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Optimal Operation of a CO_2 Absorption Plant in a Post-Combustion Unit for Cost Reduction

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The largest amount of CO_2 released into the atmosphere is produced by combustion of fossil fuels in power plants to produce electricity. This acid gas greatly contributes to climate change and its emissions must be limited. The most common capture technology for post-combustion capture is CO_2 absorption with aqueous amines, a process characterized by high energy requirements for CO_2 release from the solvent and compression of the obtained rich-CO_2 stream. Adding a CCS system to a power plant allows advantages from environmental point of view, though the power output is significantly reduced.

This work is focused on a study for determining the best operating conditions of the absorption plant with the aim of limiting the impact of the CO_2 capture operation while maintaining substantial reduction of CO_2 emissions in a coal-fired power plant. One of the possibilities to achieve this goal is to operate the CO_2 removal plant in flexible mode. Since it is located downstream the power system, the process of post-combustion amine scrubbing is well-suited for this type of operation.

Several flexible solutions have been studied and applied to a natural gas combined cycle system located in Italy, considering a chemical absorption system by means of monoethanolamine (30% wt.) aqueous solution. The analysis takes into account both the cost of electricity and the amount of electricity sold during the day.

The results are discussed also on the basis of different values of the carbon tax.

1. Introduction

Carbon dioxide (CO_2) is essential to life on Earth, however its concentration in the atmosphere has significantly increased since pre-industrial era, causing global warming and climate change (Wirman, 2016).

CO_2 is released during industrial processes (25%) such as refining of oil or production of iron, steel, cement and ammonia. Other major sources include emissions from cars, trucks, ships and airplanes, and also emissions from domestic sources, such as home heating. The largest amounts of released CO_2 (40%) is produced in the power sector, generated from the combustion of fossil fuels to produce electricity. Therefore, applying carbon capture technology to this sector - whether in new or existing plants - has the potential for the greatest reduction of CO_2 emissions compared to other sectors (IEA, 2016).

The 2015 Paris Agreement (UN, 2015), adopted on 12 December 2015, marked the latest step in the evolution of the UN climate challenge, after the United Nations Framework Convention on Climate Change of 1992 and the Kyoto Protocol (UN, 1997). The main objective is to strengthen the global response to climate change, in particular by keeping the global temperature rise below 2°C above the temperature of the pre-industrial era.

In response to reduction targets imposed by international treaties, many countries have implemented carbon taxes on carbon dioxide emissions, so, though CO_2 removal represents a cost for the power plant, the cost of electricity may be significantly increased if carbon dioxide is not removed and is emitted to the atmosphere.

Considering both the higher thermal efficiency of generators and lower carbon content of fuels, electricity generation using natural gas emits a lower amount of carbon dioxide than the one emitted from a coal-fired unit producing the same amount of electricity (Global CCS Institute, 2013). The low emissions of natural gas have influenced the shift towards natural gas fed plants, with retirements of many coal units. Moreover, the drop in natural gas prices in recent years, coupled with highly efficient natural gas fired combined cycle plants, has made natural gas being preferred as fuel source. However, a lot of carbon dioxide is still emitted to the atmosphere, also with this technology.

There are three basic types of CO_2 capture (Giuffrida et al., 2016, Moioli et al., 2017b, Lucquiaud et al., 2009, Chalmers et al, 2009): pre-combustion, oxyfuel with post-combustion and post-combustion. Among these, CO_2 capture from exhaust gas (post-combustion) is usually preferred for power plants and is generally accomplished by absorption with alkaline solution (Freguia, 2002, Dugas, 2006, Frailie, 2014, Freeman, 2014). Amine scrubbing is one of the leading technologies for CO_2 removal from flue gases of power plants (Alhajaj et al., 2013), however the energy requirement for the regeneration of the solvent and the compression of carbon dioxide is high and can reduce the electrical output by 20-30% if compared to the one obtained in units without the CCS plant (Cohen et al., 2012). Operating the system in flexible mode may be a good solution for avoiding emitting carbon dioxide while saving costs, selling electricity at higher prices.

This work focuses on the analysis of a flexible operation for CO_2 removal to be applied to a natural gas combined cycle power plant in Italy, taking into account different values for the carbon tax (CTC, 2017).

1.1 The power demand in Italy

In Italy there are 4751 thermal power and heat generating plants (Terna Group, 2014), a lot being of small scale, and only 18 units producing more than 500 MW.

Figure 1a) reports the requested electric power in Italy for the year 2015, considering the third Wednesday of each month. Data are taken from Gestore Mercati Energetici (GME, 2017), an institution of the Italian Ministry of Economy and Finance, and show a great variation depending on the hour of the day and the period of the year.

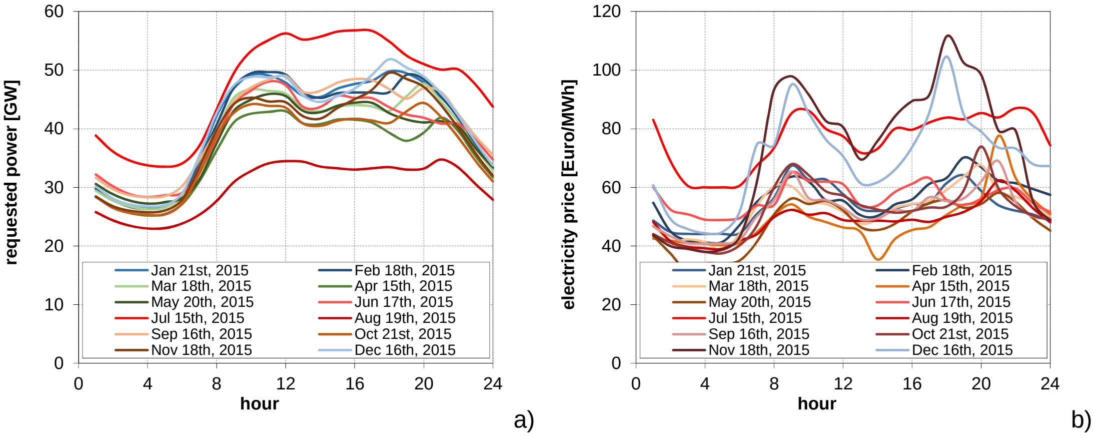

Figure 1: a) Requested power and b) electricity price in Italy in the third Wednesday of each month of year 2015.

Because of the great difference in the demand, the price of electricity varies a lot (Figure 1b)), reaching values higher than 110 Euro/MWh, particularly in summer.

Since the price is lower during nights and / or when the demand is low, adding the energy consumption of the operation of a CO_2 removal plant during these hours, and then reducing the power sold, may cause less economic disadvantages than doing the same operation during the peak hours.

2. The case study

The current work focuses on the flue gas stream of an advanced Natural Gas Combined Cycle (NGCC) plant (Fout et al., 2015), with a power output of 630 MW, in the range of the big plants operating in the Italian territory. The flue gas characteristics are reported in Table 1.

The CO_2 capture from exhaust gas is usually obtained by absorption with alkaline solution. Aqueous MonoEthanolAmine (MEA) solutions, used in this work, are usually the preferred chemical solvent for flue gas streams. In the traditional base case, the CO_2 removal plant consists of an absorption section and a regeneration section. The gas to be purified flows upwards through the absorber, countercurrent to a stream of aqueous amine solution. The rich solvent from the bottom of the absorber is heated by the lean solvent from the bottom of the stripping column and it is then fed to the stripping column at some point near the top. The lean solvent from the stripper, after partial cooling in the lean-to-rich solution heat exchanger, is further cooled with cooling water and fed to the top of the absorber. The acid gas removed from the solvent in the stripping column is cooled to condensate a major portion of the water vapor, which acts as additional reflux in the distillation column, and is then sent to the CO_2 compression station.

The compression of carbon dioxide is fundamental for storing carbon dioxide and, together with the regeneration at the reboiler, it is a major energy expense in a power plant with CO_2 removal unit, bringing the CO_2 stream to a volume 500 times smaller compared with the one of the same stream in gaseous conditions (Romeo et al., 2009).

Table 1: Flue gas characteristics.

Parameter	Value
Flowrate [kmol/h]	130538
Temperature [°C]	117
Pressure [atm]	0.1
Component	Mole fraction
Carbon dioxide	0.0391
Water	0.0841
Nitrogen	0.7442
Oxygen	0.1238
Argon	0.0089

The simulation has been performed in rate-based mode by employing the commercial software ASPEN Plus®, that is used as a framework and linked to external subroutines developed by the GASP group of Politecnico di Milano (Moioli et al., 2017a; Moioli et al., 2017c; Moioli and Pellegrini, 2016; Moioli and Pellegrini, 2015). The complexity of the considered system, which involves also chemical reactions, requires to properly take into account the influence of thermodynamics, kinetics and mass transfer.

3. Analysis of a flexible configuration

The solvent storage (SS) mode allows to maintain a constant CO_2 removal and to operate most of the regeneration when the energy price or the demand is low, with some periods when the stripping and the compression systems operate at partial or zero load (Chalmers and Gibbins, 2007). A modification of the scheme is needed, to introduce a lean and a rich solvent storage tanks, for collecting the rich solution before regeneration and the lean regenerated solvent during periods of high electricity demands and/or prices.

Full load CO_2 capture is maintained by using the stored lean solvent because amounts of solvents higher than the ones needed for the absorber in full operation at a given time have been regenerated and stored during times of low electricity demand/prices.

This study focuses on the month of January, generally the coldest month in Italy. The effect on power plant output losses due to carbon dioxide capture system, and consequently on revenues, can be mitigated by operating the capture plant in flexible modes, using a profit objective function for process optimization.

The net power W_{out} [MW] that can be effectively sold on the electricity market is the difference between the full power plant capacity and the energy required for the CO_2 capture system.

$$W_{out} = W_{out}^{MAX} - (W_{reb} + W_{comp}) \tag{1}$$

where W_{out}^{MAX} [MW] is the power station net capacity without capture system; W_{reb} and W_{comp} [MW] are respectively the reboiler and compression energy penalties. For the reboiler, the equivalent work is calculated, considering that steam is withdrawn from the turbine.

The profit associated with the power station with CO_2 capture system can be expressed as:

$$P = W_{out} C_{energy} - F_{CO_2} C_{CO_2 Tax} - F_{fuel} C_{Fuel} - C_{b,O\&M} \tag{2}$$

where C_{energy} [€/MWh] is the price of energy and C_{CO2Tax} [€/ton$_{CO2}$] is the carbon tax; F_{CO2} [ton$_{CO2}$] is the amount of carbon dioxide released in atmosphere in an hour; F_{fuel} [kg/h] and C_{fuel} [€/kg] are the fuel consumption and the fuel cost; $C_{b,O\&M}$ [€/h] is the operation and maintenance cost of the plant, assumed constant.

The equipment start-up and shut-down costs, the solvent and water make-up, the costs for transport and storage of carbon dioxide and the CO_2 capture ramping costs associated with the efficiency losses during transient CO_2 capture operation are neglected.

The objective function (2) has been maximized by varying the stripper load, considering also the constraints related to the storage capacity.

The analysis has been performed considering a carbon tax from 5 to 100 €/ton$_{CO2}$, in order to take into account a wide range of possible values for this tax (CTC, 2017).

4. Results and discussion

In base plant configuration, when no flexible operation is applied, the capture level is fixed at 95% as and so the amount of CO_2 vented to the atmosphere is constant. The maximum capacity of the storage system has been varied considering five different values that correspond to the volumes of the rich solvent storage tank for 1h, 2h, 3h, 4h and the maximum allowable time of operation in one day.

The hourly optimized values of the stripper load are reported in Figure 3, for different dimensions of the storage tank, depending on the storage time. SS-1H corresponds to a storage time of 1h, SS-4H of 4h and SS-MAX to the maximum allowable storage time.

Since the tank is full at the start of the cycle (as initial assumption), extra-regeneration becomes necessary to permit storage in the first hours. In the early hours of all the days, the electricity price is lower than the average value so the regeneration is suitable: at about 2-3 am, the stripper starts to extra-regenerate in SS-1H configuration whereas the regeneration starts at the beginning of the day with SS-4H and SS-MAX systems (Figure 3).

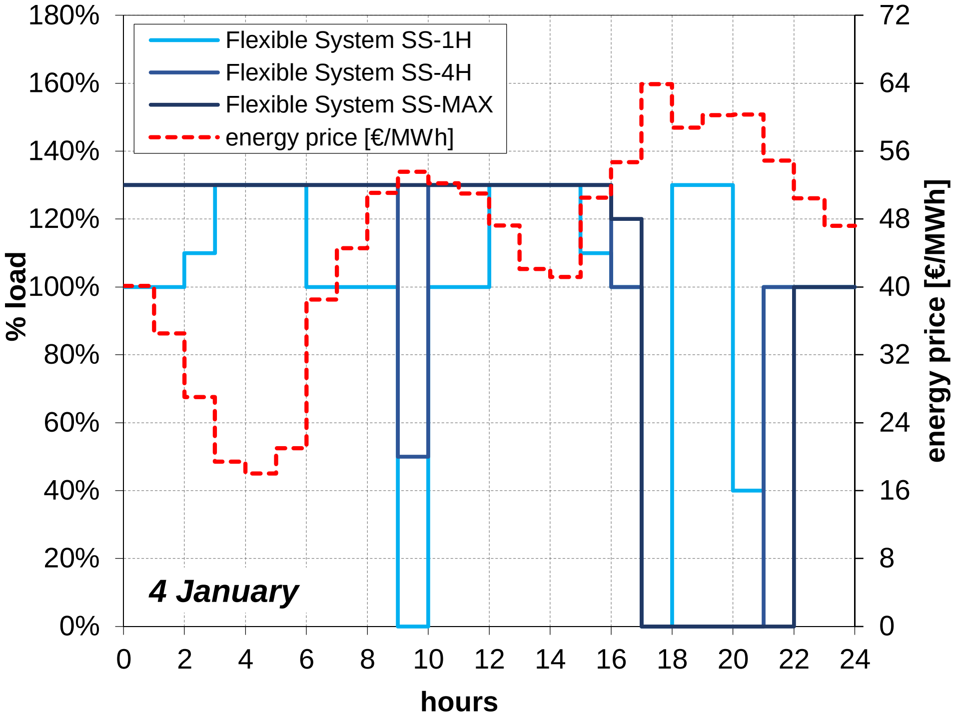

Figure 3: Optimum stripper load profile in flexible system SS-1H, SS-4H and SS-MAX on 4th January 2015.

With larger tanks, regeneration time at higher rate is longer because the higher storage capacity allows a convenient longer storage time during the hours of high electricity cost for regeneration at low electricity cost.

The analysis has also been performed by considering the per cent variation in the profit resulting from Eq. (2) with respect to the power plant with no removal of carbon dioxide, for which a carbon tax is paid for all the carbon dioxide present in the flue gas, which is totally emitted carbon dioxide, and for different values of the carbon tax.

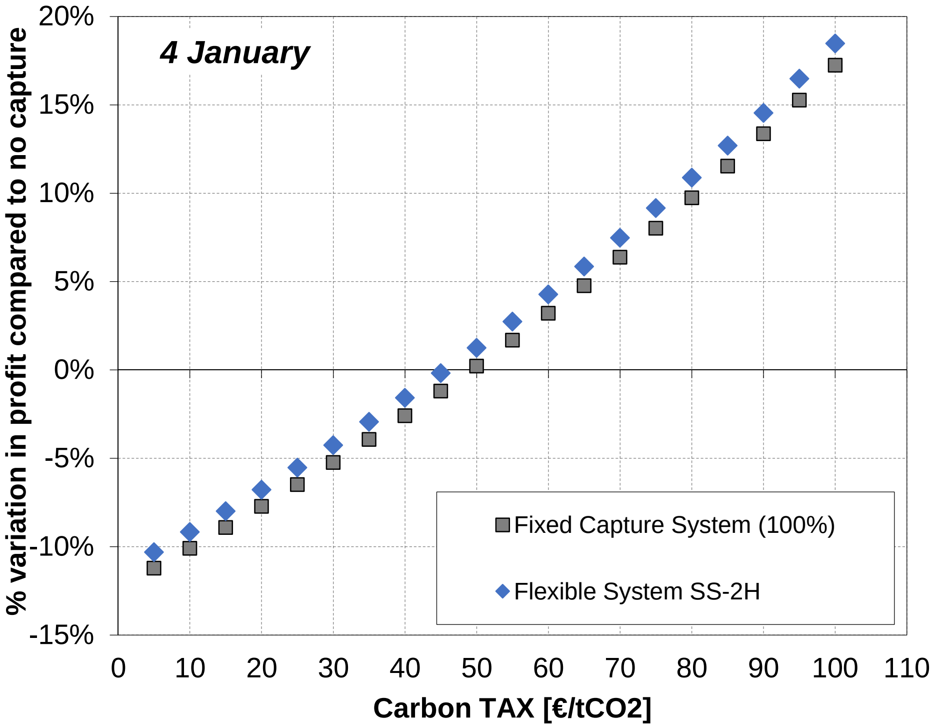

Figure 4: Comparison between the SS-2H configuration and the base CO_2 removal system related to the plant without removal of carbon dioxide.

The SS mode becomes advantageous only for carbon tax values higher than 50 €/ton_{CO2} (see Figure 4) and shows a trend similar to the one of the base case, though resulting with higher profits because of the flexible regeneration. The trend is due to the fact that when operating with a storage system, the absorber is always performing a 95% removal of carbon dioxide, as in the base case. The amount of carbon dioxide removed is very high and influences the energy needed for regeneration and compression.

5. Conclusions

To be in line for meeting greenhouse gas emissions reduction targets established as part of the Paris Climate Agreement, all sectors must find solutions to rapidly decarbonize, and Carbon Capture and Storage (CCS) technology is the only path for energy-intensive industries as electricity production, *i.e.* natural gas combined cycle power plants.

In this paper, a strategy of flexible operation is analyzed for possible application to power production in Italy, to accomplish environmental regulations while limiting the energy and economic losses. The solvent-storage mode operation results useful when strict emission regulations are imposed because it allows a constant rate of CO_2 capture and, therefore, limits the payment of the carbon tax.

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