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Multi-level optimization approach for directly coupled photovoltaic-electrolyser system

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ABSTRACT

In this study, directly coupled photovoltaic-electrolyser system is designed and optimized and a new method for optimization is given. The accurate electrical models of advanced alkaline electrolyser, photovoltaic system, and hydrogen storage tank are simulated using Matlab. The system is investigated for a day using actual meteorological data of Miami, FL. The purpose of the optimization, which has been performed using genetic algorithm, is to produce maximum hydrogen, minimum excess power, and minimum energy transfer loss. In each iteration of the optimization, due to crucial role of temperature in overall performance of the system, the average operating temperature is optimized using genetic algorithm. The system is optimized in a way that the operating condition is as close as possible to the maximum power point of the photovoltaic array. The operation of the system is discussed in 24 h period and working hours to make the system comparable to other studies with different power sources. The result of the analysis shows that optimal system for a 10 kW electrolyser can produce the average hydrogen of 0.0151 mol/s when the system is operating with 2.2% power loss and 4.7% power transfer loss.

Introduction

The rising demand for new procedures of energy production and storage has been the focus of study in recent years. Among them, due to the environmentally friendly features, abundancy, and reduced costs photovoltaic (PV) systems are one of the most popular power production methods [1,2]. However, due to limited availability of solar irradiation during day and unreliable power production, it can be converted to a reliable fuel. Hydrogen can be a good choice due to high energy density, low energy loss, mature technology, on-site provision capability, and compactness [3–5]. One of the most promising ways of producing hydrogen from the electricity produced by PV systems is water electrolyser because their electrical characteristics match in a way that the overall system is efficient.

For the combined PV electrolyser system, several studies have been done [6–9]. In a study in 2008, the operation of coupled photovoltaic-electrolyser system with controlled DC–DC converter is investigated [10]. The maximum power point of the PV system is chosen by safe optimum searching algorithm and the buck-boost converter, which connects the PV array to electrolyser, is controlled. In some other studies, the power electronic devices are used to ensure optimal power transfer between the systems [11,12]. The advantage of

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using directly coupled system is that the cost and complexity of the overall system is reduced and because in case the system is optimally designed, the electrical characteristics of electrolyser can follow the maximum power point of the PV with appropriate accuracy, the overall economics of renewable-hydrogen systems compared to conventional fuels is improved. In a study in 2009, the direct-coupled PV system with proton exchange membrane (PEM) electrolyser is investigated. The fail-safe operation of electrolyser with multiple levels of safety and operational redundancy is designed [13]. In 2010, the operation of directly coupled PV power regulator for stand-alone power systems with hydrogen generation is evaluated [14]. Few studies have tried to find the optimal operational set points and size of directly coupled PV-electrolyser. In order to obtain optimal performance, several optimization algorithms have been investigated [15–20]. In 2011, optimized method for direct-coupled PV-PEM electrolyser was proposed for relative sizing between components based on simple modelling of both polarization curves [21]. The optimization was based on minimization of energy transfer loss. In 2014, a novel integrated system was proposed that by using energy and exergy methodology, combined photocatalysis, photovoltaics, thermal engine and chemical energy storage for better solar energy harvesting [22]. In 2014, multi-objective optimization of direct coupling of PV-electrolyser systems using imperialistic optimization algorithm is performed [23]. The optimization was based on minimum energy transfer loss, which is equal to the difference of power of maximum power point to the power of system. In another study, hydrogen generation is maximized by optimizing the size and the operating conditions of an electrolyser directly connected to a photovoltaic module at different irradiances using particle swarm optimization (PSO) [24]. In mentioned studies, the objective is to minimize the gap between actual operational points and maximum power points. In another study, Optimization and sensitivity analysis of directly coupled photovoltaic-electrolyser system in Beijing is performed. Parameter of V/V_m as the ratio of actual voltage to voltage of maximum power point was introduced to analyze the efficiency changing point (ECP) which is the working point that distinguishes the variation trends of the system efficiency [25]. In 2015, the optimum analysis of photovoltaic-driven electrolyser system for hydrogen production was studied. The optimization was based on efficiency of hydrogen production with numerical calculation method with considering parameters including solar irradiance, the operating temperature of the electrolyser, and band-gap energy of the electrolyser [26].

In this study, the electrical performance of combined PV-Electrolyser system is evaluated and the electrical production of the PV system is optimized in a way that the output be as much as possible near to maximum power point of the system with maximum hydrogen production and minimized excess power. Beside optimization of the dimensions of the system, the optimal working temperature of the electrolyser is also evaluated. Therefore, a two combined level GA is designed for the optimization process. Also, for optimization of the system, a new index has been proposed. The comparison between the electrical performance of direct-coupled system and the system with DC/DC converter that follows the maximum power point of the PV is assessed. Then, a view of the operation of the system in operating time and in 24 h period is given. Finally, for validation of the results, a comparison with another study is given. The schematic of the proposed system is given in Fig. 1.

Electrolyser

Alkaline electrolysers are one of the most widely used instruments for hydrogen production through water electrolysis. For conduction of ions between the electrodes liquid electrolyte is used. Because of the optimal conductivity and corrosion resistance of the stainless steel, potassium hydroxide (KOH) is widely used as electrolyte. The reactions for the alkaline electrolyser anode and cathode is given by

$$\begin{aligned}&Cathode: 2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^-{}_{(aq)}\\&Anode: 2OH^-{}_{(aq)} \rightarrow \frac{1}{2}O_{2(g)} + H_2O_{(l)} + 2e^-\end{aligned} \tag{1}$$

Electricity is needed for the process of hydrogen production. The electrical equivalent of electrolyser can be considered as a nonlinear load that as the input voltage rises, more hydrogen is produced, due to current increase. In addition, the power rises, which is restricted to the power characteristics of power delivery source. The U–I characteristics of an advanced alkaline electrolyser is defined as [27]

$$U_{electrolyser,Cell} = U_{reversible} + \frac{r_1 + r_2 T}{A} I + s\log\left(\frac{t_1 + t_2/T + t_3/T^2}{A} I + 1\right) \tag{2}$$

where $U_{electrolyser,cell}$ is the cell terminal voltage (V), $U_{reversible}$ is reversible cell voltage (V), r_1, r_2 are parameters for ohmic resistance ($\Omega.m^2$, $\Omega.m^2/^\circ C$), as the coefficients for ohmic voltage, s, t_1, t_2, t_3 are parameters for overvoltage (V, m^2/A, $m^2.^\circ C/A$,n $m^2.^\circ C^2/A$), A is the area of cell electrode (m^2), I is electrolyser current (A), and T is cell temperature (°C). $U_{reversible}$ is given by the Gibbs free energy change of the electrical process as

$$U_{reversible} = -\frac{\Delta G}{zF} \tag{3}$$

where, z is the number of molecules transferred per hydrogen molecule which is 2, ΔG is Gibbs free energy, and F is Faraday constant. So, $U_{reversible}$ can be expressed as an empirical equation as

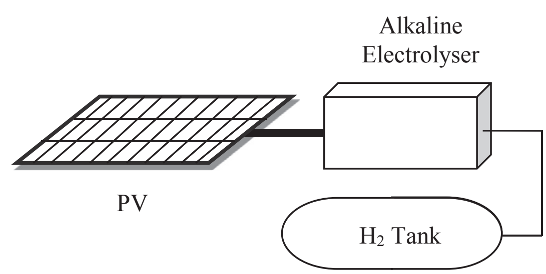


Fig. 1 – Simplified schematic of directly coupled PV-Electrolyser system with hydrogen storage.

$$U_{reversible} = U^0{}_{reversible} - k_{reversible}(T - 25) \quad (4)$$

where $U^0{}_{reversible}$ is the reversible cell voltage at standard condition (V), and $k_{reversible}$ is empirical temperature coefficient of $U_{reversible}$ (V/°C). For the electrolyser cells connected in series the current is the same and the voltage is

$$U_{electrolyser} = n_c \cdot U_{electrolyser,cell} \quad (5)$$

Knowing the voltage and current of the electrolyser, the amount of hydrogen production can be derived as

$$\dot{n}_{H_2} = \eta_F \frac{n_c I}{2F} \quad (6)$$

where $\dot{n}_{H_2}$ is the hydrogen production rate (mol/s) and η_F is the current (Faraday) efficiency. With increasing of the current, the ratio of parasitic current at the electrolyte decreases and causes η_F to increase. The equation of Faraday efficiency can be given as

$$\eta_F = \frac{(I/A)^2}{f_1 + (I/A)^2} f_2 \quad (7)$$

where f_1 (mA^2 cm^{-4}), and f_2 are parameters in current efficiency calculation. The current efficiency is also a function of the temperature, as the current of the electrolyser varies with temperature. When the temperature rises, the resistance of water decreases and the efficiency increases. However, at very high temperatures, the bulb production causes to generate parasitic currents in the electrolyte that decreases the efficiency. Although Due to thermal operation of the electrolyser system, and heat balance of the electrolyser, the temperature varies during the operation of the system, we suppose that the ventilation system of the electrolyser is designed in a way that the temperature of the system is fixed. The parameters of the electrolyser are given in Table 1.

Hydrogen storage system

The equation for storage pressure of the hydrogen using its flow rate is calculated using physical hydrogen storage technique is given by

$$P_b - P_{bi} = z \frac{n_{H_2} R T_b}{M_{H_2} V_b} \quad (8)$$

where M_{H_2} is the molar mass of hydrogen (kg kmol^{-1}), P_{bi}, P_b are the initial and operating pressure of tank (Pa), R is the universal gas constant (J kmol^{-1} K^{-1}), T_b is the operating temperature (K), V_b is the volume of the tank (m^3), z is the compressibility factor as a function of temperature.

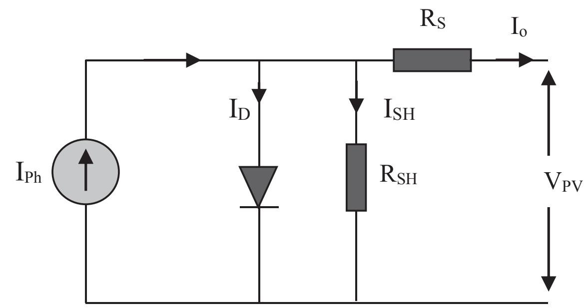


Fig. 2 – Model of photovoltaic cell.

PV

The assessment of the solar cells must be based on the electrical characteristics of the photovoltaic system, i.e. the U–I characteristics under different radiation levels and temperatures. Based on how accurate the model is needed to be designed, many cell models have been developed [29,30].

A one-diode model of the photovoltaic system which represents the dark current in parallel with PV cells, a shunt resistance and series resistance as shown in Fig. 2 is used in this study. The PV cells are connected in series and parallel to increase the operating voltage and current leading to raise the output power.

Based on the model of photovoltaic cell, shown in Fig. 2, the current of the cell is expressed as [31]

$$I_{o,cell} = I_{ph} - I_d - I_{sh} \quad (9)$$

where I_{ph} is the current generated by irradiance (A) which is proportional to solar irradiation, I_d is the current of diode (A), and I_{sh} is the current of parallel resistor (A). For the PV array with combination of PV cells, the output current is given by

$$I_0 = N_p I_{ph} - N_p I_{rs}\left[e^{\frac{q(V+R_s I_0)}{A \cdot k \cdot T \cdot N_s}} - 1\right] - N_p \frac{q(V + R_s I_0)}{N_s R_{sh}} \quad (10)$$

where, I_{rs} (A) is the cell reveres saturation current, k is Boltzman constant, T is the temperature of the cells (K), N_s and N_P are the number of PV cells in series and parallel, q is the electron charge, and A is the p–n junction ideality factor. I_{ph} (A) is proportional to solar irradiance by

$$I_{ph} = \frac{G}{1000}(I_{SC} + k_i(T - T_r)) \quad (11)$$

where, I_{sc} (A) is the short circuit current, k_i is the short circuit current coefficient, T_r is the cell reference temperature, and g is the solar radiation. Also, the saturation current of the cells which is highly dependent to temperature is given by

$$I_{rs} = I_{rr}\left[\frac{T}{T_r}\right] \exp\left(\frac{q \cdot E_G}{k \cdot A}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right) \quad (12)$$

Table 1 – Parameters of electrical characteristics of alkaline electrolyser [28].

Parameter	r_1	r_2	t_1	t_2	t_3	A	f_1	f_2
Value	7.3×10^{-5} Ω m^2	-1.1×10^{-7} Ω m^2 C^{-1}	-1.002 A^{-1} m^2	8.424 A^{-1} m^2 C	247.3 A^{-1} m^2 C^2	0.25 m^2	250 mA^2 cm^{-4}	0.96

Table 2 – Specification of the photovoltaic module.

Parameter	P_m	V_{oc}	I_{sc}	V_{MP}	I_{MP}	E_G	A	T_r	Q
Value	45 W	21.93 V	2.66 A	18.85 V	2.47 A	1.6 eV	0.75 m^2	25 °C	1.6×10^{-19}

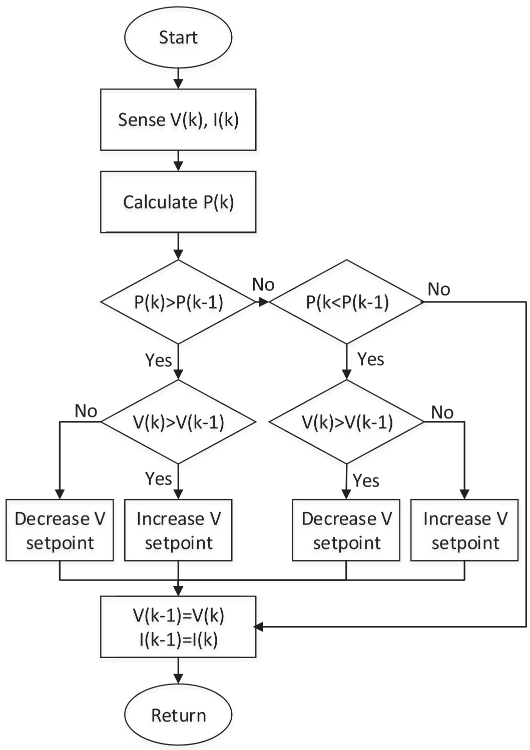


Fig. 3 – Maximum power point tracking.

where, I_{rr} (A) is the reverse saturation current at reference temperature which is dependent to the material of the PV cell, E_G is the energy of the band gap of the cells, and T_r (K) is the reference temperature. The specifications of the used PV modules is given in Table 2.

As it is shown in Fig. 3, for getting the maximum power from the photovoltaic array, the derivative of the produced power to voltage should be zero which is called maximum power point (MPP) as expressed by

$$\frac{dP}{dV} = 0 \tag{13}$$

So,

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = V\frac{dI}{dV} + I = 0$$
$$\frac{dI}{dV} = -\frac{I}{V} \quad \text{at MPP} \tag{14}$$

System simulation

The combination of the photovoltaic system and electrolyser is possible directly or with DC/DC power electronics converter. As it is shown in Fig. 4, the individual characteristics of PV systems and electrolyser are in a way that, the system can be very close to MPP. Several factors including number of PV panels in series and parallel, the operating temperature of the electrolyser, and

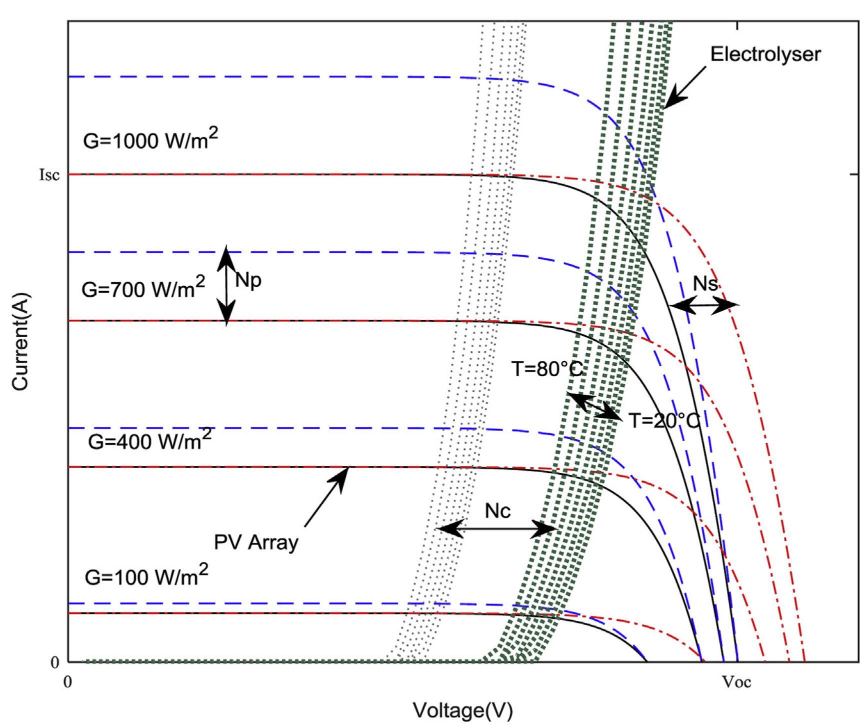


Fig. 4 – U–I characteristics of photovoltaic system and alkaline electrolyser.

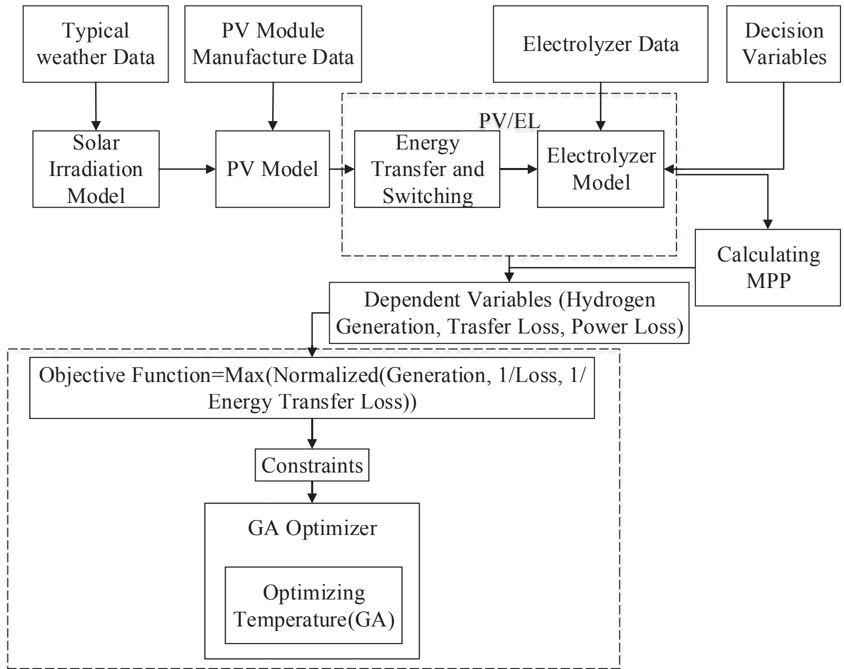


Fig. 5 – Simulation procedure.

the number of the stacks of electrolyser play important role in optimal operation of the directly connected system. So, with changing these factors, the U–I characteristics of PV and electrolyzer can operate in different working points.

With using a DC/DC converter, it is possible to get the maximum power of the photovoltaic system and inject it to the electrolyser. However, in these systems, there should be a simple optimal sizing to give the needed power to electrolyser. So, an optimum operating condition for a directly coupled PV-electrolyser should be proposed. On the other hand, the dimensions of the PV system for getting maximum hydrogen from the electrolyser are needed to be optimized. Because of the changing of the price of the PV system, another index for optimization has been proposed. So, the optimization function is based on maximum hydrogen production of electrolyser with minimum excess power production of PV system and minimum power transfer loss. The flowchart of the simulation procedure is given in Fig. 5.

Results and discussions

For the simulation of the system, actual meteorological data for diurnal temperature and irradiation of Miami from local

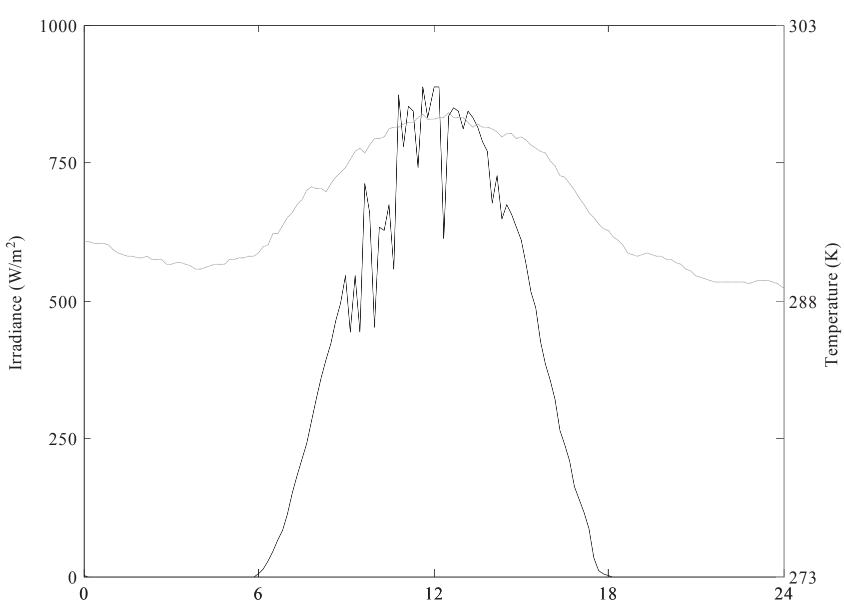


Fig. 6 – Temperature and Irradiance of Miami for a day.

utility of Florida is given in Fig. 6. This data is selected as it is represents the average weather characteristics of Miami. The latitude of Miami is 25.77°, so close to the tropic of cancer, as the most northerly circle of latitude on the Earth at which the Sun may appear directly overhead at its culmination. Based on our previous study [32], the most appropriate values for β "angle between surface of collector and horizon" and γ "surface azimuth angle" to obtain maximum irradiation are the latitude of the region and zero, respectively.

The system is optimized using genetic algorithm (GA). As it is shown in Fig. 7, the optimization has two level of GA process. So, the first level is optimizing the dimensions of the system, and the second level is to give the optimal temperature of the system using the dimensions of each iteration as input parameters. As it is discussed in Ref [23], the minimum energy transfer loss does not necessarily leads to maximum hydrogen production. For optimal sizing, a new objective function is proposed based on maximum hydrogen production and minim excess power production of PV system and minimum power transfer loss. So, the objective function for optimization of the system is expressed as:

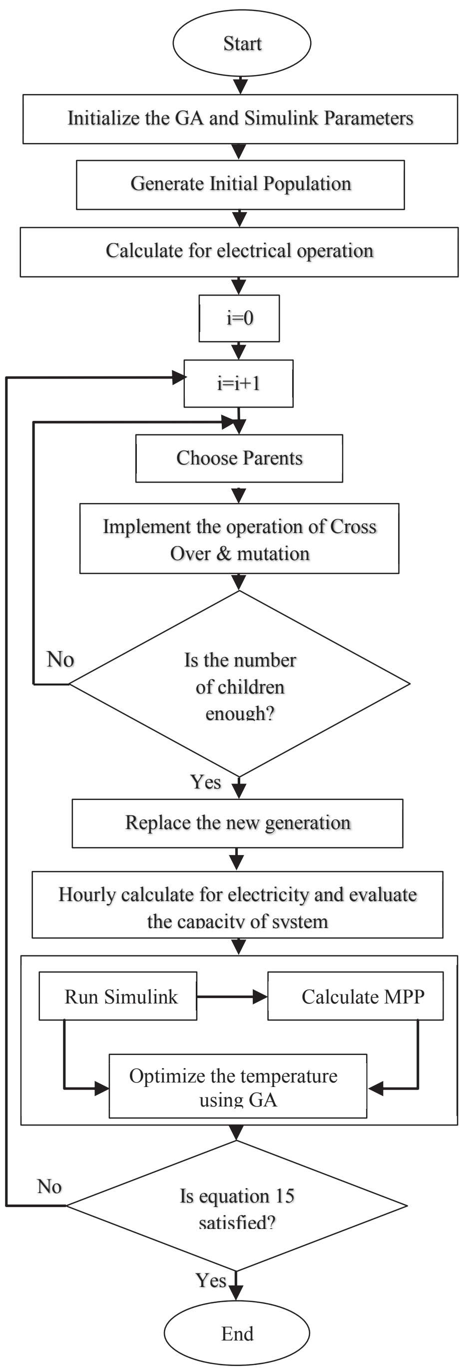


Fig. 7 – Flowchart of the GA optimization.

Table 3 – Optimization result.

Parameter	Result
PV nominal power	12.4 kW
N_s	2
N_p	133
N_c	21
Average temperature	72 °C
Average (V_{Direct}/V_{MPPT})	0.88
Average (P_{Direct}/P_{MPPT})	95.3%
$P_{direct\_Mean}-P_{MPPT\_Mean}$	96 W
Hydrogen production	656.64 mol
Energy loss	5.08 kJ
Average daily operation voltage	31.25 V
Total energy consumption	2.42*10^5 kJ
Pressure	3.4 MPa

$$Objective\_Function = Maximize\left(\frac{Ave\left(\frac{P_{Actual}}{P_{MPP}}\right)\cdot \dot{n}_{H2}}{Ave(P_{Loss})}\right) \tag{15}$$

The excess power is considered as the loss power, because it is produced when the power produced by PV is more than nominal power of electrolyser and the energy cannot be used. As in our study, we did not consider the cost of the system for optimization purpose, minimizing the excess power production could be appropriate substitution, because it indirectly deals with the cost of the system. The power transfer loss refers to the lost power because of working of the system in voltages other than voltage of maximum power point. Also in each iteration of the optimization process, the optimal temperature is given to make sure the best condition for the operation of the system. If we consider fixed operating temperature of electrolyser, the results will not be accurate, because each dimension gives the maximum power in a specific temperature. Although the temperature of the electrolyser is affected by ambient temperature and the operating condition of the system and time, the optimum temperature can be set in the electrolyser using the cooling system with controlled fluid flow rate and fluid temperature. The optimization results is shown in Table 3. The optimal size of the PV array for supplying the 10 kW alkaline electrolyser with 21 stacks, connected in series, is 12.4 kW which is the combination of 2 parallel rows of panels and 133 panel in each raw. The number of solar panels in series is more than parallel because, as obvious in electrolysers characteristics, we need more current for voltages around 36 V.

U_I characteristic of the system is illustrated in Fig. 8. The average operating voltage when the PV is on is 31.25 V that is the 84.5 percent of the nominal operating voltage of the system. Also, the current of the system which follows the pattern

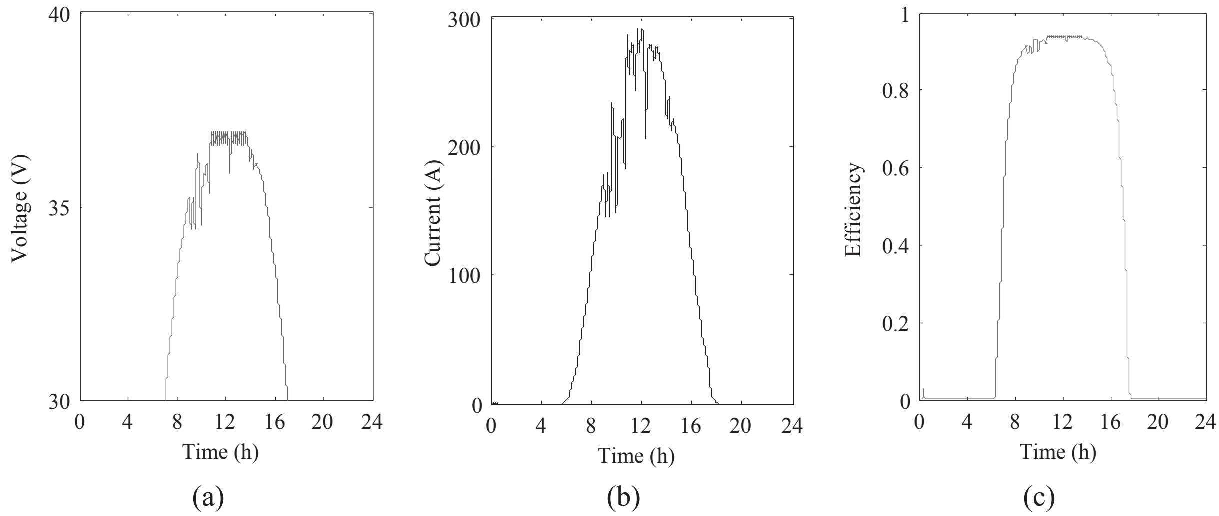


Fig. 8 – Electrical characteristics of direct coupled PV-electrolyser system.

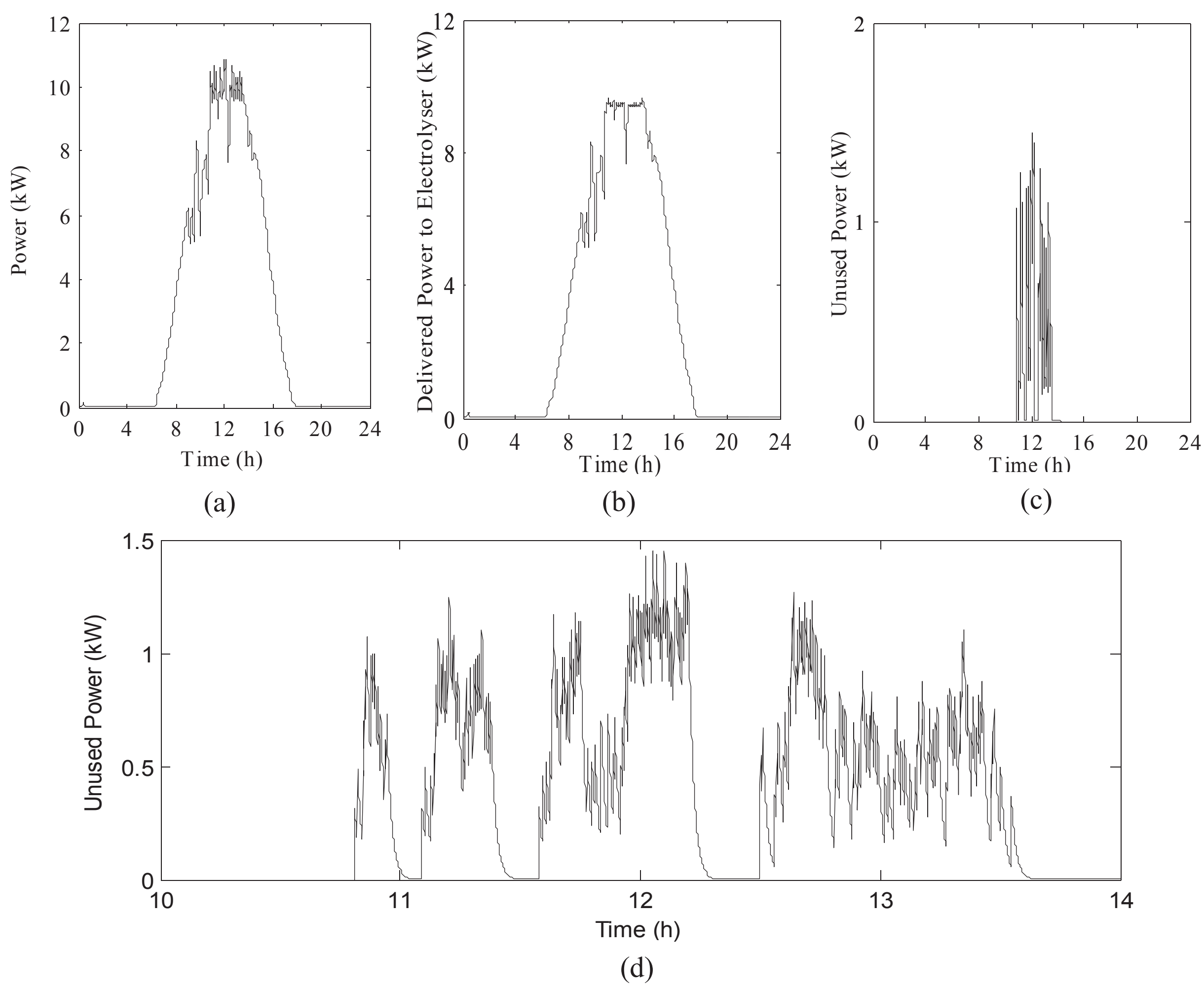
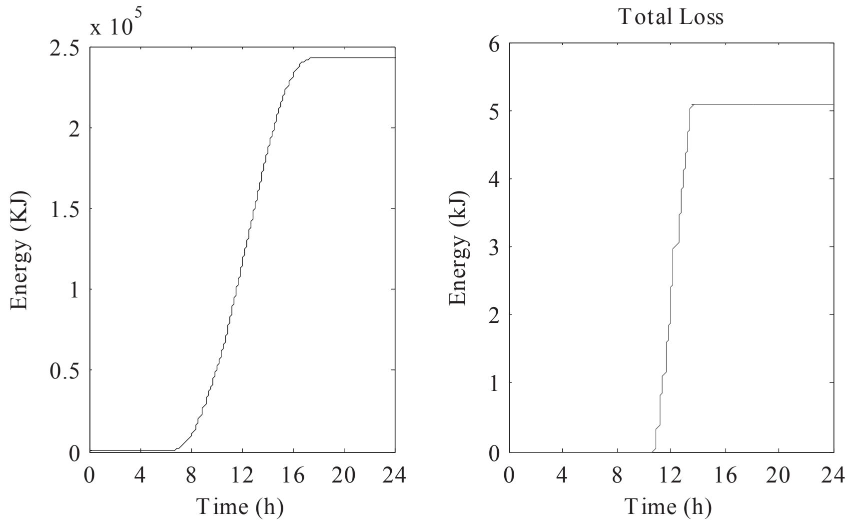


Fig. 9 – Produced power of photovoltaic array (a) Consumed power by electrolyser (b) and power loss (c) with focused view of power loss (d).

of the voltage is shown in Fig. 8 b. In addition, the faraday efficiency is given in Fig. 8 c. The average faraday efficiency for operating points is 79.25 percent, which is 14.6 percent less than the maximum faraday efficiency. Although at higher temperatures, the average faraday efficiency is closer to the maximum value, its variation at proximity of nominal



(a) (b)

Fig. 10 – Energy production (a) and loss (b) of the system.

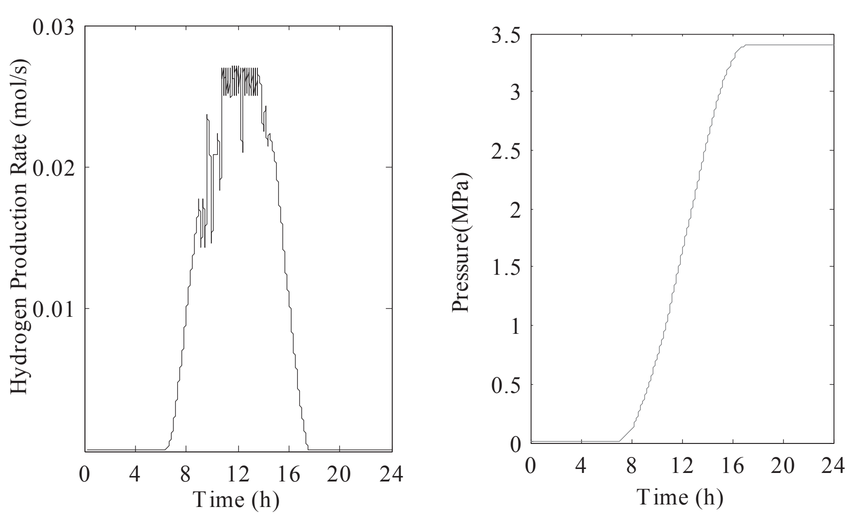
condition is negligible in comparison to effect of temperature in U–I characteristics.

Fig. 9 shows the power production, consumption, and excess power of the system along with focused view of unused power. The average power production is 5.61 kW with operating efficiency of 45 percent, which its 97.8 percent is used in the electrolyser and the rest is the unused power that has been minimized. The power consumption of the electrolyser at noon is at its maximum amount. The unused power is produced at noon when the irradiation is high. The average power consumption of electrolyser for operating hours is 5.49 kW that is 54.9 percent of nominal power of the electrolyser.

By evaluating the energy of the PV system shown in Fig. 10, it can be seen that the produced unused energy is 2.08 percent of produced energy that can be neglected. Therefore, the optimum systems lost energy is very low that the PV production is in its most efficient mode. The produced energy of the electrolyser is just due to electrical power production and other possible ways of energy production or consumption in PV and electrolyser system such as thermal power is not been considered in this study.

The hydrogen production rate and the pressure is shown in Fig. 11. The average rate of hydrogen production for 24 h of the day is 0.0076 mol/s and for operating time is 0.0151 mol/s. At the end of the day, total amount of 656.64 mol hydrogen is produced and the pressure of the hydrogen storage tank with initial pressure of zero is raised to 3.4 MPa.

The operation of the connected PV system in both directly coupled and maximum power point modes is shown in Fig. 12. As it can be seen, the power of two systems are so close to each other with only average 96 W lack of production in



(a) (b)

Fig. 11 – Hydrogen production rate of the electrolyser (a) and hydrogen storage pressure of tank (b).

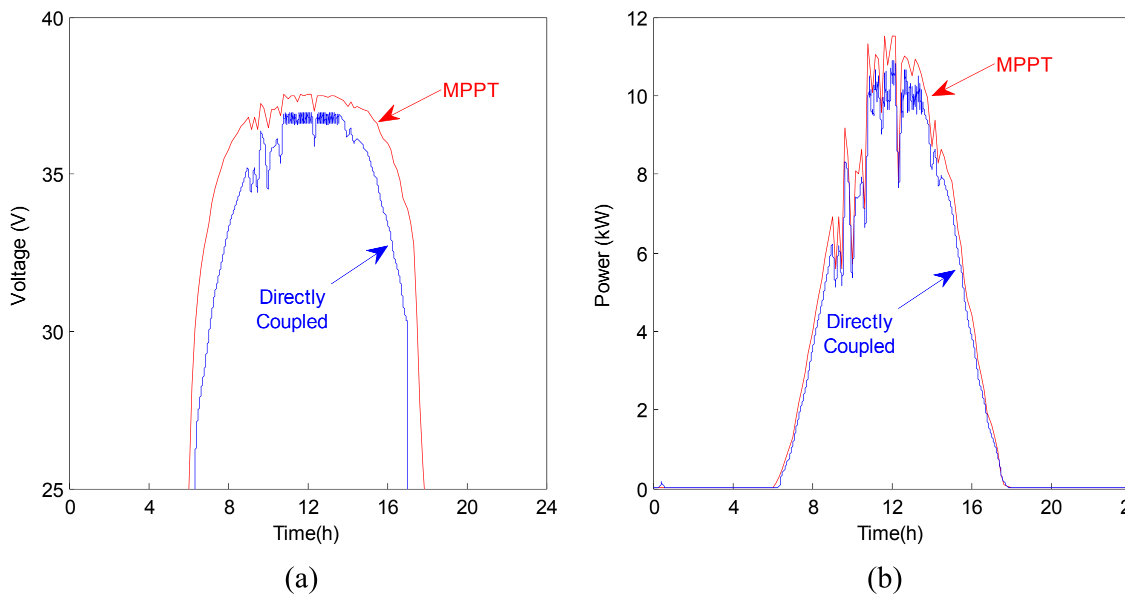


Fig. 12 – Voltage (a) and power production (b) of photovoltaic array in directly coupled system and with MPPT.

directly coupled mode. In addition, the average voltage of the directly coupled system is 4.26 V less than maximum power point mode. Therefore, the system can produce maximum hydrogen without using power electronics devices, making the system more affordable for future usage.

For making the system capable of being comparative with other power production methods as the power sources of electrolyser, the 24 h mean characteristics of the system should be generated which is given in Table 4. The results show that considering the evaluation of system in 24 h period, the average amount of hydrogen production is much lower than the operating time amount.

For validation of this study, a comparison between the result of proposed system and two similar systems is given with the comparison results given in Table 5. In the first study [33], optimal direct coupling of solar-hydrogen system with PEM electrolyser was investigated. The optimization was simply based on minimizing the energy loss. In addition, because the number of panels and electrolysers were known, a global search between the different possible combinations could find the best result without need for any optimization algorithm. The total energy loss is derived from the difference of the produced power to delivered power and energy transfer is derived from the difference of actual delivered energy and theoretical maximum deliverable energy. In both terminologies, the proposed method gives better results. In the second study [24], the objective of optimization is to reduce the energy transfer loss using particle swarm optimization (PSO). The system is not necessarily operating at its optimal point to produce maximum hydrogen. Although the energy transfer loss is lower, in our study, energy loss and hydrogen production and overall efficiency is optimized.

Table 4 – Average Specifications of the system in 24 h period and in bright hours when there is irradiation.

	24 h period	Bright hours
Average Faraday efficiency	38.14 Percent	79.25 Percent
Average power consumption of electrolyser	2.75 kW	5.49 kW
Average hydrogen production rate	0.0076 mol/s	0.0151 mol/s
Average current	79.13 A	158.22 A
Average voltage	15.63 V	31.25 V
Average power loss	0.059 kW	0.118 kW

Conclusion

The electrical operation of directly coupled PV-electrolyser system is investigated. The optimized system can operate with 4.7 percent power transfer loss in comparison with the system operating with MPPT. Due to decent matching of the U–I characteristics of electrolyser with PV system, as the result of simulation shows, is very efficient. Two levels optimization made it possible to be able to get as closer as possible to the maximum power point of the photovoltaic system. Optimal sizing with a new optimization objective function gives the maximum hydrogen production of 656.64 mol with average power loss of 0.118 kW for the 12.4 kW photovoltaic system which gives the high efficiency at mentioned dimensions. The electrolyser operating at temperature of 72 °C feeds the hydrogen storage tank with final pressure of 3.42 MPa. The comparison of our proposed system with previous studies shows significant improvement in operation of the system, due to multi-level optimization and considering more general optimization objective function. The results shows that with the optimal dimensions, the system can operate efficiently without requiring power electronics devices making it more.

For the future studies, actual operating temperature of the electrolyser along with optimized cooling system can be added to the design process to give result that is more precise.

Table 5 – Comparison of the operation of the proposed system with ref [33].

	Proposed study	Ref [33]	Ref [24]
Electrolyser	Advanced Alkaline electrolyser	PEM Electrolyser	PEM Electrolyser
Connection mode	Directly coupled	Directly coupled	Directly Coupled
Objective	Maximize hydrogen, minimize excess energy production, minimize energy transfer loss, and optimize operating temperature	Minimize the energy loss	Minimize the energy transfer loss
Optimization method	Two level Genetic Algorithm	–	PSO
Energy Transfer	95.3%	94%	97.8%
Energy loss	2%	5.82%	–

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