DYNAMIC MODELS AND CONTROL STRATEGIES FOR ABSORPTION-BASED CARBON CAPTURE PROCESSES

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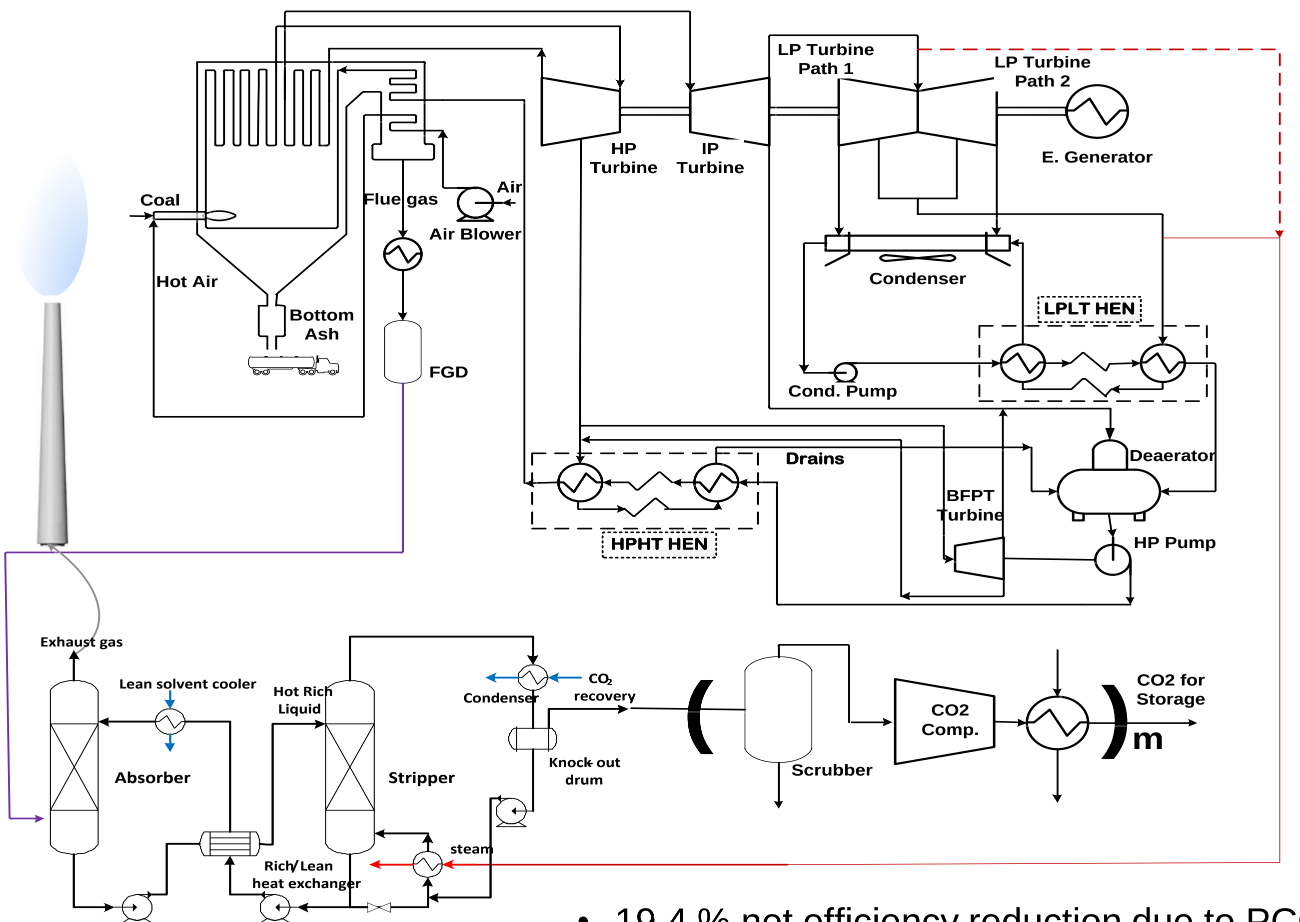
Content

Background



- 19.4 % net efficiency reduction due to PCC
- High capital cost
- Flexibility in operation

Ref. : Rajab Khalilpour and Ali Abbas, HEN optimization for efficient retrofitting of coal-fired power plants with post-combustion carbon capture. International Journal of Greenhouse Gas Control, 2011. 5(2): p. 189-199.

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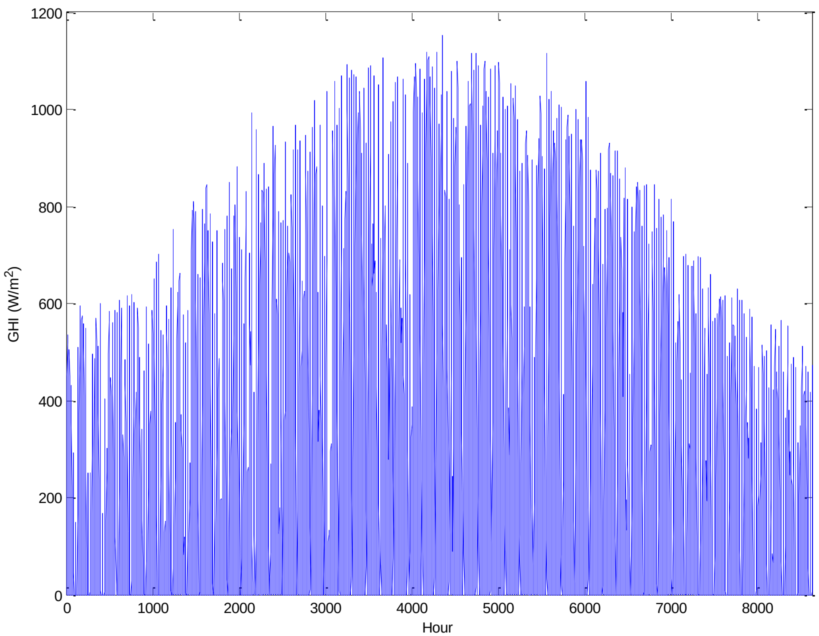
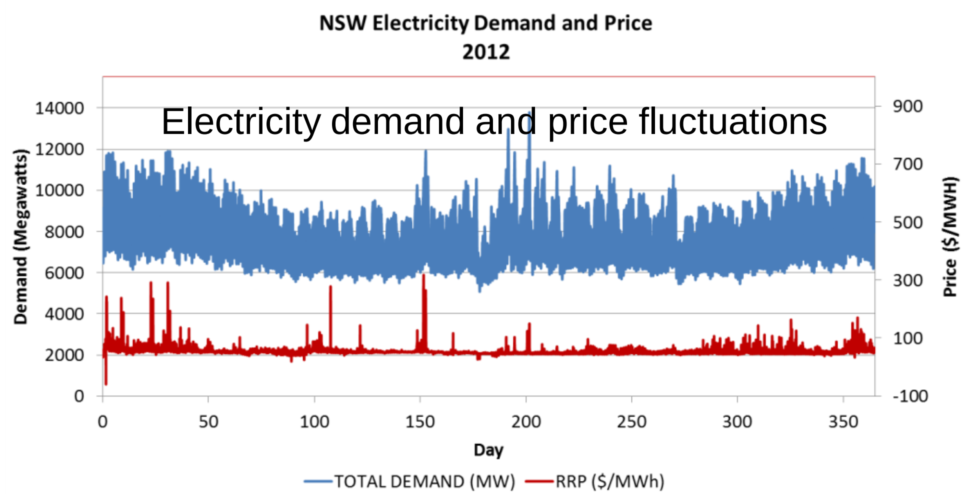
Motivation: A domain of operational uncertainties

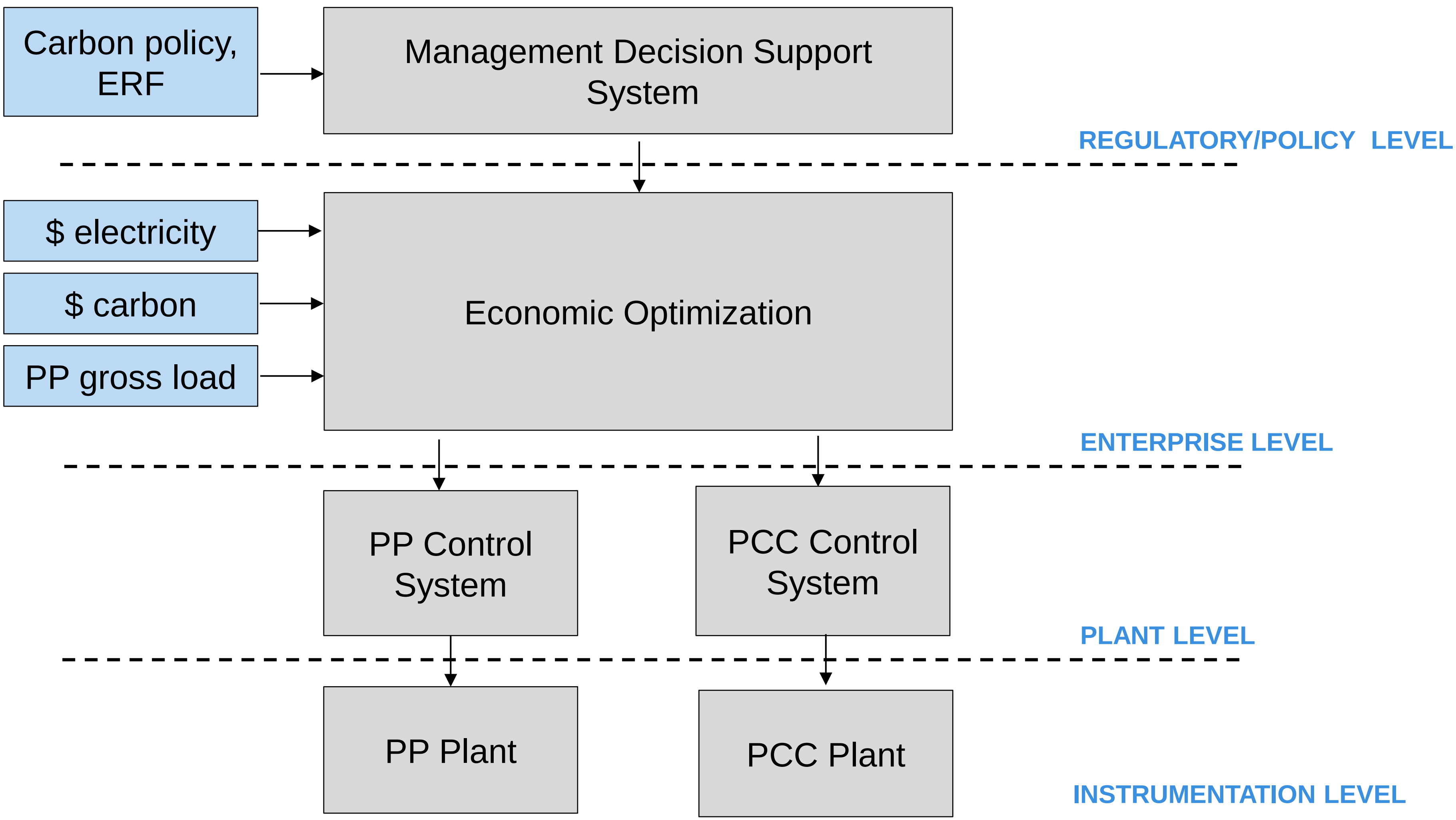
- Carbon tax scheme started in July 2012, scrapped July 2014
- Variations in GHI, electricity price, electricity demand & carbon price

Hourly Global Horizontal Irradiation (GHI) in Sydney





Outlook


Carbon policy, ERF
Management Decision Support System
REGULATORY/POLICY LEVEL
$ electricity
$ carbon
PP gross load
Economic Optimization
ENTERPRISE LEVEL
PP Control System
PCC Control System
PLANT LEVEL
PP Plant
PCC Plant
INSTRUMENTATION LEVEL

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Significance and objective

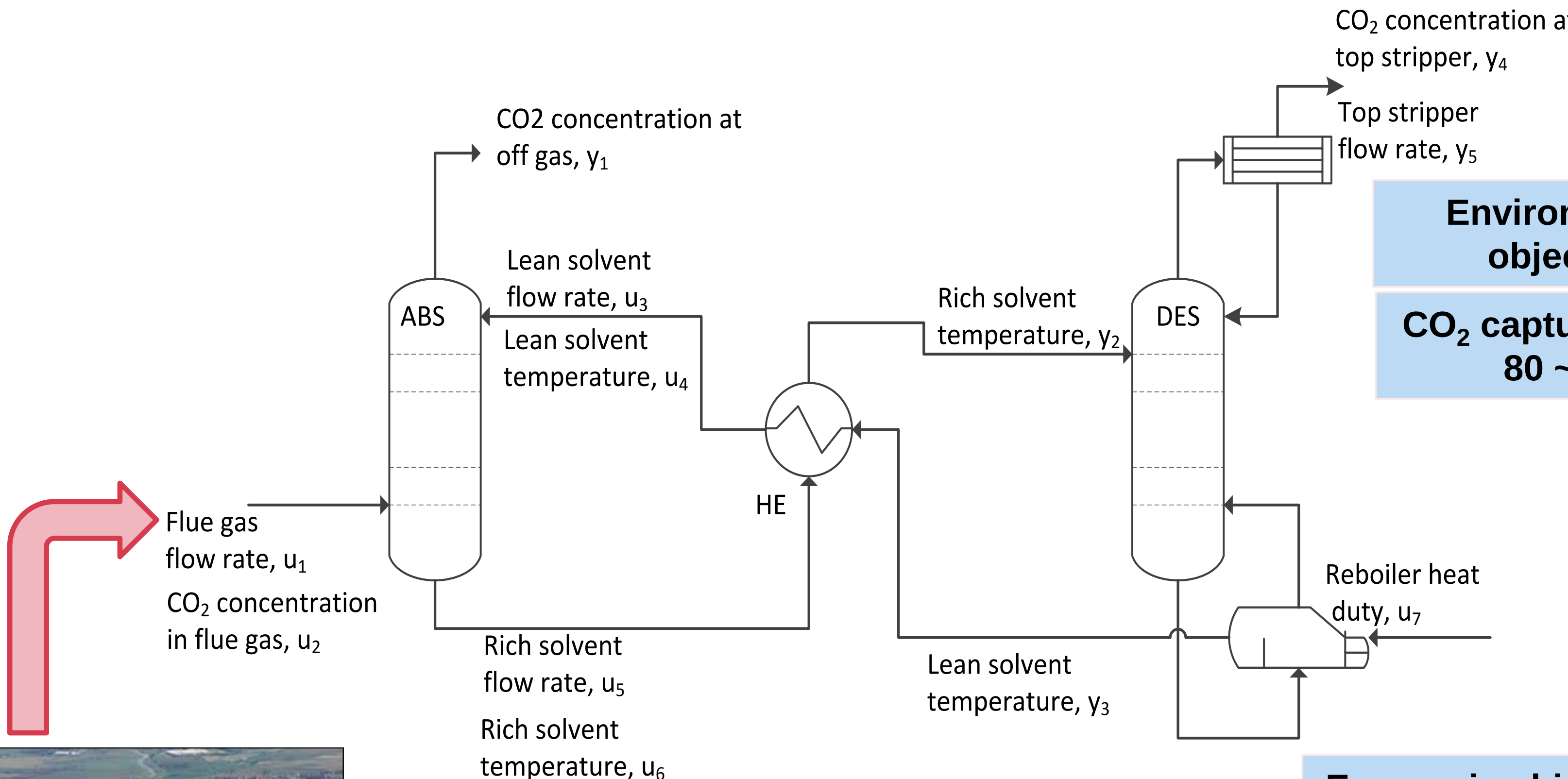
Integration of PCC into coal-fired power plant requires understanding dynamic operations.

The PCC plant must respond flexibly to three significant scenarios:

1. Power plant operations at full and partial loads,
2. Under external disturbances from power plant and auxiliary systems, and
3. Considering fluctuations in electricity and carbon prices.

The objective of this study is to develop a dynamic model and use it in simulation analysis for techno economic study includes advanced control, optimization and management decision support system.

Significance and objective



Environmental objective:

CO_2 capture, CC% = 80 ~ 95%

Economic objective:

Energy Performance, EP = 3.5 ~ 4.5 MJ/kg CO_2

Modelling Approach 1: Empirical model

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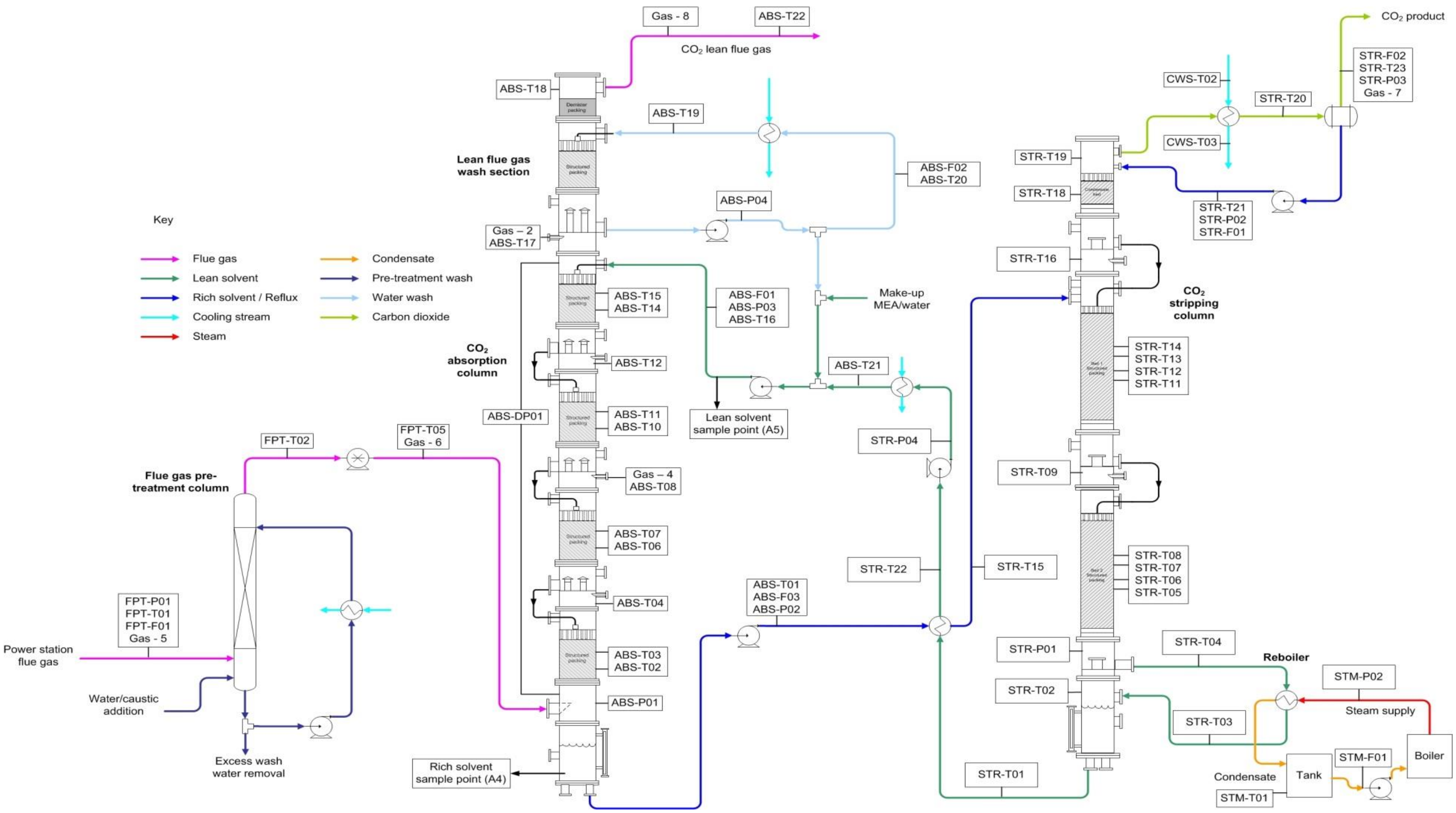
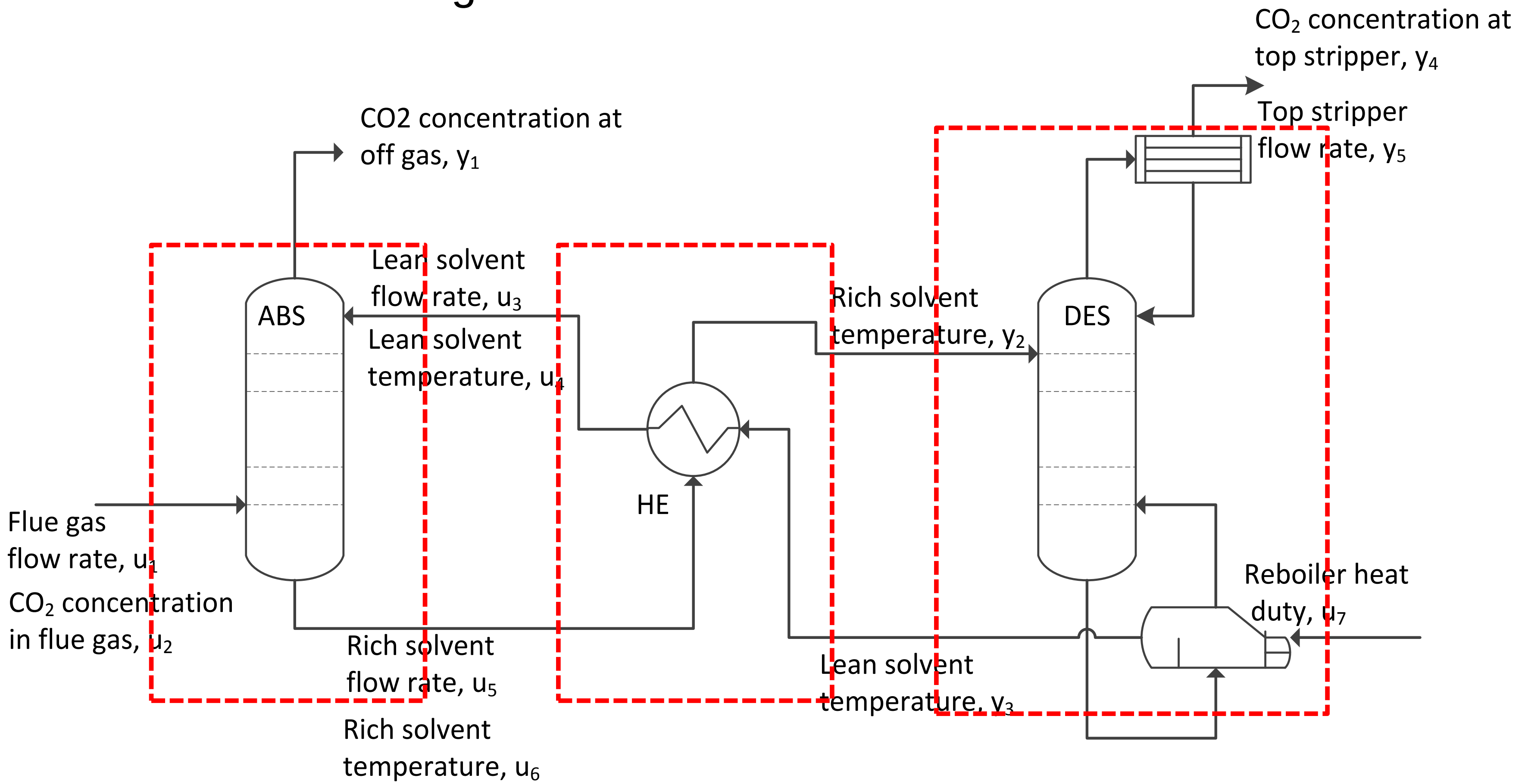
Tarong PCC pilot plant process flowsheet



Modelling Approach 1: Empirical model

Model boundaries using **NARX data-based model**[1,2]

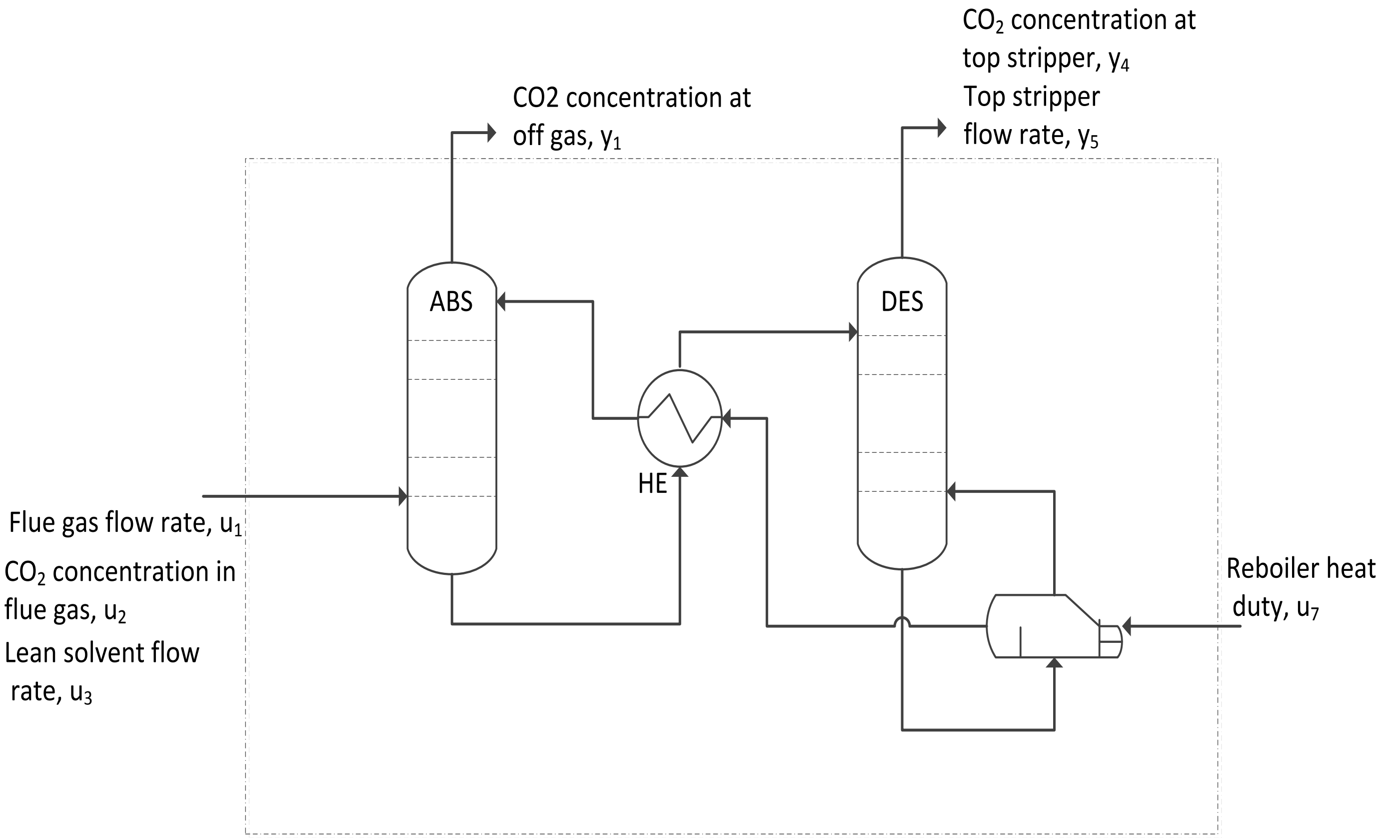


[1]Norhuda, A. M., Ashleigh , C., Paul, F. & Ali, A. 2014. Dynamic Modelling and Simulation of Post Combustion CO2 Capture Plant. *CHEMECA 2014: Western Australia*

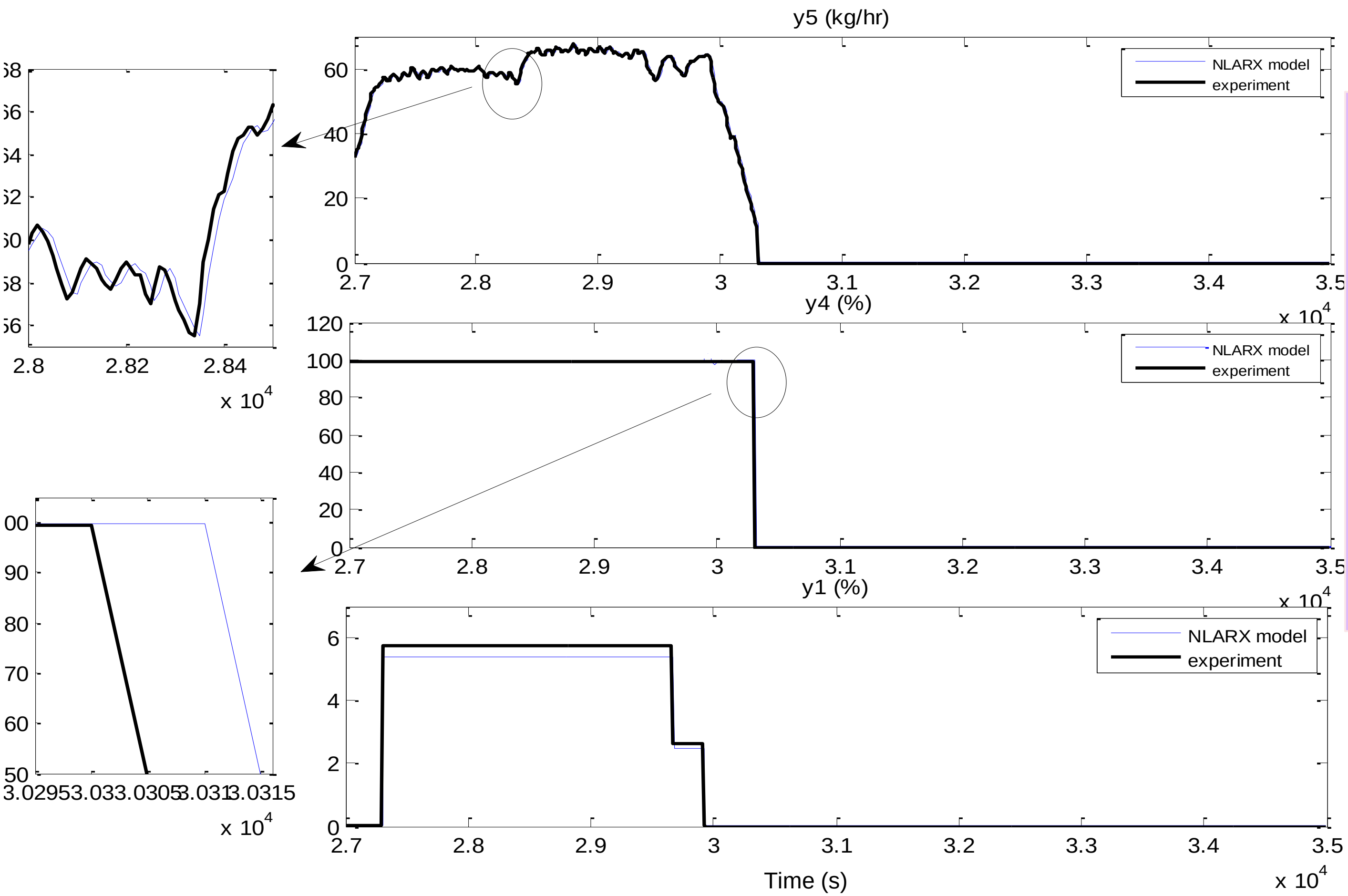
[2]Norhuda, A. M., Ashleigh , C., Paul, F. & Ali, A. 2014. Dynamic modelling, identification and preliminary control analysis of an amine-based post-combustion CO2 capture pilot plant. Journal of Cleaner Production (in review)

Modelling Approach 1: Empirical model

Integrated **NARX data-based model**



Model validation for NARX model



Pilot plant data operation : ≈ 6 hours

Sampling time: 10 sec

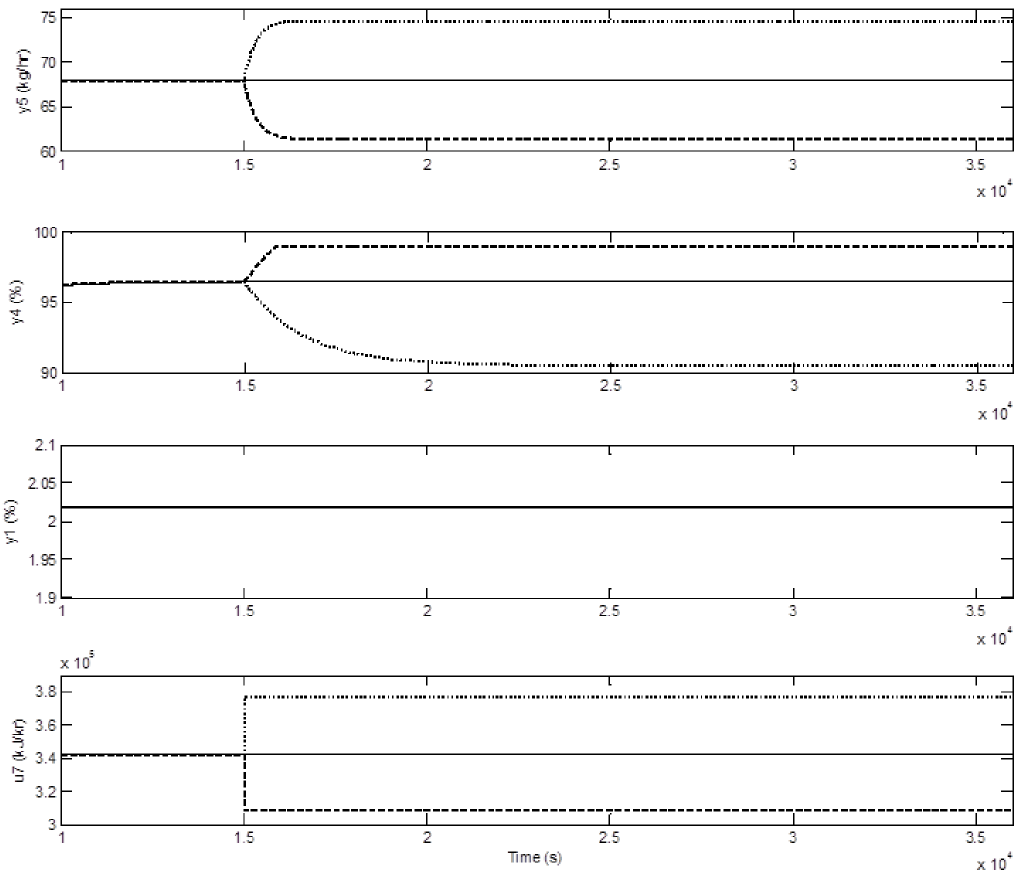
Data points: ≈ 2000

Estimate data points: ≈ 1200

Validation data points: ≈ 800

Modelling Approach 1: Open-loop dynamic analysis

Step changes in reboiler heat duty



Step changes in Reboiler heat duty (straight line: base case; dotted line: positive step change; dashed line: negative step change).

CO_2 concentration in top stripper, y_4 and top stripper flow rate, y_5 have significant open loop dynamic responses while CO_2 concentration in off gas, y_1 does not show any significant response.

Process time constants:

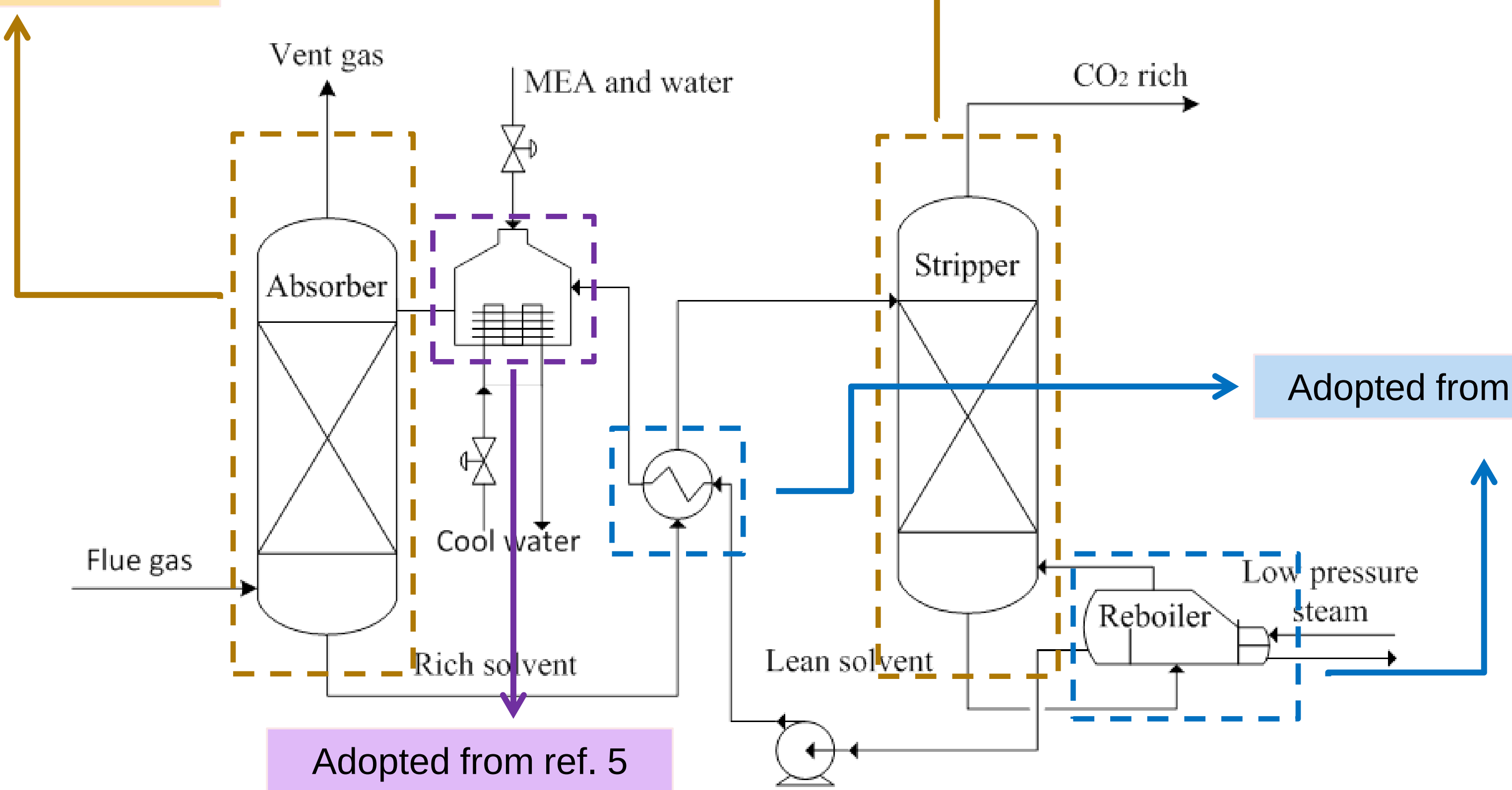
1) 6 – 15 mins for the fastest dynamics (reboiler heat duty – CO_2 concentration in top stripper relationship).

2) 8 -27 mins for the slowest dynamics (reboiler heat duty – top stripper flow rate relationship).

Modelling Approach 2: Mechanistic model

Model boundaries using **mechanistic model** [3,4,5]

Modified from ref. 3,4



Adopted from ref. 4

Adopted from ref. 5

3.Kvamsdal, H. M., Jakobsen, J. P. & Hoff, K. A. 2009. Dynamic modeling and simulation of a CO2 absorber column for post-combustion CO2 capture. Chemical Engineering and Processing: Process Intensification, 48(1), pp 135-144.
4.Harun, N., Nittaya, T., Douglas, P. L., Croiset, E. & Ricardez-Sandoval, L. A. 2012. Dynamic simulation of MEA absorption process for CO2 capture from power plants. *International Journal of Greenhouse Gas Control,* 10(295-309).
5.Nittaya, T., Douglas, P. L., Croiset, E. & Ricardez-Sandoval, L. A. 2014. Dynamic modelling and control of MEA absorption processes for CO_2 capture from power plants. *Fuel,* 116(0), pp 672-691.

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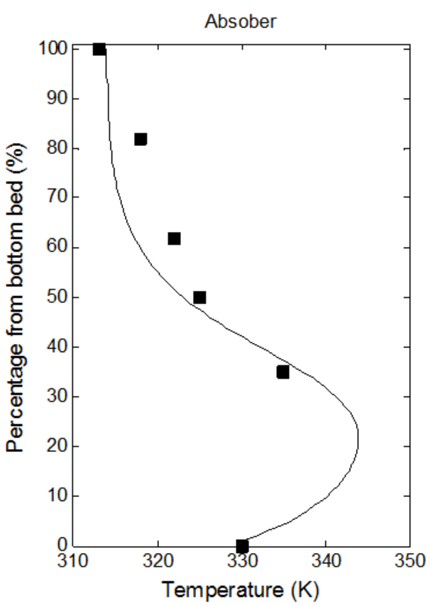
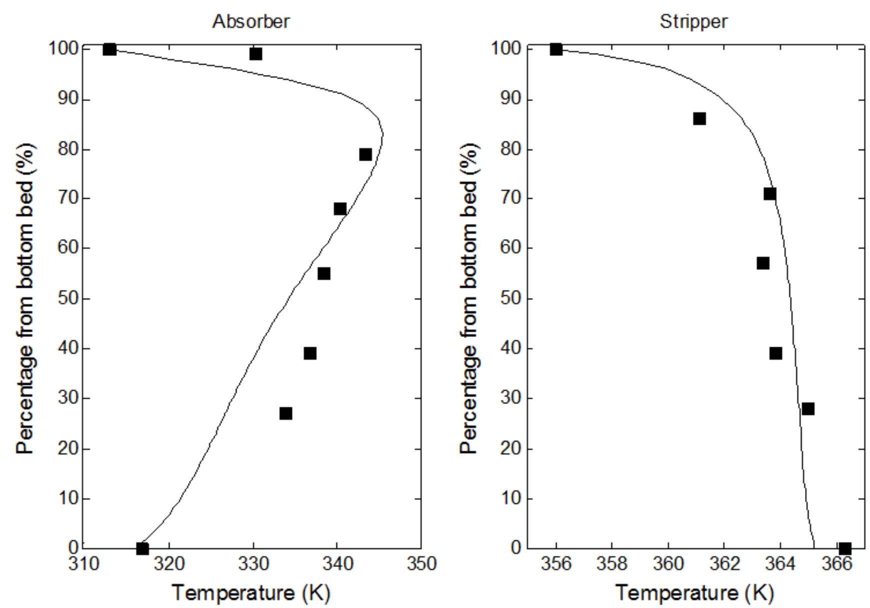
Modelling Approach 2: Mechanistic model

Model validation for **mechanistic model**[6]



Column temperature profiles from the simulation (line) and the pilot plant study (dot) for the pilot plant test no. 32[7].



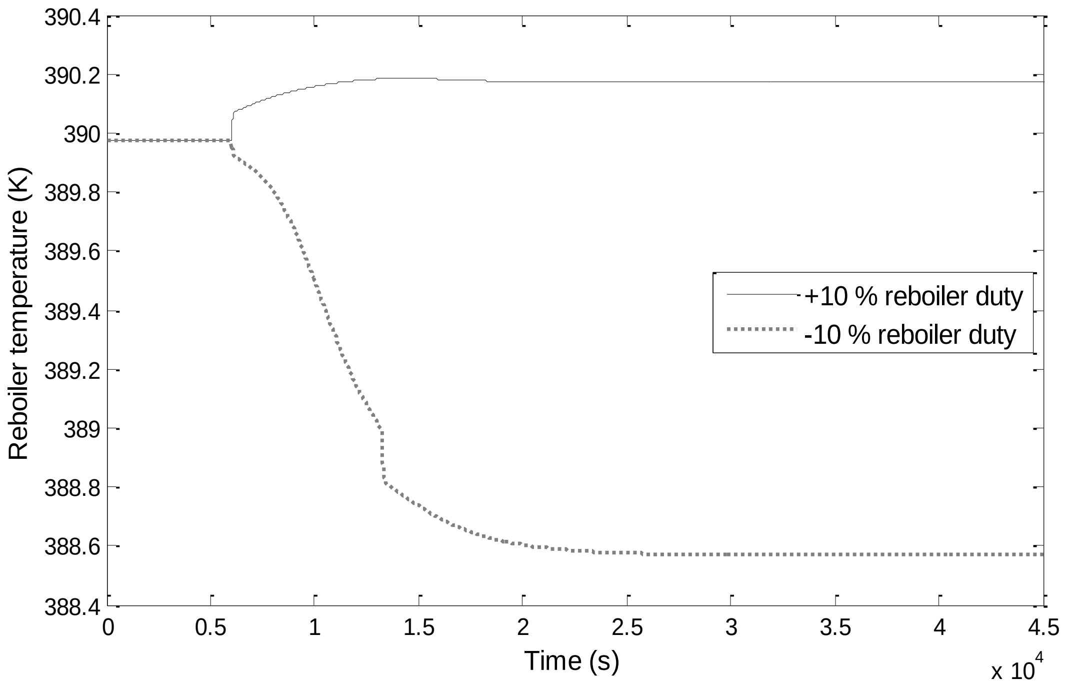
Column temperature profiles from the simulation (line) and the pilot plant study (dot) for the pilot plant test no. 47[7].

	Flue gas		Lean solvent		Rich solvent	
Case number	32	47	32	47	32	47
Temperature (K)	320	320	314	314	358	356
Flow rate (mol/s)	4.013	9.3	31.19	26.7	31.19	26.7

[6]Minh Tri Luu, Norhuda Abdul Manaf, Ali Abbas. Control strategies for flexible operation of amine-based post-combustion CO_2 capture systems. Journal of Greenhouse Gas Control (accepted with revisions)
[7]Dugas, R. E. 2006. Pilot Plant Study of Carbon Dioxide Capture by Aqueous Monoethanolamine. M.S.E. Thesis, The University of Texas

Modelling Approach 2: Open-loop dynamic analysis

Step changes in reboiler heat duty



Step changes in reboiler duty (straight line: positive step change; dashed line: negative step change).

It can be seen that a 10% reduction (increment) in the heat duty caused the temperature to reduce by 1.4°C (increased by 0.2°C).

Process time constants:

1) 3 hours for the fastest dynamics at 10% increment of heat duty

2) 4.3 hours for the slowest at 10% reduction of heat duty

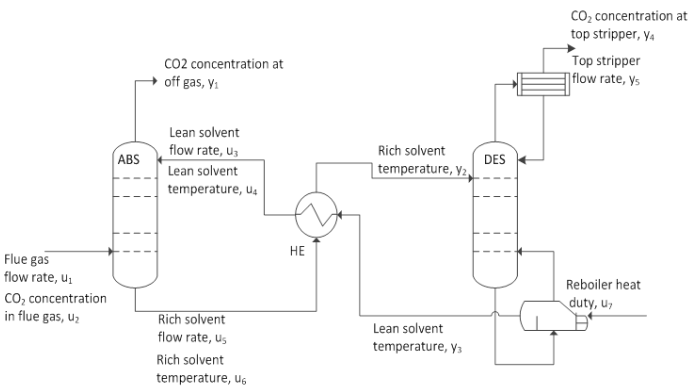
* High time constant : Due to a large amount (1.5 m^3) of holdup solvent, the reboiler temperature inherited a high time constant

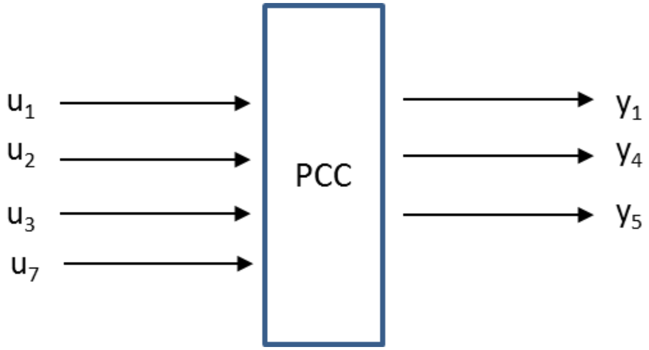
Control Approach

Identified 2 key performance metrics:

1. Carbon capture efficiency, $CC\ (\%) = \dfrac{(y_4/100)\ y_5}{u_1\ (u_2\ /100)}$

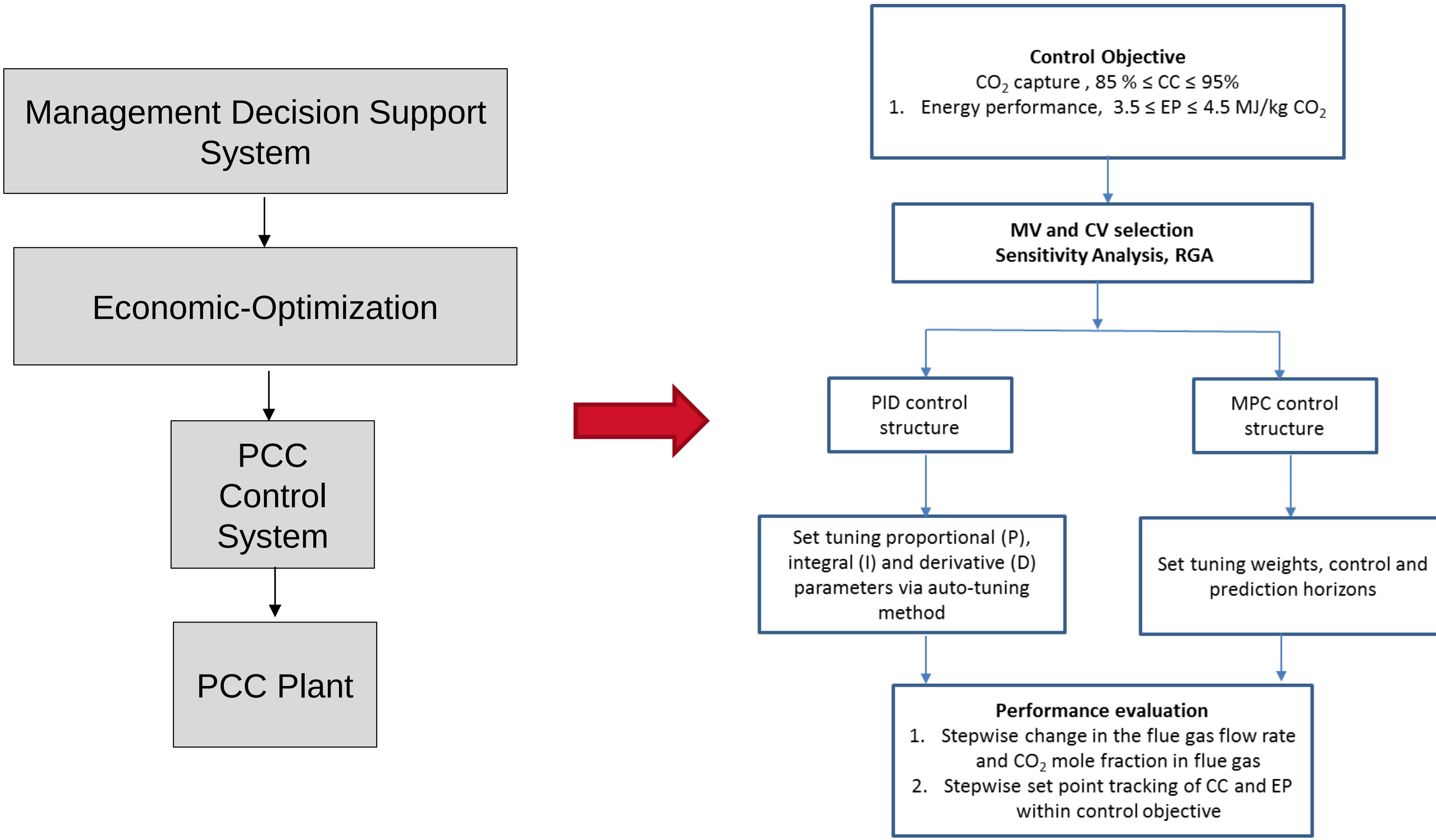
2. Energy performance, $EP\ (\text{MJ/kg}) = \dfrac{u_7}{(y_4/100)\ y_5}$





Simplified 4 x 3 PCC system

Control Approach



Control Approach – RGA Analysis

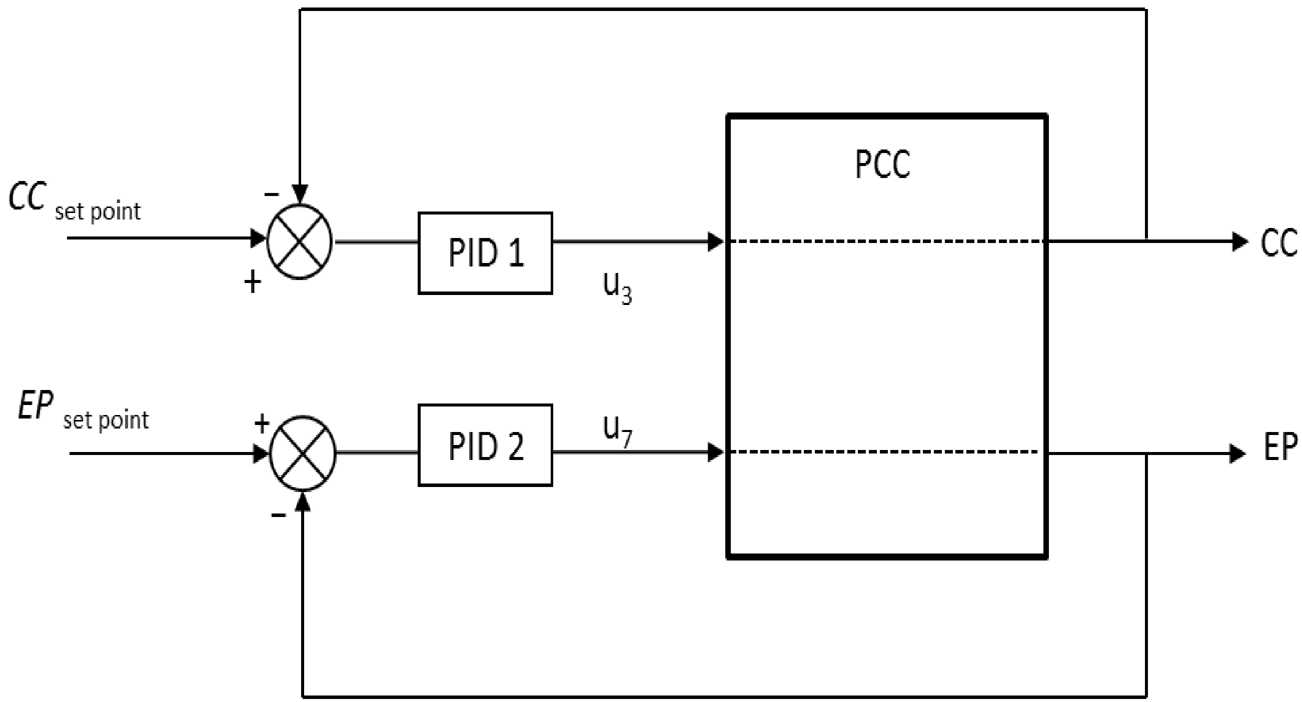
RGA results for different steady-state operating conditions

Condition	Steady state input values				Final steady state output values		RGA*
	u_1 (kg/hr)	u_2 (mass %)	u_3 (L/min)	u_7 (kJ/hr)	*CC* (%)	*EP* (MJ/kg)	
Condition 1	500	16	24	270 000	≈ 80	≈ 4	$\begin{array}{cc} & \begin{matrix} EP & CC \end{matrix} \\ \begin{matrix} u_3 \\ u_7 \end{matrix} & \begin{pmatrix} 0.1934 & 0.8066 \\ 0.8066 & 0.1934 \end{pmatrix} \end{array}$
Condition 2	550	16	25	288 000	≈ 70	≈ 5	$\begin{array}{cc} & \begin{matrix} EP & CC \end{matrix} \\ \begin{matrix} u_3 \\ u_7 \end{matrix} & \begin{pmatrix} -0.3790 & 1.3790 \\ 1.3790 & -0.3790 \end{pmatrix} \end{array}$
Condition 3	650	16	30	324 000	≈ 40	≈ 8	$\begin{array}{cc} & \begin{matrix} EP & CC \end{matrix} \\ \begin{matrix} u_3 \\ u_7 \end{matrix} & \begin{pmatrix} -2.9065 & 3.9065 \\ 3.9065 & -2.9065 \end{pmatrix} \end{array}$

*RGA was performed by introducing +10% perturbation in u_3 and u_7.

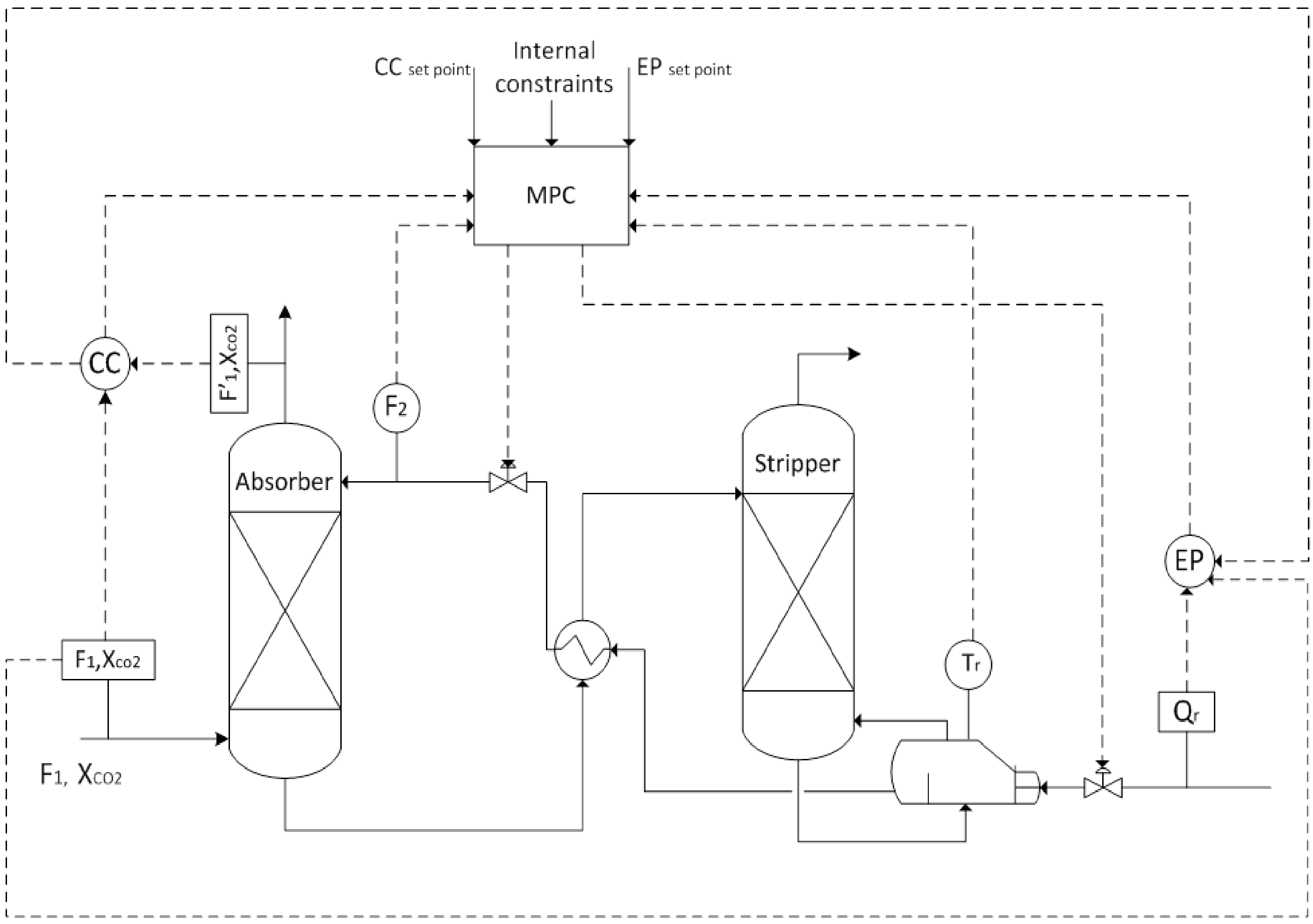
Negative pairing = The control loop is unstable

Control Approach 1 – PID Controller



PID Control Scheme

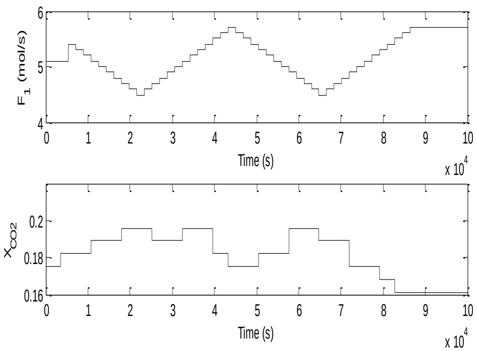
Control Approach 2 – MPC Controller

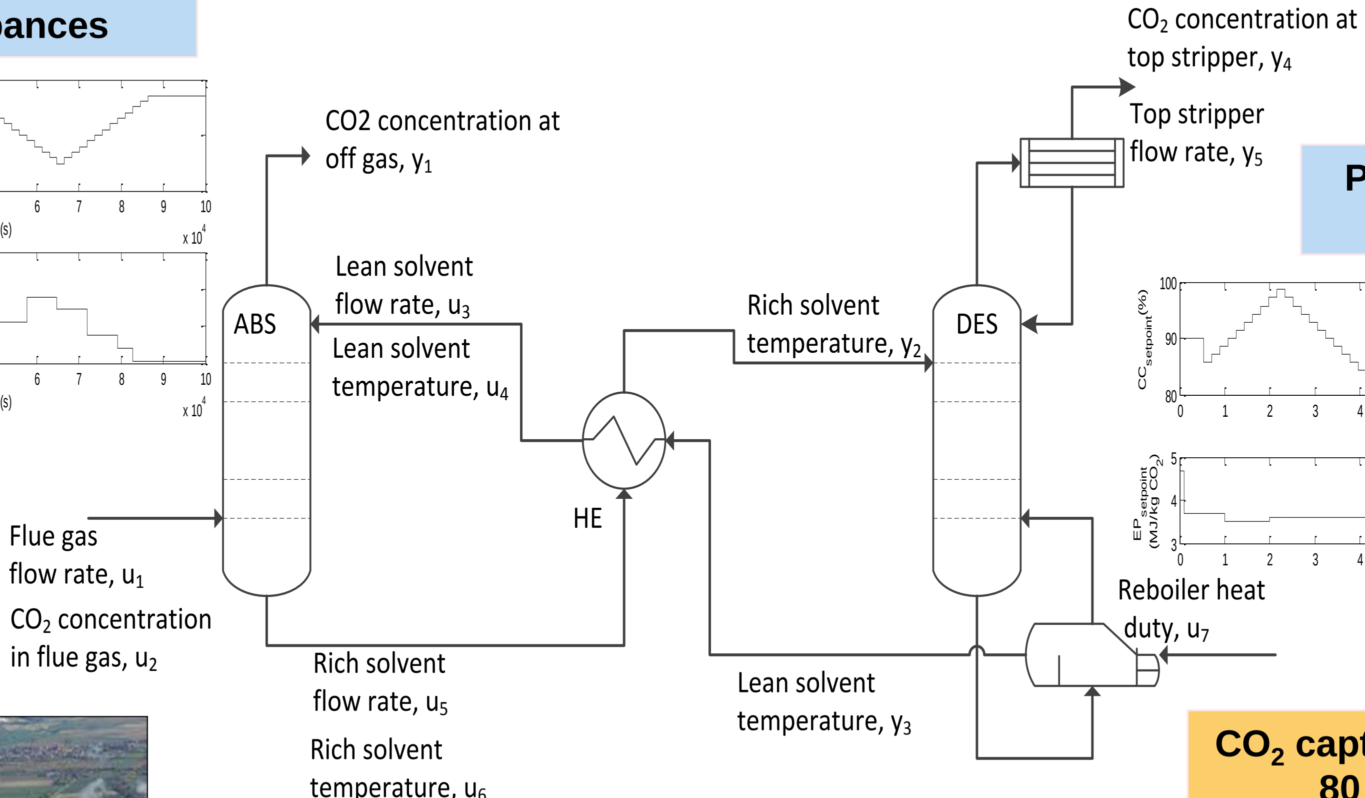


MPC Control Scheme

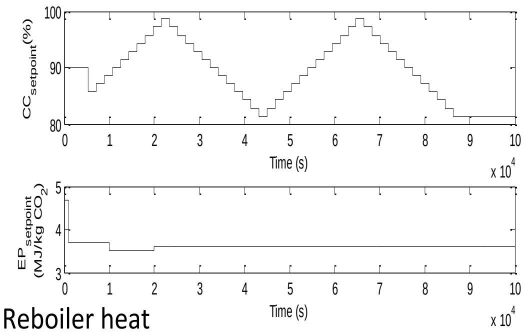
Control Approach – Controllability Analysis

Upstream disturbances





PCC control objective

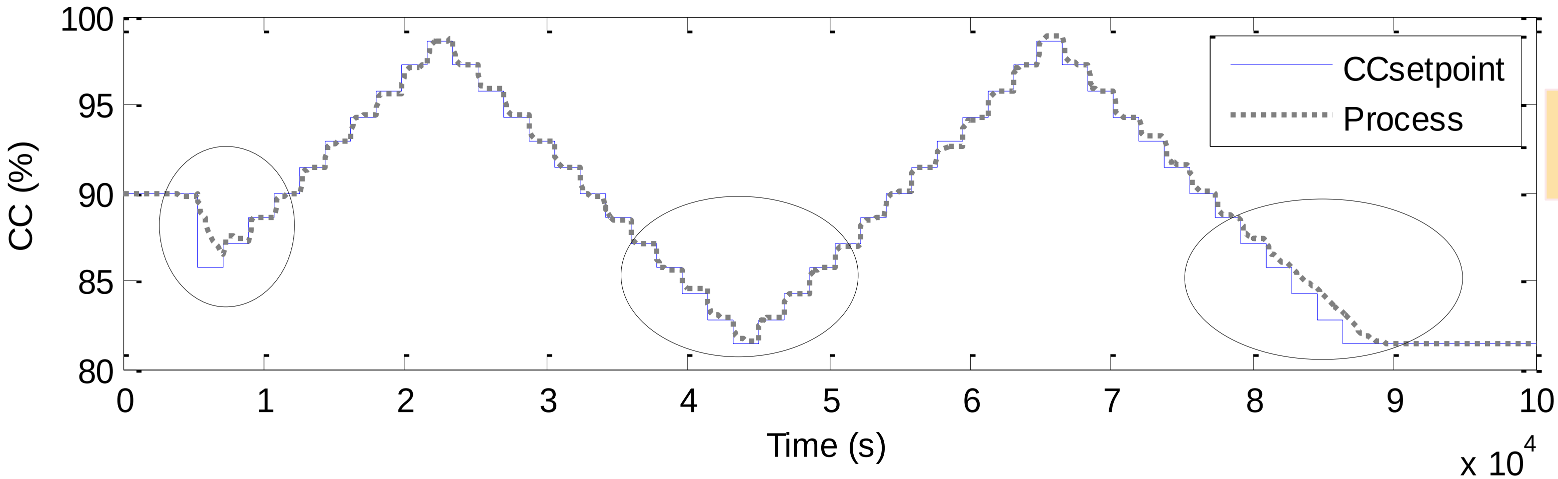


CO_2 capture, CC% = 80 ~ 95%

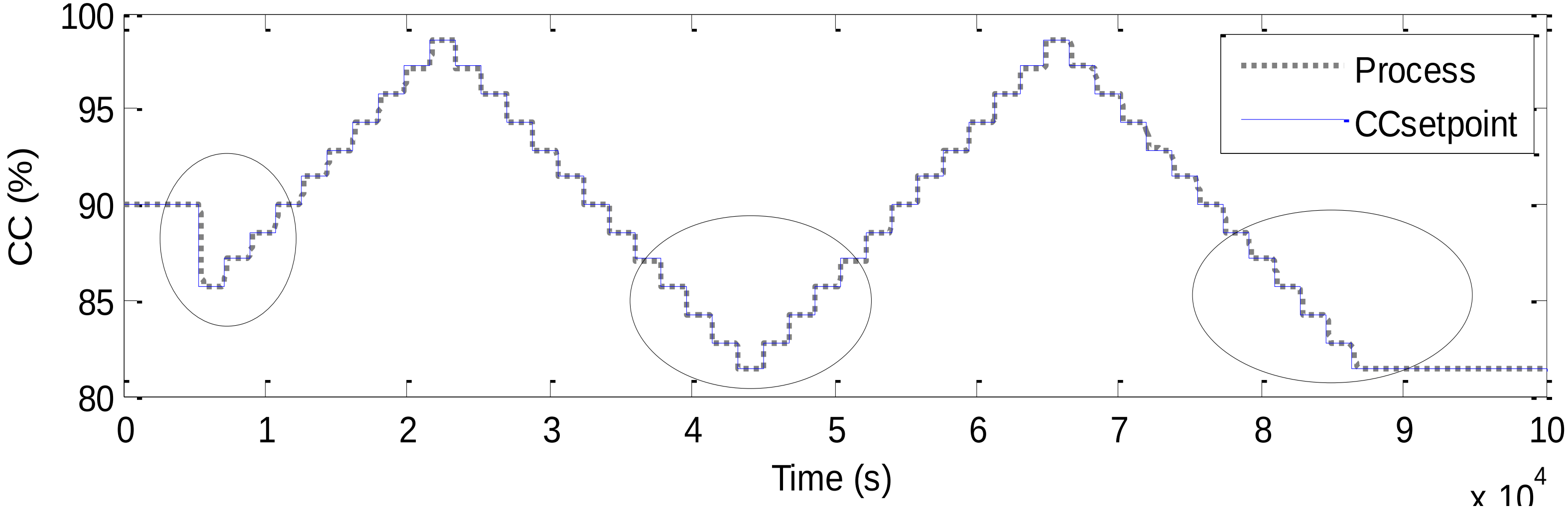
Energy Performance, EP = 3.5 ~ 4.5 MJ/kg CO_2

Control Approach – Controllability Analysis

Controllability analysis on set point changes and rejection disturbances.



PID Controller



MPC Controller

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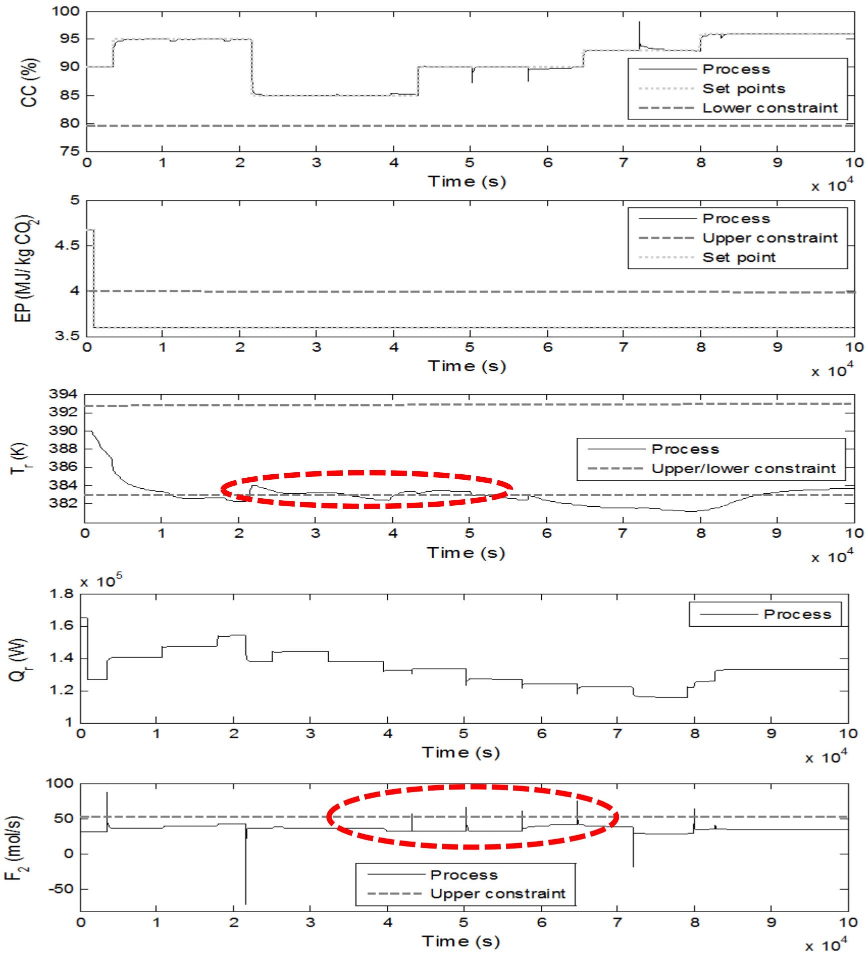
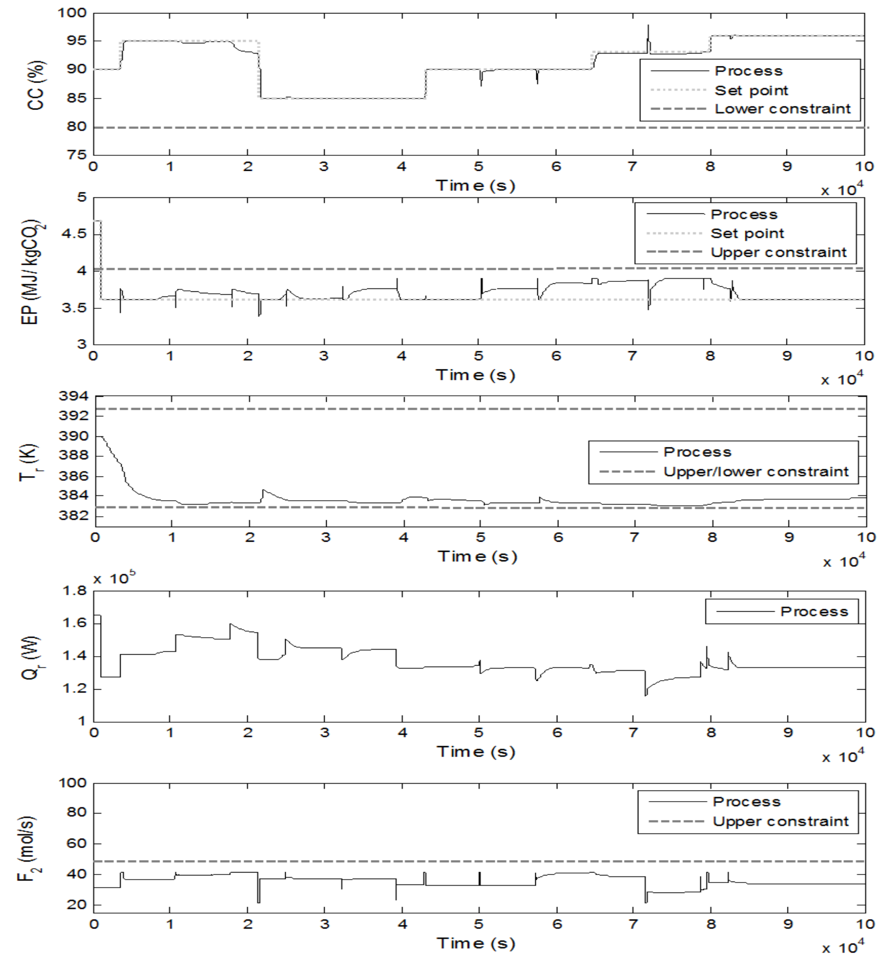
Control Approach – Controllability Analysis

Control performance under process operational constraints



PID Controller



MPC Controller

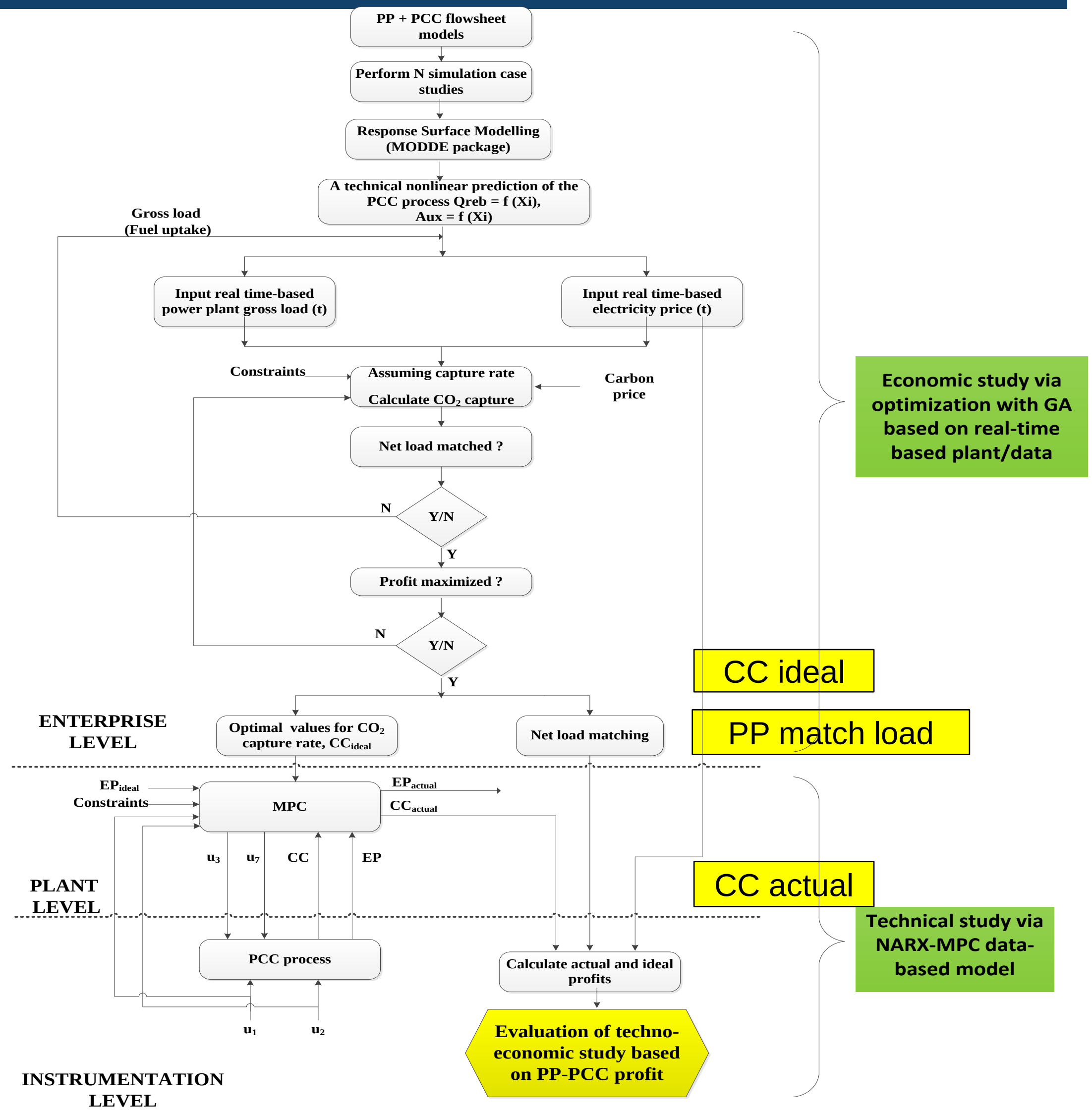
Control-Optimization Approach

Management Decision Support System

Economic-Optimization

PCC Control System

PCC Plant



Control-Optimization Approach

PP-PCC plant revenue

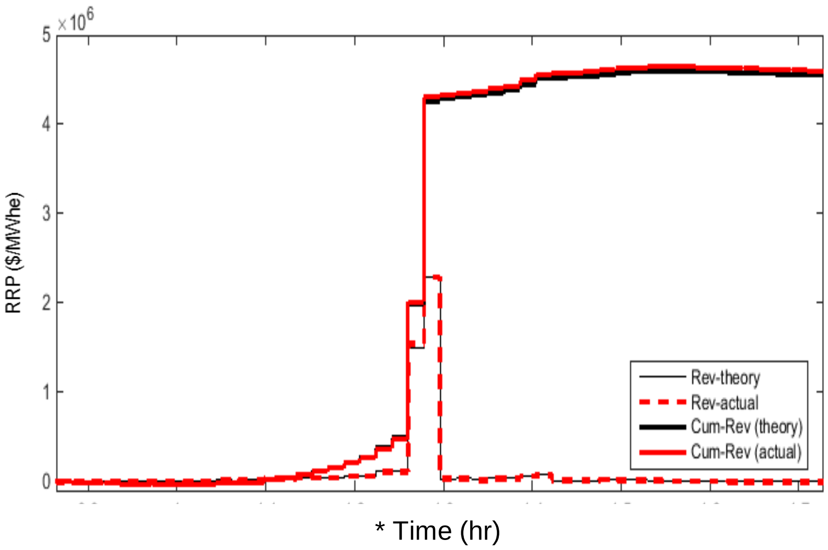
$$Revenue = \int P_e * \overbrace{(Power\ plant\ net\ load - PCC\ penalty)}^{\textbf{Rev-PP}} * dt -$$

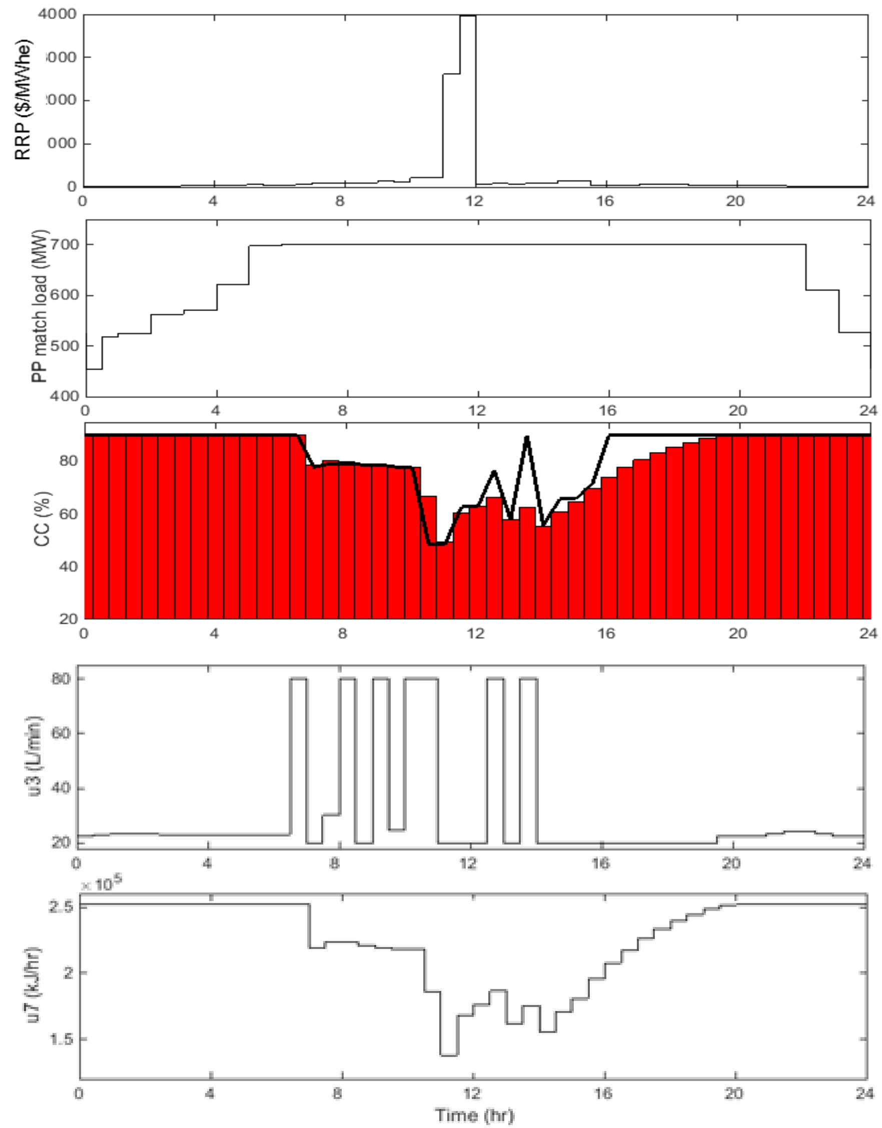
$$- \int \underbrace{C_t * CO_2\ emitted\ dt}_{\textbf{A}} \;-\; \underbrace{P_{PP}}_{\textbf{B}} - \underbrace{P_{PCC}}_{\textbf{C}}$$

Rev-PP:	**Revenue generated through selling of electricity**
A:	**Cost of CO2 emission**
B:	**Power plant operating cost (PP-OPEX)**
C:	**PCC operating cost (PCC-OPEX)**

Techno-economic Approach – Optimization Control

Scenario:
Simulation period: 24 hrs
$ RRP : 2011
CT: $ 25/ tonne-CO_2





* 24 hours

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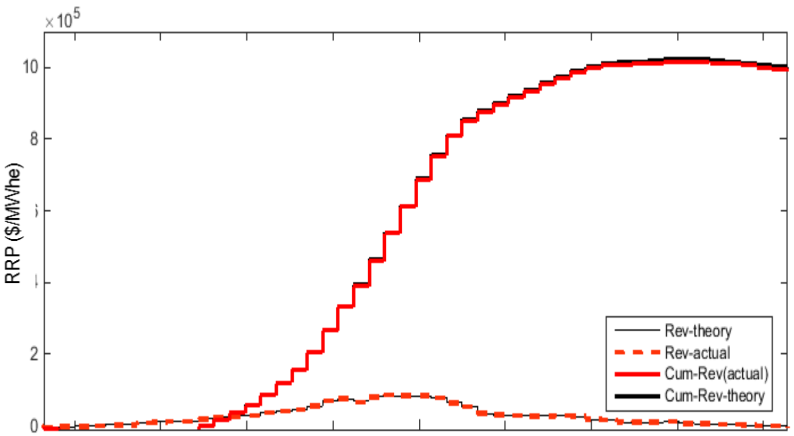
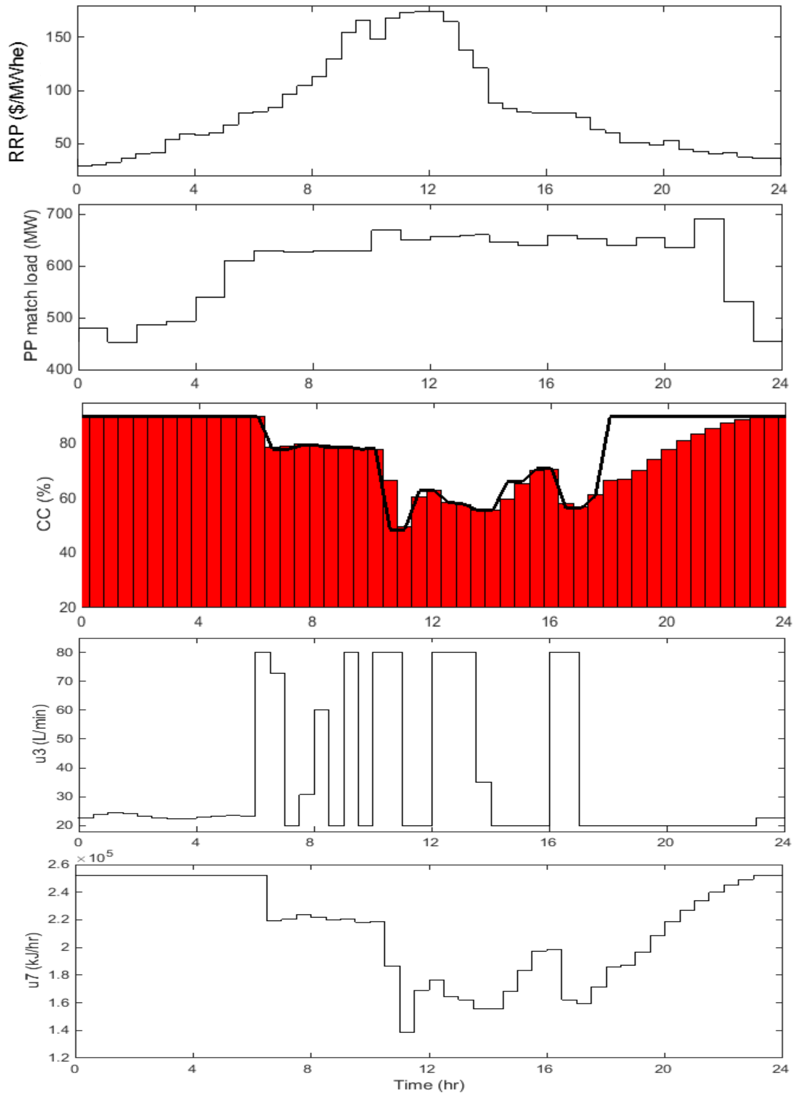
Techno-economic Approach – Optimization Control

Scenario:
Simulation period: 24 hrs
$ RRP : 2020 (assuming 5% yearly increment from the base year 2008)
CT: $ 25/ tonne-CO_2



* Time (hr)

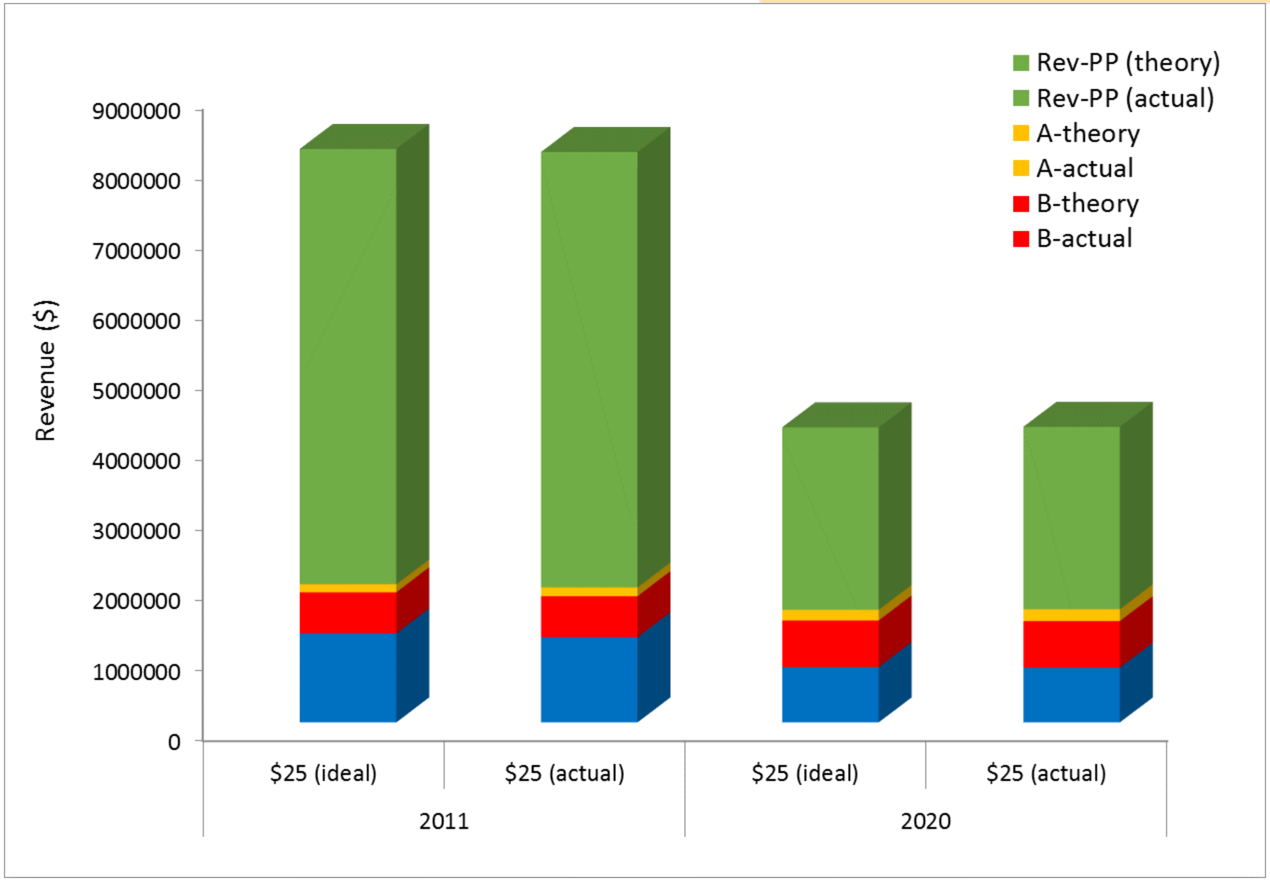


* 24 hours

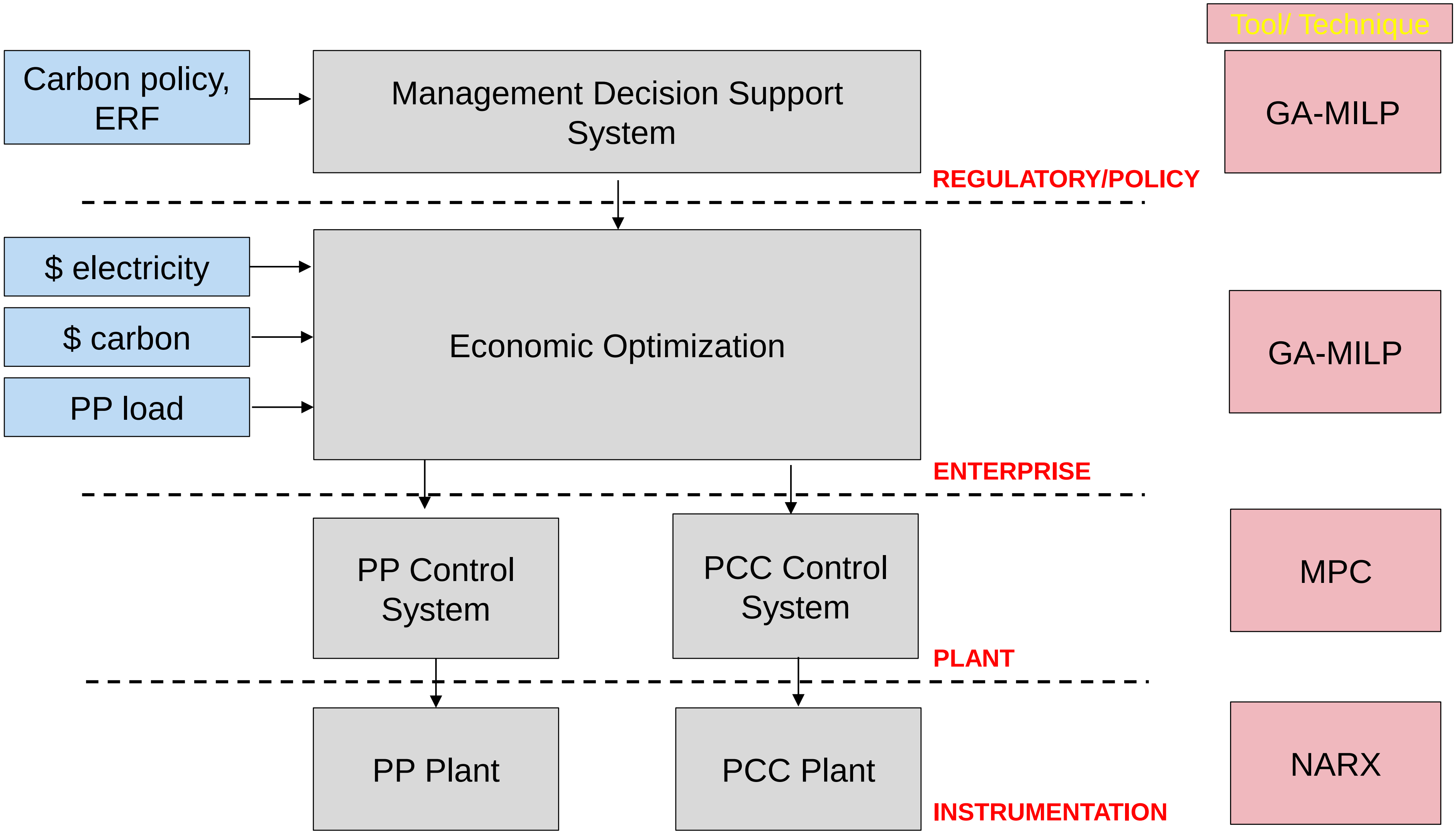
Control-Optimization Approach

Revenue Composite

Rev-PP: Revenue generated through selling of electricity
A: Cost of CO_2 emission
B: Power plant operating cost (PP-OPEX)
C: PCC operating cost (PCC-OPEX)



Opportunity



ACKNOWLEDGMENT

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Norhuda Abdul Manaf

The University of Sydney

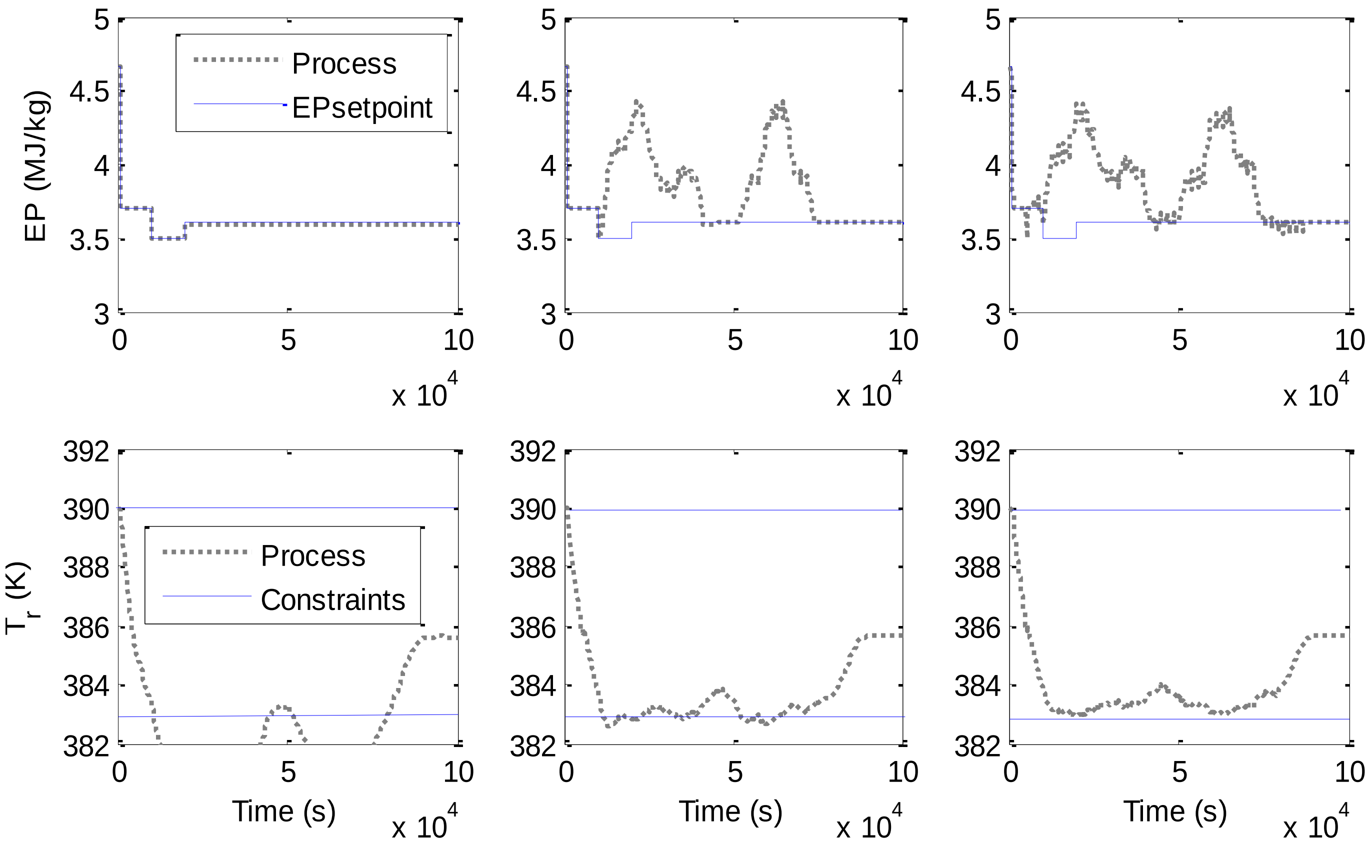
Ashleigh Cousins & Paul Feron

CSIRO

THANK YOU!

Control Approach – Controllability Analysis

Control performance of *EP* under process constraint (T_r)



PID Controller

PID-Cascade Controller

MPC Controller

The MPC-PCC did not violate the specified operational constraints for Tr and F2. However, the other two controllers were incapable to maintain respective process variables (Tr and F2) from violating its specified constraint.

Table 4.2 Operating conditions for case studies 32 and 47 (inputs to gPROMS simulations)

	Flue gas		Lean solvent		Rich solvent	
Case number	32	47	32	47	32	47
Temperature (K)	320	320	314	314	358	356
Flow rate (mol/s)	4.013	9.3	31.19	26.7	31.19	26.7
Mole fraction						
H_2O	0.025	0.032	0.86	0.846	0.846	0.828
MEA	-	-	0.11	0.12	0.104	0.1181
CO_2	0.175	0.167	0.029	0.034	0.05	0.0534
N_2	0.8	0.8	-	-	-	-
CO_2 loading	-	-	0.264	0.28	0.48	0.46
L/G ratio	-	-	6.5	4.6	-	-