Application of Solar Energy and Reversible Solid Oxide Fuel Cell in a Co-Generation System

R. K. Akikur, K. R. Ullah, H. W. Ping, and R. Saidur

***Abstract*—The sustainable energy sources have been concentrated over the last few decades. The solar energy and solid oxide fuel (SOFC) technology will be the promising possibility to tackle the energy poverty and environment pollution. Hence, the solar energy coupling with fuel cell technology can be a green energy solution for the next generation. In this study, a co-generation system is presented using the solar energy and reversible solid oxide fuel cell (RSOFC). The solar energy is used for power supply and steam electrolysis and the solid oxide fuel cell is used for hydrogen production from steam electrolysis as well as electricity and heat from generated hydrogen fuel (H_2).**

***Index Terms*—Solar energy, solid oxide fuel cell, hydrogen, co-generation.**

I. INTRODUCTION

The World Business Council reported, for Sustainable Development 40% of the world primary energy will be used for cooling, heating and providing power, and most of it is from electricity generated at centralized power stations, where at present up to 70% of available energy already lost. That energy is generated by the finite sources like natural gas, coal, unprocessed oil. However, the increasing rate of populations and energy demands are growing faster than the energy generation. Hence to meet the climbing energy demands the world cannot depend only on the limited conventional sources [1]. Therefore, over the last few decades the world has been looking for alternative sustainable energy sources. The SOFC is one of the finding and the finest technologies in order to tackle the energy crisis. The auspiciousness of SOFC is: it can provide both electrical and thermal energy with high efficiency compared to the conventional system. Moreover it has no harmful emission that is another major concern of the world. The operating temperature of SOFC is high (800-1000 ^{0}C) which gives it variety of fuel utilization facilities [2]. Among the fuel of SOFC, hydrogen is the cleanest and environment friendly. The hydrogen production by the endothermic electrochemical reactions of water can possible in reverse SOFC operation. The main advantage of H_2 production at high temperature is, the electricity requirement so as to water electrolysis is significantly low compared to the low temperature system. If the required electrical and heat input could be provided by the non-fossil fuel, CO_2 emission free sources (solar, wind, hydro, biomass, geothermal etc.) the sustainable H_2 production by water electrolysis would be the more promising in economical and cleanliness point of view. In this study, the solar energy is used for H_2 production. Approximately 60% of total emitted solar energy from the sun reaches to the earth surface. If 10% conversion efficiency is considered, about 0.1% of that energy can generate 3000 GW power; the amount is four times larger than the world's total generation capacity [3].

The H_2 production and the electricity generation by a single solid oxide fuel cell make it economically competitive. Some novel studies have also done on dual mode operations of SOFC. For example, Ni *et al.* [4] presented a theoretical model of SOFC in dual mode operations and developed successfully. Jie Guan *et al.* [5] developed a high performance reversible SOFC. They have been tested 10 RSOFC stack over 1000 hours alternating the modes. The project was successful for producing hydrogen and electricity with high efficiency. Recently lots of studies have done to improve the performance of RSOFC such as Rao *et al.* [6] proposed a co-doped BaZrO3 (BZC-x) samples of a single phase air electrode for reversible solid oxide cells and found the polarization resistance promisingly lower. Nguyen *et al.* [7] built a two-cell planar stack in the Jülich F-design with solid oxide cells and demonstrated the reversible operation between fuel cell and electrolysis modes. Zhang *et al.* [8] developed a designed apparatus for testing of single solid oxide cells in both fuel cell and electrolysis modes of operation. Laguna-Bercero *et al.* [9] presented a electrochemical performance of LSCF and LSM/YSZ composites as oxygen electrodes for RSOFC. Both LSCF and LSM/YSZ were shown as good applicants as reversible oxygen electrodes using Scandia stabilized zirconia based cells. He *et al.* [10] studied on a RSOFC, where the RSOFCs with thin proton conducting electrolyte films of BaCe0.5Zr0.3Y0.2O3−δ were fabricated and their electro-performance was characterized with various reacting atmospheres.

From the literature review on RSOFC, it can be concluded that the RSOFC in order to the hydrogen production as well as heat and power generation will be the promising alternative energy solution in future. In this study, the proposed co-generation system is comprises of RSOFC, solar-PV, parabolic trough solar collectors (PTSC). Where, the solar PV is used for the steam electrolysis and the electric

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loads. The PTSC is used for supplying high temperature steam to produce H_2.

II. METHODOLOGY

The proposed system's operation descriptions and the mathematical analysis are presented in this section.

A. System Description

The presented co-generation system operation diagram is shown in Fig. 1.

In this study, the hydrogen is produced and stored using solar energy for steam electrolysis during the daytime to ensure the continuous power supply at night time. The system is considered in three operation modes: a SOFC mode, which is low solar radiation time when the PV and SOFC are used for electric and heat load supply; a solar-solid oxide steam electrolyzer (SOSE) mode, which is high solar radiation time when PV is used for power supply to the electrical load and to the steam electrolyzer to generate H_2; and a SOFC mode, which is the power and heat generation mode of reversible SOFC using the storage H_2 at night time. The system operations of those three modes are described below:

1) Solar-SOSE mode

The higher solar radiation time in the day is solar-SOSE mode. During the time, the system operation is described below:

Water is supplied from the water storage tank to the PTSC where the water absorbs the heat energy provided by the solar collectors. After that the steam is heated by the heat exchanger (HEX)-1 before being fed into the electrolyzers, when the steam gains at least 800 ^{0}C then goes to the cathode of the RSOFC or if the steam gains lower than 800 ^{0}C, it goes through the heater. In this mode the RSOFC works for steam electrolysis.

The solar PV is providing the required electricity to electrolyze the steam for hydrogen production as well as to the electric load during this mode of operation.

The produced H_2 with unreacted steam and O_2 pass through the HEX-1 and releases heat for the steam. After that heat energy (60-100 ^{0}C) extract from the H_2 and the H_2O for the heat load through HEX-3 than they go to the hydrogen tank and water tank respectively.

2) SOFC mode

After the sunset, the night time and until sunrise the SOFC provides electricity for the load using the storage hydrogen as a fuel. The operation of SOFC mode is described below:

The hydrogen from the hydrogen tank is preheated by the preheater initially then goes to the anode of SOFC. Heat energy is provided by the SOFC to heat up the input H_2 at operating temperature. On the other hand air (O_2) is provided to the cathode. After the electrochemical reaction the produced electricity goes to the load and steam goes through the HEX-2 where it releases the heat that is absorbed by the input H_2 when passes through the HEX-2.

3) Solar-SOFC mode

The time of the system operation in a solar-SOFC mode is after the sunrise, early time of the day and to till the sunset, the solar energy collected by the PV modules is used for the loads supply and by the collectors used for thermal storage. And the additional power for the load is delivered by the SOFC. The operation of the SOFC has been described in SOFC mode. For the heat load, PTSC provides the heat energy in this mode of operation and the heat is stored in the heat storage tank.

B. Mathematical Modelling

The mathematical expression of the different parts of the proposed co-generation system is representing in this section. The parametric values of the subsystems given in Table I are used to analyze the system. The details mathematical explanation has found in [3].

TABLE I: VALUES OF INPUT PARAMETERS USED IN THE PRESENT SYSTEM

Parameter	***Value***
Solar thermal subsystem [11]	
Stefane Boltzmann constant,	5.67×10^{-8}
Emittemce,	0.87
Reflectance of the mirror,	0.931
Intercept factor,	0.93
Transmittance of the glass cover,	0.94
Absorbance of the receiver,	0.94
Incidence angle modifier,	1
Collector width, w (m)	3.5
Collector length, L_c (m)	20
Collector outer diameter $D_{c,o}$ (m)	0.09
Solar photovoltaic subsystem [12]	
Temp. coefficient of open circuit voltage at reference solar irradiance, (V/C)	0.248
Temp. coefficient of short-circuit current at reference solar irradiance, (A/C)	0.0054
Reference solar radiation, S_{ref} (W/m^2)	1000
Reference temperature, T_{ref} (^{0}C)	45
Ambient temperature, T_{ab}(^{0}C)	25
Open-circuit voltage, V_{oc} (V)	62
Short-circuit current, I_{sc} (A)	5.4
Voltage at max. power point, V_{mp} (V)	50
Current at max. power point, I_{mp} (A)	5
Module rated power, P (Watt)	250
Solid oxide fuel cell subsystem [13]	
Pressure, P (bar)	1
The pre-exponential factors of cathode, γ_c (A/m^2)	1.344×10^{10}
The pre-exponential factors of anode, γ_a (A/m^2)	2.051×10^{9}
The activation energy level at the cathode, $E_{act,c}$ (J/mol)	1.00×10^{5}
The activation energy level at the anode, $E_{act,a}$ (J/mol)	1.20×10^{5}
Electrode tortuosity,	5.0
Electrode porosity n,	0.4
Average electrode pore radius, r (μm)	0.5
Constant, k (J/K)	1.38×10^{-23}
Electrolyte thickness, L (μm)	50
The thickness of anode, d_{a} (μm)	500
The thickness of cathode, d_c (μm)	50

1) Parabolic trough solar collector

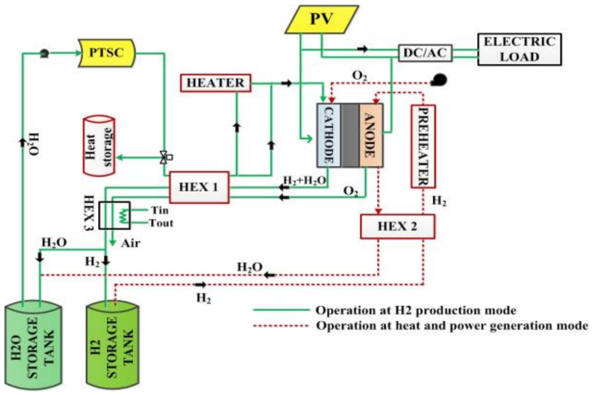

Fig. 1. Block diagram of a solar energy and solid oxide fuel cell based co-generation system.

The mathematical analysis of the parabolic trough solar collector (PTSC) is presented in this sub-chapter [14].

The delivered useful power of the collector is calculated by the following equation.

$$\dot{Q}_u = \dot{m}_r \left(C_{p_{r,o}} T_{r,o} - C_{p_{r,i}} T_{r,i} \right) \tag{1}$$

The power also can be calculated by

$$\dot{Q}_u = A_{ap} F_R \left(S_{r,ar} - \left(A_r / A_{ap} \right) U_L \left(T_{r,i} - T_0 \right) \right) \tag{2}$$

Where the aperture area of the collector A_{ap}, the receivers absorbed radiation $S_{r,ar}$, the heat removal factor F_R and the overall heat loss co-efficient between the ambient and the receiver of the collector U_L can be defined by the Eqs. (3), (4), (5) and (6) respectively.

$$A_{ap} = \left(w - D_{c,o} \right) L_c \tag{3}$$

$$S_{r,ar} = S\,\eta_r \tag{4}$$

$$F_R = \dot{m}_r C_{p_r} / \left(A_r U_L \right) \left(1 - \exp\left(- A_r U_L F_1 / \left(\dot{m}_r C_{p_r} \right) \right) \right) \tag{5}$$

$$U_L = \left(A_r / \left(\left(h_{c,ca} + h_{r,ca} \right) A_c \right) + 1/h_{r,cr} \right)^{-1} \tag{6}$$

In Eq. (5), C_{p_r} and F_1 are the working fluid's specific heat in the receiver and collector's efficiency factor that can defined as

$$F_1 = U_0 / U_L \tag{7}$$

In Eq. (7), U_0 is the overall heat coefficient that can be calculated by the Eq. (12).

$$U_0 = \left(1/U_L + D_{r,o} / \left(h_{c,r,in}\ D_{r,i} \right) + \left(D_{r,o} / \left(2\,k_r \right) \ln\left(D_{r,o} / D_{r,i} \right) \right) \right)^{-1} \tag{8}$$

2) Solar photovoltaic

To design an optimum solar photovoltaic module system for a particular site, the mathematical equations are presented below based on a stochastic method [12].

The total power generated by the PV array is,

$$W_{PV} = V_{PV}\, I_{total} \tag{9}$$

Here, I_{total} is the total current from PV that is defined by,

$$I_{total} = I_{Load} + I_{SOSE} \tag{10}$$

Here I_{SOSE} is the delivered current by the photovoltaic array for steam electrolysis.

The total current delivered by the PV can be evaluated by solving the following equations

$$I_{total} = I_{SC} \left\{ 1 - C_1 \left[\exp\left(\left(V - \Delta V \right) / \left(C_2 V_{OC} \right) \right) - 1 \right] \right\} + \Delta I \tag{11}$$

where ΔV, ΔI are the change of voltage and current of module

The constants C_1 and C_2 in Eq. (17) can be calculated by the Eqs. (18) and (19).

$$C_1 = \left(1 - I_{mp} / I_{SC} \right) \exp\left(- V_{mp} / \left(C_2 V_{OC} \right) \right) \tag{12}$$

$$C_2 = \left(V_{mp} / V_{OC} - 1 \right) / \ln\left(1 - I_{mp} / I_{SC} \right) \tag{13}$$

3) Solid Oxide fuel cell

The output potential at hydrogen production mode and power generation mode can be determined by [13],

$$V^{SOSE} = E + \eta^{SOSE}_{conc,i} + \eta_{ohmic} + \eta_{act,i} \tag{14}$$

$$V^{SOFC} = E - \eta^{SOFC}_{conc,i} - \eta_{ohmic} - \eta_{act,i} \qquad i = a, c \tag{15}$$

The Nernst potential can be determined by the Nernst equation. That can be written as,

$$E = E_0 + RT/(2F) \ln\left[P^0_{H_2} \left(P^0_{O_2} \right)^{1/2} / P^0_{H_2O} \right] \tag{16}$$

where $P^0_{H_2}$, $P^0_{H_2O}$ and $P^0_{O_2}$ are the partial pressure of hydrogen, water and oxygen on the electrode surfaces respectively

The Ohmic over potential is related with the current density *J*, the electrolyte thickness *L*, and the operating temperature *T* as the following equation,

$$\eta_{ohmic} = JL\varphi \tag{17}$$

The activation over potentials can be determined by the Butler–Volmer equation.

$$\eta_{act,i} = \left(RT/F \right) \sinh^{-1}\left(J / \left(2J_{o,i} \right) \right) \tag{18}$$

The concentration overpotential at anode and cathode can be determined by

$$\eta^{SOSE}_{conc,a} = \left(RT/(4F) \right) \ln\left(\sqrt{\left(P^0_{O_2} \right)^2 + \left(JRT\mu d_a / 2FB_g \right)} / P^0_{O_2} \right) \tag{19}$$

$$\begin{aligned} \eta^{SOSE}_{conc,c} &= RT/(2F) \\ &\ln\left(1 + JRTd_c / \left(2FD^{eff}_{H_2O} P^0_{H_2} \right) / \left(1 - JRTd_c / 2FD^{eff}_{H_2O} P^0_{H_2O} \right) \right) \end{aligned} \tag{20}$$

where μ and B_g are the dynamic viscosity of oxygen and the flow permeability

The concentration overpotential equations at anode and cathode in SOFC mode are,

$$\begin{aligned} \eta^{SOFC}_{conc,a} &= -\left(RT/(2F) \right) \\ &\ln\left[1 - \left(RT/(2F) \right) \left(Jd_a / \left(D^{eff}_{H_2} P^0_{H_2} \right) \right) / \left(1 + \left(RT/(2F) \right) \left(Jd_a / \left(D^{eff}_{H_2} P^0_{H_2} \right. \right. \right. \right. \end{aligned} \tag{21}$$

$$\begin{aligned} \eta^{SOFC}_{conc,c} &= -RT/(4F) * \\ &\ln\left[\left(1/P^0_{O_2} \right) \begin{pmatrix} \left(p_0/\delta_{O_2} \right) - \left(\left(p_0/\delta_{O_2} \right) - P^0_{O_2} \right) \\ * \exp\left[\left(RT/(4F) \right) \left(J\delta_{O_2} d_c / \left(D^{eff}_{O_2}\, p_0 \right) \right) \right] \end{pmatrix} \right] \end{aligned} \tag{22}$$

where $D^{eff}_{H_2O}$, $D^{eff}_{H_2}$, $D^{eff}_{O_2}$ (Eq. 21, 22), are the effective diffusion coefficient of water, hydrogen and oxygen respectively.

The heat energy input at H_2 production mode and heat generation from fuel reaction at SOFC mode can be determined by

$$Q_{heat,SOSE} = \left[T\Delta S - \sigma_i \right] \dot{N}_{H_2O,utilized} \tag{23}$$

$$Q_{fcr} = \dot{N}_{H_2} U_f \left(\Delta G - \Delta H_{fr} \right) \tag{24}$$

Here $\dot{N}_{H_2}$ is the mass flow of H_2 and ΔH_{fr} is the heat required by the reforming process from the enthalpy of reaction.

4) Heat exchanger

In this study, counter flow heat exchangers are used to extract the heat energy from the hot fluids. The heat exchanger can be calculated by the effective number of transfer units (ε-NTU) method. The actual heat exchange rate (Q) between two fluid steams can be evaluated by

$$Q = \varepsilon_{eff}\, Q_{\max} \tag{25}$$

For counter flow heat exchangers, the effectiveness is

$$\varepsilon_{eff} = 1 - \exp\left[-NTU(1-C_r)\right] / \left(1 - C_r \exp\left[-NTU(1-C_r)\right]\right) \tag{26}$$

where C_r is the heat capacitance ratio.

III. RESULTS AND DISCUSSIONS

The electricity from solar PV in high solar radiation period of time is utilized for the electric load supply and the steam electrolysis. As we know the power delivered by the PV varies with the solar radiation's intensity. The effects of solar radiation on power generation of solar-PV are shown in Fig. 2, that have been calculated by solving the equation (9) and using the data from Table I. As well as the variations of the solar radiation also effect on the heat energy generated by the PTSC, that can be evaluated by solving the equations given for parabolic trough solar collector. As a result, the existing fluid temperature inside the PTSC's tube changes with the radiation, shown in Fig. 3 where the water flow rate inside the tube is 0.02 kg/s.

In addition, the solar radiation is also the cause of the change of hydrogen production. Considering 1 m^2 of active area of RSOFC with 250W of solar-PV and the input data from Table I, the changes of H_2 production rate with the solar radiation is illustrated in Fig. 4.

According to the literature the cathode supported RSOFC is recommended so as to generate higher electricity on the other hand the anode supported RSOFC is for higher hydrogen production [13]. The anode supported RSOFC has been selected where, the flow rate of H_2O is considered 0.05 mol/s for active area of $1m^2$ to evaluate the temperature effects on the cell. For hydrogen production from steam electrolysis, temperature is one of the vital parameter. Considering the parametric value of RSOFC in Table I, the temperature effects on a single cell has been investigated. The cell potential of SOSE is the summation of the overpotentials and the cell potential increases with increasing temperature. It is because, the Ohmic and activation overpotentials significantly increase with increasing temperature, although the concentration overpotential increases but its effect is very low compared to the other potentials.

In order to calculate the heat requirement it is necessary to know the heat generation by the cell of SOSE through irreversibility (σ_i). After solving the Eq. $Q_{heat,SOSE} = [T\Delta S - \sigma_i]\, \dot{N}_{H_2O,utilized}$ it has been found that the heat production by irreversibility varies with the operating temperature, such as the Fig. 5 is shown at low operating temperature (873 K) the additional heat requirement is not needed above the current density 500 A/m^2 but for higher operating temperature (1273 K) the additional heat is needed for SOSE up to current density 17,000 A/m^2.

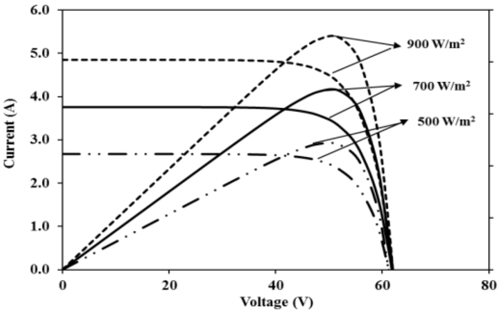

Fig. 2. The variations of voltage, current and power of PV with solar radiations.

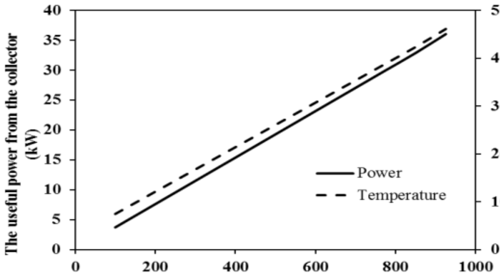

Fig. 3. The variations of the useful power delivered by the PTSC and the existing fluid temperature gain with the changes of solar radiation

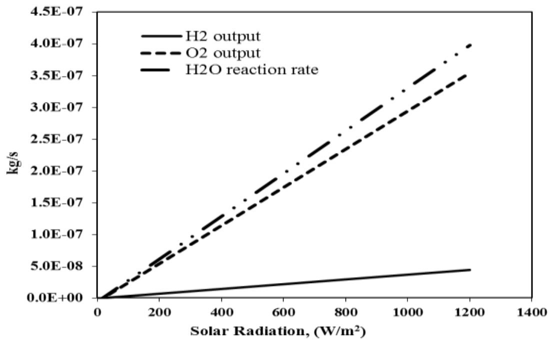

Fig. 4. The variation of H_2 and O_2 generation and H_2O input flow requirement with the change of solar radiation

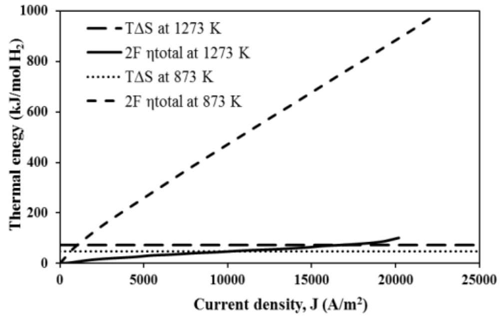

Fig. 5. Comparison of the thermal energy demand and the heat generation caused by irreversible losses at different operating temperature with the variation of current density.

During the night time, few hours before the sun set and after the sun raise the RSOFC works as a SOFC mode where the H_2 and O_2 are supplied as the input. The rate of O_2 utilizations is half of the H_2 utilizations. Fig. 6 shows the fuel cell output voltage and the useful electric power changes with the variation of H_2 flow rate at different temperature. The temperature changes, for the most part, instantaneously reflected in the cell's potential as well as power curve because the current density (J A/m^2) is limited by the cell's operating temperature. The cell potential decreases more rapidly at low temperature than the high temperature because both the activation and the Ohmic overpotential increase with increasing temperature, due to the higher reaction rate. On the other hand, as the temperature rises, polarization may increase due to material constraints. The cell can provide more power at high temperature than the low operating temperature.

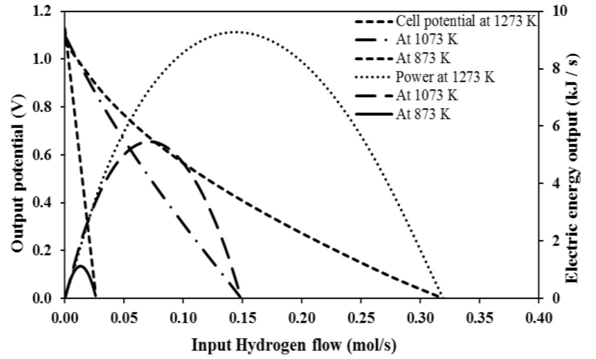

Fig. 6. Effects of H_2 flow rate variation on cell potential and power output of SOFC at different cell operating temperature.

IV. CONCLUSION

The novel concept of a co-generation is presented in this study. The parametric effects on the system components are also illustrated. The hydrogen production during the day time depends on the solar radiation. Alternatively, the changes of solar radiation the electric supply by solar-PV and the steam provided by PTSC are changed; as a consequence the hydrogen production rate is varied. From this study, it can be recommended that the proposed solar energy and the SOFC technology based system will be an alternative energy solution for small to large scale applications such as in hospital, office building, hotel, single or multifamily residential buildings as well as the remote area far from the grid connection.

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