Energy 66 (2014) 285–294

Contents lists available at ScienceDirect

Energy

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

3E (energy, environmental, and economy) evaluation and assessment to an innovative dual-gas polygeneration system

Qun Yi [a,b], Jie Feng [a,b,*], Yanli Wu [a,b], Wenying Li [a,b,*]

[a] Key Laboratory of Coal Science and Technology, Taiyuan University of Technology, Ministry of Education and Shanxi Province, Taiyuan 030024, China
[b] Training Base of State Key Laboratory of Coal Science and Technology Jointly Constructed by Shanxi Province and Ministry of Science and Technology, Taiyuan 030024, China

ARTICLE INFO

Article history:
Received 11 April 2013
Received in revised form
13 January 2014
Accepted 16 January 2014
Available online 13 February 2014

Keywords:
Polygeneration system
Coal gasified gas
Coke oven gas
CO_2 recycling
3E assessment

ABSTRACT

To resolve problems surrounding simultaneous CO_2 conversion and COG (coke oven gas) utilization, a novel system combining a dual-gas of CGG (coal gasified gas) and COG with the technology of CO_2 recycling into a single gasifier and reforming unit is proposed. 3E performance (energy, environmental, and economic) analysis showed that this novel system renders unnecessary the traditional water–gas shift process, and realizes the conversion and utilization of CH_4 and CO_2 that would otherwise be directly discharged into the air. Under a weak carbon mitigation policy, the economics of co-producing low-carbon fuels and electricity from a dual-gas of CGG and COG are promising. The "dual-gas" technology is a potentially viable option for clean coal and its efficient use in the co-production of low-carbon fuels and electricity in areas possessing COG, natural gas or other unconventional natural gas resources.

1. Introduction

In the search to find ways to cleanly and efficiently use coal, many kinds of technologies have been investigated. IGCC (integrated gasification combined cycle) with CCS (carbon capture and sequestration) is a common power generation system used to efficiently reduce CO_2 emissions, and different CO_2 emission reducing technologies such as physical absorption, membrane reactors, chemical looping, oxy-fuel combustion and other related technologies have been studied [1–3]. The above technologies can achieve about a CO_2 recovery rate of approximately 90%, but will incur a thermal energy loss between 7 and 13% and also a 20 and 30% increase in investment cost [4,5]. The estimated costs for CO_2 transportation (US$ 1–3/(t·100 km)) and sequestration (4–8 US$ t^{-1}-CO_2) are lower than that of CO_2 capture, which is estimated at 35–55 US$ t^{-1}-CO_2 captured. The high cost of CO_2 capture stems from the considerable amount of energy required in the separation process and extra equipment investment [6].

Polygeneration system, integrating the IGCC with chemicals production, could be an option for solving the balance between energy production and economic benefit. For instance, the production costs of methanol in a methanol/electricity polygeneration plant could be 40% lower than that in a stand-alone methanol plant, and resulted in about 3.9% energy saving [7,8]. In order to investigate the reliability and tap potential of polygeneration system, Liu [7] proposed a multi-objective optimization approach to improve the total efficiency of the polygeneration system, Gao [9] and Li [10] researched polygeneration plant with methanol/nature gas/electricity products by use of exergy analysis, and revealed the essence for energy efficiency upgrade of polygeneration plant. Economic analysis and assessment of a coal based polygeneration system with CO_2 capture indicated that a co-production plant with high CO_2 recovery can simultaneously achieve higher energy utilization and economic benefits. The thermal efficiency of polygeneration plant with 90% CO_2 capture was about 7–16% higher than that of IGCC or coal-pulverized supercritical plant with 90% CO_2 capture, and the unit investment of the polygeneration system could be decreased to 600–900 US$ kW^{-1} through plant efficiency upgrade [11]. Polygeneration system with CCS is an energy efficient and carbon mitigation initiative technology. However, most of the aforementioned CCS technologies based on the polygeneration system do not take into consideration CO_2 treatment, transport and storage after the CO_2 is separated out. As Hetland [12] pointed out: "just

* Corresponding authors. Key Laboratory of Coal Science and Technology, Taiyuan University of Technology, Ministry of Education and Shanxi Province, Taiyuan 030024, China. Tel.: +86 351 6018957; fax: +86 351 6018453.
E-mail addresses: fengjie@tyut.edu.cn (J. Feng), ying@tyut.edu.cn, goatwing2010@gmail.com (W.Y. Li).

0360-5442/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.energy.2014.01.053

Nomenclature

Abbreviations

CAPEX	the unit capital expenditures, US$
$CO_{2\ avoided}$	cost of CO_2 avoided, US$ t^{-1}
$CO_{2,R}$	CO_2 emission reduction of the systems, t y^{-1}
$CO_{2,Tax}$	CO_2 tax price, US$ t^{-1}
COE	cost of electricity, US$ kWh^{-1}
COE_{CCT}	COE of systems with CO_2 capture or use considering benefits from CO_2 tax, US$ kWh^{-1}
IRR	internal rate of return, %
OPEX	operating expenditures, US$ y^{-1}
P	power output of the plant, MW

Acronyms

3E	energy, environmental and economy
ASPEN	advanced system for process engineering
ASU	air separation unit
ATR	autothermal reforming
BGL	British gas Lurgi
Capture plant	IGCC–CCS, IGCC–CRS, PL–CCS
CCS	carbon dioxide capture and sequestration
CF	the plant capacity factor
CGG	coal gasified gas
COG	coke oven gas
CT	chemicals transportation
DGP	dual-gas polygeneration
GHG	greenhouse gas
HHV	high heat value
IGCC	integrated gasification combined cycle
LHV	lower heat value
M	million
MeOH	methanol
Mt	million tons
NG	natural gas
PM	particulate matter
PT	power transportation
RAU	reforming auxiliary unit
Reference plant	IGCC
SMR	steam methane reforming
TUT	Taiyuan University of Technology
UNG	unconventional natural gas
US$	US dollar
WGS	water gas shift
WGSR	water gas shift reactor

capturing the CO_2 without storage makes no sense". In actuality, CO_2 transportation requires high quality pipeline materials and the cost of transportation rises with the prolonged distance, along with some geopolitical risks [13]. Jillson [14] and Oki [15] designed the oxy-fuel IGCC with CO_2 recycle to gasifier for CO_2 use and capture, the system thermal efficiency was more than 40% even after capturing CO_2, as high as that of a state of the art IGCC plant. Yi [16] proposed polygeneration system with CO_2 recycle and use, and the new system realized 11.5% increase of chemical exergy, 1.3% increase of internal rate of return and 33.8% reduction of CO_2 emission. CO_2 recycling would be a suitable way to convert CO_2 into CO for chemical synthesis and liquid fuel.

As the main by-product of the coal coking process, COG (coke oven gas, containing 6 vol% CO, 59 vol% H_2, 26 vol% CH_4, 3 vol% CO_2, and 6 vol% N_2) is a presently underutilized hydrogen-rich product [17]. Approximately 400 million tons of coke, more than half or the world's annual coke production, is generated by China, with a resulting by-product of about 1.6×10^{11} m^3 of COG. However, only half of this COG is burnt to supply heat through recycling back into the coke oven, an inefficient process which only consumes 10% of the available COG [18]. The implications are that 95% of COG produced is either directly released into the atmosphere or discharged after combustion, not only wasting a potential energy resource but also contributing significantly to air pollution. Since COG is rich in hydrogen and methane, and CGG (coal gasified gas) is rich in carbon, the mixture of COG and CGG could adjust the mole ratio of C/H in the syngas by either ATR (autothermal reforming) or SMR (steam methane reforming) [19] instead of the conventional WGS (water–gas shift) process. As a result, a D-PL system (dual-gas polygeneration), which combines coal and COG to simultaneously produce ultraclean synthetic fuels and electricity, has attracted much interest since first being proposed [20]. The D-PL would efficiently utilize CH_4 in COG and CO_2 in CGG and thereby reduce GHG (greenhouse gas) emissions. Particularly in comparison with stand-alone production, the benefits of the D-PL system are significant in the areas of capital investment, cost of unit product and pollution reduction, as well as energy efficiency [21].

This paper aims to address the problems surrounding the conversion and use of CO_2 and simultaneous COG utilization. Based on previous research [21,22], a novel system – D-PL-CR (dual-gas polygeneration system with CO_2 recycling) – was proposed. In order to investigate the overall performance and potential advantages of the novel system and assess the feasibility and reliability of its future application, the novel system as a case study was researched in the coal chemical industry park of Xinzhou city, Shanxi. 3E (energy, environmental, and economy) analyses of D-PL-CR are presented.

2. System design

The D-PL system was implemented on a pilot scale in Xinzhou, Shanxi, and the novel system (D-PL-CR) Fig. 1 proposed on the basis of the D-PL [22]. Coal is gasified with steam and oxygen, which is from ASU (air separation unit). High temperature flue gas is fed into a waste heat boiler in order to vaporize the supplied water and produce the saturated steam necessary for the power generation system. After cooling and removal of particulates, the cooled gas enters into thick-desulfurization tower and fine-desulfurization tower successively, and the concentration of (H_2S + COS) in the clean gas are reduced to below 1 ppm, which can effectively avoid the adverse effects of sulfur on the reforming catalysts and synthesis catalysts in the subsequent process. The resultant clean gas is mixed with purified COG and recycled CO_2 before entering the CH_4/CO_2 reforming unit. Energy for the reaction is provided by the direct combustion of partially unreacted gas in the RAU (reforming auxiliary unit). The resulting clean syngas is compressed to 6.5 MPa, and then is sent into methanol (MeOH) in the synthesis reactor. After processing in the synthesis reactor, CO_2, MeOH and water are separated out from the unreacted gas. Two distillation towers were used in the separation process: the first to separate out CO_2, the second to separate out MeOH and water. A portion of the separated CO_2 (95 wt%) is recycled back into the gasifier, and the remainder used in the reforming unit. Part of the unreacted syngas underwent compression and was then recycled for use in the synthesis reactor,