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Cost estimation of heat recovery networks for utilization of industrial excess heat for carbon dioxide absorption

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ABSTRACT

The absorption of CO_2 using solvents (e.g., amines) is considered a state-of-the-art, albeit energy-intensive process for CO_2 capture. While it is generally recognized that the utilization of waste heat has potential to reduce the energy-associated costs for CO_2 capture, the cost of waste heat recovery is seldom quantified. In this work, the cost of heat-collecting steam networks for waste heat recovery for solvent regeneration is estimated. Two types of networks are applied to waste heat recovery from the flue gases of four process industries (cement, silicon, iron & steel, and pulp & paper) via a heat recovery steam generator (HRSG). A novel approach is presented that estimates the capital and operational expenditures for waste heat recovery from process industries. The results show that the overall cost (CAPEX + OPEX) of steam generated from one hot flue gas source is in the range of 1.1–4.1 €/t steam. The cost is sensitive to economic parameters, installation factors, the overall heat transfer coefficient, steam pressure, and to the complexity of the steam network. The cost of steam from an existing natural gas boiler is roughly 5–20-times higher than that of steam generated from recovered waste heat. The CAPEX required to collect the heat is the predominant factor in the cost of steam generation from waste heat. The major contributor to the CAPEX is the heat recovery steam generator, although the length of the steam pipeline (when heat is collected from two sources or over long distances) is also important for the CAPEX.

1. Introduction

Carbon dioxide is emitted in large quantities by industries worldwide. Process industries are significant polluters, as shown in Table 1. CO_2 capture is urgently needed to reduce industrial CO_2 emissions to a level that will meet the United Nations 2 °C goal, according to International Energy Agency (IEA) (IEA, 2016).

Absorption-based separation (post-combustion capture) is considered to be the most mature CO_2 capture technology. To separate the CO_2 from the flue gas stream and regenerate the solvent, considerable amounts of energy in the form of heat (> 120 °C) are required (Figueroa et al., 2008; Wang et al., 2011). The heat demand lies in the range of 2.5–4.0 MJ/kgCO_2 depending on the process design, type of solvent used, and the quality of the CO_2 source. Efforts are being continuously made to reduce the energy demand.

In many industrial processes, waste heat is available as sensible heat in warm flue gases (typically at temperatures in the range of 175°–600 °C). While the temperature of the flue gases is too low to use in the main process, it could be sufficiently high to power the capture process. One attractive option, which could considerably lower the cost of capture, is to utilize this excess heat from the main process to power the CO_2 separation process. Hektor and Berntsson (2007) have studied thermal process integration in pulp mills and concluded that heat integration significantly reduces fuel consumption for CO_2 capture. Hegerland et al. (2006) have proposed a concept for waste heat utilization in which flue gases in the cement industry are used to power the post-combustion carbon capture plant. They assumed that waste heat contributes less than 15% of the total energy, although the cost of waste heat utilization was not provided. The remaining energy demand was proposed to be provided by a coal- or natural gas-fired boiler at a cost of 20–22 €/t steam generated. A techno-economic analysis of an oil refinery with amine-based carbon capture plant has been performed by Andersson et al. (Andersson et al., 2016). In this work, excess heat from the refinery was shown to decrease the specific cost of carbon capture. A report by the IEA Clean Coal Centre (Henderson, 2015) has indicated that heat integration of an amine-based CO_2 scrubbing system with the

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Table 1
Typical CO_2 emissions for different industrial sectors (Leeson et al., 2014).

Industrial Sector	CO_2 emissions (Mt/yr)	Percent of total industrial CO_2 emissions
Refineries	1678	20
Cement	1258	15
Chemicals	1090	13
Iron & Steel	1007	12
Pulp & Paper	252	3
Other sources	3104	37

main power plant, so as to recover energy, is vital for the realization of CO_2 capture in industry, although the report has not provided any information as to the related costs.

In summary, several studies have concluded that there are considerable opportunities for recovering waste heat in the temperature range suitable for solvent regeneration. However, the costs of recovering the waste heat and, thus, the economic potential have seldom been investigated. Johansson et al. (2012) have estimated an overall cost for waste heat utilization for the petrochemical industry, including the capital and other costs related to waste heat recovery. They have shown that excess heat is the most cost-effective alternative, in that it reduces the capture cost to 37–70 €/tCO_2-avoided. In the present study, the discussion of excess heat centers on the overall value of heat recovered from the whole process. There are very few studies of process industries that focused on the individual locations of excess heat-extraction points and investigated the effect on cost of waste heat when this heat is being collected from more than one source.

The aim of this study was to estimate the cost of waste heat recovery from hot flue gases exiting process industries. The investigation includes simulations of heat-collecting steam networks, as well as calculations of both the capital expenditures (CAPEX) and operational expenditures (OPEX) for these heat-collecting networks. The results are compared to heat generation using an existing natural gas-fired boiler.

2. Methodology

Waste heat recovery from four industrial case studies, i.e., Cement, Pulp & Paper, Steel, and Silicon, is investigated. This work proposes two heat-collecting steam networks to collect the heat from the hot flue gases so as to power solvent regeneration in the stripper reboiler. The conceptualization of the heat network focuses on a simple design, such that items of equipment, such as heat pumps, a demineralized water-shifting system or water preheater, are not considered, although they could have important impacts on system cost optimization depending on the market conditions. The two configurations are illustrated in Fig. 1a and b. In the heat-recovery networks, the flue gases are introduced into a heat-recovery steam generator (HRSG). A heat exchanger will be installed in the flow area of the hot flue gas, to recover the waste heat and vaporize the water. Here, it is assumed that all the water is converted into steam. In a scenario in which the water is not completely vaporized and we have two phases after the HRSG, a water separator/steam drum might be added and the collected water could be recycled back to the HRSG. In case some of the steam condenses in the pipeline, steam traps can be used to remove the water from the steam pipeline, thereby ensuring that dry saturated steam enters the reboiler.

A typical boiler or HRSG comprises three main heat-exchange sections, i.e., an economizer (preheats the feed water), an evaporator (converts water into steam), and a superheater (turns saturated steam into superheated steam). In this study, it was assumed that the water is preheated, so an economizer is not included. Since saturated steam is required in the present study, a superheater is not included. Therefore, the only heat exchanger required in this study is the evaporator.

The temperature of the flue gas after heat recovery is case-specific, as it depends on the process and on whether the industrial plant is using this heat for other purposes. The produced steam is introduced into the reboiler of the stripper to cover the energy demand for solvent regeneration. In this work, saturated steam at 3 bar is produced, as the amines are efficiently regenerated at around 120 °C. In Network 1 (Fig. 1a), the condensate from the reboiler is reduced to 1 bar and introduced into a condenser to condensate the remaining steam. The use of atmospheric pressure allows for a low-cost atmospheric storage tank in the setup. A centrifugal pump is installed to increase the pressure of the demineralized water fed to the HRSG, thereby completing the loop. In Network 2 (Fig. 1b), there is no condenser, as all the steam is assumed to condense in the reboiler, and rather than the steam being reduced to 1 bar it is stored in a pressurized tank. This option reduces the energy losses from the system and the amount of pump work required.

To consider industries that have more than one heat source, a network with the multiple collection points of the N1 configuration is investigated. The layout of the network is illustrated in Fig. 2. The results are illustrated through a case study of a cement plant in which heat is collected from two hot flue gases, i.e., String 1 (S1) and String 2 (S2) originating from the pre-calciner. For this case, two separate HRSGs are required, along with the two centrifugal pumps that will feed them demineralized water. There will be a combined condenser for the condensate that is exiting the reboiler. When the heat is being collected from more than one hot flue gas, long steam and water pipelines must be considered. In this scenario, the following four case studies for the Cement case are investigated:

i. **Cement S1N1**–The heat-collecting steam N1 for one hot flue gas source, i.e., String 1. This study assumes water and steam pipelines that are usually short (< 20 m). This is incorporated into the cost estimate when calculating the installation factors.
ii. **Cement S1a-N1**–Heat-collecting steam N1 for one hot flue gas, i.e., String 1 but with the addition of a 125-m-long steam pipeline. Here the cost of the steam pipeline is estimated separately.
iii. **Cement S1&S2a-N1**–Heat-collecting steam network for two hot flue gases, i.e., String 1 and String 2. The distance between the two Strings is 125 m. Here it is assumed that String 1 has a short steam pipeline (< 20 m) and that String 2 has a steam pipeline and water pipeline, each of which is 125 m in length.
iv. **Cement S1&S2b-N1**–Heat-collecting steam network for two hot flue gases, i.e., String 1 and String 2. The distance between the two Strings is 400 m. Here, it is assumed that String 1 has a short steam pipeline (< 20 m) and that String 2 has a steam pipeline and water pipeline, each of which is 400 m in length.

The evaluation of the heat recovery networks is performed in two steps:

1. Simulation and dimensioning of the heat-collecting steam network.
2. Cost estimation of the steam network using a detailed factor estimation method.

The two steps are described in detail below. Typical values for the flow rate and CO_2 concentration in the flue gas for the industries included in the evaluation are presented in Table 2.

2.1. Simulation of the heat-collecting steam network

The Aspen Hysys (ver. 8.6) software was used with the NRTL vapor/liquid equilibrium model to calculate the performance and equipment dimensioning of the steam network. In the model, the stripper reboiler is represented as a heat sink for the system. The reboiler is not described in detail, as the cost of the reboiler is assigned to the capture system rather than to the heat-collecting networks in focus here. The HRSG and the condenser are represented by a shell and tube heat exchanger. The overall heat transfer coefficients of the HRSG and condenser are set at