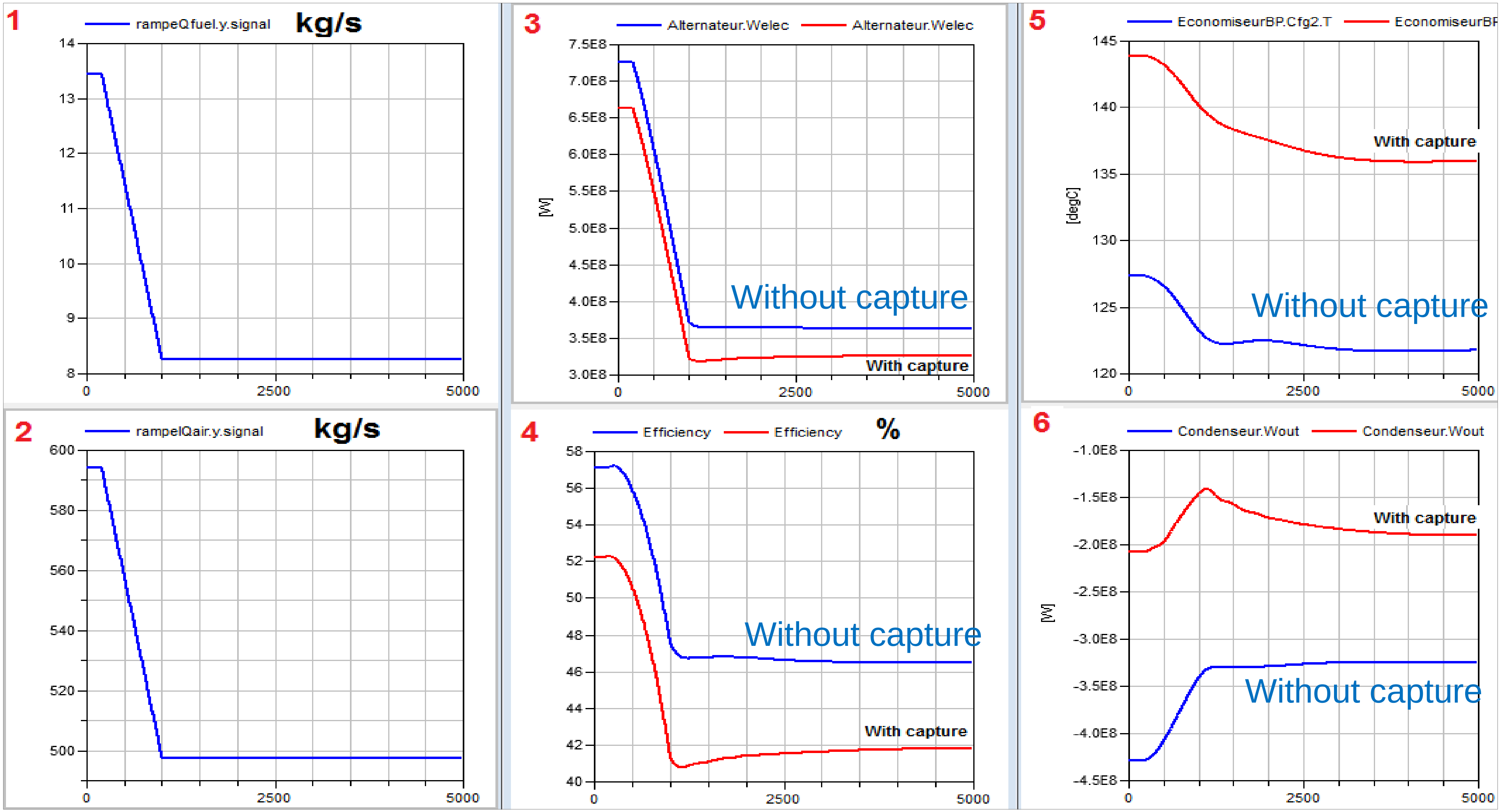
Simulation scenario

The scenario is a power generator step reduction from 100 to 50% load:

- Initial state (combined cycle): 100 % load
- Final state (combined cycle): 50% load (800 s slope).

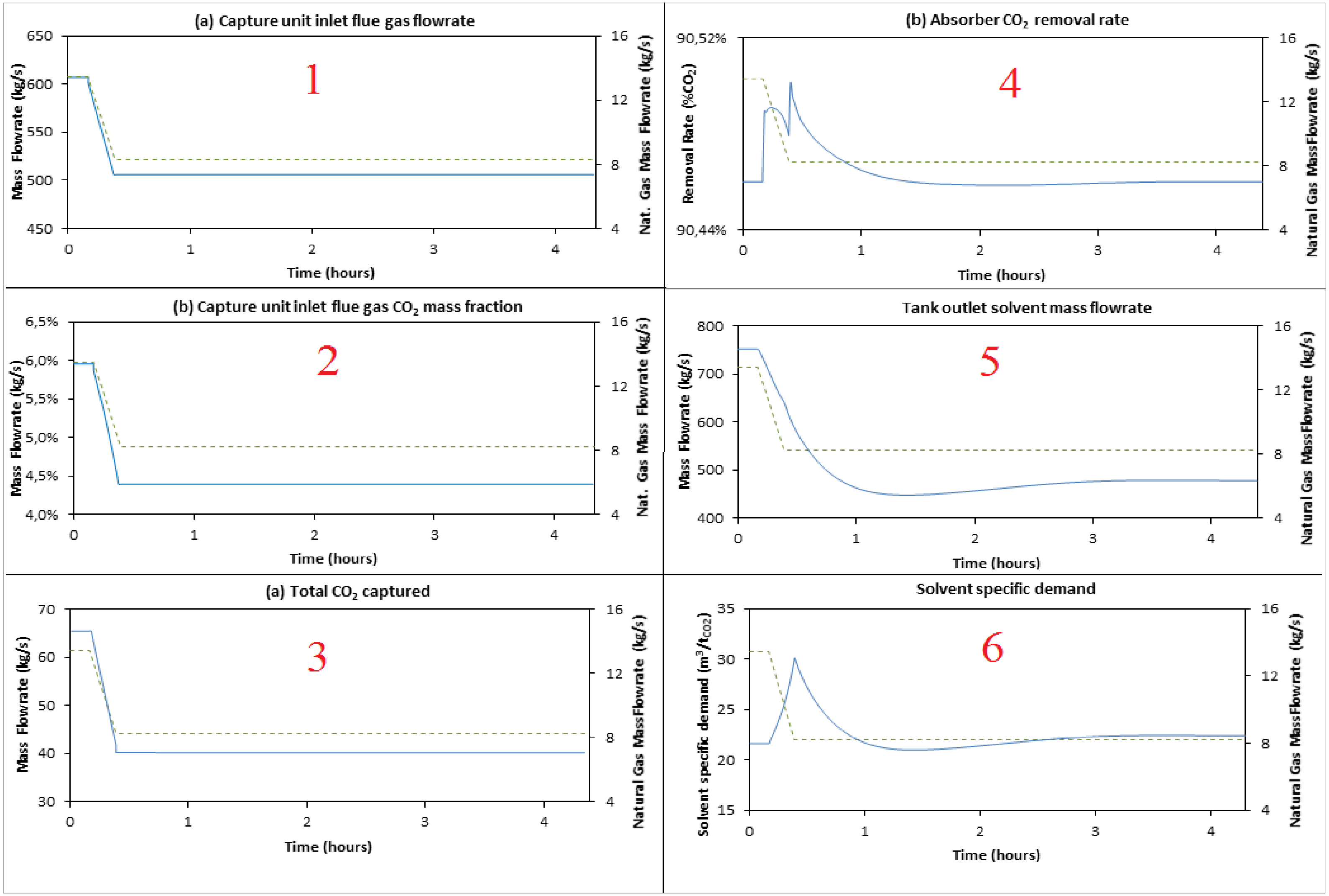
The simulation runs were done using Dymola tool

Dynamic model of the Combined-Cycle Power Plant with CO_2 capture unit: simulation results



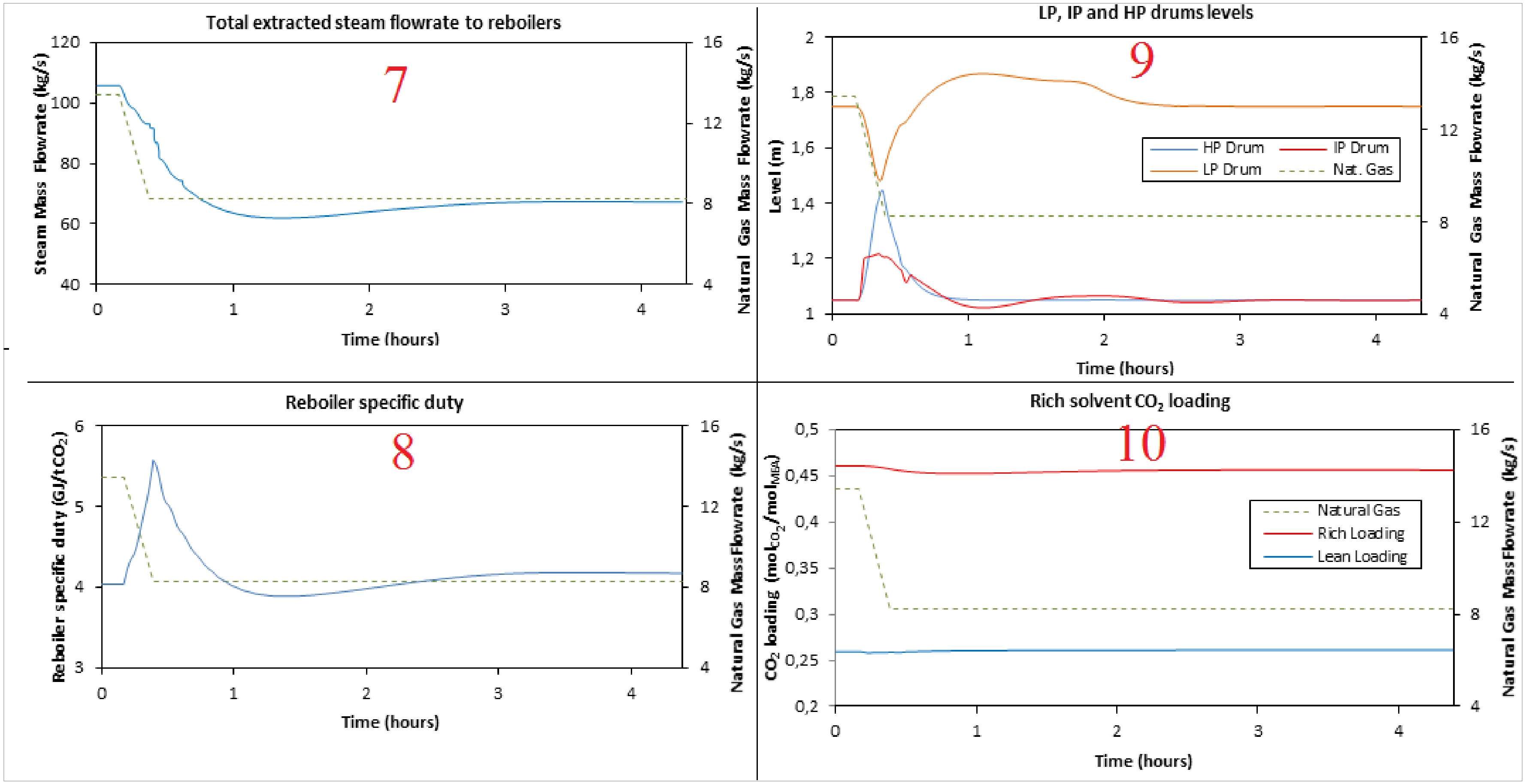
(1) The natural gas mass flow rate, (2) Air mass flow rate, (3) Power generator blue (without capture) red (with capture), (4), Power plant efficiency, (5) Flue gases exhaust temperature (HRSG) at the outlet, and (6) Power evacuated by the condenser

Dynamic model of the Combined-Cycle Power Plant with CO_2 capture unit: simulation results



(1) flue gases mass flow rate, (2) CO_2 mass fraction, (3) total mass flow rate of CO_2 captured by the two capture trains, (4) the absorber removal rate (in percentage of the total inlet CO2 flow rate), (5) the solvent mass flow rate, and (6) the solvent specific demand.

Dynamic model of the Combined-Cycle Power Plant with CO_2 capture unit: simulation results



(7) extracted steam mass flow rate for the two capture trains, (8) the reboiler specific duty, (9) the variations of level for the three drums, and (10) the variations of rich and lean solvent CO_2 loadings (the variation of natural gas mass flow rate is represented with a dashed green line),

Dynamic model of the Combined-Cycle Power Plant with CO_2 capture unit: simulation results

The model results has been compared with CAESAR project and with simulation results of the PSE's gCCS model (gPROMS) (at 100 % load).

Parameter	Unit	CAESAR	Modelica	Deviation [a]	PSE's gCCS	Deviation
Gross power output without capture	MW	837	725.80	13.3 %	746.0	2.78%
Gross power output with capture	MW	759.9	653.70	14 %	671.5	2.72%
Absolute loss of gross power output	MW	-77.1	-72.1	-6.48%	-74.5	3.33%
Relative loss of gross power output	%	-9.20%	-9.93%	7.98%	-9.98%	0.50%
Gross electric efficiency (LHV base)	%	58.8	57.1	2,9 %	57.8	1.23%
Gross efficiency with capture	%	53.4	51.5	3.6 %	52.0	0.97%
Gross efficiency loss	pt	5.40	5.68	5.10%	5.76	1.41%
"	%	9.21	9.93	7.86%	9.98	0.50%
Removal efficiency	%	90.46	90.46	0.00%	90.00	-0.51%
Flue gas flow rate [b]	kg/s	665.3	607.44	-8.70%	607.4	-0.01%
CO_2 feed content	%kg	6.10%	5.95%	-2.40%	5.83%	-2.02%
CO_2 Captured [b]	t/hr	132.9	117.8	-11.38%	114.8	-2.55%
Solvent MEA Concentration	wt-%	30.0	30.00	0.00%	30.0	0.00%
Lean Solvent Flowrate [b]	m3/s	0.87	0.71	-18.62%	0.73	2.82%
Solvent Specific Demand	$m3/tCO_2$	23.5	21.6	-7.90%	22.9	6.02%
Reboiler specific duty	MJ/tCO_2	3.96	4.03	1.83%	4.00	-0.74%
CO_2 Rich Loading	mol_{CO2}/mol_{MEA}	0.466	0.461	-1.15%	0.460	-0.22%
CO_2 Lean Loading	mol_{CO2}/mol_{MEA}	0.257	0.259	0.88%	0.260	0.39%
Emissions without capture [c]	kg_{CO2}/MWh_{el}	351.8	358.75	1.98%	345.9	-3.58%
Emissions with capture [c]	kg_{CO2}/MWh_{el}	36.2	38.5	6.47%	38.1	-1.04%
CO_2 Avoided	%	89.71%	89.26%	-0.51%	89.00%	-0.29%
SPECCA [c]	MJ_{LHV}/kg_{CO2}	2.0	2.3	13.91%	2.3	0.00%

[b] : For one train only; [c] : These values only take into account the steam cycle auxiliary electric losses.

Conclusion

Dynamic model of the Combined-Cycle Power Plant with CO_2 capture unit: Conclusion

- A detailed dynamic model of a combined cycle power plant with a CO_2 post-combustion capture unit, has been developed and validated,

- Most of the ThermoSysPro model values are in consistent with the CAESAR project results. However, several differences are observed, due in the difference in the power plants characteristics:
  - The solvent specific demand is 8% lower compare to CAESAR,
  - The total flow of CO2 captured is 11.4% lower, due to the differences in the power plants characteristics (lower flue gases flow rate, etc.),
  - The solvent flow rate is 18.6% lower,

- Also, the model results has been compared with PSE's model (gPROMS). The results are in quite good agreement, for most key performance indicators (under 1%), except solvent specific demand is 6% higher,

- The numerical robustness of the model has been verified.

References

Dynamic model of the Combined-Cycle Power Plant with CO_2 capture unit: References

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Thank you for your attention