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Solar hydrogen from photovoltaic-electrolyzer systems

E. Bilgen *

Ecole Polytechnique, University of Montreal, C.P. 6079, Centre-ville, Montreal Que., Canada H3C 3A7

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Abstract

A mathematical model has been developed to determine and optimize the thermal and economical performance of large scale photovoltaic-electrolyzer systems, either with fixed or sun tracking panels using hourly solar radiation data. It has been found that the overall thermal efficiency of photovoltaic-electrolyzer systems may be as high as 10.85% with sun tracking panels and 10.33% with fixed panels. The levelized solar hydrogen cost using either fixed or sun tracking panels is well correlated with the total annual solar radiation on a horizontal surface. Climatic conditions, altitude and latitude are not significant parameters affecting this correlation. The results show that there is a practical minimum cost of hydrogen, which is 44.5 $/GJ hydrogen when the PV system cost is 1 $/Wp and the capital charge rate is 15%.

Keywords: Solar hydrogen; Photovoltaic system; PV-electrolizer; Electrolytic hydrogen

1. Introduction

Hydrogen production using direct solar energy and electrolyzer systems can be achieved in various ways. The following methods can be mentioned: (i) solar thermal electrical power generation and water electrolysis; (ii) photovoltaic electrical power and water electrolysis. Hydrogen production using these methods seems to be the processes with near future application potentials for their most important subsystems, namely either thermoelectric solar power and photovoltaic generator systems or electrolyzer systems, are well developed technologies. Further, the last method has an additional advantage, as the direct current electrical power by a photovoltaic generator can be supplied directly to an electrolyzer.

* Tel.: +1-514-340-4711, ext.: 4579; fax: +1-514-340-5917.
E-mail address: bilgen@meca.polymtl.ca (E. Bilgen).

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Nomenclature

A	polynomial coefficient
CE	capital component of electrolyzer system cost
C_t	total estimated system cost
C_{su}	total investment at start-up
E_a	annual hydrogen production in GJ hydrogen/year
f	load fraction at maximum power point, P_1
H_b	beam component of radiation
H_d	diffuse component of radiation
H_D	yearly hydrogen production
H_T	total radiation on horizontal surface
I_{ph}	photocurrent
I_0	reverse saturation current
I, i	current
i_{dc}	interest rate during construction
i_r	rated current density
j_i	interest rate in next y years
k_1	fraction of cell cost
k_2	fraction of accessory cost
F_{om}	annual operation and maintenance cost
P	point on characteristic curves
R_b	beam correction factor
R_s	series resistance
R_{sh}	shunt resistance
r_{dc}	inflation rate during construction
r_i	inflation rate in next y years
s	slope
V	voltage
V_i	electrolyzer voltage at operating current density
v	hydrogen production rate (m^3/s)
x_m	cost parameter in $\$/m^2$ separator area
x_k	input power
χ_R	rectifier cost (\$/kW a.c.)
y	write-off period (years)

Greeks

η_1	efficiency at nominal power
η_{f_1}	efficiency at load fraction, f_1
η_{f_2}	efficiency at load fraction, f_2
η_{Re}	rectifier efficiency
Λ	completion factor
β	$1 + R_s/R_{sh}$
ρ	albedo

There are various experimental (see, for example Refs. [1–4]) and theoretical (see, for example Refs. [5,6]) studies in the literature on photovoltaic-electrolyzer systems. In experimental studies, various technologies are tested, system performances in actual conditions are studied and safety issues are addressed. In the theoretical studies, overall system performance for selected conditions is evaluated, and the cost of hydrogen is estimated in view of present and future technologies. Some other issues, mainly an optimized operation of the two subsystems mentioned above and that of the cost of solar hydrogen in actual operational conditions have not been addressed. In particular, there are no simulation studies using actual solar radiation data for a given specific location with various operational possibilities, such as with fixed or sun tracking photovoltaic panels. In addition, problems concerning scale-up of small systems for large scale hydrogen production have not been considered.

The aim of this study is to investigate the performance of photovoltaic-electrolyzer systems using an hourly radiation model, establish optimal operating conditions and address problems concerning systems with fixed or sun tracking PV panels for large scale hydrogen production.

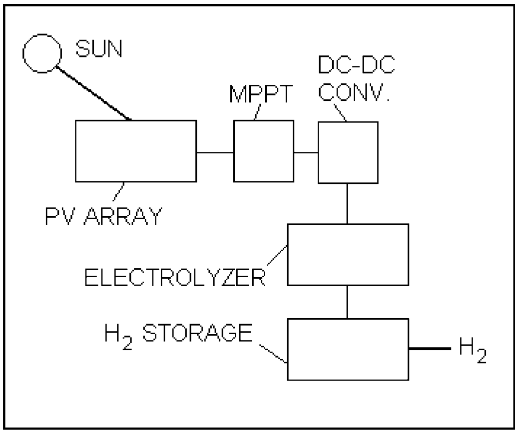

Fig. 1. Schematic of PV-hydrogen production system.

2. System description

The photovoltaic-electrolyzer system studied consists of the following major components (see Fig. 1): PV array which is made of several units; a maximum power point tracker (MPPT); a DC–DC converter, which is used to operate the system at the maximum power of the photovoltaic system at all times and to supply the necessary DC current to the electrolyzer; an industrial electrolyzer system; and a storage system for hydrogen.

3. Simulation model

The simulation model consists of various subsystems:

- the model to calculate the (I, V) characteristics of the photovoltaic generator;
- the model to determine the (I, V) characteristics of the electrolyzer;
- the model to calculate the solar energy received by a sloped fixed or tracking surface using hourly solar radiation data;
- the model to determine the open circuit voltage, V_{oc} and short circuit current, I_{sc} following the solar radiation received by the photovoltaic cells;
- the model to optimize the system operation;
- the model to estimate the solar hydrogen cost.

3.1. Photovoltaic system

The characteristic of the photovoltaic system is expressed as follows [7]:

$$V = -IR_s + \Lambda^{-1} \ln \left(\frac{I_{ph} - \beta I - (V/R_{sh})}{I_0} + 1 \right) \tag{1}$$

$$I = I_{ph} - I_0(\exp(\Lambda(V + IR_s)) - 1) - \frac{V + IR_s}{R_{sh}} \quad (2)$$

where R_s is series resistance; R_{sh}, shunt resistance; Λ, completion factor; β, $1 + R_s/R_{sh}$; I_{ph}, photocurrent; I_0, reverse saturation current; I, current; and V, voltage.

3.2. Derivation of I–V characteristics of PV system

The I–V characteristic of the solar cell may be defined by N current–voltage experimental data points; or by using a few selected points, such as open circuit voltage, short circuit current, I and V at maximum power and I–V slopes at $V = 0$ and $I = 0$. In either case, the solution of Eq. (1) can be accomplished by using iteration methods.

The algorithm used to solve Eq. (1) in this study follows that of Kennerud [8] who has used the following information on the PV characteristics:

- V_{oc} = open circuit voltage;
- I_{sc} = short circuit current;
- $(dI/dV)_{I=0}$ = tangent of I–V at $I = 0$;
- $(dI/dV)_{V=0}$ = tangent of I–V at $V = 0$;
- $\mathrm{Max}(I, V)$ = maximum power point.

Based on these, a system of five non-linear equations can be written:

$$0 = I_{ph} - I_0(\exp(fV_{oc}) - 1) - \frac{V_{oc}}{R_{sh}} \quad (3)$$

$$I_{sc} = I_{ph} - I_0(\exp(fI_{sc}R_s) - 1) - \frac{I_{sc}R_s}{R_{sh}} \quad (4)$$

$$(dI/dV)_{I=0} = -I_0(f(1 + (dI/dV)_{I=0}R_s)\exp(fV_{oc})) - \frac{1 + (dI/dV)_{I=0}R_s}{R_{sh}} \quad (5)$$

$$(dI/dV)_{V=0} = -I_0(f(1 + (dI/dV)_{V=0}R_s)\exp(fI_{sc}R_s)) - \frac{1 + (dI/dV)_{V=0}R_s}{R_{sh}} \quad (6)$$

$$-I_M/V_M = -I_0(f(1 - (I_M/V_M)R_s)\exp(f(V_M + I_MR_s))) - \frac{1 - (I_M/V_M)R_s}{R_{sh}} \quad (7)$$

The solution of this system by a numerical method (Newton–Raphson, for example) yields the I–V characteristics of the PV system, as a solution of Eqs. (1) and (2).

3.3. Determination of I_{ph} and I_0

The photocurrent I_{ph} and the reverse saturation current I_0 are determined using the measured values of V_{oc} and I_{sc} and by Lagrange interpolation at various intensities of solar radiation. The approximate equations are:

$$I_{ph} = \beta I_{sc} \quad (8)$$

$$I_0 = \frac{\beta I_{sc} - (V_{oc}/R_{sh})}{\exp fV_{oc}} \quad (9)$$

3.4. Electrolyzer system

The characteristics of the electrolyzer system are expressed as a polynomial equation:

$$V = A_0 + \sum A_i I_i \quad (10)$$

where the polynomial coefficients A_0 and A_i are determined using the least square method from empirical data.

3.5. Solar radiation model

The solar energy received by a sloped surface is determined using hourly total and diffuse radiation data on a horizontal surface. The algorithm follows the well established methods in the literature (see, for example Ref. [9]).

$$H_T = H_b R_b + 0.5 H_d (1 + \cos s) + 0.5 (H_b + H_d)(1 + \cos s)\rho \quad (11)$$

3.6. Optimization model

The optimum operation of the photovoltaic-electrolyzer system is accomplished by searching and operating the system at the maximum power point for a given solar radiation intensity.

With reference to Fig. 2, the labeled PV system and electrolyzer curves represent the I, V characteristics of the PV and electrolyzer systems, respectively. The one labeled locus of MPPT shows the maximum power for a given radiation intensity.

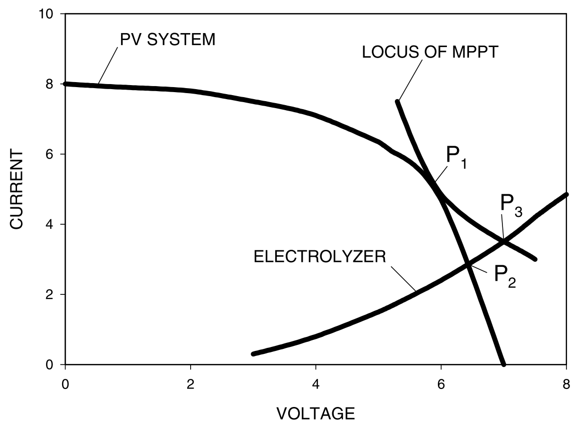

Fig. 2. Characteristics of PV and electrolyzer systems.

Determination of the maximum power point, P_1*:* Since the power–voltage characteristics of the PV system represent a unimodal function, in order to locate the maximum power point on the curve I–V, a sequential dichotomous search is conducted to find the $P = IV$ which gives the maximum value of the power.

Determination of P_2*:* The intersection point of the two characteristic curves is obtained by using an iteration method.

Determination of P_3*:* The MPPT can be specified by using its nominal load and efficiency. The latter is a quadratic function of the actual load [10]. The efficiency of the MPPT can be written as:

$$\eta(f) = \eta_1 \frac{(f - f_1)(f - f_2)}{(1 - f_1)(1 - f_2)} + \eta_{f_1} \frac{(1 - f)(f - f_2)}{(1 - f_1)(f_1 - f_2)} + \eta_{f_2} \frac{(1 - f)(f_1 - f)}{(1 - f_2)(f_1 - f_2)} \tag{12}$$

where f is load fraction at P_1, the maximum power point; η_1, efficiency at nominal power; η_{f_1}, efficiency at load fraction, f_1; and η_{f_2}, efficiency at load fraction, f_2.

The power at P_3 will be equal to $\eta(f)$ times the power at P_1. Once the power at P_3 is calculated, (V_3, I_3) can be determined from Eq. (3), which should satisfy it at all times.

Hydrogen production: The hydrogen production v (m^3/s) is proportional to the current $I(A)$ passing through the electrolyzer cells and is determined from [11]:

$$v = 1.22 \times 10^{-7} I_3 \tag{13}$$

3.7. Cost estimation model

The cost of energy conversion is based on estimates made for plant capital costs and operation and maintenance costs [12]. Energy conversion costs are determined for a utility financing case. The major guidelines in determining costs are as follows:

- capital and operating costs are in constant 1996 US dollars; escalation of plant investment during construction has not been taken into account;
- installation time for the entire system is 0.5 years;
- maintenance, including labor, supplies, materials and overhead, is 1% of the total installed cost for each of the PV generator, MPPT and H_2 storage unit and 4% for the electrolyzer;
- plant utilization is 2000 h per year;
- plant life for economic write-off is 25 years for each of the PV generator, MPPT and storage systems and 20 years for the electrolyzer;
- interest during construction is assumed to be 5% per year;
- for utility financing, the annual charge rate for capital recovery, F_c, is assumed to be 15%.

The cost of hydrogen, \$/GJ hydrogen, by the system is calculated as:

$$C = (F_c + F_{om}) C_{su} / E_a \tag{14}$$

$$C_{su} = (1 + i_{dc})(1 + r_{dc})^n C_t \tag{15}$$

$$F_{om} = F_{om_i} \frac{\sum_i (1 + r_i)^y (1 + j_i)^{-y}}{\sum_i (1 + j_i)^{-y}} \tag{16}$$

where C_{su} is the total investment at start-up, F_{om} is the levelized annual operation and maintenance cost factor evaluated by Eq. (16), F_{mo_i} is the initial operation and maintenance cost factor which is assumed 2% of C_{su} and E_a is the annual hydrogen production in GJ.

4. Case study

The study was conducted for 13 locations with four different climates at various latitudes. They are shown in Table 1.

Each photovoltaic generator was assembled of 200 units, each with 666 Wp power made of 18 Solarex HE60 modules; each module is rated as 37 Wp. Hence, the total power of a generator was 133.2 kWp. The electrolyzer was 119 kW DC, model A1000 of Electrolyzer Corp. The total power of the MPPT was 140 kW.

Several PV generator-electrolyzer systems can be put together to produce large amounts of hydrogen. In the following examples, only one generator will be considered, however, the cost is for large systems made of several generators.

The cost data for various components were as follows:

- the installed cost of the PV generator was taken as 1 \$/Wp, which represents the future technology in the 2010 time frame [6];
- for the sun tracking system, heliostats are used, each 54 m^2 supporting 10 units or 6.66 kWp PV modules. The cost of heliostat was taken as 78 \$/m^2 less 10.8 \$/m^2 for the cost of support structure used in the fixed system; hence, the cost of the heliostat for the sun tracking system was 0.545 \$/Wp;
- cost of land is 1 \$/m^2;
- the capital component of the electrolyzer system is [13]:

Table 1
Locations and climates

Climate	Location	Latitude (°N)	Altitude (m)	Optimum slope (deg)
Tropical	Miami (FL)	25.78	3	20
	Dakar (SE)	14.70	40	10
	Sulayyil (SA)	20.47	600	17.5
Dry	El-Paso (TX)	31.80	1194	30
	Las Vegas (NE)	36.08	659	40
	Salt-lake City (UT)	40.77	1286	40
Warm temperate	Istanbul (TR)	40.96	18	40
	Izmir (TR)	38.57	5	40
	Kansas City (MO)	39.28	226	40
	Marrakech (MO)	31.60	463	30
	Riverside (CA)	33.95	461	30
Cool snow-forest	Indianapolis (IN)	39.73	242	30
	Montreal (CND)	45.50	30	30

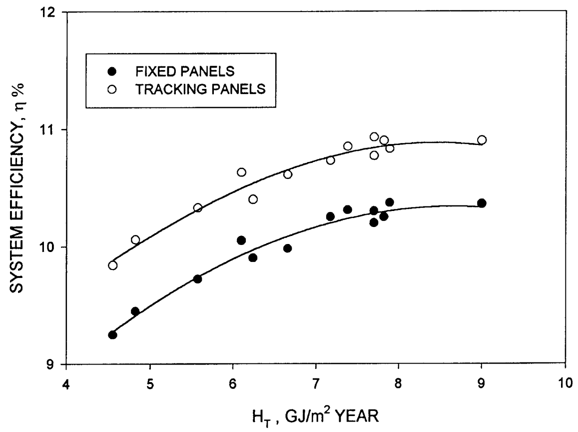

Fig. 3. The overall efficiency of PV-electrolyzer systems with fixed and tracking panels.

$$\mathrm{CE} = 777H_\mathrm{D}\left(\left(\frac{k_1}{i}+\frac{1-k_1}{i_\mathrm{r}}\right)x_\mathrm{m}+0.5k_2\left(\frac{1}{i}+\frac{1}{i_\mathrm{r}}\right)x_\mathrm{m}\right)+\frac{V_\mathrm{i}\chi_\mathrm{R}}{100\eta_\mathrm{Re}} \tag{17}$$

$$x_\mathrm{m} = \frac{V_\mathrm{r}i_\mathrm{r}x_\mathrm{k}}{100} \tag{18}$$

The parameters for the unipolar electrolyzer are $k_1 = 0.90$, $k_2 = 0.45$, $x_\mathrm{k} = 179.70$ \$/kW, $i_\mathrm{r} = 134.00$ mA/cm^2, $V_\mathrm{r} = 1.74$ V, all updated to constant \$ US

- MPPT cost for large systems is assumed to be 0.15 \$/Wp.

Synthetic hourly total and diffuse solar radiation data on a horizontal surface for the locations in Table 1 were used.

The study was conducted using fixed as well as sun tracking panels. In the case of fixed panels, the optimum slope for each location was first determined by a parametric analysis. The optimum slopes which are shown in Table 1 were used for the case with fixed panels. The system performance and the levelized solar hydrogen cost, \$/GJ hydrogen, as a function of average yearly total solar energy received by a horizontal surface are calculated for both fixed slope and sun tracking PV panels, as shown in Figs. 3 and 4.

5. Results and discussion

The results obtained with the present model were checked against simulation and experimental results available for system performance in Ref. [14]. For the case of 3.4 GJ/m^2 year horizontal solar radiation, for example, the overall performance of a PV array and electrolyzer system was found to be 8.15%, which compares well with 8.11% given for their system 1 [14].

The overall thermal performance of the PV hydrogen production system is defined as the ratio of the higher heating value of hydrogen produced in one year to the yearly total solar energy on the PV panels. The results are presented in Fig. 3, where the overall thermal performance is shown as a function of the annual total solar radiation on a horizontal surface. It can be seen that the overall thermal performance varies from 9.25% (Montreal) to 10.33% (Riverside, CA) with fixed panels and from 9.84% (Montreal) to 10.85% (Sulayyil) with sun tracking panels. The variation of the overall system performance with total solar radiation on a horizontal surface is, in addition to solar radiation conditions, due to climatic conditions. It is seen that for places with solar radiation on a horizontal surface exceeding 8000 GJ/m^2 year, the system performance may be at the upper limits noted above: 10.33% for systems with fixed panels and 10.85% for those with tracking panels.

It can be seen that due to low efficiency of the photovoltaic conversion, the overall thermal efficiency is on the order of 10%, as discussed elsewhere (see, for example Ref. [15]). Other types of solar hydrogen producing systems, for example solar thermal electricity and electrolyzer and thermochemical or thermochemical and electrochemical cycles, may have an overall thermal efficiency twice as much as the PV and electrolyzer systems (see, for example Refs. [12,16,17]). Others, such as semiconductor electrode and particle systems, sensitized semiconductor systems and homogeneous and heterogeneous systems have efficiencies one order of magnitude lower than those of PV based systems [15]. With these systems, basic research is needed before doing any system studies.

The levelized solar hydrogen cost, $/GJ hydrogen, as a function of average yearly total solar energy received by a horizontal surface is calculated for both fixed slope and sun tracking photovoltaic panels. The results are shown in Fig. 4, which shows that the solar hydrogen cost correlates well with the yearly total solar energy received by a horizontal surface with fixed and sun tracking panel systems:

$$C = 297.2864 - 73.159H_\mathrm{T} + 7.2158H_\mathrm{T}^2 - 0.2437H_\mathrm{T}^3 \quad (19)$$

This correlation is valid for the range of total solar radiation on a horizontal surface shown, and its correlation coefficient is $R \simeq 0.98$. It is also seen that neither climate type, latitude nor altitude are significant parameters affecting cost, although it was noted earlier with Fig. 3 that

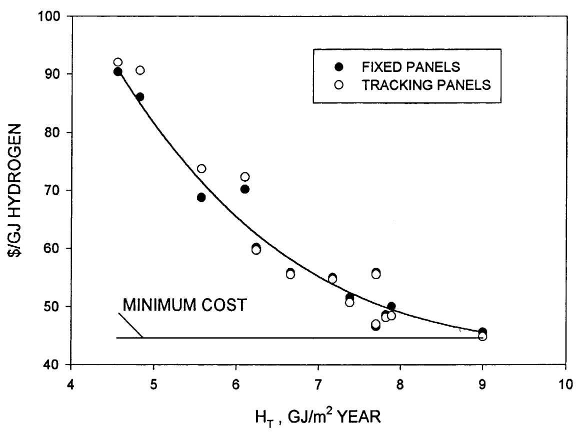

Fig. 4. The levelized solar hydrogen cost versus the average yearly total solar energy on the horizontal surface for fixed and tracking panels systems.

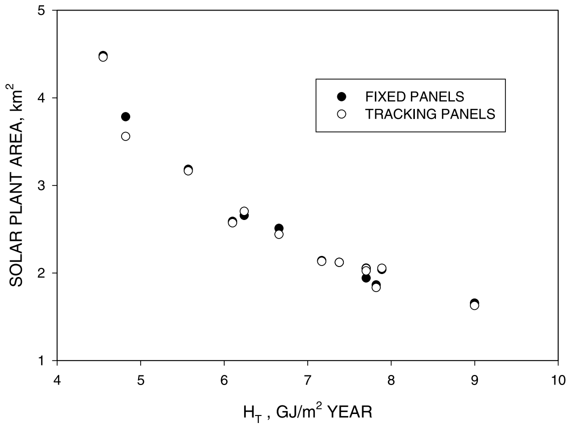

Fig. 5. Land usage for a solar plant producing 10^6 GJ hydrogen per year as a function of annual total solar energy on the horizontal surface for fixed and tracking panels systems.

these parameters affect the overall thermodynamic performance. It is seen that the levelized solar hydrogen cost has a limiting practical value shown as minimum cost in Fig. 4. This cost can be obtained in places where the average yearly solar energy received by a horizontal surface exceeds 8 GJ/m^2 year (see, for example Ref. [18] for Saudi Arabia's potential). The practical minimum cost using the technology of year 2010 is estimated to be $ 44.5/GJ hydrogen. This is comparable to the cost estimates of solar hydrogen from thermochemical and hybrid cycles [16,19], although as discussed earlier, the overall thermal performance of these systems is much superior to that of the PV-electrolyzer systems.

The land area required for production of 10^6 GJ hydrogen per year as a function of the annual total solar radiation on a horizontal surface is shown in Fig. 5. It can be seen that using fixed or sun tracking panels, land usage will be more or less the same for a given location: for a 10^6 GJ hydrogen per year production plant, the minimum is about 1.6 km^2.

6. Conclusions

In view of the results presented, the following conclusions can be summarized:

1. There is no general correlation between the optimum slope of the fixed PV panels and the latitude. The cost optimization is necessary for each location.
2. The cost of solar hydrogen correlates well with the annual total solar energy received by a horizontal surface.
3. The overall thermal efficiency of the PV-electrolytic hydrogen production by using semiconductor solid state photovoltaic cells may be as high as 10.33% for fixed panels and 10.85% for sun tracking panels.
4. There is an ultimate minimum cost of solar hydrogen: for 1 $/Wp PV system cost and a typical charge rate of 15%, it is 44.5 $/GJ hydrogen.

5. For a plant of 10^6 GJ hydrogen annual production, the minimum land usage for the most favorable locations is about 1.6 km^2.
6. The results indicate that if the PV installed cost can be reduced to 1 $/Wp, or lower values in year 2010, the production of solar hydrogen by the PV-electrolysis method may become economically competitive in areas where the total solar energy received on a horizontal surface is greater than 8 GJ/m^2 year.

Acknowledgements

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