Comparison of CLR and SS Flexible Systems for Post-Combustion CO₂ Removal in a NGCC Power Plant

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Carbon dioxide 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. To reduce these effects, the Paris Climate Agreement has established greenhouse gas emissions reduction targets, which can be achieved by decarbonizing energy-intensive industries as electricity production. Post-combustion removal of carbon dioxide can be obtained by employing aqueous solutions of amines - in most of the cases MonoEthanolAmine (MEA) is used - which absorb this acid gas from the flue gas streams and are then regenerated and recycled. They are widely employed, though being characterized by several drawbacks, as the high energy requirement at the reboiler of the regeneration section. Therefore, though adding Carbon Capture & Storage (CCS) to a power plant makes the production of electricity more advantageous from an environmental point of view, its operation represents an economic loss for the plant. Possible ways of minimizing the economic disadvantages due to the carbon dioxide removal section include running this section in flexible mode, on the basis of the price of electricity which varies from hour to hour and from day to day. The Capture Level Reduction (CLR) and the Solvent Storage (SS) methods are two possible solutions for flexible operation. This work focuses on the purification of a flue gas stream from a power plant fed with natural gas and performs simulations and techno-economic analyses of the CLR and SS modes, taking into account also the possible application of a carbon tax. By analysing the obtained results a comparison between the two options is carried out, and the best operating mode is determined.

1. Introduction

Anthropogenic carbon dioxide emissions are growing year by year, at an estimated rate of 2.6% per year in the period 2000-2014, much higher than the one of the previous thirty years (1970-2000) (IPCC, 2012). In the last years, moreover, the increase has been much higher, and the value of 35.5 Gton of carbon dioxide emitted per year has been reached (Mac Dowell et al., 2017).

In order to reduce global CO₂ emissions, many international treaties have been developed, from the Kyoto protocol (UN, 1997) to the Paris Agreement (UN, 2015), so that by 2050 up to a cumulative 160 Gton of carbon dioxide must be sequestered (Mac Dowell et al., 2017).

Purification of gases from power plants pre-combustion (Moioli et al., 2017) and post-combustion (Lucquiaud et al., 2009) is one of the most effective ways of reducing carbon dioxide emissions because of the huge gas flowrates and the relevance of this type of plants in the share of anthropogenic emissions. In particular, coal-fired power plants emit more carbon dioxide than Natural Gas Combined Cycle (NGCC) plants, because of the different compositions and characteristics of the fuel fed to the power generation section (Global CCS Institute, 2013). This is one of the main reasons for which in recent years they have started to be converted to natural gas units, contributing to the increase of the global natural gas consumption. Indeed, 22% of the energy used worldwide is produced by natural gas, with about 25% of it being employed for electricity production (IEA, 2018).

Despite lower emissions if compared to coal-fired power plants, also NGCC units need to be integrated with a CO₂ removal section, in order to accomplish the targets of the Paris Agreement of making the global temperature achieve the value of maximum 2°C above the one of the pre-industrial era (UN, 2015).

Chemical absorption by aqueous amines can be employed to this aim for post-combustion CO_2 removal in power plants (Kohl and Nielsen, 1997), with MonoEthanolAmine (MEA) being employed in most of the cases (Alhajaj et al., 2013; Freguia, 2002). However, this process is characterized by high energy requirement, in particular at the reboiler of the regeneration section. Moreover, additional power is needed for compressing the removed carbon dioxide for downstream steps (geological sequestration).

It follows that adding Carbon Capture and Storage (CCS) to a power plant makes the production of electricity more advantageous from an environmental point of view, though its operation represents an economic expense for the plant, with relevant losses of profits. In order to foster the construction of new power plants with integration of the CO_2 removal plant, or the addition of this section to already existing power plants (retrofitting), many countries have implemented carbon taxes, with different values on the basis of national regulations (WBG, 2016).

To offset the economic disadvantages, the carbon dioxide removal section may be run in flexible mode (Chalmers et al., 2009a; Chalmers et al., 2009b), on the basis of the price of electricity, which continuously varies from hour to hour and from day to day (GME, 2017). Several methods have been studied for flexible operation, including the Capture Level Reduction (CLR) and the Solvent Storage (SS) modes.

This work aims at determining the best operating mode between the CLR and the SS options for application to the flue gas stream of a power plant fed with natural gas located in Italy, on the basis of an economic assessment that considers also the introduction of the carbon tax.

2. Flexible operation

The operation in flexible mode allows the steam which is generally employed for the reboiler of the CO_2 removal section to be sent to a low pressure turbine to produce electricity. In addition, the lower amount of CO_2 exiting the top of the regeneration column (when low regeneration is performed) requires lower energy for compression, therefore further increasing the net output of the power plant (Cohen et al., 2012).

Figure 1 and Figure 2 report the scheme of the CO_2 removal plant run in flexible mode, with the modifications with respect to the base configuration highlighted in red.

The work focuses on the purification of the flue gas stream of an advanced NGCC plant with a power output of 630 MW (Moioli and Pellegrini, 2018b; Moioli and Pellegrini, 2019), for removal of 95% of carbon dioxide.

The base plant is composed of three parallel absorption columns and one regeneration column. The flue gas is counter currently contacted with a 30% wt. MEA aqueous solution and exits purified from the top. The rich solvent exiting the bottom of the absorber is sent to regeneration, after heat exchange with the hot lean regenerated solution in a lean-rich heat exchanger for recovery of heat. After regeneration, the lean solvent is cooled and recycled back to the absorption section, where it is split into three streams (with identical flowrate, one third of the total flowrate each one) and fed to the three absorbers. The CO_2 rich stream obtained from the top of the regeneration column, containing the absorbed carbon dioxide, is sent to compression.

The CO_2 Capture Level Reduction mode 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 absorbed totally as in the full capture base case (95% of the one 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, the energy requirement for CO_2 stripping and compression decreases as the CO_2 removal rate decreases. The difference between this configuration and the base one is the presence of bypasses on the rich solvent streams exiting the absorbers (Figure 1). 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).

The Solvent Storage mode allows to maintain a constant CO_2 removal in the absorption section and varies the time of operation for solvent regeneration. In particular, regeneration is run when the energy price or the demand is low (Chalmers and Gibbins, 2007). A lean and a rich solvent storage tanks (Figure 2) for the collection of the rich solution before regeneration and the lean regenerated solvent during times of high electricity demands and/or prices are needed and influences the investment costs of the CO_2 removal plant.
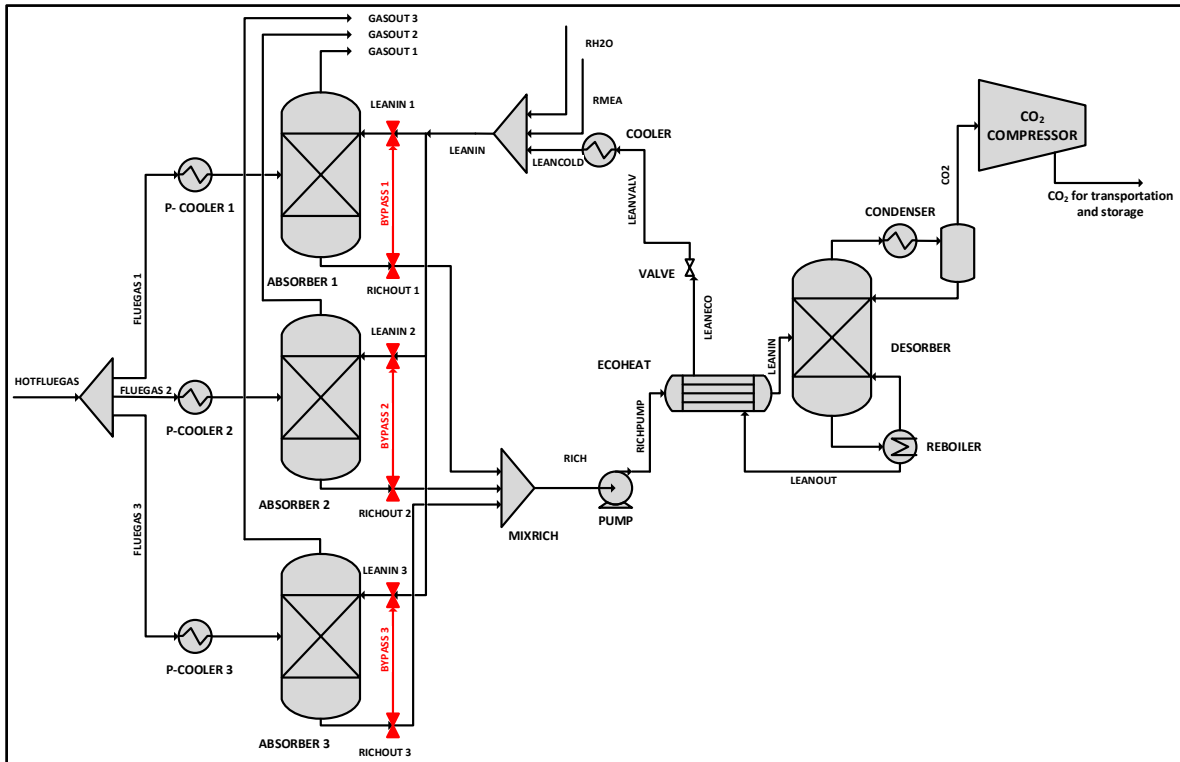
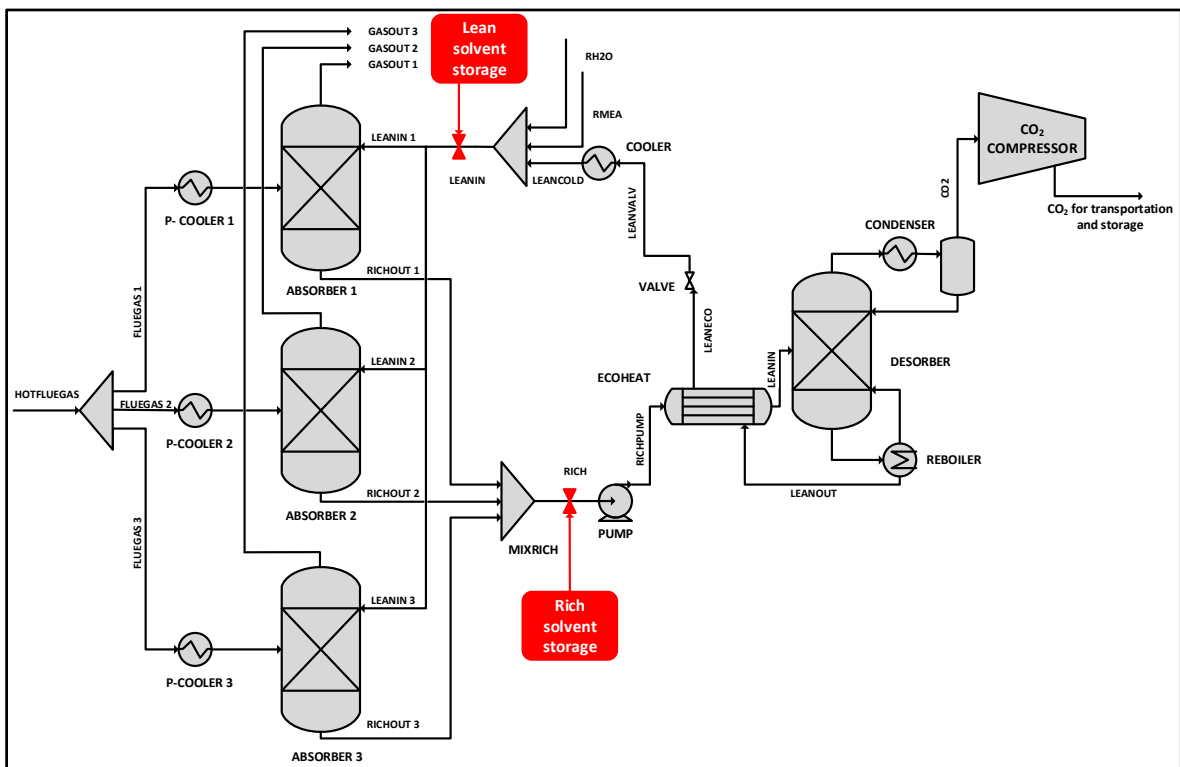Figure 1: Scheme of the Carbon Level Reduction operation.

Figure 2: Scheme of the Solvent Storage operation.

3. Methodology

The simulations of the CO_2 removal plants have been performed by using ASPEN Plus®, properly customized by the GASP group of Politecnico di Milano to best describe the system, which is characterized by equilibrium and kinetic-controlled reactions generating ions, and mass transfer from the vapor phase to the liquid phase (Moioli and Pellegrini, 2015, 2016, 2018a).

The techno-economic analysis has been carried out by employing a software created by the GASP group for the selection of the best operation for each flexible mode on the basis of the maximization of the profit of the overall power generation system.

The objective function takes into account the net power output, the price of energy varying with time from hour to hour (GME, 2017), the carbon tax (CTC, 2017), the cost of fuel for producing power (EIA, 2019) and the operation and maintenance costs of the overall power plant (Fout et al., 2015) including those for CO_2 removal, calculated from Turton et al. (Turton et al., 2012) and Peters and Timmerhaus (Peters and Timmerhaus, 1991).

For the study, data from the electricity demand and market in Italy have been considered and taken from Terna (Terna Group, 2014) and Gestore Mercati Energetici (GME, 2017).

For SS mode, 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 (5.54 h) have been considered as the maximum capacity of the storage system.

Several values of carbon tax from 0 €/tonCO_2 to 100 €/tonCO_2 have been taken into account, with the aim of analyzing its influence on the overall profits of the plant.

4. Results and discussion

Figure 3 and Figure 4 report the results obtained for one day in winter and one day in summer, taken as a reference, considering both CLR and SS modes. For this latter, Figure 3b) and Figure 4b) detail the results for each maximum time of storage of the amine aqueous solution (from 1 h to SS-MAX).

The comparison with 100% fixed capture, indicating the plant running in base case for 95% CO_2 removal, show that an increase in profits can be obtained both operating with CLR and with SS modes.

The CLR mode generally allows to obtain higher profits than the SS-2H mode, for any value of the carbon tax. Considering Figure 3b) and Figure 4b), the profit obtained for all the SS modes is similar, and lower than the one reported in Figure 3a) and Figure 3b), therefore SS-2H mode can be considered representative of all SS modes.

During summer, the profit variation is lower (for CLR mode the maximum profit variation is lower than 20%) in comparison with the winter period (for CLR mode the maximum profit variation is higher than 65%). This is due to the high power request and high price of energy, which makes for CLR bypass being performed for most of the time, therefore high values of carbon taxes to be paid. As for SS, the regeneration during the day, though performed when the price of electricity is lower, reduces the power output to be sold to the market, with influence on the total profit, which results more similar to the one of fixed operation.
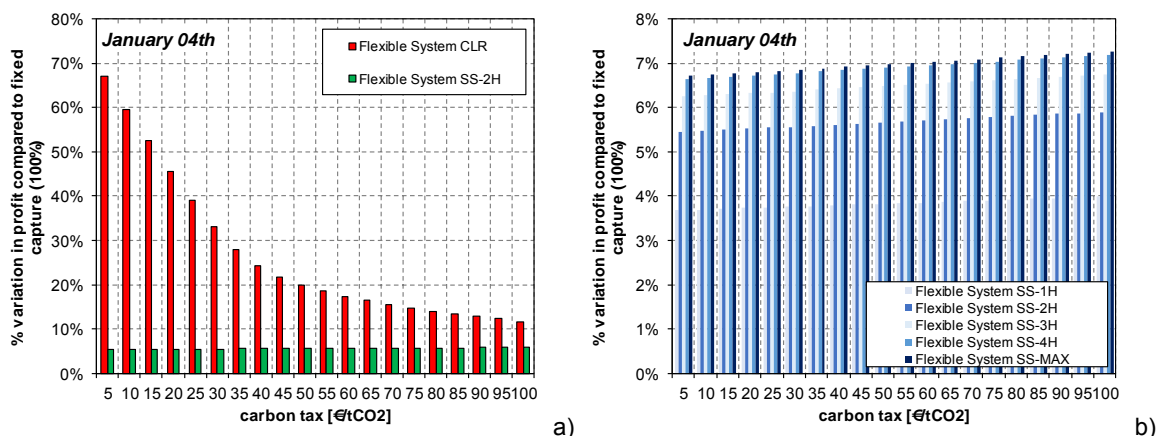

Figure 3: Obtained profits for the optimized a) Capture Level Reduction mode and Solvent Storage operation with storage of maximum 2 h and b) all the Solvent Storage operations for January 04th, 2015.
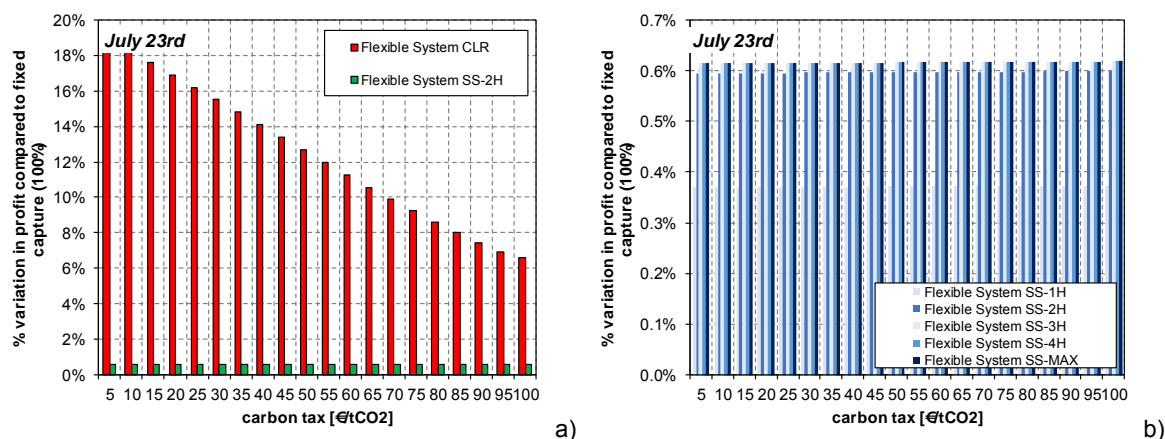
Figure 4: Obtained profits for the optimized a) Capture Level Reduction mode and Solvent Storage operation with storage of maximum 2 h and b) all the Solvent Storage operations for July 23rd, 2015.

The SS mode shows a trend characterized by few increase in profit with respect to fixed mode as the carbon tax value increases, 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 carbon tax to be paid is the same in SS mode and in fixed mode at any time. In addition, the amount of carbon dioxide removed is very high and influences the needed energy for regeneration and compression. Operating with SS-MAX would allow for the highest profits, in particular in winter periods (Figure 3b), though requires higher investment costs (not considered in this paper) for tanks and initial solvent.

In the case of CLR mode a 95% removal of carbon dioxide is never operated, because of the optimization of the system, so, though more carbon dioxide is emitted to the atmosphere, higher energy savings may be obtained, with a resulting higher total profit. However, the operation with CLR mode does not guarantee an overall fixed CO_2 removal, therefore resulting in lower benefits in terms of reduced carbon dioxide emissions.

5. Conclusions

CO_2 emissions must be reduced in order to decrease climate change due to greenhouse gases in the atmosphere. CCS applied to the power production sector is generally considered a possible way to decrease carbon dioxide emissions, by performing purification of flue gases by chemical absorption with aqueous amines.

This paper has focused on the analysis of flexible configurations (Carbon Level Reduction and Solvent Storage modes) to be applied to the post-combustion CO_2 removal section of a Natural Gas Combined Cycle power plant. On the basis of the overall profits of the plant and considering different values of carbon taxes, the CLR mode results more economically advantageous than the SS mode. It is however to be considered that a higher amount of carbon dioxide is globally emitted to the atmosphere.

References

Alhajaj, A., Dowell, N.M., Shah, N., 2013, Multiscale Design and Analysis of CO2 Capture, Transport and Storage Networks, Energy Procedia 37, 2552-2561.

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 CO2 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., 2012, Optimizing post-combustion CO2 capture in response to volatile electricity prices, Int. J. Greenh. Gas Control 8, 180-195.

CTC, 2017. https://www.carbontax.org/

EIA, 2019. https://www.eia.gov/naturalgas/monthly/pdf/table_03.pdf

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.

Freguia, S., 2002, Modeling of CO2 Removal from Flue Gase with Monoethanolamine. The University of Texas, Austin, Texas.

Global CCS Institute, 2013. http://hub.globalccsinstitute.com/insights/capturing-co2-gas-or-coal-power-generation-what%E2%80%99s-difference

GME, 2017. http://www.mercatoelettrico.org/it/

IEA, 2018, Market Report Series - Summary.

IPCC, 2012, Renewable Energy Sources and Climate Change Mitigation. Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Kohl, A.L., Nielsen, R., 1997, Gas Purification, 5th ed. Gulf Publishing Company, Book Division, Houston, Texas, USA.

Lucquiaud, M., Chalmers, H., Gibbins, J., 2009, Capture-ready supercritical coal-fired power plants and flexible post-combustion CO2 capture, Greenhouse Gas Control Technologies 9 1, 1411-1418.

Mac Dowell, N., Fennell, P.S., Shah, N., Maitland, G.C., 2017, The role of CO2 capture and utilization in mitigating climate change, Nature Climate Change 7, 243-249.

Moioli, S., Pellegrini, L.A., 2015, Physical properties of PZ solution used as a solvent for CO2 removal, Chem. Eng. Res. Des. 93, 720-726.

Moioli, S., Pellegrini, L.A., 2016, Modeling the methyldiethanolamine-piperazine scrubbing system for CO2 removal: Thermodynamic analysis, Front. Chem. Sci. Eng. 10, 162-175.

Moioli, S., Pellegrini, L.A., 2018a, Describing physical properties of CO2 unloaded and loaded MDEA+PZ solutions, Chem. Eng. Res. Des. 138, 116-124.

Moioli, S., Pellegrini, L.A., 2018b, Optimal Operation of a CO2 Absorption Plant in a Post-Combustion Unit for Cost Reduction, Chem. Eng. Trans. 69, 151-156.

Moioli, S., Pellegrini, L.A., 2019, Operating the CO2 absorption plant in a post-combustion unit in flexible mode for cost reduction, Chem. Eng. Res. Des. https://doi.org/10.1016/j.cherd.2019.03.027.

Moioli, S., Pellegrini, L.A., Giuffrida, A., 2017, Use of Recycle for H2S Removal by MDEA Scrubbing in IGCC Systems, Chem. Eng. Trans., 1141-1146.

Peters, M.S., Timmerhaus, K.D., 1991, Plant design and economics for chemical engineers. McGraw Hill Book Co., Singapore.

Terna Group, 2014, Power Plants.

Turton, R., Bailie, R.C., Whiting, W.B., Shaeiwitz, J.A., Bhattacharyya, D., 2012, Analysys, Synthesis & Design of Chemical Processes. 4th ed. Prentice Hall International Series in the Physical and Chemical Engineering Sciences, Upper Saddle River, New Jersey, USA.

UN, 1997. http://unfccc.int/2860.php

UN, 2015. http://unfccc.int/paris_agreement/items/9485.php

WBG, 2016, State and Trends of Carbon Pricing 2016 (October), by World Bank. World Bank Group Climate Change, Washington DC, USA.