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Proposing New Algorithm for Modeling of Regenerative Fuel Cell (RFC) System

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ABSTRACT

Regenerative Fuel Cell (RFC) systems are used for the enhancement of sustainable energy aspect in conventional fuel cells. In this study, a photovoltaic-electrolyzer-fuel cell integrated cycle has been presented. The proposed system has been designed as a novel approach for alleviating the restrictions on energy streams in the RFC systems. Modeling of the system has been performed from the mass and energy point of view, based on both theoretical and practical procedures. To generate electricity from hydrogen, a proton exchange membrane fuel cell, integrated with an electrolyzer system which works by solar energy, has been used. Optimized results of required photovoltaic area have shown significant differences between theoretical and practical approaches. Moreover, all efficiencies of two scenarios including total efficiency have been indicated and analyzed. The main advantage of this system in comparison with single solar systems, is generation of internal energy of about 2.3 kW for producing 1 kW electricity by the fuel cell.

1. INTRODUCTION

Fuel Cell (FC) is now one of the modern technologies which has obtained a good grade of compatibility with the environment. Beside the environmental privileges and because of high energy efficiency in fuel cells, much more attention is being attracted to fuel cells application [1]. As the process of energy conversion in FC takes place with high-efficiency, the first part of designing two versions of integration and part designs should be developed, so that we can step forward to the next request, assembling and manufacturing, which is considered as one of the most complicated work divisions. Regarding the growing development of such technologies in the 21st century, it seems that FC would be a suitable substitute for the combustible process of fossil fuels in the energy production system [2-6]. Generally, providing the required fuel is one of the main problems, which this technology is facing. In other words, the process of production, storage and transportation of hydrogen, which would be used as the fuel in this kind of fuel cells, is almost difficult and even in some cases, there is no advantage for using this technology. Trying to remove all these challenges on providing hydrogen fuel, Regenerated Fuel Cells (RFC) –combined of FC and Electrolysis– is considered as the latest solution for shooting problem in energy generation system. RFC systems are the power generators and their reactors are recovered to reproduce electricity current. These systems are based on some cell layers which are bounded together in series [7].

Initial attempts for using URFCs in the proton exchange membrane technology have been implemented since 1960. Due to deficiencies existing in membrane and electro-catalysts, their electrochemical performance was low [8]. However, the General Electric Company (GEC) achieved the outcomes which persuaded the researchers to search for better efficiencies during the 1970s [9]. At the end of the 1990s, a typical URFC stack was invented by researchers at the Lawrence Livermore National Laboratory (LLNL) which produced a power density of 450 Wh.kg-1 [10]. Moreover, in 1998, a commercial RFC was designed by Proton Energy Systems that used up 15 kW in electrolyzer mode and produced up to 5 kW electricity in the fuel cell mode [11].

Research and development on URFCs have been performed by various scientific teams in which some of the principals are Canadian company Green Volt Power Corp [12,13], American companies Lynntech Inc., Glenn Research Center [14], Giner Inc. and research centers. At the Toulouse University (LAPLACE Laboratory), in France experimental development on URFC is taking place [15].

Recently, Massimo Guarnieri et al. [16] have presented a zero-dimensional steady-state model to evaluate the operation of UR-PEMFCs in both electrolysis and fuel

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*Corresponding Author's Email: h.ghadamian@merc.ac.ir (H. Ghadamian) cell modes. This model considers UR-PEMFCs as an energy storage system. These type models can be used for both stationary and mobile electric applications by predicting the performance of hydrogen-based energy storage systems. In the research done by Amit C. Bhosale et al. [17], the performance of UR-PEMFC in electrolysis mode is modeled and also investigated experimentally. In this study, the effect of the increase in operating gas pressure due to the contact pressure between the gas diffusion layer and the bipolar plate is investigated.

The other studies performed in the UR-PEMFCs field, are more related to the implemented materials type and load of catalysts [18-20].

The RFCs are suitable for the applications far from the fuel sources or in which the fuel is not accessible in short time intervals. It also is recommended as an appropriate option for those applications which are sensitive to the mass/energy ratio.

One of the general advantages of these systems is the production of sustainable energy in a transitive rate. This advantage has made the RFCs to be used more than chargeable cell systems and more attractive for the users [7, 21].

Lack of comprehensive analysis to calculate the total efficiency of an integrated photovoltaic, electrolyzer and fuel cell system has always been a substantial constraint for the developing RFCs. Therefore, indicating the optimum PV surface area is the main goal of the presented study. This is basically due to different operational mechanisms and working conditions, materials, and fuel cell technologies of individual integrated system elements. Thus, proposing a design method for these complicated systems is considered as an effective approach for the mentioned purpose.

In this paper, a novel and applicable energy system modeling to develop regenerative fuel cell systems has been proposed which includes electrochemical and electrical sections in conjunction with mechanical model sections. This model has been investigated for indicating efficiencies at certain output power. The proposed model has been developed and analyzed based on theoretical and practical approaches, which assisted to create a comprehensive model considering both aspects.

2. SYSTEM CONFIGURATION

In a fuel cell, reproduced water is injected to the electrolysis system as a feed and then it is reduced to oxygen and hydrogen. Oxygen molecules can enter the environment or stored if needed, but hydrogen molecules are stored in a storage tank or system. Then the stored hydrogen molecules enter the fuel cell and attend the process of producing electrical energy. Water leaves the cell as the reaction product and it is used again as the electrolysis feed. Controlling the rate of energy production by hydrogen, the insufficient mass of produced Oxygen (due to efficiency or deficiency of Electrolysis system) and the high cost of storage are the main reasons for oxygen storage prohibition [1, 22, 23, 24]. In Fig. 1, the schematic of the RFC system mentioned above is depicted.

The significant privilege of developing RFC is pertained to enhance energy generation in form of hydrogen production. Hydrogen consumption in the fuel cell which is a high efficient energy generator, increase the total efficiency of proposed integrated system, however, photovoltaic systems do not have high energy conversion efficiency. Furthermore, the mentioned internal energy enrichment has much more positive effects rather than common losses in the system elements.

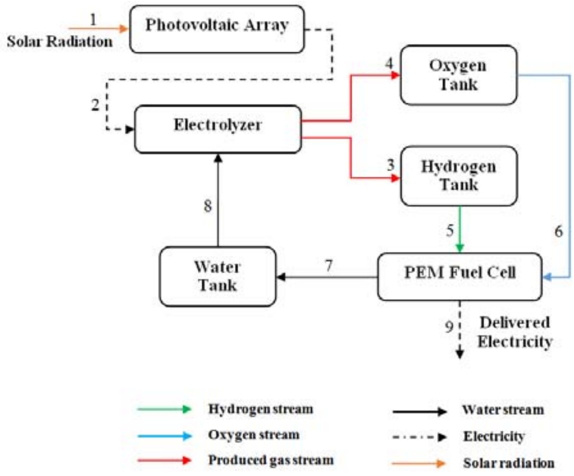

Figure 1. The schematic of the RFC system

Generally, engineering view in designing compound systems consisting of separate units, in fact, is making the connection and combination between its individual elements in a way that designing the compound system and appropriate algorithm would lead to achieve the main goal of compound system designing and integration.

The optimum process of designing includes the following parts in five sections:

1) Data collection and overall system reorganization,
2) Determination of the basic solution for the optimum system,
3) Making Objective function and physical and structural limits for solving the equation,
4) Simplifying the model; and
5) Solving the model equation by the use of mathematical programming techniques of software such as GAMS and Matlab.

3. MODEL DEVELOPMENT

The proposed RFC system design algorithm shown in Fig. 2, includes a fuel cell, electrolysis and P.V. cells as follows:

1) Choosing the capacity of fuel cell with regard to the required energy,
2) Calculating the number of cells, the stack current intensity, and other technical characteristics of fuel cell with regard to its efficiency,
3) Calculating mass discharge of required hydrogen (as input fuel),
4) Calculating the required potential difference for water electrolysis regarding the irreversibility cause voltage drops,
5) Calculating the electrolysis efficiency in various scenarios of theoretical and real conditions; and
6) Calculating the P.V. cell areas to produce required electrical energy for electrolysis.

Therefore, the advantages of applying the modern algorithm are as follows:

- Ability to make engineering design calculation in individual and separate systems per each unit;
- The possibility of electrical energy production system assessment in P.V. unit simultaneously in ideal and real conditions;
- The simplicity for analyzing any variations in energy intensity & total system efficiency.

Every model consists of an objective function, model assumptions, constraint non-equation, parameters, and dependent and independent variables. The model sections are present with regard to calculated assessments as follows:

3.1. Objective function

Determination of the minimum P.V. area that is required for the system, which is assumed as the objective function:

$$Min\ Area = [(1/EFPV)\times(1/P_S)\times V_{OC}\times I_{SC}\times FF] \qquad (1)$$

In this formula, EFPV stands for the efficiency of the photovoltaic system, PS for solar radiation intensity, VOC for open circuit voltage, ISC for short connection current intensity and FF for filling factor.

3.2. Model assumptions

Model assumptions that include physical theory and technical aspect limits are as followed:

1) In the first scenario of the model solution, the PEM fuel cell [22] is considered fixed in voltage and performs in an ideal technical condition. Whereas in the second scenario, based on the fuel cell voltage drops, a new model is designed. Finally, the P.V. module of RFC systems was optimized for these two scenarios.
2) The electrolysis efficiency of the system considering the operation in real condition, is assumed constant. This assumption is related to the ideal amount of hydrogen required by the fuel cell during the modeling approach.

3.3. Model constraints

1) The produced voltage of each part of PEM fuel cell is assumed as $0.6 \le V_C \le 0.7$ which is 0.7 in ideal condition [4, 6],
2) Since the type of P.V. module is crystal in the sample case study and regarding that short connection intensity of module is available in both min/max area of short connection, intensity is $3.45A \le I_{SC} \le 6.9A$ [25],
3) The efficiency of PEM fuel cell is identified as $0.35 \le \eta_{FC} \le 0.6$ and is defined as one of the non-equations constraints of model solution; and
4) According to practical results, the required voltage of PEM (VELER) electrolysis for refraction of one-mole water in real condition is $1.6V \le V_{EL} \le 1.8V$ [23].

3.4. Model parameters

We assume some fixed or low-effect parameters to reduce the variables in RFC model. These parameters include:

1) P_0 system efficiency power (energy production capacity) assumes 1kW,
2) The solar radiation intensity is assumed fixed and is [25] (The value of is selected based on the average local solar radiation intensity used in the calculations),
3) The calculated electrolyze efficiency FEEL is fixed as $\eta_{el} = 54.67\,\%$,
4) System efficiency voltage is as $V_0 = 225\ V$,
5) Filling factor for P.V. cell is 0.73 and is considered as fixed in modeling process,
6) The selected crystal photovoltaic system efficiency is assumed as 0.14; and
7) SF of system designing calculated in regard to the required electricity of electrolysis for water refraction and producing the FC required hydrogen and the production of it, is 1.41 as calculated in photovoltaic systems.

There are some variables related to EFFC (PEM Fuel Cell efficiency) and ISC (P.V. short connection current module) which are considered in the model.

Dependent variables in the first scenario model are related to independent variables which were mentioned previously as shown in Table 1.

It is important to notice that all dependent and independent variables are positive except the objective function variable (AREA) which is of free variable type. The model of the second scenario is represented according to the voltage loss of fuel cell. In this model, the objective function is the total output power of PEM fuel cell that is calculated according to Eq. 2 [2]:

$$P = VI \tag{2}$$

Where, V is for fuel cell voltage and I is for the current intensity of the cell. In order to affect the voltage loss of a cell in the calculation, all other losses like activation loss, fuel crossover loss, mass transfer loss & Ohmic loss, concentration loss are named as total irreversibility causing the voltage drops which is deducted from the objective function.

Analysis of fuel cell operation and design features are described in consequent steps in this section. Gibbs free energy or the ideal level of energy system's activities should be calculated then reversible open circuit voltage (ROCV) and open circuit voltage (OCV) evaluation must be done. The mentioned correspondence items are maximum ideal & operational potentials whereas activation losses will be explained by Tafel equation and it should be noted that they are considerable in the cathode.

Fuel cross-over or internal currents will be calculated and this case is not considerable during energy losses, but fuel cross over seriously affects the OCV reduction. Continually Ohmic loss will be reviewed which is the simplest case in modeling and understanding. Ohmic losses contain electro-conductivity resistance in electrodes and ion transportation resistance in the electrolyte. Electrolyte resistance is more effective and considerable, comparatively. Mass transport or concentration losses will be calculated. It should be noted, this type of losses is considerable whenever we apply reforming system for air injection instead of oxygen in a cell system. By this means, in the simulated H2/O2 working cell, this loss is not considerable and should be negligible. Finally, the formula for irreversibilities causes voltage drops and final output voltage which indicates all types of losses would be calculated. Besides, based on quantification of effects on voltage drops in a prototype PEM fuel cell it is also found that the following parameters are determining factors for reducing the voltage drops:

- Temperature rise,
- Pressure rise,
- Increase in hydrogen or oxygen concentration,
- Increase in electrode effective surface,
- Reducing electrolyte thickness up to possible limitation,
- Use of electrodes with highest possible electro-conductivity; and
- Good design of plates and cell connections or in a brief phrase "Connection modification".

TABLE 1. Dependent variables in the first scenario model [2, 4, 23]

Description	Relation
Fuel Cell voltage (V)	(VC) = 1.48(EFFC) / 0.95
Fuel Cell current intensity	(I) = P_0/VC
Number of cells in an FC system	(N) = V_0/VC
Mass flow rate of fuel cell required hydrogen (kg/h)	(MH) = I×0.000037605
Mass flow rate of produced Oxygen (kg/h)	(MO)= (1/3600) ×(1/VC) ×P_0×0.000829 ×1000
Mass flow rate of produced water in fuel cell (kg/h)	(MW)= (1/4) ×MH×36
Required electrolysis voltage obtained from the basic formula (V)	(VEL1) = (1/4) ×MH×VELR×1000
Required electrolysis voltage obtained from the efficiency formula (V)	(VEL2)= VEL1/FEEL
The required electrolysis voltage obtained from SF	(VEL3)= VEL2×SF
Internal produced energy in system (kCal/h)	(KCPH)= (1/2.0) × (MH×68.3) ×1000
Internal produced energy in system (kJ/h)	(KJPH)= KCPH×4.1868
Internal produced energy in system (W)	(EP)= (1/3600.0) ×KJPH×1000

4. THEORETICAL AND PRACTICAL APPROACHES

4.1. Electrolysis

4.1.1. Theoretical Approach

In this condition, the electricity voltage required for electrolysis should be calculated. It should be noted that the following equation is used to calculate the electrical energy [23]:

$$E = V.I.t \tag{3}$$

Since the electrolysis takes place independent of time and the power, current remains almost without change, also time and ampere are assumed unchangeable in Eq. 3. Then it is obvious that used voltage is the main parameter in changing the amount of energy in Eq. 3. The voltage is calculated through the following formula [25]:

$$\left(V_{required}\right)_{theory} = \frac{\left(\dot{m}_{H_2}\right)_{theory} .V_{tn}}{M_{H_2}} \tag{4}$$

$$\left(\dot{m}_{H_2}\right)_{theory} = \frac{I}{2F} M_{H_2} \tag{5}$$

$$V_{tn} = \frac{\Delta H}{2F} \tag{6}$$

4.1.2. Practical Approach

The amount of electricity required for water electrolysis is almost 30 to 40 percent more than the one obtained in ideal condition. It means that we need 1.7 to 1.8 V of electricity for the electrolysis process of 36 gr water [25]:

$$\left(V_{required}\right)_{real} = \frac{\left(\dot{m}_{H_2}\right)_{theory} .V_{tn} \times (1.6)}{M_{H_2}} \tag{7}$$

4.1.3. Electrolysis Efficiency

Estimating the efficiency of current intensity and energy and using the relevant equation, and applying interpolation step, we can obtain the efficiency amount of electrolysis [26].

$$\eta_{Faraday} = \frac{\dot{m}_{H_2}}{\frac{i}{2F} \cdot M_{H_2}} \tag{8}$$

$$\eta_{Energy} = \eta_{Faraday} \times \eta_{HHV} \tag{9}$$

The results of calculations considering the electrolysis are presented in Table 2, in following.

TABLE 2. Electrolysis voltage and efficiency in theoretical and practical approaches

	$V_{required}\,(Volt)$	$\eta_{Faraday}$	$\eta_{Faraday}$
Theoretical approach	17.38	97.4	63.28
Practical approach	23.18	93.4	54.67

4.2. Photovoltaic

Solar cells are the smallest and the main parts of the solar arrays that produce electricity in exposure to light, exactly like a small battery. These cells area does not have any particular effect on the amount of the voltage produced and current intensity depends on cell measuring and solar radiation intensity.

Technical assumptions that make the synthesis basic affairs are as follows:

1- The size of each cell is of 100 mm × 100mm and is made of crystal silicon,

2- The cell temperature is to be 25°C,

3- The open circuit voltage of 0.5 V, and

4- The solar radiation intensity as 1000 W/m² (The value of Ps = 1000 W/m² is related to the standard value considering ASTM E927 standard).

Moreover, cells are placed in a bigger unit called module in series and parallel joints so that voltage current would be increased [25]. The overall efficiency equation coordinates with power and area; those are related to voltage, current and area. These are demonstrated in following [27]:

$$\eta = \frac{P_{\max}}{P_t} = \frac{P_{\max}}{P_s.A} = \frac{V_m.I_m}{P_s.A} = \frac{V_{oc}.I_{sc}.FF}{P_s.A} \tag{10}$$

4.2.1. Theoretical approach

Optimum surface area of photovoltaic cells based on theoretical formulations will be indicated in this approach. This means that certain efficiency, voltage and current density will be considered and total PV cell area will be obtained. The P.V. cell areas are calculated to produce required electrical energy for electrolysis in ideal condition (Through estimating P.V. cell areas in general condition and without use of the maximum rate of solar radiation).

4.2.2. Practical approach

The practical calculation will be performed based on specific commercial PV panel and its facilities. Therefore, additional technical restrictions of installation and operation for photovoltaic systems will be considered in this approach. Moreover, the optimum result of surface area will be calculated with different constraints. Therefore, the discrepancy between theoretical and practical outcomes should be reasonable.

5. RESULTS AND DISCUSSION

In order to implement the proposed model, a 1 kW regenerative fuel cell power generator for a digital transmitter has been considered. These transmitters are usually used to send digital signals in radio or television stations. The different phases of this design are presented in Table 3.

Moreover, solving the optimum model through using General Algebraic Modeling System (GAMS) software has been done. In order to gain a correct answer, the models calculated in the steps were analyzed by GAMS software.

The mentioned variables in Table 4 which have been defined in Table 1, show the optimum point of the presented model design for RFC system calculations by advanced non-linear mathematical programming through using CONOPT calculator. The results and their line numbers in Figure 1 are shown in Table 4.

It is suggested to use PV*SOL software for designing the module applied in RFC systems. Since the results of designing an RFC system will lead to achieve the photovoltaic area required for the system, the accuracy of the calculated digits in P.V. module designing section is obviously important. Therefore, it suggests using the mentioned software for calculating the optimum photovoltaic area required for the system, regarding the electrical power that electrolysis needs to refract a particular volume of water.

This software helps us obtain the exact amount of the required solar cells with regard to the complete detail of their technical designing [29].

As a result, we can put the calculated variables obtained through GAMS software for required voltage as an input to PV*SOL software regarding the intensity of solar radiation, so that we can confirm the accuracy of the performed conclusion. Moreover, the photovoltaic system was assumed independent from the network, so the results obtained through PV*SOL software are presented below in comparison with other results:

TABLE 3. Results of proposed design algorithm in a 1 kW RFC system

Phase name	Description	Equation summary	Result
1st Step [2]	Calculating each fuel cell voltage	$\eta = \frac{V_C}{1.48} \times 0.95$ Generally, $\eta_{PEM} = 0.6$ $V_C = 0.6 - 0.7V$	Through Try & Error $V_C = 0.65V$
2nd Step [23]	Calculating the number cells in each FC	It is assumed: $V_0 = 225V$ N = Number Of Cell/Cell Voltage	N = 347
3rd Step [23]	Calculating the current intensity and required hydrogen mass	Cell Power = Cell Voltage × ΣCurrent /Cell No. $I = \frac{P}{V}$ Cell Current = Stack Power / Cell Voltage $mH_2 = \; = 1.05 \times 10^8 \times (P_e / V_c)$	$I = 1538A$ $I_{stack} = 4.43A$ $mH_2 = 0.05796 \, {}^{kg}\!/_{hr}$
4th Step [25]	Calculating the required electricity for electrolysis	Theory: $H_2O \rightarrow H_2 + {}^1\!/_2 O_2 + 1.22V$ Real: $V_{real} \cong 1.3 - 1.4V_{Theory}$	$V_{Theory} = 17.38V$ $V_{Real} = 23.18V$
5th Step [26]	Calculating electrolysis efficiency	$\eta_{Faraday} = \frac{\dot{m}_{H_2}}{\frac{i}{2F} \cdot M_{H_2}}$ $\eta_{Energy} = \eta_{Faraday} \times \eta_{HHV}$	Electrolysis Energetic Efficiency = 54.67%
6th Step [27]	Calculating photovoltaic system area	Theory: using the P.V. arrays in ideal condition Real: Using standard module $\eta = \frac{V_{OC} . I_{SC} . FF}{P_S . A_{Cell}}$ $F.F. = \frac{V_m . I_m}{V_{OC} . I_{SC}}$	$A_{Theory} = 0.909 \; m^2$ $A_{Real} = 1.68 \; m^2$
7th Step [28]	System energy balance and efficiency calculation	$E_{OUT} = (E_{in} + E_P)(\eta_{RFC})$ $\eta_{RFC} = \frac{E_{OUT}}{E_{in} + E_P}$	$\eta_{RFC} = 0.2945$ $E_{OUT_{(Theory)}} = 963.6 \, W$ $E_{OUT_{(Real)}} = 999.5 \, W$

The answers concluded from 1kW RFC system model solution were studied by using GAMS software package with regard to the intensity of solar radiation (650 W/m^2).

For an exact evaluation of the result for the optimum point of RFC system design, the solar radiation intensity is assumed as the annual average for assumed location. Therefore, the first scenario was modeled by GAMS assuming 14 types of solar radiation and the answers related to the optimum point of design were calculated according to the required photovoltaic cells area. Moreover, for a precise demonstration of the changes in the area of solar arrays required for RFC systems and through using the Table 4, a curve was drawn for the photovoltaic module area changes according to the solar radiation intensity. It is shown in Fig. 3.

As it is observed in Fig. 3, the opposite relation between the intensity of solar radiation and the required area of photovoltaic cells is approved. In addition, a small increase or decrease in the intensity of solar radiation in a slow rate causes small changes in the RFC system required P.V. area (In moderate climate parts of the world). Whereas in very hot or cold climates, with small up and downs of solar radiation intensity, the photovoltaic cells area makes a considerable change.

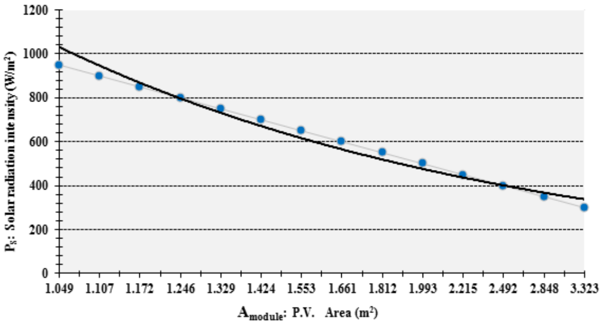

Figure 3. Curve of photovoltaic module area changes according to the solar radiation intensity

TABLE 4. GAMS software processing for theoretical and practical scenarios

Variables (No.)	Theoretical scenario's results	Practical scenario's results
VAR AREA	1.786	1.405
VAR N	321.429	294.503
VAR I	1,428.570	1,308.901
VAR VC	0.700	-
VAR ISC	3.450	3.450
VAR VOC	55.421	50.779
VAR EP	2,133.624	1,954.891
VAR VEL1 (No.2)	21.489	19.688
VAR VEL2 (No.2)	39.306	36.013
VAR VEL3 (No.2)	55.421	50.779
VAR EFFC	0.449	-
VAR MH (Nos.3&6)	0.054	0.049
VAR MO (Nos.4&5)	0.329	0.301
VAR MW (No.7)	0.483	0.443
VAR VELR	1.600	1.405
VAR KCPH	1,834.587	1,680.904
VAR KJPH	7,681.048	7,037.609

The V_C obtained from cell voltage calculation (based on practical experiments and technical studies of PEM fuel cells) is higher than that of the first scenario. As a result, the amount gained for the optimum point of design in the second scenario model is less than one, which was calculated for various variables of the first scenario. For RFC systems, the mentioned words were quite predictable. The results obtained from the second scenario are represented in Fig. 4.

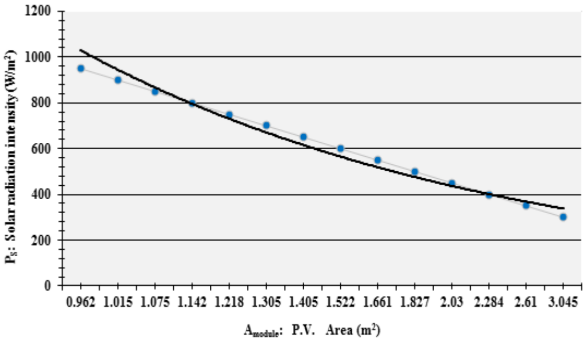

Figure 4. Curve of photovoltaic module area changes according to the solar radiation intensity with voltage drops consideration

The calculated area of this software is 1.7 m². Thus, average solar local radiation intensity is equal to 500-650 W/m^2 and it is based on the outcomes achieved from the proposed model. This band of values is related to Runs 1 to 3 at Table 5.

TABLE 5. Power versus area rendered in model

Variables	Run 1	Run 2	Run 3
P_S (W/m²)	500	550	600
$A_{P.V.}$ (m²)	1.993	1.812	1.661

We claim that the results are of high accuracy.

It is possible to calculate the optimum point of RFC system designing through the simultaneous use of PV*SOL and GAMS software. It is also possible to use RFC compound system designing model for analyzing the results.

It is therefore recommended to use a combination of engineering designing software and advanced mathematical programming software in order to gain the optimum point of technical system designing.

Other studies are done through PV*SOL software to validate the results. The optimum point of photovoltaic area system can be assessed with regard to the required electrical power electrolysis which is needed for refracting a particular volume of water and entering it as an input parameter. The area amount calculated by PV*SOL is 1.7 m² as the average solar radiation intensity is 500-650 W/m² per a year. Studying the obtained results shows the high accuracy of this software for comparison.

TABLE 6. Comparisons of samples constructed in high capacity RFC systems

System Type	Delivered Power	Output Voltage	Current Density	Reference
NASA RFC Lab.	5.25 (kW)	52.5 (V)	100 (A)	[28]
NASA Aircraft	1.5 (kW)	70 (V)	24 (A)	[30]
PV-Fuel Cell	2.24 (kW)	72 (V)	31 (A)	[31]
Proposed System	1 (kW)	225 (V)	4.4 (A)	-

Therefore, for using this voltage calculation, model and achieving the RFC required P.V. area; some changes are made in this model. Hence, another equation was added for calculating the cell voltage, using a variable called VC. The voltage is, therefore, calculated by deducting number of losses and it depends on fuel crossover and mass transfer of fuel cell. As a result, in model 2, instead of calculating VC in the related equations, we use the VC of the changed calculation of cell voltage that is 0.764V. Since the changed amount of voltage calculation was exactly measured for each cell of FC, it was considered among the parameters as a fixed amount in solving the RFC system model.

For a comparative assessment between real models and the represented ones, it seems necessary to compare the similar capacities in the range of kilo Watt with designed system and model from technical and operational aspects. In Table 6, comparison between three systems is shown for our informed research case study.

6. CONCLUSION

In this study, a novel approach for modeling regenerative fuel cell systems was proposed for attaining high accuracy as a comprehensive algorithm. The most important results of this modeling are:

- The outline tips of Figs. 3 and 4 reveals the exact exponential equation term called $P_S = 1,122.3e^{-0.0858}{}_{(A_{module})}$ for both scenarios, which explain the correlation between solar radiation intensity and P.V. module area;
- The preference for using RFC systems in comparison to other direct energy conversion systems is internal energy generation. According to the relations among all three parts of the sample case study, the generated internal energy is EP = 2.302 kW;
- As mentioned above, a considerable efficiency improvement was obvious in RFC system in comparison to P.V. individual systems. Efficiency calculation in the sample case study was done based on two scenarios. In the first scenario, the total efficiency of RFC system was 29.45% with energy balance applying. In the second scenario, by using power density assessment from weight and power aspect, the system efficiency was 52% while the efficiency of individual P.V. systems was about 14% in an optimized look;
- One of the main ambiguities of RFC system designing is the calculation of electrolysis efficiency. It is calculated by assessing the two outputs of current intensity and energy intensity by using what connects them and by making an interpolation. Therefore, the electrolysis output 54.67% has a near accordance with the real ones;

Modeling based on modern design algorithm has made a favorable condition for obtaining the optimum design point and analyzing the results of sample case study (1kW capacity). The modeling took place in the form of two scenarios. In the first scenario, the model designs RFC system according to the patterns. Nevertheless, in the second scenario the model designs according to the studies done on voltage loss of PEM fuel cells (V_C = 0.764 V) [32]. Modeling method, mathematical programming, in the non-linear equation in regard to parameters, is the equation and non-equation constraints of RFC systems and the objective function is minimizing P.V. array area. The models were entered the GAMS software that uses CONOPT calculator for solving the mentioned models. The first scenario result was 1.553m² and the second scenario has shown 1.405m² for solar radiation intensity of 650 W/m².

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NOMENCLATURE

A	Useful area (m^2)
A_{cell}	Cell area (m^2)
A_{module}	Module area (m^2)
$A_{P.V.}$	Photovoltaic array area (m^2)
A_W	Net weight of system accessories (kg)
E	Electrical motive force - emf (Volt)
E°	Standard electrical motive force (Volt)
E_{in}	Input energy (Watt)
E_{out}	Output energy (Watt)
E_p	Internal energy generated (Watt)
F.F.	Fill factor
HHV	High Heating Value
I	Average exiting intensity (Ampere)
I_{SC}	Short circuit current (Ampere)
I_{stack}	Fuel Cell stack current (Ampere)
$\dot{m}_{H_2}$	Hydrogen flow rate (kg/hr)
M_{H_2}	Molecular weight of Hydrogen (g/mol)
M	Mass (m)
M_W	Water weight (kg)
n	Stack cell number
P	Power (Watt)
P_e	Fuel Cell total power (Watt)
P_S	Solar radiation intensity (Watt/m2)
P_t	Total obtained solar power (Watt)
Q	Outgoing released energy (kCal)

R	Gas constant (kJ/kg.K)
S_W	Stack net weight (kg)
t_d	Exit time (hr)
T	Temperature (K)
T_W	Net weight of gas storage system (kg)
V_C	Average voltage of cells (Volt)
V_d	Cell discharge voltage (Volt)
V_{el}	Average voltage of electrolysis (Volt)
V_0	Output system voltage (Volt)
V_{OC}	Open circuit voltage (Volt)
$V_{required}$	Electrolysis required voltage (Volt)
V_{tn}	Thermo-neutral potential (Volt)
W_W	Net weight of water storage system (kg)

Greek letters

η	Efficiency
η_{el}	Electrolysis efficiency
η_{FC}	Fuel Cell efficiency
η_{RFC}	Regenerative Fuel Cell efficiency
$\eta_{Faraday}$	Faraday efficiency
η_{HHV}	High Heating Value efficiency

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