Journal of CO_2 Utilization 10 (2015) 23–29

Contents lists available at ScienceDirect

Journal of CO_2 Utilization

journal homepage: www.elsevier.com/locate/jcou

Carbon capture and reuse in an industrial district: A technical and economic feasibility study

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ARTICLE INFO

Article history:
Received 5 December 2014
Received in revised form 4 February 2015
Accepted 17 February 2015
Available online 27 March 2015

Keywords:
Carbon capture
Carbon reuse
Industrial symbiosis
Feasibility study

ABSTRACT

In recent years, increasing attention from both industries and research has been focused on carbon capture and, subsequently, storage technologies. These technologies will contribute to companies' strategies for reducing greenhouse gas emissions from fossils fuels. However, less effort has been spent on evaluating another interesting option after carbon capture: carbon utilisation or reuse. A feasibility study regarding an Italian industrial district is discussed: the district is characterised by the nearby locations of a CO_2 producer (i.e. an natural gas combined cycle power plant) and a CO_2 user (i.e. a sugar factory). The annual average CO_2 emission by the power plant is about 1.7 million tonnes. Under current conditions the sugar factory 'produces' CO_2 to use it in the sugar refining process; thus, the idea is to evaluate the feasibility of capturing CO_2 emitted from the power plant and reusing it in the sugar factory process from both a technological and an economic point of view. The results indicated a cost saving of about 42% in the operational costs of the sugar factory due to the introduction of the carbon reuse technology.

1. Introduction

Carbon capture and storage (CCS) technologies are developing rapidly worldwide from pilot to full scale projects, mainly due to their potential contribution to mitigation of carbon dioxide (CO_2) emissions [1–6]. CO_2 is captured at fixed point sources, such as power plants and cement manufacturing facilities, and transported to specific destinations for storage. Different technological options for carbon capture have been available for several years, for example absorption, adsorption, separation by membranes, and cryogenic separation [7,8]. Current options for CO_2 storage mainly include geological storage, ocean storage, and mineralisation. However, the debate about the overall economic and environmental effectiveness of CCS systems is still open and controversial [9]: the critical point in CCS is the storage option [10], rather than the carbon capture technology developments, which have been consolidated.

On the other hand, less attention has been focused on two other options: CO_2 utilisation and reuse. CO_2 utilisation refers to the possibility of using CO_2 for other end uses, such as in building-material production, fuels, and chemicals [11].

There is no single, universally applicable pathway for CO_2 utilisation. In brief, CO_2 can be utilised in three major pathways:

(1) as a storage medium for renewable energy [12];
(2) as a feedstock for various chemicals [11];
(3) as a solvent or working fluid in several processes (e.g. in the food industry).

CO_2 reuse refers to use of the major greenhouse gas captured from industrial plants rather than releasing it (and its warming potential) into the environment [13,14].

The focus of the proposed study is on CO_2 reuse in an industrial district: the basic idea is to apply the concept of industrial symbiosis [15–17] to increase the environmental sustainability of both the whole industrial district and the single companies by reusing CO_2 captured from one plant in another plant where it is required during processes. This strategy, compared to traditional CCS, could be more effective from an economic point of view, as it aims to maximise CO_2 reuse as an industrial resource to make a profit by exploiting it as a primary resource [12,13]. It still has to be captured and extracted from industrial emissions, but, instead of

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http://dx.doi.org/10.1016/j.jcou.2015.02.004

being stored, it will be reused in new chemical, industrial, or biological applications. It has to be noted that CO_2 reuse does not fully replace storage as, depending on the application, it could eventually return to the atmosphere after it has been used. However, from a global perspective, it will contribute to reducing carbon emission levels [18]. The CO_2 reuse also contributes to the generation of economic value, opening up possibilities to develop new technologies, markets, and employment. Moreover, CO_2 reuse could be economically convenient if the additional energy expended to capture the CO_2 is not high [19]; thus, an industrial symbiosis strategy based on reusing CO_2 locally – that is, where it is emitted – could be a very effective solution [16]. The current paper proposes a technological and economic analysis for evaluating the capture of CO_2 and its reuse in an Italian industrial district; a general framework for supporting CO_2 capture and the reuse process is also outlined. Furthermore, the results obtained demonstrate the potential of reusing CO_2 in industrial districts to support new business models and services.

The remainder of the paper is organised as follows: the main features characterising the industrial district under analysis are described in Section 2; next, in Sections 3 and 4, the technological and economic analyses are respectively discussed.

2. The industrial district: main features

The industrial district under analysis is composed of several industrial firms, and the focus of this study is on two major plants: a natural gas combined cycle (NGCC) power plant and a sugar factory. The NGCC power plant has a total capacity of 770 MW, allowing an annual electricity production of about 4 billion kWh, and an annual steam production of about 20,000 tonnes for industrial use. Focusing only on carbon emissions, the annual average CO_2 emission level is about 1.7 million tonnes, estimated for a productivity level of 8000 h/year. The sugar factory is located near the power plant; each location is outlined in Fig. 1.

The white sugar is mainly produced from sugar beets; the plant's annual production capacity is about 750,000 tonnes of sugar beet, thus producing about 84,300 tonnes of white sugar.

Processes in the sugar factory start after the raw material washing process. Sugar beets are reduced into cossettes by a

Fig. 1. Location of the two plants under analysis (red: the sugar factory; green: the power plant). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mechanical shredding process in order to offer a maximum surface area for the next extraction process. Following that, the sugar juice is extracted from the sugar beets: cossettes are lifted from the bottom to the top of the diffuser as hot water washes over them, absorbing the sugar. After the juice extraction, a carbonation process is carried out to remove impurities from the raw juice; the output is the so-called thin juice. The carbonation process requires lime milk and CO_2; during the process CO_2 reacts with lime, thus producing calcium carbonate (limestone). Lime milk and CO_2 are produced in vertical and rotary kilns fired by natural gas, where the limestone dissociation is obtained by combustion at high temperature.

Next, a refining process is carried out to transform the thin juice into thick juice; the product is now characterised by a high (i.e. about 70%) sugar concentration. In order to produce sugar in a crystalline form, water evaporation is required: the crystallisation process is developed at a reduced temperature and pressure in vacuum pans. The output is defined as 'massecuite', which is a mix of sugar crystals and juice. Finally, clarification and filtration produce white sugar. The process is summarised in Fig. 2.

The process in which carbon reuse is evaluated is the carbonation process, in which CO_2 is a process input. The idea is to capture CO_2 emitted from the power plant for reuse in the carbonation process in the sugar factory, as depicted in Fig. 3.

Thus, the vertical kiln for producing CO_2 and lime milk will be definitively eliminated from the sugar refining process as the lime milk will be purchased directly from an external supplier. Furthermore, a carbon capture process has to be added in the industrial district with the aim of capturing emission from the NGCC power plant and transporting it to the sugar factory. Furthermore, the insertion of a carbon capture process will lead to determine a negative impact on the power generation efficiency; these values are strictly connected to the technology applied for capturing CO_2. Thus, a feasibility study based on evaluating technology options for capturing CO_2 is proposed in the next section; an economic analysis is also discussed with the aim of supporting both firms in evaluating the proposed solution.

3. The technological analysis

The technological assessment was carried out in different phases. The first analysis concerns the phase in which the capture technology is applied (before or after the combustion process). CO_2 capture could be developed in fossil fuel power plants following two alternative routes [20]: before and after the combustion process. The first type refers to removing CO_2 from fossil fuels before combustion is completed. Two main methods are currently applied [21,22]: pre-combustion by a decarbonisation process and denitrogenation by an oxy-combustion process (often called oxy-combustion). The first one is called a *pre-combustion capture process*: the fossil fuel and steam are converted into synthesis gas (or syngas) in a traditional steam reformer; the most common configuration involves gasification with air or oxygen. Syngas contains carbon monoxide (CO) and hydrogen gas; subsequently, the CO reacts with steam to form CO_2. Typical applications of the pre-combustion capture process are in integrated gasification combined cycle plants [23–25]. The *oxy-combustion capture process* significantly modifies how the combustion process is conducted: it uses oxygen instead of air, thus eliminating nitrogen from the oxidant gas stream and producing a CO_2-enriched flue gas. This flue gas is ready for sequestration after water has been condensed and other impurities have been separated out. Its main limitation is due to the stringent requirement for nearly pure oxygen – rather than air – for the fuel combustion: this requirement provides positive impacts, as the final product is nearly pure CO_2, but also negative ones, due to the high capital cost of producing oxygen [26].