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# Design and thermodynamic analysis of a hybrid power plant using torrefied biomass and coal blends

Po-Chih Kuo, Wei Wu *

*Department of Chemical Engineering, National Cheng Kung University, Tainan 70101, Taiwan*

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ABSTRACT

This study developed a clean hybrid power plant using a combination of integrated torrefied biomass co-gasification (TBCG), solid oxide fuel cell (SOFC), and calcium looping (CaL) $CO_2$ capture. Based on pre-SOFC (Design I) and post-SOFC (Design II) configurations, thermodynamic analysis is adopted to examine the performance of hybrid power generation plants. The carbon boundary points (CBPs) for different torrefied biomass blending ratios (TBBRs) are found using specific optimization algorithms to maximize the syngas yield. From the viewpoint of energy utilization, the simulation results show that Design I is superior to Design II. However, the $CO_2$ emissions of Design II are lower than those of Design I by 94.19%, although it has an accompanying energy penalty of 4.17%. Due to its use of the internal heat recovery approach, the energy penalty of Design II falls to 1.09%. As a whole, Design II with the heat integration design is recommended for use in hybrid power plants.



## 1. Introduction

Fossil fuels, such as coal, petroleum, and natural gas, have long been the most important sources of energy. However, the burning of such fuels not only contributes to global warming due to the release of greenhouse gases (GHG) into the atmosphere, but also faces the problem of decreasing reserves, due their finite supply and greater consumption due to a growing global population and economy [1,2]. There is thus considerable interest in developing forms of renewable energy to meet global demands and reduce GHG emissions.

Biomass is a sustainable and promising alternative source of energy, as it has low nitrogen and sulfur contents compared with fossil fuels, and thus lower $NO_x$ and $SO_x$ emissions, as well as the characteristic of being carbon-neutral [1,3]. One thermal conversion technique that has attracted particular attention with regard to producing bioenergy from biomass is the process of biomass gasification, in which feedstock undergoes a partial oxidation reaction with gasifying agents, such as air, oxygen, or steam, to produce syngas ($H_2$ and CO) [4]. This can then be used to synthesize a variety of chemicals, such as methanol [5], ethanol [6], and dimethyl ether (DME) [7], via the Fischer–Tropsch process, or to generate heat through a combined heat and power (CHP) system [8]. There has also been growing research interest in the co-gasification of biomass with coal in recent years [9]. Co-gasification technology can not only decrease the use of a significant amount of coal, and thus lower GHG emissions, but also enhance the gasification efficiency [1,9,10].

In contrast to conventional power generation systems, such as an integrated biomass gasification combined cycle (IGCC) system or coal/biomass-fired power plant, one integrated hybrid power system is now attracting more attention is the use of a combination of biomass gasification (BG) and solid oxide fuel cell (SOFC) systems [11–13]. Several researchers have used process simulation and modeling to examine integrated BG/SOFC systems. For example, Doherty et al. [14] developed a model of a BG/SOFC system using Aspen Plus. They compared the performance of the BG/SOFC system with the Güssing CHP plant, and found that the electrical efficiency of the former was 8% better than that of the latter. Bang-Møller et al. [15] evaluated the performance of a decentralized CHP plant with a BG/SOFC system, and they also reported that the proposed system was more efficient than the traditional decentralized biomass CHP plants. More recently, El-Emam and Dincer [12] studied the performance of a BG/SOFC system using thermodynamic modeling. They found that the steam to biomass mass flow ratio (S/B) had a significant impact on system performance. Moreover, Jia et al. [13], investigated the performance of a BG/SOFC system when using three different gasification agents, including air, steam, and oxygen-enriched air. They concluded that steam biomass gasification provided the best overall thermodynamic performance of the hybrid power system. These earlier studies show

* Corresponding author. Tel.: +886 6 2757575x62689; fax: +886 6 2344496.
*E-mail address:* weiwu@mail.ncku.edu.tw (W. Wu).

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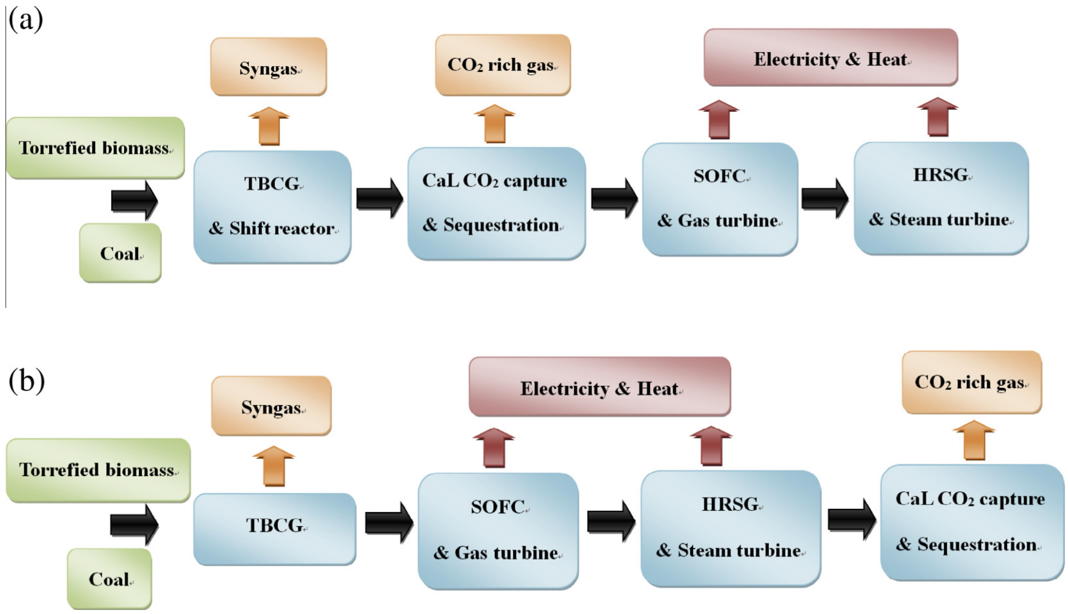


**Fig. 1.** Simplified flow diagram for the hybrid power system of (a) pre-SOFC (Design I), and (b) post-SOFC (Design II).

that a BG/SOFC hybrid power system has better performance compared to that of a conventional power plant.

Despite its numerous advantages as a renewable form of biomass energy, raw biomass is generally characterized by a relatively low calorific value and hygroscopic nature, and thus a high moisture content, which causes the low combustion efficiency [4,16]. In addition, the fibrous structure and low bulk density of raw biomass mean that there is a high energy demand for grinding it to a small particle size for further use, as well as high costs for transport and storage, thus limiting its ease of use [3]. Torrefaction is a promising technology that can be used to overcome these problems. In this process, raw biomass is heated in the temperature range of 200–300 °C under an inert atmosphere or nitrogen environment [7,17]. This results in a number of improvements to the torrefied biomass, including a reduction in moisture, enhancement of energy density, reduction in the energy needed for grinding, and the formation of hydrophobic and uniform solids, which make the fuel more economic and energy efficient [3,6,16,17]. Furthermore, several studies report that using torrefied biomass as a feedstock in gasification can enhance the gasification performance [4,5,8].

A review of research into using torrefied biomass in downstream applications shows that most of the studies are focused on torrefied biomass fired plants [2,8] or co-firing with a coal power plant [3,18], and few examine the use of integrated torrefied biomass gasification (TBG) for the production of methanol [5], corn ethanol [6], and dimethyl ether (DME) [7]. While there are a number of studies on conventional torrefied biomass power plants, there are no works that investigate integrating TBG with an SOFC hybrid power generation system, nor those that examine torrefied biomass co-gasification (TBCG) with coal. For this reason, the present study develops a TBCG/SOFC hybrid power system.

On the other hand, carbon capture and storage (CCS) is an important technique for dealing with $CO_2$ emissions, and several capture technologies have been developed, such as pre-combustion, amine-based post-combustion, oxy-combustion with $CO_2$ capture, a chemical looping combustion process, and a calcium looping (CaL) process [19,20]. Among these CaL $CO_2$ capture process has attracted the most interest, as it has several advantages [19–22], including: (1) the low cost and wide availability of sorbents (limestone); (2) the lower efficiency and cost penalties compared to the other $CO_2$ capture technologies; (3) the excess heat can be recovered to the system; and (4) the waste from the calcium looping process can be integrated into the cement industry. On account of these advantages, the CaL $CO_2$ capture process is also integrated into the proposed hybrid power generation system.

Despite the potential advantages of using a BG/SOFC system in a hybrid power plant, as detailed above, the process of integrating TBCG with an SOFC in a hybrid power plant has not yet been investigated. In addition to developing a TBCG/SOFC hybrid power generation system, the CaL $CO_2$ capture process is also implemented in the proposed hybrid power plant in the present study to provide an insight into the reduction of $CO_2$ emissions. The performance of two configurations of a hybrid power plant, namely, pre-SOFC (Design I) and post-SOFC (Design II) $CO_2$ capture, are designed and compared with each other. The influences of some parameters, i.e., steam to fuel mass ratio ($S/F$), torrefied biomass blending ratios (TBBRs), and make-up ($CaCO_3$) to fuel mass ratio ($M/F$), on the performance of the hybrid power generation system are taken into account. The optimization algorithm for maximizing the syngas yield in a TBCG system is used to identify the carbon boundary points (CBPs) for different TBBRs. Finally, the maximum waste heat recovery design is added to the hybrid power generation systems to enhance the net system efficiency.

## 2. Process design and simulation

The simulation is carried out using a process simulator, Aspen Plus V8.4. In the simulation, the Peng–Robinson equation of state with the Boston–Mathias alpha function (PR–BM) are selected as the thermodynamic properties of the system. Two configurations of the proposed hybrid power plant are designed, namely, pre-SOFC (Design I) and post-SOFC (Design II), as shown in Fig. 1. As a whole, the hybrid power plant consist of a TBCG system, an SOFC system, a gas turbine system, a CaL $CO_2$ capture and sequestration system, and a heat recovery steam generator (HRSG) and steam turbine systems. In Design I, a water gas shift reaction in a shift reactor and a CaL $CO_2$ capture system are connected behind the TBCG system, and thus $CO_2$ in the product gas is captured before entering the SOFC system. In Design II, the CaL $CO_2$ capture system is installed in the downstream of the SOFC system. The key subsystems in the hybrid power plant, such as the TBCG process, SOFC