Techno-economic assessment of supercritical carbon dioxide integrated with anaerobic digestion

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Abstract

Biomass conversion to energy is paramount for the future of renewable energy production. It has proven to have some advantages over other renewable sources in case of storage and consumption in times of need. In this study, supercritical carbon dioxide power cycle is integrated with a gas turbine to recover the waste heat of exhaust gas from combusting the biogas derived from anaerobic digestion (AD). AD is fed with a mixture of biomass and pyrolysis-derived biochar to improve its stability and biomass-to-methane conversion efficiency. A technoeconomic assessment of the proposed system has been carried out. According to the results, the highest theoretical achievable thermal, exergy efficiencies and net work output, and payback period are 39.76%, 38.57%, 9936 kW, and 4.835 years, respectively.

1. Introduction

Recently, excessive consumption of fossil fuels and resulting problems have led scholars to find suitable sources to replace the fuel source. In this regard, renewable sources have shown some advantages. However, most of the sources such as solar energy require more advancement in technology regarding storage and inconsistency. Among renewable sources, biomass has shown promising results in case of being abundantly available and stored easily. Biomass conversion to energy has been widely studied and mainly consists of two routes namely thermochemical and biochemical routes. Thermochemical treatments require high energy intake while the biochemical route occurs through bacterial processes, which makes it a more interesting method. Among biochemical routes, anaerobic digestion (AD) is a mature technology and takes place in the absence of oxygen. Biogas is the main product of AD and can produce energy by being combusted and producing thermal power which then can be converted to mechanical power and electricity power. It consists mainly of carbon dioxide (CO_2) and methane (CH_4) and in some cases on the biomass composition, hydrogen (H_2). Adding biochar to AD along with the main feed has been proven to be beneficial for the biomass to CH_4 conversion efficiency [1]. Moreover, several researchers in the literature have developed novel layouts for the purpose of power production, co-generation, and multi-generation systems and have proven that biogas is a suitable source to be utilized as the fuel in the power production industry [2].

In this study, AD is integrated with a gas turbine (GT) and supercritical CO_2 (SCO_2) in which the produced biogas from the AD is generated through the conversion of a mixture of chicken manure and biochar. The biogas is combusted in the combustion chamber to produce power in the GT. SCO_2 power cycle is employed to recover heat from the hot exhaust gas to increase power production. Thermodynamic and economic assessment along with a sensitivity analysis for influential parameters have been carried out in this study.

2. Methodology

The modeling of the proposed system (Fig. 1) is carried out with the Engineering Equation Solver (EES). In the modeling of the digester, a mesophilic type (35 ℃) has been considered with a global reaction to produce biogas from biomass has been considered which is as follows [3]:

$$C_xH_yO_z + wH_2O \rightarrow x_1CH_4 + x_2CO_2 \quad (1)$$

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As for the thermodynamic and economic analysis Eqs. 2-4 have been recruited which are expressed as follows:

$$\dot{Q} - \dot{W} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \tag{2}$$

$$\dot{E}_Q - \dot{E}_W = \sum \dot{m}_{out} e_{out} - \sum \dot{m}_{in} e_{in} + \dot{E}_D \tag{3}$$

$$TAC = \dot{C}_{inv} + \dot{C}_{O\&M} \tag{4}$$

where Eqs. 2 and 3 represent the first and second thermodynamic law, respectively. In Eq. 4, TAC stands for total annual cost consisting of annual investment cost ($\dot{C}_{inv}$) and operation and maintenance cost ($\dot{C}_{O\&M}$).

Four different Case scenarios regarding the methane production from AD have been considered for the purpose of comparison and feasibility of different fuel sources based on the above-mentioned analyses.

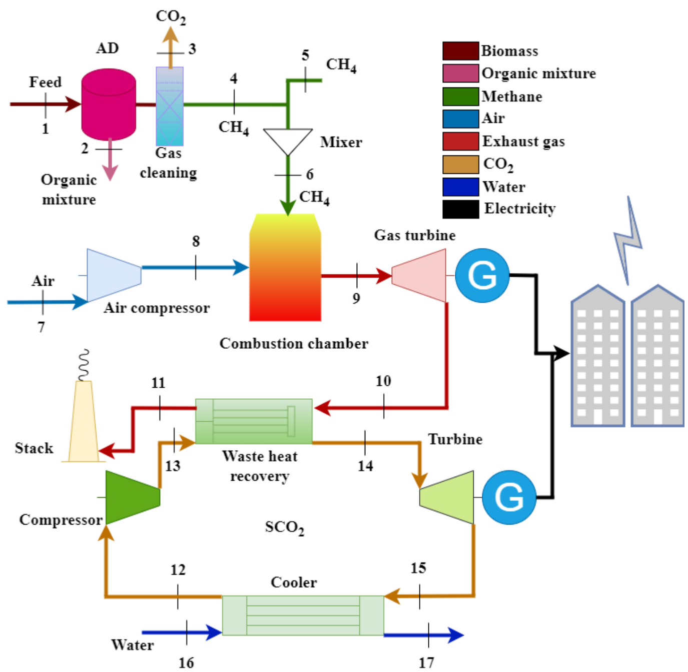

Fig. 1. Schematic diagram of the integrated SCO_2 with AD

3. Results

As for the CH_4 production from AD, four distinct Case scenarios have been considered (Fig. 2). In Case 1, the total required CH_4 is produced by AD, and in Case 4, the total required CH_4 is provided by an external source.

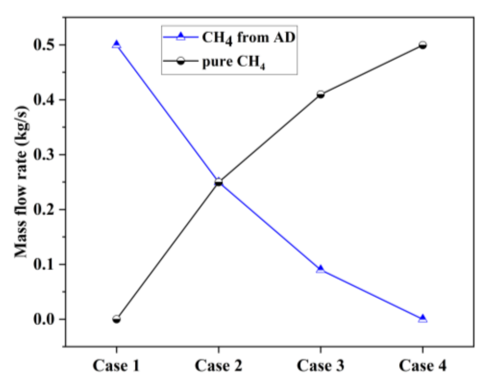

Fig. 2. Variation of CH_4 mass flow rate produced by AD and pure CH_4

As for Case 1, in which the total required CH_4 is produced by AD, the Sankey diagram (Fig. 3) is provided for the exergy flows in which the highest exergy destruction belongs to AD followed by the combustion chamber. It is attributed to the dominance of chemical exergy in these flows and in both components, chemical reactions, conversion, and temperature differences (especially in the combustion chamber) exist. As a result, the highest exergy destruction takes place in the aforementioned components.

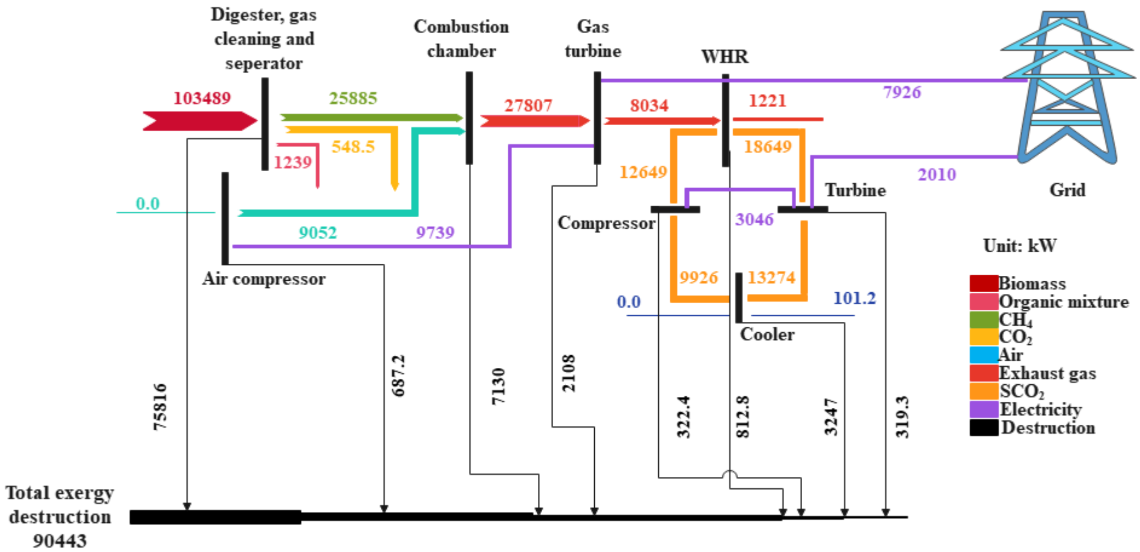

Fig. 3. Sankey diagram

For all Cases, the exergy destruction ratio has been computed and the results have shown that by reducing the mass flow rate of the mixture in the AD, the proportion of exergy destruction in the AD reduces and it can be seen from Fig. 4.

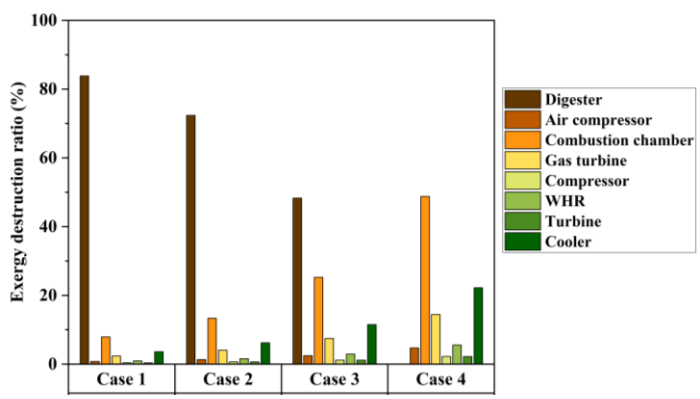

Fig. 4. Exergy destruction ratio for different Case scenarios

For sensitivity analysis, two parameters are considered for the bottoming cycle which are SCO_2 turbine inlet temperature and compressor pressure ratio. As can be seen from Table 1, the influential parameters with their intervals are presented.

Table 1
Influential parameters for sensitivity analysis

Parameters	Intervals
SCO_2 turbine inlet temperature, $T_{in,T}$ (K)	$620 < T_{in,T} < 720$
SCO_2 compressor pressure ratio, CR_C (-)	$2 < CR_C < 3.7$

Fig. 5 demonstrates the increasing in SCO_2 turbine temperature and it can be seen that thermal, exergy efficiencies and net work output increased by 0.22%, 0.185%, and 193 kW, respectively, while TAC decreased by 700,000 $.

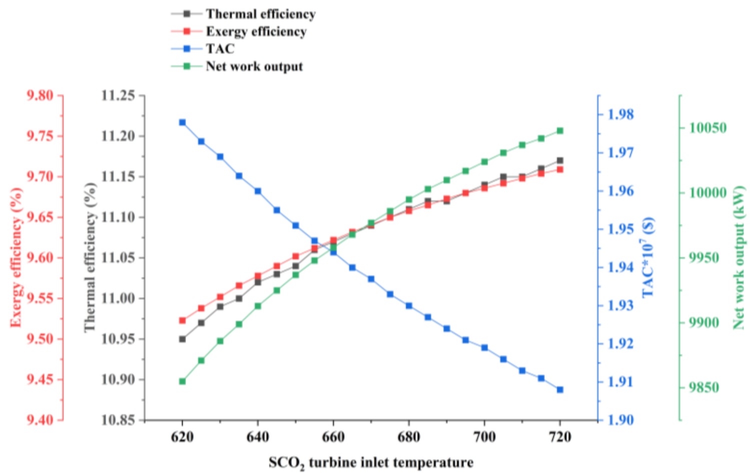

Fig 5. SCO_2 turbine inlet temperature

Fig. 6 depicts the effect of the pressure ratio on the overall performance of the system. By increasing the pressure ratio, thermal efficiency increased by 1.09%, exergy efficiency has seen an increase by 0.942%. net work output and TAC, both increased by 975 kW and $0.127 * 10^7$ $, respectively.

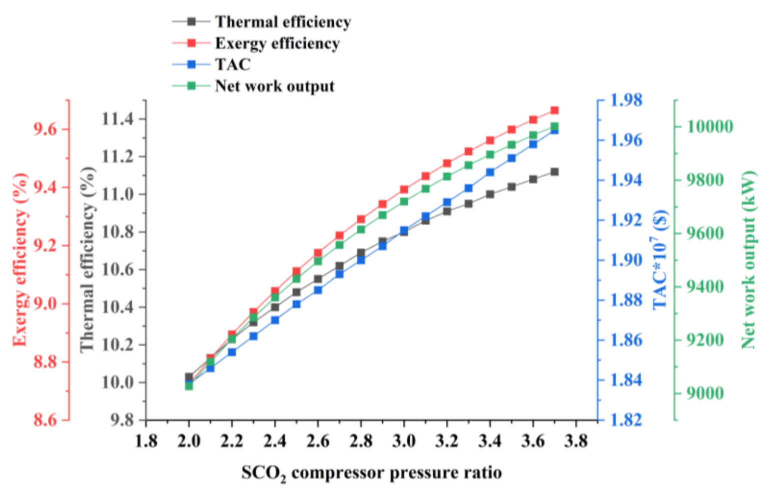

Fig. 6. SCO_2 compressor pressure ratio

According to the results, the compressor pressure ratio has proven to be more effective than the turbine inlet temperature.

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