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Opportunities for applying solvent storage to power plants with post-combustion carbon capture

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ABSTRACT

One way of implementing Carbon Capture and Storage (CCS) on fossil fired power plants is by means of post-combustion capture. Regenerating the solvent and compressing the CO_2 in this process requires a significant amount of energy and therefore increases the cost of the produced electricity, as less electricity can be sold. By implementing solvent storage, this energy penalty can be delayed until moments with a low electricity price (i.e., more electricity could be sold when the electricity price is high and less when the electricity price is low). Investing in solvent storage, however, is only profitable if the profit increase is sufficiently high. This paper presents an analytical optimization framework for solvent storage implemented on a coal-fired power plant in an electricity market with a methodological, two-step electricity price profile (peak and off-peak). This analysis identifies distinct ranges of peak and off-peak price combinations in which solvent storage can lead to an increased profit. Depending on the problem parameters, these price ranges can vary, mostly depending on the emission certificate cost and the investment cost of the solvent storage infrastructure.

1. Introduction

To reduce CO_2 emissions and mitigate climate chance on a longer time frame, Carbon Capture and Storage (CCS) might play an important role (Bennaceur and Gielen, 2010; Electric Power Research Institute, 2011; European Commission, 2011; International Energy Agency, 2008, 2012). Especially in the power sector (on power plants fired by fossil fuels), CCS might become an indispensable technology if stringent carbon reductions are to be pursued (Odenberger and Johnsson, 2010). CCS is a technique that allows CO_2 to be taken out of the combustion cycle and be stored instead of being released in the atmosphere. Since capturing and storing all flue gases would require too much storage capacity and would simply be inefficient, the most difficult part of CCS is to separate the CO_2 from the combustion cycle, so only the CO_2 ends up being stored (International Energy Agency Greenhouse Gas R and D Programme, 2007).

One way of implementing CCS is by applying post-combustion capture. The working principle is schematically illustrated in Fig. 1 (Chalmers and Gibbins, 2007). The flue gases that leave the combustion chamber are blown into the bottom of an absorber column. From the top of the absorber column, a solvent fluid flows downwards, which binds with the CO_2 and takes it along to the bottom of the absorber column. The CO_2 is hereby separated from the rest of the flue gases, which rise through the top of the absorber and are vented into the atmosphere. The solvent, which is now CO_2 rich, then goes through a desorber column, where the bonds between the solvent and the CO_2 are heated (by using steam) so they break again. As a result, the CO_2 becomes gaseous again and rises through the top of the desorber, where it is captured, compressed and stored. The solvent is CO_2 lean again and brought back to the entrance of the absorber column, closing the solvent cycle.

As a solvent, a 30–40% by weight mixture of monoethanolamine (MEA) with water is typically considered (Abu-Zahra et al., 2007; Lawal et al., 2008; Möller et al., 2007). By managing the loading ratios and mass flow of the solvent, capture rates can be controlled. A large fraction of the emitted CO_2 can typically be captured, i.e., a fraction of 90% or more, depending on the process variables (Abu-Zahra et al., 2007; Kather and Linnenberg, 2009). This, however, comes at a cost. Not only does the CCS installation require a significant investment cost, the capture process also requires a large amount of energy. At rated operation point, the power required for the capture process for coal-fired power plants is estimated to be around 20–25% of the output power (Kather and Linnenberg, 2009; MIT, 2007). This required power will further be referred to as the energy penalty.

The breakdown of this energy penalty is considered – following MIT's (2007) Future of Coal study – for the case of an ultra-supercritical coal-fired power plant with net efficiency without CCS

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Nomenclature

Main symbols

AC	CO_2 allowance cost [€/ton CO_2]
CR	CO_2 capture rate [–]
$d(t)$	desorption ratio [–]
$d_{\max}$	maximum desorption ratio [–]
EF	CO_2 emission factor [ton CO_2/MWh_{th}]
ER	fraction of power penalty recovered when venting CO_2 [–]
FC	fuel cost [€/MW_{th}]
$I_{h,1}$	investment cost for CCS part [€/h]
$I_{h,2}$	investment cost for CCS part with solvent storage [€/h]
MC	marginal cost [€/MWh]
$M(t)$	solvent mass flow (with solvent storage) [kg/s]
M_{rated}	solvent mass flow (without solvent storage) [kg/s]
OM_0	operations and maintenance cost for plant without CCS
$OM_{1,2}$	operations and maintenance cost for plant with CCS (types 1 and 2)
P	electrical output [MWh]
p_{op}	peak electricity price [€/MWh]
p_p	off-peak electricity price [€/MWh]
P_{th}	thermal output [MWh_{th}]
T_{op}	duration of off-peak price period [h]
T_p	duration of peak price period [h]
V	solvent storage tank capacity [m^3]
$\dot{V}_{solvent}$	solvent volume flow rate [m^3/s]
x	investment factor [–]
ΔP	power penalty due to CCS [MW]

Subscripts

0	type 0 power plant (no CCS)
1	type 1 power plant (with CCS, no solvent storage)
2	type 2 power plant (with CCS and solvent storage)
p	peak price period
op	off-peak price period
capt	capture mode
vent	venting mode
max	upper threshold
min	lower threshold

of 43.3%. The efficiency reduction due to CCS amounts to 9.2% pts. 5.0% pts of this efficiency reduction are required as heat (steam) to recover the solvent in the desorber, and 3.5% pts of the energy penalty is required as electrical power to compress the CO_2 after leaving the desorber to prepare it for storage (the remaining 0.7% pts remain unassigned). This high efficiency reduction and corresponding energy penalty together with the large investment cost results into CCS being expensive, which might be a hurdle for its future development and possible roll-out.

A first means of flexibility for a power plant with CCS operating in an electricity market is by operating the post-combustion carbon capture in a flexible way (Chalmers et al., 2009). By allowing to shut down the capture plant, both the electricity output and the efficiency would be increased (recovering the main share of the CCS energy penalty). CO_2 emissions would be vented to the atmosphere, so a corresponding CO_2 price would have to be paid.[1] Such flexible operation might increase overall profit of a power plant (and might help for CCS to become profitable). At moments of high prices, the revenue of additional electricity output might outweigh the CO_2 cost. Delarue et al. (2012) discuss the benefits of such a flexible operation, both analytically and by using a simulation model. Cohen et al. (2012) present a profit maximization model for a power plant operating under volatile electricity prices, and demonstrate the profitability of flexible capture. Patiño-Echeverri and Hoppock (2012a) define a certain threshold for electricity price differentials, for reducing the average cost of CO_2 capture. Mac Dowell and Shah (2013) present an optimization study to determine the optimal degree of carbon capture (identifying a cost-optimal rate of 95% capture), also including in their analysis the option of capture bypass. Arce et al. (2012) present a more technical novel control algorithm for the flexible operation of solvent regeneration.

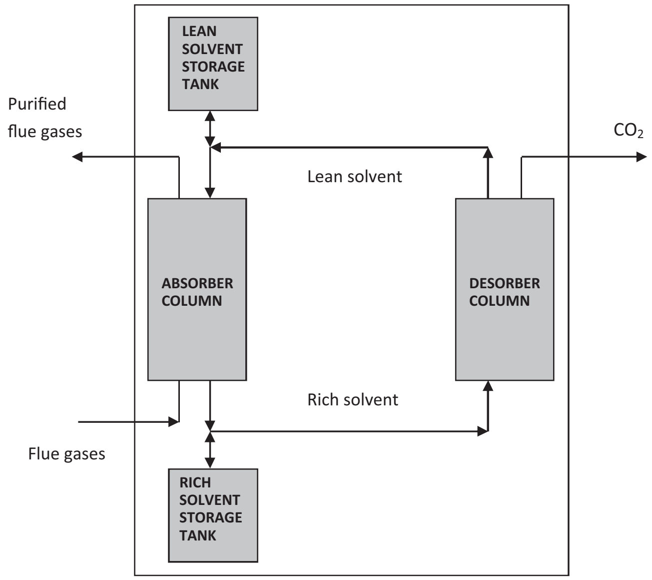

Fig. 1. Schematic representation of the working principle of post-combustion capture, including solvent storage infrastructure. Flue gases enter the absorber column, where they are purified in an absorption process involving a solvent which takes out most of the CO_2. The hereby purified flue gases can be vented. The enriched solvent is brought to a desorber column, where the CO_2 is extracted from the solvent, after which it can be compressed and stored. Solvent storage tanks can be applied to decouple the absorption and desorption process by temporarily storing the solvent.

When focusing on the breakdown of this efficiency reduction, it can be seen that a total of 8.5 out of 9.2% pts (i.e., over 90% of the energy penalty) is not directly related to the capture of CO_2 in the absorber column, but to the regeneration of the solvent (after the CO_2 is bound to it) and consecutive CO_2 compression. If this part of the process energy consumption can be delayed, more electricity can be sold when the electricity price is high and less electricity will be sold when the electricity price is low (i.e., effectively shifting the energy penalty in time), while still continuing capturing CO_2 emissions. By doing so, the plant owner can increase its profit. This will, however, require temporal storage of the solvent until the electricity price is lower, a process which will further on be referred to as solvent storage.

Next to a flexible operation of the capture plant, solvent storage essentially provides additional flexibility and possibly additional profit opportunities. Chalmers et al. (2009) provide a general discussion of the potential benefits and difficulties of solvent storage (amongst other). Haines and Davison (2009) perform a basic economic analysis and conclude that solvent storage could be cost

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[1] A CO_2 price can be set by a fixed CO_2 tax, or by the CO_2 allowance price under a cap and trade system (like the EU Emission Trading Scheme). In this paper, we will in general refer to a CO_2 allowance price, but note that this is perfectly equivalent to a CO_2 tax.