

Modeling Heat and Power Generation for Green Buildings based on Solid Oxide Fuel Cells and Renewable Fuels (Biogas)

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Abstract

The use of green buildings is increasing these days, and many activities have been done in order to improve the efficiency of this type of constructions by the advancement of this technology. Fuel cells are an equipment that are used to generate power and heat for residential buildings in the recent years. For this purpose, in this work, a building in a cold region was studied. The fuel of a fuel cell was provided from renewable fuel reforming, which fermented waste and wastewater. First, a SOFC modeling was carried out, which was fed by biogas from a building waste. The modeling results of the renewable-fuel fuel cell of this building showed that 72% of electricity and 13% of the required heating could be provided using its wastes. All in all, using biogas that was produced from building waste, most of the required power and a part of the required hot water could be provided, and the environmental pollution was reduced by utilizing waste and trash. This utilized all the wastes of the building for biofuel production and also provided the majority of the electricity and heating demand of the building.

Keywords: Green buildings; fuel cells; renewable fuels; environmental pollution; biogas.

1. Introduction

By the growth in the use of green buildings and technology, several solutions have been proposed to meet the human energy needs. It is known that increasing the energy efficiency will reduce the environmental pollution [1]. Application of renewable energy resources such as fuel cells would be an efficient way to reduce carbon dioxide and other pollutants [2, 3].

The main purposes of a green building design are optimization of energy consumption and reducing the environmental pollution. Since the fuel cells are highly efficient power generators, and also have a significant amount of produced heat (solid oxide and molten carbonate cells, in particular), they can be a viable option for powering buildings. On the other hand, their pollution is inconsiderable [4, 5]. For this purpose, by installing a high-temperature fuel cell setup in a building, the city gas or biogas (that is mainly methane) could be utilized as a fuel. The required heat and power of the building will be generated with the least amount of environmental pollution. If the same amount of power (electricity) is generated by combined cycle plants, and to provide the required heat of the buildings combustion equipment, a high environmental

pollution will occur [5]. If the fuel cell utilizes biogas as the fuel (a renewable fuel that is produced from fermentation of waste, etc.), all the mentioned disadvantages could be solved.

In 2013, Wongchanapai *et al.* studied the hybrid system of solid oxide fuel cell and gas turbine by biogas feed. They studied the operational parameters of fuel utilization, turbine inlet temperature, and compressor compression ratio. They also studied the operational parameter impact on the overall performance of the hybrid system, heat to power ratio, and turbine to fuel cell power ratio [6].

In 2017, Hagen *et al.* investigated the performance of a biofuel-based solid oxide fuel cell. They compared the steam and dry biofuel reforming and studied their impacts on the improvement of the system performance. They reported a 3-hour fuel cell operation by biofuel steam reforming [7].

In 2018, Ramírez-Minguela *et al.* studied several fuels including biofuels produced from agricultural products and industrial waste, and their use in solid oxide fuel cells. They performed a thermodynamic analysis and reported that approximately 40% of the entropy generation of the fuel cell was related

to the drop in ohmic, concentration, and polar voltages in the fuel cell, and 30% of the total entropy generation was due to methane reforming and shifting. They also presented that the maximum produced entropy was related to the methane fuel [8].

In 2009, Ghaffarpour and colleagues [9] carried out the thermodynamic and economic analysis of an integrated system of solid oxide fuel cell, gas turbine, and Rankine cycle, the fuel of which was fed from a biomass gasification unit. By studying the thermodynamic parameters of the systems such as the operating pressure and temperature, fuel flow, current density, and compression ratios, and also their impacts on the system performance and total costs, they found that the fuel produced from the Pine Saw Dust resulted in a better economic and

thermodynamic performance than the fuel derived from solid municipal waste and poultry waste [9]. Biogas is one of the renewable energy resources that can help with the production of agricultural fertilizers and increase the level of public health and control diseases, and also is a perfect solution for solid waste disposal [10]. This gas can be extracted from the decomposition of human and animal excreta and vegetable and organic wastes by aerobic or anaerobic methods. In the anaerobic method, no energy is used to produce the gas, and a great amount of energy is produced in the form of biogas [10]. Table 1 presents the composition of biogas.

Application of biogas in residential buildings reduces pollution and fossil fuels by utilizing waste and trash from building, and can be used in the heat and power system [11].

Table 1. Composition of biogas [12, 13].

Components	Household waste	Wastewater treatment plants sludge	Agricultural waste	Waste of agrifood industry
CH ₄ % vol.	50-60	60-75	60-75	68
CO ₂ (%vol.)	34-38	19-33	19-33	26
N ₂ (%vol.)	0-5	0-1	0-1	-
O ₂ (%vol.)	0-1	< 0.05	< 0.05	-
H ₂ O (%vol.)	6 (@ 40 °C)	6 (@ 40 °C)	6 (@ 40 °C)	6 (@ 40 °C)
Total (%vol.)	100	100	100	100
H ₂ S (mg/m ³)	100-900	1000-4000	3000-10000	400
NH ₃ (mg/m ³)	-	-	50-100	-
Aromatics (mg/m³)	100-800	-	-	-

In this work, we tried to model a solid oxide fuel cell for a residential complex, which was fed by renewable fuel. By applying this system, the power and heating requirements with a high efficiency and the lowest environmental and pollution was provided. On the other hand, energy losses decreased, and energy recovery of wastes increased. In this work, both the power (electrical) and heating demands were considered. Due to the

amount of produced waste and the corresponding biogas, a great amount of the building energy demand was provided.

2. Materials and Methods

In order to study this case, a student dormitory in the city of Tabriz with a population of 220 was considered. Table 2 presents the data about the amount of waste disposal.

Table 2. Building properties.

Variable	Amount
Population	220
Amount of biodegradable waste production	380 kg/day
Produced wastewater	230 kg/day
Power consumption	180 kW
Heat required for heating and hot water	1583 kW

The residential complex had a restaurant for its 220 inhabitants. A part of wet waste was related to this restaurant and the rest was related to waste production in the complex. The amount of waste water was assumed to be equal to the amount of consumed water that could also produce some methane gas.

In order to calculate the building heat load, according to the calculations presented in reference [14], in terms of the floor area, the building heat load could be calculated as follows:

$$Q_1(kw) = 0.094A$$

in which parameter A is the area of the building. In our case, A is equal to 4700 m² and the amount of heat for hot water per person is:

$$Q_2(kw) = 1.172C$$

in which C is the number of people in the building, and sum of Q_1 and Q_2 results in the total heat requirement of the building.

A schematic representation of the solid oxide fuel cell is depicted in figure 1. Assumptions in modeling the SOFC process are as follow:

- The system is in a steady state.
- The temperature is constant.
- The temperature, pressure, concentrations, and flow velocities in the channels are uniform.
- The reformer pressure drop is negligible.

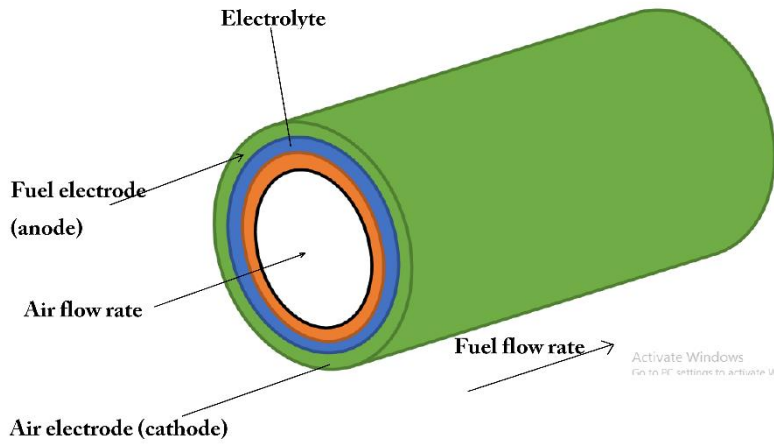
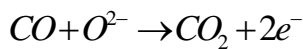
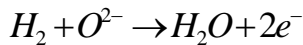


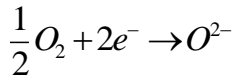
Figure 1. Tubular SOFC.

The fuel cell reactions are as follow:

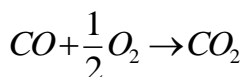
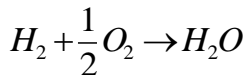
Anode:



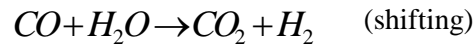
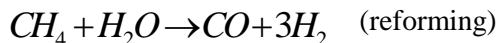
Cathode:



Overall:



In the internal reforming process, carbon monoxide and methane could be utilized as the fuel. The reaction of the reforming process is totally endothermic. The required heat is obtained from the fuel cell. The reactions are as follow:



In the reforming reaction, the natural gas (methane) is reformed to hydrogen in the fuel cell, and hydrogen participates in the electrochemical reactions of the fuel cell [15].

It was assumed that the reactions of reforming and shifting, and the overall reactions were in equilibrium [16]. Therefore, the equilibrium values for the reactions could be determined as x, y, and z by these equations:

$$K_{ref}(T_{outlet}) = \frac{n_{H_2}^3 n_{CO}}{n_{H_2O} n_{CH_4}} \left(\frac{P_{cell}}{P_0} \right)^2 \quad (1)$$

$$K_{shift}(T_{outlet}) = \frac{n_{H_2} n_{CO}}{n_{H_2O} n_{CO}} \quad (2)$$

$$z = U_f (n_{H_2, inlet} + 3x + y) \quad (3)$$

As K_{ref} is the reaction constant of the reforming reaction of water steam and methane, K_{shift} is the reaction constant of the shifting reaction. x , y , and z are the progress degrees of the methane reforming and shifting and overall reactions, respectively, and U_f is the fuel utilization factor. x , y , and z are the molar rates of the reaction, and by calculating them, we have [16]:

$$n_{CH_4} = n_{CH_4,inlet} - x \quad (4)$$

$$n_{H_2O} = n_{H_2O,inlet} - x - y + z \quad (5)$$

$$n_{CO} = n_{CO,inlet} + x - y \quad (6)$$

$$n_{H_2} = n_{H_2,inlet} + 3x + y - z \quad (7)$$

$$n_{O_2} = n_{O_2,inlet} - \frac{z}{2} \quad (8)$$

$$n_{CO_2} = n_{CO_2,inlet} + y \quad (9)$$

It was assumed that only hydrogen reacts electrochemically. The cells were connected in series. Thus the total voltage was equal to the voltage of each cell, and the total electrical current was equal to summation of all the currents. The fuel cell voltage was effected by:

1. operational temperature and pressure
2. anode, cathode, electrolyte, and inter connection width
3. the material of the fuel cell
4. the geometry of the fuel cell
5. the length of the fuel cell
6. the U_f
7. the fuel and air consumption values
8. current density

The voltage of a cell could be defined as a function of temperature, current density, pressure, chemical composition of the reactants, and the geometry of the fuel cell, which is expressed as the difference of the reversible voltage and voltage losses:

$$V = E - V_{act,A} - V_{act,C} - V_{ohm} - V_{conc,A} - V_{conc,C} \quad (10)$$

in which V is the main voltage of the fuel cell, E is the maximum theoretical voltage of the fuel cell, $V_{act,A}$ is the activation voltage of the anode, $V_{act,C}$ is the activation voltage of the cathode, V_{ohm} is the ohmic voltage loss, $V_{act,A}$ is the concentration voltage loss of the anode, $V_{act,C}$ and is the concentration voltage loss of the cathode. By the reaction of each mole of hydrogen, 2 moles of electrons were generated. Thus the maximum theoretical voltage of the fuel cell can be defined as:

$$E = -\frac{\Delta \bar{g}_f^0}{2F} \quad (11)$$

in which $\Delta \bar{g}_f^0$ is the Gibbs free energy changes in standard pressure and F is the Faraday's constant (96,439 C/moles of electrons). Thus the reversible voltage can be calculated by the Nernst equation, as follows:

$$E = -\frac{\Delta \bar{g}_f^0}{2F} + \frac{RT}{2F} \ln \frac{a_{H_2} a_{O_2}^{1/2}}{a_{H_2O}} = E_0 + \frac{RT}{2F} \ln \frac{a_{H_2} a_{O_2}^{1/2}}{a_{H_2O}} \quad (12)$$

in which E_0 is the electrical potential in standard pressure, and α_{H_2} , α_{O_2} and α_{H_2O} are the hydrogen, oxygen, and water activities, respectively. As SOFCs operate in high temperatures, the gases could be assumed to be ideal gasses. Thus the Nernst equation can be simplified as follows:

$$E = E_0 + \frac{RT}{2F} \ln \frac{p_{H_2} p_{O_2}^{1/2}}{p_{H_2O}} \quad (13)$$

in which p_i is the partial pressure of hydrogen, oxygen, and water. In order to perform the electrochemical reactions, the activation energy or polarization should be obtained. This is directly related to the reaction kinetics. The activation polarization for anode and cathode can be calculated by the Butler-Volmer equation, as follows [8]:

$$i = i_0 \left[\exp\left(\alpha \frac{n_e F}{RT_s} V_{act}\right) - \exp\left(-\left(1-\alpha\right) \frac{n_e F}{RT_s} V_{act}\right) \right] \quad (14)$$

in which i is the current, i_0 is the exchange current (mA/cm^2), α is the charge transfer coefficient, n_e is the number of moles of electrons per each reacted mole of hydrogen, T is the solid structure, and V_{act} is the activation voltage loss.

The exchange current density of two electrons could be calculated as follows:

$$i_{0,anode} = \gamma_{anode} \left(\frac{p_{H_2}}{P_{ref}}\right) \left(\frac{p_{H_2O}}{P_{ref}}\right) \exp\left(-\frac{E_{act,anode}}{RT_s}\right) \quad (15)$$

$$i_{0,cathode} = \gamma_{cathode} \left(\frac{p_{O_2}}{P_{ref}}\right)^{0.25} \exp\left(-\frac{E_{act,cathode}}{RT_s}\right) \quad (16)$$

in which γ_{anode} and $\gamma_{cathode}$ are the current density constants (mA/cm^2), and the reference pressure is assumed to be 1 bar. The amount of exchange current density increases by increasing the operational temperature or by applying low activation energy catalysts [17].

In high amounts of activation voltage loss, the second term in the Butler-Volmer equation could be neglected, and thus the equation can be simplified as:

$$\Delta V_{act} = A \ln \left(\frac{i}{i_0} \right) \quad (17)$$

n which A is the active area (cm^2), and is equal to:

$$A = \frac{RT_s}{n_e \alpha F}$$

The summation of these losses is:

$$\Delta V_{tot} = (A_{anode} + A_{cathode}) \ln \left(\frac{i}{\left(\frac{A_{anode}}{i_{0,anode}} \right)^{A_{anode} + A_{cathode}} \left(\frac{A_{cathode}}{i_{0,cathode}} \right)^{A_{anode} + A_{cathode}}} \right) \quad (18)$$

If the amount of activation voltage loss is low, the Tafel equation could be expressed as a first-order Taylor expansion:

$$\Delta V_{act} = \frac{RT_s}{n_e \alpha F} \left(\frac{i}{i_0} \right) \quad (19)$$

The gas partial pressure decreases when it enters the electrodes. The partial pressure of the gases in this region gets lower than the main flow pressure, and a voltage loss occurs as a result, which is named the concentration voltage loss (concentration polarization). This pressure drop is calculated by:

$$V_{conc} = \frac{RT_s}{2F} \log \left[\left(i - \frac{i}{i_{l,H_2}} \right) \left(i - \frac{i}{i_{l,O_2}} \right)^{0.5} \right] \quad (20)$$

in which i_{l,H_2} and i_{l,O_2} are the limiting current densities of hydrogen in anode and oxygen in cathode. These values can be calculated as follow:

$$i_{l,i} = \frac{n_e - F}{v_i} \frac{C_{i,0}}{i} \frac{A_{cell}}{h_m} \quad (21)$$

in which n_e is the number of electrons participating in the electrochemical reaction, $C_{i,0}$ is the concentration of the substance i in the bulk flow (Kg/m^3), v_i is the stoichiometric coefficient in the reaction of the substance i , $i_{l,i}$ is the limiting current density of the substance i , h_m is the mean penetration factor, and A_{cell} is the active area of the cell [17].

$$A_{cell} = \pi L_{cell} d_0^{cell} \quad (22)$$

in which L_{cell} is the length of the fuel cell and d_0^{cell} is the outer diameter of the cell. In order to solve the V_{conc} equation, we have:

$$i_{l,H_2} = 2F \frac{C_{H_2,0}}{i} \frac{A_{cell}}{h_{m,H_2}} \quad (23)$$

$$i_{l,O_2} = 4F \frac{C_{O_2,0}}{i} \frac{A_{cell}}{h_{m,O_2}} \quad (24)$$

$$C_{H_2,0} = \frac{\bar{y}_{H_2}^{anode} p_{cell}}{RT_{cell}} \quad (25)$$

$$C_{O_2,0} = \frac{\bar{y}_{O_2}^{cathode} p_{cell}}{RT_{cell}} \quad (26)$$

$$\bar{y}_{H_2}^{anode} = \frac{\bar{y}_{H_2,i}^{anode} + \bar{y}_{H_2,o}^{anode}}{2} \quad (27)$$

$$\bar{y}_{O_2}^{cathode} = \frac{\bar{y}_{O_2,i}^{cathode} + \bar{y}_{O_2,o}^{cathode}}{2} \quad (28)$$

in which $\bar{y}_{H_2}^{anode}$ is the mean mole fraction of hydrogen, $\bar{y}_{O_2}^{cathode}$ is the mean mole fraction of oxygen, $\bar{y}_{H_2,i}^{anode}$ is the inlet mole fraction of hydrogen, $\bar{y}_{H_2,o}^{anode}$ is the outlet mole fraction of hydrogen, $\bar{y}_{O_2,i}^{cathode}$ is the inlet mole fraction of oxygen, and $\bar{y}_{O_2,o}^{cathode}$ is the outlet mole fraction of oxygen.

Ohmic polarization is because of the resistance against the flow of oxide ions and electrons. The ohm law expresses that there is a linear relationship between the voltage and current density based on a series circuit between anode, cathode, electrolyte, and connections, presented in Ref. [16] as follows:

$$V_{ohm} = i \sum_{j=1}^4 r_j \quad (29)$$

in which i is the cell current density and r_j is the special surface resistivity defined as:

$$r_j = \rho_j \delta_j \quad (30)$$

$$\rho_{anode} = \xi_{anode} \exp \left(\frac{\lambda_{anode}}{T} \right) \quad (31)$$

$$\rho_{cathode} = \xi_{cathode} \exp \left(\frac{\lambda_{cathode}}{T} \right) \quad (32)$$

$$\rho_{electr} = \xi_{electr} \exp \left(\frac{\lambda_{electr}}{T} \right) \quad (33)$$

$$\rho_{interconn} = \xi_{interconn} \exp \left(\frac{\lambda_{interconn}}{T} \right) \quad (34)$$

in which the experimental constant ρ_i is the exponential coefficient of resistance (Ωcm) and λ_i is the exponential resistance (K); Ref [18] has presented these values. The total cell voltage could be calculated by Equation 12. Thus for the power calculations, we have:

$$I_{cell} = iA_{cell} \quad (35)$$

$$Power_{dc-cell} = V_{cell} \times I_{cell} \quad (36)$$

The number of cells and AC power are calculated as follow:

$$I_{tot} = 2Fz \quad (37)$$

$$Power_{ac-cell} = Power_{dc-cell} \times \eta \quad (38)$$

$$n = \frac{Power_{dc-tot}}{Power_{dc-cell}} \quad (39)$$

in which n is the cell numbers and η is the efficiency of the DC to AC current conversion that is equal to 9.0.

As the reforming reactions is an endothermic reaction and shifting and electrochemical reactions are exothermic, by driving energy balance equations, the fuel cell total heat could be calculated [19, 20].

$$\dot{Q}_r = x(\bar{h}_{CO} + 3\bar{h}_{H_2} - \bar{h}_{CH_4} - \bar{h}_{H_2O}) \quad (40)$$

$$\dot{Q}_{sh} = y(\bar{h}_{CO_2} + \bar{h}_{H_2} - \bar{h}_{CO} - \bar{h}_{H_2O}) \quad (41)$$

According to the heat of electrochemical reaction, the total produced heat is [20]:

$$\dot{Q}_{elec} = zT\Delta S - I\Delta V_{loss} \quad (42)$$

$$\dot{Q}_{net} = \dot{Q}_{elec} + \dot{Q}_{sh} - \dot{Q}_r \quad (43)$$

Tabl 3. Fuel cell properties.

Parameter	Value
Cell area (m^2)	1036
Pressure (bar)	1
Stack temperature (K)	1273
Current density ($\frac{A}{m^2}$)	3000
Fuel utilization	85
Fuel flow rate ($kmol/hr$)	86.3
Air flow rate ($\frac{kmol}{hr}$)	3885

The fuel flow rate is exactly equal to the methane produced by the residential waste and trash.

3. Results and Discussion

According to the modeling results, the effect of the fuel cell temperature on the current density and power is depicted in figure 2. In other words, the

fuel cell power is related to the temperature and current density, and if current density increases more than expected, the fuel cell power reduces suddenly. As shown in figure 3, the fuel cell power increases with increase in the temperature but the maximum power occurs in a specific voltage.

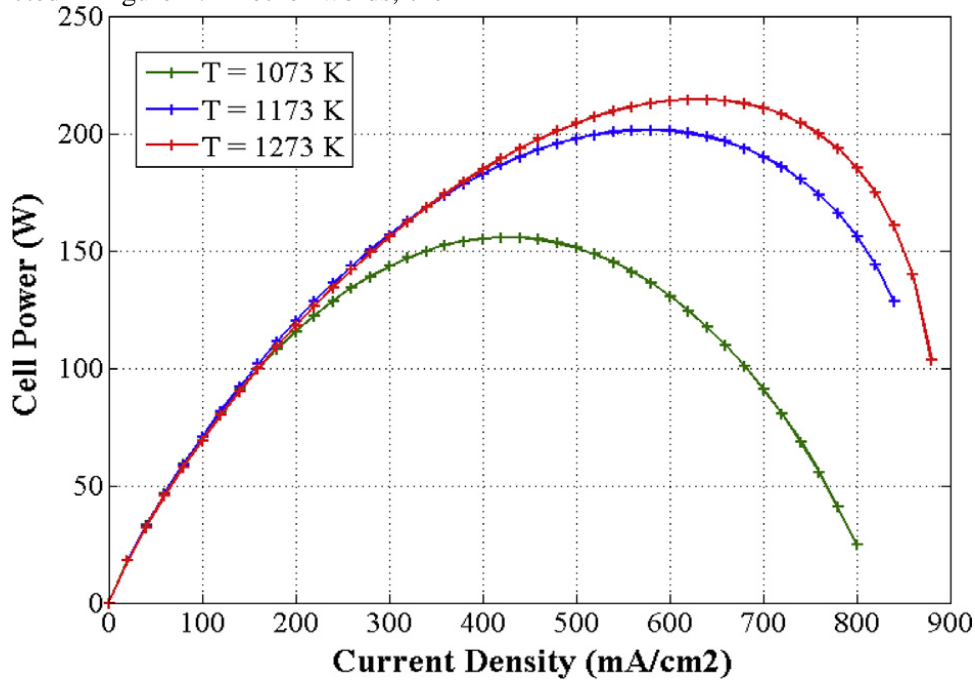


Figure 2. Fuel cell power changes with the current density and temperature.

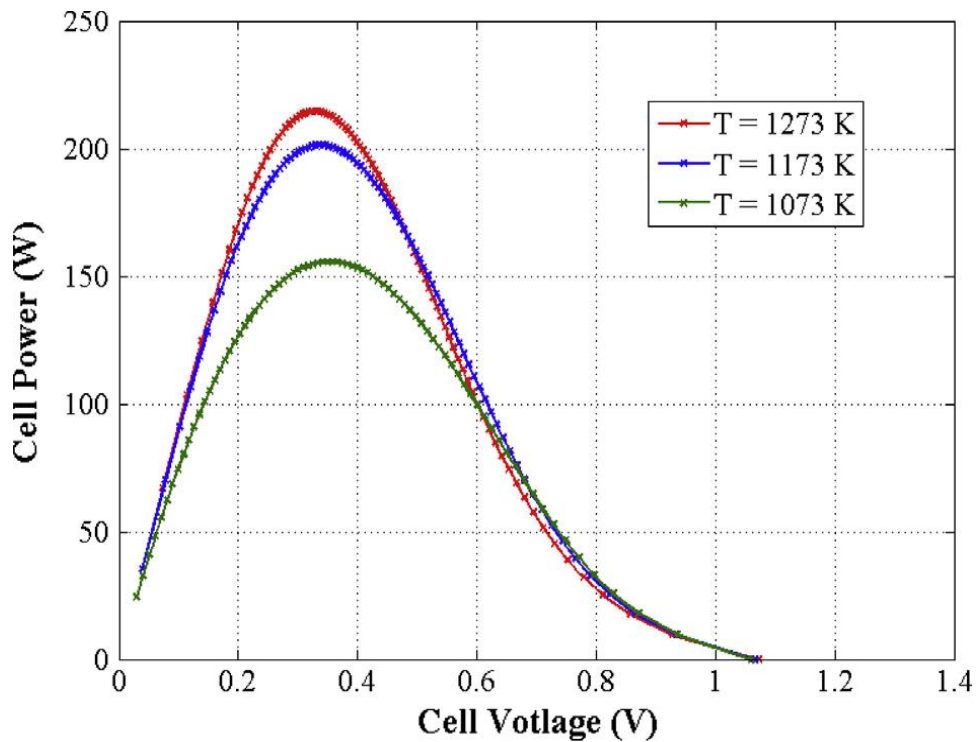


Figure 3. Fuel cell power changes with temperature in different voltages.

Figure 4 shows the fuel cell power changes with the fuel flow rate. The fuel cell power increases with increase in the fuel flow rate. However, according to the former calculations, the amount of produced

methane by the wastes was equal to 0.3885 kmol/hr, and the aim of this work was to provide fuel gas by renewable approaches.

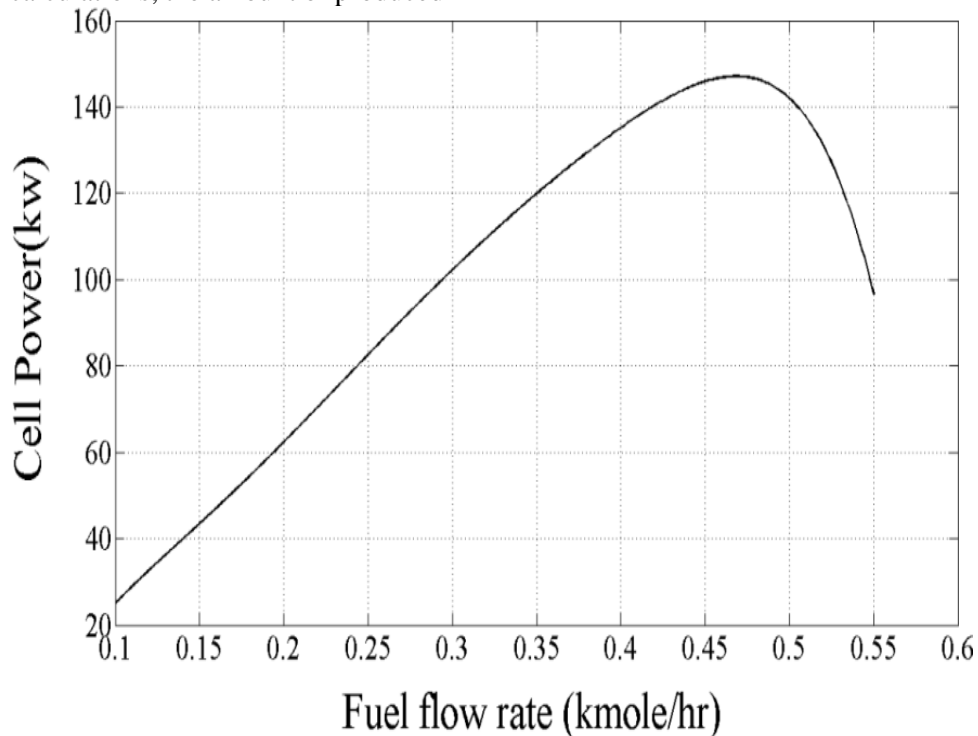


Figure 4. Fuel cell power changes with fuel flow rate.

Considering the methane produced by the residential waste fermentation process as fuel, and

the optimum air to fuel ratio of 10:1 [21], the modeling results is presented in table 4.

Table 4. Modeling results of the fuel cell.

Parameter	Value
Output power (kW)	130
Output heat (kW)	215
Number of cells	742

4. Conclusion

According to the modeling results:

- Using waste and trash of the residential building, 72% of the electricity could be provided.
- More than 13% of hot water of the complex could be provided in the winter.
- The amount of pollution of the fuel cell was very low.
- The trash produced by the people in the building was used in an optimum method, and residue of the process could be used as heavy fuel.
- This system reduced the use of natural gas (city and stationary).

As concluded from the modeling results, if the trash and waste of a residential building is used in order to produce and provide the renewable fuel of a high temperature solid oxide fuel cell, most of the required power and a part of the required hot water could be provided (72% of the electricity and more than 13% of hot water of the complex could be provided). On the other hand, the environmental pollution was reduced by utilizing waste and trash and the low pollution SOFC technology.

Nomenclature

A	Area (m ²)
A	Activity
$C_{i,0}$	Concentration of the <i>i</i> th substance
d_0^{cell}	Outer diameter of the cell (m)
D_{eff}	Effective gas diffusion factor (m ² s ⁻¹)
E	Reversible voltage of the fuel cell (V)
E_0	Fuel cell voltage under standard conditions (V)
F	Faraday's constant (96485 C mol ⁻¹)
h	Specific enthalpy (kJ kmol ⁻¹)
i	Current density (Am ⁻²)
i_0	Exchange current density (Am ⁻²)
i_L	Limiting current density (Am ⁻²)
I	Current (A)
K	Reaction constant
L	Electrode thickness (m)
M	Molecular weight (kg kmol ⁻¹)
N	Molar flow rate (kmol hr ⁻¹)
n_{cell}	Cell numbers
n_e	Number of electrons

p	Partial pressure (bar)
P	Operating pressure (bar)
$Power$	Electrical power (kW)
Q	Heat generation rate (kW)
r	Ohmic resistance (Ω)
r_j	Special surface resistivity
r_{por}	Average pore radius
R	Universal gas constant (8.134 J mol ⁻¹ K ⁻¹)
T	Cell temperature (K)
U_a	Air utilization factor
U_f	Fuel utilization factor
V_{act}	Activation polarization (V)
V_{cell}	Cell voltage (V)
V_{conc}	Concentration polarization (V)
V_{loss}	Voltage losses (V)
V_{ohm}	Ohmic polarization (V)
x	Molar rates of progress of the cell reforming reactions (kmol hr ⁻¹)
y	Molar rates of progress of the cell shifting reactions (kmol hr ⁻¹)
z	Molar rates of progress of the cell overall reactions (kmol hr ⁻¹)
$\Delta g_f^{\bar{0}}$	Gibbs free energy of formation (kJ kmol ⁻¹)

Greek symbols

α	Charge transfer coefficient
β	Transfer coefficient
δ	Current flow length (m)
ϵ	Porosity
γ	Exchange current
η	Efficiency
ρ	Material resistivity (Om)
τ	Tortusity
ν_i	Stoichiometric coefficients

Subscripts

0	Reference point
A	Anode
C	Cathode
$Cell$	Fuel cell
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
H_2	Hydrogen

H_2O	Steam
N_2	Nitrogen
O_2	Oxygen
elec	Overall reactions
f	Fuel feed
i	Gas species
k	Fuel cell components
r	Reforming reaction
ref	Reforming reaction
s	Solid structure
sh	Shifting reaction
shift	Shifting reaction
tot	Total

Superscripts

an	Anode
ca	Cathode
o	Outlet
i	Inlet

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