Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 00 (2008) 000–000

Energy Procedia

www.elsevier.com/locate/XXX

GHGT-9

Redesign, Optimization, and Economic Evaluation of a Natural Gas Combined Cycle with the Best Integrated Technology CO_2 Capture

Cristina Botero[a]*, Matthias Finkenrath[a], Michael Bartlett[a], Robert Chu[b], Gerald Choi[b], Daniel Chinn[c]

[a]General Electric Global Research, D-85748 Garching n. Munich, Germany
[b]Nexant, Inc., 101 Second Street, San Francisco, CA 94105, USA
[c]Chevron Energy Technology Company, 100 Chevron Way, Richmond, CA 94802, USA

Elsevier use only: Received date here; revised date here; accepted date here

Abstract

The Best Integrated Technology (BIT) concept for post-combustion CO_2 capture was evaluated for a 400 MW natural gas combined cycle power plant. The power plant was redesigned and optimized to include exhaust gas recirculation, an amine reboiler integrated into the heat recovery steam generator, and a low-cost amine unit capturing 90% of the CO_2 through absorption into a 30-wt% monoethanolamine solution. A detailed performance evaluation of the CO_2-lean power plant as well as a cost estimation of the power island and CO_2 compression sections of the plant was carried out in order to evaluate the performance penalty of CO_2 capture, the additional costs associated with this technology, and the advantages relative to state-of-the-art solutions retrofitting the power plant with a conventional CO_2 capture unit.

Keywords: Best Integrated Technology; post-combustion CO_2 capture; natural gas combined cycle; exhaust gas recirculation;

1. Introduction

Carbon dioxide (CO_2) capture and storage (CCS) is increasingly gaining recognition as a viable technology option for the mitigation of greenhouse gas emissions from large stationary sources such as power plants. According to the International Energy Agency (IEA), the importance of CCS as an emissions reduction technology could rank second only to energy efficiency improvements by 2050 [1]. The capture of CO_2 from power plants may be carried through separation of carbon either from the fuel (pre-combustion) or from the exhaust, the latter further differentiated according to whether pure oxygen (oxyfuel combustion) or ambient air (post-combustion) is used as an oxidant.

Post-combustion capture based on chemical absorption with aqueous amines is considered to be an attractive CO_2 capture option given its past commercial deployment in other industries such as natural gas processing, hydrogen

* Corresponding author. Tel.: +49-89-5528-3541; fax: +49-89-5528-3180.
E-mail address: botero@ge.com.

and ammonia manufacturing. Nevertheless, this route has traditionally been considered to be too expensive for CO_2 mitigation as a result of the high capital and operating costs of the amine plant required to separate the highly diluted CO_2 from large volume flows of power plant exhaust at atmospheric pressure.

The Best Integrated Technology (BIT) concept for CO_2 capture was developed by the CO_2 Capture Project (CCP) consortium [2] with the purpose of reducing the cost and improving the performance of post-combustion CO_2 capture through an integration of the power cycle with the amine plant as well as through design improvements in the capture plant. The key elements of integration include exhaust gas recirculation (EGR), an integrated amine reboiler, and the optimization of steam extraction to the amine-based capture plant.

The present study evaluates the performance and costs of a 400 MW NGCC plant redesigned and optimized for operation with 90% CO_2 capture according to the BIT concept. The impact of exhaust gas recirculation, of the amine reboiler integration, and of the required steam extraction on the power plant performance were evaluated, as well as the design, operability aspects, and economics associated with them. While the low-cost amine unit constituting part of BIT will be introduced, the study will focus on the power island and CO_2 compression sections of the CO_2-lean power plant and the economic analysis will accordingly be limited to these.

2. The Best Integrated Technology (BIT) Concept for CO_2 Capture

The CCP consortium proposed the term Best Integrated Technology for a power plant configuration that combines a set of three measures to significantly reduce the traditionally high costs associated with state-of-the-art MEA-based post-combustion capture in NGCC plants. The key features of the BIT concept are schematically illustrated in Figure 1. As depicted in the figure, power plant exhaust gas is chemically treated in a MEA-based absorption plant, where most of the CO_2 content is separated, while the remaining CO_2-lean gas is released to the atmosphere through the stack. The captured CO_2 is subsequently compressed and dehydrated in preparation for transportation through a pipeline to the sequestration site. Exhaust gas recirculation, the integration of an amine reboiler into the heat recovery steam generator (HRSG) of the power plant, and a low-cost CO_2 capture unit are the main characteristics of BIT.

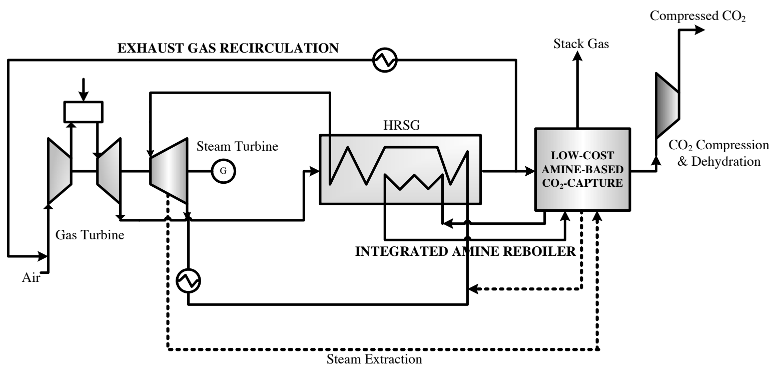

Figure 1: The Best Integrated Technology for post-combustion CO_2 capture (developed by CCP)

During operation with EGR, a fraction of the HRSG exhaust gas is cooled down and recirculated to the gas turbine inlet, where it is mixed with fresh ambient air before the gas turbine compressor. This is advantageous in two ways; first, the flow of gas to the capture unit is reduced proportionally to the EGR rate. Secondly, the concentration of CO_2 in the exhaust increases, doubling to about 8% at an EGR rate of 50%. The resulting higher CO_2 partial pressure in the gas entering the amine plant leads to the enhancement of the driving forces in the separation process. EGR hence ultimately results in a reduction of the footprint – and thus cost – of the complete gas-path equipment in the capture plant. While higher EGR rates accordingly favor the overall capture plant economics, a limit of 40% EGR was established for the plant design in order to avoid potentially challenging gas turbine operating regimes with respect to combustion stability or combustion efficiencies [4].

The integrated amine reboiler concept involves the reallocation of a fraction of the heat required to regenerate the amine solvent in the CO_2 capture plant to the HRSG of the power plant. Solvent regeneration is the most energy-intensive step in the chemical absorption-based CO_2 capture process, requiring the extraction of up to 80% of the total steam flow in the steam turbine and accordingly very large reboiling equipment in the capture plant. By integrating part of the reboiler duty into the HRSG, the size and number of external reboilers within the amine stripper can be reduced, and hence its overall cost. Additionally, through this approach heat is transferred from the exhaust to the monoethanolamine solution in a one step process instead of a two-step process with intermediate steam generation, hence minimizing the temperature gradients required for efficient heat transfer and consequently maximizing the utilization of high-grade heat.

The Low-Cost-Amine-Plant Design is the third component of the overall BIT concept and is characterized by the presence of multiple cost reduction features. These include the use of efficient structured packing, plate and frame heat exchangers, less costly equipment design specifications for the low-pressure, non-critical and non-flammable flue gas, and better heat integration for the absorber and stripper columns. The latter includes flashing the hot lean amine solution to recover some of the heat as steam and re-injecting it back to the stripper via an ejector to reduce the overall reboiling duty [3].

3. Optimization and Redesign of a 400 MW NGCC Plant for BIT

A 400 MW NGCC plant in a Norwegian location constituted the baseline used for the study, i.e. it is the reference plant without CO_2 capture, based on which efficiency penalties, cost increase, and CO_2 emission reductions were estimated. A 9FB gas turbine from General Electric is coupled through a shaft with a 3-pressure bottoming cycle producing steam for a General Electric's condensing reheat steam turbine. Condensation is carried out with seawater in a once-thru manner.

3.1. Exhaust Gas Recirculation

The effect of EGR fraction (fraction of exhaust recirculated to the gas turbine inlet) on the CO_2 concentration in the exhaust gas to the CO_2 capture plant and on the net LHV combined cycle efficiency loss is illustrated in Figure 2 for cases ranging between uncooled EGR and cooling to ambient temperature. Though the effect of EGR on the gas turbine performance is the result of a complex interaction of multiple influencing parameters as well as of a complex control strategy of the machine, two main influences can be identified, namely the temperature of the gas entering the gas turbine as well as its composition.

The temperature effect is similar to the behavior of a gas turbine in a hot day; for a fixed EGR rate, given its lower density, less gas enters the turbine as the recirculated exhaust gas temperature increases, resulting in a reduced

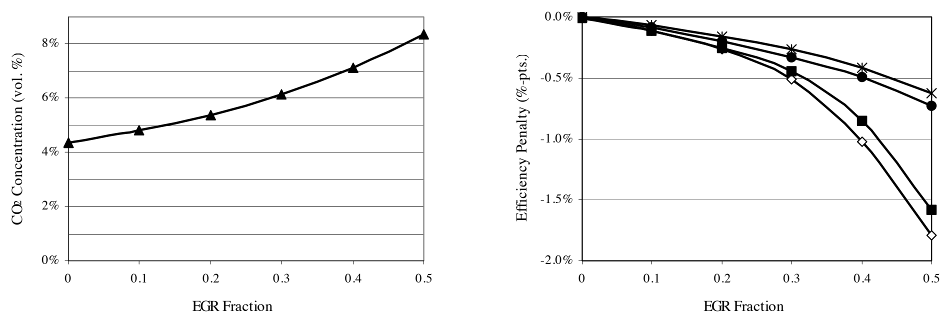

Figure 2: Effect of EGR fraction on CO_2 concentration in exhaust (left) and on combined cycle efficiency penalty for uncooled EGR (◇), intermediate cooling (■,●), and cooling to ambient temperature (✳)

gas turbine power output and hence system efficiency. The same effect occurs for a fixed EGR temperature as the EGR rate increases and accordingly also the temperature of the fresh air/exhaust gas mixture.

Though the effect of the gas turbine inlet temperature is indeed the most important factor dominating the performance hit of a system operating with EGR, it is certainly not the only one, as it can be observed in Figure 2. An efficiency penalty results from the operation with EGR, even if the recirculated exhaust is cooled down to ambient temperature. The reduced combustor inlet temperature in the gas turbine resulting from the higher heat capacity of the more humid gas when operating with EGR is responsible for this behavior.

The EGR cooler design is of a non-adiabatic evaporative type; the exhaust gas is cooled and humidified in a single piece of equipment through direct contact with sprayed water and simultaneous indirect cooling with a heat-absorbing medium, usually water. The indirect heat exchange enables the cooling of the exhaust beyond its adiabatic saturation temperature, as opposed to pure adiabatic cooling methods. Most importantly, however, the SO_2 levels in the recirculated exhaust can be reduced by up to an estimated 20% with this type of cooler thanks to absorption into the sprayed water. This is necessary in order to reduce the risk of corrosion in the gas turbine compressor due to sulfuric acid formation.

The optimum EGR cooling temperature is platform-dependent and results as a tradeoff between gas turbine performance and EGR cooler costs. The optimization was carried out as part of this study by means of a levelized cost of electricity (LCOE) calculation including the equipment costs from multiple vendors of non-adiabatic evaporative coolers.

3.2. HRSG-Integrated Amine Reboiler

The integration of the amine reboiler into the HRSG consists on inserting an additional set of tubes into the exhaust gas path of the HRSG, to which a fraction of the amine solution is pumped from the stripper, boiled, and then returned to the amine plant; by this, 80% of the total amine regeneration duty is reallocated from the capture plant to the power plant. The reboiler must be located in a position inside the HRSG where the gas is hot enough to efficiently transfer heat to the amine solution at about 120°C. Due to risk of degradation, however, an amine temperature of no more than 130°C in the hottest spots close to the tube wall must be guaranteed. This corresponds to a temperature of around 250°C in the bulk of the gas in contact with the amine reboiler tubes.

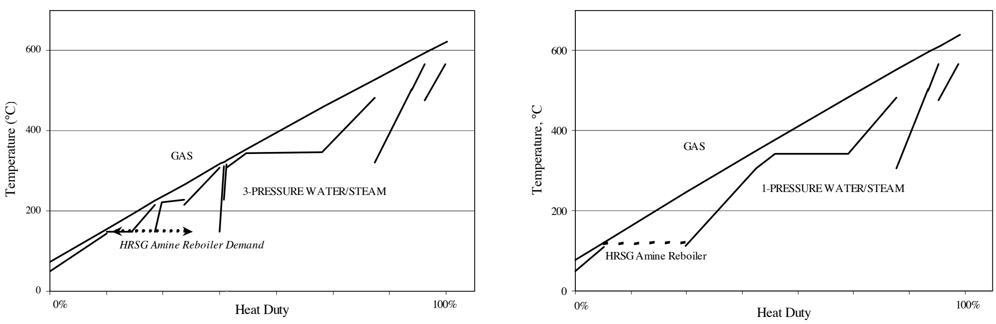

Figure 3: Heat release diagram of HRSG in baseline plant (left) and of the redesigned HRSG in the BIT plant (right)

The heat release diagram of the HRSG in the baseline power plant is depicted in Figure 3, where also the temperature level and relative heat requirement of the integrated amine reboiler are indicated. As it can be seen from the Figure, the heat demand of the amine reboiler accounts for almost 20% of the total heat exchanged in the baseline HRSG and hence corresponds very closely to the heat duty exchanged in its low-pressure (LP) section. Nevertheless, only a fraction of the LP duty is actually exchanged in the baseline HRSG at temperatures above the 120°C of the amine solution, so a simple substitution of the LP steam production with the amine reboiler is not feasible. As it can be seen from Figure 3, where the heat release of the redesigned HRSG with an integrated amine reboiler is illustrated, the integration requires that all low-pressure, intermediate-pressure (IP) and even a fraction of the high-pressure (HP) steam cycle be removed, i.e. reallocated to the amine cycle. Hence, the redesigned BIT HRSG includes single-pressure steam generation and an integrated amine reboil cycle.

The absence of multiple pressure levels and the fact that the pinch point in the pinch-constrained HRSG is dictated by the fixed amine inlet temperature lead to an inferior temperature match between the cold and hot fluids of the redesigned HRSG, compared to the baseline. As a result, not only does the steam production decrease by the flow of LP and IP steam, but the HP steam production is also reduced. The overall steam production is reduced by 30% as a result of the amine reboiler integration.

The vapor content of the amine-water mixture in the reboiler is typically between 5 and 10% and it is limited by the maximum temperature allowable in order to avoid degradation. Despite the potential cost savings and ease of operation that a once-thru reboiler could offer, a drum-type reboiler was selected as a first approach in this study given the difficulties associated with the multiphase flow return line of the once-thru type. The latter would require a design with a diameter large enough to keep the pressure drop low, increasing the risk of slug flow formation. Low pressure drops are desired in order to avoid the need to pump the amine solution, which would result in unacceptably high temperatures going beyond the degradation limit. In the drum-type reboiler approach, vapor and liquid are returned separately to the amine plant so the slug flow risk is nonexistent and the return line may be dimensioned with no further limitations.

In spite of the need to use stainless steel in the integrated amine reboiler tubes to avoid potential corrosion problems, a 50% lower heat transfer area in the redesigned, more compact HRSG leads to an estimated 20% cost saving for this component in the BIT plant.

3.3. Steam Extraction and Steam Turbine Selection

For process control reasons, 20% of the total heat requirement of the amine plant is not reallocated to the power plant but is still provided through steam extraction from the steam turbine with subsequent heat exchange in the stripper's kettle reboiler. This, plus the motive steam required for the eductor in the capture plant, results in a total steam flow requirement corresponding to about 30% of the flow in the steam turbine, leading to pressure level drops by up to 40% at the extraction point.

While there are several possible extraction sources in the turbine, the cold reheat (CRH) line, or HP-section outlet, of the steam turbine was selected, even though the pressure of the CRH is about two times higher than the 8 bar required for the amine plant; the pressure requirement is governed by the ejector design. The CRH approach is preferred over the extraction from the casing at exactly the required pressure, given the significant complexity and aerodynamic issues that the latter would potentially imply and the modest performance benefits anticipated. The low pressure level in the crossover pipe between the IP and LP sections makes the extraction from this source unfeasible.

The combined effect of steam extraction and a reduced steam generation in the HRSG results in an estimated 50% reduction of the steam turbine exhaust flow in the LP section of the turbine. To accommodate the redesigned system to the reduced flow of steam, a more compact steam turbine with a lower last-stage bucket annulus area was introduced to the BIT plant. The economically optimum exhaust annulus velocity resulting in the machine was the main criterion used for its selection.

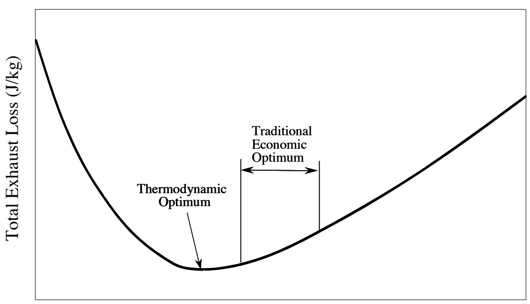

Figure 4: Typical exhaust loss curve for a steam turbine

Operation with the baseline overdimensioned steam turbine would have resulted in a reduced last stage efficiency, given the decrease of the exhaust velocity arising from a lower steam flow through an otherwise identical exhaust area and the departure from design conditions. On the other hand, for excessively high velocities in an underdimensioned steam turbine, leaving losses would dominate as a result of the large amounts of kinetic energy of the steam leaving to the condenser. This is illustrated in Figure 4, which shows a typical steam turbine exhaust loss curve. The economical optimum is slightly shifted to higher velocities and hence lower exhaust areas, sacrificing performance but reducing turbomachinery size and hence costs.

Previous studies of the steam extraction capability of the selected steam turbine for other applications have indicated its preliminary suitability at full-load conditions for extraction flows in the required range. Though a more detailed analysis including, among others, the mechanical integrity of the steam turbine under these conditions would have to be conducted, no operability issues are preliminarily expected from the steam extraction at full-load operation.

3.4. CO_2 Compression

The CO_2 compressor chain selection is a tradeoff between compressor costs and compressor performance. While the performance entitlement of isothermal compression is approached as the number of intercooled compression sections is increased, the price of the turbomachinery and balance-of-plant equipment increases accordingly. The selected configuration is based on General Electric's turbomachinery and includes an integrally geared centrifugal compressor with six intercoolers, the last in which the CO_2 is liquefied to a dense supercritical fluid as it is cooled down at a supercritical pressure of 80 bar. The dense CO_2 flow is subsequently brought to a final delivery pressure of 220 bar with a barrel pump. The compression chain is electrically driven and includes an interstage triethyleneglycol-based dehydration unit reducing the water content of the CO_2 stream to 100 ppm.

4. Performance and Economics of BIT CO_2 Capture

The performance of the BIT plant is summarized in Table 1, together with that of the baseline without capture and with that of a similar plant with state-of-the-art MEA-based post-combustion capture, i.e. without the BIT characteristics. The estimated contribution of the individual BIT measures to the resulting total efficiency penalty of BIT is illustrated in Figure 5. While the biggest contributor to the performance loss is the HRSG amine reboiler, the effectiveness of the integration of this component becomes evident from the results; even though 80% of the duty is being provided by the HRSG reboiler, this component contributes to only about 50% of the penalty associated with the amine plant heat supply.

Table 1: Performance and economics of BIT plant in a Norwegian location compared to a similar plant with state-of-the-art CO_2 capture and to the baseline at ISO conditions

	Baseline	State-of-the-art CO_2 Capture	BIT CO_2 Capture
Net Power Output, MW	413 [5]	367	361
Net LHV Efficiency	58% [5]	49%	50%
CO_2 Emissions, g/kWh	363	56	60
Specific Plant Cost, $/kW	100%	132%*	143%*

*Amine plant cost not included

The total plant cost, or turnkey price, of the BIT plant was estimated by using a bottom-up cost model, i.e. the cost of each component was estimated separately and the results were rolled-up to produce an estimate for the whole plant [6]. The cost model results were consistent with real plant costs for a 9FB combined cycle power plant with the characteristics of the baseline used for this study. Table 1 summarizes the plant cost per kilowatt output for the BIT plant and for the plant with state-of-the-art CO_2 capture, relative to that of the uncontrolled baseline.

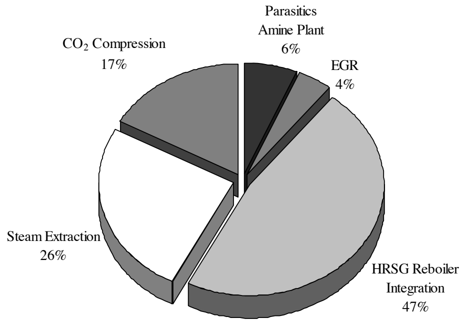

Figure 5: Individual contributions to overall performance penalty of CO_2 capture in BIT plant

The overall direct cost increase resulting from the introduction of the Best Integrated Technology concept is illustrated in Figure 6 and can be attributed mainly to the 1) CO_2 compressor, 2) CO_2 dehydration equipment, 3) EGR loop components (cooler, fan, ducting, gas distribution system), and 4) CO_2 capture plant, the latter being outside the scope of the present economic evaluation and hence not included in the figure. Modest cost savings also result in the power island due to the reduced steam flow conditions in the bottoming cycle, specifically in the 1) HRSG, 2) steam turbine, and 3) condenser.

Costs or savings related to components present in the BIT plant – but not in the baseline – were estimated from a combination of internal cost data, vendor quotes, and cost estimating relationships. Costs related to equipment modifications in the power plant, e.g. HRSG or steam turbine, were estimated internally. The levelized cost of electricity was estimated from the total plant cost and used as the main criteria for optimization purposes, mainly regarding the exhaust gas recirculation cooling temperature and the CO_2 compression chain configuration.

While the cost trend shown in Table 1 shows that if the CO_2 capture plant is excluded, the specific capital cost for the plant with state-of-the-art capture is lower than that of the BIT plant, the difference between the costs of the two plants with CO_2 capture is within the cost estimation uncertainty for the total plant cost. As a result, considering an estimated 20-30% savings in the capture plant resulting from the BIT measures and the fact that the capture plant is the most expensive component in the system after the gas turbine, it is expected that that the economics of the overall plant including the amine unit will strongly favor the BIT design.

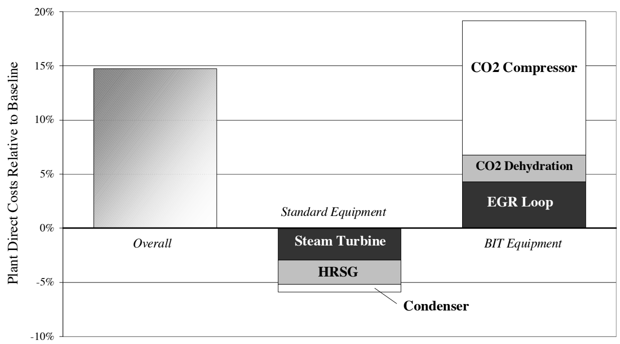

Figure 6: Overall direct cost increase in BIT plant (left) and distribution of corresponding cost savings (middle) and additional costs (right). Amine plant cost not included.

5. Conclusions

A NGCC power plant was redesigned and optimized for the Best Integrated Technology post-combustion CO_2 capture to include exhaust gas recirculation, an amine-reboiler integrated into the heat recovery steam generator, and a low-cost MEA-based CO_2 capture unit. The performance and economics of the BIT-based CO_2-lean plant were evaluated and compared with that of a baseline power plant without CO_2 capture and with a state-of-the-art post-combustion capture solution.

The power plant with BIT capture has a power output of 361 MW at an LHV efficiency of 50%. While the implementation of BIT capture results in a 43% specific capital costs increase in the power island and CO_2 compression sections of the plant, relative to the baseline plant without capture, 20-30% cost savings are expected in the capture unit as a result of its significantly reduced footprint for the BIT design. Since this is the most expensive component after the gas turbine, the power plant with Best Integrated Technology CO_2 capture is expected to be economically superior to that with state-of-the-art post-combustion CO_2 capture, offering a similar performance at an only slightly higher power island cost with a significantly cheaper capture unit.

6. Acknowledgements

The authors would like to thank the valuable contribution of all the individuals who supported this study, especially Jim Hagan, John Gulen, Nestor Hernandez, and Mark Steffen from GE Energy as well as Enrico Gori and Romeo Del Lama from GE Oil & Gas. Special thanks also to the CCP2 consortium for the fruitful cooperation and for the permission to publish this work.

7. References

1. International Energy Agency (IEA): *Energy Technology Perspectives 2006*, OECD/IEA, Paris, 2006
2. The CO_2 Capture Project: *The Capture Program for Phase II (2004-2008)*, NGO Meeting, Washington D.C., 2006
3. Chinn, D., Choi, G. N., Chu, R., Degen, B.: *Cost* Efficient Amine Plant Design for Post-combustion CO_2 *Capture from Power Plant Flue Gas*, Paper presented at the GHGT-7, Vancouver, 2004
4. ElKady, A., Evulet, A., Brand, A., Ursin, T.P., Lynghjem, A.: *Application of Exhaust Gas Recirculation in a DLN F-Class Combustion System for Postcombustion Carbon Capture*, Journal of Engineering for Gas Turbines and Power, Vol. 131, published online, 2008
5. *Gas Turbine World Handbook 2006*, Vol. 25, Pequot Publishing, Inc., 2006
6. Gulen, S.C.: *Combined Cycle Power Plant Total Installed Cost*, General Electric, 2002