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Domestic hydrogen production using renewable energy

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Abstract

A brief review shows that domestic production of hydrogen to fuel a car is feasible by using various means. Among these, the solar—photovoltaic electricity—electrolysis process seems to be the most practical if a renewable energy source is to be used. A simplified model has been developed to determine and optimize the thermal and economical performance of domestic photovoltaic-electrolyzer systems, either with fixed or sun tracking panels using annual total solar radiation on a horizontal surface and climatic data. Twelve locations in the United Sates from four climatic zones (tropical-sub tropical, dry, temperate, cool snow-forest) have been selected. Simulations have been carried out to produce data for hydrogen production for these various locations and the resulting data have been correlated to obtain hydrogen production in kg/kW$_p$/year photovoltaic system as a function of total annual solar radiation on horizontal surface. The economical feasibility has been studied by taking the photovoltaic and electrolyzer systems' price as variable parameters. It is assumed that the necessary capital is 100% borrowed from a financial institution to pay back in monthly installments. It has been found that the hydrogen production with fixed photovoltaic panels varies from 26 to 42 kg/kW$_p$/year and the cost from 25 to 268 \$/GJ.

Keywords: Solar hydrogen; Domestic hydrogen; PV-hydrogen

1. Introduction

Car manufacturing companies are continuing their research and development efforts on vehicles powered with hydrogen fuel cell (California Fuel Cell Partnership, 2003). Presumably within this decade hydrogen fueled cars will start rolling from the assembly lines. However, to service these new vehicles the infrastructure for manufacturing, storage and distribution of hydrogen is not in place, although the technology, in part, seems to be already available (H2Cars, 2003; Stuart Energy, 2003). Following demand—offer relation the service sector will certainly develop. Until then, during the transition and also thereafter is it possible for the consumers to service these vehicles? One of the possibilities mentioned is, for example, domestic hydrogen production from natural gas. Are there possibilities to generate it by using renewable energies?

Domestic hydrogen production can be accomplished by various practical means. For example, (1) catalytic cracking of natural gas; (2) catalytic cracking of biogas generated domestically, (3) electrolysis of water by using electric energy from the grid; (4) electrolysis of water by using electric energy generated by a renewable energy source available to consumers, such as wind power, biomass and direct solar radiation. Although the first method seems to be the most practical, it requires a primary energy source, which is not considered as renewable. The second method requires a domestic biogas production plant, which may consist of biogas digester—biogas storage—biogas catalytic cracking system. It may be easily shown that it is not a feasible

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Nomenclature

C	cost
E	electrical energy
EE	electrical energy per standard m^3 of hydrogen
$\dot{E}$	annual energy production
$\dot{e}$	annual energy production per kW_p
H_D	daily hydrogen production in GJ
H_T	annual total radiation on a horizontal surface
I	current, non-dimensional current density, hourly solar radiation
i	operating current density
i_r	rated current density, mA/cm^2
k_1	current independent fraction of the cell and accessory costs
k_2	installation related fraction of the cell and accessory costs
$\dot{M}$	annual hydrogen mass production
$\dot{m}$	annual hydrogen mass production per kW_p
MP	monthly pay
n	write-off period (years)
P	non-dimensional power, price
q	solar energy flux
R	ratio of beam radiation on a tilted to that total on a horizontal surface
r_i	annual interest rate
T	temperature
U_L	overall loss coefficient
V	voltage
V_i	electrolyzer voltage at the operating current density
V_r	cell voltage at the rated current density, V
v	hydrogen production rate (m^3/s)
x_m	separator area cost parameter in $\$/m^2$
x_k	input power
x_R	rectifier cost in \$/kW A.C.

Greek symbols

α	absorption coefficient
β	slope
η	photovoltaic cell efficiency
η_R	rectifier efficiency
η_T	overall efficiency
θ	incidence angle
ρ_g	albedo
τ	transmission coefficient

Subscripts

a	annual, absorbed, ambient
b	beam
CONV	converter
c	cell
d	diffuse
E	electrical
EL	electrolyzer
H	hydrogen
HE	per GJ hydrogen
HM	per kg hydrogen
MPPT	maximum power point tracker
m	monthly
PV	photovoltaic
r	reflection, reference
sys	system
t	transmitted

method for domestic production: the biogas is a poor hydrogen source and requires a complicated chemical process, such as catalytic steam reforming process for conversion (Shiga et al. (1998)). Hence, the feed required will exceed that domestically produced quantity for a reasonable hydrogen production rate. The third method may be practical, however the electricity from the grid is usually produced by using non-renewable sources of energy. Except in places where almost all the electricity is produced by renewable resources, such as hydro-power, wind-power or biomass, this method does not make a good choice, if it uses non-renewable fossil fuel resources. Excluding biomass for the same reason as in (2), the last method using wind energy or direct solar radiation combines the two requirements for a domestic application, (i) renewable energy source is usually available where it is needed, (ii) they are well developed technologies.

A rough estimate for hydrogen requirement of a small car powered by hydrogen-fuel cell could be done based on published information on prototype vehicles (Honda, 2003). For example, five passenger fuel cell powered Honda FCX (Stack)'s published characteristics show that the hydrogen consumption/range is 4.6 kg hydrogen/395 km range. If we assume 12,000 km driving per year, the annual hydrogen consumption will be 140 kg or using HHV of hydrogen about 20 GJ. This may be generated by using about 6900 kW h electricity if a 80% efficient electrolyzer is used. It is obvious that either of the renewable energy sources discussed in item (4) can be used for this purpose. Among the two sources of renewable energy, we will not consider the wind energy in this study for the simple reason that direct solar energy conversion by photovoltaic system will be easier to integrate with residential houses and there will be less noise and esthetic pollution in residential areas.

There are various experimental (see, for example, Daous et al. (1994), Szyszka (1998), Sharke (1999) and Hollmuller et al. (2000)) and theoretical (see, for example, Friberg (1993), Vanhanen et al. (1994), and Bilgen (2001)) 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, cost of hydrogen is estimated in view of present and future technologies. Some other issues, mainly an optimized operation of the photovoltaic and electrolyzer subsystems and that of cost of solar hydrogen in actual operation conditions have also been addressed.

The aim of this study is to investigate the possibility of domestic hydrogen production by photovoltaic-electrolyzer systems, to establish its performance and economics using a simulation model, and to provide guidelines for a preliminary design.

2. System description

The photovoltaic-electrolyzer system studied consists of the following major components: photovoltaic array + maximum power point tracker (MPPT) + DC–DC converter + electrolyzer system. MPPT and DC–DC converter systems are used to operate the system at its maximum power of the photovoltaic system at all times and to supply the necessary DC current to the electrolyzer. The electrolyzer system is 'turn-key' installation consisting of electrolyzer cells, water treatment unit, compressor to compress generated hydrogen if necessary or without compressor delivering hydrogen at process pressure (Proton Energy Systems, 2003; Stuart Energy (2003); Teledyne Energy Systems (2003)).

3. Simulation model and code

The simulation code consists of the following models:

- to calculate the solar radiation received by photovoltaic panels;
- to calculate electric energy produced by photovoltaic panels;
- to calculate hydrogen production by electrolyzer system;
- for cost and economics.

These models are briefly reviewed in the following sections.

3.1. Solar radiation model

The solar energy received by a sloped surface is determined using the monthly average daily radiation on a horizontal surface, H. The average beam and diffuse radiation components of daily radiation and the average hourly components are calculated following the isotropic diffuse model. The algorithm to calculate the hourly total radiation on a tilted surface, photovoltaic panels at a given location in our case, for a particular day, follows the well established methods in the literature (Liu and Jordan, 1963). The resulting final equation is

$$I_T = I_b R_b + I_d \frac{(1+\cos\beta)}{2} + (I_b + I_d) \times \rho_g \frac{(1-\cos\beta)}{2} \tag{1}$$

Once the hourly radiation components are known, the solar time, the hour angle, the declination, the solar altitude and azimuth angles, and the angle of incidence are calculated (see, for example, Duffie and Beckman (1991)). Finally using Eq. (1), the total hourly radiation on the photovoltaic panels is calculated.

3.2. Photovoltaic system

The solar energy received by the photovoltaic panels is transmitted through a glass cover and absorbed by the cells. It is partly converted into electrical energy and partly into thermal energy. The thermal energy is dissipated by a combination of heat transfer, through the front and back of the panel. They are indeed similarly evaluated as for a flat plate solar collector, by calculating so called upward and back losses. The principal relations are as follows.

The effective incident angles for diffuse and ground reflected radiations are respectively (Brandmuehl and Beckman, 1980)

$$\begin{aligned} \theta_d &= 59.68 - 0.1388\beta + 0.001497\beta^2 \\ \theta_g &= 90 - 0.5788\beta + 0.00269\beta^2 \end{aligned} \tag{2}$$

The coefficient of overall transmission is

$$\tau(\theta) \approx \tau_r(\theta)\tau_a(\theta) \tag{3}$$

The absorption coefficient of the photovoltaic cells is

$$\alpha(\theta) = 1 - \exp(-0.0255 - 6.683\cos\theta + 5.947 \times \cos^2\theta - 2.48\cos^3\theta) \tag{4}$$

where θ takes the values for direct, diffuse and ground reflected incident angles to calculate corresponding absorption coefficients, α.

The solar energy transmitted and absorbed are respectively

$$\begin{aligned} q_t &= \tau_b I_{b,\theta} + \tau_d I_{d,\theta} + \tau_g I_{g,\theta} \\ q_a &= \alpha_b \tau_b I_{b,\theta} + \alpha_d \tau_d I_{d,\theta} + \alpha_g \tau_g I_{g,\theta} \end{aligned} \tag{5}$$

The efficiency of single-crystal silicone photovoltaic cell is (Siegel et al., 1978)

$$\begin{aligned} &\eta = \eta_r[1 - c_r(T_c - T_r)] \\ &0.08 < \eta_r < 0.18 \\ &0.0025\ ^\circ\mathrm{C}^{-1} < c_r < 0.004\ ^\circ\mathrm{C}^{-1} \end{aligned} \quad (6)$$

The usual values used are $T_r = 0$ °C, $\eta_r = 0.12$, $c_r = 0.004\ ^\circ C^{-1}$.

The efficiency of a photovoltaic cell can be defined as

$$\eta = \frac{E}{q_t} \quad (7)$$

The electrical energy produced is

$$E = q_a - U_L(T_c - T_a) \quad (8)$$

The upward and back losses are calculated following the well established relations and algorithm (see, for example, Duffie and Beckman (1991)) and the overall loss coefficient U_L is calculated. Then the photovoltaic cell temperature is obtained from Eqs. (6)–(8) as

$$T_c = \frac{(q_a + U_L T_a - \eta_r q_t(1 + c_r T_r))}{(U_L - c_r \eta_r q_t)} \quad (9)$$

Monthly and annual system efficiencies for electrical energy production are calculated from

$$\begin{aligned} \eta_m &= \frac{\sum_{i=1}^{24} E_i}{\sum_{i=1}^{24} q_{t,i}} \\ \eta_a &= \frac{\sum_{j=1}^{12}\left(N_j \sum_{i=1}^{24} E_i\right)}{\sum_{j=1}^{12}\left(N_j \sum_{i=1}^{24} q_{t,i}\right)} \end{aligned} \quad (10)$$

3.3. Electrolyzer model

The power range of a domestic electrolyzer would be from 5 to 10 kW nominal power and it is difficult to find a commercial electrolyzer to satisfy a photovoltaic-hydrogen system design requirement. Therefore the voltage–current density performance characteristic curves of electrolyzers are used to derive generic non-dimensional equations. To this end, the electrolyzer Stuart model A-100 has been taken as a base. It is a unipolar electrolyzer of a 15 kW rated power, with a rated voltage and current of 2.05 V and 7314 A respectively. Another smaller model of 4.3 kW rated power was also used for validation of the resulting equations.

By taking rated current density and power as reference, a third degree polynomial expression of non-dimensional current density, $I = I/I_{\mathrm{rated}}$ as a function of non-dimensional power, $P = P/P_{\mathrm{rated}}$ is derived. Similarly, the electrical energy to produce 1 standard m^3 of hydrogen, EE in ($\mathrm{kW\,h/m^3 H_2}$) as a function of the non-dimensional current, I is derived. They are

$$\begin{aligned} I &= 0.0027 + 1.2450P - 0.4656P^2 + 0.2206P^3 \\ \mathrm{EE} &= 3.2467 + 2.5499I - 1.7683I^2 + 0.4178I^3 \end{aligned} \quad (11)$$

The derived generic characteristics could be used to model any domestic electrolyzer with sufficient accuracy. Indeed, the hydrogen production by the smaller model obtained with Eq. (11) was identical to that quoted at its rated power and also was within 1% when compared to that obtained with the following dimensional relation often used in the literature (Cox and Williamson, 1977)

$$v = 1.22 \times 10^{-7} I \quad (12)$$

where I is the current in A and v is the hydrogen production in m^3/s.

3.4. Cost estimation model

The cost of product is determined based on the total investment required for a photovoltaic-hydrogen generating system, operation and maintenance costs, and the production rate of hydrogen. The price of the major items such as photovoltaic panels and electrolyzer is taken as variable parameter. The present price of each is considered as an upper limit and their lower limit is taken as the price expected in the future, assuming that new technologies will be used in their higher volume production.

The present price for photovoltaic panels for consumers is about 5$ to 6$ per W_p (Independent Power & Light, 2003). The price of the future technology is assumed at 1$ per W_p, which is often quoted to be reasonable (Friberg, 1993). The additional cost for sun tracking panels is estimated at about 0.6$ per W_p at the present (Bilgen, 2001). It is noted that if its cost is similarly reduced in the future, its effect on the overall cost of hydrogen may become negligible. MPPT and DC–DC converter costs are assumed to be 0.15$ per W_p.

Presently it is highly difficult to obtain price quotations on turn-key domestic electrolyzers to couple with photovoltaic systems. However, similar industrial systems are sold by major manufacturers and a reasonable price estimate is possible (Proton Energy Systems, 2003). For example, the present price of a turn-key electrolyzer using solid electrolyte, running with AC power and producing 1 standard m^3/h is \$52,000. When reduced to the photovoltaic system peak power, it is about 11$ per W_p. This is taken as the upper price limit of electrolyzer price. It is assumed that the lower price limit is 1$ per W_p. This is also a reasonable assumption, which is verified by extrapolating costs of industrial electrolyzers. The present installed cost of industrial electrolyzers is estimated following Leroy and Stuart (1978) as

$$C_{EL} = 775H_D\left(\left(\frac{k_1}{i} + \frac{1-k_1}{i_r}\right)x_m + 0.5k_2\left(\frac{1}{i} + \frac{1}{i_r}\right)x_m + \frac{V_i x_R}{100\eta_R}\right)x_m = \frac{V_r i_r x_k}{100} \qquad (13)$$

The parameters for unipolar electrolyzers are $k_1 = 0.90$, $k_2 = 0.45$, $x_k = 251$ \$/kW DC, $i = 200$ A, $i_r = 134.00$ mA/cm^2, $V_r = 1.74$ Volt, $V_i = 2.04$, $\eta_R = 0.96$, $x_R = 142$ \$/kW AC, all updated to constant 2002\$. $H_D =$ (hourly maximum hydrogen production in GJ)$\times$(24 h)(1.3), where the last term is a design parameter. C_{EL} is the electrolyzer installed cost in dollar.

It is noticed that Eq. (13) gives the installed cost of a system, which includes the equipment to run it by using AC power. This is represented by the last term of the equation.

The cost found by Eq. (13) has the same order of magnitude as the assumed lower limit for small electrolyzers.

The major guidelines for economics in determining costs are as follows:

- the investment is 100% financed by borrowing the required capital from financial institutions for 25 years;
- it is in constant 2002 US dollar, the interest rate is 5% per year and paid back in monthly installment;
- installation, operation and maintenance are done by the owner at no cost;
- the installation is integrated with the dwelling and there is no extra cost for land;
- plant life for economic write-off is 25 years for photovoltaic panels, MPPT, DC–DC converter, storage systems and 15 years for the electrolyzer.

Monthly payment of the borrowed capital is calculated as

$$MP = C_{sys}\frac{(1+r_i)^n r_i}{(1+r_i)^n - 1} \qquad (14)$$

where C_{sys} is $C_{PV} + C_{MPPT} + C_{CONV}$ for photovoltaic system and C_{EL} for electrolyzer system.

The cost of hydrogen, (\$/kg hydrogen) and (\$/GJ hydrogen) by the system is calculated based on the annual production and capital cost as:

$$C_{HM} = 12MP/\dot{M}_H$$
$$C_{HE} = 12MP/\dot{E}_H \qquad (15)$$

where $\dot{M}_H$ is the annual hydrogen production in (kg/year) and $\dot{E}_H$ is the annual hydrogen energy production in (GJ/year).

4. Results and discussion

The study was carried out using fixed as well as sun tracking panels at twelve US locations, namely, tropical: Hilo (HA), Orlando (FL), dry climate: Albuquerque (NM), El Paso (TX), Las Vegas (NE), Salt Lake City (UT), warm temperate: Phoenix (AR), San Diego (CA), cold snow forest: Burlington (VT), Madison (WI), Indianapolis(IN), Denver (CO). The locations are selected to obtain a wide range of annual total radiation on a horizontal surface: the annual sum of the monthly average of daily radiation on a horizontal surface, H_T in GJ/m^2/year varies from 4.3 to 7.8 GJ/m^2/year. This together with lower and upper price limits assumed earlier for photovoltaic and electrolyzer systems in Section 3.4 determines the upper and lower limits of electricity and hydrogen costs.

The sun tracking system was included to obtain an upper limit for production rates or a lower limit for cost of products, otherwise it is not considered too practical for residential applications, except in rare cases. In the case of fixed panels oriented due south in northern hemisphere, the optimum slope for each location was first determined by a parametric analysis and then used in the simulation. It was seen that for most of the locations, a slope at its latitude angle or near latitude angle was satisfactory. Annual electrical and hydrogen energy production rates in kW h, kg H_2 and GJ H_2 per kW$_p$ photovoltaic power are computed as a function of annual solar radiation on a horizontal surface and shown in Figs. 1–3. The cost of electrical energy in cent/kW h as a function of a correlation parameter of annual solar radiation on a horizontal surface and photovoltaic system price is computed and shown in Fig. 4. Similarly, the hydrogen energy costs in \$/kg H_2 and \$/GJ H_2, as a function of a correlation parameter of annual solar radiation on a horizontal surface, photovoltaic system price and electrolyzer system price are computed and presented in Figs. 5 and 6. Finally, the overall thermal

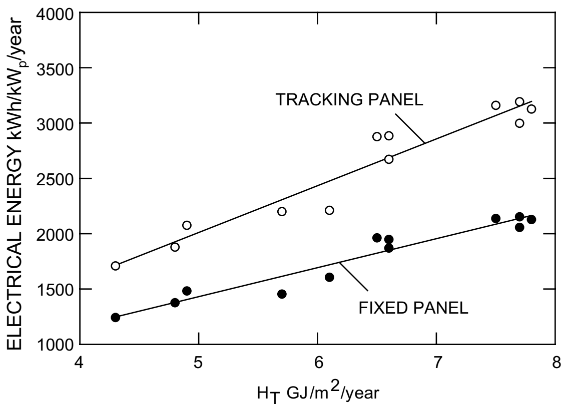

Fig. 1. Annual electric energy produced in kW h per kW$_p$ as a function of annual solar radiation on a horizontal surface in GJ per m^2 for fixed and tracking photovoltaic panel.

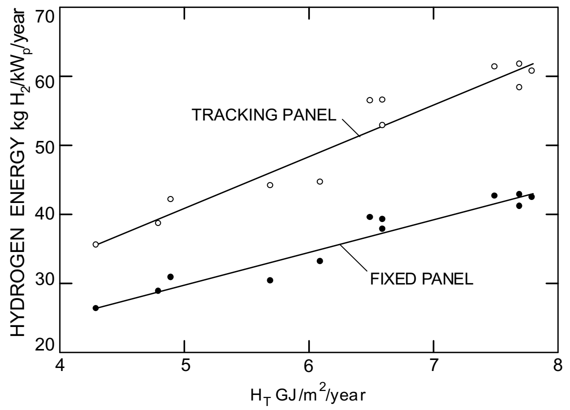

Fig. 2. Annual hydrogen energy produced in kg H_2 per kW_p as a function of annual solar radiation on a horizontal surface in GJ per m^2 for fixed and tracking photovoltaic panel.

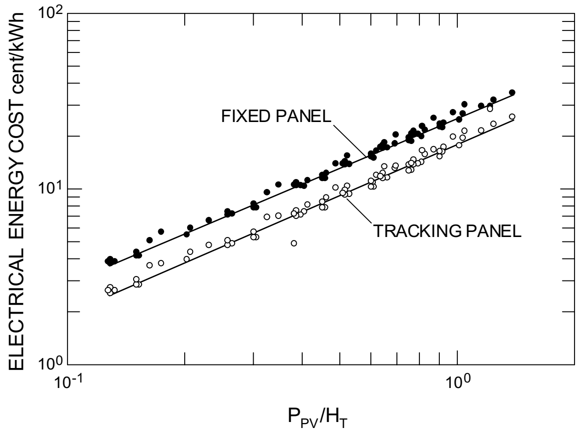

Fig. 4. Electric energy cost in cent per kW h as a function of the correlation parameter using photovoltaic panel cost and annual solar radiation on a horizontal surface for fixed and tracking panel systems.

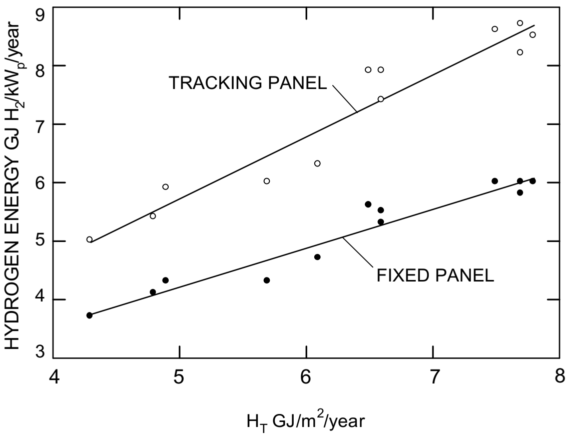

Fig. 3. Annual hydrogen energy produced in GJ H_2 per kW_p as a function of annual solar radiation on a horizontal surface in GJ per m^2 for fixed and tracking photovoltaic panel.

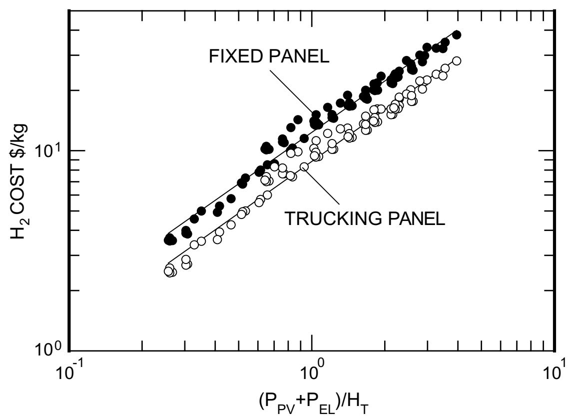

Fig. 5. Hydrogen cost in \$/kg as a function of the correlation parameter using photovoltaic panel cost and annual solar radiation on a horizontal surface for fixed and tracking panel systems.

efficiency and electrolyzer size are presented in Fig. 7 and discussed.

Electrical energy production by the photovoltaic system using either fixed or tracking panel in kW h/kW_p/year as a function of H_T in GJ/m^2/year is presented in Fig. 1. It appears that the electrical production correlates well with the annual average solar radiation on a horizontal surface. This is the sum of the monthly average daily radiation on a horizontal surface, usually available as meteorological data. It is seen that the electrical energy production with fixed panels varies from about 1200–2100 kW h/kW_p/year. The upper limit of the electrical energy production, obtained by using tracking panels, varies from about 1700–3200 kW h/kW_p/year. It is seen that by using tracking panels the electrical energy production can be increased by as much as 50%. A correlation for the case of fixed panels is

$$\dot{E} = 121.13 + 261.93 H_T \qquad 4.3 < H_T < 7.8 \tag{16}$$

The correlation coefficient is $r^2 = 0.93$.

Similarly hydrogen energy production in (kg H_2/kW_p/year) as a function of H_T in (GJ/m^2/year) is presented in Fig. 2. We observe a similar trend to that of Fig. 1: the hydrogen energy production varies from 26 to 42 (kg H_2/kW_p/year) for fixed panels with upper limit of 36 to 62 (kg H_2/kW_p/year) with the tracking panels for the same range of H_T in (GJ/m^2/year). A correlation for the case of fixed panels is

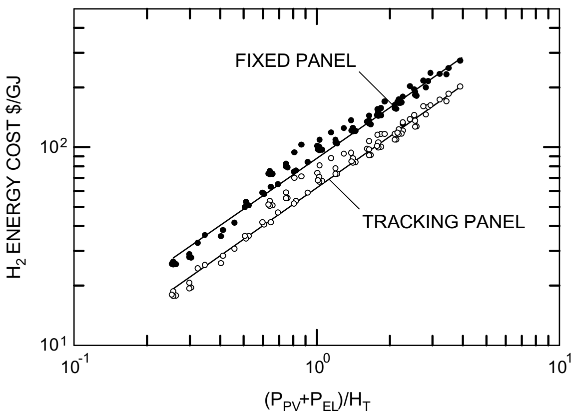

Fig. 6. Hydrogen energy cost in \$/GJ as a function of the correlation parameter using photovoltaic panel cost and annual solar radiation on a horizontal surface for fixed and tracking panel systems.

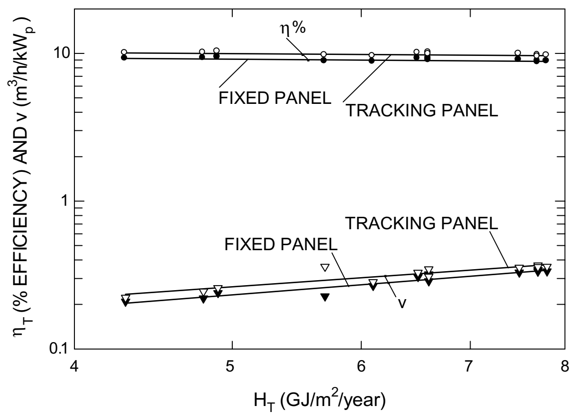

Fig. 7. Overall efficiency of solar hydrogen and the electrolyzer's size as a function of annual solar radiation on a horizontal surface for fixed and tracking panel systems.

$$\dot{m}_H = 6.05 + 4.74H_T \quad 4.3 < H_T < 7.8 \tag{17}$$

The correlation coefficient is $r^2 = 0.94$.

Hydrogen energy production in (GJ H_2/kW_p/year) as a function of H_T in (GJ/m^2/year) is also computed and presented in Fig. 3. A correlation for the case of fixed panels is

$$\dot{e}_H = 0.88 + 0.67H_T \quad 4.3 < H_T < 7.8 \tag{18}$$

The correlation coefficient is $r^2 = 0.94$.

Electrical energy cost in (cent/kW h) as a function of (P_{PV}/H_T) is presented in Fig. 4 for both the fixed and tracking panel cases. We see that the cost varies from about 4–35 (cent/kW h) for the fixed panel case while from 2.5 to 25 (cent/kW h) for the tracking panel case. We note that the lower and upper limits correspond to the photovoltaic system cost of $P_{PV} = 1$ and 6 (\$ per W_p) and $H_T = 7.8$ and 4.3 (GJ/m^2) respectively. The electrical energy cost correlation for the fixed panel case is

$$C_E = 25.12(P_{PV}/H_T)^{0.94} \quad 0.128 < P_{PV}/H_T < 1.395 \tag{19}$$

The correlation coefficient is $r^2 = 0.99$. It is noted that the range of the solar electrical energy cost seems to be competitive in many locations, since the price charged by utility companies for domestic consumption may often be within the stated range. For example, in New England states, after including various charges and taxes, the price of electrical energy comes to about 27 cent/kW h.

Hydrogen energy costs in (\$/kg H_2) and (\$/GJ H_2) as a function of $((P_{PV} + P_{EL})/H_T)$ are presented in Figs. 5 and 6 respectively. The costs vary from 3.5 to 38 (\$/kg H_2) for fixed panels and 2.5 to 28 (\$/kg H_2) for tracking panels. Similarly they vary from 25.3 to 268 (\$/GJ H_2) for fixed panels and 17.7 to 199 (\$/GJ H_2) for tracking panels. In these cases also the lower and upper limits correspond to $P_{PV} = 1$ and 6 \$ per W_p, $P_{EL} = 1$ and 11 (\$/W_p), and $H_T = 7.8$ and 4.3 (GJ/m^2) respectively. The hydrogen energy cost correlations for the fixed panel case are

$$C_{HM} = 12.34((P_{PV} + P_{EL})/H_T)^{0.85} \quad 0.25 < (P_{PV} + P_{EL})/H_T < 4 \tag{20}$$

$$C_{HE} = 87.79((P_{PV} + P_{EL})/H_T)^{0.85} \quad 0.25 < (P_{PV} + P_{EL})/H_T < 4 \tag{21}$$

The correlation coefficient is $r^2 = 0.99$ for both cases.

We should note that the present price of energy for gasoline engine powered vehicles is about (0.5\$/liter)/(0.73 kg/liter × 0.046 GJ/kg) ≈ 15\$/GJ. Considering that if a fuel cell powered vehicle is claimed to be more efficient than gasoline engine powered vehicles, the lower end price of about 25 \$/GJ may just be competitive in heavily subsidized situations. Otherwise it is clear that as expected, with the present price structure, domestic produced hydrogen will not be competitive with the fossil fuel derived gasoline or similar fuels.

The annual overall efficiency of the photovoltaic-electrolyzer system for hydrogen production is computed as the ratio of annual hydrogen energy produced by 1 kW_p photovoltaic system to annual solar energy received by the panels. It is presented as a function of H_T in Fig. 7. As expected η_T decreases slightly from 9.34% to 8.64% when H_T varies from 4.3 to 7.8 GJ/m^2/year on a horizontal surface. The correlation equation for the fixed photovoltaic panel case is

$$\eta_T = 10.35H_T^{-0.078} \tag{22}$$

The electrolyzer size was determined by searching the maximum hourly hydrogen production for a given location, which is presented as a function of H_T in Fig. 7. It varies from 0.209 to 0.342 $m^3/h/kW_p$ for H_T from 4.3 to 7.8 GJ/m^2/year on a horizontal surface. As expected the electrolyzer size increases almost proportionately with H_T. The correlation equation of the electrolyzer size in standard $m^3/h/kW_p$ for the fixed photovoltaic panel case is

$$v = 0.058 H_T^{0.86} \tag{23}$$

The correlation coefficients for Eqs. (22) and (23) are 0.87 and 0.91 respectively.

5. A case study

Let us assume we would like to generate 140 kg hydrogen per year at Austin (TX) where $H_T = 6.174$ GJ/m^2/year on a horizontal surface. Using Eq. (17), we find $\dot{m}_H = 6.05 + 4.74(6.174) \approx 35$ kg hydrogen/kW_p/year or the required photovoltaic size is (140 kgH_2/year)/(35 kg/kW_p/year) = 4 kW_p. The size of the electrolyzer is, from Eq. (23), $v \approx 1.11$ m^3/h. The annual efficiency from Eq. (22) is $\eta_T \approx 9\%$. The photovoltaic panel installation area is about 30 m^2 (Siemens Co., 2003).

Let us assume that photovoltaic system cost is 3\$/W_p and that of electrolyzer is 2\$/W_p, the total investment will be $(4000)(3+2) = \$20{,}000$ and according to Eqs. (20) and (21) the cost of hydrogen will be $C_{HM} = 12.34[(3+2)/(6.174)]^{0.85} = 10.3$ \$/kgH_2 and $C_{HE} = 87.79[(3+2)/6.174]^{0.85} = 73.38$ \$/GJ.

For more favorable conditions, assuming that both costs for photovoltaic and electrolyzer systems are 1\$/W_p, which are the lower price limits discussed earlier, and for the same location as before, the total investment will be \$8000 and from Eqs. (20) and (21) the cost of hydrogen will be 4.73\$/kgH_2 and 33.68\$/GJ.

6. Conclusions

A brief review is presented on the domestic production of hydrogen using renewable energy. The domestic production of solar hydrogen by photovoltaic-electrolyzer system is opted as a practical method and studied in detail. Useful correlations are derived for a preliminary system design study at a given location. It is shown that the system thermal performance can be correlated by using annual total solar radiation on a horizontal surface. The economical feasibility can be correlated as a function of photovoltaic system price, electrolyzer system price and the annual solar radiation on a horizontal surface.

The results show that for a 1 kW_p photovoltaic system with fixed panels, depending on the annual solar radiation on a horizontal surface the hydrogen energy production varies from 26 to 42 kg/year. The cost of hydrogen varies from 3.5\$/kg to 38\$/kg with the corresponding energy cost from 26\$/GJ to 268\$/GJ. It is clear that with the present photovoltaic and electrolyzer price structure domestic hydrogen is not economically competitive with the present day automotive fuels. If, on the other hand, government programs and subsidies are established for domestic hydrogen production, it may become economically competitive. In fact, electricity production has become competitive in Japan (Hamakawa, 1997) and in Germany (Hoffman, 2001) with long term incentives and subsidies. This may be the case if the photovoltaic-electrolyzer system price is several times lower than the present, and/or the price of fossil fuels becomes several times higher and/or the annual total solar radiation received on a horizontal surface is above average, say higher than 6 GJ/m^2/year.

It is also noted that the overall thermal performance of these systems varies from 9.34% to 8.64% depending on the annual solar radiation on a horizontal surface.

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