Operating the CO_2 absorption plant in a post-combustion unit in flexible mode for cost reduction

Stefania Moioli*, Laura A. Pellegrini

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

Corresponding Author: Stefania Moioli (stefania.moioli@polimi.it)

Abstract

Carbon dioxide greatly contributes to climate change and its emissions must be limited. Combustion of fossil fuels in power plants to produce electricity generates the largest amount of CO_2 released into the atmosphere, therefore application of Carbon Capture and Storage (CCS) to this sector would help in reducing the emissions of this acid gas.

CO_2 absorption with aqueous amines is the most common capture technology for post-combustion CO_2 removal and is characterized by high energy requirements, mainly for CO_2 release from the solvent and compression of the obtained rich-CO_2 stream. For this reason operating the CCS system in a power plant significantly reduces the power output and, consequently, the revenues from selling electricity.

In order to deal with this issue while maintaining low carbon dioxide emissions, flexible operation may be applied.

In this work, a detailed analysis of the application of the Solvent Storage mode for flexible operation of the CO_2 removal section of a natural gas combined cycle power plant has been performed.

Simulations in ASPEN Plus®, properly customized for the description of the system, and a techno-economic model created by the GASP group of Politecnico di Milano have been run to find the best solution. The variation of price of electricity from hour to hour for key days and for the overall year have been considered. Different values of carbon tax to be applied have been also taken into account.

Keywords

MEA solvent; energy requirement; electricity price; NGCC power plant; flexible operation; solvent storage.

1. Introduction

Most of the carbon dioxide emitted to the atmosphere is released by the combustion of fossil fuels to produce electricity. This sector emits about 40% of the total CO_2 emissions (IEA, 2016), therefore performing CO_2 removal would help in achieving the targets established by international treaties. Indeed, after the United Nations Framework Convention on Climate Change of 1992 and the Kyoto Protocol (UN, 1997), in order to strengthen the global response to climate change, the 2015 Paris Agreement (UN, 2015) established to keep the global temperature rise below 2°C above the temperature of the pre-industrial era.

One way to make the industrial sector perform Carbon Capture and Storage (CCS), then, is by setting taxes on carbon dioxide emissions (carbon taxes), which have been implemented by many countries. In this way, the cost of electricity production may be significantly increased if carbon dioxide is not removed and is emitted to the atmosphere.

Recently new sources for energy and electricity production have started to be exploited to cope with environmental issues, with biogas (Pellegrini et al., 2018) being considered a possible source because of its being renewable and a carbon neutral fuel. However, to produce electricity in power plants fossil fuels are still employed, because of the huge amounts needed.

Generally, 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), so, considering also the low prices of natural gas in recent years, there has been a shift towards natural gas fed plants. The increasing demand has made also low quality natural gas reserves being exploited for production of energy (De Guido et al., 2015). Despite the lower concentration of carbon dioxide present in the flue gas streams of a NGCC plant, because of the huge flowrates of gas circulating in the plant, a lot of carbon dioxide is still emitted to the atmosphere and CCS must be applied also to power production in natural gas fed plants.

Amine scrubbing is one of the leading technologies for post-combustion CO_2 removal from flue gases of power plants (Alhajaj et al., 2013). Amines are widely employed for the purification of several gaseous streams including syngas for production of hydrogen and power production (Giuffrida et al., 2016) and biogas for biomethane production (Pellegrini et al., 2015). For the technology employing these solvents, however, the energy requirement for the regeneration of the solvent and the compression of carbon dioxide is high. It has been estimated that it can reduce the electrical output by 20-30% if compared to the one obtained in units without the CCS plant (Cohen et al., 2012). Therefore, in order to reduce the losses of revenues due to losses of power outputs for CCS, flexible operation must be taken into account.

Some modes of operation, as the one considered in this work, allow to avoid emitting carbon dioxide while saving costs and to sell electricity at higher prices, and have been studied in the literature for coal-fired power plants (Chalmers and Gibbins, 2007; Chalmers et al., 2009a; Chalmers et al., 2009b; Lucquiaud et al., 2014; Mac Dowell and Shah, 2014; Zaman and Lee, 2015).

This paper deals with an in-depth analysis of a flexible operation for CO_2 removal to be applied to a natural gas combined cycle power plant in Italy. A techno-economic estimation of the best operation for key days during the year and for the overall year has been carried out. The study has been performed also by considering the influence of the carbon tax.

1.1. The price of electricity

Italian electricity is mostly produced by thermal power and heat generating plants (Terna Group, 2014), with 18 units producing more than 500 MW.

Data of the requested electric power in Italy for the year 2015 from Gestore Mercati Energetici (GME, 2017), an institution of the Italian Ministry of Economy and Finance, have been used to understand the variation of the requested power in Italy. In particular, a great difference depending on the hour of the day and on the period of the year occurs (Moioli and Pellegrini, 2018b). It follows that also the price of electricity is different from time to time, ranging from very low values (as 18 €/MWh) to very high values (as 144.57 €/MWh), higher than 110 €/MWh in summer.

The operation of the CO_2 removal plant is related to power consumption in high amount due to heat requirement (Moioli et al., 2017; Nagy et al., 2017) and, therefore, to lower electricity available to the market. Its impact on the overall economics of the power plant may be reduced by running the carbon dioxide removal plant in flexible mode. Indeed, adding the energy consumption of the operation of a CO_2 removal plant when the price of electricity is lower may cause less economic disadvantages than doing the same operation during the peak hours.

2. The case study

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, has been considered. The gas, with a flowrate of 130538 kmol/h and a composition (mole fraction) of carbon dioxide (0.0391), water (0.0841), nitrogen (0.7442), oxygen (0.1238) and argon (0.0089), is available at 117°C and is cooled before being fed to the CO_2 removal plant.

The design of the plant has 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 built by Fluor (Fluor, 2017) and Shell (Shell, 2017) have been considered. The solvent is an aqueous solution of monoethanolamine (MEA) 30% wt., with lean loading and solvent flowrate chosen on the basis of a minimum energy requirement analysis, resulting equal to 0.224 (Figure 1) and to 49.23 kmol/s respectively.

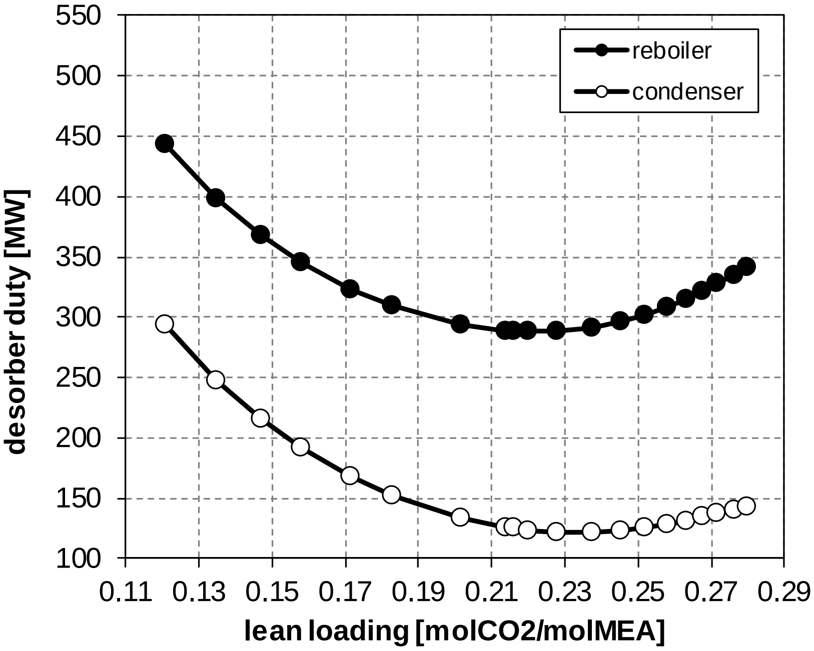


Figure 1. Requirements at the regeneration column vs. lean loading for the fixed configuration of the plant removing 95% of carbon dioxide.

Figure 2 shows the PFD of the plant designed for removing 95% of carbon dioxide present in the flue gas stream in fixed operation mode. Because of the very high flowrate, 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*). The cooled gaseous streams, which must be purified, flow upward through the absorbers (*ABSORBER 1, ABSORBER 2* and *ABSORBER 3*), counter-currently to the respective streams of aqueous amine solution (*LEANIN 1, LEANIN 2* and *LEANIN 3*) for achieving a 95% removal of the carbon dioxide present in the flue gas. The rich solution (*RICHOUT 1, RICHOUT 2* and *RICHOUT 3*) from the bottom of each absorber is mixed in *MIXRICH* forming a single stream (RICH). The *RICH* pressure is increased with a pump (*PUMP*) to the desired stripper pressure and then the solution (*RICHPUMP*) is heated in the heat exchanger *ECOHEAT* by the lean solution (*LEANOUT*) from the bottom of the stripping column (*DESORBER*). The rich solution (*RICHIN*) is then fed at the top of the stripping column. After partial cooling in the lean-to-rich solution heat exchanger, the pressure of the lean solution from the stripper (*LEANOUT*) is lowered to 1 atm in an isenthalpic valve (*VALVE*) and furtherly cooled by heat exchange with cooling water (*COOLER*). After this step, the solvent is integrated with MEA and water and then *LEANIN* is split into three identical streams (*LEANIN 1*, *LEANIN 2* and *LEANIN 3*) and fed 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 compression station.

The main features of the columns are reported in Table 1.

Table 1. Main features of the columns and of the compression train for the chosen configuration.

Parameter	Value
number of absorption columns	3
height [m]	7.92
diameter [m]	12.5
pressure [bar]	1.1
number of regeneration columns	1
height [m]	6
diameter [m]	9.5
pressure [bar]	2
maximum pressure in compressors [bar]	80
maximum pressure in pumps [bar]	150
intercooling temperature [K]	303.15
isentropic efficiency for compressors (Moioli et al., 2016)	0.85
mechanical-electric efficiency for compressors (Moioli et al., 2016)	0.94

In order to reduce the initial capital investment, the possibility of regenerating the total rich solvent flowrate in one single distillation column, with feasible dimensions, had been analyzed. One single column, with 9.5 m diameter, can be employed for regeneration.

The CO_2 intercooling compression (simplified in the scheme as *CO_2 COMPRESSOR*) has been designed considering that the stream coming from the top of the regeneration section is mainly composed of carbon dioxide, with an amount of water of about 5% mol. Most of the water is removed in a first section, where the gas is cooled down, then the gaseous stream is fed to the compression train. The compression system 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). It is generally recommended an outlet pressure higher than 86 bar, in order to avoid dramatic changes in CO_2 compressibility along the pipelines (McCoy and Rubin, 2008), with a pressure usually of 90-150 bar (Kohl and Nielsen, 1997), so the highest pressure (150 bar) has been chosen to perform a conservative study.

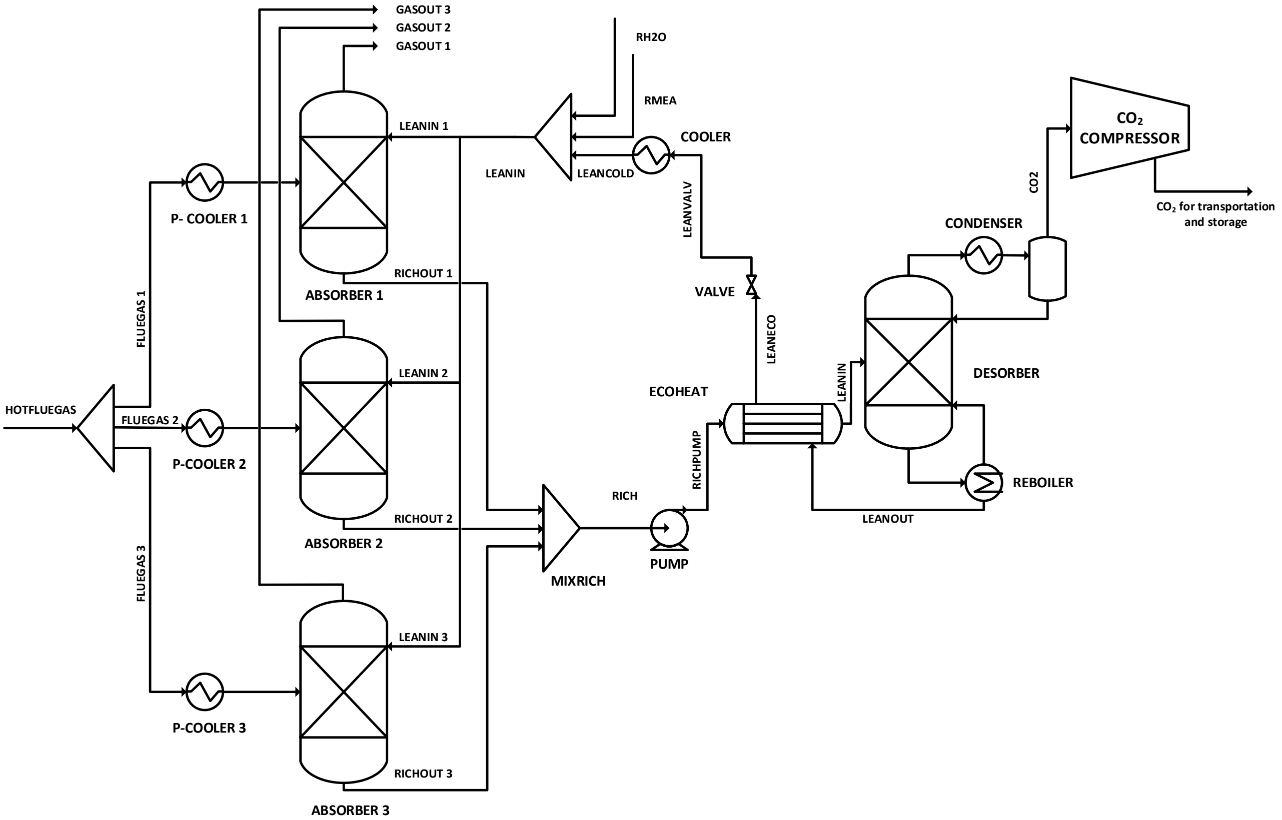


Figure 2. PFD of the base plant.

3. Flexible configuration

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

When running in fixed mode, the operation is steady-state with no variations of captured CO_2 with time. This allows an easy operation and management of the plant, for which all variables are set to given values and the same conditions are constantly maintained. However, operating in flexible mode would help in reducing the loss of revenues due to a lower amount of electricity sold, in particular during peak hours.

Among the several modes of flexible operation, comprising also the options of venting part of the carbon dioxide present in the flue gas stream to the atmosphere or of varying the time for solvent regeneration so that a lower amount of solvent may be regenerated, in this work the Solvent Storage mode has been selected. The time for regeneration can be varied, therefore globally providing a leaner or richer solvent for carbon dioxide removal. All the options aim at reducing the energetic requirements for purification of flue gases to increase the power output and therefore revenues (Oates et al., 2014; Sanchez Fernandez et al., 2016; van der Wijk et al., 2014). Venting part of the CO_2 to the atmosphere can be performed by diverting part of the flue gas towards the stack before it enters the CO_2 removal system (Abdilahi et al., 2018) or by feeding the overall flue gas stream to the absorber and redirecting part of the rich solvent directly to the absorption section without regenerating it (Cohen et al., 2011). Differently from other methods, the Solvent Storage mode allows to maintain a constant CO_2 removal while operating most of the regeneration when the price of electricity is low, so presenting advantages also from an environmental point of view. When high revenues may be obtained from selling electricity, the stripping and the compression systems operate at partial load (Chalmers and Gibbins, 2007). To this aim, a lean and a rich solvent tanks are needed to store the rich solution before feeding to the stripping column and the lean solvent exiting from the regeneration section during periods of high electricity demands and/or prices. The stored lean solvent is employed to maintain a constant carbon dioxide removal in the absorption section, while the regeneration section works in flexible mode.

The scheme of the plant is therefore as in Figure 3.

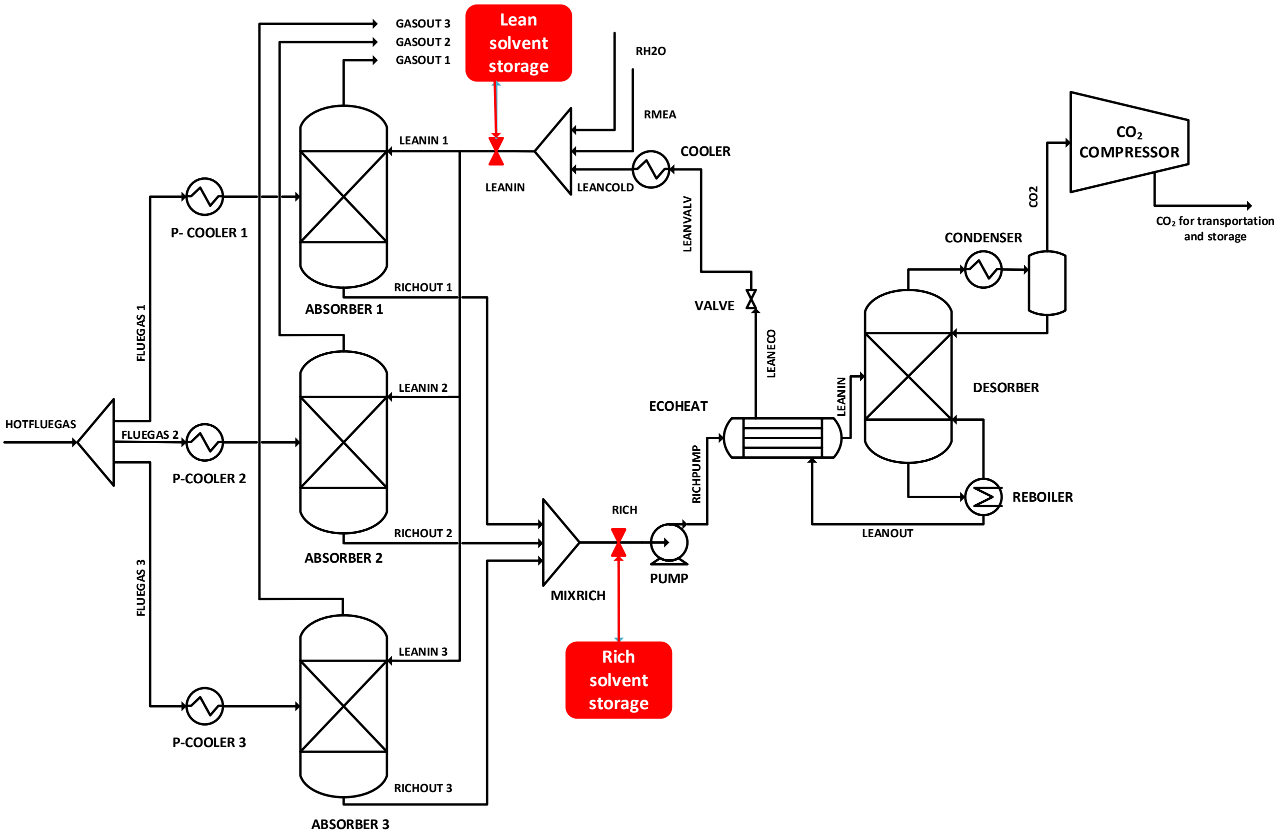


Figure 3. PFD of the base plant for Solvent Storage operation.

The tank can be designed in order to store solvent for a given maximum period of time. In this work, several possible times for storage have been considered (1 h, 2 h, 3 h, 4 h), up to the maximum time which allows the regeneration of the solvent employed during the day, with no accumulation to the following day, equal to 5.54 h.

4. Tanks for Solvent Storage

For storing solvent at given times during the day in order to increase the power output of the plant, additional tanks must be considered in the design of the plant and also a higher amount of solvent is initially needed. These factors have an influence on the initial costs of the plant. Indeed, according to the literature (Chalmers et al., 2009a; Chalmers et al., 2009b; Gibbins and Crane, 2004), about 10% additional costs must be considered for storage tanks and pipework and 8000 \$/tonCO_2 for additional solvent. Results from economic studies (Patiño-Echeverri and Hoppock, 2012) suggest that even if additional investment costs have to be considered, amine storage systems offer an alternative to potentially decrease the average cost of carbon dioxide capture, in particular when applied in retrofitting already existing power plants.

In any case, the final decision on the type of operation must take into account the potential additional profits obtained by operating in flexible mode and the total expenditure required to make it available.

5. Methodology

5.1. Choice of the day

The analysis has been carried out considering the real price of the electricity applied in Italy. Official data from 2015 were made available by the Italian Ministry of Economy and Finance and used for the study (GME, 2017).

The work has focused on significant periods during the year, which have been selected according to the following considerations:

1) the profiles in winter and in summer differ significantly;

2) the difference between the values of the lowest and the highest energy prices during the day may exert an influence on the flexible configuration of the plant. Literature works (Patiño-Echeverri and Hoppock, 2012; Zaman and Lee, 2015), indeed, state that “*Savings from adopting a flexible operation mode will be significant if the difference between low and high market electricity prices is significant*”;

3) for winter the coldest month and for summer the hottest month have been considered.

The selection of the month to be taken into account has been made on the basis of temperature data referring to the city of Milano, for which the maximum and the minimum temperature of every day for each month were available.

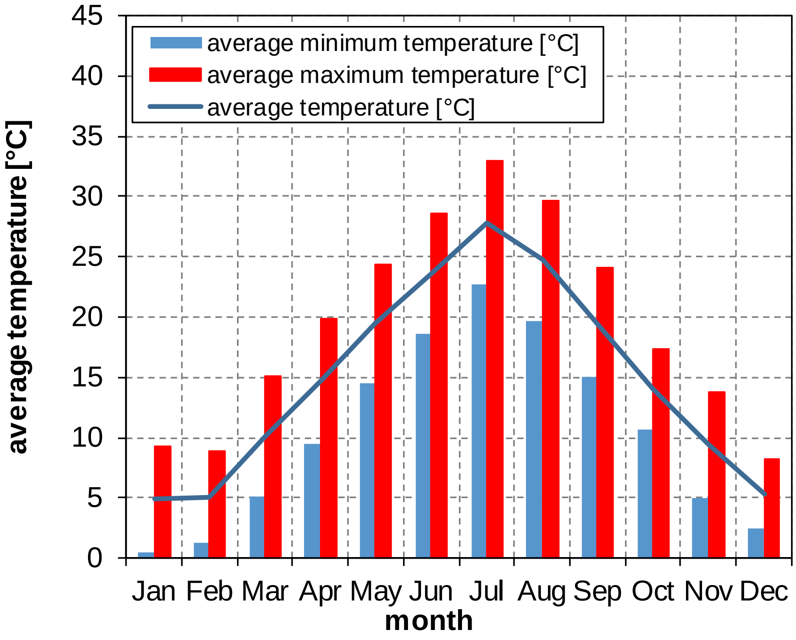
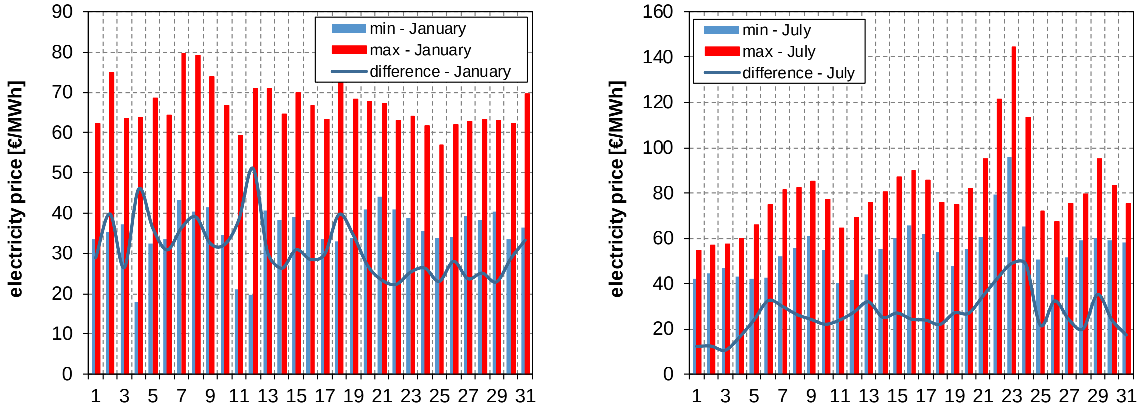


Figure 4. Average monthly temperature profile during the year 2015.

Figure 4 shows the trend of temperatures, where the relevant temperature difference between summer and winter in Italy can be outsourced. The coldest month is January, with a minimum average temperature of 0.48°C and an average temperature of 4.85°C, while the hottest month is July, with a maximum average temperature of 32.96°C and an average temperature of 27.86°C. The average temperatures also correspond to single values, with a minimum temperature in January of -3°C and a maximum one in July of 37°C.

The choice of the day for the analysis has been performed considering the daily trends of the price of electricity (Figure 5).



a) b)

Figure 5. Profile of average maximum and minimum price of electricity during the month of a) January 2015 and b) July 2015.

The maximum price shows low deviations in January if compared to the month of July, for which the maximum price (144.57 €/MWh) occurs and significant differences (up to 90 €/MWh) occur from one day to the other. The minimum price in July follows a trend similar to the maximum price, though the difference with the maximum price can be as high as more than 45 €/MWh.

For this reason, the choice of the days in July has been based on:

- day with the highest energy price: resulting July 23rd, 2015;
- day with the highest difference between maximum and minimum energy prices: resulting July 23rd, 2015 also in this case.

In order to perform an analysis which may take into account cases when low electricity prices are applied, the lowest price of electricity and the lowest difference between the highest and the lowest electricity prices have been considered as parameters for the selection of the days to be studied for the month of January.

Therefore, the chosen days in January are:

1) day with the lowest electricity price: resulting January 04th, 2015;
2) day with the lowest difference between maximum and minimum electricity prices: resulting January 22nd, 2015.

Table 2 reports the characteristics of the chosen day.

Table 2. Days considered for the techno-economic analysis.

Parameter	**Day**	**Maximum electricity price [€/KWh]**	**Minimum electricity price [€/KWh]**
day with the highest energy price	July 23rd, 2015	144.57	95.91
day with the highest difference between maximum and minimum energy prices	July 23rd, 2015	144.57	95.91
day with the lowest electricity price	January 04th, 2015	63.91	18.00
day with the lowest difference between maximum and minimum electricity prices	January 22nd, 2015	63.13	40.88

5.2. Model

The present work employs both a process simulator for the simulations of the CO_2 removal and compression plants, and a software environment for the development of the techno-economic analysis. In detail, ASPEN Plus® has been used as a framework and linked to external subroutines developed by the GASP group of Politecnico di Milano (Moioli and Pellegrini, 2015, 2016, 2018a) to take into account the complexity of the chemical reacting system, by considering the influence of thermodynamics, kinetics and mass transfer. Matlab has been employed for implementing the techno-economic model and optimizing the flexible operation of the plant (Moioli and Pellegrini, 2018b).

The developed techno-economic model takes into account the effect on the power plant output losses of the CO_2 capture and compression system and the influence of the carbon tax on the revenues obtained by selling electricity. A profit objective function, considering also these terms, has been created and the optimization for determining the flexible mode of operation which maximizes the revenues has been performed.

The effect of carbon dioxide capture and compression system on power plant output losses, 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 $Wout$ [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 and compression systems.

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

where $Wout^{MAX}$ [MW] is the power station net capacity without capture system; $Wreb$ and $Wcomp$ [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 $Cenergy$ [€/MWh] is the price of energy and C_{CO2Tax} [€/tonCO_2] is the carbon tax; F_{CO2} [tonCO_2] is the amount of carbon dioxide released in atmosphere in an hour; F_{fuel} [kg/h] and C_{fuel} [€/kg] are the fuel consumption (Fout et al., 2015) and the fuel cost (EIA, 2019); $C_{b,O\&M}$ [€/h] is the operation and maintenance cost of the plant, assumed constant.

The equipment start-up and shut-down costs have been neglected, considering that in the studied system the maximum shut-down would be for 5.54 h and that for a CO_2 removal plant by amines hot restart can be considered instead of cold restart if done within 16 h after shutdown (Ceccarelli et al., 2014). As reported in the literature, for the overall CO_2 removal section of a Combined Cycle with Gas Turbines (CCGT) power plant, the rate at which the setpoint is achieved is much faster than the time for achieving steady-state operations (typically estimated as 60 minutes after steam is fed to the reboiler). Moreover, considering that in Solvent Storage mode only regeneration is shut-down and restarted, with all the remaining units continuously in operation, the assumption of neglecting equipment start-up and shut-down costs can be reasonable for the purposes of the present work.

Also the solvent and water make-up, the costs for transport and storage of carbon dioxide and the CO_2 capture transient costs associated with the efficiency losses during transient CO_2 capture operation have not been accounted for.

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

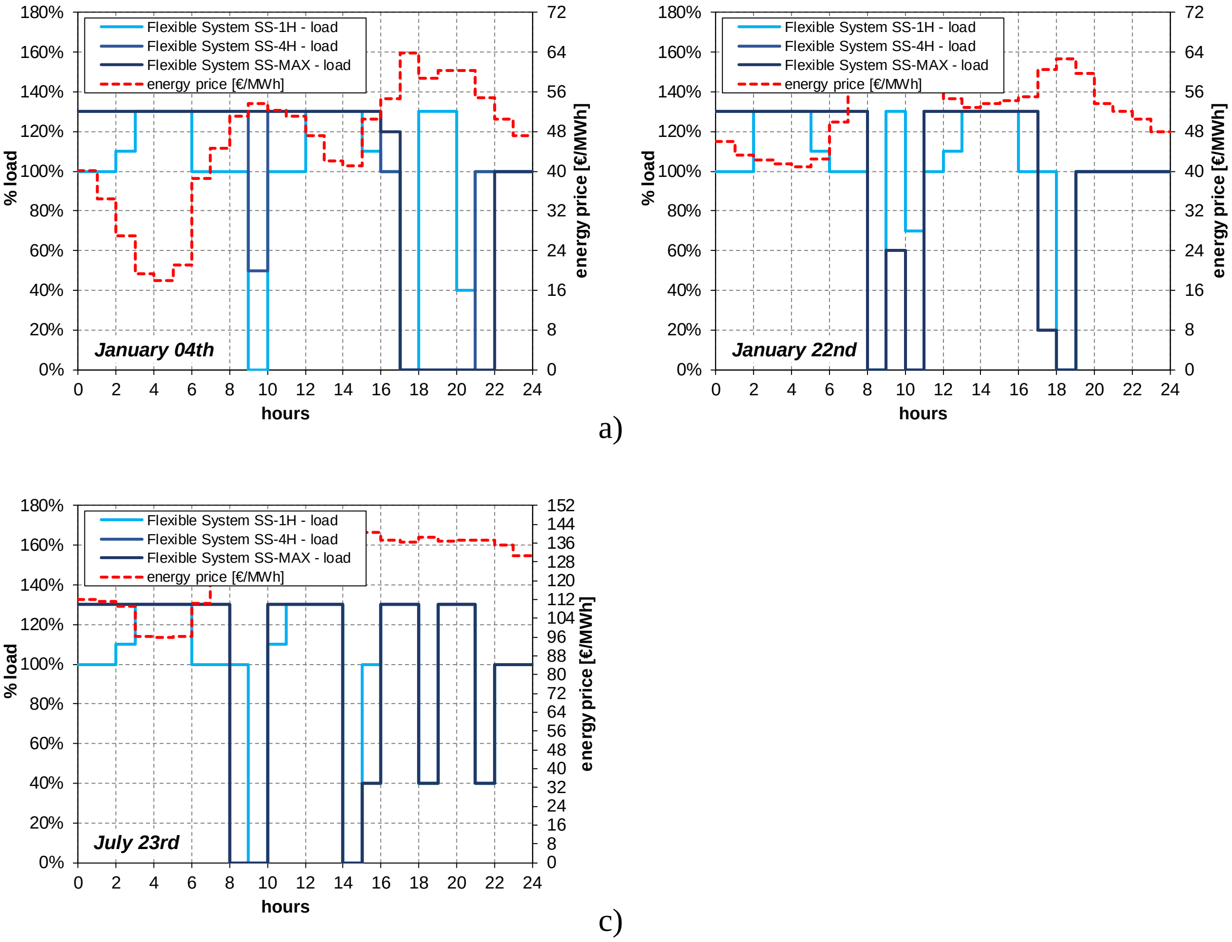
- the volume of stored solvent must be in the range from 0 to the maximum volume of storage;
- the stored volume at the beginning and at the end of the day must be the same, with no accumulation during the day so that part of the solvent must be regenerated in following days.

The analysis has been performed considering a carbon tax from 5 to 100 €/tonCO_2, in order to take into account a wide range of possible values for this tax (CTC, 2017).

6. Results and discussion

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 amount of CO_2 vented to the atmosphere is constant, since it is the same of the base plant configuration, when no flexible operation is applied, characterized by a 95% removal of carbon dioxide.

Results of the flexible analysis are reported in Figure 6, showing the trends for the considered days of the stripper load at every hour for different solvent storage options as a result of the optimization. The same figure reports the hourly electricity price which strongly influences the choice of the stripper load. Results for storage times of 2 h and 3 h are not shown for reasons of space, and are reported in Figure 7 and in Figure 8 with the volume of stored rich solvent for January 04th, 2015 and July 23rd, 2015.



a)

b)

c)

Figure 6. Energy price and stripper load for different operation modes (SS-1H = solvent storage for maximum 1 h, SS-4H = solvent storage for maximum 4 h, SS-MAX = solvent storage for the maximum time of the day) for a) January 04th, 2015, b) January 22nd, 2015 and c) July 23rd, 2015.

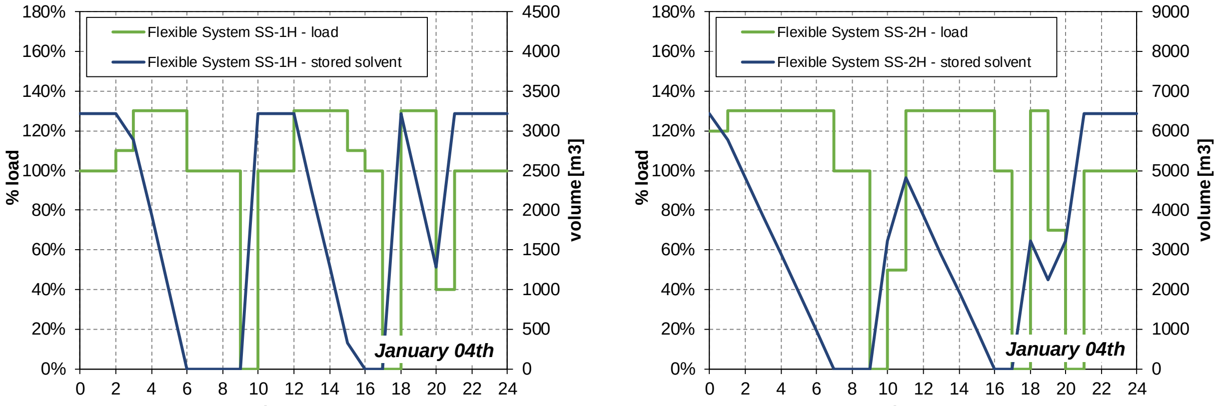
The best load profile varies a lot during the day and is strongly influenced by the storage of solvent. For the case with storage of 1 h, indeed, most of time the regeneration column works at base load, with only few hours working at different loads. These hours correspond to times during the day when prices of electricity are high, so that regenerating the solvent would cause high losses of revenues, or to times when the price of electricity is lower and more solvent can be regenerated. For instance, at 09 am there is a local peak of price of electricity, which causes the non-regeneration of the solvent and the subsequent regeneration periods (as between 2 am and 6 am or between 12 am and 2 pm) when the price of electricity decreases. A similar operation can be found at 5 pm, when the maximum price of electricity for January 04th occurs.

Moreover, also the fact that storage can be for 1 h results in regenerating when the tank is full because no additional storage can be done. The solvent storage for 1 h occurs only in peak hours.

For solvent storage of 4 h or more, a very different stripper load profile is obtained. In particular, for SS-MAX (storage with the maximum time, equal to 5.54 h) from 5 pm to 10 pm no regeneration is performed and all the solvent circulating during the day is regenerated in the distillation column running from 12 pm to 4 pm at the maximum stripper load (130%).

Generally, similar trends are obtained for January 22nd. For the solvent storage of 1 h regeneration is preferred in the early morning (from 2 am to 5 am) and at noon time (from 12 am to 2 pm). The profiles of SS-4H and SS-MAX show no differences each other and are characterized by a solvent regeneration at high stripper loadings (equal to 130%) from 12 pm to 5 pm, with the exception of 8 am and 10 am. This difference in the profile, compared to the one of January 04th, is due to the fact that the values of price of electricity are slightly different, though both of them being characterized by a similar trend, typical of the winter period.

In summer time the price of electricity is characterized, overall, by a different profile during the day and different values. In detail, the lowest price of electricity occurring on July 23rd, equal to 95.91 €/MWh, is higher than the highest price of January 04th and of January 22nd. This high difference greatly affects the obtained best stripper load profiles, for all the solvent storage cases. When considering storing solvent for 1 h, regeneration at high stripper loads occurs from 3 am to 6 am, from 11 am to 2 pm, from 4 pm to 6 pm and from 7 pm to 9 pm, in order to be able to limit regeneration in peak hours, when it is decreased to stripper loads lower than 100%. Differently from the winter cases, for July 23rd a very similar profile (with differences only for few hours) is obtained also when considering storage for 4 h or more (maximum time), with no storage for the time for which the vessel has been built. Similar trends are obtained also when considering storage times of 2 h and 3 h.



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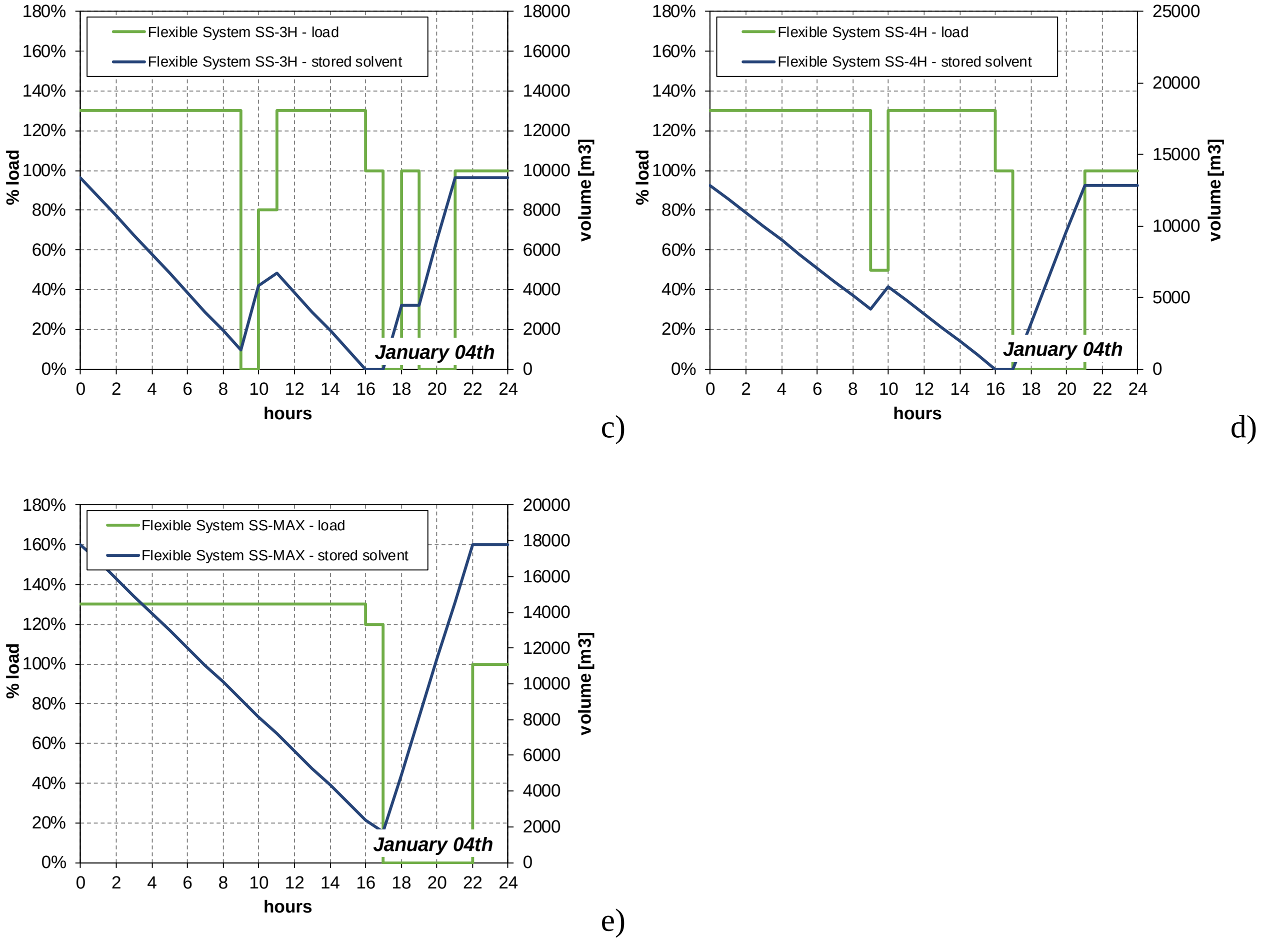


c)

d)

e)

Figure 7. Volume of stored solvent and stripper load for January 04th, 2015 considering a) SS-1H = solvent storage for maximum 1 h, b) SS-2H = solvent storage for maximum 2 h, c) SS-3H = solvent storage for maximum 3 h, d) SS-4H = solvent storage for maximum 4 h and e) SS-MAX = solvent storage for the maximum time of the day.

Figure 7 reports the volume of rich solvent stored for being regenerated. Details of each considered storage option are reported because the obtained trends differ a lot one from the other, though all of them being characterized by the common feature of having the same volume at the beginning and at the end of the day with no accumulation at the end of the day (all the employed solvent is regenerated the same day of use). The volume of stored solvent remains constant when regeneration is at base stripper loads (100%), decreases for higher stripper loads and increases for lower stripper loads.

For January 04th and SS-1H case, the volume of solvent starts decreasing at 2 am, when regeneration is operated at stripper loadings higher than the base one, and after four hours, at 6 am, all the rich solvent is completely regenerated. When the electricity price increases and the stripper load decreases, a lower amount of rich solvent is regenerated, therefore the volume of rich stored solvent increases (from 9 am to 10 am). The solvent is stored until times when the regeneration section is operated at stripper loads higher than the base one, in this case from 12 am to 4 pm, and, later, from 6 pm to 8 pm.

The maximum time considered for storing solvent (1 h, 2 h, 3 h, 4 h or maximum time) strongly influences the profile of stored rich solvent, as shown in Figure 7. For SS-MAX on January 04th there is only one emptying and one filling of the rich solvent storage, because of the obtained profile of stripper load due to the price of electricity.

The trends obtained for January 22nd are similar to those obtained for January 04th (though taking into account the differences in the stripper load as described before), while those of July 23rd are strongly different and are reported in Figure 8. In particular, for this day several variations in emptying and in filling the storage vessel occur for all the considered cases. For storage of more than three hours the tank is never completely emptied, differently from the winter period.

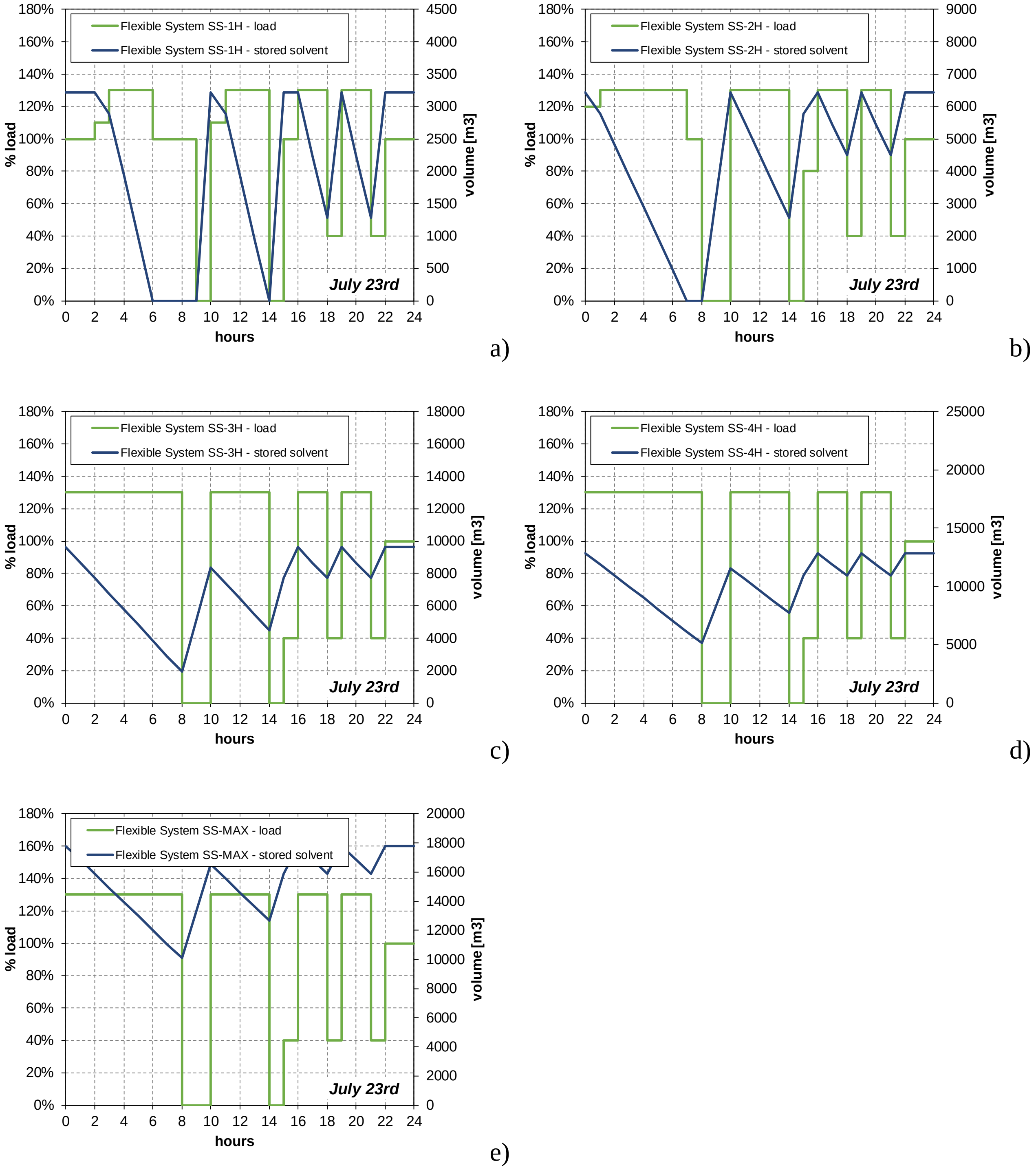


Figure 8. Volume of stored solvent and stripper load for July 23rd, 2015 considering a) SS-1H = solvent storage for maximum 1 h, b) SS-2H = solvent storage for maximum 2 h, c) SS-3H = solvent storage for maximum 3 h, d) SS-4H = solvent storage for maximum 4 h and e) SS-MAX = solvent storage for the maximum time of the day.

The influence on the carbon tax is shown in Figure 9, where the results of the techno-economic analysis performed are reported in terms of variation in the values of the profit function in comparison with those referring to a NGCC plant without the CO_2 removal and compression sections.

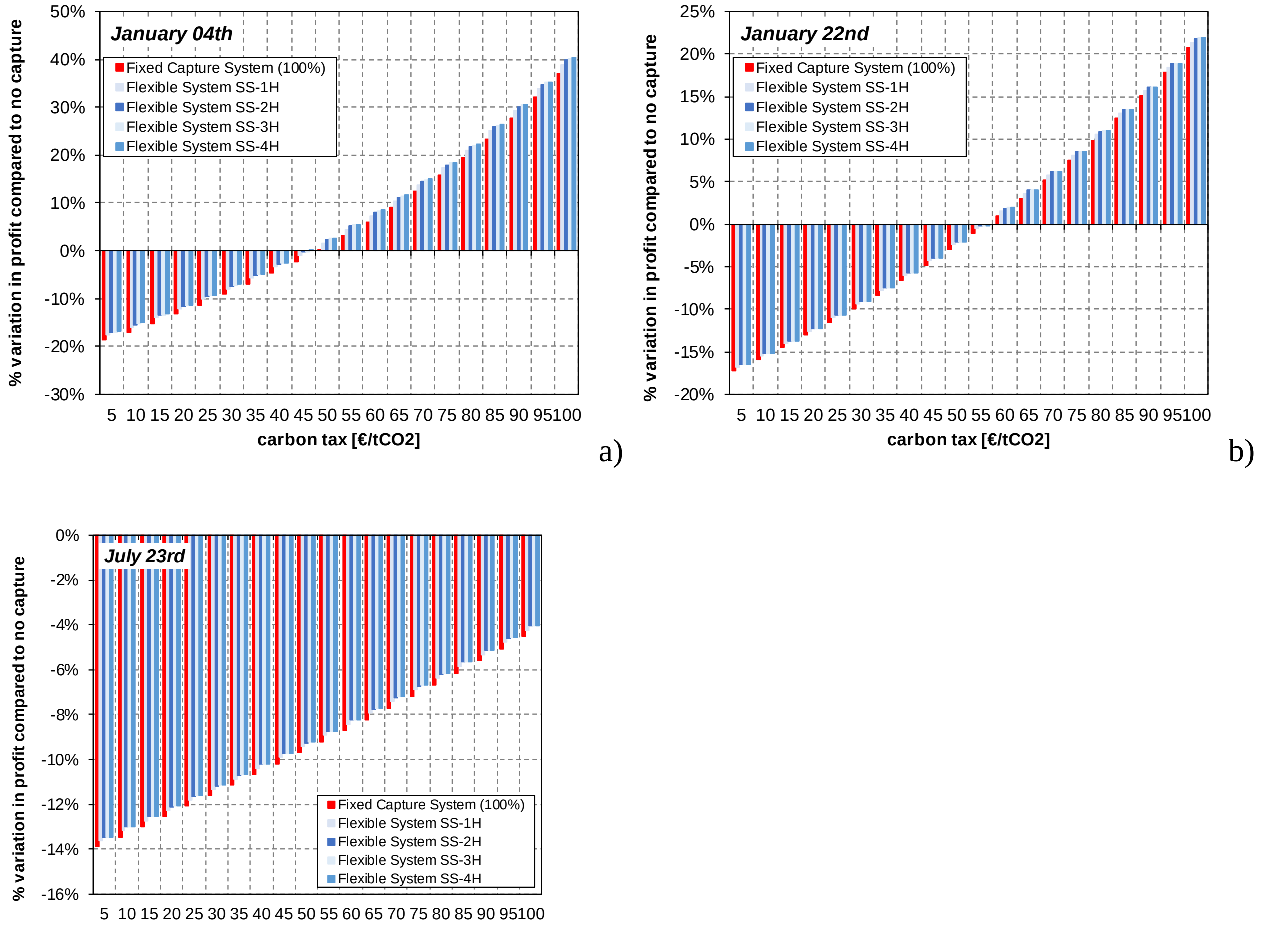
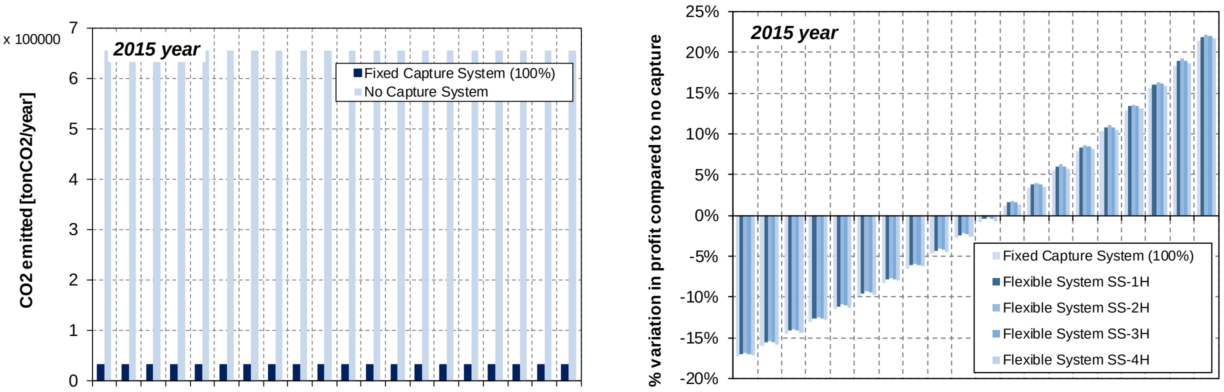


Figure 9. % variation in the value of the profit function compared to no capture for fixed capture and regeneration system (Fixed Capture System (100%)) and for different operation modes (SS-1H = solvent storage for maximum 1 h, SS-2H = solvent storage for maximum 2 h, SS-3H = solvent storage for maximum 3 h, SS-4H = solvent storage for maximum 4 h) for a) January 04th, 2015, b) January 22nd, 2015 and c) July 23rd, 2015 ($C_{b,O\&M}$ not considered).

As shown also in Eq. (2), the carbon tax represents a negative term in the economics of the power plant. Its value may determine whether removing carbon dioxide can be advantageous or not for the plant incomes. When dealing with the configuration of solvent storage, the CO_2 removal is kept constant, the absorption section is always run at 100% load. This favors a low amount of emissions of carbon dioxide, which does not depend on the carbon tax value (Figure 10a)) and which is the only variable in the term $F_{CO_2}C_{CO_2Tax}$.



a) b)

Figure 10. a) yearly emissions of carbon dioxide from the power plant with and without carbon dioxide capture and b) % variation in the value of the profit function compared to no capture for fixed capture and regeneration system (Fixed Capture System (100%)) and for different operation modes (SS-1H = solvent storage for maximum 1 h, SS-2H = solvent storage for maximum 2 h, SS-3H = solvent storage for maximum 3 h, SS-4H = solvent storage for maximum 4 h) for 2015 year.

For the winter period the obtained results show that there is a tradeoff between the amount of money lost due to a lower amount of energy sold to the market and the amount of money paid for emitting carbon dioxide (carbon tax). This occurs both for a configuration with fixed solvent regeneration and for the one with flexible operation by solvent storage. In case of January 04th, there is a change in the sign of the function for a carbon tax in the range 45-50 €/tonCO_2, with the options for storage of three or more hours being advantageous at the lower value of 45 €/tonCO_2, while those of storage of two hours or less being advantageous at 50 €/tonCO_2. A higher storage time provides better performances because of higher flexibility in the operation of regeneration, which may be run at stripper loads lower than the base one for a wider period of time.

Similar results are obtained also for January 22nd, though the value of carbon tax for which removing carbon dioxide becomes advantageous is slightly higher (60 €/tonCO_2). This confirms the influence of the electricity price on the objective function.

When considering the summer period, different results are obtained. In particular, since the price of electricity is very high during the day, no values of carbon tax up to 100 €/tonCO_2 make CO_2 removal advantageous for any considered configuration, and paying the carbon tax for the emission of all the carbon dioxide produced in the plant would give higher revenues than selling lower amounts of electricity.

To deeply understand the economic viability of employing the CO_2 removal section in the NGCC plant, therefore, an additional analysis taking into account the overall year 2015 has been performed. In this way, the influence of the price of electricity for each hour of each day from January to December can be considered. Results, reported in Figure 10b), highlight that globally removing carbon dioxide can be advantageous for carbon tax values higher than 60 €/tonCO_2.

7. Conclusions

Carbon Capture and Storage (CCS) can be applied to power plants with the aim of mitigating CO_2 emissions, which must be reduced to achieve the goals of the Paris Agreement by removing the acid gas from flue gases.

The operation, performed by commonly employed MEA solvent, is characterized by high energy consumptions, which decrease the power output of the plant, and, therefore, the obtained revenues.

In this paper, the Solvent Storage flexible operation has been deeply analyzed to evaluate its performances compared to the configuration with fixed carbon dioxide absorption and regeneration. Moreover, the influence of the carbon tax has been considered. Results show that a carbon tax higher than 55 €/MWh would make CCS economically viable and would help in significantly reducing the amount of emitted CO_2.

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