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# Electrochemical Modeling and Techno-Economic Analysis of Solid Oxide Fuel Cell for Residential Applications

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In this paper, an electrochemical model was developed to investigate the performance analysis of a Solid Oxide Fuel Cell (SOFC). The curves of voltage, power, efficiency, and the generated heat of cell have been analyzed to accomplish a set of optimal operating conditions. Further, a sensitivity analysis of major parameters that have a remarkable impact on the economy of the SOFC and its residential applications has been conducted. The results illustrate that the current density and cell performance temperature have vital effects on the system efficiency, output power and heat generation of cell of the SOFC. The best system efficiency is approached up to 53.34 % while implementing combined heat and power generation might be further improved up to 86 %. The economic evaluation results indicate that parameters such as overall efficiency, natural gas price and additional produced electricity that has prone to be sold to the national power grid, have a significant impact on the SOFC economy. The results indicate the strong reduction in the purchasing cost of the SOFC, i.e. not more than $2500, and improving the electrical efficiency of SOFC, i.e. not less than 42 %, can be the breakeven points of investment on such systems in residential applications. Also, it is found that the target of this SOFC cogeneration system for residential applications in Iran is relying on considerable technological enhancement of the SOFC, as well as life cycle improvement; improvement in governmental policies; and profound development in infrastructures to mitigate legal constraints.

## 1. INTRODUCTION

Although a variety of co-generation technologies are available to provide residential buildings demands, individually heating and lighting, employing clean energy generation is still a significant source of energy supply.

Co-generation systems are able to produce two or more forms of useful energy using a primary energy source such as Natural gas. If properly designed and operated, these systems have prone to save energy due to their higher efficiency and lower emissions in comparison to parallel systems. Some systems such as Micro Gas Turbines, Internal Combustion Engines, Stirling Engines, and Fuel cells are considered as Combined Heat and Power (CHP) systems [1-4].

Renewable energy production techniques have been intensively studied in recent years. Since fuel cells inherently produce both electricity and heat simultaneously, they are thoroughly fitted to use in CHP applications. Among these existing technologies, solid oxide fuel cells (SOFC) have been extensively developed. Since SOFC work at high temperatures, this provides the opportunity of the CHP concepts employment and leading to a considerable improvement of the overall system efficiency. This technology also offers special benefits such as the ability to internal fuel conversion and the potential of efficient utilization of the generated heat energy. There are growing appeals for using the SOFC systems applications in small scale and residential buildings in recent years [5-8].

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A techno-economic model for both Polymer Membrane Fuel Cell (PMFC) and SOFC for CHP applications in residential buildings that have been analyzed by Napoli, et al. It has suggested for reducing electricity network dependency, employing PEMFC is more suitable while using SOFC is more appropriate to decrease initial energy consumption [8]. Optimal design and operation of a SOFC cogeneration system for residential applications which was fed by syngas fuel have been evaluated by Yang, et al. in the mentioned study, the ability and capability of a SOFC system for supplying required energy demand of a residential building have examined thoroughly [9]. Longo, et al. [10], have studied the life cycle energy and environmental performances of a SOFC system for residential applications, their results revealed that eco-design solutions of the assessed system can be traced in the improvement of the energy system efficiency and reduction of emissions during the operation, and in the increase of the durability of the system components, thus reducing the number of their substitutions. The results also clarified that in order to avoid concurrent energy generation from conventional sources the recovery of the thermal energy generated by the SOFC is significantly useful [10]. Besides, [11-13] have investigated other applications of SOFC CHP systems in both commercial and residential buildings, as well as employment hybrid concept with Gas Turbine (GT) and Gasifier. Although, the SOFC systems are usually supplied by natural gas, which is converted by means of an internal reformer. This will dramatically reduce the system capital cost since any external fuel processing will be no longer required [12], Employing SOFC and gas turbine (GT), the gaseous fuel can be turned into heat and power. However, the combination of SOFC and GT has yielded higher performance [13, 14]. Ghadamian, et al. [15], proposed a novel hybrid pressurized SOFC/ GT power generation system, fed by biomass to serve in a small-scale industrial application. This hybrid system will provide superior utilization of natural resources that considerably decreases harmful impacts on the environment as well as making higher profit. The results have revealed, employing a decent cooling system such as an absorption chiller for cooling the inlet air will enhance the overall efficiency of combined cycle meaningfully [15].

Although this is now a mature field that is now being spun out into commercial, it has not developed in Iran's energy supplying sector suitably neither in small scale nor power plants.

However, addressing the fundamental challenges of the SOFC such as its cost and life-cycle have a crucial impact on nurturing and mastering this technology in Iran's energy sector which makes it able to compete with existing systems, some impediments such as high investment cost, natural gas price as well as the sale price of surplus electricity to the government are adding fuel to this challenge, too. To our knowledge, there are a variety of studies aimed to analyze SOFC cost, power or efficiency while a few studies might have examined economy of the SOFC versus efficiency, however, this study investigates the impacts of some operating parameters such as the efficiency of the system on the SOFC's economy, thoroughly.

As discussed earlier, a variety of the previous literature has focused solely on the technical aspects of the SOFC technology, whereas the technical and economic aspects of technology are firmly coupled to each other. For this study, it was of interest to investigate a sensitivity analysis on key performance parameters of the SOFC aimed to achieve the best operating conditions, further some pivotal parameter on the economy of the system such as fuel cell purchase cost, operational life-cycle, sell price of surplus electricity to government, and the effect of feeding fuel of the SOFC will be examined and evaluated. Since not all prevailing factors have been comprehensibly studied, it is still necessary to apply a tailored approach. Therefore, this work intends to develop a parametric investigation of a SOFC performance to assist in obtaining appropriate operating conditions and a more sophisticated analysis of the economy of the SOFC system to apply this technology in Iran's energy sector individually in residential sectors.

The main objectives of the present study can be summarized as follows:

(1) development of a validated model depicting a SOFC system behavior to form a basis of economic evaluations.
(2) investigation of the effects of all three polarization losses on the voltage regard to various working conditions.
(3) performing a parametric investigation of the system on key performance parameters of the SOFC aimed to assist finding the best-operating conditions.
(4) study the impact of some pivotal parameters on the economy of the system using in residential applications.

## 2. MATERIAL AND METHODS

### 2.1. SOFC system

The schematic diagram of the electrochemical processes occurring in a tubular SOFC system is illustrated in Figure 1. As can be seen, The SOFC system consists of two Anode and Cathode electrodes separated by a ceramic electrolyte. To conduct negative oxygen ions within the cathode electrode and the anode electrode a solid oxide electrolyte is facilitated. Further, the electrons created at the anode side pass within an external circuit and will introduce to the cathode electrode. Then electrical circuit will be completed and electricity will be generated [16].

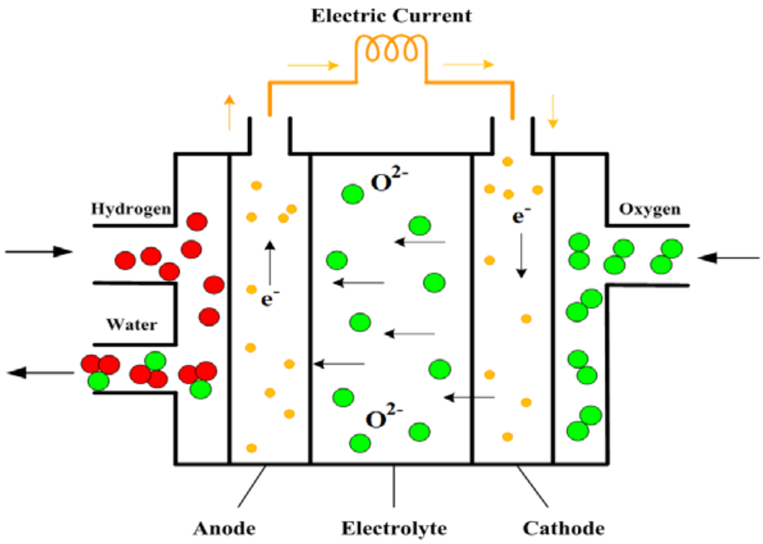


**Figure 1.** The schematic of SOFC system.

### 2.2. Model assumption

Principal assumptions of developing the SOFC system are listed as follows [16, 17]:

- All gases are considered as ideal gas.
- Internal distribution of temperature and pressure is assumed uniform through the SOFC.
- The fuel supplied to the system is assumed to be Natural gas with a composition of 97 % $CH_4$, 1.5 % $CO_2$, and 1.5% $N_2$.
- The air composition, provided for the cathode side is assumed to consist 79 % $N_2$ and 21 % $O_2$.
- By using internal reformer, the fuel inside of the SOFC will be formed into hydrogen.

These assumptions are employed throughout the analysis to derive the corresponding equations of each the SOFC system[16, 17].

## 2.3. System modeling

Among all developed electrochemical models of the SOFC, a zero-dimensional model that has employed in the present study is considered as the most suitable option for analyzing the system performance in terms of both integrity and fast response [16].

One of the key intentions of the developed model is acquiring the voltage variations and current density with an acceptable fluctuation. Briefly, the developed model should comprise the following features:

- Calculation process must be precise and reliable;
- The developed model must provide a vast operating range and running sensitivity analysis;
- The model can be easily integrated into the economic model;

In the present study, some of the influential factors such as the Nernst equation, Activation, Ohmic, and Concentration polarization have taken into consideration. In the economic sector, first and foremost, the mathematical correlation between SOFC investment cost, operation, and maintenance costs with its power generation have examined. Moreover, the financial index will be examined regarding the vital economic parameters of the system. To simulate the model MATLAB environment is used.

### 2.3.1. Electrochemical model of SOFC

In order to analyze the SOFC system parameters, it is crucial to consider a model that is capable of predicting the performance based on its operating condition. The proposed SOFC is built on a tubular design which has been designed and demonstrated by Siemens-Westinghouse [18].

The gas flow will enter the pre-reformer, then reforming and shifting reactions occur, i.e. ($CH_4 + H_2O \leftrightarrow 3H_2 + CO$) and ($CO + H_2O \leftrightarrow H_2 + CH_4$), respectively. As a result, a portion of methane will be turned into hydrogen.

The exhaust gas composition of the internal reformer may be obtained from $k_r$, and $k_s$ constants as follows:

$$k_r = e^{(\Delta G_T/RT)} = \frac{(p_{H_2})^3 \cdot p_{CO}}{p_{CH_4} \cdot p_{H_2O}} \quad (1)$$

$$k_s = e^{(\Delta G_s/RT)} = \frac{p_{H_2} \cdot p_{CO_2}}{p_{CO} \cdot p_{H_2O}} \quad (2)$$

here the subscripts s and r denote the shifting and reforming reactions, respectively, R is the universal gas constant, $\Delta G$ indicates Gibbs free energy at standard conditions for the electrochemical reaction, and the partial pressures of the reacted gas streams is presented by $p_i$ [17].

The fuel utilization factor, $U_f$, is an important parameter that represents the ratio of hydrogen amount consumed in the SOFC to the amount of supplied fuel may be formulated as [17]:

$$U_f = \frac{\dot{z}}{4.\dot{n}_{CH_4} + \dot{n}_{H_2} + \dot{n}_{CO}} \quad (3)$$

where $\dot{z}$ indicates the hydrogen amount that reacted at the electrochemical reaction [17].

The reversible voltage of the SOFC can be obtained by the Nernst equation, as following while the Nernst voltage can be calculated as follows [16]:

$$V_{nernst} = -\frac{\Delta G^0}{2F} - \frac{RT}{2F} \ln \left[\frac{p_{H_2} \cdot p_{O_2}{}^{1/2}}{p_{H_2O}}\right] \quad (4)$$

where F refers to Faraday's constant (96485.33 $C\,mol^{-1}$), cell temperature is introduced by T and p indicates the partial pressure of respective species.

The operating voltage drops when the electric current is drawn from the cell, mainly because of some loss such as ohmic, activation and concentration polarization, which are individually categorized as electrochemical reaction activation, $V_{act}$ ohmic polarization, $V_{ohm}$ and concentration depletion, $V_{Con}$. Operating cell voltage, $V_{Cell}$, can be calculated as following [16]:

$$V_{cell} = V_{nernst} - (V_{act} + V_{ohm} + V_{con}) \quad (5)$$

Chemical reactions, comprising electrochemical reactions, consist of energy restrictions that must be addressed by reacting species. This energy barrier is named the activation energy and appears in activation polarization, the main reason behind this is charges transferring between the electronic and ionic conductors.

Activation polarization can be calculated by the Butler-Volmer equation, expressed as [16]:

$$j = j_0 \left[\exp\left(\frac{\beta n_e F V_{act}}{RT}\right) - \exp\left(-(1-\beta)\left(\frac{n_e F V_{act}}{RT}\right)\right)\right] \quad (6)$$

where j indicates the current density, $\beta$ refers to transfer coefficient, and $j_0$ refers to exchange current density [16].

$$j_0^{an} = \gamma^{an}\left[\left(\frac{p_{H2}}{P^0}\right)\left(\frac{p_{H2O}}{P^0}\right)\exp\left(\frac{E_{act}^{an}}{RT}\right)\right] \quad (7)$$

$$j_0^{ca} = \gamma^{ca}\left[\left(\frac{p_{O2}}{P^0}\right)^m \exp\left(-\frac{E_{act}^{ca}}{RT}\right)\right] \quad (8)$$

here $\gamma$ is denoted pre-exponential coefficient, P is ambient pressure, E refers to activation energy.

Moreover, ohmic polarization which is related with electron and ion transmission processes is determined by the following equations based on ohm's law [16]:

$$V_{Ohm} = i\sum_k r_k \quad (9)$$

$$r_k = \sum_k \frac{\rho_k \delta_k}{A} \quad (10)$$

$$\rho_k = \sum_k a_k \exp^{\left(b_k/T\right)} \quad (11)$$

where $r_k$ is ohmic resistance, $\delta_k$ refers to the current flow length and $\rho_k$ indicates the material resistivity. The coefficients of a and b are the characteristics of component materials [16].

The concentration loss which is a result of the transport of gases to the electrodes will be calculated as [16]:

$$V_{con} = \frac{RT}{2F}\ln\left(1 + \frac{p_{H_2} \cdot j}{p_{H_2} \cdot j_{lim}}\right) - \frac{R.T}{2F} Ln\left(1 - \frac{j}{j_l}\right) \quad (12)$$

while $j_l$ is the limiting current density and j refers to the current density that will be estimated by the following electrochemical reaction [16]:

$$j = \frac{n_e . F . \dot{z}}{A_c} \tag{13}$$

where $n_e$ is the number of electrons that are produced per hydrogen mole by electro-chemical reactions, i.e. ($H_2 + \frac{1}{2} O_2 \rightarrow H_2O$), $A_c$ is the cell activation area and z refers to the number of hydrogen moles per second, which reacts in the electrochemical reaction.

The electrical power generated from the SOFC can be calculated as [16]:

$$\dot{W}_{SOFC} = N . V_{Cell} . j . A_C \tag{14}$$

where N indicates number of cells. Also, the net electrical power of the SOFC can be given as:

$$\dot{W}_{SOFC,net} = \dot{W}_{SOFC} . \eta_{inv} \tag{15}$$

where $\eta_{inv}$ (0.98) is the inverter efficiency [17].

The heat generated from SOFC electrochemical reactions can be calculated by following equation [16]:

$$\dot{Q}_{SOFC} = (\dot{m}_f * U_f * LHV) \tag{16}$$

Overall efficiency of the SOFC can be determined as following [16]:

$$\eta = \frac{\dot{W}_{net}}{\dot{Q}_{tot}} \tag{17}$$

### 2.3.2. Economic model of SOFC

Regarding the investment, operating, maintenance costs, the total annual cost of the system can be calculated by equation (18) [19]:

$$C_t = C_c + C_f + C_m \tag{18}$$

where, $C_t$ is total investment cost, $C_c$ annual investment cost, $C_f$ operation cost and, $C_m$ is maintenance cost.

Also, the annual investment cost, regardless of the cost of replacing the cells over the life-span of the SOFC, can be obtained from the following equation [19]:

$$C_c = C_{FC} \left( \frac{i_r (1 + i_r)^n}{(1 + i_r)^n - 1} \right) \tag{19}$$

here, $C_{FC}$ is SOFC purchase cost regardless of the cost of replacing cells over the its life- span n, and $i_r$ is annual interest rate (%).

Since thermal energy is considered as a by-product of the SOFC and is producing at a constant rate of electrical energy, the cost of production can be formulated as the following equation [19]:

$$C_f = \left( \frac{\gamma_{Ng} . E_{ep}}{\eta} \right) \tag{20}$$

where, $\gamma_{Ng}$ is natural gas price $\$kWh^{-1}$ and η is electrical efficiency.

Although repair and maintenance costs of the SOFC are highly dependent on its technology, in the previous literature is recommended 4 % to 10 % of the SOFC's cost accordingly in this study is assumed 10 % [19].

$$C_f = \left( \frac{\gamma_{Ng} . E_{ep}}{\eta} \right) \tag{21}$$

Further, the cost of each unit of electrical energy production $\$kWh^{-1}$ is calculated by the following equation [19]:

$$\gamma_p = \left( \frac{C_t}{E_p} \right) \tag{22}$$

where, $E_p$ is annual energy production.

In residential applications, part of produced electricity will be consumed, which is signified by $E_{ec}$ and surplus electricity will be sold to the government which is denoted by $E_{es}$ as indicated following [19]:

$$E_p = E_{ec} + E_{es} + E_{th} \tag{23}$$

In this paper, it is assumed that surplus energy produced can be contracted to the government by $\gamma_{es}$ ($), while there is not any appropriate infrastructure for selling the surplus thermal energy to the government, only can be stored in the user home by fascinating a thermal storage energy tank.

The economic value between thermal energy and electrical energy cannot be treated equally as they are priced differently in the market. Assuming consistent energy generation, the annual profit can be calculated from the following equation [19]:

$$B = E_{es}(\gamma_{es} - \gamma_p) + E_{ec}(\gamma_{ec} - \gamma_p) + E_{th}(\gamma_{th} - \gamma_p) \tag{24}$$

where B is the annual profit, $\gamma_{es}$ is the electricity sale price and $\gamma_{ec}$ is the electricity purchase price from the network.

Moreover, the Net Present Value (NPV), which is considered as a significant parameter in the economic evaluations of an energy system can be calculated as follows [19]:

$$NPV = \left( \sum_{t=1}^{n} \frac{B}{(1 + i_r)^t} \right) \tag{25}$$

where t is operation period and $i_r$ is annual interest rate.

NPV can be interpreted as some kind of income the owner of the SOFC generator can get during the whole lifespan of the SOFC, discounted by an interested rate. For example, for a family with a yearly income of $12,000, the $2000 NPV from the SOFC generation means 2 months' additional income for the family.

It should be noted that when the NPV of proposed system is bigger than zero, the economic feasibility of the system can be considered acceptable, otherwise the plan has not offered an economic justification [19].

## 2.4. Solution procedure

The calculation methodology is to first to determine the cell current at a given current density value. The amounts of hydrogen and oxygen required for the electrochemical reaction can be calculated at this identified current amount. Later, the value of utilization factor can be calculated by equations (1-3), then inlet molar flow rates of anode and cathode can be determined. Then, the cell voltage can be found by Nernst equation (4) and then voltage equation (5) at given operating cell temperature and pressure. Finally, heat and electrical power and efficiency will be calculated. More details about calculation procedures of voltage, polarizations and current density may be found in [15, 16].

## 2.5. Simulation and validation

The proposed model developed in the preceding sections is employed to determine and assess the performance of the SOFC system. Input parameters for simulation of SOFC system is presented in Table 1, also more detailed may be found in [16, 17, 19].

Temporal variations of energy demand concerning various factors such as climate, building insulation, and consumption patterns are considered as a principal measure in designing a CHP system. In order to choose an appropriate capacity for the CHP system, it is necessary to determine the electricity and heat demand. On this basis, it is crucial to obtain the electrical and thermal demand curves of a residential building.

**Table 1.** Model input parameters and operating condition [16].

| Parameter | Unit | Value |
|---|---|---|
| Pressure | bar | 1 |
| Temperature | K | 1273 |
| Fuel utilization factor | % | 85 |
| Air utilization factor | % | 16.7 |
| Anode energy activation | kJ kmol$^{-1}$ | 110,000 |
| Cathode energy activation | kJ kmol$^{-1}$ | 155,000 |
| Porosity | % | 30 |

Therefore, in this study it is assumed that the electricity consumption profile for a typical household is alike in Figure 2, similarly the heat consumption profile is given by Figure 3 [19].

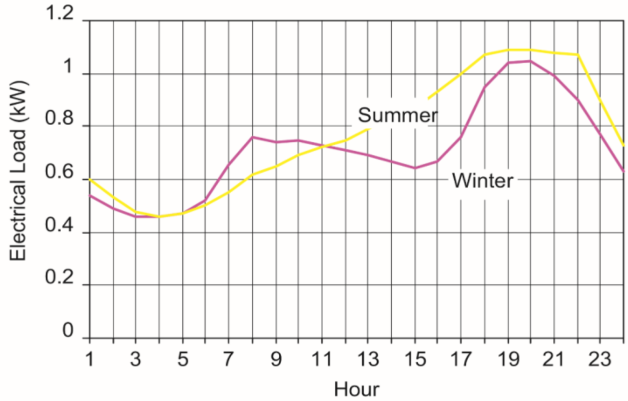


**Figure 2.** Electrical consumption profile a residential building [19].

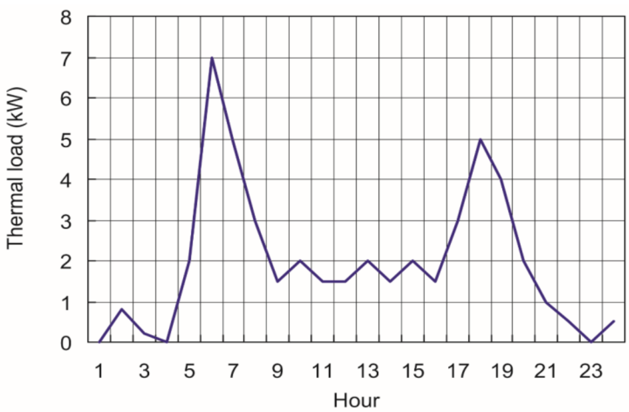


**Figure 3.** Thermal consumption profile of a residential building [19].

In Table 2, some basic economic information of SOFC that use natural gas as fuel is provided.

It is assumed that during the winter season, the recovered thermal energy is used to heat the environment while in the summer season, the SOFC's heat recovered, will be used to produce cold water through a lithium bromide-water absorption cycle, which is fed by hot water.

**Table 2.** Economic model input parameters [19].

| Economic parameter | Value | Unit |
|---|---|---|
| SOFC purchase cost | 4000 | $ |
| Natural gas purchase price | 0.065 | $kWh$^{-1}$ |
| Thermal energy purchase price | 0.05 | $kWh$^{-1}$ |
| Electrical energy purchase price | 0.13 | $kWh$^{-1}$ |
| Electrical energy sale price | 0.16 | $kWh$^{-1}$ |
| Cost of energy production | 0.136 | $kWh$^{-1}$ |
| Interest rate | 5 | % |
| Operating period | 5 | Year |
| Reference Net Present Value | -4239 | $ |

In Table 3, in order to indicate the model validation and accuracy, some simulation results of the proposed model are compared to existing studies [16]. Our results are in a reasonable agreement with counterparts in literature.

**Table 3.** Simulation results of the present study compared to literature [16].

| Parameter | literature | Simulation results | Relative error (%) |
|---|---|---|---|
| Cell voltage (V) | 0.678 | 0.617 | -9.8 |
| DC electrical power (kW) | 187 | 187.53 | 0.28 |
| AC electrical power (kW) | 176 | 175.2 | -0.45 |
| Electrical Efficiency (%) | 57 | 58.47 | 2.57 |

After simulating, the results are compared for cell voltage and power in Figures 4 and 5, respectively. Power at the current density range of 1500-6500 Am$^{-2}$ shows excellent compliance with reference model [16].

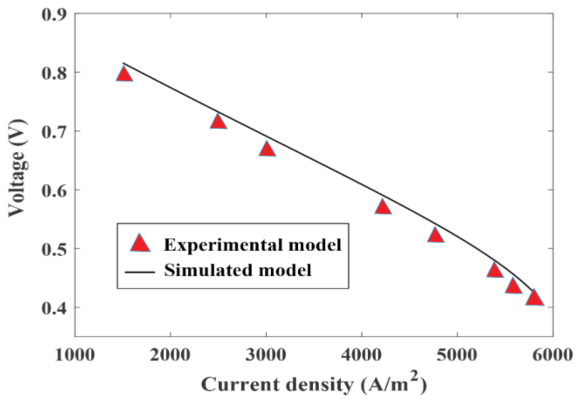


**Figure 4.** Cell voltage comparison of experimental model and simulated model.

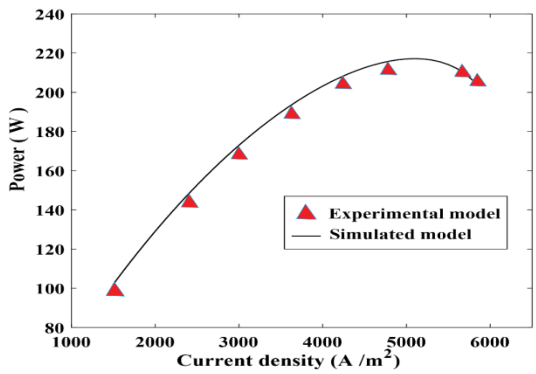


**Figure 5.** Cell power comparison of experimental model and simulated model.

As a result, it can be said that the model demonstrates good capability in evaluating SOFC performance.

## 3. RESULTS AND DISCUSSION

The results of modeling are given first to prove the impact of the operating parameters. Then, sensitivity analysis has been performed on some key operating parameters to determine a situation that makes the SOFC system an affordable and attractive system for residential applications.

### 3.1. Effect of the cell operating temperature variation on ohmic polarization

The influence of the cell operating temperature on ohmic polarization regard to different electrolyte thicknesses is illustrated in Figure 6. Current density is considered as fix parameter with value of 3000 $Am^{-2}$. As shown in Figure 6, increasing temperature leads to decrease ohmic potential loss which is mainly because of the reduction in ohmic resistance. Besides, the increase in electrolyte thickness, will raise the ohmic polarization drop, for example at a constant temperature of 1050 K, the ohmic drop values regard to the thicknesses of 10, 40 and 100 microns are 0.05, 0.09 and 0.2 V, respectively.

As indicated, increasing the electrolyte thickness will affect the length of the current, thus the ohmic resistance will be increased consequently, while its growth rate will be decreased when the temperature has increased. Accordingly, it can be concluded that higher operating temperatures as well as a lower electrolyte thickness will enhance the SOFC performance by reducing ohmic polarization drop.

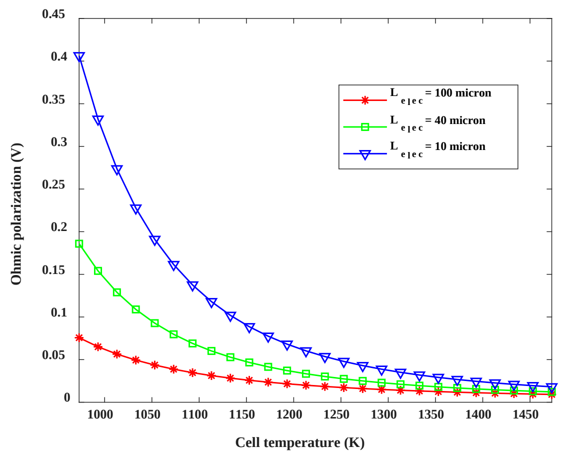


**Figure 6.** The cell operating temperature on ohmic polarization.

### 3.2. Effect of the cell operating temperature variation on activation polarization

The impact of cell operating temperature on activation polarization regard to different activation energy is determined in Figure 7. As it can be observed from Figure 7, activation polarization voltage will be decreased when the operating cell temperature is increasing, particularly in lower activation energy.

Activation energy depends on the cell's temperature and the properties of the material that is used in the electrolyte. In this model, the various values of activation energy from 12000 to 16000 (kJ/kmol) are investigated. As it can be seen, at a constant current density of 3000 $Am^{-2}$, by decreasing cell operating temperature, the activation loss will be raised while increasing cell temperature, will result in activation loss reduction significantly. This occurs mainly because the exchange current will be improved when the cell operating temperature is enhanced. Since higher exchange current density brings a more powerful electrochemical reaction rate, the activation loss will be reduced desirably.

Regarding the above analysis, to reach an improvement in the operating performance of the SOFC, materials with lower activation energy should be practiced for manufacturing purposes.

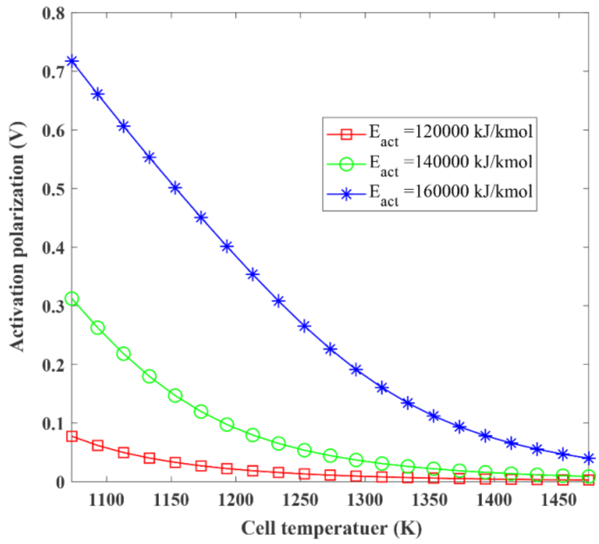


**Figure 7.** The cell operating temperature on activation polarization.

### 3.3. Effect of current density variation on diffusion polarization

The impact of the current density on diffusion polarization with respect to various pore size is examined and the results is shown in Figure 8. Since in concentration polarization, one of the most significant parameters is anode and cathode pore size, concentration polarization is examined concerning different pore sizes. The results prove that under atmospheric conditions, the concentration polarization drop will rise when the pore size diameter increased. For instance, in atmospheric condition and a constant value of 3000 $Am^{-2}$, for current density diffusion polarization is equal to 0.15, 0.25 and 0.5 V for thicknesses of 1.5, 1 and 0.5 microns, respectively.

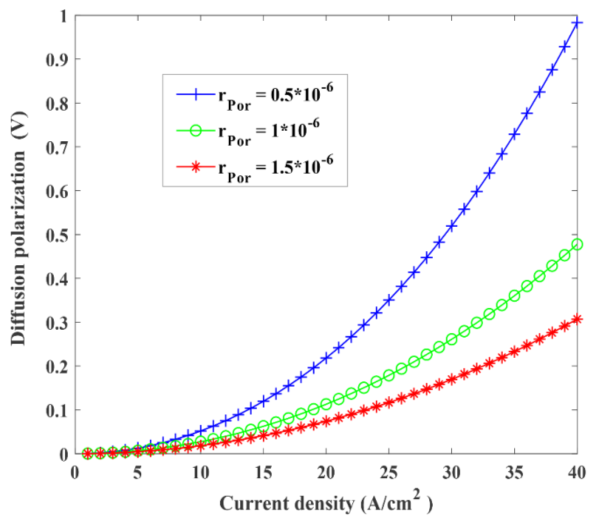


**Figure 8.** The current density variation on diffusion polarization.

### 3.4. Effect of current density variation on polarizations

To observe the variation of each polarization loss over the cell voltage, under standard operating conditions, the polarization of each loss for a given range of current density has been examined and illustrated in Figure 9.

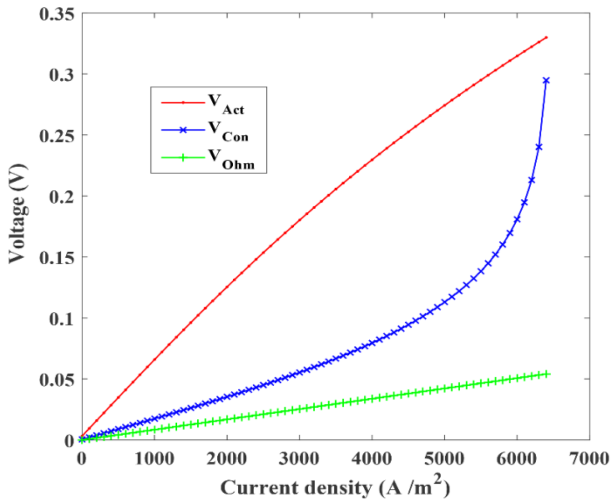


**Figure 9.** The current density variation on polarizations.

All polarization losses have risen when the current density has increased however, the most striking drop in the upward trend is the activation loss in which at a current density of 3000 $Am^{-2}$, its value is approximately 0.18 V. On the flip side, when the current density is approaching the limiting current density, the diffusion polarization is considerably increased at that point, which is even greater than the activation loss. Although the ohmic drop decreases linearly with the current density, it does not exceed 0.05 V even in the limiting current density range.

Therefore, by considering the above analysis it can be concluded that for a better voltage performance, the SOFC should be operating at a lower current density and this will lead to more power generation, too. However, for achieving this aim the cell surface must increase which will result in increasing SOFC's cost.

### 3.5. Effect of current density variation on voltage and power generation

The effect of the current density on voltage and power is examined, simultaneously and the results is shown in Figure 10.

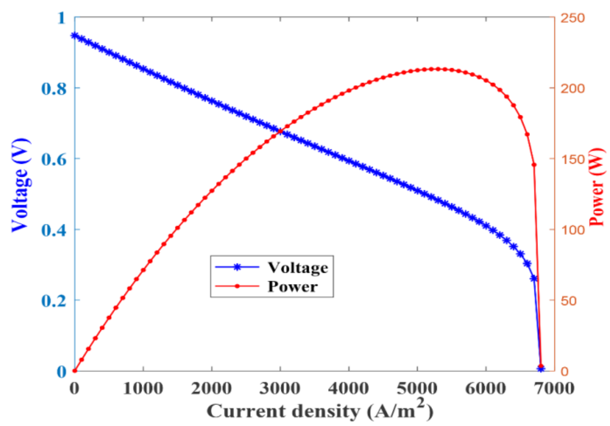


**Figure 10.** The current density variation on voltage and power.

The effect of the current density on voltage and power is examined, simultaneously and the results is shown in Figure 10. As indicated, the voltage and power curves intersect in the current density range of 3200 $Am^{-2}$, in which the voltage value is about 0.7 V and power generated at corresponding voltage is approximately 175 W. It can be observed that the maximum power of the cell obtains in the current density range of 5200 and has a value of about 210 W, at this point the cell voltage value is 0.48 V. Although the cell power improves when current density increase, the best operating region should be determined while both power and voltage best performance are taking into consideration. Therefore, it can be noticed that the best current density operating range has laid slightly lower than maximum power generation current density.

### 3.6. Effect of current density variation on voltage in different temperatures

The effect of the current density on voltage in different temperatures is investigated and the results is shown in Figure 11. It can be observed that higher working temperature leads to a lower Nernst potential.

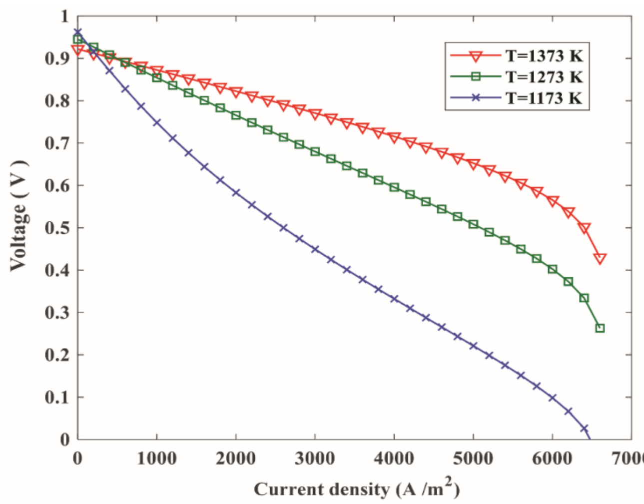


**Figure 11.** The current density variation on voltage in different temperatures.

For example, at the current density of 3200 $Am^{-2}$, at temperatures of 1173 K, 1273 K, and 1373 K the cell voltage value is approximately equal to 0.37, 0.65, 0.74 V. The main reason behind it is that there is a significant decrease in both the ohmic and the activation polarization will occur while the operating temperature is rising. Moreover, it can be seen that higher working temperatures will result in better power generation as well as limiting current density.

### 3.7. Effect of current density variation on power in different temperatures

In Figure 12, the impact of temperature variation on the power output has examined. As shown in Figure 12, at a constant value of current density of 3200 $Am^{-2}$, at temperatures of 1173, 1273, and 1373 K, the cell power generation will reach 110, 170, and 210 W, respectively.

From the above analysis, it can be concluded that a higher temperature provides a higher maximum power. Besides, it can be observed that by increasing temperature, the amount of maximum power agrees with the increase of the limiting current density. For example, by increasing cell temperature from 1173 to 1373 K in a fix current density, the maximum power generation improves about 100 %.

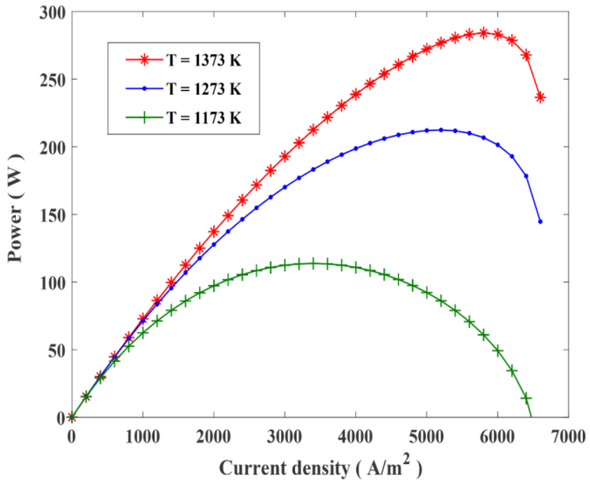


**Figure 12.** The current density variation on power in different temperatures.

### 3.8. Effect of the cell temperature Variation on the heat generation and efficiency

As discussed earlier, heat generated from the cell as well as cell efficiency are two crucial factors for predicting SOFC performance. In Figure 13, the cell efficiency is considered as an independent variable and the values of heat generation and cell efficiency at the constant current density of 3200 $Am^{-2}$, have investigated. The results prove that, since a lower operating temperature leads to more polarization losses, consequently heat generation of the cell will be enhanced considerably.

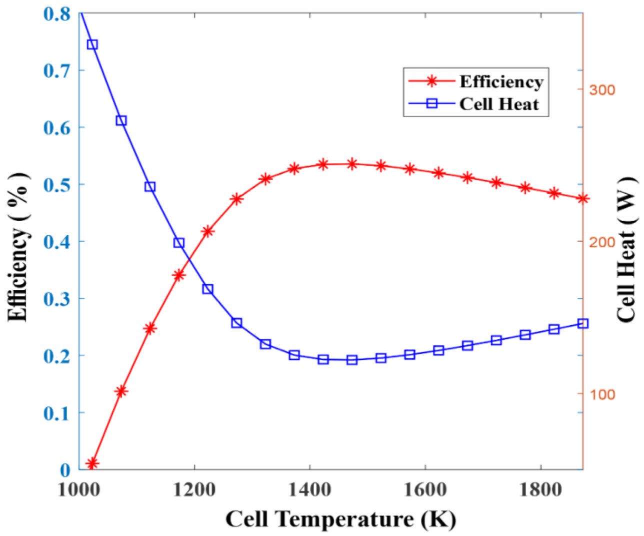


**Figure 13.** Cell temperature variations versus efficiency and cell's heat.

The heat generated by the SOFC electrochemical reactions declines while the temperature is increased to approximately 1430 K, later this value its trend turns to down. This is mainly because, the entropy-generated heat will be greater than the polarization-induced heat that will lead to a slight increment in the generated heat.

This individual characteristic of SOFC may provide the best opportunity to develop hybrid concepts and employing this technology as a CHP system in residential buildings. In this way, the user will be able to enhance the overall system efficiency by using heat recovery equipment.

## 4. ECONOMIC SCENARIO ANALYSIS

Sensitivity analysis has been performed on some key parameters of SOFC to make it an affordable and attractive system for residential applications.

### 4.1. Effect of SOFC efficiency improvements

The economic feasibility of the SOFC is strongly coupled with its efficiency somehow, developing technology and the internal design of SOFC leads to finished product cost reduction and make it economically viable and attractive. In Figure 14, the NPV variations regard to different efficiency range between 38 % and 46 % and the SOFC purchase price is evaluated. As it is shown, the NPV of the system will rise while the system efficiency has enhanced, and a similar trend can be seen while the purchase price of the SOFC is reducing.

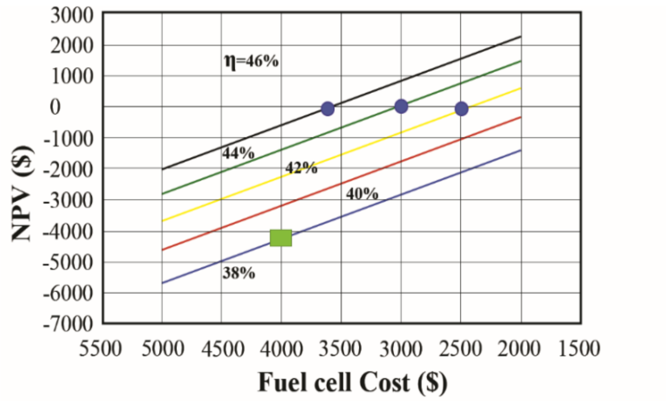


**Figure 14.** NPV variations regard to different efficiency.

In Figure 14, the reference status is shown with a green square. It can be seen, at the reference point with efficiency of 38 % and SOFC cost around $4000 the system provides a minimum economy attractiveness in which the NPV value is about -4200.

The first scenario could drastically fall in the purchase price of the SOFC, at least to less than $2,500 and improving efficiencies above 42 %, simultaneously. From another point of view, lowering prices below $3600 and advancing efficiencies above 46 % will lead to more attractive values of NPV and could make the SOFC system feasible for residential application purposes.

To accomplish this target, extensive research, and development program is required to address technical barriers and reach a more desirable efficiency and operating performance.

### 4.2. Effect of electricity sale price to the government

Increasing the purchase price of electricity, which is generated by a green or environmentally friendly power generation system, is considered as one of the most promising and efficient policies which are practiced by some developed countries.

As illustrated in Figure 15, at the reference point that is denoted with a green square, the grid sale price of $0.16 the fuel cell cost of $4000 the NPV value is about -4200 which is not desirable for any investment purposes.

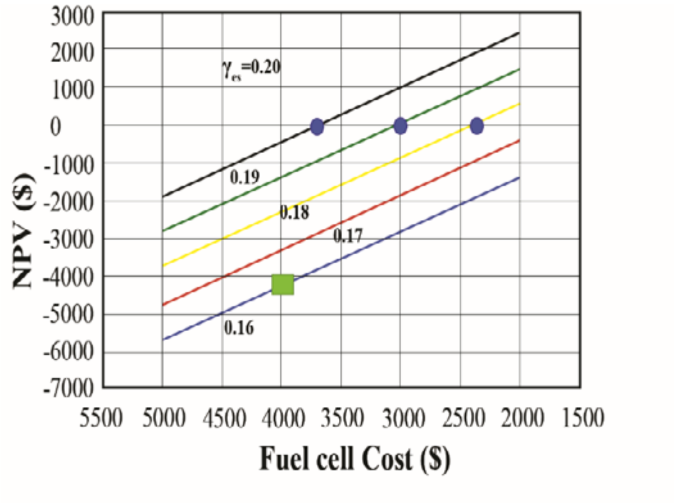


**Figure 15.** NPV variations versus different sale price of surplus electricity.

The effect of the sale price of surplus electricity in the range of $0.16 to $0.20 per kWh has demonstrated by Figure 15. As can be seen, the breaking even point will appear while the purchase price is lower than $2400, and the sale price of electricity is $0.18 per kWh.

As indicated, the increase in government electricity sale price has a significant impact on the economy of the system, with electricity purchasing at around $0.20 per kWh, even at prices below $3700 the system economy will reach to the break-even point. To provide ground for investment on mentioned technology, the governmental support in terms of guaranteed renewable electricity purchase tariffs is a vital action.

### 4.3. Effect of SOFC feed price

The income of a SOFC cogeneration system also is highly dependent on other factors such as the price of natural gas, consumed in the SOFC. Feed price is considered as one of the main concerns of SOFC -CHP application in residential buildings. Increasing the Natural gas rate will lead to a higher electricity price, which is generated by the SOFC system, and the economic feasibility of the CHP system might be endangered, significantly.

As depicted in Figure 16, the reference green square has demonstrated a $0.065 price for the Natural price and $4000 as the cost of SOFC. These conditions lead to NPV values of -4200 which is not attractive for investment.

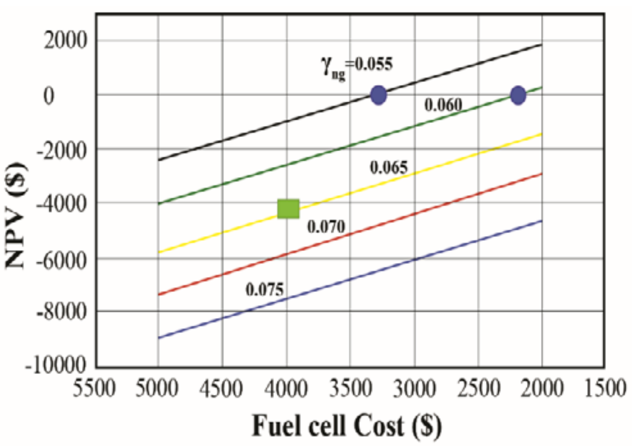


**Figure 16.** NPV variations versus different Natural gas price.

As is illustrated in Figure 16, the considered range of the Natural gas price is from $0.05-$0.055 per kWh. By assuming all variables fix, with a purchase price of less than $2400, the break-even point will appear at prices below $0.06 per kWh.

From the above analysis it can be concluded that to develop residential applications of the SOFC system, it is highly advisable to the government that may be reforming energy incentive policies can lead to spreading the SOFC cogeneration application, particularly in residential buildings.

### 4.4. Efficiency improvement in combined heat and power

Since the SOFC is operating at high temperatures, one way to improve efficiency is to recycle heat output from it. Applications of this heat recycling include space heating and supplying hot water for residential applications. In this study, at the best working point of electricity generation, the efficiency of the system 53.34 % at 1400 K working temperature. At this point, assuming the whole of thermal energy generated by the cell, the efficiency reaches 86.12 %. It should be noted that, whenever the electrical efficiency is decreased, the heat generation by the SOFC will be increased, as result by employing the CHP applications, the overall efficiency will be improved while this leads to a more fuel-efficiently and consequently a more economically efficient system.

## 5. CONCLUSIONS

In the present study, an electrochemical model has developed and the results concerning the economy of the proposed SOFC system have investigated. The chemical reactions within the SOFC have considered in which the SOFC performance investigation regard to some principal variables such as temperature, pressure and current density have discussed. The system polarization losses variation versus some key parameters such as the cell performance temperature have analyzed. Similarly, some functional properties of the SOFC such as anode and cathode pore size, activation energy and electrolyte thickness, have studied and analyzed. To accomplish this goal, the operating parameters have been modified to reach the best performance characteristics in both the technical aspect and financial attractiveness of the SOFC system. As analyzed above, the SOFC economy is highly dependent on its efficiency, therefore the NPV value will improve as efficiency being enhance. Further, simulation results were employed in economic evaluations. Economic analysis shows that the target cost of a SOFC residential application usage is about $2400 regard to current Iranian network price in which in today's energy market, a 1 kW SOFC purchase price with an efficiency of about 38 % to 46 % has a purchase price of around $6,000-$7,000, therefore for economizing on the use of mentioned technology in residential applications, it requires a significant reduction in finished cost (at least $2400>) and remarkably enhancement of efficiency. The present study is established to examine the possibility of the SOFC cogeneration system in hope of seeking a new resolution to employ this technology in residential building applications. Concerns have raised with regard to the technical issues and the economic viability of the system. In brief, destiny of this SOFC cogeneration system for residential usage in Iran is relying on: (1) considerable technological enhancement to improve the affordability of the

SOFC; (2) improvement in governmental policies in terms of guaranteed renewable electricity purchase tariffs; (3) improvement in life cycle of SOFC systems and (4) Profound development in infrastructures to mitigate legal constraints and address distributed generation systems barriers for network connection.

By considering the above aspects, this technology application will be more affordable and reliable for residential applications in Iran.

## 6. ACKNOWLEDGEMENT

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## NOMENCLATURE

| | |
|---|---|
| A | Area ($m^2$) |
| $A_c$ | Cell activation area |
| $D_{eff}$ | Effective gas diffusion factor ($m^2\ s^{-1}$) |
| E | Activation energy ($kJ\ kmol^{-1}$) |
| F | Faraday's constant ($kmol^{-1}$) |
| $i$ | Current (A) |
| j | Current density ($Am^{-2}$) |
| $J_o$ | Exchange current density ($Am^{-2}$) |
| $j_L$ | Limiting current density ($Am^{-2}$) |
| L | Electrode thickness (m) |
| M | Molecular weight ($kgkmol^{-1}$) |
| n | Molar flow rates ($kmol^{-1}$) |
| ne | Number of electrons |
| p | Partial pressure (bar) |
| P | Operating pressure (bar) |
| $Q_{Cell}$ | Heat generation rate (W) |
| r | Ohmic resistance (Ω) |
| $r_{Por}$ | Average pore radius |
| R | Universal gas constant (8.134 $Jmol^{-1}k^{-1}$) |
| k | Fuel cell components |
| T | Cell temperature (K) |
| $U_f$ | Fuel utilization factor |
| $V_{Cell}$ | Cell voltage (V) |
| $V_{nerst}$ | Nernst potential (V) |
| $V_{Act}$ | Activation polarization (V) |
| $V_{Con}$ | Concentration polarization (V) |
| $V_{Loss}$ | Voltage losses (V) |
| $V_{Ohm}$ | Ohmic polarization (V) |
| $W_{el}$ | Electrical power (W) |
| z | Reacted hydrogen molar follow rate ($kmols^{-1}$) |
| NPV | Net Present Value |
| **Greek letters** | |
| β | Transfer coefficient |
| δ | Current flow length (m) |
| ε | Porosity |
| γ | Pre-exponential coefficient |
| η | Efficiency |
| ρ | Material resistivity (Ωm) |
| τ | Tortuosity |
| **Superscripts** | |
| an | Anode |
| ca | Cathode |
| e | Exit |
| i | Inlet |

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