Applied Energy 111 (2013) 175–185

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Potential for solar-assisted post-combustion carbon capture in Australia

Abdul Qadir [a], Marwan Mokhtar [b], Rajab Khalilpour [a], Dia Milani [a], Anthony Vassallo [a], Matteo Chiesa [b], Ali Abbas [a,*]

[a] School of Chemical and Biomolecular Engineering, The University of Sydney, Sydney, Australia
[b] Laboratory for Energy and Nanosciences (LENS), Masdar Institute of Science and Technology, Abu Dhabi, United Arab Emirates

HIGHLIGHTS

- We assess techno-economics of solar-assisted PCC (SPCC) for Australian context.
- A suite of solar thermal technologies is investigated with/without heat integration.
- Evacuated tube collectors perform best for SPCC system with heat integration.
- Parabolic trough collectors perform best for SPCC system without heat integration scenario.
- Energy certificates proposed for extra electricity produced with solar thermal collectors.

ARTICLE INFO

Article history:
Received 15 November 2012
Received in revised form 30 March 2013
Accepted 26 April 2013
Available online 25 May 2013

Keywords:
Solar thermal
Energy
Carbon capture
Power plant
Heat integration
Techno-economics

ABSTRACT

A techno-economic analysis has been performed for a coal-fired power plant retrofitted with Solvent-based Post-combustion Carbon Capture (PCC) technology which is partially supplied with thermal energy by solar thermal collectors. The plant is compared with a generic PCC plant where all the thermal energy is provided by steam bled from the steam cycle. The individual merits of a suite of solar collector technologies which includes Flat Plate Collectors (FPCs), Compound Parabolic Collectors (CPCs), Linear Fresnel Collectors (LFCs), Evacuated Tube Collectors (ETCs) and Parabolic Trough Collectors (PTCs) to supply thermal energy for the PCC plant have been studied. The plant has been simulated for three different locations in Australia: Sydney, Townsville and Melbourne. The overall system consists of three subsystems: power plant, PCC plant and solar collector field. A base case scenario is studied in which there is no heat integration between the three subsystems and is compared to a system with heat integration. Additionally incentives such as Renewable Energy Certificates (RECs), carbon tax/credits and government subsidies have been added to the economic model and a sensitivity analysis performed for each scenario of incentives for all five solar collector technologies at the three locations. The ETC case performs best amongst solar collectors when the three subsystems have heat integration while PTCs perform best in the case with no heat integration. The best location for the solar-assisted PCC (SPCC) plant is Townsville. It was found that the addition of the solar field reduces the carbon tax in order to make carbon capture and storage viable in comparison with a conventional non-capturing coal fired plant.

1. Introduction

Global warming and climate change are great challenges facing humanity today and are perceived to have caused much destruction of life and property [1]. The single largest driver of global warming is attributed to the increasing concentration of carbon dioxide in the atmosphere [2]. In order to mitigate global warming, immediate measures need to be taken to stop the escalation of carbon dioxide in the Earth's atmosphere and bring the CO_2 concentration levels down to 350 ppm (ppm) [3] from the current level of 396 ppm [4]. The Kyoto Protocol was introduced to bind signatory nations to reduce carbon dioxide emissions to their assigned levels [5], and to provide a legal structure to promote reductions in anthropogenic GHG emissions [6]. In order to reduce carbon dioxide emissions, alternative energy sources must be developed. While alternative sources of energy are being developed and deployed, the rate of deployment is slow and carbon dioxide levels in the atmosphere continue to rise. In some jurisdictions, such as Australia, governments have sought to encourage low emissions technology through the introduction of a price on carbon dioxide emissions. The Australian Emissions Trading Scheme (ETS) has commenced operation since July 2012. The Clean Energy Regulator in Australia has fixed the carbon price for the first 3 years of operation. The carbon price in the first year 2012–2013 will be \$23/tonne while the price in the following 2 years will be \$24.15/

* Corresponding author. Tel.: +61 2 9351 3002; fax: +61 2 9351 2854.
E-mail address: ali.abbas@sydney.edu.au (A. Abbas).

0306-2619/$ - see front matter
http://dx.doi.org/10.1016/j.apenergy.2013.04.079

Nomenclature

AEMO	Australian Energy Market Operator
CPC	Compound Parabolic Collector
CR	Capture Ratio
DNI	Direct Normal Irradiation
ETC	Evacuated Tube Collector
FLH	Full Load Hour
FPC	Flat Plate Collector
GHI	Global Horizontal Irradiation
HEN	Heat Exchanger Network
IMO	Independent Market Operator
LFC	Linear Fresnel Collector
LGC	Large-scale Generation Certificate
MEA	Monoethanolamine
$MW_{e/th}$	Mega Watt (electric/thermal)
PCC	Post-combustion Carbon Capture
PCM	Phase Change Material
PTC	Parabolic Trough Collector
REC	Renewable Energy Certificate
REDP	Renewable Energy Deployment Program
SF	Solar load Fraction
SPCC	Solar-assisted Post-combustion Carbon Capture
STC	Small-scale Technology Certificate
TS	Thermal Storage

tonne and $25.4/tonne respectively [7]. The following 3 years (2015–2018) were initially meant to be a semi-flexible trading period in which the carbon price would be allowed to fluctuate according to the open market rate but with a floor (minimum) and ceiling (maximum) price. The carbon floor price was decided to be $15/tonne, $16/tonne and $17.05/tonne for the years 2015–2016, 2016–2017 and 2017–2018 respectively [8]. The ceiling price was decided to be $20 higher than the international carbon price at the start of the flexible price trading period in 2015 [9]. However, very recently the floor price and consequently the semi-flexible trading period have been scrapped, possibly allowing for free trading between the European ETS and Australian ETS for the years to come [10]. Therefore the Australian carbon price is likely to be very similar to the European carbon price by 2015. The current price of carbon (September 2012) in the EU ETS is $9.8 which is expected to rise in the future [10]. However there is a possibility that the Australian carbon market may behave in a way similar to the European and New Zealand carbon markets, in which the carbon price dropped sharply within a year of introduction of the carbon tax [11]. A recent report has predicted that the carbon price in Australia could drop down to $4/tonne by 2020 [12]. However the Australian Government is likely to put restrictions on the buying of cheap United Nations-backed credits which would prevent such a drop in prices [10].

Carbon capture and storage (CCS) has been proposed as a means of reducing GHG emissions from fossil-fuelled power stations. Carbon capture technology is not new and has been used for decades in the petroleum industry to enhance oil recovery [13]. Since 40% of the carbon dioxide emissions in United States [13] and 50% of CO_2 emissions in Australia [14] can be attributed to the power sector, it is important to evaluate technologies to sequester the carbon dioxide emissions from these power plants. For existing power plants, post combustion capture (PCC) is considered the only viable means of carbon capture. However the PCC process consumes a moderate amount of energy, which is parasitically extracted from the power plant, leading to a decrease in its power output [15]. Most of the energy required in the PCC process is in the regeneration of the solvent which absorbs the CO_2 from the exhaust gases of combustion [15]. Thermal energy is required in order to heat the solvent and release CO_2 from it, which is then compressed and pumped into a CO_2 reservoir underground, or sequestered otherwise. Conventionally this thermal energy would be obtained by bleeding steam from the power plant turbine circuit and consequently leads to a reduction in the power produced on the order of 20–40% [15]. The steam bled from the inlet of the low pressure turbine is at a higher temperature (245 °C) than that required for the regeneration of the absorbent (120 °C) and would otherwise be used to generate additional electricity [15]. The use of solar thermal collectors in providing thermal energy for regeneration of the solvent (termed SPCC) in the process has been discussed by Mokhtar et al. [16]. They argued that providing all of the thermal energy from solar collectors would be prohibitively expensive as a very large solar field and Thermal Storage (TS) would be required for night operation. Thus they proposed that TS of 15 Full Load Hours (FLHs) be used and an on/off switching scheme be implemented. In this on/off switching scheme, if the combined thermal energy from the collectors and storage is equal to or greater than the energy required for regeneration, the solar hot water would be used for solvent regeneration. Otherwise steam would be bled from the turbine circuit and the thermal energy would be used to regenerate the solvent. Fig. 1 illustrates the switching scheme.

Li et al. [17] performed an economic feasibility study of a SPCC plant using two types of solar collectors at three different locations around the world. The economic model they presented was based on the cost of electricity and cost of avoidance of CO_2 rather than the net revenue generated by the plant as described by Mokhtar et al. [16]. The authors further evaluate the sensitivity of the solar collector price, Phase Change Material (PCM) price and carbon dioxide recovery ratio on the economic feasibility of the plant. They reported that the price of vacuum tube collectors and parabolic trough collectors would need to be lower than 90 USD/m^2 and 150 USD/m^2 respectively in order for the installation of the solar collectors to be feasible.

The work presented by Mokhtar et al. [16] described the integration of a field of Fresnel collectors that supplied heat for the regeneration of the CO_2 solvent for one location in Australia. They further evaluated the economic feasibility of the project on the basis of a costing model and presented the net revenue of the project against the solar fraction of the collector field. Due to the lack of information on the costing of the collectors the authors presented the net revenue for a range of collector costs from $100/m^2 to $600/m^2. Furthermore due to the lack of information regarding carbon prices, the authors used carbon prices ranging from $0/tonne to $200/tonne. Since then, a carbon tax structure has been introduced in Australia and this current paper takes into account the revised carbon tax prices in the costing model. Mokhtar concluded that a carbon price of $100/tonne would be required for the SPCC plant to be feasible as the carbon savings they assessed on a system level were in comparison with a PCC plant rather than a conventional plant. For this reason the amount of carbon dioxide mitigated in their calculation was much lower than when compared to a conventional plant. In this paper, we compare the carbon dioxide emissions mitigated through the addition of the solar field with a conventional coal fired power plant.

In Australia, the Commonwealth government has made available some funding to assist coal-fired generators to implement CCS technology. Funding up to $30 million is available under the