CHEMICAL ENGINEERING TRANSACTIONS

VOL. 39, 2014

A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Peng Yen Liew, Jun Yow Yong
Copyright © 2014, AIDIC Servizi S.r.l.,
**ISBN** 978-88-95608-30-3; **ISSN** 2283-9216
DOI:10.3303/CET1439242

# Identification of Process Integration Options for $CO_2$ Capture in Greek Lignite-Fired Power Plant

Peng Yen Liew*[a], Jiří Jaromír Klemeš[a], Aggelos Doukelis[b], Nan Zhang[c],
Panos Seferlis[d]

[a]Centre for Process Integration and Intensification – CPI$^2$, Research Institute of Chemical and Process Engineering - MŰKKI, Faculty of Information Technology, University of Pannonia, Egyetem u. 10, H-8200 Veszprém, Hungary
[b]National Technical University of Athens, Laboratory of Steam Boilers and Thermal Plants, Heroon Polytechniou 9, 15780 Zografou Campus, Greece
[c]Centre for Process Integration, School of Chemical Engineering Analytical Science, The University of Manchester, Sackville Street, Manchester M13 9PL, UK
[d]Department of Mechanical Engineering, Aristotle University of Thessaloniki, P.O. Box 424, Thessaloniki, 54124, Greece
pengyenliew@cpi.uni-pannon.hu

Electricity is mostly generated from non-renewable fossil fuels such as natural gas and coal. The burning of fossil fuel releases greenhouse gases particularly $CO_2$. An important research objective is needed to reduce the emissions of $CO_2$ to the atmosphere by capturing it. The capture types, which can be distinguished, are pre-combustion, oxyfuel combustion, post-combustion and chemical looping combustion. Post-combustion configuration is commonly used due to its simplicity in design. Carbon capturing technologies require energy and utilities, resulting in power penalty. The energy used directly increases the load of the power plant and emission. Various studies have been conducted on energy penalty. There is a strive for reducing the energy and utilities used by integrating with the power plant. This work aims at the optimisation of the performance of fossil-fired post-combustion power plants with carbon capture technology by examining the possible options of heat/process integration, cooling and the utilisation of low-grade waste heat. The use of fans, coolers and gas polishing and capture equipment is considered. The paper will examine several possible designs of the $CO_2$ capture module by varying the solvent and the system topology with monoethanolamine (MEA) plant as a benchmark. This paper will serve as an insight to power penalty reduction with carbon capture technology and decision factor to the industry.

## 1. Introduction

Global warning and carbon emission issues increased the awareness of industry on the importance of carbon capture process. In year 2011, fuel burning process in energy industry emitted a total of 31,342 Mt of $CO_2$ (IEA, 2013). The emission is increasing with the increase of world energy demand. As a result, the local authorities are committed to international agreement for lowering carbon emission in different industries. In order to avoid penalty by the local authorities, industrial efforts in carbon emission reduction become essential for meeting the allowable emission limit.

Carbon Capture and Storage (CCS) is one of the effective alternatives to decrease the greenhouse gases emission by 19 % in energy generation process which involves fuel burning process (Nataly Echevarria Huaman and Xiu Jun, 2014). Carbon capture process could be categorised in four different types, which are post-combustion, pre-combustion, oxyfuel combustion and chemical looping combustion. Post-combustion carbon capture process is one of the preferable to be most promising type of carbon capture process for industrial implementation. Several types of $CO_2$ separation process from flue gas could be used in post-combustion carbon capture facility, which are chemical absorption (amine absorption, aqua ammonia absorption, dual alkali absorption, and absorption with sodium carbonate slurry), adsorption (zeolites, activated carbon, amine functionalized adsorbents, and metal organic frameworks) and membrane separation.

Please cite this article as: Liew P.Y., Klemeš J.J., Doukelis A., Zhang N., Seferlis P., 2014, Identification of process integration options for $CO_2$ capture in greek lignite-fired power plant, Chemical Engineering Transactions, 39, 1447-1452 DOI:10.3303/CET1439242

Power penalty of a coal-fired power plant with post-combustion carbon capture is studied by Goto et al. (2013). Cormos et al. (2013) examined the efficiency and power penalty for two different types of Carbon Capture facilities with a super-critical coal-based power plant. Post-combustion carbon capture with gas-liquid absorption and calcium looping cycle are considered in the study. Berstad et al. (2013) suggested a process design with low temperature pre-combustion carbon capture with coal derived syngas for an IGCC plant. Damartzis et al. (2013) proposed a generalised methodology for designing an optimal post-combustion Carbon Capture process. Liew et al. (2014) analysed the Process Integration opportunity of monoethanolamine (MEA)-based carbon capture process and a natural gas power plant. They suggested integration for satisfying the heat requirement of stripper reboiler with the energy excess in the low pressure steam condenser. However, exit temperature of the low pressure steam condenser is not allowing heat exchange with the stripper reboiler. The exhaust pressure of low pressure turbine is suggested to be increased for the heat exchange between the equipment. The power penalty became the main consideration of the study. In this work, a similar study is done for a MEA-based carbon capture process with a supercritical coal power plant (Kakaras et al., 2013). The Process Integration options between the processes are examined.

## 2. Methodology

The Process Integration option is able to be identified using Pinch Analysis and Mathematical Programming approaches (Klemeš and Kravanja, 2013). Pinch Analysis is generally performed using graphical (Composite Curves - CCs and Grand Composite Curve - GCC) and cascade (Problem Table Algorithm) methodologies (Klemeš, 2013). Process energy utilisation is analysed by Pinch Analysis. The methodology used to identify Process Integration options in this study is listed as below:

### 2.1 Data Extraction

Stream data of the coal power plant and carbon capture process is extracted from the process flow diagram generated from the process simulator. It is essential to obtain several specifications of process streams, which are the source temperature, target temperature, flow rate and heat capacity. The heat duty for existing designed energy demanding equipment, e.g. heat exchangers, condensers, heaters and coolers are also collected for getting the missing stream data.

### 2.2 Pinch Analysis

The energy requirements of the process are targeted using Composite Curves and Grand Composite Curve based on the stream data extracted. These requirements represent the theoretical energy requirement, which also represents the maximum energy recovery in the system.

### 2.3 Process Modification and Integration Options Identification

Besides the steam generation process from flue gas, Process Integration and modification options should be identified for minimizing energy consumption of the process. The design of steam turbine in the turbine island is also examined for maximum power generation. The use of re-heater/ heat pump also considered for upgrading heat sources at low temperature to integrate with heat sink at high temperature.

### 2.4 Pinch Analysis: Reassessment

The optimum operating condition is determined after the processes modification options identification. The effects of the process modification are analysed. The CCs and GCC are constructed to inspect the improvement of process energy consumptions.

### 2.5 Heat Exchanger Network Design

The Heat Exchanger Network for the process is designed using Grid Diagram for maximising the energy recovery in the process. The process integrated flowsheet is then drawn based on the Grid Diagram.

### 2.6 Economic Analysis

The gross profit of the integrated process is analysed for preliminary cost saving assessment from the process modifications. Detailed calculation is also essential for accounting other energy consuming equipment, as well as the investment cost, for confirming the economic potential of the modifications suggested.

## 3. Result and Discussions

### 3.1 Data extraction

Figure 1 and 2 are the process flow diagram for the lignite-fired power plant and the carbon capture unit taken from Report of D4.2. Data extraction is done based on the given stream data in the report. Table 1 summarised the steam data extracted for both lignite-fired power plant and carbon capture unit.

*Table 1: Stream data for lignite-fired power plant and carbon capture unit*

| Stream name | | Ts ($^0$C) | Tt ($^0$C) | m (kg/s) | Cp (kJ/kg.-$^0$C) | DH (kW) |
|---|---|---|---|---|---|---|
| Lignite-Fired Power Plant | | | | | | |
| Air preheater | C1 | 18.87 | 341.23 | 588.33 | 1.03 | 195,408 |
| Condensate return heater | C2 | 32.49 | 151.21 | 313.28 | 4.21 | 156,427 |
| Condensate return heater 2 | C3 | 102.63 | 151.21 | 55.57 | 4.25 | 11,484 |
| Feed water heaters | C4 | 198.55 | 290.01 | 495.10 | 4.55 | 205,922 |
| HP preheater | C5 | 290.01 | 340.00 | 495.10 | 5.29 | 130,890 |
| HP evaporator | C6 | 340.00 | 341.00 | 495.10 | 508.84 | 251,929 |
| HP superheats | C7 | 341.00 | 600.01 | 495.10 | 5.45 | 699,495 |
| IP reheats | C8 | 374.72 | 612.49 | 410.16 | 2.51 | 244,804 |
| Flue gas 1 | H1 | 1,869 | 390.57 | 670.82 | 1.3381 | 1,327,117 |
| Flue gas 2 | H2 | 414.04 | 149.05 | 670.82 | 1.1233 | 199,683 |
| LP turbine condenser | H3 | 32.15 | 31.15 | 362.80 | 930.41 | 337,553 |
| HP turbine extraction 1 | H4 | 394.88 | 224.46 | 12.71 | 12.67 | 27,438 |
| HP turbine extraction 2 | H5 | 374.72 | 224.46 | 72.23 | 14.14 | 153,482 |
| IP turbine extraction 1 | H6 | 269.30 | 102.12 | 10.87 | 15.37 | 27,936 |
| IP turbine extraction 2 | H7 | 474.23 | 224.46 | 9.97 | 9.76 | 24,312 |
| LP turbine extraction 1 | H8 | 224.22 | 102.12 | 23.41 | 20.34 | 58,146 |
| LP turbine extraction 2 | H9 | 121.86 | 102.12 | 21.28 | 116.01 | 48,730 |
| LP turbine extraction 3 | H10 | 62.14 | 61.02 | 14.80 | 1,997.95 | 33,118 |
| Carbon Capture Unit | | | | | | |
| Stripper’s reboiler | C9 | 120 | 121 | 1.00 | 475,404 | 475,404 |
| MEA lean cooler | H11 | 69.63 | 40.00 | 2,683.37 | 3.39 | 269,759 |
| Stripper’s condenser | H12 | 100.53 | 40.00 | 255.41 | 19.89 | 307,515 |
| Intercooler 1 | H13 | 162.17 | 40.00 | 136.15 | 1.30 | 21,553 |
| Intercooler 2 | H14 | 177.87 | 40.00 | 133.88 | 1.08 | 20,002 |
| Intercooler 3 | H15 | 134.33 | 68.00 | 133.44 | 1.31 | 11,623 |
| Intercooler 4 | H16 | 99.04 | 25.00 | 133.44 | 3.25 | 32,146 |

### 3.2 Pinch Analysis

The lignite-fired power plant theoretically does not require external energy supply because the power plant is designed to generate steam for power generation purpose (Figure 3). The turbine condenser is the only equipment unit in the power plant which requires cooling utility at 341.2 MW. The effect of the installation of carbon capture on the plant’s energy demand is analysed. The Grand Composite Curve for the combined processes (power plant and carbon capture) is shown in Figure 2. The curves are plotted assuming minimum temperature difference is 15 °C. The hot and cold utility requirements of the combined process are 443.3 MW and 971.7 MW, while the hot and cold Pinches are located at 100.5 °C and 85.5 °C.

### 3.3 Process modification and integration options identification

Several process modification options are identified for supercritical Greek lignite-fired power plant and MEA-based carbon capture process. The stripper’s condenser is suggest for integrating with the air preheater (Scheme 1), while $CO_2$ inter-coolers are integrated to closed loop cooling water for condensate return heating (Scheme 2). The use of steam extraction from low pressure steam turbine is found to be the best heat source for reboiler heating (Scheme 3).

### 3.3.1. Integration of stripper’s condenser and air preheater (Scheme 1)

The stripper’s condenser has heat available from 100 °C to 40 °C, while the combustion air is required to be heated up from 19 to 341°C. It is beneficial if both streams could be integrated for heating air up to 80 - 85 °C, while the remaining energy could be supplied by flue gas exits from the steam generation process.

### 3.3.2. Integration of intercoolers and condensate return heater (Scheme 2)

There are a total of 85.3 MW energy sources to be cooled by utility from intercoolers in $CO_2$ compression train. The condensate return exit from condenser is required to be preconditioned to fulfil the supercritical deaerator requirement at 151 °C. The integration of these streams are able to reduce the power penalty due to stream extraction for condensate return heating.

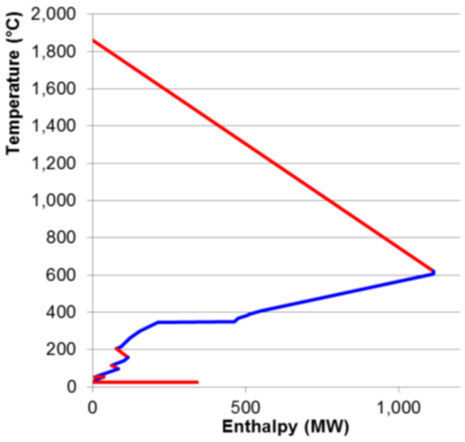

*Figure 1: Grand Composite Curve for lignite power plant*

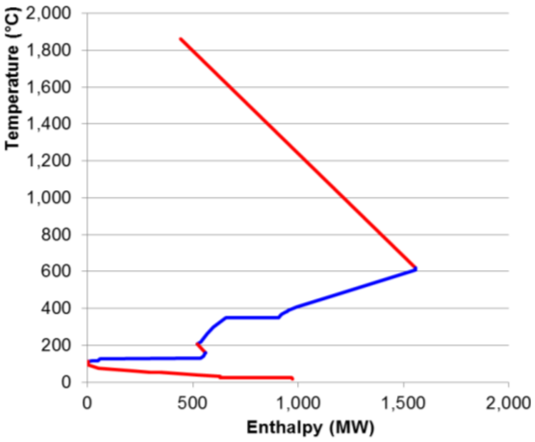

*Figure 2: Grand Composite Curve for combined lignite power plant and carbon capture process*

### 3.3.3. Modification of steam extraction condition for stripper's reboiler (Scheme 3)

The stripper's reboiler (120-121 $^0$C) is required to be heated by extracting steam from LP turbine. The optimum steam extraction pressure should be determined by selecting pressure with its saturated temperature is just above the allowable heat transfer temperature ($T_{reboiler}$ + $\Delta T_{min}$ = 135 $^0$C). The amount of steam extracted should be able to provide sufficient amount of energy to the reboiler by its latent heat (Heat duty of reboiler/ heat of condensation = 475,404 kW / 2156.03 kJ/kg = 220.5 kg/s). However, the steam extracted is required to be desuperheated (34,846 kW) by heat sink before heating the reboiler. The condensate is then required to be heated (14,190 kW) to achieve the condition required by the deaerator.

### 3.4 Pinch Analysis: Reassessment

The suggested heat integration schemes are reassessed using Pinch Analysis. The stream data is updated based on the process modifications and new GCC is plotted (Figure 3). The hot utility requirement of the integrated processes is eliminated, while cold utility requirement has a slight increment to 927.7 MW.

### 3.5 Heat Exchanger Network Design

The streams involves in the process modification are selected for the Heat Exchanger Network design. Figure 4 shows the scoping of Heat Exchanger Network design. The network is designed as shown in Figure 10, while the flowsheet for condensate system (Scheme 3 - Figure 5) and inter-coolers in $CO_2$ compression train (Scheme 2 - Figure 6) are drawn.

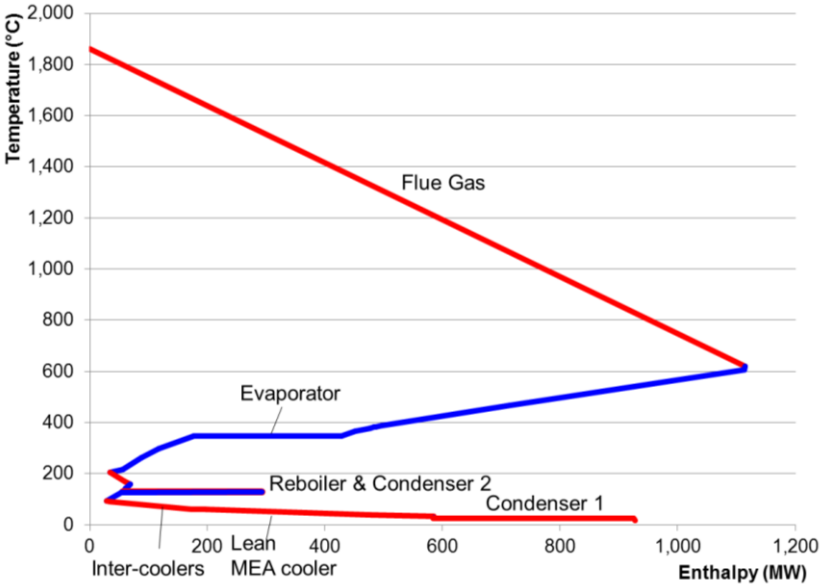

*Figure 3: Grand Composite Curve for the lignite power plant and carbon capture after process modification.*

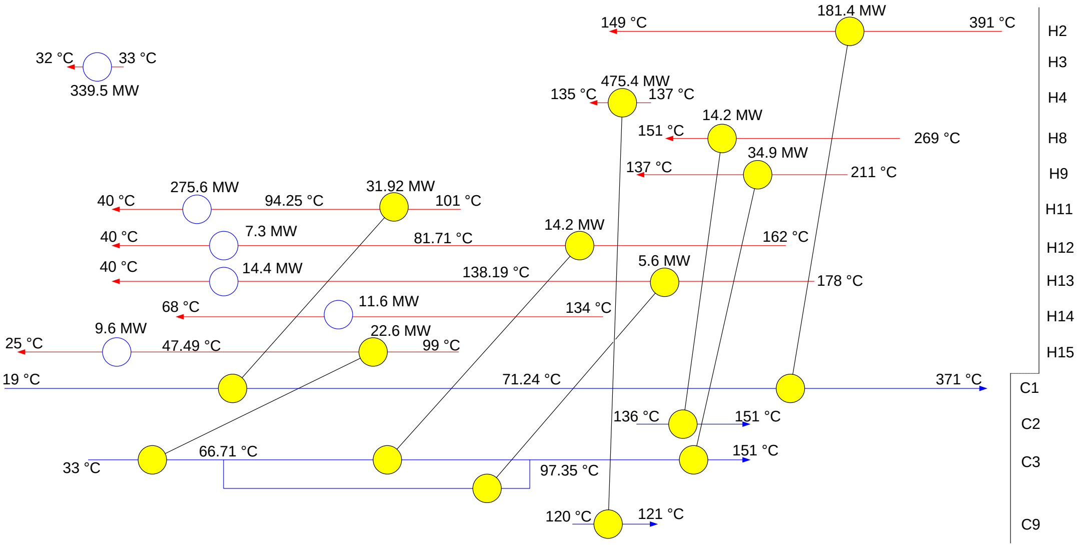

*Figure 4: Heat Exchanger Network design*

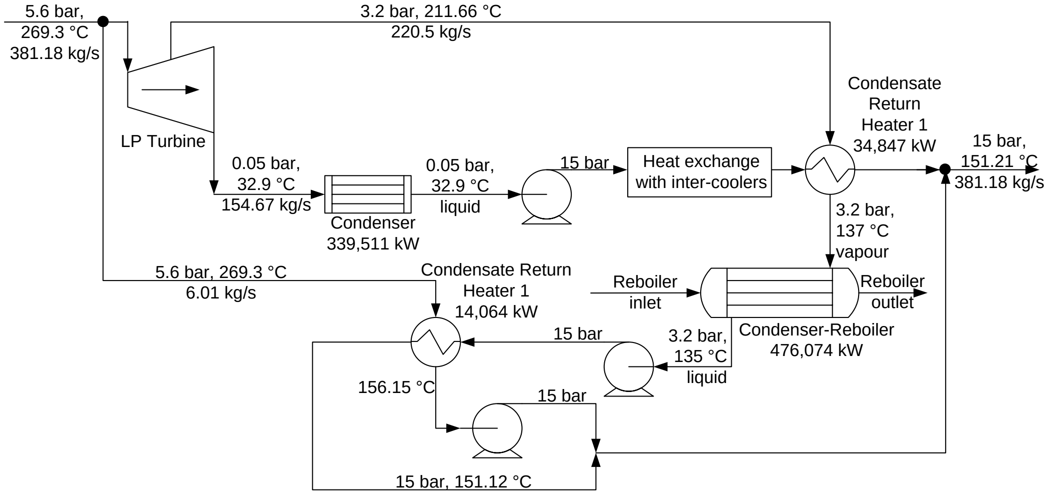

*Figure 5: Flowsheet for Integration Scheme 3*

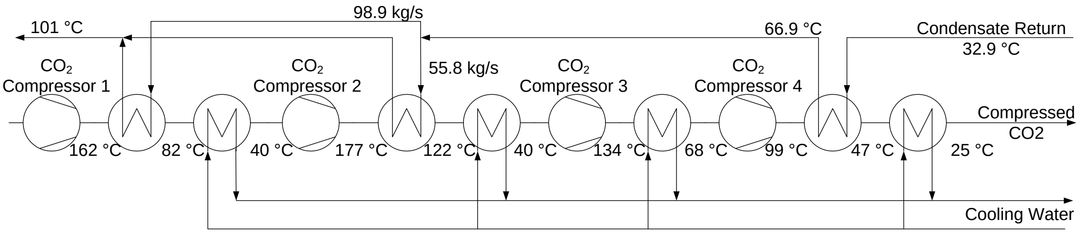

*Figure 6: Flowsheet for Integration Scheme 2*

### 3.6 Economic Analysis

The suggested integration schemes are required to be assessed in economic point of view. The integration of power plant and capture unit by supplying steam to stripper’s reboiler from turbine extraction, without other process integration options, is used as the base case of this study (Case A). The suggested network is represented as Case B in this part.

The recommended integration options are then analysed from operating cost viewpoint. The cost external LP Steam supply and cooling water supply are assumed at 22.5 €/t and 0.35 €/m3. Break-even electricity selling price is used to calculate the equivalent power penalty due to the integration option. Sensitivity analysis of the electricity price is also done in the same analysis, which the electricity price is assumed at 0.05, 0.075 and 0.1 €/kWh. The gross power generation and utility cost is used for calculating the profit. Table 2 show the analysis result of the operating cost at different electricity selling prices versus turbine exhaust pressure. The plant configuration of non-integrated power plant and $CO_2$ capture unit is used as the basis (Case A) of the economic feasibility study. The reboiler is satisfied by steam extraction from the LP turbine, while there is no other integration in the plant. The process in this case consumed relatively bigger amount of energy for cooling proposes. Case B has more power generation opportunity and lower utility cost.

*Table 2: Power lost and utility cost comparison for all integration options*

| Electricity price (€/kWh) | 0.05 | 0.075 | 0.1 | Utility cost (€/y) |
|---|---|---|---|---|
| | Gross Power Generation (€/y) | | | |
| Case A | 241,907,400 | 362,861,100 | 483,814,800 | 241,808,902 |
| Case B | 254,654,952 | 381,982,428 | 509,309,904 | 222,464,900 |

## 4. Conclusion

The Process Integration options for super-critical lignite coal-fired power plant and MEA-based carbon capture process is inspected in this study. The hot and cold utility requirements of integrated power plant and carbon capture unit before process modification are 475 MW and 972 MW. The heat exchange between stripper's condenser cooler and air pre-heater is suggested to be implemented. The air coolers in $CO_2$ compression train is suggested to provide energy for condensate return heating, instead of using steam extraction from LP turbine. The stripper's reboiler duty is conventionally satisfied by extracting steam from the LP steam turbine. The steam extraction pressure should be determined by selecting pressure with its saturated temperature at just above the allowable heat transfer temperature. The quantity of steam extracted should be able to provide sufficient amount of energy to the reboiler by its latent heat. The process modification for integrating carbon capture unit has improved the power penalty caused on the power generation system and the utility cost is also reduced by € 19 $x10^6$ /y. For future work, a more detailed techno economy feasibility study is required to be carried out for confirming the feasibility of the work.

## Acknowledgements

The authors gratefully acknowledge the financial support from the EC FP7 project "Design Technologies for Multi-scale Innovation and Integration in Post-Combustion $CO_2$ Capture: From Molecules to Unit Operations and Integrated Plants" – CAPSOL, Grant No. 282789.

### Reference

Berstad D., Anantharaman R., Nekså P., 2013, Integrated low-temperature CO2 capture from IGCC power plant by partial condensation and separation of syngas, Chemical Engineering Transactions, 35, 355-360.

Cormos C.C., Cormos A.M., Agachi P.S., 2013, Assessment of carbon capture options for super-critical coal-based power plants, Chemical Engineering Transactions, 35, 367-372.

Damartzis T., Papadopoulos A.I., Seferlis P., 2013, Generalized framework for the optimal design of solvent-based post-combustion CO2 capture flowsheets, Chemical Engineering Transactions, 35, 1177-1182.

Goto K., Yogo K., Higashii T., 2013, A review of efficiency penalty in a coal-fired power plant with post-combustion CO2 capture, Applied Energy, 111, 710-720.

IEA, 2013, Key World Energy Statistics 2013, International Environmental Agency (IEA), Paris, France.

Kakaras E.K., Koumanakos A.K., Doukelis A.F., 2013, Greek lignite-fired power plants with CO2 capture for the electricity generation sector, Chemical Engineering Transactions, 35, 331-336.

Klemeš J., Ed. 2013, Handbook of Process Integration (PI): Minimisation of Energy and Water Use, Waste and Emissions, Woodhead/Elsevier, Cambridge, UK.

Klemeš J.J., Kravanja Z., 2013, Forty years of Heat Integration: Pinch Analysis (PA) and Mathematical Programming (MP), Current Opinion in Chemical Engineering, 2 (4), 461-474.

Liew P.Y., Varbanov P.S., Bulatov I., Perry S.J., Gharaie M., Zhang N., Fenelon E., Doukelis A., Dimitriadis G., 2014, Identification of Process Integration Options for Carbon Capture, Computer Aided Chemical Engineering, 33, 1873-1878.

Nataly Echevarria Huaman R., Xiu Jun T., 2014, Energy related $CO_2$ emissions and the progress on CCS projects: A review, Renewable and Sustainable Energy Reviews, 31, 368-385.