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Optimization of the design, operating conditions, and coupling configuration of combined cycle power plants and CO_2 capture processes by minimizing the mitigation cost

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ABSTRACT

This paper deals with the optimization of the coupling between a natural gas combined cycle (NGCC) plant and a post-combustion CO_2 capture process by minimizing the mitigation cost – defined as the ratio between the cost of electric power generation and the amount of CO_2 emitted per unit of total net electric power generated – while satisfying the design specifications: electric power generation capacity and CO_2 capture level. Three candidate coupling configurations, which differ in the place where the steam is extracted from, are optimized using detailed and rigorous models for both the NGCC and the CO_2 capture plants. By comparing the mitigation cost of each configuration, the optimal integration configuration and the corresponding optimal sizes and operating conditions of all process units (steam turbines, gas turbines, heat recovery steam generators HRSGs, absorption and regeneration columns, reboilers and condensers, and pumps) are provided. In the computed optimal solution, the steam required by the CO_2 capture plant is extracted from both the steam turbine and the HRSG (evaporator operating at low pressure), and the mitigation cost is 90.88 \$/t CO_2. The optimal solution is compared with suboptimal solutions corresponding to the other two candidate coupling schemes. These solutions are compared in detail regarding capital investment and operating costs, HRSG configuration, process unit sizes, and operating conditions.

1. Introduction

The combustion of fossil fuels for electricity generation, industry, and transportation is the largest source of CO_2 emissions, and it is considered to be the main contributor to the greenhouse effect. The reduction of CO_2 emissions is one of the most challenging issues that the world community faces today, which requires joint actions and close cooperation between government, industries, and researchers.

The most important strategies to reduce the global CO_2 emissions are the CO_2 capture and storage (CCS) and the CO_2 capture and utilization (CCU), which differ in the final destination of the captured CO_2. In the former the captured CO_2 is transferred to a suitable site for long-term storage whereas in the latter the captured CO_2 is converted into valuable fuels, chemicals, building materials, and other products. Cuéllar-Franca and Azapagic [1] and Kravanja et al. [2] presented an overview of recent advances in CCS and CCU, among other environmental issues.

There are studies in which the CO_2 is utilized as a carbon source for methanol production [3–6]. Roh et al. [6] developed a methodology for a sustainable design and implementation strategy of CO_2 utilization processes. They considered two CO_2 utilization processes for methanol production: combined reforming and direct synthesis. They showed that the integration or replacement of an existing conventional methanol plant with a combined reforming process represents a sustainable solution. Furthermore, there are studies in which the CO_2 is utilized for the production of dimethyl carbonate [7], dimethyl ether [8], urea [9], and for enhanced oil recovery (EOR) [10]. Kongpanna et al. [7] applied a systematic computer-aided framework for the synthesis and generation of processing networks for dimethyl carbonate production with CO_2 utilization. Martin [8] proposed a mathematical

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Nomenclature

Symbols

AC	total additional cost (M$/yr.)
CAPEX	capital expenditures (M$)
COE	cost of electric power generation ($/MWh)
CRF	capital recovery factor (dimensionless)
C_{inv}	total investment cost (M$)
$C_{inv}{}^{k}$	individual acquisition cost of the pieces of equipment (k) of the power plant and the capture system (M$)
C_{mant}	cost of maintenance (M$/yr.)
C_{mp}	cost of manpower (M$/yr.)
C_{rm}	cost of raw materials and utilities (M$/yr.)
$C_{rm}{}^{u}$	specific cost of raw materials and utilities ($/t, $/GW)
C_S	supervision and support labor (M$/yr.)
DMC	total direct manufacturing cost (M$)
E	amount of CO_2 emitted per unit of total net electric power generated (kg/MWh)
f_1, f_2, f_3	economic indexes (dimensionless)
g_t	set of inequality constraints t
HETP	height equivalent to a theoretical plate (m)
HTA	heat transfer area (dam^2)
HTU	height of a transfer unit (dimensionless)
h_s	set of equality constraints s
i	interest rate (%)
IFC	investment on fix capital (M$)
IMC	total indirect manufacturing cost (M$)
LMTD	logarithm mean temperature difference (K)
MC	minimal mitigation cost ($/t CO_2)
m^u	annual consumption of raw materials and utilities (kg/yr.)
MW_{CO2}	molecular weight of CO_2 (g/mol)
MW^{34}	molecular weight of gaseous mixture in the stream #34 (g/mol)
OPEX	operating expenditures (M$/yr.)
PC	total production cost (M$/yr.)
R_{CO2}	CO_2 recovery (%)
TAC	total annual cost (M$/yr.)
W_{GT}	net electric power generated by the gas turbines (MW)
W_{net}	required total net electric power generation (MW)
W_{ST}	net electric power generated by the steam turbines (MW)
$W_B{}^{CP}$	total electric power required by blowers B in the CO_2 capture plant CP (MW)
$W_C{}^{PP}$	total electric power consumed by compressors C in the NGCC power plant PP (MW)
$W_C{}^{CP}$	total electric power required by compressors C in the CO_2 capture plant CP (MW)
$W_P{}^{PP}$	total electric power consumed by pumps P in the NGCC power plant PP (MW)
$W_P{}^{CP}$	total electric power required by pumps P in the CO_2 capture plant CP (MW)
W_{net}	generated total net electric power (MW)
NTU	number of transfer units (dimensionless)
N_{CT}	number of CO_2 capture trains (dimensionless)
N_{GT}	number of gas turbines (dimensionless)
N_P	number of pumps (dimensionless)
N_{ST}	number of steam turbines (dimensionless)
n	project lifespan (yr.)
X^k	size of the process unit k (dam^2, MW, m^3)

Acronyms

CCS	CO_2 capture and storage
GAMS	General Algebraic Modeling System
HETP	height equivalent to a theoretical plate
HRSG	heat recovery steam generators
HTA	heat transfer area
HTU	height of a transfer unit
IGCCs	integrated gasification combined cycles
LMTD	logarithm mean temperature difference
MINLP	mixed-integer nonlinear programming
NGCC	natural gas combined cycle
NLP	nonlinear programming
NTU	number of transfer units
SNG	synthetic natural gas

Abbreviations

AE, IC, CT	heat exchangers
AMP	amino-methyl-propanol
B	blower
BZA	benzylamine
C	condenser
CC	combustion chamber
COM	compressors
C1, C2, C3	coupling scheme
EC	economizer
EC	lean/rich solutions cross heat exchanger
EV	evaporator
EX	expander
GEN1, GEN2	generator
GT	gas turbine
gPROMS	general PROcess Modelling System
HMPD	4-hydroxy-1-methylpiperidine
HPST	high pressure steam turbine
IPST	intermediate pressure steam turbine
LPST	low pressure steam turbine
MEA	monoethanolamine
OS	optimal solution
P, CO_2P	pumps
P1	optimization problem
PZ	piperazine
R	reboiler
REG	regeneration column
SH	superheater
SOS1, SOS2	suboptimal solution

Subscript

PP + CP	NGCC power plant coupled to the CO_2 capture plant
SAPP	NGCC power plant operating in a standalone mode

Greek letters

α_{CO2}	CO_2 loading in the liquid phase (mol/mol)
τ	working hours per year (8000 h/yr.)

optimization framework to select the flow sheet and determine the operating conditions for the synthesis of dimethyl ether from CO_2 captured and H_2 produced by water electrolysis using renewable energy sources such as solar or wind energy. Hasan et al. [10] developed a multi-scale framework for CO_2 capture, utilization, and storage (CCUS) to minimize costs while reducing the stationary CO_2 emission in USA. The studies have shown that more than 3% of the total stationary CO_2 emission in USA can be eliminated by a CCUS network. Bose et al. [9] investigated the possibility of recycling the CO_2 captured at coal-based power plants rather than its capture and storage which would