

Research Article

The Production of PV Hydrogen

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Summary. A significant drawback of direct solar and wind energy is that they are intermittent. Moreover, supply and demand peaks may not coincide, which could lead to energy shedding in specific situations. A system was investigated where solar flux was first converted to DC electrical energy using photo-voltaic (PV) cells, and then the generated electricity used to produce hydrogen by electrolysis of water.

The V-I characteristics of a PEM electrolyser were determined using laboratory DC sources. Various types of PV panel, of known efficiencies, were then connected to the electrolyser and conditions for obtaining maximum efficiency in hydrogen production were determined. With careful matching of PV output to electrolyser, efficiencies as high as 10% could be obtained. These are comparable to the best published results. The match of actual hydrogen output conditions to those best suited to storage in a metal hydride tank or to direct use in a fuel cell were investigated.

Areas of PV material required to produce quantities of hydrogen necessary for specific tasks were determined. Improvements to the hydrogen generating and storage systems were suggested.

Introduction

Malta is almost completely dependent on imported fossil fuels for its energy needs. This makes security of supply and price stability of primary concern to our economy. Developments expected over the next fifty years, as well as commitments to greenhouse gas (GHG) reductions, make it imperative that we reduce our dependence on fossil fuels.

The prime candidates for (partial) substitution of fossil fuels are solar and wind energy, which could have a combined potential to displace perhaps 15% of the primary energy currently used to generate electricity. However, inevitable fluctuations in the supply of renewable energy (RE), mismatches between supply and demand, and the difficulty of storing electrical energy prevent RE sources from achieving a total substitution of fossil fuels. But the practical degree of substitution can be improved by a flexible energy carrier, used to buffer mismatches between RE generators and overall demand.

Hydrogen is widely seen as the prime candidate for such a carrier (Dutton 2003). Of course, it has to be produced by using a primary source of energy, which may not itself be environmentally benign e.g. oxidation of CH₄; but there are emission-free methods of generation, like electrolysis of water. In use hydrogen is free of harmful emissions; it can be used to generate electricity with high efficiency in a mobile or static fuel cell, or it can fuel internal combustion engines. Concern with safety has led to the evolution of procedures which make for very safe handling of hydrogen.

In this work we have determined the potential of the local solar flux to produce hydrogen by electrolysis using standard PV panels and a small PEM electrolyser. Problems associated with direct use of the hydrogen in a small fuel cell and with storage at atmospheric pressure in a metal hydride tank were also investigated.

Electrolyser Performance

The electrolyser was a Proton Exchange Membrane type requiring de-ionised water (conductivity <1 μ S/cm) and a D.C. voltage of 5V to 7V. It is rated at a maximum power of 250W at a temperature of 75°C and a pressure of 10Bar. Characteristic I-V curves of the electrolyser were obtained using a variable DC power supply. The performance was characterised by two main factors, one being the minimum voltage at which current starts to flow through the electrolyser and the other the ratio of V to I which is equivalent to the internal resistance R of the electrolyser.

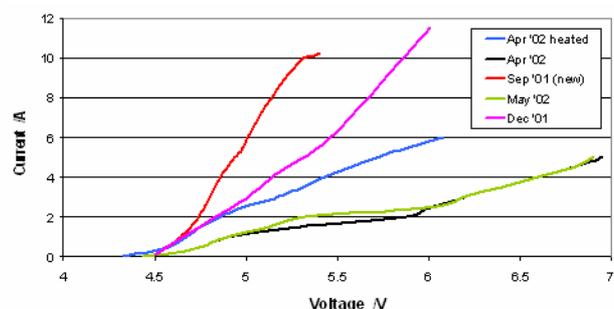


Figure 1. Electrolyser degradation.

A progressive degradation in electrolyser performance was noted after some months of use. Referring to fig 1,

the internal resistance of the electrolyser increased from 0.1Ω when new to 0.5Ω after 6 months of use; the V-I ratios showed that the resistance decreased to 0.29Ω when the electrolyser was heated to 60°C . The loss in electrolyser performance required a higher voltage for the same current flow, and in turn more energy for a constant rate of hydrogen production. This phenomenon of electrolyser loss in performance is well documented (Lehman and Chamberlin, 1991) in the case of an alkaline electrolyser, the degradation being attributed to loss of electrode surface and catalyst efficiency.

The current and energy efficiencies of the electrolyser were also determined at varying power densities. This was done by measuring the volume of hydrogen produced on a graduated scale and comparing its Higher Heating Value (HHV) of 146MJ/kg with the electrical energy used. The volume was 637cm^3 at a pressure of approximately 40mbar as measured from the height difference between the water levels of the central water reservoir and hydrogen gas cylinder.

A series of electrolysis runs were conducted at a number of fixed values of current and their corresponding time and voltage to produce 637cm^3 of hydrogen was recorded. In all cases the electrolyser was unheated.

Voltage /V	Current /A	Time /s	Charge /C	Current eff.	Energy /kJ	Energy eff.
4.97	5.0	352	5280.0	98.31	8747.20	88.03
5.29	10.0	179	5370.0	96.67	9469.10	81.32
5.79	15.0	119	5355.0	96.94	10335.15	74.50

Table 1 September 2001 Electrolyser efficiency (new).

Voltage /V	Current /A	Time /s	Charge /C	Current eff.	Energy /kJ	Energy eff.
5.14	4.9	359	5245.0	98.97	8986.42	85.68
5.17	4.2	413	5203.8	99.75	8967.88	85.86
5.46	6.0	294	5292.0	98.09	9631.44	79.95
5.88	10.2	178	5446.8	95.30	10675.73	72.13
6.01	11.5	151	5209.5	99.64	10436.37	73.78

Table 2 December 2001 Electrolyser efficiency.

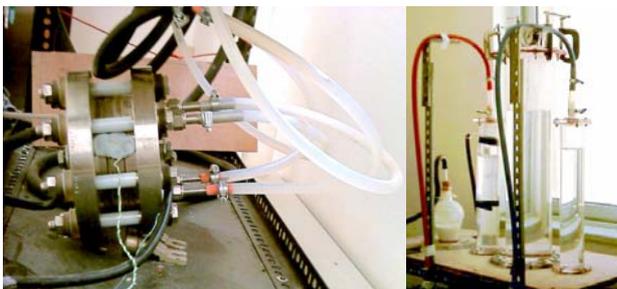


Figure 2. Electrolyser and Perspex cylinders

Hydrogen has a density of 0.0898 g/L at s.t.p. so 637cm^3 at 40mbar and 26.5°C is equal to a mass of 0.0542g or 0.0269mol H_2 . As one mole theoretically requires a charge of 2Faraday, 0.0296mol requires 5191C and has an energy of 7.7kJ . Comparing the actual charge and electrical energy needed with the theoretical values provides the electrolysis efficiencies. The total charge is taken as $3\Sigma It$ since the electrolyser has three cells in series. The time in the third column of tables 1 and 2

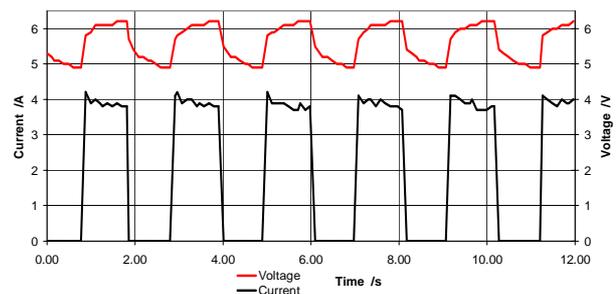
refers to that taken to produce 637cm^3 of H_2 , the charge is the product $3\Sigma It$ and energy used is the total $3\Sigma VIt$.

The current and energy efficiencies are taken with respect to 5191C and 7.7kJ as 100%. The current efficiency should be high ($>95\%$), since it is a measure of the effective reactions that are occurring during electrolysis. Each electron should react with 1 H; however other unwanted reactions may occur such as those involving impurities in the electrolyte or electrodes. These reactions would consume some of the electrons involved and hence reduce the actual amount of hydrogen produced for a given charge. On the other hand, energy efficiency involves the actual energy carried by the electrons, which is a function of the voltage potential. Since each produced H_2 molecule has a specific energy, any energy excess used to perform the reaction is lost and not carried by the product; so high working voltages result in low energy efficiencies.

From tables 1 and 2 it can be deduced that within the current range used, the current efficiency is independent of the current flow but the energy efficiency decreases with increasing electrolysis current. This data implies that during lower insolation periods, such as those occurring during cloudy days, the electrolyser efficiency does not deteriorate; but actually increases as it works at a lower current density.

After a period of use, the electrolyser current efficiency was unaffected whilst a degradation in energy efficiency was experienced for a given current flow after three months. The average current efficiency from tables 1 and 2 is 97.96% . In the experimental work performed, the rate of hydrogen production was thus taken as 0.98 of that theoretically produced by the current flow. So 95719C theoretically produce 1g H_2 but in the experimental work this is taken to produce 0.98g . From data gathered during particular solar-driven production runs, the total insolation was measured using a pyranometer-integrator; the total electrical energy found by calculating $\Sigma V_t I_t$ where the time interval is set to one second; and the total charge from ΣIt where V_t and I_t are the voltage and current at time t respectively and are measured by the PC monitoring system through an analogue-to-digital converter and interface with PC parallel port.

Due to the polarisation properties of the electrolyser, the



I-V behaviour for pulsed DC was investigated. Figure 3. Pulsed DC (0.5Hz) fed into the electrolyser.

From fig 2 it can be seen that the electrolyser voltage increases sharply from 4.9V to 5.8V upon application of 4A current. The current flow into the electrolyser therefore occurs over a voltage range of 5.8V to 6.2V, the average being 6V. For a continuous current flow of 4A (with no pulsing), the electrolyser voltage was approximately 6.8V. This indicated that the electrolyser was working at a lower voltage for the same current flow when pulsing was used. A gain in efficiency was being obtained since by pulsing at 4A, the working voltage was reduced by 8.8%. However, as the duty cycle was 50%, the electrolyser should be actually compared to a continuous 2A current. The voltage at a steady 2A was approximately 6V, so actually the pulsing made no real improvement in practical efficiency since the effect could be directly duplicated by working at a lower current density.

A further run was carried out using high frequency pulsing at 20kHz 50% duty cycle. The average current and voltages measured using digital multimeters, were 0.47A @ 4.8V and 1.56A @ 5.33V. These points practically lie on the continuous-DC curve obtained for the same electrolyser temperature and age. This again shows that no particular benefit in terms of energy efficiency is to be found in converting electrical to hydrogen chemical energy by using pulsed DC into the electrolyser.

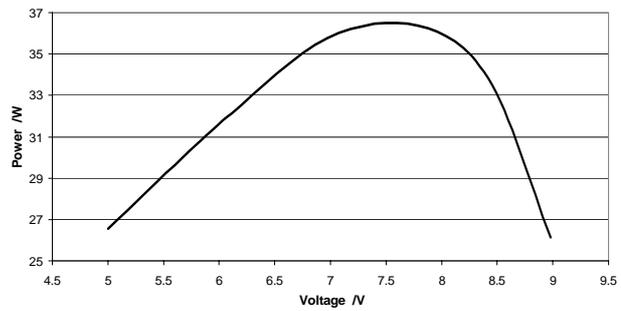
PV Panels Performance

A series of PV panels were assessed by exposing them to a measured value of insolation, using a pyranometer, and then monitoring their voltage and current output on a variable load. Initial tests, carried out with the panels distant some 50m from the electrolyser, were used to determine the effects of wire resistance on peak power output and the voltage position of the peak power point. As the latter fell between 12V to 15V, direct connection to the electrolyser would lead to a serious mismatch. Matching by inserting a series resistance is inefficient; a DC-DC converter was considered but a simpler approach was taken by centre-tapping one of the panels and use of only half the number of series connected cells of each PV module. By this set-up, the working voltage and required PV area was halved, with no loss in PV efficiency.

After March 2002 the PV modules were placed on the roof of the Physics building, only 12m directly above the electrolyser laboratory. The electrical efficiency of the set of polycrystalline panels named A using this set-up was over 10% -essentially that specified by the manufacturer-while power reached 36W at 7.5V with an insolation of 948W/m² (using two parallel centre-tapped panels).

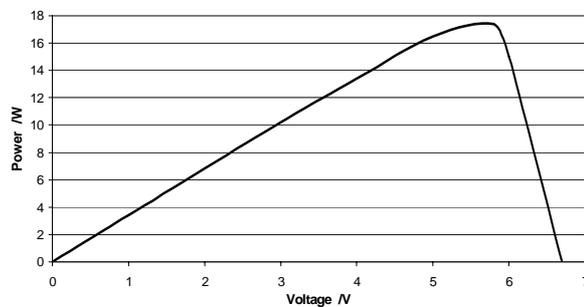
Fig 4 below shows the PP curve using the centre-tapped panels. The peak power voltage is close to that required by the electrolyser, suggesting that a high hydrogen generating efficiency should be obtained.

Figure 4 Peak Power curve of 2 parallel half-panels.



A set of two mono-crystalline panels (named panels B) was next tested. Their specified voltage at maximum power was 17.6V. These modules consisted of three vertical strings of cells and so that tapping of one third of the panels was relatively easy. This was expected to yield a voltage of approximately 5.9V at peak power by using a third of the module area. The peak power curve is shown in Fig.5.

Figure 5 Peak Power curve for one third tapped module B.



Module C was a mono-crystalline panel that could not be centre-tapped. Although its efficiency was quite high, the mismatch between V at PP (see Table 3) and the electrolyser working V made it unsuitable for extended use.

Module	V @ Pmax / V	I @ Pmax / A	Pmax / W	Insolation / Wm ²	Efficiency / %
C	16	3.69	59	910	11.8

Table 3 Measured performance of Module C.



Figure 6 Polycrystalline solar panels and pyranometer.

Data for hydrogen production were collected over several months using various types of PV modules working under different conditions. The working conditions, weather, average insolation and other relevant information are listed in Table 4 below.

The PV-to-electrolyser-to-fuel cell train was monitored by a PC through a parallel communications port using a mini-POD100 analogue-to-digital converter connected to the PC. After several months of data collection, a single day was then used to conduct data collection using different set-ups on the same day. For this run on the 3rd July, the temperature of the electrolyser was kept at an average of 60°C and pressure above atmosphere between 0 and 0.8bar. The PV modules were always kept approximately perpendicular towards the direction of the sun and their direction adjusted through the course of the day about every half an hour.

Solar Hydrogen Production

Date	PV type	No. of parallel panels	Total flux	Σ Vlt	PV eff.	Electrolyser eff.	Solar H2
			/kJ	/kJ	%	%	%
15 Nov'01	A	2	3370.0	231.30	6.86	86.35	5.93
19 Nov'01	A	2	4970.0	337.73	6.79	84.49	5.74
23 Nov'01	A	2	1296.0	89.37	6.90	85.95	5.93
30 Nov'01	A	2	907.2	59.29	6.54	84.74	5.54
4 Dec'01	A	2	1915.5	127.02	6.63	82.17	5.45
15 Feb'02	A	2	168.5	13.52	8.02	79.60	6.39
8 May'02	A	2	1477.4	136.37	9.23	70.69	6.52
8 May'02	A	2	103.7	7.57	7.30	91.57	6.69
10 May'02	A	2	4341.6	408.88	9.42	75.69	7.13
27 May'02	A	2	388.8	34.33	8.83	76.56	6.76
6 Jun'02	B	1	864.0	104.61	12.11	85.35	10.51
14 Jun'02	B	2	397.4	31.84	8.01	85.10	6.82
14 Jun'02	B	1	302.4	31.48	10.41	88.38	9.20
14 Jun'02	B	1	216.0	23.82	11.03	91.25	10.06
3 Jul'02	B	2	172.8	16.73	9.68	83.21	8.05
3 Jul'02	B	2	216.0	19.90	9.21	84.91	7.82
3 Jul'02	B	2	259.2	22.09	8.52	84.86	7.23
3 Jul'02	B	1	64.8	6.03	9.31	90.55	8.43
3 Jul'02	B	1	185.8	17.27	9.30	89.20	8.30
3 Jul'02	B	1	133.9	12.47	9.32	88.95	8.29
3 Jul'02	A	1	162.0	12.38	7.64	87.73	6.70
3 Jul'02	A	2	324.0	27.13	8.37	76.46	6.40
3 Jul'02	C	1	294.8	26.45	8.97	77.30	6.94
3 Jul'02	D	1	177.1	13.16	7.43	90.71	6.74
27 Jul'02	A	2	5119.2	496.54	9.70	67.38	6.54

Table 5 Summary of Results from Hydrogen Production runs.

The runs conducted using panel C show the effect of the PV panel characteristics on the final solar hydrogen efficiency according to their working voltage and efficiencies described earlier. The electrolyser efficiency was always quite high as it was kept at a high temperature (~60°C).

One final run was then conducted on 27th July, 2002 to reproduce the central results of the work. Data was collected continuously over a relatively long stretch of over four hours using the two centre-tapped polycrystalline panels (type A) in parallel. This PV set-up was chosen as most data available was obtained using these modules and also to provide a relatively high power hydrogen production rate. The day was expected to yield relatively good efficiencies since the sky was quite clear and maximum air temperature only reached 27°C. The maximum recorded insolation was 990W/m² at around noon solar time. The solar hydrogen efficiency was 6.54%. The electrolyser temperature was at an average of approximately 45°C so the electrolysis efficiency

could have been improved by increasing the temperature towards 65°C.

The PV efficiency was only slightly lower than the maximum ever achieved for these panels. The overall solar hydrogen efficiency was also typical for this set-up, as can be seen from a comparison with data obtained from previous runs. This shows that the solar hydrogen efficiencies claimed in this work were repeatable even after a number of months.

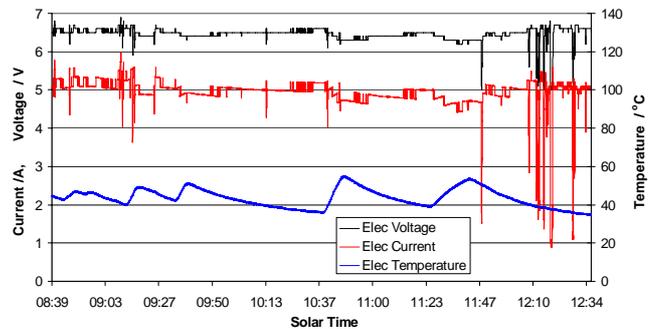


Figure 7 27th July, 2002: 2 centre-tapped polycrystalline panels (type A) in parallel.

Fuel Cell Performance

The fuel cell was of the PEM type made by Electrochem(FC25-02SP). It comprises a single cell having an active area of 100cm². For better gas circulation, the cell has both gas inlets and gas exhaust outlets. It also has two 250V resistance heaters that can be used to bring the fuel cell to a working temperature of approximately 60°C. Specified performance is a maximum of 25A at 0.5V. To obtain the I-V characteristics for the fuel cell, it was fed with continuous flows of hydrogen and oxygen produced from the electrolyser. The gases were allowed to vent out from the fuel cell gas outlets after circulating in the cell. This also helped to remove the water produced on the oxygen-reacting side inside the fuel cell.

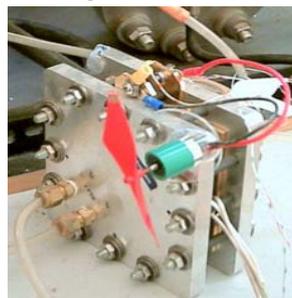


Figure 8
Fuel Cell and D.C. motor.

As the output voltage is very low while the current is high, a number of low resistances were used, including some wire loops across the fuel cell terminals. The values of these low resistances were calculated from the ratio of V to I. The voltage across the load was taken to be equal to that across the terminals of the cell. The recommended working temperature for the fuel cell is about 60-70°C. At this increased temperature, the open-circuit voltage, the short-circuit current and the maximum output power were all found to increase but only a slight improvement in current to voltage ratio is obtained (fig 6).

A number of further runs were then conducted to determine the current and energy efficiencies of the fuel cell. The current, voltages and time were measured for the fuel cell to consume a recorded volume of hydrogen. The hydrogen was fed both through the fuel cell inlet and exhaust nozzles to form a closed gas loop, so the volume change will only reflect that consumed by the fuel cell.

Voltage /V	Current /A	Time /s	Energy /J	Charge /C	H ₂ used /mg	Energy eff.	Current eff.
0.622	1.00	600	373.20	600	8.50	37.33	73.710074
0.667	1.04	600	416.21	624	8.02	44.12	81.218274
0.513	1.78	600	547.88	1068	13.70	34.01	81.402439

Table 6 Fuel Cell efficiencies.

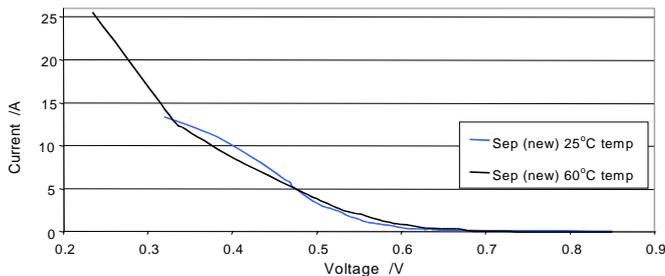


Fig 9 Fuel Cell I-V characteristics.

After the first run at 1A, the current efficiency was found to be lower than expected i.e. 73.7% as compared to ~95%. Hydrogen loss was suspected; so the gas inlets to the fuel cell were greased and re-tightened. The next two runs from table 5, show an improvement in current efficiency to over 81%, confirming the suspected hydrogen leak. The current efficiency was however still below the expected value, implying that some hydrogen was still being lost through leakage from the system. This was probably due to the gas connections to the fuel cell being a combination of rubber flexible pipes and brass olive seals, which would not be very secure against hydrogen diffusion.

From the last two runs, the current efficiency was found not to be a function of current flow, whereas the energy efficiency drops at increasing current as the working voltage decreases. This behaviour is similar to that of the electrolyser. The current efficiency reference is the same as that used in the electrolyser, that is 95719C to produce 1g of H₂ being 100% efficiency. The energy efficiency however, is with reference to the reversible energy of hydrogen at minimum entropy, that is, the L.H.V., being 117.624kJ/g at 25°C and 1bar. Using this factor the fuel cell efficiency can reach a maximum of 100%. If the H.H.V. of H₂ is used as the reference, then the absolute energy efficiencies of runs in table 5 would equate to 30.99%, 36.62% and 28.23% respectively. The energy efficiency drops (to 34%) when the fuel cell was operated at a higher current (1.78A). The maximum rated power of the fuel cell is at higher currents, so the efficiency is expected to decrease even further at higher power delivery. This energy efficiency is low compared to other commercial systems such as that of the DCH Technology cell delivering 12W of electrical power at 48% efficiency (Larminie and Dicks, 2002).

The fuel cell was found to be relatively simple to operate and the hydrogen side did not require to be completely scavenged of air by purging with hydrogen before the cell could provide power. However, the fuel cell occasionally became flooded with water produced on the oxygen side and from condensation of water vapour in the entering gases. This flooding dramatically reduced performance, particularly if the cell was being run low temperature. Opening the cell and manually drying out the membrane would restore the performance in such cases.

Metal Hydride Storage

The metal hydride storage tank used was ST-25-AL of Ergenics Inc., with a total weight of 25kg of which about 9.7kg are absorbing chemical and a volume of 3dm³. The ST-25-AL unit with Hy-Stor® 209 was designed to work at a pressure of 10bar @ 25°C and can absorb 1.2% by mass of hydrogen in the compound metal powder. The metal hydride tank was evacuated to below 50mm Hg, and then connected to the gas dryers being fed from the top of the hydrogen Perspex cylinder. Initially the tank was kept at room temperature measured as 26.5°C. The metal powder in the hydride tank combined with 2.5dm³ of H₂, but then was very reluctant to absorb any more gas even at a hydrogen gas pressure of 50mbar above atmosphere.

The cylinder was then cooled to approximately 5°C by immersing it in a bucket filled with a water-ice mixture. At this temperature, the absorption increased. This was noted from the increase of the hydrogen flow into the tank. A further 4.48dm³ were accepted inside the tank before the rate again decreased showing that the tank was unable to absorb further under those conditions.

The electrolyser was then given a new Perspex centre cylinder which could withstand pressures of up to 1.8bar. The metal hydride tank was evacuated and then filled with hydrogen at room temperature (14°C) and a pressure of approximately 1bar over a period of several days. A sum of 69.3dm³ hydrogen was put into the metal hydride. The tank was still absorbing hydrogen readily at 1.5bar but no further gas was delivered into the tank. Its release from the tank was next investigated.

Although it was not possible to measure the actual amount of hydrogen expelled from the tank, a stable Bunsen flame was supported for a total of 40 minutes, and 16.2dm³ (9bar x 1.8dm³) were still inside the tank from the total of 69.3dm³. This indicated that at least a large proportion of the hydrogen was combining with the metal alloy.

Discussion

The efficiencies of the PV panels (approximately between 8% and 13%) were the main determining factors in the overall hydrogen production efficiency. The electrolysis efficiency varied between 70% and 90% depending on the working voltage which is a factor of the applied PV power, electrolyser temperature, and insolation conditions. By choosing a high efficiency

mono-crystalline PV panel with a suitable working voltage and heating the electrolyser to over 60°C, the solar hydrogen efficiency exceeded 10% on two occasions.

The efficiencies were compared to the insolation received by the active area of each PV module. For panel types A, B and C, these corresponded to 80%, 87% and 90% of the physical module area respectively. As efficiency was referred to the cell area, the effects of variations in the construction of the different modules were eliminated. For example, the maximum efficiency of 10.51% (Table 7) obtained using module B, would result in a solar hydrogen efficiency of 9.14% compared to total module area. The module area efficiencies must be used when designing systems involving large PV areas as the physical module areas need to be considered. An interesting observation was that just after a sudden fall and rise in insolation due to the passage of a small cloud on a sunny day, the instantaneous efficiencies were particularly high. This was due to both the PV working at a lower temperature and to the electrolyser voltage decaying to a lower value due to depolarization. The electrolyser efficiency could be increased by using low power water circulating pumps so that no gas is allowed to stay on the electrodes acting as an insulator.

All the efficiencies obtained compare well with others found in the literature. The PV panel efficiencies were similar to those quoted by the manufacturer while an electrolyser efficiency of 75% (a working voltage of ~2V per cell) is also typical. These values can be compared with those from the Schatz Energy Project (Lehman and Chamberlin, 1999): PV panels running at approximately 10% efficiency and a feed of ~6kW of electricity to the electrolyser producing about 20 standard dm³ of H₂ per minute. This equates to an electrolysis efficiency of about 70% and an overall solar hydrogen efficiency of 7%. The actual measured efficiency was about 6.5%.

This work has demonstrated that solar hydrogen production efficiencies of over 9% (to module area) can be achieved. To produce an average of 1kg of H₂ (142MJ) per day, an initial solar energy of 1.56GJ/day is needed. The daily insolation averaged over a year on a surface inclined at 36° to the horizontal in Malta is 19.1MJ/day, or 17.2MJ/day on a flat horizontal surface (Iskander and Xerri, 1996). Hence, 1kg of H₂/day corresponds to a module area requirement of 82m² inclined or 91m² horizontal. A small electric vehicle carrying 2 persons requires 0.1kWh/km (Mallia and Schembri, 2002), equivalent to ~360kJ/km. As 1 kg of H₂ (L.H.V. 117.624MJ) feeding a 45% efficient fuel cell produces 52.9MJ, such a car carrying 1kg of H₂ has a range of 150km. For a household having 2 such cars each covering 50km daily, only 0.67kg of H₂ are needed, corresponding to about 60m² of module area. This is some 40% of the area occupied by a standard terrace house of 8m x 20m. However, larger electric cars, with a typical consumption of 0.25kWh/km e.g. a 1998 Peugeot 106, would need a correspondingly larger PV area. This can be compared to a modern, high efficiency small car

consuming gasoline at a rate of 5.6dm³ /100km, where traveling 100km produces ~12.5kg of CO₂.

Use of hydrogen in a household rather than a transport setting would require a different approach, as households have both direct electrical and heat energy needs. PV electricity is best used directly; so during daylight hours H₂ production should only use electrical energy surplus to household demand for direct electricity. The required amount of H₂ would be significantly reduced if daytime space/water heating requirements are met by flat plate solar heat collectors.

However, in a household using only electricity from fuel cells running on hydrogen: 1 kg of H₂ (L.H.V. 117.624MJ) in a fuel cell at 45% efficiency would produce 52.9MJ (14.7kWh) of electricity and a further 50MJ (13.9kWh) of heat energy. For an average household consuming about 10-14kWh of electricity per day, including space and water heating applications, the above quoted area producing 1kg of H₂ is adequate. In fact, if 60%-70% of the heat energy produced by the fuel cell is utilized for space/water heating, one can have a significant reduction in the area of the PV array.

Both the electrolyser and metal-hydride tank are designed to work at pressures of up to 10bar. The complete system could be designed to work at this pressure to allow metal hydride tanks to be fully utilised. Further increase in pressure would require the use of an external diaphragm compressor. Pressures of up to 200bar can be achieved allowing considerable compressed gas storage in high-pressure steel tanks. These are commonly used in commercial distribution of H₂. A 50L tank at 200bar (1kg H₂) requires an additional energy of 1MJ for compression. This is only about 1% of the chemical energy held by the gas.

An interesting comparison could be drawn between a Fuel Cell system and an advanced battery system. Both systems have the advantage of being relatively clean in terms of emissions, high efficiency and modular so can be designed to specific requirements especially in the case of vehicles. However it is quite clear that for very large systems, the fuel cell has clear advantages over the storage battery as fuel cell systems and hydrogen storage benefit from economies of scale. This is even more so in the case of supplying electricity to an industrial building; if storage batteries are used, the amount of space and investment needed would be too high. On the other hand if a simple, quick, compact and efficient power backup is required, a battery would be a favorite although small portable fuel cells are now being built to power computer laptops and mobile phones.

Below is a table comparing the equivalent electrical energy of 15kWh contained by 1kg of hydrogen.

Storage Type	Complete System Weight to store 15kWh electricity
Lead-Acid	540 kg
Li Polymer	125kg
NiMH	253kg
Na-Ni-Cl (Zebra)	200kg
H ₂ in metal hydride	270kg
H ₂ in reinforced C at 300bar	175kg

Table 7 Comparison of system weights of electrical energy carriers

In the above table, the battery systems are for 18kWh energy storage since only 80% depth discharge can be utilized. As for the hydrogen systems, the weight includes the storage tank and fuel cell.

Conclusion

The production of hydrogen by electrolysis of water using PV panels can reach overall efficiencies of 10%. With the local solar flux, such efficiencies make possible the generation of quantities of hydrogen useful in terms of urban transport from roof areas available on a standard terrace house. However, fuel cell personal transport is not predicted to reach significant levels before at least 2020. Locally, battery-powered electric cars are likely to be operational in considerable numbers much sooner than that.

PV generation of hydrogen for use in-house would require a different approach. The electrical energy needs of the household would have first call on the PV system output, with the direct beneficial effect of displacing fossil fuel use (and GHG emissions) from the power station. Only power surplus to household needs would go to the electrolyser, with the product stored at low pressure in a metal hydride tank. Subsequent use would be strongly conditioned by device cost--a 1kW commercial fuel cell sells at €30,000 – 32,000.

This latter situation reflects a current conundrum in the production of hydrogen with RE on medium-to-large scale. The prime intention of RE generation is to displace fossil fuel use, an aim best achieved by using the generated electricity directly. Spare capacity for hydrogen production would require a much accelerated program of RE generation, without there being a market for large quantities of hydrogen for a number of years. Present needs are mainly met by oxidation of CH₄, a cheaper (but not cleaner) method at current prices of natural gas. The one place hydrogen production by RE would be competitive at present is where it is used as a buffer between a wind farm and a small, isolated grid—a situation quite likely to arise on Malta when wind farms are eventually set up. With a limited distribution network, the hydrogen could be used in both static and mobile applications.

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