ARTICLE IN PRESS

Renewable and Sustainable Energy Reviews xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Dry carbonate process for CO_2 capture and storage: Integration with solar thermal power

D. Bonaventura[a,b], R. Chacartegui[b,*], J.M. Valverde[c], J.A. Becerra[b], C. Ortiz[c], J. Lizana[d]

[a] Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy
[b] Departamento de Ingeniería Energética, Universidad de Sevilla, Camino de los Descubrimientos s/n, 41092 Seville, Spain
[c] Facultad de Física, Universidad de Sevilla, Avda. Reina Mercedes s/n, 41012 Seville, Spain
[d] Departamento de Construcciones Arquitectónicas, Universidad de Sevilla, Avda. Reina Mercedes 2, 41012 Seville, Spain

ARTICLE INFO

Keywords:
Carbon capture
Post-combustion carbon capture
Coal fired power plant
Dry carbonate process
CCS economy
Solar thermal power

ABSTRACT

Capture and sequestration of CO_2 released by conventional fossil fuel combustion is an urgent need to mitigate global warming. In this work, main CO_2 capture and sequestration (CCS) systems are reviewed, with the focus on their integration with renewables in order to achieve power plants with nearly zero CO_2 emissions. Among these technologies under development, the Dry Carbonate Process shows several advantages. This manuscript analyses the integration of a CO_2 sorption-desorption cycle based on $Na_2CO_3/NaHCO_3$ into a coal fired power plant (CFPP) for CO_2 capture with solar support for sorbent regeneration. The Dry Carbonate Process relies on the use of a dry regenerable sorbent such as sodium carbonate (Na_2CO_3) to remove CO_2 from flue gases. Na_2CO_3 is converted to sodium bicarbonate ($NaHCO_3$) through reaction with CO_2 and water steam. Na_2CO_3 is regenerated when $NaHCO_3$ is heated, which yields a gas stream mostly containing CO_2 and H_2O. Condensation of H_2O produces a pure CO_2 stream suitable for its subsequent use or compression and sequestration. In this paper, the application of the Dry Carbonate CO_2 capture process in a coal-based power plant is studied with the goal of optimizing CO_2 capture efficiency, heat and power requirements. Integration of this CO_2 capture process requires an additional heat supply which would reduce the global power plant efficiency by around 9–10%. Dry Carbonate Process has the advantage compared with other CCS technologies that requires a relatively low temperature for sorbent regeneration (< 200 °C). It allows an effective integration of medium temperature solar thermal power to assist $NaHCO_3$ decarbonation. This integration reduces the global system efficiency drop to the consumption associated with mechanical parasitic consumption, resulting in a fossil fuel energy penalty of 3–4% (including CO_2 compression). The paper shows the viability of the concept through economic analyses under different scenarios. The results suggest the interest of advancing in this Solar-CCS integrated concept, which shows favourable outputs compared to other CCS technologies.

1. Introduction

There is a worldwide interest in finding competitive solutions for capturing and sequestering the carbon dioxide (CO_2) released from fossil fuel combustion processes to mitigate global warming. In the 2015 Paris Climate Conference (COP21), a universal agreement signed by the consensus of 195 countries was reached, which has been ratified in 2016, to drastically reduce CO_2 emissions in order to keep global warming below 2 °C from preindustrial levels [1]. To this end future coal-fired power plants (CFPPs) must be near to CO_2 emissions free. Currently, 76.5% of the electricity generation in the world is produced by non-renewable sources [2]. The main R & D challenge for the viability of CFPPs and other fossil fuel based facilities is to capture CO_2 by means of feasible and affordable technologies while, at the same time, penalties on power production and efficiency are minimized.

Carbon capture and storage (CCS) technologies can be classified into three main groups: pre-combustion, post-combustion and oxy-fuel combustion processes [3]. Despite post-combustion capture (PCC) processes are being widely investigated in the last years, Boundary Dam (100MWe) in Canada is currently the only commercial CFPP that applies CCS by using a chemical absorption process based on mono-ethanolamine (MEA). In amine-based systems the CO_2 loaded solvent is separated from the rest of the exhaust gas and heated, which yields relatively pure CO_2 ready for compression and sequestration. After regeneration, the solvent is cooled to be reused [4]. A main issue of systems based on amine absorption is the large amount of heat

* Corresponding author.
E-mail address: ricardoch@us.es (R. Chacartegui).

http://dx.doi.org/10.1016/j.rser.2017.06.061
Received 22 December 2016; Received in revised form 15 June 2017; Accepted 18 June 2017

Nomenclature

AC	avoiding CO_2 cost
ASU	air separation unit
BAC	biomass annual cost
BFB	bubbling fluidized bed
CaL	calcium-looping process
CARB	carbonation
CCS	carbon capture and storage
CFB	circulating fluidized bed
CFPP:	coal-fired power plant
COE	cost of electricity
COECCS	cost of electricity associated to CCS system
c_{CO2}	carbon tax
COP21	2015 Paris Climate Conference
CPU	CO2 purification unit
CSP	concentrated solar power
DCP	dry carbonate process
DECARB:	decarbonation
ECCS	emission ratio with dry carbonate process integrated
ECO2 AVOIDED	avoided cost due to the avoided emission of CO2,
EDRYCARBONATE	carbon capture system installation cost
ENET, GAIN, year	annual benefit due to avoided emissions.
EO&M	operation and maintenance cost
EINCR	revenues due to electricity incremented cost
Eref	reference plant emission ratio
ESOLAR	solar plant installation cost
ETOT, REV	total annual revenues
ETOT	total investment cost
FB	fluidized bed
FC	fuel cost
FCF	fixed charge factor
FGD	flue gas desulfurization
FGPLAN4	cooled flue gas
FGPLANT	CO_2 input flow to the carbonator
GHG	greenhouse gases
IPCC	Intergovernmental Panel on Climate Change
IRR	internal rate of return (%)
$m_{CO2,\ FGPLANT}$	CO_2 mass flows of flue gas exits the CFPP
$m_{CO2,\ CARB.OUT}$	CO_2 mass flows of flue gas exits the carbonator
MEA	monoethanolamine solvent
NGCC	natural gas combined cycles
NPV	net present value
O&M	operation and maintenance
PCC	post-combustion capture
$P_{NET,\ year}$	total electric energy per year produced by the plant.
Q_{CFPP}	CFPP thermal power consumptions
Q_{DC}	dry carbonate thermal power consumption
SE-SMR	sorption-enhanced steam methane reforming
SMR	steam methane reforming
SPB	simple payback
SPECCA	specific energy consumption for CO_2 avoided
TCR	capital cost
$ton_{CO2,\ ref}$	reference plant CO_2 emissions
$ton_{CO2,\ CCS}$	CO_2 emissions with the dry carbonate process integrated
VOM	variable cost
W_{CFPP}	CFPP net power production
W_{COMP}	electric consumption for CO_2 compression
$W_{cons,\ DC}$	dry carbonate electric power consumption
W_{solid}	electric consumption for solids conveying
WGS	water gas shift
WHATHOT	water inlet stream
YR	yearly revenues
ε_{ABS}	absorption efficiency
η_{plant}	plant efficiency
η_{CCS}	plant efficiency with the dry carbonate process integrated

required to regenerate the solvent. This heat, which is usually obtained from the steam cycle, penalizes significantly the power plant efficiency. Moreover, amine-based systems have serious problems related to toxicity and corrosion [5]. In addition, additional power is required to compress the captured CO_2 for transporting it through the pipeline network to the storage site.

Among the new generation of CCS technologies under R & D the Dry Carbonate Process stands as one of the most interesting options. This process uses Na_2CO_3 solid particles as dry sorbent to separate CO_2 from other flue gases through the gas-solid carbonation reaction. An important advantage of this approach is that sorption can occur at relatively low temperature (below 100 °C) to achieve a high capture capacity whereas regeneration is also carried out at relatively low temperatures (around 200 °C). Such temperatures do not cause significant degradation of the sorbent besides of not requiring high amounts of energy supply [6]. Other advantages of the Dry Carbonate Process are the low cost of the sorbent as well as the high CO_2 sorption capacity [7]. Due to the high interest attracted by this technology, CO_2 capture pilot plants have been integrated in CFPP in USA and Korea [8]. Recent studies have analyzed also its potential integration with the production of chemical products [9].

In this paper, a novel integration of the Dry Carbonate Process for CO_2 capture with solar thermal power is analyzed. The relative low temperature in the regeneration reactor allows for an effective integra-

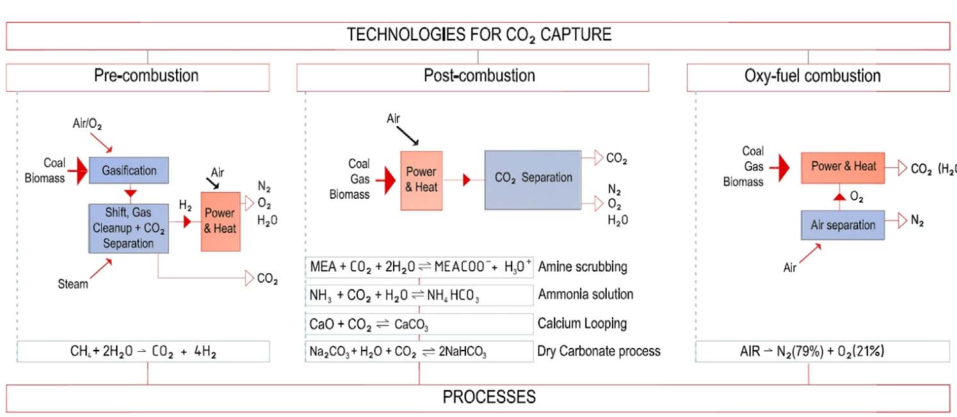

Fig. 1. Overview of technologies for CO_2 capture.