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Thermodynamic and ecological assessment of selected coal-fired power plants integrated with carbon dioxide capture

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HIGHLIGHTS

- Comprehensive thermodynamic and ecological system analysis of power units was made.
- Systems of the same power, with and without CO_2 capture installation were compared.
- Universal, detailed mathematical models for all systems were developed.
- Chemical absorption, membrane and cryogenic separation for CO_2 capture was applied.
- Comparison of thermodynamic and environmental evaluation indicators was made.

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ABSTRACT

The primary objective of the study presented in this paper was a thermodynamic and ecological analysis of coal-fired power plants integrated with carbon dioxide capture installations working in different technologies (pre-combustion, oxy-combustion and post-combustion) and a comparison of these systems with reference systems, i.e. ones not-integrated with CO_2 capture. Calculations were performed using our own developed mathematical models for the integrated units. The article quantitatively demonstrates that the integration of a carbon dioxide capture installation with a power plant causes a significant decrease in the net power and efficiency in relation to the reference system (without capture). In the case of a conventional coal unit working in the post-combustion technology and integrated with an absorption CO_2 capture installation and compression of carbon dioxide to 15 MPa, the net efficiency decreases in relation to the reference plant by 11.75 percentage points. The oxy-combustion unit was characterized by a decrease in efficiency (in relation to the power plant operating in the air combustion technology not integrated with Carbon Capture and Storage (CCS) installation) equal to 7.85 percentage points. In the unit working in pre-combustion technology (Integrated Gasification Combined Cycle (IGCC) system) integrated with a membrane CO_2 separation installation the efficiency decrease relative to the unit without capture was equal to 16.89 percentage points.

The main advantage of those systems integrated with carbon dioxide capture installations is the significant reduction of emissions to the atmosphere (environmental effect). This effect significantly depends on the separation method and the obtained effect of separation. Implementation of the capture plant in the analyzed post-combustion system allowed for a reduction of the value of the average annual CO_2 emission rate aggravating unit of net electricity produced from nearly 735 kg CO_2/MWh to 100.77 kg CO_2/MWh. In the case of the unit working in IGCC technology integrated with membrane CO_2 capture, this rate was equal to 89 kg CO_2/MWh. The lowest value was obtained for the power plant working in oxy-combustion technology, for which the emission rate was obtained at 19 kg CO_2/MWh.

1. Introduction

One of the most important priorities of the European Union's energy policy is to reduce emissions of greenhouse gases into the atmosphere, with special emphasis on reducing carbon dioxide emissions. The primary objective of these activities is to fight climate changes that manifest primarily in an increase in the average temperature of the Earth's surface. Although there is much controversy on the validity of the thesis concerning the impact of CO_2 emissions of anthropogenic origin on the greenhouse effect, it seems that most communities have accepted the need to take

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Nomenclature

AE	avoided emission, kg CO_2/MW h_n
E	energy, J
h	enthalpy, kJ/kg
LHV	lower heating value, MJ/kg
m	mass, kg
$\dot{m}$	mass stream, kg/s
N	power, W
p	pressure, Pa
q	specific heat, kJ/kg
Q	heat, J
$\dot{Q}$	heat flux, W
R	recovery rate
t, *T*	temperature, °C, K
Y	molar share
Δ	increase
ε	emission, kg/MW h
η	efficiency
δ	auxiliary power rate
ζ	pressure loss

Indices

a	annual
ASU	air separation unit
AUX	auxiliary power
B	boiler
C	carbon dioxide compression
cl	cycle
cn	condensate
cs	steam at the inlet to the condenser
cw	water at the exit of the condenser
ch	chemical
CCS	carbon capture and storage
CND	condenser
CPU	CO_2 conditioning system
d	derived
DEA	deaerator
des	desorption
el	electric
f	fuel
fw	feed water
g	gross
G	generator
GT	gas turbine
i	internal
LP	low pressure
ls	live steam
n	net
REF	reference
RH	regenerative heat exchanger
rs	reheated steam
s	supplied
S	carbon dioxide capture/air compressor
SC	steam cycle
ST	steam turbine

actions aimed at the reduction of emissions of this gas to the atmosphere.

In the European Union activities aimed at a gradual transition to a low-carbon economy have been conducted for many years [1,2]. An especially important consequence of these actions, from the energy sector, was the introduction of the European Union Emission Trading Scheme EU ETS. This program has become the cornerstone of many activities undertaken in the field of the development of new energy generation technologies and reducing emissions. The initial documents, such as the Green Paper "A European Strategy for Sustainable, Competitive and Secure Energy" (March 2006) [3], only emphasized the necessity of actions in this direction. However, over time the declarations have become increasingly demanding. Published in 2007, the Climate and Energy Package (i.e., Package 3 × 20) [4] introduced the need for significant (EU average at 20%) decreases in greenhouse gas emissions, increasing the share of renewable sources and increasing energy efficiency by 2020. Documents published later declared the desire for further reductions, by 2050, of anthropogenic greenhouse gas emissions (at least 80%) [5], which in turn should lead to limiting the increase in the Earth's surface temperature to 2 °C [1,6].

One of the major sources of anthropogenic emissions of carbon dioxide is the combustion of fossil fuels, which globally contributes to 75% of emissions. Despite many measures taken in terms of changing the structure of energy carriers, the power industry is still mostly based on fossil fuels. Therefore, the energy sector is considered to be responsible for the greatest share of emissions and is expected to undertake the most important and most radical steps to fulfill international obligations concerning the reduction of emissions.

A significant reduction of CO_2 emissions in the energy sector requires important changes in technology and huge levels of investment. The large-scale introduction of renewable energy sources is necessary. However, in many countries this involves a fundamental change in the direction of energy policy and there is not sufficient action in this respect. It is, therefore, necessary to develop and implement as soon as possible such transition technologies that work with the use of fossil fuels but which do not cause emissions. One such solution are the so-called Clean Coal Technologies, of which an integral part is the integration of carbon dioxide capture and storage (or utilization) installations, i.e. CCS (Carbon Capture and Storage) or, more and more often used term, CC(U)S (Carbon Capture, Utilization and Storage). The main advantage of these solutions is there is no need for a sudden change from an economy based on coal (or hydrocarbon fuels) to another. There is also the possibility to implement such technology into existing power generation systems and to maintain employment in the coal mining sector. Capture and storage of carbon dioxide is one of the most promising technologies, which by 2050 should enable a global reduction in emissions of this gas by about 14% [7]. Carbon capture and storage technology is specifically dedicated to large point sources using coal as a fuel. These mainly include coal-fired power plants (with an estimated annual global emissions of more than 10,500 Mt CO_2/year), cement industry plants (over 930 Mt CO_2/year), refineries (~800 Mt CO_2/year), iron ore processing plants (~650 Mt CO_2/year) and the petrochemical industry (~380 Mt CO_2/year) [8].

There are three main groups of CCS technologies, differing in terms of the location and method of separating carbon dioxide. These include post-combustion, pre-combustion and oxy-combustion capture [9–15]. At present, the most mature technology is the post-combustion capture process, which is realized on the basis of chemical absorption. The biggest disadvantage of the methods that are used is their high energy consumption, causing a significant loss of net efficiency as compared to those systems without capture. This loss may even exceed a dozen percentage points [14,16,17]. The most frequently mentioned carbon dioxide separation methods, in addition to absorption, include adsorption,