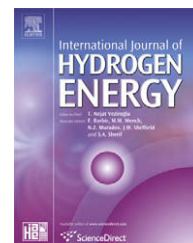


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# Direct coupling of an electrolyser to a solar PV system for generating hydrogen

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## ABSTRACT

Hydrogen as an energy currency, carrier and storage medium may be a key component of the solution to problems of global warming, poor air quality and dwindling reserves of liquid hydrocarbon fuels. Hydrogen is a flexible storage medium and can be generated by the electrolysis of water. It is particularly advantageous if an electrolyser may be simply and efficiently coupled to a source of renewable electrical energy. This paper examines direct coupling of a polymer electrolyte membrane (PEM) electrolyser to a matched solar photovoltaic (PV) source for hydrogen generation and storage. Such direct coupling with minimum interfacing electronics would lead to substantial cost reduction and thereby enhance the economic viability of solar-hydrogen systems. The electrolyser is designed for fail-safe operation with multiple levels of safety and operational redundancy. A control system in the electrolyser unit provides for disconnection when required and for auto-start in the morning and auto shut-down at night, simultaneously addressing the goals of minimum energy loss and maximum safety. The PV system is a 2.4 kW array (20.4 m<sup>2</sup> total area) comprising 30, 12 V, 80 W, Solarex polycrystalline modules in a series-parallel configuration. The integrated system has been operated for approximately 60 days over a 4-month period from September 2007 to January 2008 with many periods of unattended operation for multiple days, experiencing weather ranging from hot and sunny (above 40 °C) to cool and cloudy. The principle and practicality of direct coupling of a suitably matched PV array and PEM electrolyser have been successfully demonstrated. Details of electrolyser operation coupled to a PV array along with modelling work to match current-voltage characteristics of the electrolyser and PV system are described.

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## 1. Introduction

A number of environmentally benign technological solutions are under development globally to cater for future energy demands both for transport and stationary applications. These

include low-emission and high-efficiency fossil-fuel technologies, renewable energy (RE), biofuels and hydrogen. The need to find new energy solutions is obviously driven by the concern over increasing pollution and greenhouse gas emissions, rapidly declining liquid fuel reserves and also to extend the

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Nomenclature			
A	PV cell ideality factor (an empirical fitting parameter that describes how closely the behaviour of the p–n junction diode matches that predicted by theory, which assumes that the junction is an infinite plane and no hole–electron recombination occurs within the space-charge region)	n	number of PEM cells in series in an electrolyser stack
$A_{PV}$	area of PV module or array ( $m^2$ )	$n_s$	number of cells in series in a PV module/array
$\Delta E\%$	percentage of overall annual energy loss	$n_p$	number of modules in parallel in a PV array
$f_j$	number of hours in a year solar irradiance is falling within each interval range	m	number of PEM cells in parallel in an electrolyser stack
F	Faraday constant (96 485 C/mol)	$m_{H_2, yr}$	potential annual hydrogen production from a PV–electrolyser combination (kg)
$G, G_j$	solar irradiance ( $W/m^2$ )	$P_j^{EL}$	electrolyser power input from the PV panels (W)
I	PV cell/array output current, electrolyser current (A)	$P_j^{mPV}$	PV power output at maximum power point (W)
$I_{c,j}$	electrolyser individual cell current at solar irradiance $G = G_j$ (A)	q	charge of an electron ( $1.602 \times 10^{-19}$ Coulomb (C))
$I_r$	reverse saturation current (A)	T	temperature of solar cell (K)
$I_{ph}$	photo current (A)	t	time (s)
j	1, 2, 3...N refers to the different solar irradiance ranges	V	PV output voltage, electrolyser voltage (V)
k	Boltzmann's constant ( $1.381 \times 10^{-23}$ J/K)	$V_{max}$	PV output voltage at maximum power point (V)
		$\eta_F$	Faraday efficiency of electrolyser (%)
		$\eta_{PV-H_2}$	overall annual solar-to-hydrogen conversion efficiency (%)
		HHV <sub>H<sub>2</sub></sub>	higher heating value of hydrogen (142.92 MJ/kg = 39.7 kWh/kg)
		kW <sub>e</sub>	electric energy
		kW <sub>th</sub>	thermal energy

lifetime of finite fossil fuels such as natural gas and coal. Hydrogen is an excellent energy currency, carrier and storage medium and offers several advantages over many other energy solutions. Its combustion at end-user sites generates no pollution, particulates or greenhouse gas emissions. The use of hydrogen mixed with other fuels such as compressed natural gas (CNG), liquefied petroleum gas (LPG), or diesel in an internal combustion engine can improve combustion leading to a net gain in efficiency and reduction of pollutants, particulate matter and carbon dioxide in the engine exhaust. Hydrogen combustion in fuel cells offers very high fuel-conversion efficiency for transport applications (40–45%) and for stationary applications the overall system efficiency can approach 80–90% with heat recovery. Hydrogen offers a particular advantage in that it can store energy for indefinitely long periods, thus allowing load levelling for hourly to seasonal variations in supply and/or demand.

Hydrogen can be generated by a number of different routes, which include steam reforming of natural gas, coal or biomass gasification followed by gas separation or from water by supplying energy from fossil-fuel resources, nuclear or renewable energy [1–4]. In order to minimise environmental consequences, it is advantageous to use renewable energy for hydrogen generation. Currently about 45 million tonnes of hydrogen per annum is generated (mostly by steam reforming of methane) for use in fertiliser production, in petroleum refining, in chemical and in metallurgical industries. The use of hydrogen for stationary power generation is minimal at this stage and its increased use is very much dependent on the availability and acceptance of other clean technologies such as zero emission coal, nuclear energy, low cost renewable energy, etc. However, for transport applications, as fossil-fuel resources especially liquid fuels decline, there will be an

increasing requirement to use clean and low or zero emission fuels such as hydrogen.

The major barriers to the widespread use of hydrogen are the almost non-existence of transportation and distribution infrastructure and the lack of suitable hydrogen storage technologies especially for transport applications. Hydrogen is a flexible storage medium and it can be stored in a number of different forms (as a liquid at  $-253^\circ\text{C}$ , as compressed gas at up to 700 bar pressure, in metal hydrides, in carbon and boron nitride tubes, in glass spheres, zeolites, mesoporous materials, etc.) [5–7]. A number of different materials and technologies are under development to provide effective solutions to store hydrogen. Distributed generation of hydrogen at demand centres (homes, service stations, remote dwellings, etc.) can remove or at least delay the establishment of expensive hydrogen transportation/distribution infrastructure and can assist with the early introduction of the hydrogen economy.

Electrolysis of water provides one such solution for distributed hydrogen production and the process is compatible with existing and future power generation technologies and a large number of renewable technologies (solar, biomass, hydro, wind, tidal, wave, geothermal, etc.). Some of the advantages of water electrolysis include the following:

- Compactness, high current density and small footprint, thus making it easier to collect a large quantity of hydrogen from a small space compared, for example, with direct water splitting technologies such as photo-electrochemical conversion.
- Provision of on-site, on-demand hydrogen generation at homes, service stations and other end-user sites leading to a reduction in transport/storage costs.

- Modularity of the technology, permitting tailoring to the requirements of specific sites.
- Prior existence of the transmission/distribution infrastructure for electricity.
- An early path to the hydrogen economy, reducing the need for establishing up-front transmission distribution infrastructure.
- Greater maturity than other technologies (e.g. direct water splitting, biological routes).

Most of the water electrolysis technologies to date have used acidic or alkaline electrolyte systems for hydrogen generation [8–11]. Typical system efficiencies quoted are in the 55–75% range with most commercial systems having efficiencies below 65%. The current density is typically around 0.3–0.4 A/cm<sup>2</sup> and there are technical difficulties in maintaining the electrolyte balance and keeping hydrogen and oxygen separated.

The electrolysis technology based on polymer electrolyte membranes (PEMs) is an all solid state system with no corrosive electrolyte or electrolyte recycling. It can produce very high purity H<sub>2</sub> (>99.999%) with water and electricity as the only inputs. High-pressure operation is possible with hydrogen and oxygen gas streams separated by the membrane structure. The PEM electrolyser is capable of accepting large power input variations, thus allowing direct integration with intermittent sources of energy such as solar and wind power [11].

Water can also be electrolysed at high temperatures (900–1000 °C) using the solid-oxide fuel-cell technology, and since water dissociation is an endothermic reaction, heat generated from other sources (solar or nuclear) can be embedded in the process to reduce electric energy input and enhance electrolysis efficiency [12]. This technology still requires substantial research and development effort.

In order to interface the electrolyser to intermittent energy sources such as solar PV, interfacing control and power electronics, such as maximum power point tracker (MPPT) and/or a DC–DC converter, are conventionally used to capture the maximum available solar energy and also to allow for different current–voltage characteristics of the electrolyser and the solar PV array [13]. It would be particularly advantageous if an electrolyser can be simply and efficiently coupled directly to a source of renewable electrical energy, thus reducing the need for intervening electronics [14]. This approach would require appropriate matching of the capacities of the PV array and electrolyser. Its advantage would be to avoid the significant capital costs of a DC–DC converter and maximum power point tracking unit, potentially around US\$ 700 kW<sup>−1</sup> [15], and reduce the overall unit costs of hydrogen production by up to 10% as the costs of PV arrays and PEM electrolysers fall [16]. The economic viability of solar-hydrogen systems would thereby be enhanced.

There have been some demonstrations of renewable energy hydrogen systems, where hydrogen is generated using solar [17–20] or wind energy [21]. A solar PV plant that uses hydrogen as the energy storage media and fuel cell for generating power was installed at Humboldt State University Telonicher Marine Laboratory in 1991 [17]. In this system, a 9.2 kW<sub>e</sub> PV array was directly coupled to a 6 kW<sub>e</sub> alkaline electrolyser capable of producing 20 l of hydrogen/min. Hydrogen and oxygen gases were stored and used in a 1.5 kW<sub>e</sub>

PEM fuel cell to generate power when the PV output is insufficient to operate the load which is a 720 W air compressor that was required to supply pressurised air to fish tanks continuously. When the hydrogen and oxygen storage was depleted, the load switched to power from the utility supply. The system operated for over 3900 h and generated 797 normal m<sup>3</sup> of hydrogen in 1993. The electrolyser operated at current densities between 15 and 407 mA/cm<sup>2</sup> at an average hydrogen generation efficiency of 76.7% [17].

Another hydrogen-based renewable energy demonstration system (PHOEBUS) was installed at Forschungszentrum Jülich, Germany and supplied part of the energy to the Central Library [18]. The demonstration system consisted of a 312 m<sup>2</sup> PV array capable of peak power output of 43 kW<sub>e</sub>, a 110-cell lead acid battery bank to supply DC voltage of 220 V (capacity 303 kWh at 10 A), an alkaline electrolyser designed to operate between 5 and 26 kW power input (7 bar maximum operating pressure and maximum current density of 300 mA/cm<sup>2</sup>), and first a 6.5 kW<sub>e</sub> alkaline fuel cell and then a 5 kW<sub>e</sub> PEM fuel cell due to unreliability of the alkaline fuel cell. Both hydrogen and oxygen were stored using an external compressor. A logical algorithm, based on the state-of-charge of the battery, was implemented to determine the energy flow from the PV array to the consumer and to make the system energy efficient. During the system operation between 1997 and 2001, the PV array directly met 20–25% of required energy demand, with remaining (indirectly as stored energy) fulfilled by the battery (50–52%) and long-term hydrogen and oxygen storage and utilisation in a fuel cell (20–25%).

An industrial-scale solar-hydrogen demonstration program at Neunburg vorm Wald, Germany was started in 1986 by a joint venture company Solar-Wasserstoff-Bayern GmbH (SWB) with the aim to demonstrate solar-hydrogen energy cycle without any carbon dioxide release [19]. The facility was established in 1991 and its operation continued to about 1999 with overall cost of the project being US\$ 80 million. The facility for Phase 1 comprised solar PV generators (135 and 131 kW), electric power conditioning units, low pressure water electrolysers (alkaline – 111 and 100 kW) with hydrogen output of 47 normal m<sup>3</sup>/h, gas conditioning and storage systems, fuel-cell plants (phosphoric acid fuel cell with 79.3 kW<sub>e</sub> and 42.2 kW<sub>th</sub> thermal output, a 6.5 kW<sub>e</sub> alkaline fuel cell) for stationary and transport applications and an automated liquefied hydrogen filling station for test vehicles. In Phase 2, a number of new plant sub-systems including a high-pressure electrolyser and a 10 kW<sub>e</sub> PEM fuel cell were also installed. The electrolysers in this facility were operated on conditioned power (DC–DC conversion) from the solar PV generators. The author [19] concludes that as the facility was constructed with individual prototypes of many technologies, several integration problems were encountered and many sub-systems failed to operate satisfactorily especially in the early part of the program. However, despite these problems, the facility had been operated safely for 7 years.

Hollmüller et al. [20] have evaluated a PV, hydrogen production and storage system for a residential home in Switzerland. It consisted of a PV solar panel with 65 m<sup>2</sup> surface area and 5 kW average peak power, a DC–DC converter, a 5 kW alkaline electrolyser (62% average efficiency), a hydrogen purification unit, a compressor and two metal hydride storage tanks (one to

operate household appliances and the other to operate a hydrogen minibus). The system was evaluated for 3 days.

Agbossou et al. [21] investigated a hydrogen renewable energy system that comprised mainly of a 10 kW<sub>e</sub> wind generator, a 1 kW<sub>e</sub> PV array, a 5 kW alkaline electrolyser (capable of delivering 1 normal m<sup>3</sup>/h hydrogen compressed at 7 bar), a 5 kW PEM fuel-cell stack, 48 V deep discharge batteries for voltage stabilisation, a DC bus controller that included batteries for energy transfer and a DC-AC inverter. The system was installed and investigated at Hydrogen Research Institute, Quebec University. The voltage produced by a wind generator and solar PV array was regulated and converted to suit the electrolyser.

The present paper examines the direct coupling of a polymer electrolyte membrane (PEM) electrolyser matched to a solar PV source with a minimum interfacing electronics and gives results from a joint project between CSIRO and RMIT University. Efficient operation requires the matching of voltage and current characteristics of both components to maximise the overall energy transfer from the PV system to the electrolyser, and hence the cumulative hydrogen production, for the varying insolation over the year. The paper discusses a procedure for finding near-optimal configurations of both the PV array and electrolyser stack and modelling work to assess the corresponding energy transfer and hydrogen production. Experimental results for the operation of directly coupled PV-electrolyser system over a period of 4 months from September 2007 to January 2008 are presented. Other issues investigated included the effect of variable PV output on the long-term performance of the PEM electrolyser and refinement of appropriate safety and control strategies.

## 2. The CSIRO stand-alone PEM electrolyser

The CSIRO PEM electrolyser used in the trial is a transportable stand-alone system that provides a stack and complete balance-of-plant (BOP) in a single package requiring only DC power and water as inputs and providing H<sub>2</sub> and O<sub>2</sub> as outputs. It has been designed to operate over a wide range of input power in order to accommodate the inherent variability of renewable sources. The digital indicators in the front panel display the values of key system variables and allow upper and lower limits of the process variables to be set electronically and for tripping an alarm relay if the values are exceeded. An additional 10 status conditions are monitored by sensor switches, for pressure, flow and gas monitoring. Furthermore, control systems have been incorporated to allow the unit to shut-down and consume minimal power when the PV voltage falls below a predetermined value and to restart when it climbs above a threshold on the following day.

The system is designed for fail-safe operation with multiple levels of built-in safety and operational redundancy. Details of the electrolyser BOP design and operating characteristics are described elsewhere [22]. For example, the electrolyser BOP incorporates monitoring of pressure, temperature and flow at all critical locations, as well as a pair of hydrogen leak detectors. Any indicated fault opens a contactor that disconnects the stack from its power supply. The electrolyser BOP control system also has “auto-restart”

capability, enabling it to place the electrolyser on standby when power from the PV array falls below a prescribed minimum value (generally overnight), with automatic restart the next day. The BOP is designed to take 24–30 V input from a renewable source such as PV solar or wind with current varying from 1 to 120 A for the electrolyser stack.

A typical stack design for incorporation in the stand-alone electrolyser uses PEM cells of 100 cm<sup>2</sup> active area, which operate at about 2.0–2.2 V per cell at the maximum current density of 1 A/cm<sup>2</sup>. A 15-cell stack, therefore, would have a nominal input power requirement of about 3 kW. The stacking configuration can be modified to meet other voltage and capacity requirements. A very flexible safety and control system allows for setting of limits for current, voltage, temperature and pressure.

The polymer electrolyte membrane electrolyser stacking technology has been developed by CSIRO [9]. Fig. 1 shows the performance of single electrolysis cells and stacks ranging in size from 9 cm<sup>2</sup> to 100 cm<sup>2</sup> active area per cell.

For the development, commissioning and evaluation of the BOP and complete electrolyser system, a 13-cell stack with 100 cm<sup>2</sup> active area per cell was constructed. The initial performance of the stack is shown in Fig. 2. The efficiency of this stack at the start was around 91% at 50 A current input with individual cell efficiency varying between 90 and 92%. This stack was operated extensively over several hundred hours during the BOP construction and commissioning phase and to resolve safety related and other operational issues. The stack had gone through multiple forced and unforced shut-downs and start-ups and operation with widely varying current loads over this period. During this exhaustive commissioning stage, some cells developed problems showing degradation in the performance and the efficiency of the stack had decreased to about 75% at 50 A. However, for the main aim of this work (safe demonstration of the concept of direct coupling of the PEM electrolyser with a solar PV array with minimal interfacing electronics), the same stack was installed in the stand-alone electrolyser system.

The PEM stack operates most efficiently at ~70–90 °C and the electrolyser is designed to reach and hold this temperature at a full load of 100 A through internal heat generation. However, in actual operation with widely varying load, the

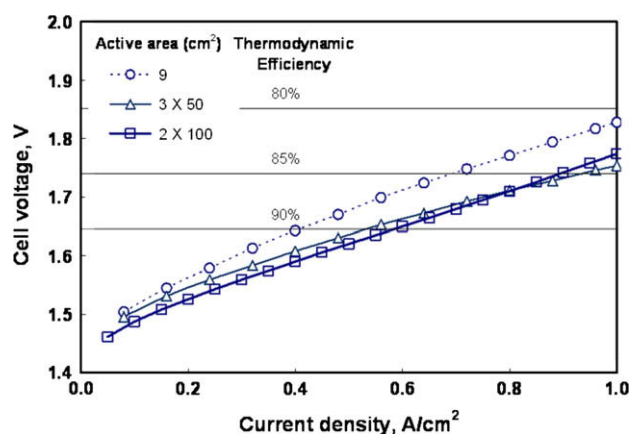


Fig. 1 – The performance of single electrolysis cells and stacks ranging in size from 9 cm<sup>2</sup> to 200 cm<sup>2</sup> active area.



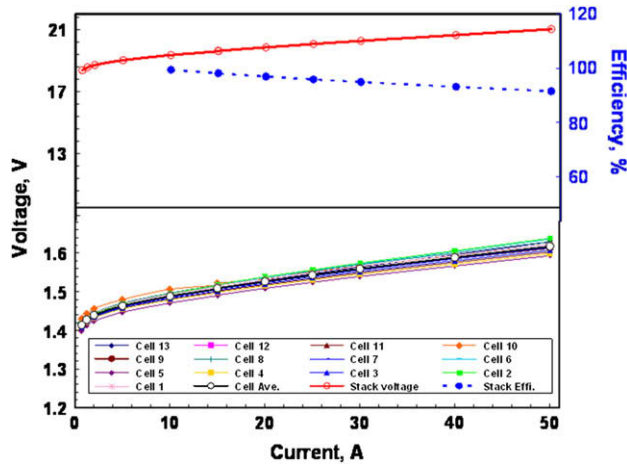


Fig. 2 – The initial performance of a 13-cell stack (top) and individual cells of the stack (bottom). Each cell has an active area of 100 cm<sup>2</sup>.

operating temperature and efficiency are expected to be lower. It is designed for operation initially at pressures of up to 6 bar on either side.

### 3. RMIT PV array

A 2.4 kW roof-mounted PV array at RMIT University's Bundoora East campus was used as the basis for the trial of direct coupling to the CSIRO's PEM electrolyser stack. The PV array comprises 30 SX 80 polycrystalline solar panels (80 W each) and occupies an area of 20.4 m<sup>2</sup>. The PV module specifications provided by the manufacturer under standard test conditions (STC) – that is, an average solar spectrum at air mass 1.5, irradiance normalised to 1000 W/m<sup>2</sup>, and a cell temperature of 25 °C – are given in Table 1. Before coupling the electrolyser with a PV array it is necessary to know the current (*I*)–voltage (*V*) characteristics of the PV panel, in order to ensure that the PV array is able to supply the minimum cut-in voltage to the electrolyser in all solar irradiances. It is also necessary to ensure that for higher irradiances the output current from the PV array should not exceed the maximum rated current of the electrolyser. *I*–*V* characteristic curves of the PV module for varying solar intensity and operating cell temperatures have been generated by mathematical modelling in an Excel spreadsheet. The relationship between current and voltage for a PV array consisting of a number of cells in series (*n<sub>s</sub>*)

Table 1 – Specifications of the PV module.

Model type = SX 80 (36 cells connected in series)
Area of each module = 1.456 × 0.467 m <sup>2</sup>
Peak power, <i>P</i> <sub>max</sub> = 80 W
Peak power voltage, <i>V</i> <sub>max</sub> = 16.8 V
Peak power current, <i>I</i> <sub>max</sub> = 4.75 A
Short circuit current, <i>I</i> <sub>sc</sub> = 5.17 A
Open circuit voltage, <i>V</i> <sub>oc</sub> = 21 V

connected in each module and a number of modules in parallel (*n<sub>p</sub>*) in an array can be expressed as [23]:

$$I = n_p I_{ph} - n_p I_r \left[ e^{\left( \frac{q V}{A k T n_s} \right)} - 1 \right] \quad (1)$$

In this analysis, series and parallel resistances of PV cells, which generally have only a small influence, have been neglected to keep the model simple. The maximum power point (MPP) of the PV panel for different solar irradiances can be determined from the following relationship [23]:

$$e^{\left( \frac{q V_{max}}{k T A n_s} \right)} \times \left[ \left( \frac{q V_{max}}{k T A n_s} \right) + 1 \right] = \frac{I_{ph} + I_r}{I_r} \quad (2)$$

This theoretical analysis has then been applied to SX 80 solar panels using the manufacturer's specifications provided in Table 1. Simulated *I*–*V* characteristic curves for different solar irradiance levels have been generated using Eqs. (1) and (2), and the MPP line drawn on the same graph (Fig. 3).

### 4. Matching the electrolyser to the PV array

The main aim for direct coupling is to maximise overall annual energy transfer from the PV system to electrolyser by avoiding the use of any MPPT and DC–DC converter between them, and hence maximising the cumulative hydrogen production. The number of cells in the electrolyser stack is an important design parameter for matching to the PV source under direct coupling operation. The matching strategy employed is to vary the series–parallel stacking of individual cells in both the PV array and the PEM electrolyser so that the MPP line of the PV array and the load line of PEM stack align as closely as possible [24]. For the theoretical and quantitative analysis of the matching of the PV–electrolyser system, *I*–*V* characteristic curves of SX 80 type PV panel for different solar irradiances were obtained by theoretical modelling; and the overall *I*–*V* characteristics of the electrolyser for a given series stack were established from the measured polarisation curve

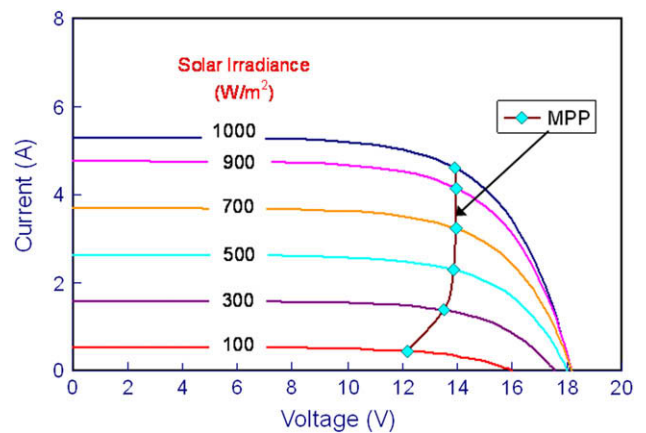


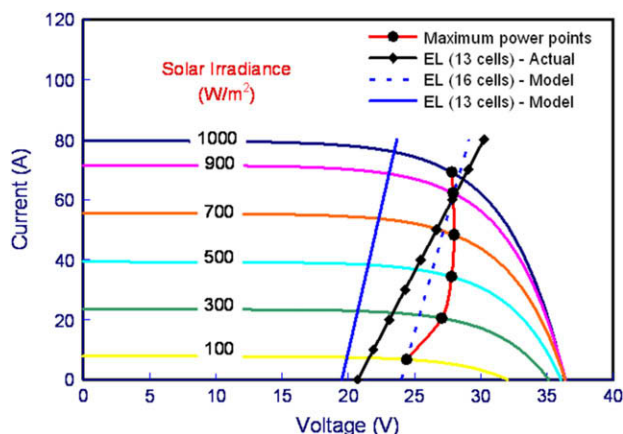
Fig. 3 – Current-voltage characteristic curves of PV module at different solar irradiance levels and corresponding maximum power point (MPP).

**Table 2 – Power delivered to the electrolyser, potential available PV energy, annual energy loss, hydrogen production, and annual solar-to-hydrogen energy conversion efficiency for different PV-electrolyser combinations.**

PV-electrolyser combination		Maximum potential PV power delivered to the electrolyser (%)						Annual maximum potential available PV energy (kWh)	Annual energy delivered to electrolyser (kWh)	Annual energy loss (kWh)	Overall annual energy loss $\Delta E$ (%)	Annual potential hydrogen production (kg) <sup>a</sup>	Overall annual solar-to-hydrogen efficiency (%)
PV module combination	Electrolyser stack combination	G = 100 W/m <sup>2</sup>	G = 300 W/m <sup>2</sup>	G = 500 W/m <sup>2</sup>	G = 700 W/m <sup>2</sup>	G = 900 W/m <sup>2</sup>	G = 1000 W/m <sup>2</sup>						
30 PV parallel	13-Cell stack	No power	No power	No power	No power	No power	No power	3117.60	–	–	–	–	–
30 PV parallel	11-Cell stack	No power	33.74	36.10	33.85	28.75	27.04		–	–	–	–	–
30 PV parallel	10-Cell stack	40.58	71.34	68.73	61.47	53.90	50.76		1835.11	1282.49	41.14	41.0	4.81
30 PV parallel	9-Cell stack	87.28	93.61	90.38	84.18	77.41	73.29		2624.01	493.59	15.83	56.4	6.62
30 PV parallel	8-Cell stack	95.78	99.09	98.20	97.02	Excess power	Excess power		–	–	–	–	–
15 Parallel pairs	13-Cell stack	83.72	83.68	85.92	87.87	90.77	92.01		2731.65	385.95	12.38	60.3	7.07
15 Parallel pairs	14-Cell stack	89.93	89.15	91.29	93.44	95.65	96.45		2897.43	220.17	7.06	64.1	7.52
15 Parallel pairs	15-Cell stack	91.72	93.70	95.11	96.81	98.48	99.33		2998.81	118.79	3.81	66.4	7.79
15 Parallel pairs	16-Cell stack	100	97.88	97.90	99.23	100	99.52		3090.73	26.87	0.86	69.0	8.10
15 Parallel pairs	17-Cell stack	92.76	100	100	99.13	98.02	96.40		3060.92	56.68	1.82	61.7	7.24

a Calculated assuming 100% current efficiency.





**Fig. 6 – Current-voltage characteristics of 15 parallel pair solar PV array, the theoretical PV maximum power point (MPP) line (•), and current-voltage lines (1.5–1.9 V, 0–100 A) for 16-cell (---) and 13-cell (—) PEM electrolyser (EL) stacks. Also included are the actual data (♦) for the 13-cell stack during initial stages of direct coupling experiment.**

and coupled to the PV array arrangement mentioned above, the operating line of the electrolyser is as shown in Fig. 6. This combination potentially gives the highest overall energy transfer and hydrogen production of all the options considered as evident from Table 2. For this PV-electrolyser combination, more than 97% of the available PV power will be captured by the electrolyser for all solar irradiance levels, and the electrolyser operating line passes through the MPP of PV array output, when the solar radiation intensity is 100 and 900 W/m<sup>2</sup> as can be seen from Fig. 6.

Thus the optimal combination is to connect 15 pairs of PV modules in parallel (with each pair of two modules in series) directly coupled to an electrolyser stack comprising 16 cells in series. In this case it is estimated that less than 1% of the maximum transferable energy from the PV panels would be lost over the year ( $\sim 26.9$  kWh) with direct coupling compared to a situation of optimal maximum power point tracking for the PV system at all times. This result compares very

favourably with electronic MPPT systems, which typically have energy losses compared to the maximum achievable of around 10% [25]. The annual potential hydrogen production from the electrolyser for the optimal combination would be 69 kg assuming 100% current efficiency for hydrogen generation. The corresponding overall annual solar-to-hydrogen energy conversion efficiency would be 8.1%.

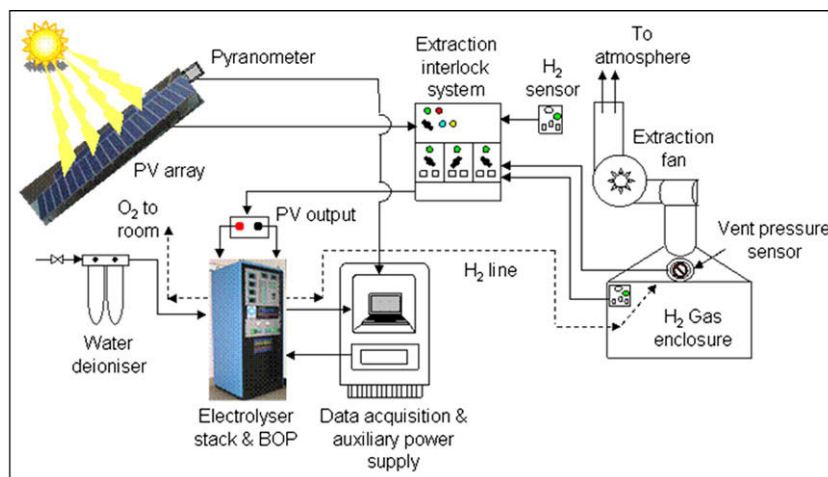
The PEM electrolyser used for the demonstration was a 13-cell stack (which had already shown degradation) and the operating current-voltage line for this stack is also shown in Fig. 6.

## 5. System setup and demonstration

For direct coupling of the CSIRO electrolyser with a PV system, the 2.4 kW PV array at the Renewable Energy Laboratory of RMIT University's Bundoora East campus was reconfigured as 15 pairs, with series connection within each pair, all connected in parallel as shown in a schematic diagram before (Fig. 5). Therefore, for this configuration the PV array open circuit voltage would be 42 V and peak power current around 71 A.

The stack used in the experimental program actually comprised 13 cells in series with 100 cm<sup>2</sup> active area per cell. The number is fewer than the calculated optimum based on the standard polarisation curve for the 16-cell stack as shown in Table 2 and Fig. 6. However, as mentioned earlier, this particular stack was available at the time. In addition, since a few cells had begun to show some degradation after a period of extensive pre-testing during commissioning of BOP, it was apparent that a good match with an actual stack might be achieved with fewer cells, some of which would be operating at a higher voltage.

The water supply to the stack was Melbourne tap water through a conventional in-line deionisation filter system. The outputs from the PEM electrolyser are separate streams of  $H_2$  and  $O_2$  saturated with water. No on-board gas drying or storage capability was incorporated at this stage but will be incorporated in the future. Although the electrolyser stack is



**Fig. 7 – Schematic diagram of direct coupling of solar PV array and PEM electrolyser.**



capable of generating hydrogen at pressures up to 6 bar, both hydrogen and oxygen were generated in this experiment at near-ambient pressure.

As discussed above, the electrolyser BOP was designed for fail-safe operation and included two hydrogen leak detectors, for sensing hydrogen in the oxygen output stream as well as in the ambient atmosphere inside the cabinet. Any indicated fault would open a contactor that would disconnect the stack from the PV input.

In addition, a safety extraction interlock system has been designed and implemented at RMIT University which would detect ventilation system failure, as well as the presence of hydrogen gas in the laboratory. A schematic diagram of the experimental setup including extraction interlock system, electrolyser and 2.4 kW solar PV panel is shown in Fig. 7. The hydrogen produced by the electrolyser was taken into a hydrogen cabinet for safe ventilation to the atmosphere. The oxygen produced by the electrolyser was discharged into the room from the rear panel of the electrolyser cabinet which also had a hydrogen leak detector fitted as mentioned above. The hydrogen cabinet was fitted with an exhaust fan inter-linked to the extraction interlock system via a ventilation pressure switch. The function of the ventilation pressure switch is to ensure that the extraction fan is working properly at all times by extracting sufficient amount of air to dilute the hydrogen well below the hydrogen flammable limit. A hydrogen detection sensor was located in the ceiling of the Renewable Energy Laboratory (in addition to the one inside the hydrogen extraction cabinet) to ensure that no accumulation of hydrogen above the flammable limit occurred inside the electrolyser cabinet, in the laboratory as well as in the extraction cabinet. The extraction interlock system has been designed in such a way that the PV power will only be available at the output terminals, if the fan is running and extracting air at an adequate rate, and no hydrogen is detected by the hydrogen sensors (set to trigger at 1000 ppm). The safety control system automatically activates the extraction fan by a programmable logic controller (PLC) and relays, when it detects any voltage output from the PV panels when sun rises and switches off the fan half an hour after sun set ensuring that no residual hydrogen gas is present in either the cabinet or in the laboratory. This automatic on-off option of extraction fan also minimises energy consumption.

For simplicity, the two safety systems (part of electrolyser BOP and that installed in the Renewable Energy Laboratory) were operated independently. This was a satisfactory arrangement although a different system may be required if the electrolyser and the PV array were designed for operation as a single system from the beginning. The auto-restart system described above allowed for simple free-running operation of the coupled electrolyser and PV array.

Data collection was passive and independent of the control system. A built-in 40-channel 'Doric Digitrend 245' data acquisition system has been employed for monitoring and recording individual cell voltages, overall stack voltage, stack current, supply water temperature, return water temperature, electrolyser stack temperature, inside and outside ambient temperature, ambient pressure, solar radiation data and PV panel temperature. Real time data were collected as spot readings at 10 min intervals continuously (day and night)

during the operation. Data collection was managed by a laptop computer using CSIRO proprietary software and saved as a text file that is able to be read by Microsoft Excel. Solar irradiance on the PV panels was measured by a 'SolData 80SPC' pyranometer; both the pyranometer and PV array were held at 40° to the horizontal, facing to the North.

The entire system was installed at RMIT University's Renewable Energy Laboratory in July 2007. Following initial testing that concentrated on optimising the control, safety and auto-restart systems, the coupled system began operation in September 2007 with occasional days missed over the ensuing period due to maintenance and repairs.

## 6. System operation and performance

The integrated system operated for approximately 63 days over the 4-month period from September 2007 to January 2008. The system had many periods of unattended operation for multiple days, experiencing weather ranging from hot and sunny (above 40 °C) to cool and cloudy. Fig. 8 shows the results obtained over the 600 h of operation with a representative 5-day period data shown as an inset. However, from the frequency histogram of experimental solar radiation data recorded during the direct coupling operation in Fig. 9, the total direct coupled time was determined to be 1519 h with effective direct coupling operation time of the electrolyser with PV being 941 h after neglecting the hours of zero solar radiation data. From Fig. 8, it can be seen that the electrolyser stack current varied rapidly with a wide variation in the solar radiation. This dynamic trend of the electrolyser stack current suggests that the system has operated reliably over this long direct-coupled experimental period. Using this experimental solar irradiance frequency histogram as input, the theoretical analysis with direct coupling of a 13-cell electrolyser stack to 15 pairs of PV modules in parallel yielded an energy transfer of 12.4% lower than the maximum 613.9 kWh that is achievable from the array. The transfer losses are greater than the minimum they could be for direct coupling (less than 1%), due to usage of the available 13, rather than the more-optimum value of 16 cells. Therefore, 537.8 kWh of energy was available

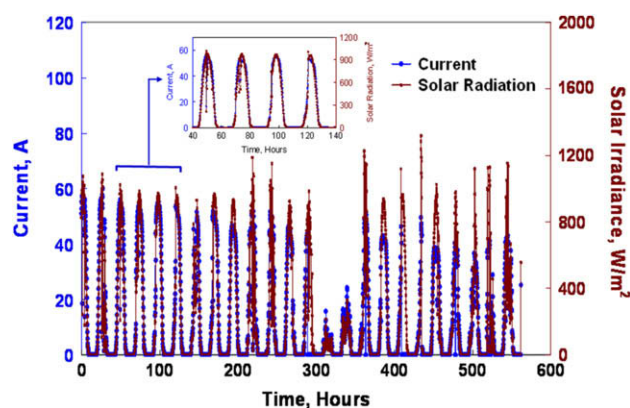


Fig. 8 – Stack current and solar irradiance data over a period of about 600 h with a 5-day period data shown as an inset.

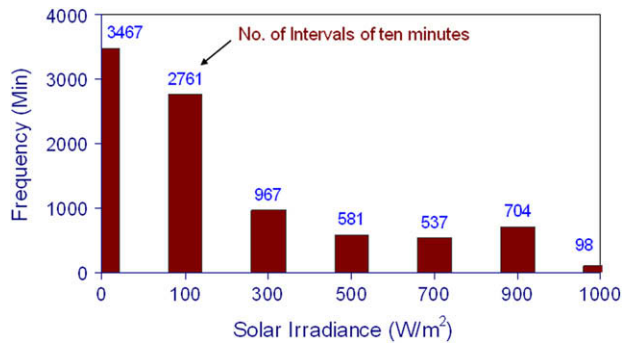


Fig. 9 – Experimental solar data frequency distribution.

to the 13-cell electrolyser for conversion to hydrogen over the 941 h of direct coupling operation. However, for our direct coupling experiment, it was calculated that the actual value delivered to the electrolyser was 455.5 kWh. Thus, the discrepancy between the theoretical and the experimental energy transfer was about 15.3% of the total energy transferred over the period. The main reason for this difference was the non-optimal performance of the stack; in particular, one cell degraded prematurely and showed very high cell voltage. Other factors that may have contributed to the difference in the calculated and actual energy transfer include considering an average solar irradiance for all irradiances that fall within each interval used in calculating the frequency distribution of solar radiation data; the assumption of constant energy transfer over each 10 min data logging interval; and slight difference between the actual performance of the PV panels and that assumed in the model.

Fig. 10 shows the actual voltage–current data and electrolyser efficiency collected in real time over a period of 5 days operation for the 13-cell electrolyser stack in the very early stages of the direct coupling experiment. It can be seen in this graph that the electrolyser performance has degraded and the efficiencies produced at the time of data recording are, for example, around 72% at 50 A as compared to the initially produced efficiency of 91% as shown in Fig. 2. If the electrolyser had not degraded, it could have produced around 10.5 kg

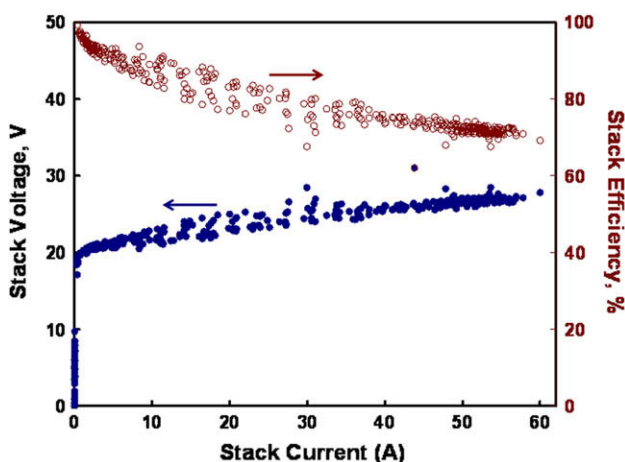


Fig. 10 – Measured stack V–I and efficiency data over the 5-day period as per Fig. 8 for the 13-cell stack.

of hydrogen, estimated using the frequency distribution of the experimental solar data and assuming average energy efficiency of the electrolyser stack to be 91%. From the time the direct coupling experiment started, the electrolyser efficiency is expected to have been no more than 75%. At this 75% efficiency, the electrolyser should have produced around 8.7 kg of hydrogen. However, approximately 7.55 kg of hydrogen has been produced at an overall electrolyser stack efficiency of ~65% during the period of operation showing further degradation in the stack performance. From the experimental solar radiation data, with the 6316.3 kWh of total solar energy input, overall solar-to-hydrogen energy conversion efficiency was found to be around 4.7%. The observed stack degradation during the commissioning phase of the stand-alone PEM electrolysis system and subsequent evaluation in the direct coupling experiment are indeed surprising as previous laboratory tests on a smaller electrolyser stack had shown significantly lower degradation [9] especially at the current densities over which the electrolyser had operated in the directly coupled mode. The performance degradation issues of a PEM electrolyser in a solar-hydrogen system have been mentioned in the literature [26].

There are several possible causes for the electrolysis stack performance degradation. The electrolyser was directly coupled to the PV array for an extended period of time (941 h of actual operation) and during this time a wide-ranging level of solar radiation provided vastly variable power input to the electrolyser. This highly fluctuating power input to the electrolyser may thus have adversely affected its performance and lifetime. Further testing is required to establish the extent to which performance degradation is due to variability of the power input over and above degradation due to constant usage over time. The main causes, in general, for electrolyser degradation are poor stack assembly, delamination or debonding at the membrane/electrode interface, loss of conductivity of the membrane due to leaching out of fluoride/sulphonic acid groups and contamination by other metallic ions, change in properties of the catalyst affecting its electroactivity at the interface, and increase in the contact resistance between the electrode supports and the interconnect plate due to interconnect surface oxidation [27].

Recently, some other direct coupling PV-electrolyser systems have been demonstrated and reported in the literature [28,29]. Arriaga et al. [28] described a PV-PEM electrolyser coupling system consisting of a 36, 75 W, solar panels interconnected in a configuration of 2.7 kW power at 48 V DC output and a commercial 5.6 kW electrolyser stack of 25 cells in series. These authors concluded that by an optimal design of the PV system, the electrolyser can well match with PV output when the solar irradiance is in the range of 600–800 W/m<sup>2</sup>. However, their study did not report any quantitative experimental result for energy transfer and also the period of direct coupling operation was not mentioned. Our theoretical analysis showed that the proposed PV-electrolyser combination (Section 4) will potentially operate near the maximum power point of PV output for all the solar irradiances; and over the year less than 1% of the maximum available energy will be lost. Another recent paper discussed an early proof-of-concept direct coupling PV-electrolyser home fueling system to supply hydrogen to a fuel-cell electric car vehicle on

average daily commute [29]. The electrolyser was a high-pressure (44.8 MPa) alkaline system capable of supplying 2.8 kg of hydrogen over a 24 h period of continuous operation with a power consumption of 156 kWh (28 kWh for 0.5 kg of hydrogen). The PV system consisted of 4 arrays of 10 modules each (total area 47.2 m<sup>2</sup>) with maximum power output of 7.6 kW and a maximum power point voltage of 54.8 V. The authors reported experimental results for only about 38 h of operation over 14 days. In the present study, our system was operated in the direct coupling mode for 63 days with an effective coupling operation of 941 h.

In order to check how effective the system would perform as the electrolyser performance degrades over a period of operation, a linear regression analysis was performed on the data in Fig. 10 and was plotted as shown by a straight line (♦) in Fig. 6. It can be seen that the degradation in the 13-cell stack has resulted in a shift in the load line from “EL (13 cells) – Model” towards the maximum power point line. This suggests that despite the degradation in electrolyser performance with time and electrolyser V–I curve shifting downwards (voltage increasing and current decreasing), it still appears possible to capture a significant portion of the available solar radiation in the form of hydrogen.

Overall, the system performed safely and satisfactorily over the entire period of direct coupling experiment (1519 h in total), providing a successful demonstration of the direct-coupling concept.

## 7. Conclusion

The functionality of a matched direct-coupled PV array and PEM electrolyser stack has been successfully demonstrated. The PEM electrolyser responded rapidly to power input variations during the day caused by variations in solar radiation and was able to cope satisfactorily with extreme temperature changes (20–40 °C), cloudy and rainy conditions, shut-down at night and start-up in the morning over a period of 4 months. About 7.55 kg (~91 m<sup>3</sup>) of hydrogen has been generated at an efficiency which is calculated to be only a few percent less than the theoretical maximum. The test was concluded due to the degradation of the stack, in particular one cell which eventually failed. Preliminary analysis suggests that it should be possible to achieve an energy transfer between the PV array and electrolyser using this approach that is only a few percent below the maximum potentially achievable under perfect maximum power point matching conditions at all times. The significant costs of a DC–DC converter and maximum power point tracking unit can thus be avoided, thereby enhancing the economic viability of solar-hydrogen systems. Long-term performance degradation of PEM electrolyser, in a direct-coupled solar-hydrogen system over an extended period of operation, is a concern, and requires further testing to determine the extent to which the degradation is directly attributable to the variability of the power input as opposed to usage over time at constant power. However, modification to the stack design and materials are likely to reduce this degradation significantly and enhance energy transfer between a directly coupled PV array and the electrolyser over an extended period of operation.

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