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# Solid Oxide Fuel Cell and Biomass Gasification Systems for Better Efficiency and Environmental Impact

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**Abstract**

In this paper, a conventional biomass fueled power production system is compared with a SOFC and biomass gasification system in terms of efficiency and greenhouse gas emissions. A heat transfer model of the SOFC and thermodynamic models for the other components of the systems are used to find the performance assessment parameters of the systems. These parameters are taken as electrical and exergetic efficiencies. In addition, specific greenhouse gas emissions are calculated to evaluate the impact of these systems on the environment. The results show that the SOFC and biomass gasification system has higher electrical and exergetic efficiencies and lower greenhouse gas emissions.

**Keywords:** biomass, SOFC, gasification, steam turbine, greenhouse gas, energy, exergy, efficiency

## 1 Introduction

SOFC is one of the high temperature fuel cells that can operate in temperatures ranging from 500 °C to 1000 °C depending on the manufacturing type, e.g., electrode-supported and electrolyte-supported. SOFCs have several advantages over low temperature fuel cells, e.g. proton exchange membrane fuel cell, such as: being simpler in design concept since there is no liquid phase, fuel flexibility, internal reformation of the gases, and integrability with other systems, e.g. gas turbine and gasifier. However, fuel containing carbon and sulphur can cause problems related to carbon deposition and sulphur poisoning, respectively. In addition, there are challenges with construction and durability due to the high operating temperature.

Biomass gasification is a thermochemical conversion technology where fuel is converted into a gas mixture called syngas, but also contaminants. The composition of this gas mixture depends on the fuel, e.g. wood and municipal solid waste, gasifier type, e.g. downdraft, updraft, and fluid bed, gasification agent, e.g. air, oxygen, and steam, and other operating parameters of the gasifier, e.g. temperature and pressure. There are two types of gasification processes: autothermal and allothermal. In autothermal gasification, heat is provided by partial oxidation that takes place within the gasifier; whereas in allothermal gasification, an external source supplies the heat needed for gasification reactions.

Studies on integrated biomass fueled SOFC systems and their analyses have increased recently. Panopoulos et al. [9][10] investigated the integration of a SOFC with an allothermal biomass gasifier using steam as the gasification agent. They found the electrical efficiency of the system as 36% and exergetic efficiency as 32%. Cordiner et al. [7] studied the integration of a downdraft gasifier with a SOFC. They calculated the electrical efficiency of the system as 45.8%. Athanasiou et al. [2] analyzed the integrated SOFC, steam turbine and gasifier system. They found the electrical efficiency of the system as 43.3%. Omosun et al. [8] compared different gas cleanup types to be used in biomass gasification and SOFC system. Their study showed that hot gas cleanup should be selected for better performance and economical solution. Colpan et al. [5] studied the effect of gasification agent on the performance of an integrated SOFC and biomass gasification system. They found that the system in which steam is used as the gasification agent yields higher electrical and exergetic efficiencies compared to the systems in which air or enriched oxygen are used as the gasification agents. In another study by Colpan et al. [6], different technologies including the internal combustion engine, the gas turbine and the SOFC are compared in terms of performance and greenhouse gas reduction to be used in a landfill site. Their study showed that the SOFC shows higher performance and greenhouse reduction compared to the other systems studied.

In this study, a conventional biomass fueled power production system, i.e. a steam turbine system using the heat recovered from the combustion of biomass, is compared with an advanced biomass gasification and SOFC system in terms of efficiency and environmental impact. Electrical and exergetic efficiencies and specific greenhouse gas emissions are calculated for performance and greenhouse gas emission comparisons, respectively.

## 2 System Description

A conventional biomass fueled power production system (System-I) and an advanced biomass gasification and SOFC system (System-II) are studied for performance comparison purposes. In both of these systems, a forced drying system is used to evaporate the moisture completely in System-I and bring the moisture content to a reasonable level according to the gasifier design in System-II.

System-I consists of a dryer, a combustor, a heat recovery steam generator (HRSG), a steam turbine, a condenser and a water pump, as shown in Figure 1. In this system, the dried biomass and air enters the combustor. The gas mixture produced from this combustion process supplies heat to the HRSG where steam is produced. The gas mixture exiting the HRSG enters the dryer to supply the required amount of heat for the drying process and then it is emitted to the atmosphere. The steam produced in HRSG enters the steam turbine where the power is produced. The exit stream from the steam turbine enters the condenser and some amount of heat is rejected to the environment. The condensed liquid enters the pump and then it is sent back to the HRSG.

A schematic of the integrated biomass gasification and SOFC system is shown in Figure 2. In the gasification subsection, steam is selected as the gasification agent and external heat is supplied by the recirculation of the depleted streams from the SOFC. The gas mixture produced by gasification, i.e. syngas, has generally high level of contaminants to be used directly in the SOFC. A gas cleanup system has to be used to clean the syngas according to the SOFC impurity levels not to cause any degradation in the fuel cell. For this study, a hot gas cleanup is preferred to be compatible with the gasifier exit and SOFC inlet streams. The cleaned syngas enters the SOFC, where the electricity is generated. It should be noted that depleted fuel stream can be recirculated to adjust the steam to carbon ratio in case there is a carbon deposition problem in the SOFC. The fuel and air streams exiting the SOFC enter the afterburner to burn the unused fuel and increase the temperature of these streams. The mixture leaving the afterburner supplies heat to the following components respectively: the blower used to supply air for the SOFC, the HRSG used to produce steam for the gasifier and the steam users, and the dryer. After exiting the dryer, this gas mixture is emitted to the environment.

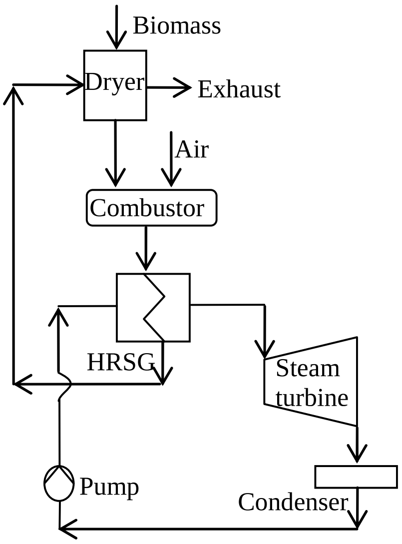


**Figure 1: Schematic of the System-I (a conventional biomass fueled power production system using steam turbine).**

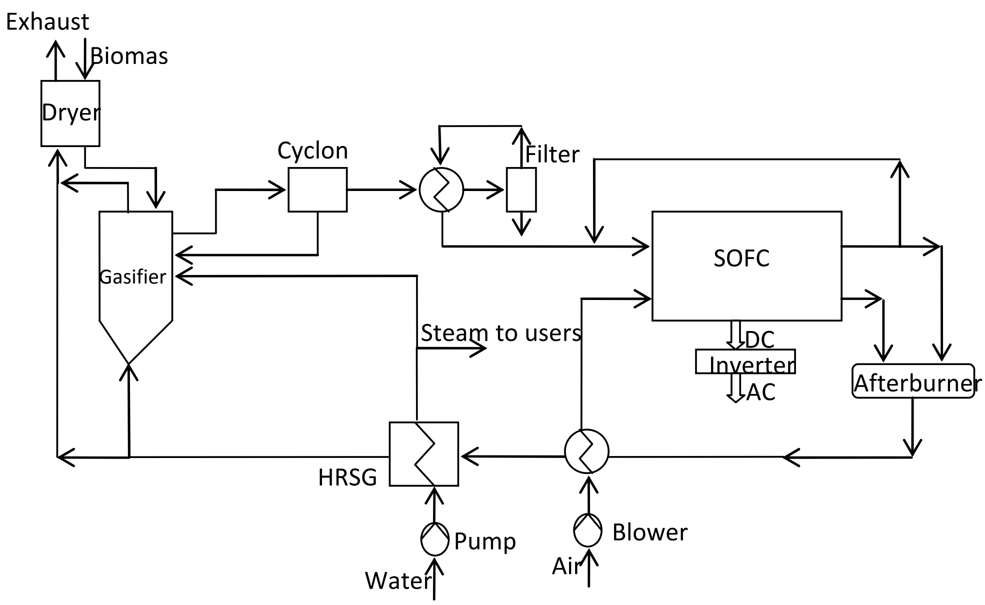


**Figure 2: Schematic of the System-II (an advanced integrated biomass gasification and SOFC system).**

## 3 Analysis

In the modeling of the conventional biomass fueled power production system, i.e., System-I, thermodynamic principles and laws are applied to the components of the system. It is assumed that complete combustion is achieved using 100% theoretical air, i.e. stoichiometric mixture. The heat recovered from the HRSG is first calculated applying an energy balance around the control volume enclosing the HRSG. Using the isentropic efficiencies of the components and the thermodynamic relations, steam produced in the HRSG is then calculated. Finally, using these finding, the power output of the steam turbine, power demand for the pump, and the net power output of the system are calculated.

For the SOFC, the transient heat transfer model developed by Colpan [4] is used. The approach and main features of this model are as follows: A control volume around the repeat element found in the middle of a planar SOFC stack is taken. It is assumed that the other repeat elements show the same characteristics with this repeat element. The solid structure, i.e. electrodes, electrolyte, and interconnects, is modeled in 2-D; whereas the air and fuel channels are modeled in 1-D. Since the gases flow with low velocity to obtain high fuel utilization, it is assumed that fully developed laminar flow conditions are achieved at the air and fuel channels. Natural convection at the heat-up stage, forced convection at the start-up stage, conduction heat transfer between the solid parts, and all the voltage losses, i.e. activation, concentration, and ohmic, are taken into account in the modeling. The input parameters of this model are cell voltage, Reynolds number at the fuel channel inlet, excess air coefficient, temperature at the air and fuel channel inlets, pressure of the cell, molar gas composition at the air and fuel channel inlets, and the geometrical dimensions of the SOFC. The output parameters are the current density, temperature, molar gas composition, and carbon activity distributions, the heat-up and start-up time, the fuel utilization, the power output and the electrical efficiency of the cell. This model is validated with IEA benchmark test [1] and Braun’s model [3].

In modeling the integrated SOFC and biomass gasification system, i.e System-II, firstly, the syngas composition and the external heat needed for the gasifier are calculated by solving the set of equations derived from the thermodynamic modeling of the gasifier. These equations include three atom balances, two chemical equilibrium relations and the energy balance around the control volume enclosing the gasifier. Secondly, using the syngas composition and the heat transfer model of the SOFC, number of the SOFC stacks, molar flow rate of gases at the inlet and exit of the air and fuel channels, temperature at the exit of the air and fuel channels, and power output of the cell are found. Thirdly, combining the outputs of the gasifier and SOFC models, the molar flow rate of the dry biomass is calculated. Fourthly, applying thermodynamic principles to the components of the system, the enthalpy flow rate of all the states are calculated. Finally, using the laws of thermodynamics, work input to the auxiliary components, i.e. blower and pump, and net power output of the system are calculated.

Electrical efficiency and exergetic efficiency are selected as the performance assessment parameters. Electrical efficiency, which is shown in Eq. (1), is the ratio of the net power output of the system to the lower heating value of the fuel. In defining the exergetic efficiency, it is necessary to identify both a product and a fuel for the system being analyzed. The product represents the desired output produced by the system. The fuel represents the resources expended to generate the product. This efficiency can also be written in terms of the total exergy destructions and losses within the system, as shown in Eq. (2).

$$\eta_{el} = \frac{(\dot{W}_{net})_{system}}{\dot{n}_{fuel} \cdot LHV} \tag{1}$$

$$\varepsilon = \frac{\dot{E}x_P}{\dot{E}x_F} = 1 - \frac{\dot{E}x_D + \dot{E}x_L}{\dot{E}x_F} \tag{2}$$

Environmental impact of these systems can be assessed calculating the specific greenhouse gas emissions, which is defined as the ratio of the GHG emission from the system to the net power output of the system. From the viewpoint of energy and environment, the lower the ratio is, the more environmentally friendly the system is.

$$\sigma = \frac{\dot{m}_{GHG}}{(\dot{W}_{net})_{system}} \tag{3}$$

## 4 Results and Discussion

The performance and environmental impact of the System-I and System-II were simulated for the same input data, which is given in Table 1. The results and discussion of these simulations are given in this section.

**Table 1: Input data.**

| | |
|---|---|
| Environmental temperature | 25 °C |
| Type of biomass | Wood |
| Ultimate analysis of biomass [%wt dry basis] | 50% C, 6% H, 44% O |
| Moisture content in biomass [%wt] | 30% |
| Exhaust gas temperature | 127 °C |
| **System-I** | |
| Conditions of the steam entering the steam turbine | 20 bar (saturated) |
| Pressure of the condenser | 1 bar |
| Isentropic efficiency of the steam turbine | 80% |
| Isentropic efficiency of the pump | 80% |
| Electricity generator efficiency | 98% |
| **System-II** | |
| Moisture content in biomass entering the gasifier [%wt] | 20% |
| Temperature of syngas exiting the gasifier | 900 °C |
| Temperature of steam entering the gasifier | 300 °C |
| Molar ratio of steam to drybiomass | 0.5 |
| Number of cells per SOFC stack | 50 |
| Temperature of syngas entering the SOFC | 850 °C |
| Temperature of air entering the SOFC | 850 °C |
| Pressure of the SOFC | 1 atm |
| Cell voltage | 0.7 V |
| Reynolds number at the fuel channel inlet | 1.2 |
| Excess air coefficient | 7 |
| Active cell area | 10x10 $cm^2$ |
| Number of repeat elements per single cell | 18 |
| Flow configuration | Co-flow |
| Manufacturing type | Electrolyte-supported |
| Thickness of the air channel | 0.1 cm |
| Thickness of the fuel channel | 0.1 cm |
| Thickness of the interconnect | 0.3 cm |
| Thickness of the anode | 0.005 cm |
| Thickness of the electrolyte | 0.015 cm |
| Thickness of the cathode | 0.005 cm |
| Pressure ratio of the blowers | 1.18 |
| Isentropic efficiency of the blowers | 0.53 |
| Pressure ratio of the pump | 1.2 |
| Isentropic efficiency of the pump | 0.8 |
| Inverter efficiency | 0.95 |

One of the most important factors affecting the performance of the System-I is the moisture content of the biomass. The more moisture content of the biomass is, the more energy demand for the dryer is. Hence, steam produced in the HRSG decreases with an increase in the energy demand of the dryer; which in turns decreases the power produced in the steam turbine and the electrical and exergetic efficiencies of the system. It is found that as the moisture content of the wood increases from 0% to 50%, electrical efficiency of the system decreases from 15.6% to 0%; whereas exergetic efficiency of the system decreases from 13.5% to 0%.

In System-II, the syngas composition is first calculated as: 2.08% $CH_4$, 42.75% $H_2$, 25.80% CO, 9.44% $CO_2$ and 19.93% $H_2O$. Using this composition and the data given in Table 1, the SOFC model is simulated. It is found the fuel utilization of the SOFC is 82%. The current density distribution is shown in 2. According to this figure, the average current density of the cell is 0.253 A/cm$^2$ for the cell operating voltage of 0.7 V.

As shown in Figure 3, the electrical and exergetic efficiencies of the System-I are found as 8.3% and 7.2%, respectively; whereas the electrical and exergetic efficiencies of the System-II are found as 44.9% and 41.1%, respectively.

The environmental impact of the systems studied is compared calculating the specific GHG emissions from these systems. It is found that System-I has higher GHG emissions compared to System-II. As shown in Figure 4, the specific GHG emissions from System-I and System-II are 4.564 g-$CO_2$.eq/Wh and 0.847 g-$CO_2$.eq/Wh, respectively.

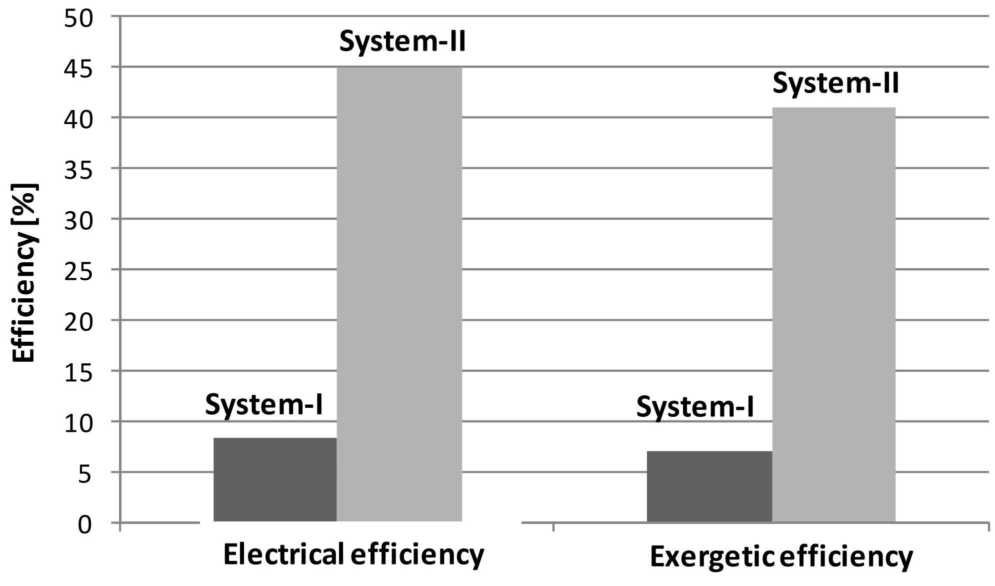


**Figure 3: Electrical and exergetic efficiencies of the System-I and System-II.**

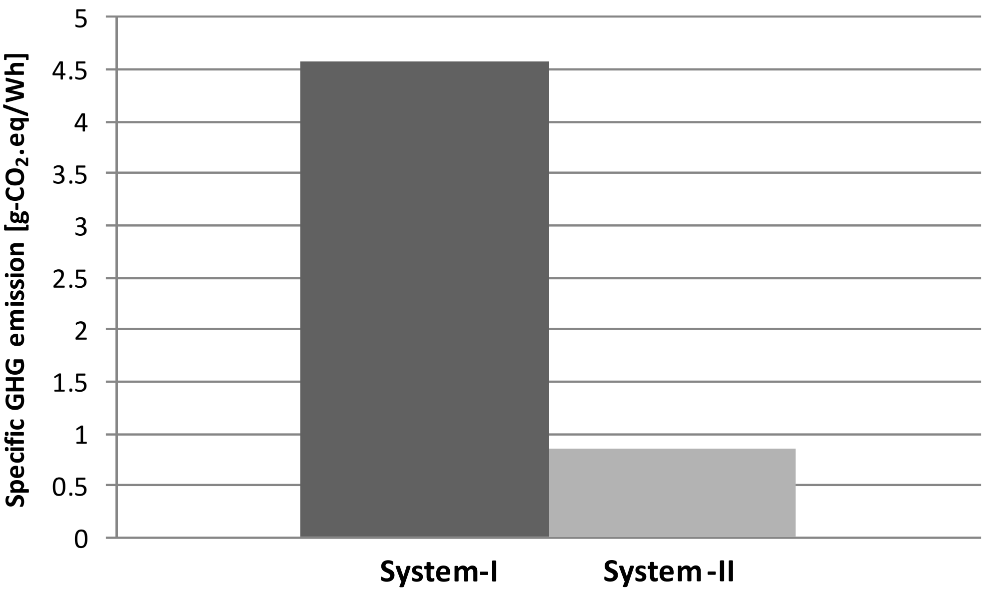


**Figure 4: Specific GHG emissions of the System-I and System-II.**

## 5 Conclusions

In this paper, the performance and environmental impact assessments of an advanced biomass gasification and SOFC system are conducted, and the results are then compared with a conventional biomass fueled power production system using steam turbine as the electricity generator. A joint model including heat transfer model for the SOFC and thermodynamic models for the rest of the components of the systems is used in the analyses. The results of the case study conducted show that the SOFC and biomass gasification system has higher electrical and exergetic efficiencies, and lower specific GHG emissions. This study has pointed out that gasifying the biomass and then using the product gas in SOFC for electricity production is a very efficient way to obtain better performance and lower GHG emissions.

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