EXTENDED ABSTRACT

Retrofitting study for a 120MW NGCC plant with post-combustion: a particular case to optimize the CO₂ capture process

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ABSTRACT

The combined cycle that was taken into consideration is a plant designed, constructed and owned by Techint group. It is a Natural Gas Combined Cycle (NGCC) composed by two gas turbines and two heat recovery steam generators where the recovered heat is converted into steam feeding a Steam Turbine. The plant has been also designed for cogeneration purposes: some steam extractions from the steam turbine are used, in fact, both for supplying heat to a steel factory, nearby the NGCC, and for district heating (DH) to the Municipality and domestic users close to the plant. Nominal electrical power is about 120 MWe, while maximum provided heat is about 12 MWth for steel factory and 35 MWth for DH. Yearly CO₂ emissions are about 300 000 tons.

Techint E&C, part of Techint Group, being highly interested in developing CCS technologies, decided to investigate the possibility to built a carbon capture unit at the mentioned power plant. A pre-feasibility study was carried out to assess if this choice may become convenient especially considering the forthcoming 3rd period of the European Emission Trading System (ETS) after the crucial date of 2013. With the announced coming EUA shortage carbon quotation is expected raising and realization of capture plants will probably become more and attractive also from an economic point of view.

The study has therefore been focused to identify specific solutions to optimize the process and, therefore, the energy consumption, so making the industrial initiative as much as possible economically free-standing.

To get this target, the project has been conceived as a modular one, so two different realization phases are envisaged. The first capture module will be limited to about 45 % of the overall emissions with delivery of the captured CO₂ to local industrial users. Second module will capture additional CO₂ quantities, up to a maximum of about 90 %. Taking into account the limited request of the Italian market this additional CO₂ flow cannot be delivered to commercial operators and should be stored underground. So, the study includes also some preliminary geological investigations.

As far as capture is concerned, being this case a retrofit application, the most viable solution is a post-combustion process. The study took into consideration a number of alternatives including the “classical” amine scrubbing with MEA and alternative solvents/processes (i.e. Econamine℠ Plus by Fluor, KS-1℠ by MHI, and Chilled Ammonia by Alstom). Since the alternative solutions are not completely described in the available literature and data are covered by license, a complete process simulation and economic analysis was possible currently only for the MEA solvent, even if the preliminary results showed the potential of significant improvements in terms of efficiency and energy cost by using such alternatives. For these reasons the results of this study are to be considered conservative.
In the MEA absorption/regeneration process specific attention has been devoted to energy efficiency optimization, keeping in mind the necessity to guarantee a large steam flow rate from the turbine to satisfy the heat requirements of factory and district heating. Particular attention has been dedicated, to this scope, to materials selection, equipment design and plant configurations.

As a matter of fact, results are in line with literature data and the overall estimated capture cost, of the order of 70 Euro/t$_{\text{CO}_2}$, is reasonable if compared with equivalent data from coal fired power plants that normally are expected to be less penalized by CO$_2$ capture. As far the final CO$_2$ disposal is concerned, the possibility to commercialize up to 30% of the CO$_2$ captured by the first module has been positively verified but it is a “tailored” solution, applicable only to the specific local industrial background.

With the realization of the second module the quantity to be delivered to commercial operators is too large, so a geological storage must be included. A preliminary geological analysis has been therefore performed showing that a suitable storage location is available at a reasonable distance (about 25 km) from the plant.

A preliminary financial analysis was developed taking into account the investment costs and energy penalty and, in term of benefits, primarily the saved emissions (valorized according to the ETS system) and the income from CO$_2$ commercialization (depending essentially on the purity that will be achieved): this last term could result important as it could potentially cover a significant quote for CO$_2$ capture realization.

**Keywords:** CO$_2$ Capture, ETS, Process solutions

**Proposed Topic:** Process optimization and CO$_2$ commercialization and industrial use
1. Introduction

As well known and highlighted in several international reports [1] emissions of greenhouse gases (GHG) are considered the first responsible of climate changes and global warming, evaluated with an increase of 0.6°C during 20th Century. Particularly the carbon dioxide (CO\textsubscript{2}), mainly originated by the combustion of fossil fuels in power production and transport, has been identified as the first cause of the greenhouse effect. Fossil fuels, in fact, still represent the most used energy source in power generation and all the evaluations carried out by primary world agencies (e.g. IEA, IPCC etc.) indicate a continuous increase of their use in the next decades, as showed in Figure 1 [2].

![Figure 1: World electricity generation by fuels in the Reference Scenario](source: World Energy Outlook 2008- PART A, Chapter 6 (Figure 6.3))

The increase in energy request, both from the industrialized and the developing countries, has induced the governments of the first ones to define policies aiming to reduce emissions of pollutants in the atmosphere: in this scenario, particular attention has been devoted to decrease greenhouse gases and mainly CO\textsubscript{2}. Kyoto Protocol and EU Emission Trade System are two of the main international attempts to gain this goal.

The renewable energies are of course the most promising technology which can contribute to GHG reduction, but replacement of fossil fuels will take a long time and could destabilise economies in emerging countries which cannot withstand the high cost of the necessary technological development.

It’s therefore essential to concentrate efforts in research and development of new technologies which, even when fossil fuel are used as energy source, can reduce the consequent CO\textsubscript{2} emissions in the atmosphere. To this scope the CCS (Carbon Capture and Sequestration) technologies play an important and potentially decisive role.

Techint Spa., primary Engineering and Construction Company, branch of Techint Group (an international group of more than one hundred companies acting worldwide, which counts 53,000 employees and operates in several fields, mainly in steel works and industrial plants manufacturing) is strongly engaged in renewable energies and CCS development. In this last field the following projects have been carried out:

- pilot plant for carbon capture through pre-combustion technology, which can be applied in Integrated Gasification Combined Cycles (IGCC) to reduce the greenhouse emissions and to produce hydrogen from fossil fuel (in co-operation with ENEA, Politecnico di Milano, Sotacarbo and Università di Cagliari);
laboratory tests to search for a new physical solvent enabling an optimisation of the absorption process in pre-combustion technology;

- feasibility study, described in this paper, for a CO$_2$ capture and sequestration plant to retrofit an existing 120 MW Natural Gas Combined Cycle (NGCC) located in Northern Italy (Dalmine - Bergamo), using post combustion technology and optimizing the process with the consequent reduction of specific consumptions. Several final utilizations of the captured CO$_2$ have been investigated, i.e.:
  - geological storage (a potential site is located 25 km from the plant, in a depleted oil & gas reservoir);
  - industrial use in food industries, situated in the area of the NGCC;
  - steel slag carbonation, being the power plant ancillary to a steel factory.

The study has been carried out in co-operation with Tenaris Dalmine (owner of the potential hosting plant), ENEA, ERSE (former CESI Ricerca) and Politecnico di Milano.

2. Description of existing NGCC plant and pre-feasibility study scope

The plant which has been considered in our pre-feasibility study is an existing 120 MW NGCC, designed to operate in full condensing mode and also with the possibility of steam extraction for use as process steam (12 MW$_{th}$ at peak and 4 MW$_{th}$ average) and/or for district heating purposes (35 MW$_{th}$ max in cold season).

The power island consists of the following sections:

- two 50 MW class, heavy duty gas turbines (GT’s), each one directly coupled to one electrical generator and exhausting directly into one heat recovery steam generator, without neither diverter nor by-pass to stack;
- one condensing steam turbine (ST) coupled to one electrical generator with intermediate low-pressure steam induction and two steam extractions for district heating;
- one water cooled condensing system including steam turbine by-pass.

An extraction at a higher pressure from the steam turbine crossover (16 bara) shall also be provided in order to supply technological use steam to the steel factory.

The ST is connected to a cooling water condenser. In full condensing mode operation all the steam is expanded in the ST modules and condensed in the condenser. Process steam can also be extracted at the cross over pipe between the two ST modules. Steam can also be extracted from the low-pressure module at two pressure levels to feed district heating exchangers.

The power plant can be controlled and monitored from the central control room through a distributed and highly automated control system.

Scope of this pre-feasibility study is to evaluate possible technical solutions to the expected heavy impact of ETS system start-up, scheduled for 2013: at that date CO$_2$ allowances shall be no more allocated on a free basis and therefore the economical consequences for energy producers will be significant.

Nevertheless, carbon capture technologies have also high impact in CAPEX and OPEX and the present study tried to put in evidence some solutions, other that the “usual” proposed geological storage, as final CO$_2$ destination: in fact, due to the particular location of the NGCC inside a steel factory and into a highly industrialized territory, different utilizations of the captured carbon dioxide have been investigated to give economical benefits to the project in conjunction with the saved cost for the EUA.

The proposed initiative is articulated in several phases:

- 1$^{st}$ phase (about one year): development of the complete project with the selection of the best technology suitable for this post-combustion application and detailed engineering, economic evaluation and financial plan in order to go through the issues carried out during the preliminary study and check the full feasibility of the initiative;
• 2nd phase (about two years): realization of a first carbon capture plant module to treat flue gas from one GT (150 000 t/year, about half of the total quantity of flue gases emissions of the power plant); in this phase the captured CO$_2$ is not planned to be stored in a geological reservoir, but can be used in industrial applications for few years and the capture process can be tested while the frame to realize the geological storage (including technical, political and other aspects, i.e. public acceptance) is defined;
• 3rd phase (about two years): realization of a second module of capture plant to treat the total amount of the flue gas emissions of the power plant (300 000 t/y). In this final phase the geological storage is supposed to be available and defined in all the related aspects.

3. Applicable technology: post-combustion

The post-combustion CO$_2$ capture technology is the most suitable for retrofit applications, since it treats the flue gases without significant modification neither on the existing plant nor in the combustion process [3].

In particular, the processes which have been taken into consideration in the present study are:

• Chemical absorption by amine-based solvents;
• Chemical absorption by Chilled Ammonia Process (CAP).

3.1 Amine-based processes

The most developed technology for the post-combustion CO$_2$ capture is based on chemical solvents as amine-based solutions [4].

The solvents considered in the present study are:

• not patented amine-based solvent (Monoethanolamine);
• patented amine based solvent (Fluor Econamine FG Plus$^{SM}$, Kansai Electric-MHI KS-1$^{TM}$).

The process flow diagrams for above technologies are similar. The flue gas is cooled to a temperature of 45 °C in Direct Contact Cooler (DCC). The cooled flue gas is fed into the bottom section of the absorber and passes upward through the packing material inside the tower. The solvent (MEA, KS-1$^{TM}$ or Econamine FG Plus$^{SM}$) is distributed evenly from the top of the packing material recovering 90% of CO$_2$. The CO$_2$-rich solution is pumped into the upper section of the stripper. The steam produced by reboiler strips the CO$_2$ from the rich solution at the stripper, yielding CO$_2$ with a high purity of 99.7 vol. % or more. The relatively high vapour pressure of solvents causes significant vaporization losses, particularly in low-pressure operations. However this difficulty can be overcome by a simple water wash treatment of the purified flue gas.

The fundamental underlying principle, for both types of solvents, is the exothermic, reversible reaction between a weak acid (CO$_2$) and a weak base (Monoethanolamine or KS-1$^{TM}$ or Econamine FG Plus$^{SM}$) to form a soluble salt. The flue gas is pumped through an absorption column where CO$_2$ binds to the absorbent at temperature between 45 °C and 60 °C.
The main reactions occurring when the monoethanolamine (MEA) is used to absorb CO₂ may be represented as:

- ionization of water:
  \[ \text{H}_2\text{O} \leftrightarrow \text{H}^+ + \text{OH}^- \]  

- hydrolysis and ionization of dissolved CO₂:
  \[ \text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3^- + \text{H}^+ \]  

- protonation of alkanolamine:
  \[ \text{RNH}_2 + \text{H}^+ \leftrightarrow \text{RNH}_3^+ \]  

- carbamate formation:
  \[ \text{RNH}_2 + \text{CO}_2 \leftrightarrow \text{RNHCOO}^- + \text{H}^+ \]  

where \(\text{R} = \text{HO-CH}_2-\text{CH}_2\).

The equilibrium concentration of molecular CO₂ in solution is proportional to their partial pressure in the gas phase (i.e. Henry’s law applies) so reaction (2) and (4) are driven to the right by increased acid gas partial pressure. The reaction equilibrium is also sensitive to temperature, causing the vapour pressures of absorbed acid gases to increase rapidly as the temperature is increased. As a result it is possible to strip absorbed gas from amine solution by the application heat. The reaction (4) is predominant, the carbamate ion ties up an alkanonammonium ion via equation (3) and the capacity of the solution for CO₂ is limited to approximately 0.5 mole of CO₂ per mole of amine even at relatively high partial pressure of CO₂ in the gas to be treated. The reason of this limitation is the high stability of the carbamate and its low rate of hydrolysis to bicarbonate.

### 3.2 Chilled Ammonia Process (CAP)

In the Chilled Ammonia Process [5]-[6] the CO₂ is absorbed in an ammoniated solution at below ambient temperature. The overall absorption reaction can be described in ionic form as follows:

\[ 2(\text{NH}_4)^+ + \text{CO}_3^{2-} + \text{CO}_2(\text{g}) + \text{H}_2\text{O} \rightarrow 2(\text{NH}_4)^+ + 2\text{HCO}_3^- \]  

At elevated temperature (about 130°C), the reaction is reversed to release CO₂ in a concentrated form. Depending on the process conditions, gaseous NH₃ could be released from ammoniated solution during absorption of CO₂.

To minimize NH₃ emission, CO₂ absorption is carried out at lower than ambient temperature. A lower absorption temperature results in a lower ammonia emission from the absorber and in higher power consumption for chilling. An optimal absorber operating temperature exists in the temperature range between 0°C to -20°C.

The CAP presents some similarities with the capture process using amine-based solvents and consists of the following main units:

- flue gas cooling
- CO₂ absorption
- high pressure regeneration

In the flue gas cooling section the flue gas is first treated in a conventional air quality control system and then sent in a DCC. Direct contact cooling of the saturated flue gas results in massive condensation of water and in the capture of residual contaminants.

The cooled flue gas enters in the CO₂ absorber. The design of the CO₂ absorber is made to operate with slurry. The flue gas flows upwards in counter current to the slurry containing dissolved and suspended mix of ammonium carbonate and ammonium bicarbonate. The low concentration of ammonia in the clean flue gas will be captured by a cold water wash column and returned to the absorber. The clean flue gas, containing mainly nitrogen, oxygen and low concentration of CO₂, flows to the atmosphere.
The CO₂ slurry from the absorber contains mainly ammonium bicarbonate in solid form and in water dissolved form. The CO₂ rich slurry is pumped through a heat exchanger to the high pressure regenerator. The proposed process strips the CO₂ from the CO₂ rich solution at high pressures of 20-40 bar or higher, thus reducing the compressor stages and the electrical consumption compared with the low pressure regeneration.

The ammonium bicarbonate in the CO₂ rich slurry dissolves as the temperature increases in the heat exchanger and it turns into a clear solution at about 60-80°C.

The hot solution is injected into regenerator which is a high pressure vessel. Additional heat for CO₂ stripping is provided by a reboiler. Low concentration of steam and ammonia are present in the regenerator overhead and they are captured in a cold water wash column at the top of the regenerator.

The modelling tool carried out from P.M. Mathias [7] et al. reveals how the process performance changes with operating conditions and identifies the optimum conditions to operate the process, which is an NH₃ solvent concentration of about 26 wt % and an absorber temperature of about 2 °C; however it has to be noted that lowering the absorber temperature below about 11 °C requires special pre-heating to avoid fouling problems in the stripper. The chilled-ammonia process is considered to be equivalent to alkanolamine-based absorption processes for LP steam consumption but may become not competitive because of the large refrigeration loads (that are not needed in alkanolamine-based processes). As the regeneration pressure is greater than alkanolamine process, the absorbed power of compression unit to CO₂ storage is lower.

4. Case Study: process description and key-factors

4.1 Process description

The considered process consists of four units: pre-cooling, chemical absorption, CO₂ compression and dehydration, with a scheme which is quite usual in gas processing units [8], [9].

Pre-cooling unit

The flue gas coming from the stack enters in the compressor to increase its pressure of 30 mbar. The compressed flue gas needs to be cooled before it is brought into contact with the solvent in DCC. The flue gas enters in the bottom where it is cooled by the industrial water flowing down from the top of the column. The DCC circulating water is cooled and filtered using dedicated means to remove particulates that may be present in the flue gas stream.

The cooled flue gas coming from the DCC is saturated at operating condition. The water from the bottom of the column is recycled to the top after cooling in a proper plate heat exchanger.
Absorption and regeneration unit

The monoethanolamine (MEA), a primary amine with chemical formula \( \text{NH}_2\text{CH}_2\text{CH}_2\text{OH} \), has a high selectivity toward the carbon dioxide when the plant works at atmospheric pressure. The cooled flue gas coming from the pre-cooling section enters in the bottom of the absorber where it is counter-currently contacted with MEA solution (concentration 30% wt) coming from the top of the column. To increase the absorption efficiency the contact between the flue gas and the solution takes place in two structured packing beds. The clean flue gas stream passes out through the top section of the absorber, which provides a wash for the gases before venting to atmosphere, ensuring that less than 1 ppmv of entrained solvent is emitted to atmosphere. \( \text{CO}_2 \) is absorbed into the lean solvent.

The rich solution coming from the bottom of the absorber passes through the rich-lean heat exchanger where increases its temperature and enters in an atmospheric flash drum to release a part of the \( \text{CO}_2 \) present in the stream. The rich solution from the flash drum goes to the top of the regenerator. As the solution flows down the column to the reboiler, it is stripped of \( \text{CO}_2 \). The amine solution leaves the bottom of the regenerator as lean solution and is pumped to the contactor through the rich/lean heat exchanger and a lean cooler to reduce its temperature. The stripper has been designed without overhead reflux system as this configuration is more efficient (see Par. 4.2) To maintain an efficient operation a reclaimer is operated in parallel to the reboilers (as an intermittent batch process) to limit heating of stable salts in the lean solvent, thereby reducing solvent losses over time. Additionally, a small percentage of the lean solvent returning to the absorbers is continuously filtered via a carbon bed to remove solids and other degradation products.

The \( \text{CO}_2 \) which leaves from the top of the regenerator, mixed with the compressed \( \text{CO}_2 \) coming from the flash drum, is cooled in a plate heat exchanger and is sent to the compression section. Figure 2 shows schematically the MEA process.
**Compression**  
(Refer to process flow diagram shown in Figure 3)

The compression section is mainly required during the 3rd stage of the initiative realization, when the geological storage will be available. It has been sized to increase the acid gas pressure up to 160 bar, a suitable value considering both the distance of about 25 km between the capture plant and the storage site and the reservoir depth (800-1500 m).

The compression train is composed of 5 stages with intercooler and separator and with final cooler to decrease the acid gas temperature down to 45°C. The intercoolers are situated between the compression steps because high temperature compression is very energy-consuming. The use of several cooling steps will, in general, lower the energy requirement but increase the complexity and hence the capital costs. Taking into account what above and that the CO₂ has to be dehydrated, the compression train has been optimized installing the triethyleneglicol (TEG) dehydration unit downstream of 4th compressor stage. The dried CO₂ leaving from the dehydration column is fed to 5th stage of compression.

**Dehydration section**  
(Refer to process flow diagram shown in Figure 3)

In the dehydration section the wet CO₂ coming from the 4th compression stage enters in the absorber where contacts in counter-current the TEG solution to reduce its water content. The water content in the dry CO₂ stream depends on storage reservoir characteristics (saline formations, depleted oil/gas fields, unmineable coal seams or enhanced oil or gas recovery) and can vary in the range of 5 to 500 ppm. The CO₂ leaving the top of the absorber has a water content less than 50 ppm (typical value for injection in depleted oil/gas fields) to avoid the acid condensate in the pipeline. The TEG rich solution leaving the bottom of the absorber is regenerated and recycled in the process. The following technologies can be used to dehydrate the CO₂ stream:

- adsorption
- drying by cooling
- chilling by compression
- TEG dehydration

TEG dehydration unit is the best technology to dehydrate the CO₂ up to a water content of 50 ppm as the OPEX and CAPEX of unit is at least 5% lower than drying by any other technologies [10].
4.2 Key factors.

The present study tried to optimize the solvent regeneration unit reducing the relevant energy consumption but avoiding, in the same time, that this affect the feasibility of the initiative causing high increase of CAPEX, OPEX and parasitic power losses. The study took into consideration a certain number of alternatives, both the “classical” amine scrubbing with MEA and alternative solvents/processes (i.e. Econamine FG Plus™ by Fluor, KS-1™ by MHI, and Chilled Ammonia Process by Alstom). Since the alternative solutions are not completely described in the available literature and data are covered by license, the regeneration optimization has been limited to MEA solvent. To optimize the MEA regeneration unit several simulation case studies have been carried out by commercial software (HYSYS from Aspen Technology Inc.).

In Figure 2 the process flow diagram of regeneration unit is show. The rich solution flows downward through the regenerator in counter-current contact with vapor generated in the reboiler. The reboiler vapor (primarily steam) strips the CO₂ from the rich solution. The heat necessary to regenerate the amine is supplied to reboiler and is a function of several parameters. To reduce the regeneration energy requirement it is possible to optimize the following figures:

- lean solvent loading;
- operating conditions of flash drum (if any);
- sensible heat \((Q_s)\) to increase the temperature of the feeding solution to the temperature of the lean solution leaving the reboiler;
- heat of reaction \((Q_r)\), which is the energy to reverse the amine acid-gas reaction and dissociate the amine acid-gas compounds;
- latent and sensible heat \((Q_v)\) required to convert reflux water into steam which serves as the stripping vapor.

The minimum purity of lean solvent is optimized to absorb 90% wt of carbon dioxide feeding to contactor, so the lean solvent loading has been fixed to 0.19 mole of CO\(_2\)/mole of solvent (see Figure 4). A greater amount of CO\(_2\) in the lean solvent does not meet the specification on the CO\(_2\) capture and vice versa a lower amount give a better performances in terms of captured carbon dioxide but requires a greater duty to reboiler to improve the stripping of the solvent (see Figure 5).

Once the lean solvent loading is fixed, to meet the captured carbon dioxide specification and the operating conditions of flash drum (if any), the reboiler duty is a function only of the \(Q_s\), \(Q_r\) and \(Q_v\) and can be calculated as the sum of the three contributions as follows:

\[
Q = Q_s + Q_r + Q_v
\]  
(6)

Where

- \(Q\) is the reboiler duty

The sensible heat is calculated by the following equation:

\[
Q_s = W C_{p\text{sol}} (T_R - T_F)
\]  
(7)

Where:

- \(W\) is solvent flow rate [kg h\(^{-1}\)]
- \(C_{p\text{sol}}\) is solvent specific heat [KJ Kg\(^{-1}\) K\(^{-1}\)]
- \(T_R\) is reboiler temperature [K]
- \(T_F\) is temperature of feeding solvent to regenerator [K]

When the solvent and his concentration has been selected (i.e. \(C_{p\text{sol}}\)) as well as the loading (i.e.\(W\)), to minimize the sensible heat, it is possible reduce only the temperature difference \((T_R - T_F)\). The reboiler temperature is fixed once the regenerator operating pressure has been selected, so to minimize the duty it is necessary to increase the solvent temperature feeding the regenerator. As an approach of 10 degree Kelvin has been selected for lean/rich solvent heat exchanger, \(T_F\) temperature is fixed too. That means the difference temperature \((T_R - T_F)\) is fixed at 10 K.

\(Q_r\) depends of the kind of solvent. For monoethanolamine (MEA) the reaction heat is 1920 KJ/kg CO\(_2\) and it is not possible to minimize it. The heat of reaction includes both heat of solution and heat of reaction.

\[
Q_r = W_{CO_2} h_r
\]  
(8)

Where:

- \(W_{CO_2}\) is the carbon dioxide flow rate in the rich solvent [kg/h]
- \(h_r\) is the heat of reaction from CO\(_2\) and MEA [KJ/kg]

\(Q_v\) is the heat to be supplied to produce the steam to strip CO\(_2\), including the heat to vaporize the reflux stream.

\[
Q_v = W_{steam} \lambda
\]  
(9)
Where:

\( W_{\text{steam}} \) is the minimum steam flow rate to strip the carbon dioxide at specified level, including also the evaporation of reflux flow rate [kg/h]

\( \lambda \) is the latent heat [kJ/kg]

The quantity of the required stripping vapor depends upon the solution purity needed to achieve the required carbon dioxide capture, the stripping column height, the nature of solution, the ratio of CO\(_2\) in the rich amine solution and the regeneration operating pressure.

According to above the only parameter to be optimized to reduce the energy requirement for amine regeneration is \( Q_v \).

For this purpose the following four scenarios have been selected:

- **Scenario 1** - Regeneration unit with flash drum, overhead condenser and reflux system. Into flash drum the vapor phase of rich solvent produced in the rich/lean heat exchanger is separated from liquid solvent to be sent to regenerator.
- **Scenario 2** - Regeneration unit with flash drum, but without overhead condenser and reflux system. The overhead vapors are sent directly to the acid gas cooler to condense them. The evaporation solvent losses condense too. The liquid is separated from the wet CO\(_2\) into suction K.O. Drum of first stage compressor and recycled as water make-up in the regeneration unit.
- **Scenario 3** - As scenario 2 but without flash drum
- **Scenario 4** - As scenario 3 but without flash drum

With the optimized selected absorber configuration to meet the 90% of captured carbon dioxide a loading lean MEA of 0.19 mol CO\(_2\) per mol MEA has to be provided (See Figure 4).

![Figure 4: Captured CO\(_2\) vs. loading lean MEA](image)

From diagram shown in Figure 5 we can see the reboiler duty necessary for each scenario. As it is shown the minimum reboiler duty at 0.19 loading lean MEA has been found for scenario 2. The gap from scenario 2 (22.89 MW) and scenario 4 (25.66 MW) is 2.77 MW, approx 10% lower. At light of above results in our design the scenario 2 (regeneration unit with flash drum but without overhead reflux system) has been selected.
To compare the result of our optimization with literature data it has been carried out the diagram shown on Figure 6 where it is shown the energy requirement for each kilogram of recovered carbon dioxide.

The energy requirement at 0.19 mol CO$_2$/mol MEA is 3.616 MJ per kilogram of recovered carbon dioxide. The required heat shown in literature is 4 MJ/kgCO$_2$, that means the scenario 2 saves approx 10 %.
5. CO₂ final destination

As anticipated, the geological storage is not the only method investigated in the Case Study since the legislation which regulates this issue has not yet been defined by the National Governments.

In the meantime, therefore, for the 2nd stage of the initiative, regarding the CO₂ capture for the first unit of the examined NGCC plant, other alternatives for an industrial use of the captured carbon dioxide have been considered.

CO₂, in fact, is currently used in several industrial processes, like: food packaging, beverages, cryogenic transportation and conservation, fertilizing, fire extinguishing, just to mention the main ones. The following Figure 7 shows a list of CO₂ industrial applications.

**Figure 7: CO₂ industrial applications (only those on a Mtonn scale): annual market, amount of used CO₂, source and product lifetime (Aresta and Tommasi, 1997; Hallman and Steinberg, 1999; Pelc et al., 2005). Data are only indicative**

<table>
<thead>
<tr>
<th>Chemical product class</th>
<th>Yearly market (Mt yr⁻¹)</th>
<th>Amount of CO₂ used per Mt product (MtCO₂)</th>
<th>Source of CO₂</th>
<th>Lifetime*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urea</td>
<td>90</td>
<td>65</td>
<td>Industrial</td>
<td>Six months</td>
</tr>
<tr>
<td>Methanol (additive to CO)</td>
<td>24</td>
<td>&lt;8</td>
<td>Industrial</td>
<td>Six months</td>
</tr>
<tr>
<td>Inorganic carbonates</td>
<td>8</td>
<td>3</td>
<td>Industrial, Natural</td>
<td>Decades to centuries</td>
</tr>
<tr>
<td>Organic carbonates</td>
<td>2.6</td>
<td>0.2</td>
<td>Industrial, Natural</td>
<td>Decades to centuries</td>
</tr>
<tr>
<td>Polyurethanes</td>
<td>10</td>
<td>&lt;10</td>
<td>Industrial, Natural</td>
<td>Decades to centuries</td>
</tr>
<tr>
<td>Technological</td>
<td>10</td>
<td>10</td>
<td>Industrial, Natural</td>
<td>Days to years</td>
</tr>
<tr>
<td>Food</td>
<td>8</td>
<td>8</td>
<td>Industrial, Natural</td>
<td>Months to years</td>
</tr>
</tbody>
</table>

* Natural sources include both geological wells and fermentation.
* The fraction of used CO₂ that is still stored after the indicated period of time drops to zero.

In Italy the global CO₂ market is about 300 000 ton/year, managed by few commercial operators and concentrated in the food application (more than 60% of the total volume).

Starting from this scenario, and considering the particular location of the NGCC under investigation, which is inside a steel factory and inserted in a highly industrialized context, our pre-feasibility study evidenced that in Italy, and particularly close to the plant, there is a potential marked able to absorb the CO₂ amount coming from the gas treatment of one single GT train and that there are reasonable margins for the commercialization of the captured CO₂ (after an adequate treatment in order to assure the purity required for human feeding).

Furthermore, this specific location of CO₂ capture plant gives the opportunity to investigate a new field of CO₂ sequestration, i.e. the mineral carbonation.

The steel factory which would host the Carbon Capture plant produces steel slag and a new frontier of research considers the treatment of such slag, containing Ca and Mg, by means of CO₂ to form carbonates, which are inert materials that could be stored in disposal sites without special permits or used in roads sub-bases.

In the examined case only a small quantity of captured CO₂ (about 10% of one GT) is required to carbonate the slag produced by the hosting steel factory, anyway this application is a partial alternative to geological sequestration and can solve an issue (the slag) typical of the steel industry.

It can not be neglected that mineral carbonation is still in the research and laboratory testing phase and a further investigation should be necessary before an implementation of a pilot plant and, even more so, for an industrial application. Nevertheless it is an interesting and promising technology which could lead to a different approach of CO₂ sequestration as total or partial alternative to the geological storage.
6. Economics

A preliminary Business Plan (BP) has been carried out in order to set some basic parameters and to evaluate which is the break-even value for the CO$_2$ EUA which makes the initiative economically sustainable, also including the economic benefits coming from the partial selling of CO$_2$ and the cost-saving of steel slag disposal.

As previously described, the base case of process simulation considered the use of MEA solvent, due to the availability of the relevant data and technical characteristics, even well knowing that the energy consumption necessary for its regeneration is not the best available on the market.

The consequent economic estimation, in such case, penalize the initiative and leads to a break-even EUA price of about 60 €/tCO$_2$ to reach a positive NPV.

In order to improve the economics some considerations have been done to optimize critical parameters and four further BP cases have been simulated, adopting the following hypothesis:

**CASE “A”**: a 10% cost reduction in capital cost has been considered, deriving from equipment optimization which can be reasonably expected during detailed engineering phase;

**CASE “B”**: additionally to the previous hypothesis, a 20% energy consumption saving has been introduced in the BP model, coming from the use of a better and licensed technology;

**CASE “C”**: additionally to the previous two hypotheses, a 10% energy price reduction is assumed;

**CASE “D”**: additionally to the previous three hypotheses, 20% reduction in operating costs is expected, deriving from integration with existing NGCC services.

The final results of the five cases (Base case + additional four cases) are reported in the Figure 8, where NPV value versus EUA price is indicated.

![Figure 8: NPV vs. EUA value to break-even](image-url)
As it can be noted in the last Case “D”, where all the optimizations have been simultaneously implemented (which represents the expected scenario for an industrial realization, where all the parameters are set in the best way), the break-even EUA price is about 40 €/tCO₂.

The conclusion of the economic evaluation is therefore that the EUA price corresponding to a positive NPV for this initiative is in the range of 40-60 €/tCO₂.

As it is shown in Figure 9 the EUA quotation is reasonably moving into this range after liberalization of ETS market in both indicated scenarios (reduction target 450 ppm and 550 ppm).

![Figure 9: EUA price evolution in two different scenarios for reduction of CO₂ concentration (ppm)](source: IEA - World Energy Outlook 2008)

7. Conclusion

In the Case Study an application of post-combustion carbon capture technology to an existing NGCC has been investigated, considering the better capture technologies available in the market and the possible final destination of the captured CO₂, not limiting the study to the “usual” geological storage but, due to the particular location of the plant, verifying other industrial applications, i.e. use in food industries and mineral carbonation through reaction with steel slag.

Even if the economics simulations evidenced the reasonable feasibility of the initiative, it cannot be ignored that the current global financial crisis represents a constrain in developing and accelerating the realization of CCS projects, unless a significant contribution from the Governments is granted. Furthermore it cannot be excluded that such negative frame may jeopardize the definition of rules and policies as well. A clearer picture will be available after the “Kyoto Protocol revision” scheduled for December 2009 in Copenhagen.

On the other hand it has finally to be highlighted the recent growing interest to climate issues from main political subjects (mainly USA and China) that can lead to unexpected, positive evolutions of the described scenario.
8. References


