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Conventional and Advanced Exergy Analysis of Post-Combustion CO₂ Capture Based on Chemical Absorption Integrated with Supercritical Coal-Fired Power Plant

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Abstract

Post-combustion CO₂ capture (PCC) based on chemical absorption is one of the strategic technologies identified to reduce emission of greenhouse gases from various power plants. However, PCC based on chemical absorption incurs serious energy penalty due to the use of energy for solvent regeneration. Reducing the energy/exergy use in this process can reduce energy penalties. It is also important to increase the efficiency of the CO₂ capture system. This study focuses on: steady state simulation of a closed-loop PCC plant integrated with supercritical coal-fired power plant (SCPP); conventional and advanced exergy analyses of the PCC; and case studies on strategies to reduce exergy destruction in the system components. The conventional exergy analysis evaluates the amount and location of exergy destruction within the whole system. The advanced exergetic analysis estimates the sources of the exergy destruction in individual component or the whole system and the potential for reducing it. **The results show that the energy consumption and the efficiency of the PCC process can be improved by recovering the avoidable exergy destroyed in the system components. This is important because for every 1% reduction in the energy required for capture, costs can be lowered to between 0.7 - 1%.**

Keywords: Post-combustion CO₂ capture; Chemical Absorption, Conventional Exergy Analysis; Advanced Exergy Analysis; Steady State simulation

Nomenclature

Symbol	Description	Units
\dot{E}_n	Exergy of component n	MW
$\dot{E}_{F,n}$	Fuel Exergy of component n	MW
$\dot{E}_{P,n}$	Product Exergy of component n	MW
$\dot{E}_{D,n}$	Exergy destruction of component n	MW
$\dot{E}_{D,n}^{un}$	Unavoidable exergy destruction of n	MW
$\dot{E}_{D,n}^{av}$	Avoidable exergy destruction of n	MW
$\dot{E}_{D,n}^{en}$	Endogenous exergy destruction of n	MW
$\dot{E}_{D,n}^{ex}$	Exogenous exergy destruction of n	MW
$\dot{E}_{D,n}^{av,ex}$	Avoidable exogenous exergy destruction of n	MW
$\dot{E}_{D,n}^{un,ex}$	Unavoidable exogenous exergy destruction of n	MW
$\dot{E}_{D,n}^{av,en}$	Avoidable endogenous exergy destruction of n	MW
$\dot{E}_{D,n}^{un,en}$	Unavoidable endogenous exergy destruction of n	MW
ΔT	Temperature difference	°C
y	Exergy loss ratio	-
Q	Heat flow	J/s
X	Mole fraction	-
Greek Symbol		
$\dot{\epsilon}$	Exergetic efficiency	%
Subscript		
n	Number of components	
F	Fuel	
L	Loss	
min	minimum	
P	product	
isent	isentropic	
D_i	Component i in the distillate	
B_i	Component i in the bottom	
G_{asi}	Component i in the gas phase	
LQD_i	Component i in the liquid phase	
$F - D$	Difference between the feed and the distillate	
ΔTD	Distillate and feed temperature difference	
ΔTB	Bottom and feed temperature difference	
$F - B$	Difference between the feed and the bottom	
Lfi	Component i in the liquid feed	
Superscripts		
niF	moles of component i in the feed	
niD	moles of component i in the distillate	
niB	moles of component i in the bottom	
$niLf$	moles of component i in the liquid feed	
niL	moles of component i in the liquid phase	
$niGf$	moles of component i in the gas feed	
niG	moles of component i in the gas phase	
Acronyms		
SCPP	Supercritical Coal-fired Power Plant	

LVR	Lean Vapour Recompression
AIC	Absorber Inter-Cooling
SF	Split-Flow
SIH	Stripper Inter-Heating
IAPWS	International Association for the Properties of water and steam
R	Real
U	Unavoidable
FGD	Flue gas desulphurization
HHV	High heating value
TH	Theoretical

1 Introduction

1.1 Background

CO₂ is the largest and most important anthropogenic greenhouse gas (GHG) [1]. With growing concerns over the increasing atmospheric concentration of anthropogenic greenhouse gases, effective CO₂ emission abatement strategies are required to combat this trend [2]. Several promising technologies have been investigated to reduce CO₂ emission from the use of fossil fuels [2–4]. Post-combustion CO₂ capture (PCC) is one of the strategic technologies identified to reduce emission of greenhouse gases in existing power plant [2]. PCC based on chemical absorption of monoethanolamine (MEA) is the most matured and preferred technology for capturing CO₂ from the flue gases in existing power plant.

Integrating PCC with Supercritical coal-fired power plant (SCPP) incurs a great deal of energy penalty. Improving the rational efficiency, reducing energy penalty and the costs of CO₂ capture can be achieved by reducing the irreversibility in the system. The different types of irreversibility in the system can be investigated by performing exergy analysis. A detailed exergy destruction analysis is performed in this study, both for the absorber and the desorber columns of the PCC process integrated to an SCPP. The main sources of exergy destruction in the absorber and stripper include: (i) mass transfer between phases (ii) heat transfer in reboiler and condenser for stripper (iii) heat transfer inside the columns (iv) heat losses through the surfaces (vi) heat of the reaction in the absorber etc. [5]. Exergy analyses can be used to identify the losses associated with this system, investigate strategies for improvement, and reduce the penalties due to the capture process. The analyses also allow for a better understanding of the exergy destruction due to a component's own inefficiency (i.e. conventional exergy analysis) and/or due to the **other** components' inefficiencies (advanced exergy analysis).

1.2 Review of Exergy analysis of Post Combustion CO₂ Capture

Conventional exergy analysis of CO₂ capture systems has been investigated in several studies. Geuzebroek et al [6], Amrollahi et al [7] and Olaleye et al [8] carry out conventional exergy analysis of MEA-Based PCC with chemical absorption, while exergy analysis of chilled ammonia process has also been studied by Valenti et al [10]. Table 1 shows a summary of some important researches on exergy analysis of standalone CO₂ capture and exergy analysis of power plant integrated with CO₂ capture. Advanced exergy analysis of post combustion CO₂ capture using chemical absorption integrated with power plant has not been investigated. This study intends to investigate the impact of advanced exergetic analysis of a capture plant integrated with SCPP to the overall system design improvement and energy penalty.

Table 1: Review of Exergy Analysis of Power Plant with CO₂ Capture

Authors	Issues	Contributions
Geuzebroek et al [6]	MEA-based post combustion CO ₂ removal	Exergy Analysis of standalone CO ₂ Capture Processes
Valenti et al [10]	Chilled Ammonia-based CO ₂ Capture	
Lara et al [11]	Comparative study of different CO ₂ capture systems' exergetic losses	
Kunze et al, [12]	Reduction of exergy loss of IGCC plant with CO ₂ capture	Exergy Analysis of power plant integrated with CO ₂ Capture
Hagi et al [13]	Exergy analysis of oxy-fuel power plant through heat integration method	
Romeo et al [14]	Optimization of coal-fired plant with calcium looping CO ₂ capture via exergy analysis & heat integration	
Amrollahi et al [7]		

Olaleye et al [8]	Natural gas-fired power plant with post-combustion CO ₂ capture Exergy analysis of supercritical coal-fired power plant integrated with post combustion CO ₂ capture	
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1.3 Aim of this study and its novel contribution

Conventional exergy analysis of PCC based on chemical absorption integrated with SCPP system was presented in Olaleye et al [8]. The study show that the boiler (~69%), the stripper & the absorber (~24%) have the largest exergy destruction while the turbine (~5%) shows very small exergy destruction [8]. However, **the study in [8]** does not include qualitatively the sources and potential for improvement of the exergy destruction in the PCC components.

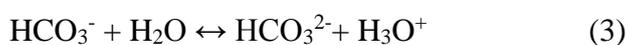
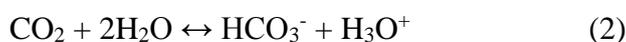
This current work is largely based on the thesis of Olaleye [9]. It focuses on addressing the limitations in [8] by performing advanced exergy analysis of MEA-based PCC with chemical absorption integrated with SCPP. Sensitivity analysis and several strategies/configurations for reducing the local exergy destructions from the absorbers and strippers in MEA-based PCC system were also considered.

1.4 MEA-based PCC

Solvent-based PCC is one of the strategic technologies identified to reduce emission of greenhouse gases in existing power plant [2]. PCC based on chemical absorption of monoethanolamine (MEA) is the most matured and preferred technology for CO₂ capture from the flue gases in existing power plant. In this study, experimental data from a CO₂ capture pilot facility is used for validation of the model.

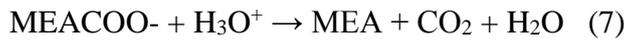
1.4.1 Chemistry of the MEA-H₂O-CO₂ System

The solution chemistry for CO₂ absorption with MEA includes water dissociation, CO₂ hydrolysis, bicarbonate dissociation, carbamate hydrolysis, and MEA protonation [8] thus:





In addition to the thermodynamic properties, the kinetics for carbamate formation (6 and 7) and the reaction for bicarbonate formation (8 and 9) were obtained from literature. Reaction rates are solved by power law expressions in Aspen Plus[®]. The equilibrium reactions (1–5) are modelled using data available in Aspen Plus[®].



2 Steady State Simulation

2.1 Process Simulation – Reference Case

Simulation of the SCPP and the carbon capture process requires the thermodynamic properties of the systems' components to be properly defined for accurate representation of the reference case. Three property methods are used in the PCC simulation: Electrolyte NRTL for the electrolytes components, Ideal gas equation for air and flue gases, and the STEAMNBS steam table (which contains the IAPWS-F97 formulation for property of water and steam) for water and steam. The details of the Aspen Plus[®] process simulation and simulation basis for the SCPP and the PCC have been presented in Olaleye et al. [8]. Table 2 shows the design parameters of the PCC unit used in the simulation. The flue gas flowrate (603.4 kg/s) corresponds to emission from a 580 MWe Greenfield SCPP with flue gas desulphurisation (FGD) as described in Woods et al. [14]. Figure 1 is the flowsheet of the Aspen Plus[®] simulation of the PCC system.

Table 2: Design Parameters for the PCC unit [8]

Description	Value
Flue gas mass flow rate (kg/s)	603.4
Flue gas composition (wt.% CO ₂)	0.2135
Flue gas composition (wt.% N ₂)	0.7352
Flue gas composition (wt.% H ₂ O)	0.0513
CO ₂ Capture level (%)	90.0
flowrate of CO ₂ captured (kg/s)	128.83
Required MEA flowrate (kg/s)	828.193
Lean solvent flow rate (kg/s)	2967.9
Rich solvent flow rate (kg/s)	3040.2
Lean MEA mass fraction (wt. %)	30.48
Lean loading (mol CO ₂ /mol MEA)	0.29

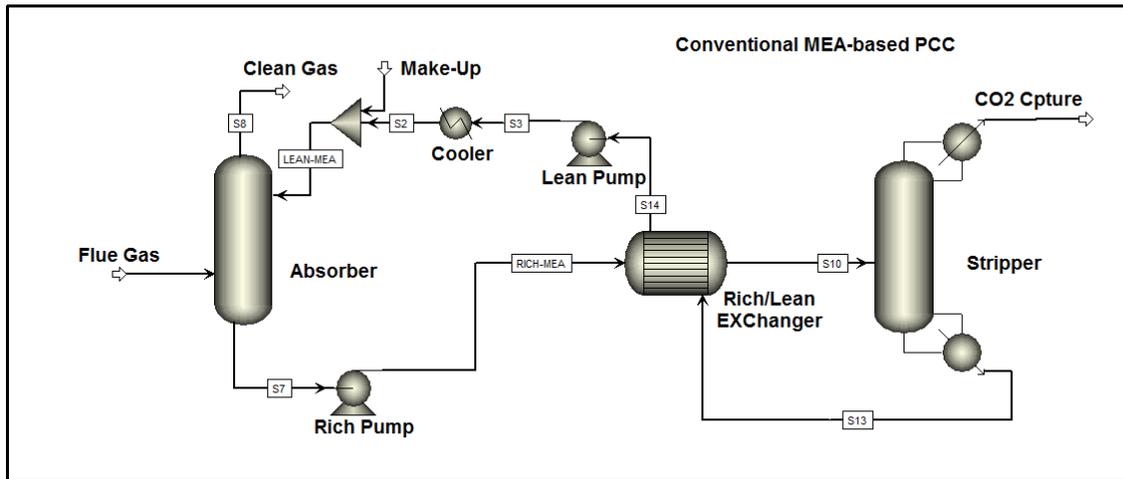


Figure 1: Simulation of MEA-based PCC process in Aspen Plus®

3 Conventional and Advanced Exergy Analysis

Exergy is the total useful work potential or available energy of a system, a stream of matter and/or heat interaction using the state of the environment as the datum [16]. Conventional exergy analysis identifies the location, magnitude, and sources of thermodynamic inefficiencies or irreversibility in a thermal system. The advanced exergy analysis on the other hand, evaluates the sources of these thermodynamic inefficiencies and the potential for improvement. Details of the theory used in developing the conventional exergy analysis in this work has already been describe in Olaleye et al [8].

3.1 Conventional Exergy Analysis of SCPP-PCC Components

In the MEA-based CO₂ absorption process, the greater part of the irreversibility in the absorber (excessive driving force) is in the middle and bottom parts of the column [17]. Also, an analysis of the equilibrium and operating lines of the stripper shows that equilibrium can be reached at only one point of a stripper of conventional design (with a single feed of spent absorbent entering the top), even if it were of infinite height [17]. Thus, the driving force at other points in the stripper can never approach zero, resulting in excessive expenditure of exergy. These led to series of modifications to the conventional flowsheet for MEA-based PCC unit. Modifications to the conventional absorption and stripping sections of the MEA-Based PCC process has been studied widely in recent years [18, 19, 20, 21, 22].

The absorbers and strippers contribute the largest share of total exergy destruction in PCC system [8]. The main sources of exergy destruction in the absorber and stripper include: (i)

mass transfer between phases (ii) heat transfer in reboiler and condenser for stripper (iii) heat transfer inside the columns (iv) heat losses through the surfaces (vi) heat of the reaction etc. [5]. The exergy destruction due to mass transfer in the columns is expressed in terms of the mixing exergy due to the change in concentration of the substances [5]. Table 3 shows the equations used to estimate the exergy destruction in the absorber and stripper.

3.1.1 Absorber

The local exergy destruction in the PCC absorber column is calculated based on the assumption that majority of the exergy destroyed is due to the absorption heat of reaction, the exergy destruction due to mass transfer in the column (accounted for by estimating the changes in concentration driving force), and due to the heat loss through the column wall (see Table 3).

3.1.2 Stripper

The local exergy destruction in the stripper is made up of the destructions due to the heat transfers in the reboiler and the condenser, heat flow through the column, mass transfer between the liquid and vapour streams, and heat losses through the column wall.

3.1.3 SCPP integrated with PCC

The integrated SCPP-PCC model described in [8] is used to estimate the exergetic performance of the entire system. The overall exergy destruction, the exergetic efficiency, and the energy penalties in the integrated system is calculated from the exergy properties set described in section 3. The exergy flows into and out of each stream in the SCPP-PCC system is first obtained from the Aspen Plus® simulation; then the exergy destruction and the exergetic efficiency for each component is then estimated in Microsoft Excel®. Further details can be found in [8].

Table 3: Equation for Distribution of Exergy Destruction in Absorber and Stripper

Driving Forces	Stripper [5]	Absorber
Mass transfer due to mixing liquid and vapour streams	$\dot{E}_{D_{mass_transfer}} = -(\dot{E}_{distillate} + \dot{E}_{bottom}) + \dot{E}_{feed}$ $= RT_0 \left[\ln \left(\prod_{i=1}^n \frac{(X_{Fi}^{niF})}{(X_{Di}^{niD} * X_{Bi}^{niB})} \right) \right]$	$\dot{E}_{D_{mass_trf}} = -(\dot{E}_G + \dot{E}_L) + \dot{E}_{Gf} + \dot{E}_{Lf}$ $= RT_0 \left[\ln \left(\prod_{i=1}^n \frac{(X_{Gfi}^{niGf} * X_{Lfi}^{niLf})}{(X_{Gasi}^{niG} * X_{LQDi}^{niL})} \right) \right]$
Heat flow (transfer) through the column	$\dot{E}_{D_{heat_transfer}} = \dot{E}_{\Delta TB} + \dot{E}_{\Delta TD}$ $\dot{E}_{\Delta TB} = \Delta h_{F-B} \left(1 - \frac{T_0}{\bar{T}_{F-B}} \right), \dot{E}_{\Delta TD} = \Delta h_{F-D} \left(1 - \frac{T_0}{\bar{T}_{F-D}} \right)$ <p>Log mean temperature, $\bar{T}_i = \frac{T_i - T_{feed}}{\ln \frac{T}{T_{feed}}}$</p>	$\dot{E}_{D_{heat_transfer}} = \dot{E}_{\Delta T_{reaction}}$ $\dot{E}_{\Delta T_{reaction}} = Q_{Reaction} \left(1 - \frac{T_0}{\bar{T}_L} \right)$ <p>Log mean temperature, $\bar{T}_L = \frac{T_L - T_{Li}}{\ln \frac{T_L}{T_{Li}}}$</p>
Heat transfer in Condenser	$\dot{E}_D = Q_c \left(1 - \frac{T_0}{T_{Distillate}} \right)$	-
Heat transfer in Reboiler	$\dot{E}_D = Q_R \left(1 - \frac{T_0}{T_{Bottom}} \right)$	-
Heat losses through the column wall	$\dot{E}_D = Q_{loss} \left(1 - \frac{T_0}{T_{av}} \right)$ $Q_{loss} = \frac{\Delta T_{overall}}{\sum R_{th}} = \left(\frac{T_i - T_0}{\frac{\ln \frac{r_1}{r_i}}{2k_w \pi L} + \frac{\ln \frac{r_0}{r_1}}{2k_i \pi L} + \frac{1}{2h \pi L}} \right)$	$\dot{E}_D = Q_{loss} \left(1 - \frac{T_0}{T_{av}} \right)$ $Q_{loss} = \frac{\Delta T_{overall}}{\sum R_{th}} = \left(\frac{T_i - T_0}{\frac{\ln \frac{r_1}{r_i}}{2k_w \pi L} + \frac{\ln \frac{r_0}{r_1}}{2k_i \pi L} + \frac{1}{2h \pi L}} \right)$

3.2 Advanced Exergy Analysis of SCPP-PCC Components

An advanced exergy analysis evaluates the interaction among components of a system and the real potential for improving the components or the overall system [23]. It can provide extra information to the conventional analysis for design improvement and operation of the SCPP–PCC integrated system. In this study, the advanced exergy analysis was applied to reveal the sources (i.e. endogenous or exogenous) and the potential for reduction (i.e. avoidable or unavoidable) of the exergy destruction in the SCPP-PCC components. The mechanisms of the splitting of the exergy destruction of the SCPP components based on its sources and potential for reduction are detailed in Olaleye et al [8]. Section 3.2.1 presents the assumptions for splitting of the MEA-based PCC components.

3.2.1 Assumptions for Splitting Exergy destruction in the PCC Components

For splitting the exergy destruction in the PCC system into exogenous and endogenous parts, the assumption for theoretical (TH) conditions for different components is: $\dot{E}_D = 0$ or $\dot{E}_D = \min$. For the rich and lean MEA pumps and the flue gas blower, the isentropic efficiency (η_{isent}) and mechanical efficiency (η_{mech}) should be 100%. As for the heat exchanger, both pressure drops (ΔP) and minimum temperature difference at the pinch point (ΔT_{min}) should equal zero. For the absorber and stripper, the calculation of endogenous exergy destruction represents a problem because no ideal condition or theoretical conditions can be defined for the reaction process. In this case, the exergy destruction in the absorber is estimated from the minimum allowable liquid to gas ratio $(L/G)_{min}$ that corresponds to the least or zero exergy destruction (i.e. $\dot{E}_D = \min$ or $\dot{E}_D = 0$) at 90% capture level. In the stripper, all the exergy destruction will be assumed endogenous, with the change in exergy destruction in the other components (i.e. the preceding and succeeding components) accounted for in the entire PCC system.

For the unavoidable conditions (UN), the best performance characteristics is derived based on the understanding and practical experience of the designer. In this study, the unavoidable conditions are selected arbitrarily based on limitations of technology such as the isentropic efficiency (η_{isent}) of between 96-98%, and mechanical efficiency (η_{mech}) of 100% for the blower and pumps. For the lean/rich MEA heat exchanger and the Trim-Cooler, the minimum approach temperature difference (ΔT_{min}) should not be equal to zero but based on the limitations of technology [24]. For the absorbers and strippers, since the exergy destruction is due to irreversible processes of heat & mass transfer, chemical reaction, and the mixing—which is directly related to entropy generation; the (UN) is selected based on the lowest

meaningful value of temperature and concentration that provides the minimal irreversibility (i.e. $\dot{E}_D = \min$). The calculations for advanced exergy analysis are conducted using standalone Aspen Plus[®] simulations for individual components and MS-Excel worksheet is used for the estimation.

4 Results and discussions

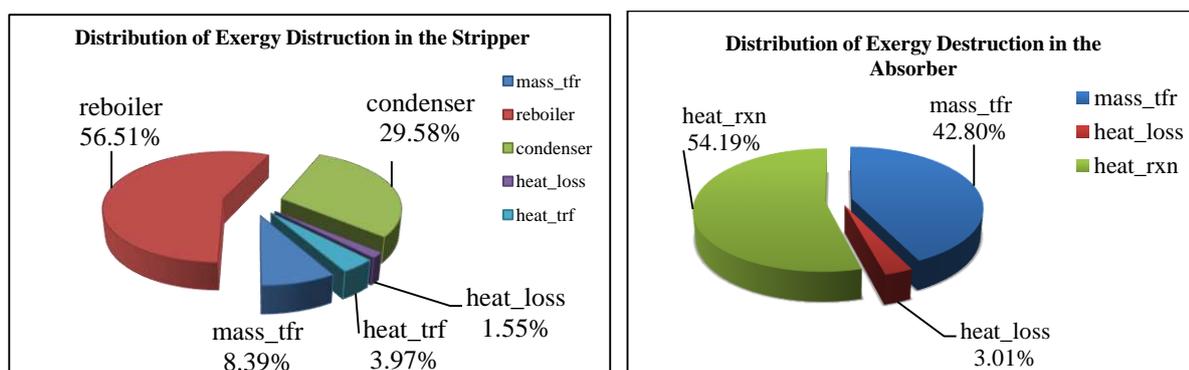
A detailed discussion on the conventional exergy analysis of SCPP integrated with PCC based on the spatial distribution of exergy destruction in the SCPP has already been presented in [8]. **Table 4** shows an extract summary of the exergy destroyed, the exergetic efficiency from individual components of the PCC unit from [8]. The discussion in the present study will focus more on detail exergetic analysis of the PCC process.

4.1 Conventional Exergy Analysis of MEA-based PCC Process

In the MEA-based PCC system, a larger part of the exergy destruction is associated with the absorber and stripper columns. The exergy destruction in the columns is largely due to effect of driving forces (i.e. simultaneous heat and mass transfers, heat transfers in the stripper reboiler and condenser, and heat loss through the column metal body) in the columns affect the overall exergy destruction in the system. In this study, the effect of each driving forces to overall column exergy destruction obtained from the Aspen Plus[®] simulation was estimated using the equations described in Ashrafizadeh et al [5] as summarised in **Table 3**.

4.1.1 Stripper

Figure 2(a) shows the spatial distribution of exergy destruction in the stripper and the absorber respectively in relation to the driving forces. The results show that majority of exergy destroyed in the stripper is due to the reboiler (~57%), the condenser (30%) and the mass transfer between phases (8.4%). Exergy destruction due to heat loss to the environment is negligible (~1.6%) due to adequate insulation of the column.



(a) (b)
Figure 2: Spatial Distribution of Exergy destruction in the (a) Stripper (b) Absorber

Table 4: Conventional Exergy Analysis of MEA-based PCC [8]

Components	$E_{F,n}$ (MW)	$E_{P,n}$ (MW)	$E_{D,n}$ (MW)	$y_{D,n}$ (%)	ξ_n (%)
FGD Unit					
BGS Filter	41.39	40.83	0.56	0.04	98.65
ID-FAN	37.91	34.43	3.48	0.24	90.82
Desulphurizer	42.62	36.95	5.67	0.40	86.70
MEA-Based PCC Unit					
FG-Cooler	70.19	36.82	33.37	2.33	52.46
BLOWER	50.08	20.06	30.02	2.10	40.06
ABSRBR	96.2	41.52	54.68	3.82	44.55
DESRBR	235.64	153.57	82.07	5.74	65.17
PUMP	11.89	11.63	0.26	0.02	97.81
T-COOLER	36.82	30.89	5.93	0.41	83.89
MHEX	48.81	36.83	11.98	0.84	75.46
Loss (MEA)			5.15	0.36	

4.1.2 Absorber

In the absorber, majority of the exergy destruction (~54%) is due to heat transfer through the exothermic absorption reaction. The mass transfer in the column (i.e. concentration gradient) also accounts for about 43%, while the heat loss accounts for ~2%. Figure 2(b) shows the spatial distribution of exergy destruction in the absorber.

This implies that effort to reduce the exergy destruction in the columns should be focused towards principles/strategies that reduces energy consumption in the reboiler (for distillation column), exothermic heat of reaction (for the absorption column), and the mass transfer driving forces in both.

4.1.3 The Closed loop MEA-based PCC System

Table 4 shows the exergy destruction and efficiency of the closed loop MEA-based PCC system. Figure 3 illustrates spatial distribution of the exergy destruction in the closed loop PCC systems [8]. The figure shows that the absorber (26%) and the desorber (36%) are the main sources of exergy destruction in the PCC. The feed cooler (18%) and the blower (16.5%) are also contributed strongly. The total exergy destruction is about 203 MW (1.58 MJ/kg CO₂). Process equipment such as the pump, and the solvent cooler are minor contributors to the

exergy destruction. Using the chemical exergy of MEA in the liquid phase of 1,536 kJ/mol [6], the exergy loss due to the consumption of MEA was included in the overall exergy destruction. Loss of 5.15 MW (0.04 MJ/kg CO₂) amounting to about 2.3 % of total exergy destroyed in the CO₂ capture process was estimated.

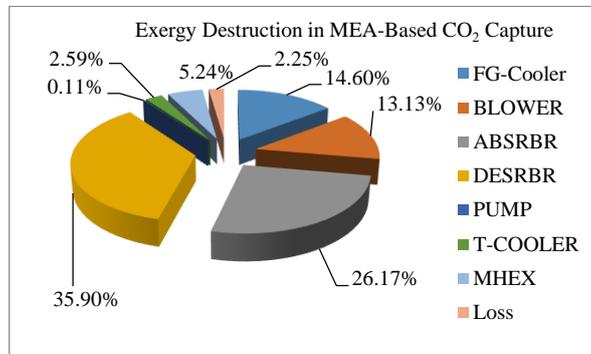


Figure 3: Distribution of Exergy Destruction in the closed loop PCC [8]

4.2 Advanced Exergy Analysis

4.2.1 Endogenous and Exogenous Exergy Destruction

Table 5 shows the distribution of the sources (i.e. endogenous or exogenous) and the potential for improvement (i.e. avoidable or unavoidable) of the conventional PCC process. Figures 4(a) and 4(b) reveal that most of the exergy destruction in the PCC components is endogenous (i.e. due to the irreversibility in the components themselves). The stripper and absorber have largest absolute endogenous exergy destruction of about 75.5 MW and 50 MW respectively. Hence, their performances will be significantly affected by improving the exergy destructions within the components themselves. However, the potential for improvement is governed by the avoidability or unavoidability of the exergy destroyed.

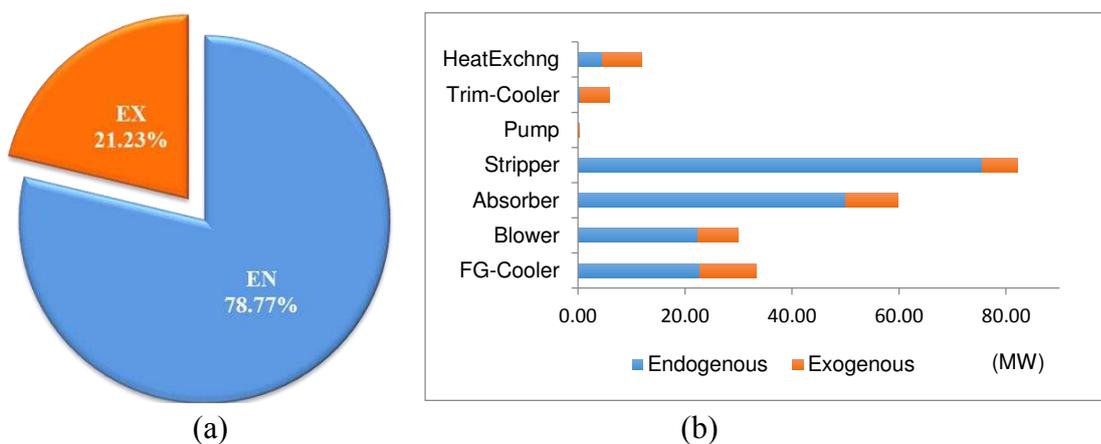


Figure 4: Endogenous and Exogenous Exergy Destruction in the PCC

4.2.1 Avoidable and Unavoidable Exergy Destruction

Figure 5(a) shows that majority of the exergy destruction within the PCC components is unavoidable (70%). However, the ratio of the avoidable part of the exergy destruction differs considerably from components to components. For the stripper, about 17% (13.83MW) of the overall exergy destroyed within it is avoidable (Figure 5(b)).

The result also reveals that about 27% (16.23MW) of the exergy destructions in the absorber are avoidable. In the heat exchanger, the blower, and the cooler, the avoidable exergy destroyed are 41% (5.01MW), 63% (5.01MW), and 65% (13.02MW) respectively as shown in Figure 5(b). It is important to know the sources (exogenous or endogenous) of the avoidable exergy destructions in the components. This will help focus attention on reducing the avoidable exergy destruction of a component based on its source.

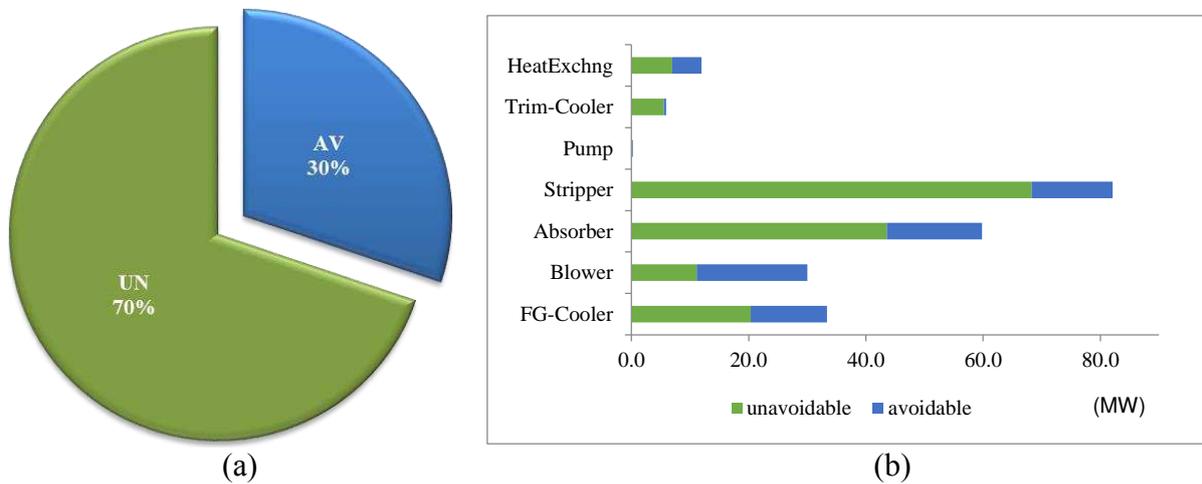


Figure 5: Avoidable and Unavoidable Exergy Destruction in the PCC

Table 5: Selected results of advanced exergy analysis of MEA-Based PCC

Components	$E^{T,n}_{F,tot}$	$E^T_{D,n}$	$E^R_{D,n}$	$E^{un}_{D,n}$	$E^{av}_{D,n}$	$E^{en}_{D,n}$	$E^{ex}_{D,n}$	$E^{en}_{D,n}$		$E^{ex}_{D,n}$	
								$E^{un,en}_{D,n}$	$E^{av,en}_{D,n}$	$E^{av,ex}_{D,n}$	$E^{un,ex}_{D,n}$
FGD Unit											
BGS Filter	1407.25	0.38	0.62	0.41	0.21	0.56	0.06	0.48	0.08	0.13	-0.07
ID-FAN	1405.90	0.00	4.21	2.86	1.35	3.67	0.54	2.87	0.80	0.55	-0.01
Desulphurizer	1403.98	2.86	5.81	4.63	1.18	4.43	1.38	2.96	1.47	-0.29	1.67
Conventional MEA-Based PCC Unit											
FG-Cooler	1406.34	22.84	33.37	20.35	13.02	22.84	10.53	12.62	10.22	2.80	7.73
BLOWER	1405.10	22.51	30.02	11.12	18.90	22.51	7.51	9.79	12.72	6.18	1.33
ABSRBR	1394.29	59.83	59.83	43.60	16.23	50.00	9.83	37.45	12.55	3.68	6.15
DESRBR	1385.29	82.07	82.07	68.25	13.82	75.50	6.57	61.49	14.01	-0.19	6.76
PUMP	1404.31	0.097	0.26	0.14	0.12	0.10	0.16	0.00	0.10	0.02	0.14
T-COOLER	1406.78	0.41	5.93	5.56	0.37	0.41	5.52	0.07	0.33	0.03	5.49
MHEX	1405.86	4.66	11.98	6.98	5.00	4.66	7.32	0.88	3.78	1.23	6.09

4.2.3 Avoidable and Unavoidable Exogenous/Endogenous Exergy Destruction

The real potential for improving a component or system is not fully revealed by its total exergy destruction, the sources or the potential for improvement alone; but by understanding the source of its avoidable part. As shown in Figure 6 for the conventional PCC, most of the avoidable exergy destructions within stripper (98%), the absorber (77%), the blower (67%), the cooler (78%) and the heat exchangers (65%) respectively are endogenous; hence, the improvement measures for these components should be concentrated on the components themselves.

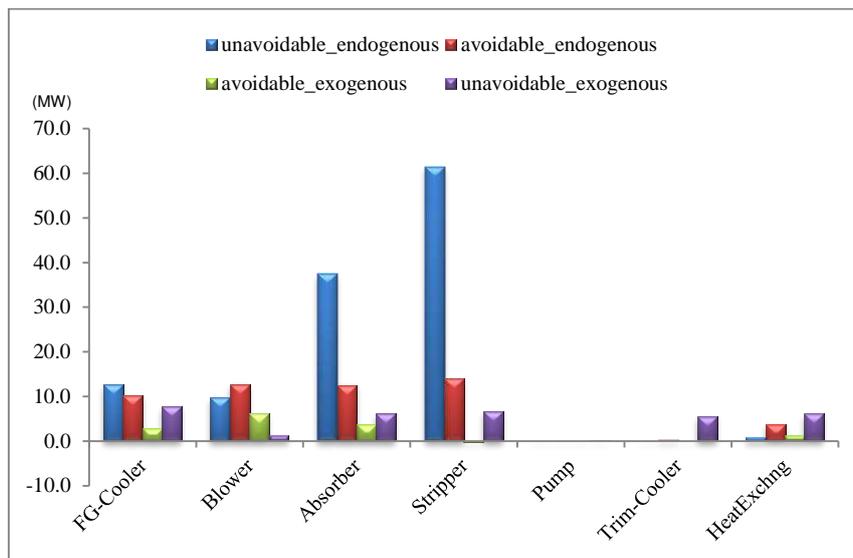


Figure 6: Avoidable and Unavoidable Endo/Exogenous Exergy Destruction in Conventional PCC

5 Case Studies on Improving Exergy Destruction in PCC Integrated with SCPP

5.1 Simulation of the Case Studies

The results of the analyses of the energy consumption of the CO₂ capture system and the overall exergy destruction in the integrated system presented in section 4 necessitated the development of several variations of the conventional PCC system to reduce the amount of exergy destruction and thereby improving its associated energy penalties. In this study, seven cases were compared; Case 1: SCPP with AIC, Case 2: SCPP with SF, Case 3: SCPP with (AIC + SF), Case 4: SCPP with SIH, Case 5: SCPP with (SIH + AIC), Case 6: SCPP with LVR, Case 7: SCPP with (LVR+AIC). **Case 1, Case 2 and Case 3 have been detailed in previous publication [8], and only a summary of the results is presented alongside Case 4 to Case 7.** The parameters shown in **Table 6** were kept constant for all the case studies for consistent comparison.

Table 6: Input Parameters fixed for the PCC Case Studies

Parameter	Data
MEA Concentrations (wt. %)	30.0
CO ₂ Removal (%)	90.0
Absorber Top Pressure (KPa)	101.325
Outlet Temperature from Lean MEA Cooler (°C)	40.0
Heat Exchanger Pressure Drop (KPa)	0.0
Stripper Condenser Temperature (°C)	50.0
Stripper Top Pressure (KPa)	161.2
Minimum Approach Temperature in Rich/lean MEA HEX (°C)	5.0

5.1.1 Case 4: Stripper Inter-heating (SIH)

The stripper inter-heating (SIH) configuration shown in **Figure 7**, has the analogous effect of the absorber inter-cooling [8] but on the regeneration process. Stripping CO₂ from the aqueous MEA solution is an endothermic process and the inter-heated stripper is a simpler approximation to the more theoretical internal exchange stripper described by Oyenekan & Rochelle [20] and Van Wagener & Rochelle [21]. In the SIH configuration, a column side stream of semi-lean solvent is heated by heat exchange with the hot lean MEA solution from the bottom of the stripper. The side stream is then returned to the stripper below its point of withdrawal while the hot lean MEA solvent maintains its conventional path to the rich-lean MEA heat exchanger. The energy performance of conventional and SIH configurations were studied by [21] on standalone stripper simulations using MEA and PZ. Their study reveals improvement of up to 7.8% and 4.6% at 0.48 and 0.52 rich loading respectively when compared to a conventional stripper. 10% of improvement was also observed when comparing the SIH configurations between the two solvents.

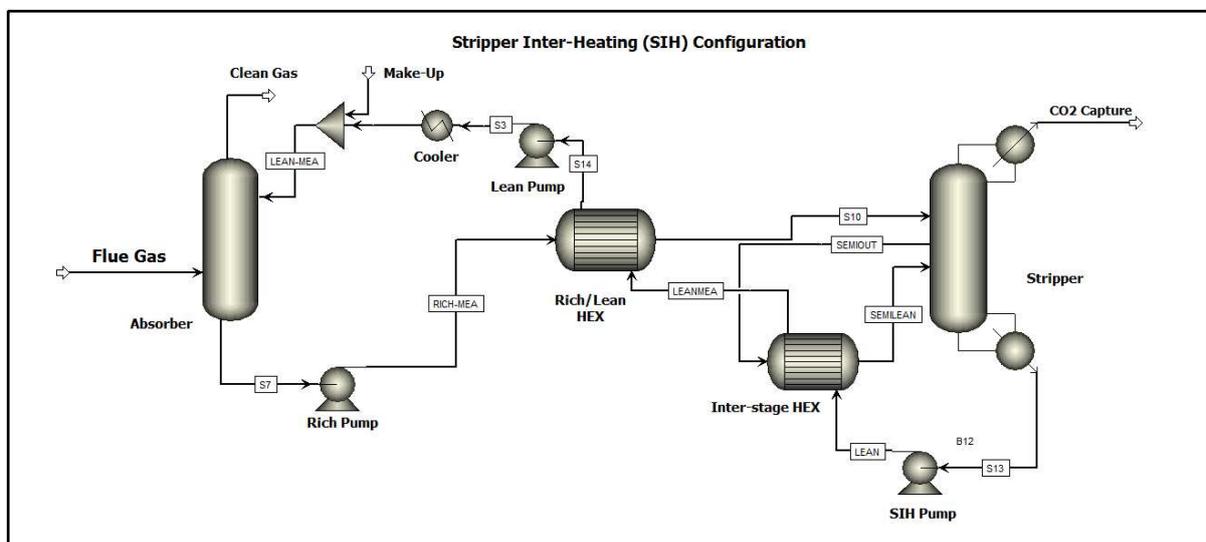


Figure 7: Aspen Plus® simulation of Stripper Inter-heating (SIH)

5.1.2 Case 5: Stripper Inter-heating and Absorber Inter-cooling (SIH + AIC)

The (SIH+AIC) configuration illustrated in Figure 8 combines the effect of the AIC and the SIH configuration. The sensitivity analysis tool in Aspen Plus® was used in standalone SIH configuration to determine the effective flow-rate of the semi-lean MEA from the stripper that provided the most efficient parameter estimate for the (SIH+AIC) configuration.

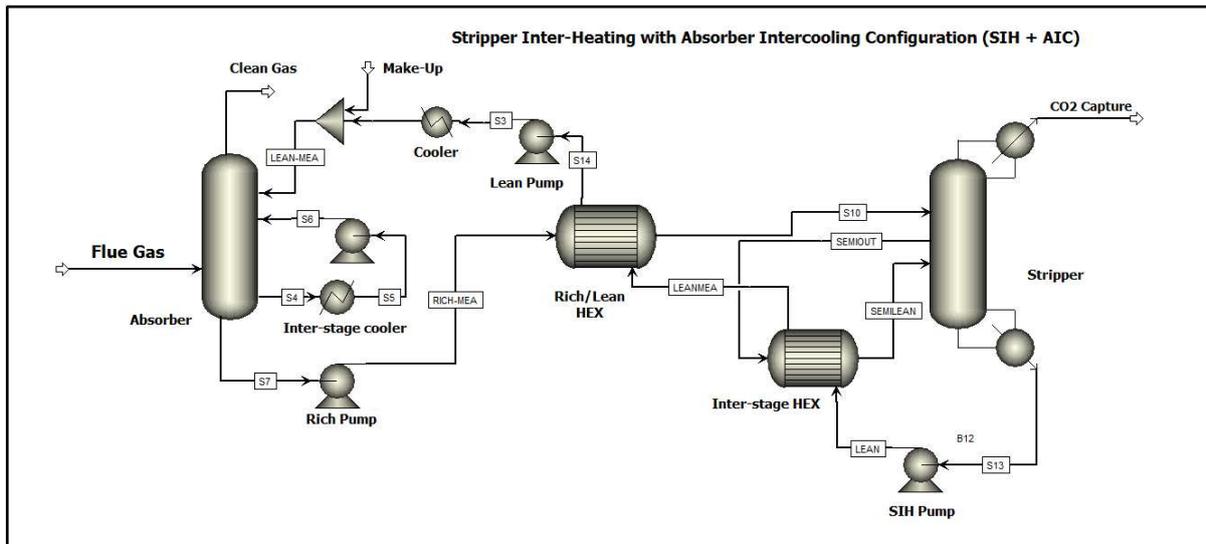


Figure 8: Aspen Plus® simulation of Stripper Inter-heating with Absorber Inter-cooling (SIH+AIC)

5.1.3 Case 6: Lean Vapour Recompression (LVR)

The concept of vapour recompression configuration (Figure 9) is to provide steam that is recovered from the stripping process as the heat source to the reboiler [7]. Jassim and Rochelle [22] presented the vapour recompression design in which the stripper bottom is used to inter-cool the gaseous stream in a multistage compressor. The idea of the design is to recover the heat of condensation of the overhead water vapour and the heat of compression to re-boil the stripper. The vapour recovered in the flash separator is majorly 90 wt. % water and 10 wt. % CO₂. The vapour is compressed and recycled to the stripper where it acts as auxiliary stripping steam and thus leading to lower reboiler duty. Some make-up water is added to the vapour stream to de-superheat it, to avoid the vapour temperature exceeding the recommended temperature of 120°C in the column.

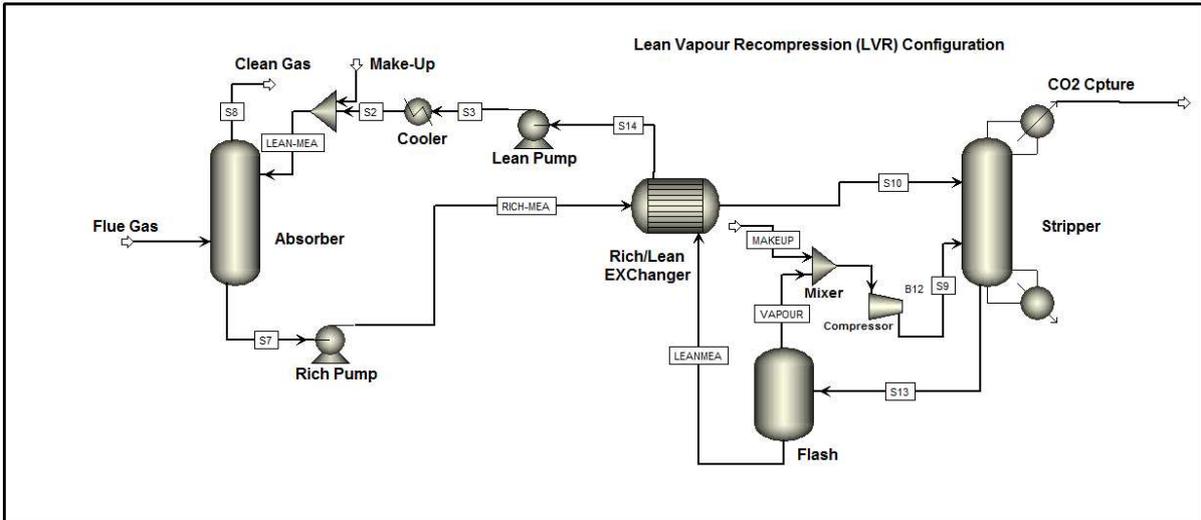


Figure 9: Aspen Plus® simulation of Lean vapour recompression (LVR)

5.1.4 Case 7: Absorber Inter-cooling with Lean Vapour Recompression (AIC+LVR)

The LVR+AIC configuration combines the effect of AIC and the LVR. The sensitivity analysis tool in Aspen Plus® was used to determine the optimal flow-rate of inter-cooled stream, the lean loading and the solvent circulation rate at 90% CO₂ capture level. (Figure 10) shows the flowsheet of the LVR + AIC simulation in Aspen Plus®.

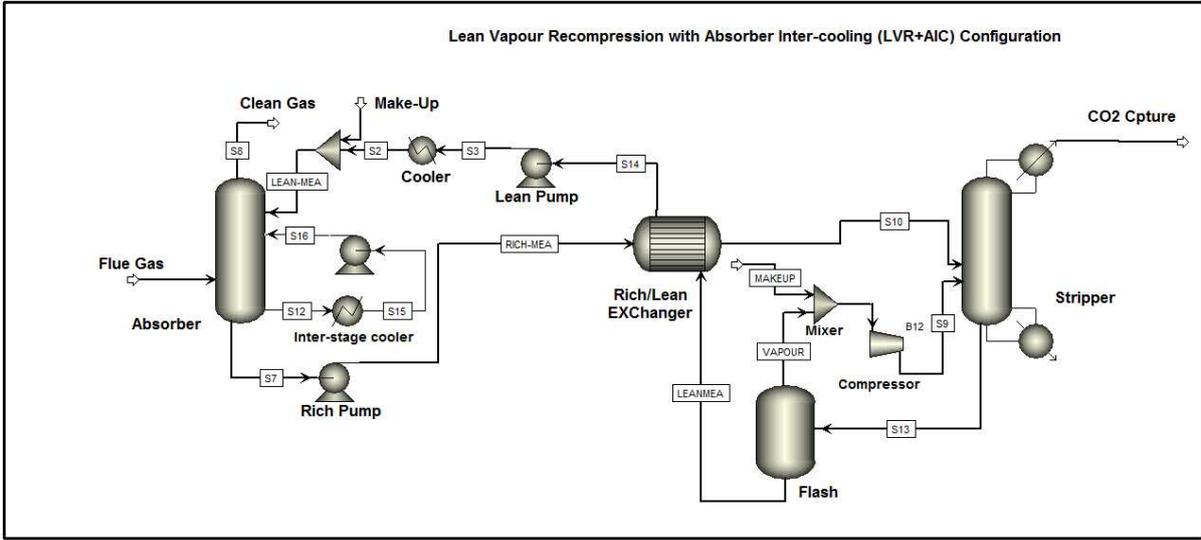


Figure 10: Aspen Plus® simulation of Lean vapour recompression with absorber Inter-cooling (LVR+AIC) configuration

5.2 Analysis of the Case Studies

5.2.1 SCPP-SIH Configuration

Figure 11(a) illustrates the spatial distribution of exergy destruction in SCPP-SIH. The SIH inclusion reduces the local exergy destruction in the PCC by ~3.9% when compared to the conventional case. Table 7 shows a summary of the system performance. The result shows

about 1.6% reduction in overall exergy destruction when compared to the SCPP system with base case CO₂ capture. The reboiler duty, energy penalty and the efficiency penalty were decreased by about 6.8%, 1.8% and 0.7% respectively. The exergetic efficiency of the SCPP-SIH integrated system was also improved by about 2.4% when compared to the conventional case.

5.2.2 SCPP-(SIH+AIC) Configuration

Figure 11(b) illustrates the spatial distribution of exergy destruction in SCPP-(SIH+AIC). The (SIH+AIC) inclusion reduces the local exergy destruction in the PCC by 5.7% when compared to the conventional case. Table 7 shows a summary of the system performance. The result shows 3.8% reduction in overall exergy destruction when compared to the SCPP system with base case CO₂ capture. The reboiler duty, the energy penalty, and the efficiency penalty decreased by about 11.03%, 4.3% and 1.7% respectively. The exergetic efficiency of the SCPP-(SIH+AIC) integrated system was also improved by about 5.7% when compared to the conventional case.

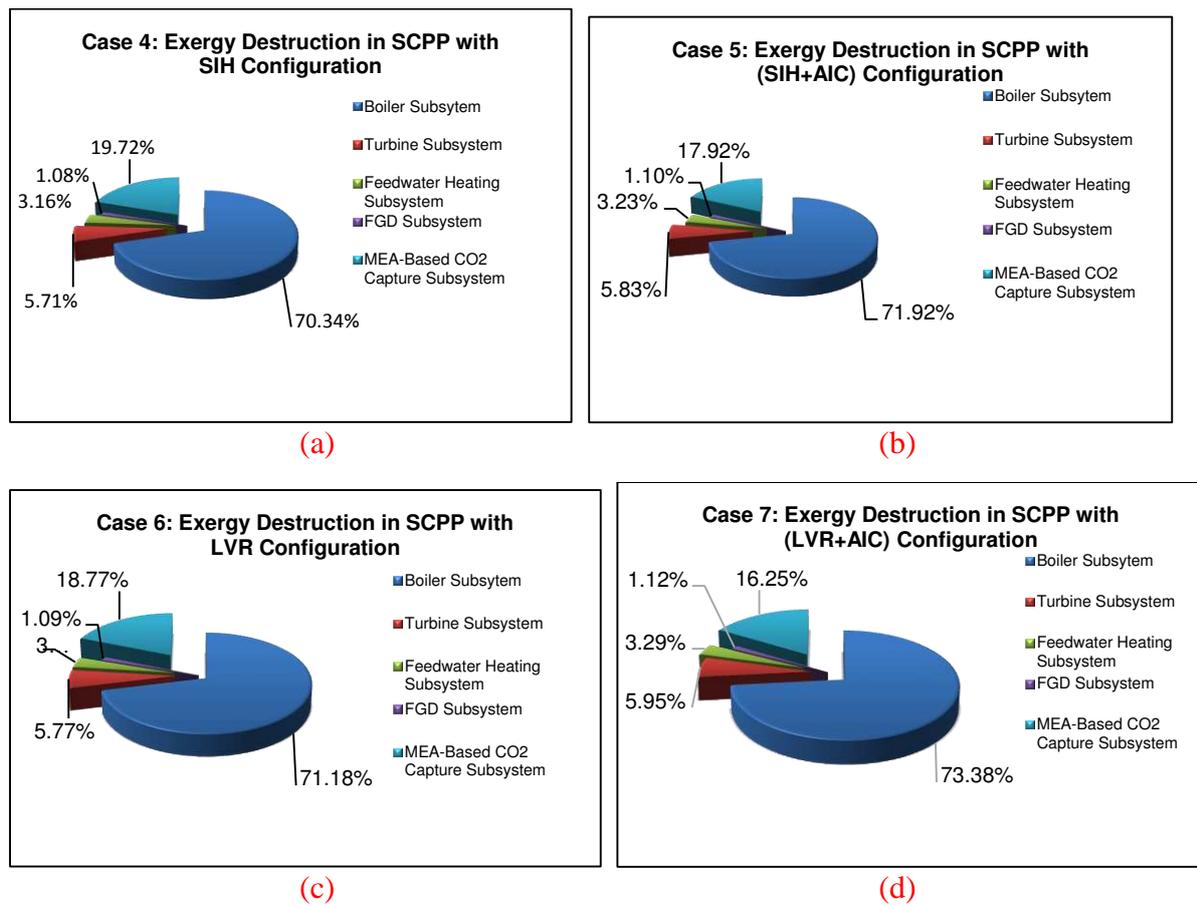


Figure 11: Case Studies of Exergy Destruction in SCPP Integrated with PCC

5.2.3 SCPP-LVR Configuration

Figure 11(c) illustrates the spatial distribution of exergy destruction in SCPP-LVR. The LVR inclusion reduces the local exergy destruction in the PCC by 4.8% when compared to the conventional case. Table 7 shows a summary of the system performance. The result shows 5.6% reduction in overall exergy destruction when compared to the SCPP system with base case CO₂ capture. The reboiler duty, the energy penalty, and the efficiency penalty decreased by 17.5%, 5.3% and 2.1% respectively. The exergetic efficiency of the SCPP-LVR integrated system was also improved by about 6.2% when compared to the conventional case.

5.2.4 SCPP-(LVR+AIC) Configuration

Error! Reference source not found.(d) illustrates the spatial distribution of exergy destruction in SCPP-(LVR+AIC). The (LVR+AIC) inclusion reduces the local exergy destruction in the PCC by about 7.3% when compared to the conventional case. Table 7 shows a summary of the system performance. The result shows about 6.6% reduction in overall exergy destruction when compared to the SCPP system with base case CO₂ capture. The reboiler duty, the energy penalty, and the efficiency penalty decreased by 19.7%, 6.9% and 2.6% respectively. The exergetic efficiency of the SCPP-(LVR+AIC) integrated system was also improved by about 7.3% when compared to the conventional case.

Table 7: System Performance Indicator of the SCPP with the CO₂ Capture Scenarios

Description	Reference SCPP	SCPP + PCC							
		Base Case	Case 1[8]	Case 2[8]	Case 3[8]	Case 4	Case 5	Case 6	Case 7
Performance Summary									
Total (steam turbine) power (MWe)	580.26	482.28	484.52	486.42	488.58	490.04	502.80	508.39	514.21
Auxiliary load (MW)	28.28	52.04	51.95	48.45	42.8	49.87	49.02	49.06	47.97
Gross plant power (MW)	551.98	430.24	432.57	437.97	445.78	440.17	453.78	459.33	466.24
Generator loss (MW)	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83
Net power output (MWe)	550.15	428.41	430.74	436.14	443.95	438.34	451.95	457.50	464.41
Unit efficiency, HHV (%)	39.10	30.45	30.61	31.00	31.55	31.15	32.12	32.51	33.01
CO ₂ Capture Performance Summary									
Reboiler Duty (MW)	-	528.78	511.81	492.02	466.57	492.77	470.45	436.24	424.61
Energy penalty (%)	-	22.13	21.70	20.72	19.30	20.32	17.85	16.84	15.25
Efficiency penalty (%)	-	8.65	8.49	8.10	7.55	7.95	6.98	6.59	6.09
Exergetic Performance Summary									
Exergy Destruction, y _D (%)	52.61	46.27	46.15	45.81	43.19	44.69	42.44	40.69	39.65
Exergy Losses, E _L (%)	8.34	5.03	4.62	4.37	3.58	4.23	3.29	2.86	2.15
Exergetic efficiency, ε (%)	39.05	48.7	49.23	49.82	53.23	51.09	54.36	54.87	56.04

6 Conclusions

This study investigates the methods of reducing energy consumption in PCC process integrated with SCPP. Conventional and advanced exergy analyses was used to estimate the magnitude, the location, the sources, and the potential for improvement of energy consumed/exergy destroyed. Seven modifications to the conventional MEA-Based PCC were analysed for their potential to reducing exergy destruction: AIC, SF, AIC+SF, SIH, SIH+AIC, LVR, and LVR+AIC.

The SIH, SIH+AIC, LVR, and LVR+AIC configuration shows approximately 2%, 4%, 5%, and 7% reduction energy penalty respectively when compared to the conventional MEA-based approach. The results show that the energy consumption and the efficiency of the PCC process can be improved by recovering the avoidable exergy destruction in system components. This is important because for every 1% reduction in the energy required for capture, costs can be lowered to between 0.7 - 1% [25].

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