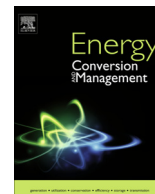




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# Carbon capture and utilization for sodium bicarbonate production assisted by solar thermal power

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## ABSTRACT

In this paper, a novel carbon capture and utilization process is proposed. It is based on using a fraction of the captured carbon dioxide to produce sodium bicarbonate, a widely used product in the chemical and food industries. The process couples the Dry Carbonate process for carbon dioxide capture with sodium bicarbonate production. Raw material is trona or sodium sesquicarbonate dehydrate, which is a relatively abundant mineral composed by approximately 46% sodium carbonate and 35% sodium bicarbonate by weight. In the process, trona is firstly converted into sodium carbonate in a fluidized bed reactor operated at 180–200 °C and 1 bar. Heat required in the fluidized bed reactor for decomposing trona can be supplied by renewable sources such as low/medium temperature solar energy or biomass. A fraction of the sodium carbonate generated is recirculated for carbon dioxide capture by means of the dry carbonate process. The rest is converted to sodium bicarbonate in a carbonating tower through the reaction with carbon dioxide and water. After separation of sodium bicarbonate and other salts from water, the sodium bicarbonate produced is suitable for direct sale. The use of renewable sources for supplying the energy required at the sorbent regenerator and for trona decomposition yields a near-zero carbon dioxide emissions global system. As case of study, carbon dioxide capture coupled to sodium bicarbonate production has been analysed for a 15 MW<sub>el</sub> coal fired power plant. Heat required in the carbon capture process penalizes the global system efficiency by a 10.2%, which is reduced just to the electricity parasitic consumption for solids transport and carbon dioxide compression (~3%) if renewable energy sources are integrated. From an economic perspective, the penalty in electricity consumption is fully compensated by the new by-product sales. Taking into account the reduction of electricity sales and current prices of trona and sodium bicarbonate a return of investment is obtained in the range between 3 and 8.7 years with an internal rate of return over 12%. These values improve the current forecast of any other carbon capture and storage process up to date, which suggests a high interest of the proposed conceptual integration specially for regions where trona is widely available.

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## 1. Introduction

A complete replacement of fossil fuels by renewable energies is not feasible in the short-term. Thus, fossil fuel power plants should be urgently retrofitted with CO<sub>2</sub> capture and sequestration (CCS) processes as a necessary measure to limit global warming below 2 °C [1]. CCS would allow continuing the use of fossil fuel until a deeper penetration of renewable energy sources into the grid is attained in an orderly fashion. CO<sub>2</sub> capture and utilization (CCU) for commercial purposes would help mitigating capture costs that mainly hinder the commercial deployment of state of the art CO<sub>2</sub> capture technologies. Current anthropogenic CO<sub>2</sub> emissions

(around 35 Gt/y) largely exceed the amount of CO<sub>2</sub> used in chemical processes (~200 Mt/y). However, promoting CO<sub>2</sub> utilization routes for the production of valuable chemicals could be a starting point to promote the deployment of CO<sub>2</sub> capture technologies [2]. According to International Energy Agency (IEA) projections, the CCS share of cumulative emissions reduction to achieve the 2 °C target would require about 3500 large-scale CCS projects in operation by 2050. Only about 15 large-scale CCS commercial projects are in operation to this date of which Boundary Dam in Canada is the only coal fired power plant applying CCS in the power sector. Yet, it is estimated that abandoning CCS in the power sector would increase the investment required over 40% in the 2 °C scenario [3]. Moreover, post-combustion capture technologies have the greatest potential for reduction of CO<sub>2</sub> emissions in the short term because

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## Nomenclature

### Components

CARBONATING TOWER CO<sub>2</sub> capture and NaHCO<sub>3</sub> production reactor  
 CARBONATOR CO<sub>2</sub> capture reactor  
 COAL FIRED PLANT coal fired plant for electricity production  
 COMP1 compressor CO<sub>2</sub> (1–10 bar)  
 COMP2 compressor CO<sub>2</sub> (10–25 bar)  
 COMP3 compressor CO<sub>2</sub> (25–75 bar)  
 COOL CO<sub>2</sub> (20 °C) intercooler  
 FLUIDIZED BED fluidized bed reactor  
 HEATEX1 H<sub>2</sub>O-flue gas heat exchanger  
 HEATEXCH NaHCO<sub>3</sub>-Na<sub>2</sub>CO<sub>3</sub> Heat exchanger  
 HEATEXT Trona - Na<sub>2</sub>CO<sub>3</sub> heat exchanger  
 HEATEXW H<sub>2</sub>O - steam + CO<sub>2</sub> heat exchanger  
 INTERC1 CO<sub>2</sub> (20 °C) intercooler  
 INTERC2 CO<sub>2</sub> (20 °C) intercooler  
 INTERC3 CO<sub>2</sub> (20 °C) intercooler  
 IP/LP intermediate pressure/low pressure  
 PTC parabolic trough collector technology  
 REGENERATOR sorbent regenerator  
 SEPA1 solid-gas separator  
 SEPA2 solid-gas separator

### Streams

CARBOUT final product from carbonator  
 CO2 CO<sub>2</sub> recovered from the system

CO2 IN CO<sub>2</sub> entering the system  
 CO2 TO STORAGE CO<sub>2</sub> to the storage system (20 °C, 75 bar)  
 CO2 + STEAM CO<sub>2</sub> and steam (220 °C)  
 CO2 + WATER CO<sub>2</sub> and water(95 °C)  
 CRUSHED TRONA crushed trona  
 FGPLANT flue gas exits the coal fired plant  
 FLUE flue gas exits the carbonator  
 FLUID OUT chemical products exits the fluidized bed reactor  
 HOT STEAM super heated steam (205 °C)  
 HOT TRONA hot trona (125 °C) entering the fluidized bed reactor  
 MAKE UP sorbent MAKE up  
 NA2CO3 COLD (Fig. 5) regenerated Na<sub>2</sub>CO<sub>3</sub> (80 °C)  
 NA2CO3 COLD (Fig. 6) cooled Na<sub>2</sub>CO<sub>3</sub> (40 °C)  
 NA2CO3 HOT (Fig. 5) regenerated Na<sub>2</sub>CO<sub>3</sub> (200 °C)  
 NA2CO3 HOT (Fig. 6) hot Na<sub>2</sub>CO<sub>3</sub> (220 °C)  
 NA2CO3 IN chemical products entering the NaHCO<sub>3</sub> production reactor  
 NAHCO3 NaHCO<sub>3</sub> produced by the system  
 NAHCO3 COLD solids exits the carbonator (60 °C)  
 NAHCO3 HOT solids entering the regenerator(140 °C)  
 WATER IN (Fig. 5) water CO<sub>2</sub> capture reactor  
 WATER IN (Fig. 6) cold water (35 °C)  
 WATER OUT process water

they can be retrofitted to existing fossil fuel power plants and are also applicable to other industrial processes.

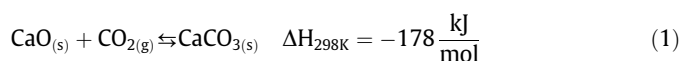
Up to date the only post-combustion capture technology commercially available at the necessarily large-scale of coal fired power plants is based on chemical absorption by amines dissolved in water. In this post-combustion capture system, the exhaust gases stream from the power plant is passed through an absorber column where it comes into contact with the liquid amine flowing downwards, which allows CO<sub>2</sub> to be chemically absorbed by the amine. The CO<sub>2</sub> rich amine solvent is then pumped to a regenerator, where heat is supplied to reverse the chemical reaction and release relatively pure CO<sub>2</sub> for its compression, transport and storage while the CO<sub>2</sub> lean liquid amine is pumped back into the absorber to be reused [4]. Although temperatures for CO<sub>2</sub> desorption are not high (~130 °C) sorbent regeneration in this process requires a relatively high amount of energy to heat the large volume of water where amines are dissolved. Thus, the energy required per ton of CO<sub>2</sub> captured is about 3.3 GJ/ton<sub>CO2</sub> for an advanced monoethanolamines (MEA) system whereas 3.9 GJ/ton<sub>CO2</sub> are required for a typical aqueous MEA system [5]. On the other hand, post-combustion capture by MEA suffers from other serious issues related to toxicity, corrosion and degradation [6]. Furthermore, amines have a relatively high cost (>1000 €/ton), which is a major problem taking into account the large scale of commercial CCS applications [7].

Thus, there is a need to develop novel post-combustion capture processes using cheap, widely available and non-toxic materials at reduced cost and energy penalty. In this line, novel amine-based solid sorbents based on direct steam stripping desorption have shown an improved performance [8]. In Ref. [9] an organic solvent was added to a CO<sub>2</sub> rich, aqueous ammonia/CO<sub>2</sub> solution under room temperature and pressure conditions. The sorbent was regenerated by using low-temperature heat, with a reduced thermal energy requirement. In Ref. [10] novel absorbents were studied using both single and mixed amine-based absorbents. Ref.

[11] presents a review about the impact of uncertainty in the sorbent thermo-physical properties on the design and operation of components and processes involved in CO<sub>2</sub> capture.

CO<sub>2</sub> capture processes using dry solid sorbents capable of capturing CO<sub>2</sub> from flue gas streams by physical adsorption show potential advantages compared with conventional CO<sub>2</sub> capture systems using aqueous amine solvents [12]. Thus, a variety of promising adsorbents such as activated carbonaceous materials, microporous/mesoporous silica or zeolites, carbonates, and polymeric resins have been proposed in the recent literature [12]. As a common feature, these solid sorbents require very small amounts of heat for regeneration although their capture capacity is generally low. Ref. [13] proposes the use of power plant's waste heat for CO<sub>2</sub> capture by nanomaterials properly designed to overcome the competitive adsorption of CO<sub>2</sub> and H<sub>2</sub>O.

The Calcium-Looping process is a promising 2nd generation post-combustion process validated at the pilot level (1–2 MW<sub>th</sub>) that uses Calcium Oxide (CaO) derived from cheap (~10 €/ton) and abundant natural limestone to capture CO<sub>2</sub> from flue gas. The process is based on the reversible carbonation/calcination chemical reaction at high temperatures [14]:



Carbonation proceeds at a satisfactory fast rate at temperatures in the range 625–680 °C while the reverse calcination reaction should be carried out at 900–950 °C under high CO<sub>2</sub> partial pressure [14]. The dry sorbent is repeatedly cycled between two reactors. In one reactor (carbonator) carbonation of CaO particles serves to capture CO<sub>2</sub> from the flue gas. The carbonated particles are then circulated into another reactor (calciner) where sorbent regeneration takes place by calcination. To close the cycle, the regenerated CaO particles are returned back into the carbonator, leaving a concentrated stream of CO<sub>2</sub> in the calciner ready for compression, transport and sequestration. However, a main drawback

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