(8130 words)

Fixed and Capture Level Reduction operating modes for carbon dioxide removal in a Natural Gas Combined Cycle power plant

Stefania Moioli*, Laura A. Pellegrini

GASP – Group on Advanced Separation Processes and GAS Processing, Dipartimento di Chimica, Materiali e Ingegneria Chimica "G. Natta", Politecnico di Milano, Piazza Leonardo da Vinci 32, I-20133 Milano, Italy

Corresponding Author: stefania.moioli@polimi.it

Abstract

The characteristics (flowrate, composition, CO_2 partial pressure) of the flue gas exiting of a Natural Gas Combined Cycle (NGCC) power plant are different from the ones of coal-fired units on which analyses in the literature are usually focusing, therefore for application of Carbon Capture and Storage (CCS) to the removal of CO_2 from this type of stream a detailed study is needed. This work applies the method of flexible operation aimed at reducing the economic disadvantages of a CCS plant, and considers the Capture Level Reduction (CLR) mode for the carbon dioxide removal section of a NGCC power plant located in Italy, of which type the number of units is constantly increasing. The CLR mode consists in emitting part of the carbon dioxide at given times during the day by bypassing part of the rich solvent and thus reducing the energy requirements for regeneration of the solvent and compression of the removed CO_2. For the study a proprietary code developed by the GASP group of Politecnico di Milano, based on real energy prices and demand and taking into account different values of possible carbon taxes, has been employed. The results show that the best load to the absorption section strongly depends on the value of the considered carbon tax, in addition to the time-dependent request and price of electricity. A carbon tax of 5 €/tonCO_2 generally do not favour the operation of the CCS system, while higher values exert a more significant influence on the revenues. Carbon taxes of 115 €/tonCO_2 for the winter period and of 145 €/tonCO_2 for the summer period make the operation of the CCS section more economically advantageous than emitting carbon dioxide to the atmosphere. In any case, also when applied to CO_2 removal in power plants fed by natural gas, the CLR mode results more advantageous than fixed or no capture operation, thus making power plants companies increasing their efforts in reducing greenhouse gas emissions.

Keywords: carbon dioxide removal; post-combustion; energy saving operation; flexibility; carbon tax.

1. Introduction

The environmental impact of industrial processes is one key points in the production of goods and sevices, with the emission of greenhouse gases to the atmosphere being one of the main issues being considered nowadays. A worldwide growing demand of energy is occurring, with more and more energy needed also in residential buildings for household services (Ma et al., 2019). Considering that this sector consumes consumes about 20% of the total energy demand and more than 35% of the global electricity production (Liang et al., 2019), causing 22% of the CO_2 emissions, (Ma et al., 2019), effective carbon dioxide mitigation measures in the activities related to this field are significant to suppress the critical global warming trends, as stated by IPCC (IPCC, 2018). The main types of energy needed are related to primary energy (coal and natural gas) and to secondary energy, *i.e.* the electrical power. In the field of electricity generation, in particular, the electrical plant needs to be built or retrofitted in order to meet the imposed acceptability criteria of energy supply and public acceptance. New renewable power plants based on solar, wind or biomass are important but can still be employed as energy supplier to the main generating units due to the limited energy supply potential and high costs (Feretic and Tomsic, 2005). Other types of renewable sources as large hydropower plants can act as main energy producer only in specific geographical areas. It follows that at the moment and for the next few decades fossil sources still remain among the main sources for electricity production, as also concluded by Yang et al. (Yang et al., 2008).

Compared to coal-fired units, natural gas-fuelled plants are increasing in Europe, US and generally because they are relatively easier to construct and emit fewer pollutants (Zhang et al., 2016) including a lower amount of carbon dioxide. The cost of electricity generation is a condition of major importance in the power plant industry and, at the same time, a drastic reduction of CO_2 emissions is needed so that CCS also in natural gas-fired power plant (NGCC) is required. Indeed, though the mole fraction of carbon dioxide in the flue gas is lower, also natural gas power plants produce and emit significant amounts of this acid gas to the atmosphere and influence the global Earth temperature level.

In the last years, new solutions to favor the CO_2 capture operation in power plants while maintaining CO_2 emissions reductions have been performed. Flexible plants allow to improve the overall plant economics (Domenichini et al., 2013) because allowing a temporary increase in the electrical output of the power plant during peak demands or when electricity prices are high. Indeed, as described by Tait et al. (Tait et al., 2018) in reference to the application of flexible operating modes in post-combustion capture (PCC) in coal-fired power plants, the PCC process variables can be modified to adjust the CO_2 removal level to a value which is optimal for fuel cost, electricity selling price and carbon dioxide emission cost, increasing short-term profitability. Moreover, the electricity available for transmission can be maximixed.

Several studies in the literature already analyzed the flexible operation of CCS power stations, though mainly focusing on coal-fired units. Chalmers et al. (Chalmers and Gibbins, 2007), Gibbins and Crane (Gibbins and Crane, 2004) and Delarue et al. (Delarue et al., 2012) focused on bypass and on solvent storage techniques. The variable capture level, optimized as a function of the electricity price and CO_2 emissions was considered by Errey et al. (Errey et al., 2014) and Rubin et al. (Rubin et al., 2007), while the variable solvent regeneration was taken into account by MacDowell and Shah (Mac Dowell and Shah, 2014) and Mechleri et al. (Mechleri et al., 2017). Generally, the technical literature on flexible PCC in power plants is focused on the purification of flue gases coming from coal-fired units. However, considering the worldwide increasing trend of NGCC plants, separating CO_2 also from flue gases of natural gas power plants would allow a significant reduction of greenhouse gas emissions and studies on flexible operation are needed (ENEL, 2018). Because of its characteristics, it may be considered particularly suitable for the post-combustion CO_2 removal system, because it is located at the end of the power station.

Several methods for purification of gaseous streams, operated with different types of equipment (Besagni et al., 2017a; Besagni et al., 2017b) and reviews on this topic (Yang et al., 2008) dealing also with LCA analyses (Cuéllar-Franca and Azapagic, 2015) and emerging CO_2 removal systems (Abanades et al., 2015) including amino acid salt solutions (Zhang et al., 2018) are reported. Granite and O'Brien (Granite and O'Brien, 2005) focused on methods for CO_2 separations from flue and fuel gases based on electrochemical pumps, membranes and chemical looping. Li et al. (Li et al., 2013) analyzed more than 1000 patents on absorption, adsorption and membranes and concluded that there are no practical processes for removing carbon dioxide from large CO_2 sources with low added Cost of Electricity (COE). Mondal et al. (Mondal et al., 2012) presented a comparative analysis of different technologies and considered emergin technologies including enzymes, facilitated transport membranes and hydrate based separation. However, most of these interesting new technologies are still under research, and when dealing with industrial post-combustion CO_2 removal chemical absorption by aqueous amine solutions is generally preferred.

The present work deals with the application of flexible operation to a CO_2 removal plant in a NGCC power plant. This is the main novelty of the work, since previous literature on this topic focused on applications of postcombustion CO_2 removal to power plants, different because of the raw material used for combustion (natural gas instead of coal), and so as for the composition of the flue gas to be treated. As stated by Bui et al. (Bui et al., 2014), indeed, for a global perspective and compatibility with zero emission energy all fossil fuels power generators potentially need a CO_2 removal technology, and studies should also focus on natural gas fueled power plants.

The power output of fossil fuelled power plants varies according to changes in supply or in demand within the electricity grid, in order to ensure the quality of the utility and the supply of energy to the final user. On the whole year, the total request of electricity is characterized by hourly peaks during the 24 h and also by daily peaks. The energy profile is different for each month, with different levels of total amount of electricity needed. For instance, data of 2015 show that in the Italian territory the highest difference among months is during summer and there are significant variations of prices, due to the great difference in the demand of electricity. When the demand is high, the price is very high, with values higher than 110 Euro/MWh. Similarly, when the demand is low, also the price is low, following the market trend. It follows that the highest amount of revenues coming from the sales of electricity are obtained during the peaks, when the demand of electricity is high and also the prices are very high. Therefore, adding the energy consumption of the operation of a CO_2 removal plant during these hours, and then reducing the power sold, causes relevant economic disadvantages if compared to performing the same in times of low electricity consumption.

The main objective of the work is the study of the flexible operation of the CCS system applied to the Italian electricity production, for which no works can be found in the literature. In particular, the paper focuses on an analysis of flexibility with Capture Level Reduction (CLR) mode, recognized to be the most performing one for coal-fired power plants, for a plant located in Italy, and performs a comparison with fixed CO_2 removal operating mode and with no capture operation. The aim is to find the advantages in terms of energy and economics and to determine the performances for the CLR mode also in NGCC power plants.

2. Materials and methods

2.1. Modes of operation

Several modes of operation, both fixed operation or flexible operation, are possible for the running of the carbon dioxide removal plant.

When running in fixed mode, the operation is steady-state with no variations of captured CO_2 with time. In managing the plant, all variables are set to given values and the same conditions are constantly maintained.

The removal of carbon dioxide may be high (usually 85%, 90% or 95%) or lower, if only the available surplus of energy produced by the power plant and not sold to the final user is employed for running the CO_2 removal section. Indeed, with fixed operation at high carbon dioxide % capture, the needed energy may be higher than the one available in the power system, therefore two options are available:

1. a lower amount of electricity is sold to the final user, but this would cause the unreliability of the power production and of the supply to the electricity grid;
2. the needed extra amount of power is taken from an external source, with additional costs.

However, if operating with a lower CO_2 removal, higher amounts of the acid gas would be emitted to the atmosphere and a higher carbon tax would be paid. It follows that for fixed operation a choice must be made taking into account the economics of the overall plant.

The operation in flexible mode makes the removal of carbon dioxide be higher or lower than in the fixed configuration at low CO_2 removal, with variations during the day (Moioli and Pellegrini, 2019a). Its operation must be chosen on the basis of an economic optimization, with the aim of minimizing losses of energy and money and at the same time excessive losses of carbon dioxide to the atmosphere, which would cause high expenses due to the carbon tax.

Plant configurations for flexible CCS in the open literature (Chalmers et al., 2009a; Chalmers et al., 2009b; Lucquiaud et al., 2014) are mainly of three types:

1. venting: not all the carbon dioxide is absorbed and part of it is emitted to the atmosphere (Chalmers and Gibbins, 2007; Gibbins and Crane, 2004), mainly during the peak hours;
2. storing solvent: the plant reduces the energy penalty due to CCS by storing the solvent to be regenerated and running the regeneration section in periods with low electricity price or demand (Chalmers and Gibbins, 2007; Gibbins and Crane, 2004; Haines and Davison, 2009; Moioli and Pellegrini, 2019c);
3. "varying the time for solvent regeneration": the solvent is not stored but it can be more or less regenerated, so the lean and rich loadings may vary during time (Mac Dowell and Shah, 2014).

This paper focuses on the venting option, also called Capure Level Reduction (CLR) mode, which is usually employed for energy and costs saving without incurring in relevant modifications of the base scheme for the CCS plant, and so avoiding additional investment costs. The CLR mode has already been studied in the literature applied to coal-fired power plants and it has been considered in this work for evaluating its performances when applied to the treatment of a NGCC flue gas stream. This operating mode is then also compared with the fixed operation at different levels (from 60% to 100% of the base CO_2 removal).

2.1.1. Fixed operation – 95%

The plant in fixed operation for the absorption of 95% of the carbon dioxide present in the flue gas had been designed previously (Moioli and Pellegrini, 2018; Moioli and Pellegrini, 2019b) and has been considered for the work carried out in this paper. The design of the plant had been performed in order to treat the very huge gas flowrate in suitable and realizable columns while minimizing the energy consumption, which is located mainly at the reboiler of the regenerating column and in the compression section. Therefore three packed absorption columns with a diameter of 12.5 m each, similar to the size of columns considered and built by Fluor (Fluor, 2017) and Shell (Shell, 2017) and acceptable in comparison with what reported in the recent literature (Zhang et al., 2016) (also in the case of low packing height), have been considered (Figure 1). The lean loading (0.224) and the flowrate (49.23 kmol/s) of the 30% wt. MonoEthanolAmine (MEA) solvent have been chosen on the basis of a minimum energy requirement analysis.

Because of the very high flowrate (Figure 1), the flue gas (*HOTFLUEGAS*) is divided into three equal streams (*FLUEGAS 1, FLUEGAS 2* and *FLUEGAS 3*), cooled in a heat exchanger (*P-COOLER 1, P-COOLER 2* and *P-COOLER 3*) and fed to the absorbers (*ABSORBER 1, ABSORBER 2* and *ABSORBER 3*) for flowing counter-currently to the 30% wt. MonoEthanolAmine (MEA) solvent (*LEANIN 1*, *LEANIN 2* and *LEANIN 3*). The rich aqueous amine solution (*RICHOUT 1, RICHOUT 2* and *RICHOUT 3*) exiting from the bottom of each absorber is mixed in *MIXRICH* and the resulting stream *RICH* is fed to a pump for increasing its pressure and to the heat exchanger *ECOHEAT* for increasing its temperature by heat exchange with the lean solution (*LEANOUT*) from the bottom of the distillation column (*DESORBER*). The rich solvent (*RICHIN*) is then fed to the top of the distillation column. The pressure of the *LEANOUT* stream, after partial cooling in the lean-to-rich solution heat exchanger, is lowered to 1 atm and its temperature is furtherly decreased by heat exchange with cooling water in the *COOLER*. After this step and the make-up, the solvent (*LEANIN)* is split into three identical streams (*LEANIN 1, LEANIN 2* and *LEANIN 3*) and recycled to the top of the absorbers.

The acid gas removed from the solution in the stripping column (*CO2*) is cooled to condensate a major portion of the water vapor and is then sent to the CO_2 intercooling compression station (simplified in the scheme as *CO_2 COMPRESSOR*). This section is composed of several stages, with an additional unit for reduction of the water content at high pressure, based on absorption by triethylene glycol (TEG). In the final part of the process the stream is cooled and liquefied and a pump is used to increase the pressure of the carbon dioxide stream up to the final pressure (150 bar) (Fout et al., 2015).

2.1.2. Fixed operation at partial load

In the fixed operation mode, the load has been set and maintained at 90%, 80%, 70% or 60% of the one of the base case (95% CO_2 removal). This mode of operation may result more or less advantageous with respect to full load depending on the time of the year, as outlined in Section 3.

2.1.3. Flexible operation

The CO_2 Capture Level Reduction mode (CLR) configuration involves a flexible CO_2 capture that vents CO_2 at partial load for specified time intervals. According to this method, carbon dioxide is not totally absorbed as in the full capture base case (95% of the content in the flue gas), but part of it is left in the treated gas and exits to the atmosphere. This is accomplished by operating a bypass of the rich solution, which is fed without regeneration to the absorption column. As a consequence, when bypass is operated, the energy requirement for CO_2 stripping and compression decreases as the solvent flowrate fed to the regeneration column lowers with also a lower CO_2 removal rate.

For a fixed design (the one of the base case), and a fixed lean loading as purity of the regenerated solvent, lower steam at the reboiler is needed to treat a lower flowrate of rich solution for regeneration, so more steam (coproduced in the power plant) is fed to a low pressure turbine and the obtained power output of the overall plant is higher.

For a new power plant, the capital cost of flexibility should include the cost of oversizing the low pressure turbine, generator, and power units to enable the increased power output when the CO_2 capture energy requirements are reduced. In a retrofit application to a power station without CO_2 removal plant, this option involves negligible capital cost if compared to a base capture system because the base power plant has been already sized to have as input also the steam flowrate that in the case of CO_2 capture (added after construction for retrofitting) is used for the reboiler and not fed to the turbine.

If compared to the base CO_2 removal, the main disadvantage of this configuration is the increase of CO_2 emissions and the related costs. When the plant is operated at lower CO_2 capture levels, the overall emission rates are higher than the ones in the fixed-point operation, therefore the CO_2 emission penalty and the carbon tax may be relevant factors. The choice of the amount of carbon dioxide to be absorbed must take into account these issues, as done in this study.

Figure 1 shows the scheme of the CLR mode. The difference between this configuration and the base one is the presence of bypasses on the rich solvent streams exiting the absorbers. When the load is lower than 100%, part of the rich streams (*BYPASS 1*, *BYPASS 2* and *BYPASS 3*) is recirculated directly to the absorbers, after being mixed with the lean streams (*LEANIN 1*, *LEANIN 2* and *LEANIN 3*). With 100% load no rich solvent is recirculated, while, with 0% load, all the rich solvent is recirculated and the desorber is totally bypassed. In this case, no stripping steam would be required for regeneration and the column would not operate. However, for a good operation of the overall plant, a non zero load is needed to prevent some issues, as stripping drying out, and so, to promote a later fast load increase, a value of 30% has been chosen as the lowest possible operation load, as suggested in the literature (Cohen et al., 2011).

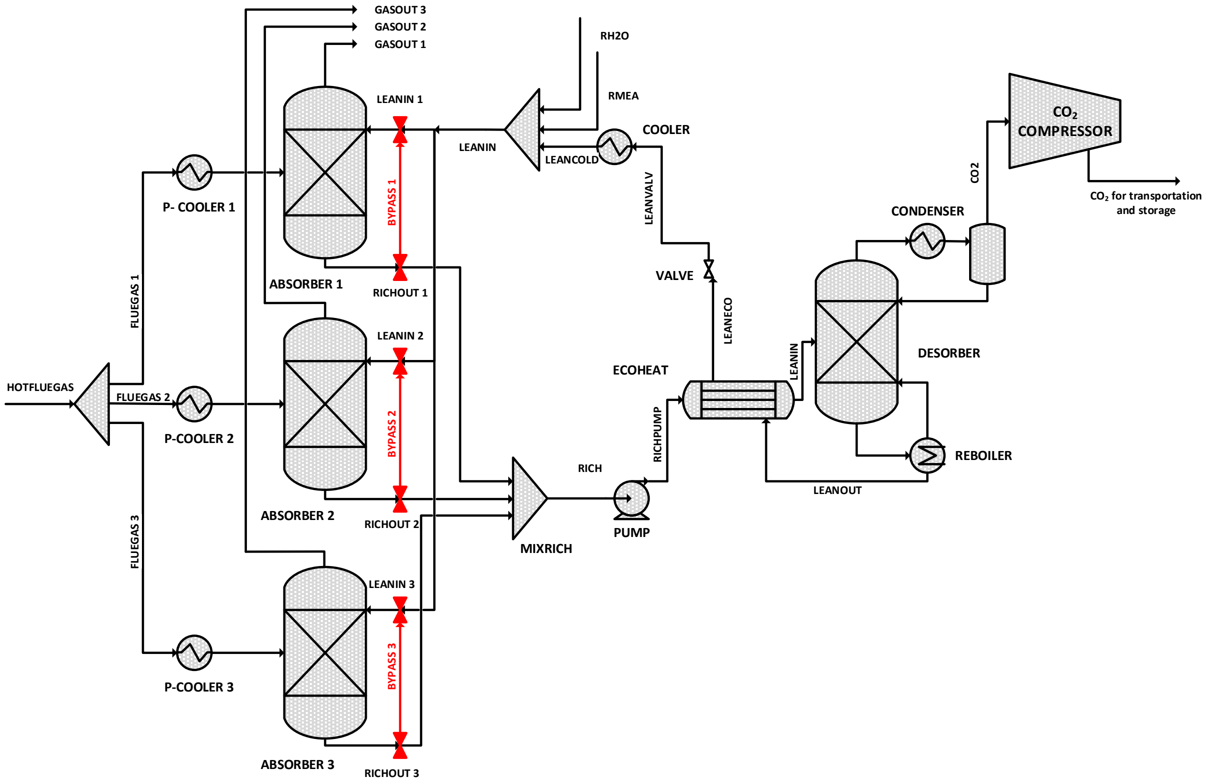


Figure 1. PFD of the CO_2 Capture Level Reduction (CLR) system.

2.2. Methodology

The work has been carried out by performing an economic optimization with an in-house tool developed by the GASP group of Politecnico di Milano on the basis of the methodology outlined below and taking as input the result of simulations in ASPEN Plus®, in addition to the data of electricity request and price.

The power 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.

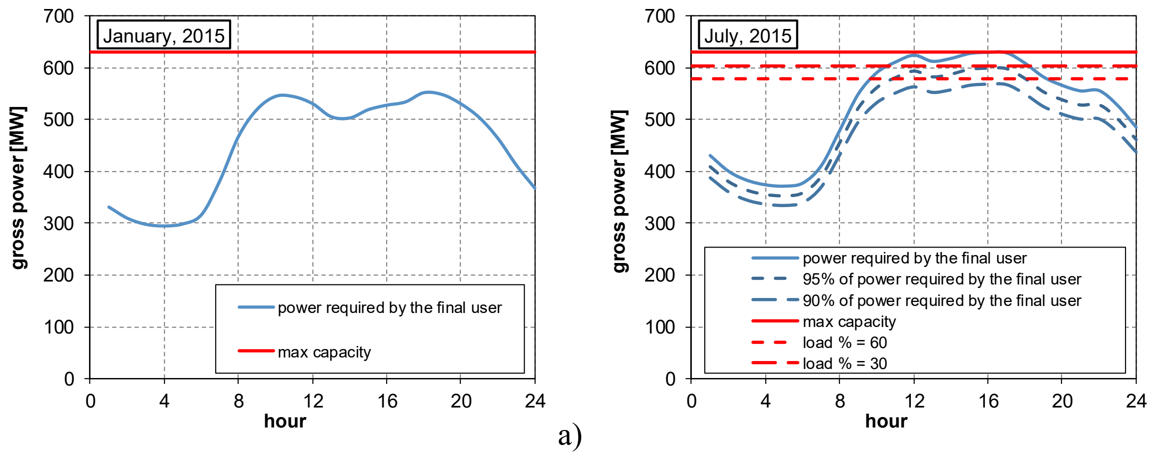
$$W_{out} = W_{out}^{MAX} - (W_{reb} + W_{comp}) \tag{1}$$

where W_{out}^{MAX} [MW] is the power station net capacity without capture system, 630 MW; W_{reb} and W_{comp} [MW] are respectively the reboiler and compression energy penalties, with the reboiler energy penalty calculated as equivalent work considering that steam is withdrawn from the turbine.

W_{out} is the power that can be sold to the market, but, as shown in Figure 2, the power required by the final user varies hour per hour. Therefore, it may happen that the net power produced W_{out} is higher than the one required.

The % CO_2 removal value of fixed operation at low levels has been determined considering the available energy resulting from the difference of the maximum energy produced by the power plant and the power required by the final user.

In order to allow the operation of the plant for all the day with no taking of power from an external source, the hourly peak of power sold to the final user has been considered for the computation of the available energy, as shown in Figure 2.



a) b)

Figure 2. Maximum capacity of the plant and power required on the third Wednesday of a) January 2015 and b) July 2015 (GME, 2017).

For January 2015 it results equal to 77.56 MW, higher than the overall power needed for running the CO_2 removal and compression system, while for July 2015 the difference between the power produced and the power required by the final user is zero at noon and in the afternoon, since it is the yearly peak of power demand and the peak is covered with all the power produced by the plant. Therefore, the CO_2 removal operation would cause an additional cost to the plant for energy consumption, though allowing a removal of carbon dioxide and thus lower carbon taxes. Alternatively, the power plant may provide a lower amount of electricity to the market and use part of the produced power to run the CO_2 capture section. For instance, as shown in Figure 2, for a plant removing 95% of carbon dioxide, if only a 60% load is applied (*i.e.* the plant works to remove only 60% of CO_2 for which it has been designed), about 10% of the produced power is used to run the CO_2 capture section, so during peaks the power plant would be able to provide to the final user only 90% of the requested power. The remaining power (10%) needed should be bought by the user elsewhere. This value is equal to 5% if a load of 30% is applied, for which 95% of power produced can be sold.

For flexible operation, the conditions are chosen so to maximize the profit, which is the objective function, in order to reduce the effect on power plant output loss due to CO_2 capture system by operating capture plant in flexible modes.

On hourly basis, the profit associated to the power station with CO_2 capture system is:

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

where W_{out} [MW = MWh/h] is the net energy production in one hour exiting from the power station; C_{energy} [€/MWh] is the price of energy and C_{CO2Tax} [€/tonCO_2] is the carbon tax; F_{CO2} [tonCO_2] is the amount of CO_2 vented in an hour; F_{fuel} [kg/h] and C_{fuel} [€/kg] are the fuel consumption and the fuel cost respectively; $C_{b,O\&M}$ [€/h] is the cost for base plant operation and maintenance, excluding the cost of W_{out}, separately computed in Eq. (5) (this cost is composed of a term related to the power plant operation and a term related to the CO_2 removal section operation, which is assumed to be present also during times of low or no % load because of the operation of the auxiliary units).

The plant is assumed to be already in operation, so that start-up and shut-down costs have been neglected, though taking into account the efficiency losses during transient CO_2 capture operation due to variations in % CO_2 removal. Therefore, for the absorber and the stripper a ramp of 5%/min (Cohen et al., 2012), assumed to be the same in either direction and the same for absorber and regenerator (Cohen et al., 2011), has been considered.

The fuel consumption is constant because the power plant load is fixed to its base value resulting therefore independent on the capture plant load.

The electricity price has been assumed to be known for each time interval (1h) over 24 h operation period with values taken from Gestore dei Mercati Energetici (GME, 2017) on the basis of historical electricity prices, given on an hourly basis and referring to the Italian market in 2015.

The analysis has been performed considering a possible carbon tax from 5 to 200 €/tonCO_2, in order to take into account a wide range of values for this tax (CTC, 2017).

Two cases have been considered:

A. all the net power output of the plant is sold to the market, regardless the real market needs (it is assumed in this case that the market is able to employ all the energy that is produced by the power plant);
B. only the power really needed by the market on the basis of the hourly request (data taken from GME (GME, 2017) is sold, or a lower amount in case the net power output from the plant is lower than the market needs due to the CO_2 removal and compression plant. If additional power is produced and not sold to the market, this power is considered lost.

3. Results and Discussion

The analysis cosiders as case study the possible application of CO_2 capture in Italy to a power plant of 630 MW. January (generally the coldest month in this country) and July(the month with the highest variation of demand and electricity prices (Moioli and Pellegrini, 2018)) have been chosen as the months on which the analysis is focused, taking into account that a different variation in the energy demand during the day strongly influences the flexibile operation of the plant.

The study has been carried out considering the following cases:

- % CO_2 removal when no flexible operation is applied (base case): 95%;
- modes of operation: no capture, fixed capture at 100%, 90%, 80%, 70% and 60% of the base case (corresponding to 95% CO_2 removal) and CLR flexible operation;
- power sold to the final user: all the power remaining after CO_2 removal (case A) and only the power required proportionally to the Italian request (case B);
- period of the analysis: hourly.

3.1. Flexible operation

Figure 3 show the resulting optimal load obtained for the flexible operation of plants for 95% CO_2 removal in January and in July considering that all the energy available is sold to the market (case A).

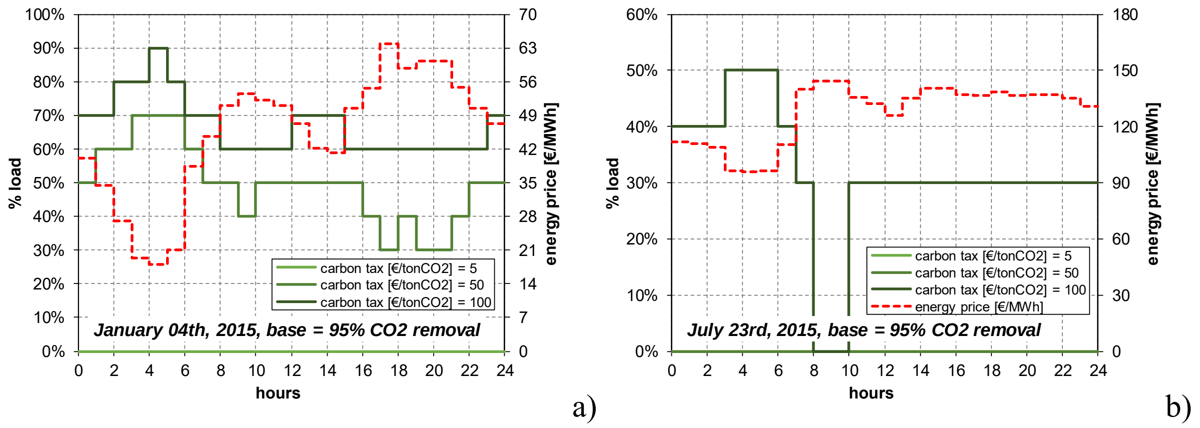


Figure 3. Optimum load profile in flexible system on a) 4th January 2015 and b) 23rd July 2015, considering that all the energy available is sold to the market (case A) for different carbon taxes (5, 50 and 100 €/ton$_{CO_2}$).

A load of the plant equal to 100% means the plant is running to remove the total amount of carbon dioxide for which it has been designed (*i.e.* for a plant designed for 95% CO_2 removal, the plant is being operated to remove 95% of carbon dioxide). Lower loads refer to fractions of the total removal, meaning that part of the amine is recycled back to the absorber without being regenerated.

The variations of load level almost follow the electricity price during the 24 h period: the load is reduced at the time of high electricity price and is increased at the time of low electricity price. With a carbon tax equal to 5 €/ton CO_2, the capture system should be always switched off because the capture operation is not justified from an economical point of view. Because of its low value, the carbon tax has no effect on making the plant operators run the CO_2 capture system, considering that the loss in revenues from sales is higher than the payment of a tax for all the carbon dioxide emitted to the atmosphere. The higher the value of the carbon tax, the higher the average load of the CO_2 capture system.

Moreover, considering the summer month, when the energy demand and the price for electricity is very high, venting carbon dioxide into the atmosphere and paying a carbon tax as high as 50 €/ton CO_2 results more economically advantageous than operating CCS. This is mainly due to the high value of electricity, whose losses due to carbon capture operation heavily affect the economics of the system. With a carbon tax of 100 €/ton CO_2, on the contrary, flexible absorption may be advisable.

An even higher carbon tax value, as 200 €/ton CO_2, makes the carbon dioxide removal system being operated at higher loads, both in winter and in summer (though not reported here for reasons of limiting space). The price of electricity, however, makes the maximum % load being different in summer and in winter, with the optimal one resulting 60% in July and 80% in January.

The trend is different if the power sold to the user is proportional to the one required by the market (case B). In this case, since the revenues are different, their value significantly influences the profit function and hence the results of the optimization. It follows that the optimal operation differs from the one reported in Figure 3, as shown in Figure 4 and in Figure 5.

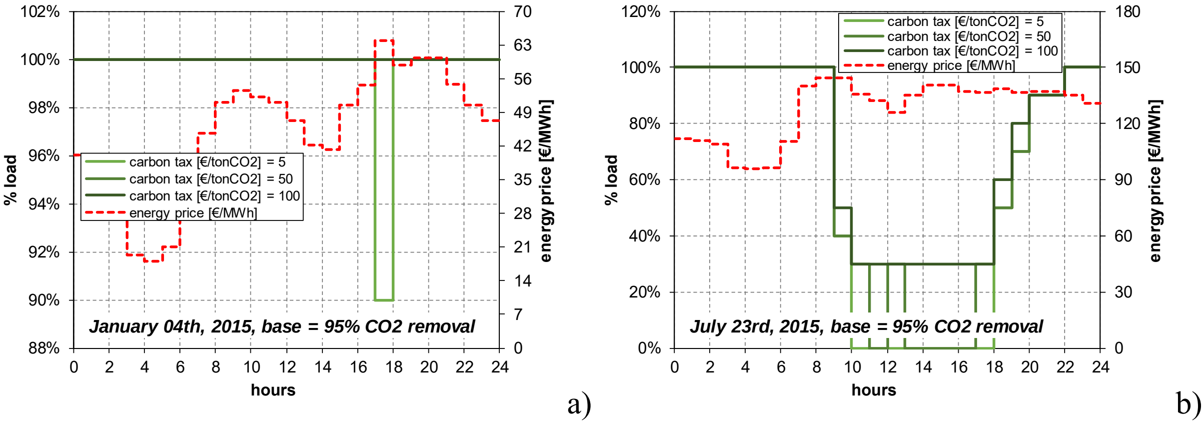


Figure 4. Optimum load profile in flexible system on a) 4th January 2015 and b) 23rd July 2015, considering that only the energy required by the market is sold (case B) for different carbon taxes (5, 50 and 100 €/ton_{CO2}).

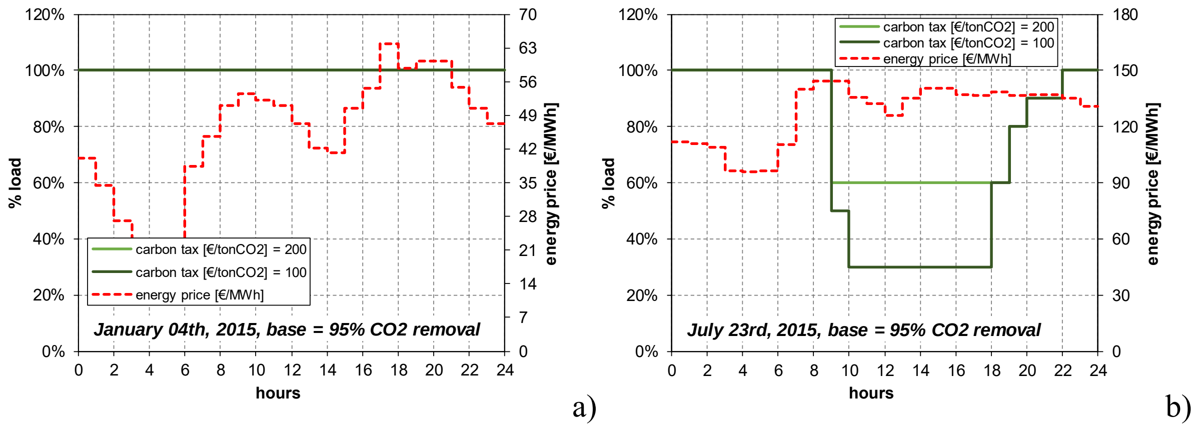
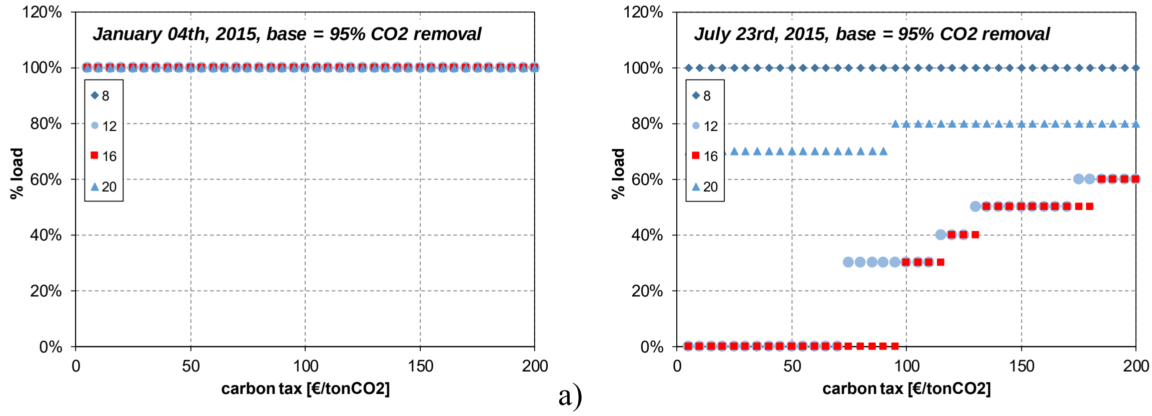


Figure 5. Optimum load profile in flexible system on a) 4th January 2015 and b) 23rd July 2015, considering that only the energy required by the market is sold (case B) for a carbon tax of 100 €/ton$_{CO2}$ and 200 €/ton$_{CO2}$.

In particular, this effect is enhanced in winter. In July, because of peaks in the power requirements and of the high price of energy, revenues from selling of electricity are high and more similar to the ones of case A than revenues obtained in January. In January the power sold to the final user is always lower than the one remaining after removal of carbon dioxide (as shown in Figure 2a)) and revenues are lower. Therefore, in order to increase the overall profit, losses of money due to the payment of the carbon tax for CO_2 emissions must be avoided, so the optimal load results equal to 100% during all day for most of the values of carbon tax. Only if considering a carbon tax of 5 €/tonCO_2, during the hour when the electricity price is the highest of the day (from 17:00 to 18:00), a reduction of the load to 90% results more advantageous. As for summer, on the other hand, 100% load is present only for times of low electricity requirements and prices, *i.e.* during nights and early in the morning.

The influence of the carbon tax on the load is shown in Figure 6, where significant differences result by comparing different hours of the day, mainly due to the combined effect of price of electricity and market demand (Figure 6). Indeed, for the same day, the amount of electricity sold, and consequently the demand from the market, exerts a high influence on the optimal operation of the CO_2 removal plant. For this reason, though calculations have been performed for both the cases, in the following only results for case B are presented.



a) b)

Figure 6. Variation of the optimum load profile as function of the carbon tax in flexible system at different hours of the day (8,12,16 and 20) on a) 4th January 2015 and b) 23rd July 2015, considering that only the energy required by the market is sold (case B).

The % variation in profit compared to no capture (for which the $C_{b,O\&M}$ for the CCS section is not considered) is strongly influenced by the value of the carbon tax, the type of operation (fixed or CLR) and the time of the year (Figure 7). In particular, there is a break-even point for a value of the carbon tax which makes the power company choose to run in environmental safe mode, by absorbing carbon dioxide. This value varies from winter (for CLR mode resulting equal to 115 €/tonCO_2) to summer (for CLR mode being equal to 145 €/tonCO_2). In addition, as described in detail in Section 3.2, running the CO_2 removal plant at different loads in fixed mode provides different profits. The Carbon Level Reduction mode results however the most advantageous one, because of its varying operation in response to hourly electricity prices and demand. These two factors, together with the value of the carbon tax (Figure 8), affect the trend of the daily profit.

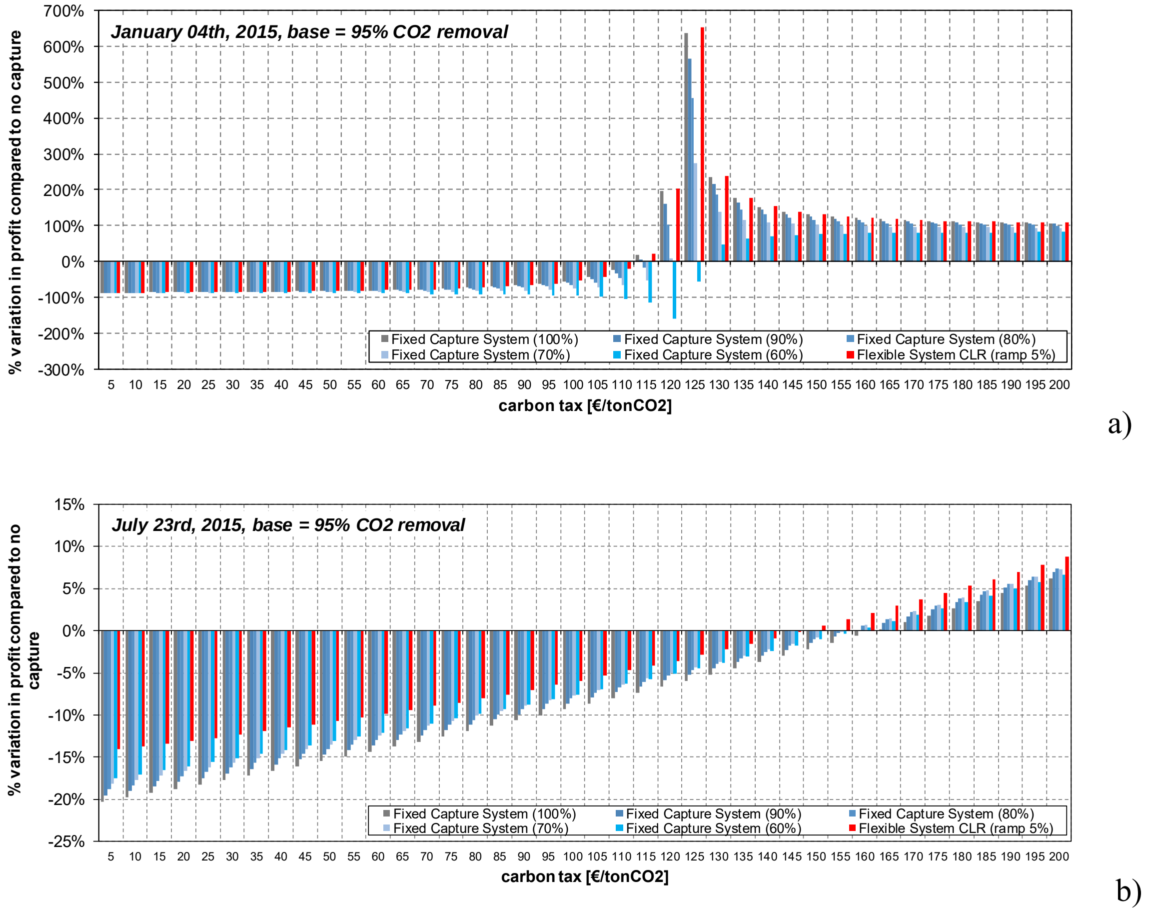


Figure 7. % variation in profit compared to no capture on a) 4th January 2015 and b) 23rd July 2015, considering that only the energy required by the market is sold (case B).

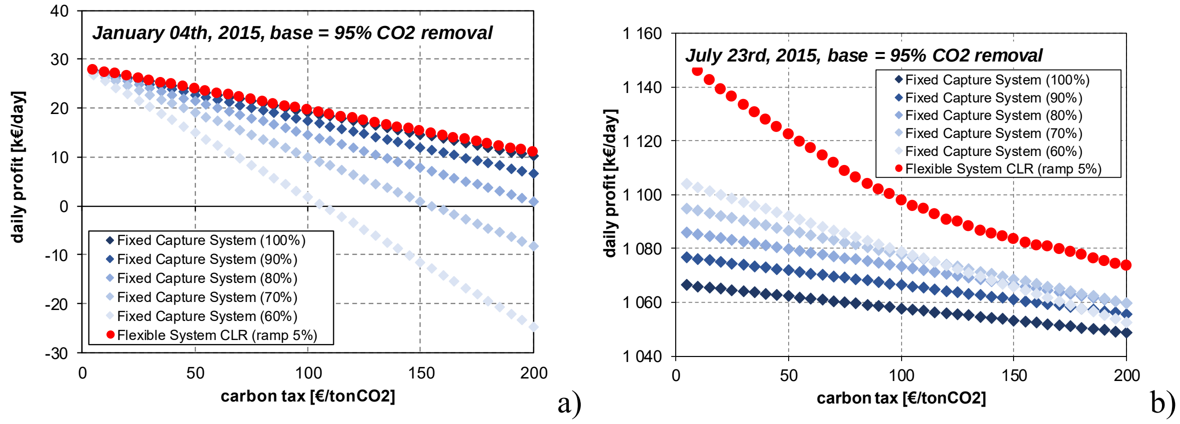
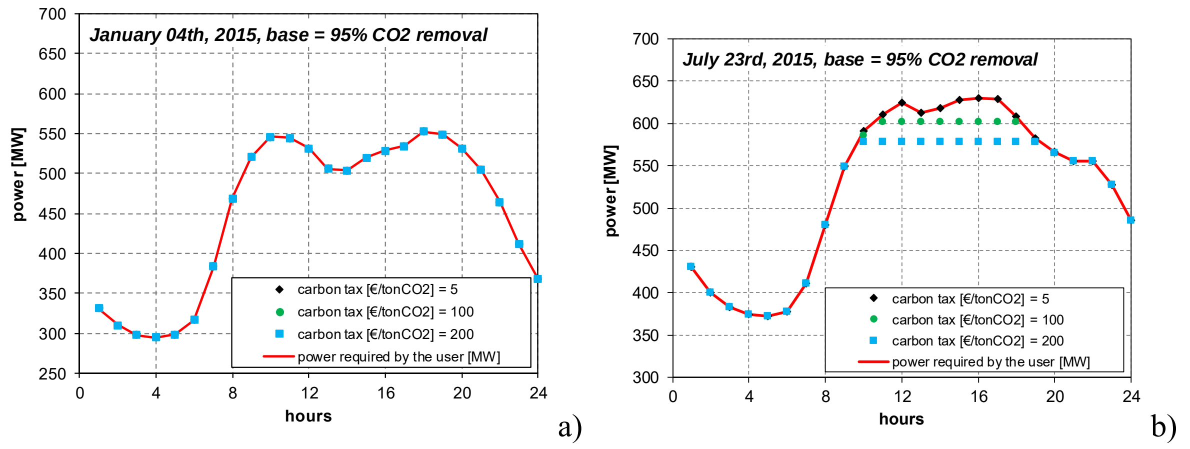
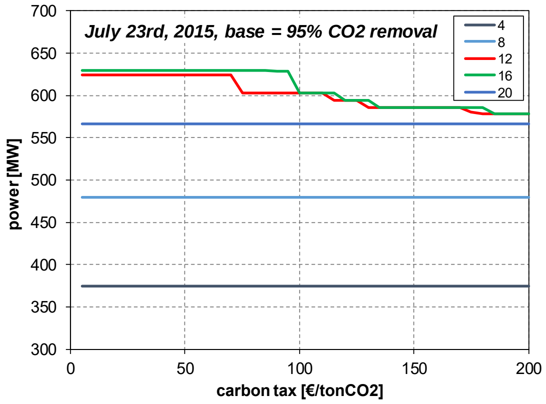


Figure 8. Variation of the daily profit as function of the carbon tax for a) 4th January 2015 and b) 23rd July 2015, considering that only the energy required by the market is sold (case B).

For January, as the value of the carbon tax increases, the resulting profit decreases and, as the load in fixed mode decreases, the profit decreases. Below 70% load economic losses with negative profit result for high values of the carbon tax. A different trend results for July, for which high profits are obtained because of the high amounts, and so high prices, of electricity required by the market. So no value of profit below 0 occurs from 0 €/tonCO_2 to 200 €/tonCO_2, though a decrease results for higher carbon taxes. Moreover, higher % loads are in this case less advantageous, because they cause a reduction of the net power output sold to the market, and the overall electricity demand is not satisfied.

The CLR mode provides a significant increase in the profits also in the case of application to a NGCC power plant. A similar conclusion on the flexible operation had been obtained by Husebye et al. (Husebye et al., 2011) for a coal-fired power plant, who underlined that profits are also strictly related to the electricity price volatility.





c)

Figure 9. Variation of the power sold to the market during the day for a) 4th January 2015 and b) 23rd July 2015 and c) for different carbon taxes on 23rd July 2015, considering that only the energy required by the market is sold (case B).

Figure 9 highlights the difference of the effect of consuming power for removal and compression of carbon dioxide in winter and in summer. While, during winter, the all required energy is sold to the market for any value of the carbon tax applied, in summer differences in the power sold and in the revenues are relevant. For a carbon tax of 5 €/tonCO_2, when no CO_2 removal is applied, the profile of the provided power corresponds to the one of the power requested by the market. For higher carbon taxes, on the other hand, the power sold to the market is lowered at noon (for values higher than 70 €/tonCO_2) and at 4 pm (for values higher than 90 €/tonCO_2) (Figure 9c)).

Differently from the fixed operation mode, in CLR mode the paid amount of carbon tax is strongly dependent on the market, therefore a constant monotonic profile increasing with the unitary carbon tax value does not result (Figure 10). The amount paid for no capture is much higher (up to one order of magnitude), thus making the company always choose to operate the CO_2 removal system, at least partially. This result confirms the usefulness of policy decisions in many countries to apply carbon tax.

It is also in line with what previously found in the studies on coal-fired power plants by Gibbins and Crane (Gibbins and Crane, 2004) and Chalmers et al. (Chalmers and Gibbins, 2007; Chalmers et al., 2009a; Chalmers et al., 2009b; Lucquiaud et al., 2009; Lucquiaud et al., 2014), concluding that removing carbon dioxide is economically valuable when the cost of the emitted CO_2 is significantly higher than the electricity price.

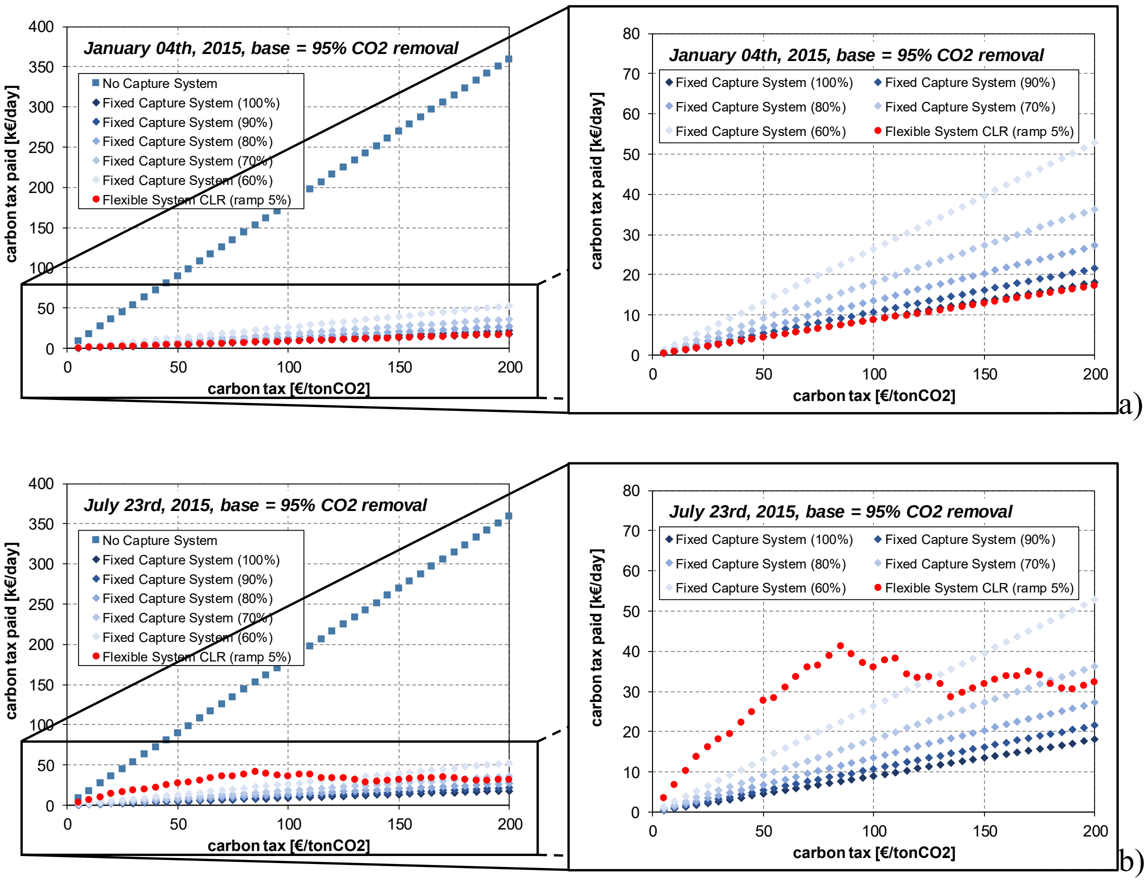


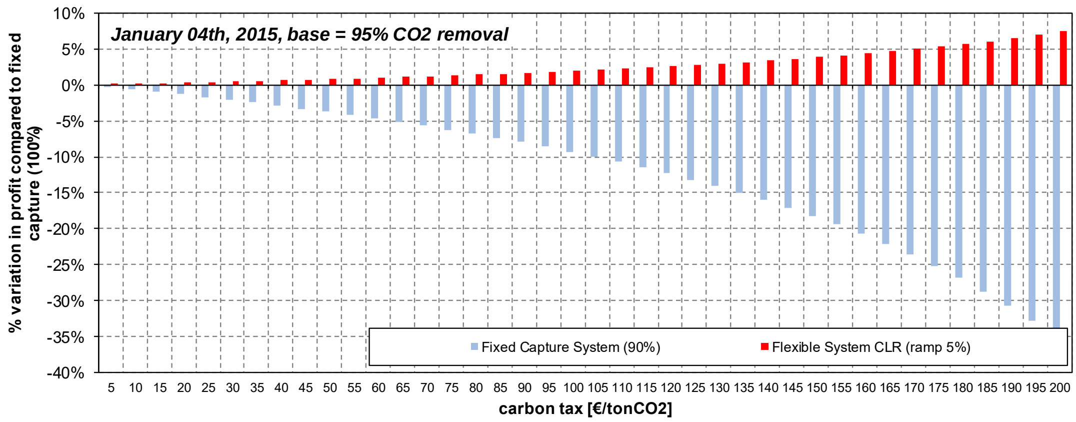
Figure 10. Variation of the carbon tax paid for emitting CO_2 as function of the carbon tax for a) 4th January 2015 and b) 23rd July 2015, considering that only the energy required by the market is sold (case B).

3.2. Fixed operation

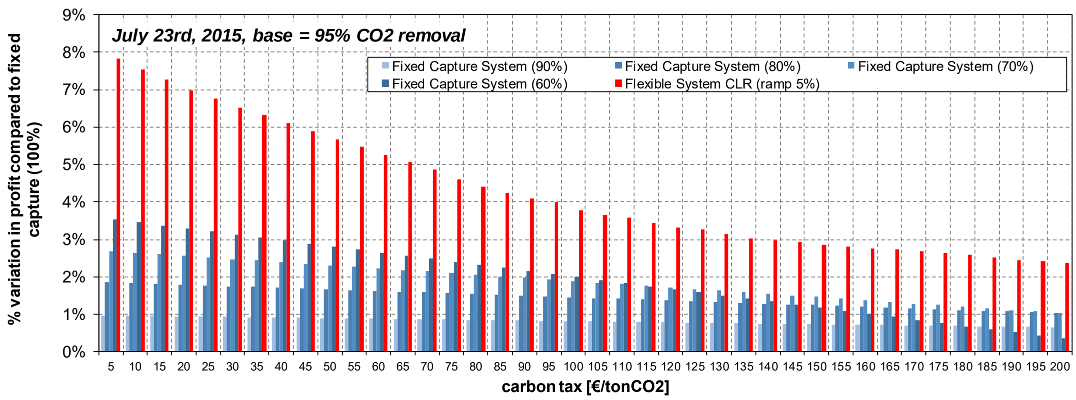
Figure 11 shows % variation in profit compared to fixed capture at 100% load for 95% CO_2 removal, considering that only the energy required by the market is sold (case B) (case A is not reported here for reasons of space). For a 95% base CO_2 removal plant run on July 23rd in case

B, operating CCS in fixed mode at reduced level results advantageous for any carbon tax and any % of considered reductions. In particular, for lower loads, the advantage is higher. This is because if more carbon dioxide is removed (higher loads), a lower amount of power is available to the final user. In summer, with high peaks and high prices for electricity, paying carbon tax for emitting carbon dioxide results more advantageous than performing a high absorption of it. This advantage does not result in winter, for which a decrease in profit higher than 30% occurs by simply operating at 90% load. Indeed, when the request for electricity is lower, more CO_2 is absorbed, the better is because a lower carbon tax is paid. So, among fixed operation modes, the full 95% CO_2 removal must be performed.

If choosing to operate in fixed mode, the load can be selected on the basis of the period of the year, and on the requested energy.



a)



b)

Figure 11. % variation in profit compared to fixed capture at 100% load for 95% CO_2 removal on a) 4th January 2015 and b) 23rd July 2015, considering that only the energy required by the market is sold (case B).

For both January and July, the flexible operation is also reported, showing that in any case it provides economic advantages in comparison to the fixed operating mode.

4. Conclusions

In the efforts of increasing actions to reduce greenhouse gas emissions, carbon capture and storage has gained increasing attention as a good and effective technology for decarbonizing the electricity sector.

This paper has performed a techno-economic analysis for determining the best operating mode of a post-combustion CO_2 removal section in a NGCC power plant assumed to be located in Italy, for which data of hourly electricity prices and demands are available.

Considering the maximization of the profit, carbon capture is applied when the losses of profit due to the payment of the carbon tax are higher than the ones deriving from selling a lower amount of electricity, in particular at high price.

Both the cases of all net power output being sold to the market and of only the requested power output being sold to the market have been considered. Depending on the value of the carbon tax, the best % load has been determined on a hourly basis. In addition, results of the daily profit, the overall paid carbon tax and the power produced obtained for fixed 95% CO_2 removal, for lower fixed modes and for CLR operation mode have been deeply analyzed.

Results for case A show that in summer paying carbon taxes of 50 €/tonCO_2 is more economically advantageous than operating the CO_2 removal plant, while the same value of carbon tax favors the absorption operation in winter, when electricity prices are lower.

When considering also the electricity demand, different results are obtained. The power sold in winter, and the price of electricity at which it is sold, make the system in CLR mode being operated almost at full load for any value of the carbon tax, while in summer from 09 to 22 carbon dioxide is preferably vented to the atmosphere.

The study has also focused on the comparison of the fixed and flexible removal modes with a no capture system, determining the breakeven point of the carbon tax which makes the CO_2 removal operation advantageous (resulting for CLR mode in 115 €/tonCO_2 for January 04th, 2015 and in 145 €/tonCO_2 for July 23rd, 2015).

On the basis of the obtained results it can be concluded that, similarly to PCC in coal-fired units, also the flexible CLR mode in NGCC plants allows to reduce the economic losses of operating CCS and therefore this technique can be employed to favor CO_2 removal in the field of electricity generation.

As for the implications for theory and practice, the challenges of balancing variable renewable energy supplies in a low carbon power producing system can be addressed by highly flexible and low-carbon electricity generation with natural gas fired units equipped with a CO_2 removal section for treatment of the flue gas stream.

The analysis carried out in this work and the obtained results can be used both at industrial and academic level. As for the former, the developed methodology can be successfully employed to assist the management and the operation of the CCS section of power stations in order to favor the lowest economic an power production losses while being in compliance with the environment. In addition, the study provides the academic institutions support for carrying out further research on the application of technologies for treatment of flue gas streams, in particular in the field of power production.

An interesting further development of the work may focus on the applications of the employed methodology to treatment of power generating units bases on low carbon dioxide emissions fuels as coal power plants co-fired with biomass.

References

Abanades, J.C., Arias, B., Lyngfelt, A., Mattisson, T., Wiley, D.E., Li, H., Ho, M.T., Mangano, E., Brandani, S., 2015. Emerging CO_2 capture systems. Int. J. Greenh. Gas Control 40, 126-166.

Besagni, G., Inzoli, F., De Guido, G., Pellegrini, L.A., 2017a. The dual effect of viscosity on bubble column hydrodynamics. Chemical Engineering Science 158, 509-538.

Besagni, G., Inzoli, F., De Guido, G., Pellegrini, L.A., 2017b. Gas holdup and flow regime transition in spider-sparger bubble column: effect of liquid phase properties. Journal of Physics: Conference Series 796, 012041.

Bui, M., Gunawan, I., Verheyen, V., Feron, P., Meuleman, E., Adeloju, S., 2014. Dynamic modelling and optimisation of flexible operation in post-combustion CO2 capture plants—A review. Comp. Chem. Eng. 61, 245-265.

Chalmers, H., Gibbins, J., 2007. Initial evaluation of the impact of post-combustion capture of carbon dioxide on supercritical pulverised coal power plant part load performance. Fuel 86, 2109-2123.

Chalmers, H., Leach, M., Lucquiaud, M., Gibbins, J., 2009a. Valuing flexible operation of power plants with CO_2 capture. Greenhouse Gas Control Technologies 9 1, 4289-4296.

Chalmers, H., Lucquiaud, M., Gibbins, J., Leach, M., 2009b. Flexible Operation of Coal Fired Power Plants with Postcombustion Capture of Carbon Dioxide. J. Environ. Eng.-Asce 135, 449-458.

Cohen, S.M., Rochelle, G.T., Webber, M.E., 2011. Optimal operation of flexible post-combustion CO_2 capture in response to volatile electricity prices. Energy Procedia 4, 2604-2611.

Cohen, S.M., Rochelle, G.T., Webber, M.E., 2012. Optimizing post-combustion CO_2 capture in response to volatile electricity prices. Int. J. Greenh. Gas Control 8, 180-195.

CTC, 2017. Carbon Tax Center.

Cuéllar-Franca, R.M., Azapagic, A., 2015. Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. Journal of CO_2 Utilization 9, 82-102.

Delarue, E., Martens, P., D'haeseleer, W., 2012. Market opportunities for power plants with post-combustion carbon capture. Int. J. Greenh. Gas Control 6, 12-20.

Domenichini, R., Mancuso, L., Ferrari, N., Davison, J., 2013. Operating Flexibility of Power Plants with Carbon Capture and Storage (CCS). Ghgt-11 37, 2727-2737.

ENEL, 2018. L'energia di Enel contro il cambiamento climatico.

Errey, O., Chalmers, H., Lucquiaud, M., Gibbins, J., 2014. Valuing Responsive Operation of Post-combustion CCS Power Plants in Low Carbon Electricity Markets. Energy Procedia 63, 7471-7484.

Feretic, D., Tomsic, Z., 2005. Probabilistic analysis of electrical energy costs comparing: production costs for gas, coal and nuclear power plants. Energy Policy 33, 5-13.

Fluor, 2017.

Fout, T., Zoelle, A., Keairns, D., Turner, M., Woods, M., Kuehn, N., Shah, V., Chou, V., Pinkerton, L., 2015. Cost and Performance Baseline for Fossil Energy Plants. Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity. Revision 3. DOE/NETL-2015/1723.

Gibbins, J.R., Crane, R.I., 2004. Scope for reductions in the cost of CO_2 capture using flue gas scrubbing with amine solvents. Proceedings of the Institution of Mechanical Engineers Part a-Journal of Power and Energy 218, 231-239.

GME, 2017. Gestore Mercati Energetici.

Granite, E.J., O'Brien, T., 2005. Review of novel methods for carbon dioxide separation from flue and fuel gases. Fuel Processing Technology 86, 1423-1434.

Haines, M.R., Davison, J.E., 2009. Designing Carbon Capture power plants to assist in meeting peak power demand. Greenhouse Gas Control Technologies 9 1, 1457-1464.

Husebye, J., Anantharaman, R., Fleten, S.-E., 2011. Techno-economic assessment of flexible solvent regeneration & storage for base load coal-fired power generation with post combustion CO2 capture. Energy Procedia 4, 2612-2619.

IPCC, 2018. Global Warming of 1.5 °C - an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

Li, B., Duan, Y., Luebke, D., Morreale, B., 2013. Advances in CO_2 capture technology: A patent review. Appl. Energy 102, 1439-1447.

Liang, Y., Cai, W., Ma, M., 2019. Carbon dioxide intensity and income level in the Chinese megacities' residential building sector: Decomposition and decoupling analyses. Science of The Total Environment 677, 315-327.

Lucquiaud, M., Chalmers, H., Gibbins, J., 2009. Capture-ready supercritical coal-fired power plants and flexible post-combustion CO_2 capture. Greenhouse Gas Control Technologies 9 1, 1411-1418.

Lucquiaud, M., Fernandez, E.S., Chalmers, H., Mac Dowell, N., Gibbins, J., 2014. Enhanced operating flexibility and optimised off-design operation of coal plants with post-combustion capture. 12th International Conference on Greenhouse Gas Control Technologies, GHGT-12 63, 7494-7507.

Ma, M., Ma, X., Cai, W., Cai, W., 2019. Carbon-dioxide mitigation in the residential building sector: A household scale-based assessment. Energy Conversion and Management 198, 1-15.

Mac Dowell, N., Shah, N., 2014. Optimisation of Post-combustion CO_2 Capture for Flexible Operation. Energy Procedia 63, 1525-1535.

Mechleri, E., Fennell, P.S., Dowell, N.M., 2017. Flexible Operation Strategies for Coal- and gas-CCS Power Stations under the UK and USA Markets. Energy Procedia 114, 6543-6551.

Moioli, S., Pellegrini, L.A., 2018. Optimal Operation of a CO_2 Absorption Plant in a Post-Combustion Unit for Cost Reduction. Chem. Eng. Trans. 69, 151-156.

Moioli, S., Pellegrini, L.A., 2019a. Comparison of CLR and SS Flexible Systems for Post-Combustion CO_2 Removal in a NGCC Power Plant. Chem. Eng. Trans. 74, 829-834.

Moioli, S., Pellegrini, L.A., 2019b. Design of a CO_2 Removal Section Treating Very High Flue Gas Flowrates. Chem. Eng. Trans. 74, 859.

Moioli, S., Pellegrini, L.A., 2019c. Operating the CO_2 absorption plant in a post-combustion unit in flexible mode for cost reduction. Chem. Eng. Res. Des. 147, 604.

Mondal, M.K., Balsora, H.K., Varshney, P., 2012. Progress and trends in CO_2 capture/separation technolgies: A review. Energy 46, 431-441.

Rubin, E.S., Chen, C., Rao, A.B., 2007. Cost and performance of fossil fuel power plants with CO_2 capture and storage. Energy Policy 35, 4444-4454.

Shell, 2017. CANSOLV Carbon Dioxide (CO_2) Capture System.

Tait, P., Buschle, B., Milkowski, K., Akram, M., Pourkashanian, M., Lucquiaud, M., 2018. Flexible operation of post-combustion CO_2 capture at pilot scale with demonstration of capture-efficiency control using online solvent measurements. Int. J. Greenh. Gas Control 71, 253-277.

Yang, H.Q., Xu, Z.H., Fan, M.H., Gupta, R., Slimane, R.B., Bland, A.E., Wright, I., 2008. Progress in carbon dioxide separation and capture: A review. Journal of Environmental Sciences-China 20, 14-27.

Zhang, Y., Freeman, B., Hao, P., Rochelle, G.T., 2016. Absorber modeling for NGCC carbon capture with aqueous piperazine. Faraday Discussions 192, 459-477.

Zhang, Z., Li, Y., Zhang, W., Wang, J., Soltanian, M.R., Olabi, A.G., 2018. Effectiveness of amino acid salt solutions in capturing CO_2: A review. Renewable and Sustainable Energy Reviews 98, 179-188.