Energy Management of a Solar/Hydrogen Driven Power Plant

Marius Viljoen[1], Christo Pienaar[2]

[1]Senior Lecturer, Faculty of Engineering, Vaal University of Technology, Privatebag X021, Vanderbiljpark, South Africa
Corresponding author email: marius@vut.ac.za
[2]Professor, Faculty of Engineering, Vaal University of Technology, Privatebag X021, Vanderbiljpark, South Africa

ABSTRACT
Hydrogen, being one of the major fuels employed in fuel cells, can be generated from various sources. Its production from fossil fuels, such as coal or natural gas has a negative environmental impact and results in air pollution. It is therefore imperative to find an alternative and environmentally friendly method of generating hydrogen for fuel cells. This paper focuses on the generation of hydrogen from solar energy. It presents a management system for the optimization of a solar/hydrogen power plant for use in a rural community.

Keywords: Hydrogen fuel cell, Electrolyser, Programmable logic controller (PLC), Solar Voltaic Cells, Graphical User Interface (GUI), Maxim Power Point Tracker (MPPT).

1.0 INTRODUCTION

With approximately 60% of the population in South Africa not having access to electricity, the Department of Minerals and Energy (DME) is determined to promote non-grid power as the technological equal of grid electrification (Lisa 1999). Fifty six percent (56%) of Eskom's (Electricity Supply Commission of South Africa) prepayment customers consume less than 50 kWh per month, indicating that electricity is not used for any thermal applications such as cooking, space heating or water heating. If electricity is only used to provide energy for lighting and entertainment, other energy requirements should also be addressed to ensure adequate supplies (Wentzel 2004).

From the point of view of government, the following lessons were learnt from the grid-based electrification programme so far (Kotze 2000):

- The electrification programme is not commercially viable, since operating costs need also to be subsidised.
- Financing such a programme from inside the electricity supply industry places an undue burden on the utility and jeopardises the sustainability thereof.
- Such financing is not transparent and is difficult to co-ordinate with other infrastructure investment programmes.
- Rural areas are particularly costly and difficult to electrify.
- It is imperative to consider a suite of capacity differentiated supply options.
- Non-grid technologies should be used in all cases where electricity supply through a grid connection is too expensive. This will concern a significant portion of rural households.
- Substantial capital subsidies and soft loan funding are prerequisites to drive such a programme. In addition, tariffs need to be restructured so that operating costs are covered.

Energy issues pose a major problem in Africa, more so than anywhere else in the world. In the decades to come, Africa will have to consume far more energy if it is to climb out of under-development and satisfy its societies' demands for better living conditions. Therefore, challenges ahead require political will, as well as commitment to innovation and applying energy efficient technologies and systems to all sectors of the economy (Lisa 1999). It is necessary to develop processes of energy storage both for short-term; relatively small amounts of energy with great power fluctuations, and for long-term (seasonal) large energy volumes (El-

Shatter et al 2002:478). A solar/hydrogen power-plant is offered as an alternative solution to solve the problem of supply of renewable energy.

2.0 SOLAR/BATTERY/HYDROGEN FUEL CELL POWER PLANT

Figure 1 shows a solar/battery/hydrogen fuel cell power plant. In this system a battery backup is shown, however a battery backup has the following disadvantages:

- Once the batteries are fully charged the excess power from the solar panel are not fully utilised.
- The lifetime of batteries is relatively short (2 to 4 years).

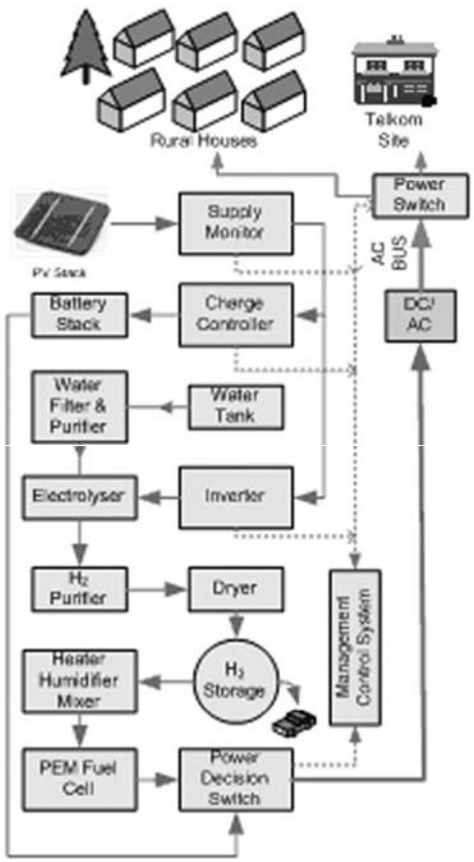


Figure 1: Layout of regenerative solar/hydrogen power plant.

The design of an electrical management system for optimising the available energy and its subsequent distribution considers the following:

- Main management system.
- Solar voltaic panels and control.
- Battery system and control.
- Inverter control and monitoring.
- Hydrogen generation.

When the solar supply is not available (cloudy weather or night time) the system will automatically switch over to the fuel cell system and use either the battery or hydrogen backup power. The solar panels are used with a maximum power point tracker (MPPT) to ensure energy efficiency from the solar cells. The regulated power from the MPPT is fed to battery banks and a DC to AC inverter. The inverter supplies 230V AC to the electrolyser and to the electrical distribution board. The electrical distribution board supplies power for lighting and computers. The intended power generation for this power plant is based on a scale model that can produce 500 watts continuously for 24 hours per day.

3.0 THE MAIN MANAGEMENT SYSTEM

The main element in the management system which controls all the different parts of the power plant as well as the distribution of energy is a programmable logic controller connected to a notebook computer via an Ethernet port.

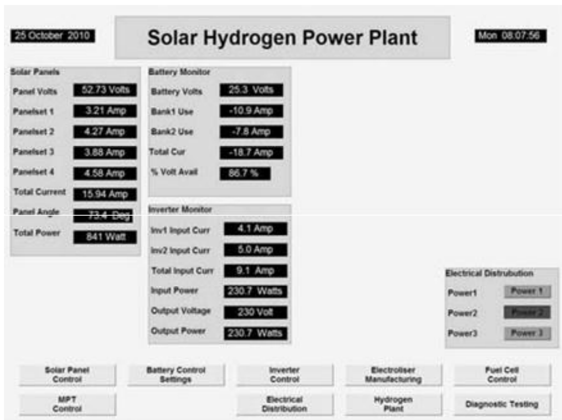


Figure 2: Main control panel

A Graphical User Interface (GUI) was developed to control and monitor the whole system from the notebook computer. This includes the rotation of the solar panels and monitoring up to the final electrical distribution stage. Various data sets can be logged for future processing and analysis. Figure 2 shows a GUI of the main control panel from which the power plant can be monitored. At the bottom of the screen there are buttons that link to various control screens of the power plant. The main control was setup so that the whole system could be monitored from a single screen. Readings from different sections of the power plant could thus be monitored in the monitor section.

4.0 SOLAR VOLTAIC PANELS AND CONTROL

Eight 220 W Solar-world panels are used to supply more than 1500 W (1760 W Maximum) to the MPPT. The eight panels used are connected two-two in series thus making up four panel pairs. Connecting all the panels in series could be a problem in that the supply voltage becomes too high. This panel setup results in an output voltage of 56 V (28 V per panel), depending on sunlight exposure. The panel pairs are connected through 20 A DC circuit breakers which makes it possible to isolate some or all the pairs.

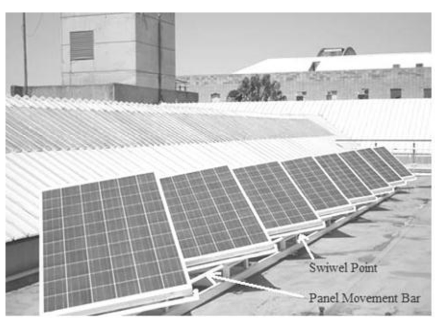
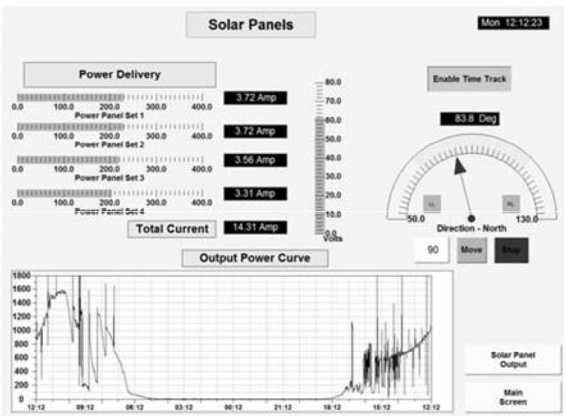


Figure 3: Solar panel mounting

The design of the solar panel mounting brackets were dictated by the position and space allocation available at the Vaal University of Technology, as can be seen in Figure 3 where each panel has its own frame.

The advantage of this system is that it is not prone to wind disturbances since it is mounted between a higher roof on the left of the photograph and a 500 mm wall not visible in the photograph on the right hand side. All the panels can be swung from left to right in order to follow the sun and are controlled by a movement bar (shown in the picture) and thus only one motor mounted on the first panel is used to swing all the panels at the same time using less than 1 Watt hour of energy for the whole cycle moving from east to west through north. The disadvantage of mounting the panels like this is that the panels may cast shadows on other panels leading to a drop in output current.



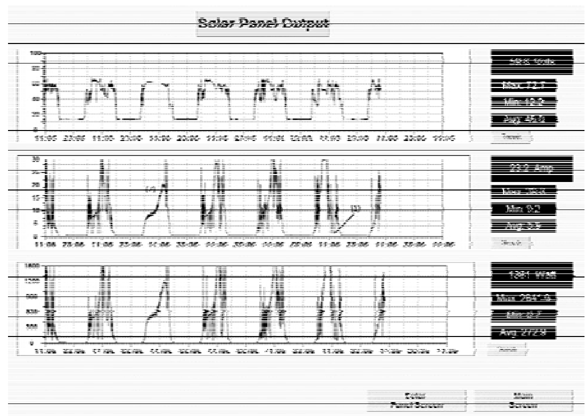


Figure 4: Solar panel control interface

Figure 5: Solar output and data logging

The angle at which the PV cells are mounted needs to be adjusted manually to compensate for winter and summer, since it will not be cost or energy effective to motorize each panel on its own. The motor used is a 12 V DC motor and a chain system with a gear ratio of 1:22 to increase the torque on the motor and to decrease the speed of movement. The solar panel control screen is shown in Figure 4.

In the solar panel interface the power delivery from the PV cells can be monitored and displayed in graphical format. The direction of the panels can be controlled manually or automatically according to a time algorithm for the automatic mode (right top side of Figure 4). A needle gauge is used to indicate the direction in which the panels are facing, with north as 90° and east as 0°. On this screen, there is a button linking to the solar output screen in Figure 5.

The solar output screen shows the voltage, current and power generated respectively over a seven day period. This data is logged to 3 different files every 60 seconds for later analysis. On the right-hand side the maximum, mean and minimum values are displayed with a reset button to do readings of minimum and maximum for a specific time. From the current graph and the power graph it can be seen that the most current is drawn in the morning while the batteries are charging and that it reduces as the battery banks are getting more charged. In the current graph point (1) the effect of shading on the PV cells can be seen. The current curve marked (2) above shows the difference in power when solar tracking is switched off and left in the position facing north. In the image above tracking was switched off for one day only and the power peak is not as high as the other power peaks. The MPPT to which the PV cells are connected also sometimes referred to as the charge controller is Flexmax 80 controller that can handle up to 2500 W and a maximum of 80 A. The MPPT seeks the maximum power available from the solar array.

5.0 BATTERY SYSTEM AND CONTROL

The current power plant has two banks of lead calcium batteries consisting of 6 batteries each, 12 in total. The batteries are 102 Ah deep cycle batteries capable of giving a total of 1224 Ah to the system. The batteries are connected two-two in series to produce a 24 V battery system with 3 sets in parallel in each bank. The reason for using a 24 V system is because of the fact that the higher the DC voltage the more effective and efficient the inverter becomes. Another reason for using a 24 V DC system was that the fuel cell used to produce 1 kW supplies 24 V on the output. Unfortunately batteries will always be part of the system since the fuel cell will also need power to start up.

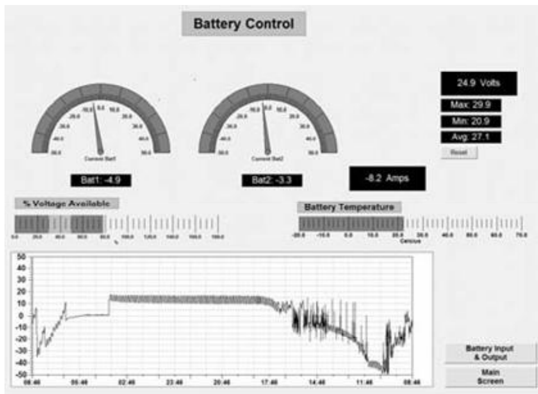


Figure 6: Battery output and data logging

The charging of the batteries is monitored with Hall Effect sensors which can measure the charging as well as the discharging currents. In this system, the charging of the batteries is indicated as a negative current since it using system current and as a positive value when it is supplying current to the system. Figure 6 shows the control GUI setup to monitor battery behaviour.

On the top left, there are 2 needle gauges indicating the charging currents of the two battery banks and just below that a graph displaying the total charging current over time. From the graph it can be seen that during the day when there is sunlight the batteries are charging while at night they help to supply to the demand. On the top right, the 24 V bus voltage is monitored. The battery temperature is also monitored on the right-hand side. It was found that a dead battery in the system can have a negative impact on the rest of the batteries used in that a lot less power was available at night and therefore the batteries should be load tested on a regular basis.

6.0 INVERTER CONTROL AND MONITORING

A 3000 W Cotek pure sinewave inverter is connected to the system to provide for the 230 V AC output. The inverter is connected to an electrical distribution board which supplies energy to the hydrogen generator and the load testing unit. The inverter control panel in the management system monitors the input current to the inverter and the power consumption to the inverter. The graph in Figure 7 shows the total current and the dashed line indicates 230 V output. The total battery power was depleted at about 03:50 in the morning and that the power was restored at about 06:30, when the solar cells recharged the system sufficiently to enable the inverter to power up again.

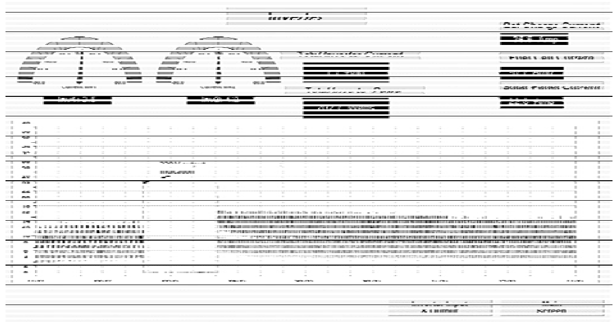


Figure 7: Inverter control

7.0 HYDROGEN GENERATION

The testing of this circuit was done on a Hogen GC 300 hydrogen generator using a fuel cell in reverse mode, which is using power to generate hydrogen. This generator can produce 300 ml of hydrogen per minute with only 0.3 ml of water consumption per minute. The power consumption needed for the generator to start up is 700 W during the heating phase, which then drops to 200 W for constant hydrogen production. If taken into consideration that South Africa has an abundance of sun available and on a sunny summers day the sun will shine from 05:30 until about 18:00 (October – March) giving more than 12 hours of sun light and in winter it will drop to about 10 hours per day. The number of hours of sunshine per day averages 8.7 hours.

The power needed to produce 300 ml of hydrogen per minute is approximately 200 W. It can therefore be concluded that on a 300 ml system we can produce about 156 litres of hydrogen per day at 1300 kPa pressure. The fuel cell produces energy based on the reduction reaction of hydrogen, which in turn reacts with oxygen from air to produce water vapor. The reaction set is as follows:

$$H_2 \rightarrow 2H^+ + 2e^- \tag{1}$$

$$\frac{1}{2}O_2 + 2e^- \rightarrow O^{-2} \tag{2}$$

$$2H^+ + O^{-2} \rightarrow H_2O \tag{3}$$

$$Net: H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{4}$$

Since oxygen from the air is supplied in excess to the fuel cell, the reaction of concern is the reduction of hydrogen, reaction (1). Using this reaction, the equivalent molar quantity and mass of hydrogen per hour-Amp can be determined by the following relation:

$$n_{H2} = \frac{1 C/\sec}{1\,Amp} * \frac{1\,equiv.\,e^-}{96487\,C} * \frac{1\,mol\,H_2}{2\,equiv\,e^-} * \frac{3600\sec}{hr} = 0.01866\,\frac{mol}{Amp*hr} \tag{5}$$

$$m_{H2} = \frac{0.01866\,mol}{hr*Amp} * \frac{2.02\,g\,H_2}{1\,mol\,H_2} * \frac{1\,kg}{1000\,g} = 3.76*10^{-5}\,\frac{kg\,H_2}{Amp*hr} \tag{6}$$

Where:

$n_{H2} \equiv$ *molar quantity per ampere hour*

$m_{H2} \equiv$ *molar mass per ampere hour*

The amount of hydrogen needed can be determined for a given power and voltage specification. For the fuel cell to provide 500 W of power with a total voltage of 24 V at 40% efficiency at full load, the current, *i*, and the amount of hydrogen required can be determined as follows:

$$i = \frac{P}{V} = \frac{500}{24} = 20.833\,Amp \quad (7)$$

$$M_{H2} = 20.833\,Amp * \frac{3.76*10^{-5}\,kg\,H_2}{hr*Amp} = 7.833*10^{-4}\,\frac{kg\,H_2}{hr} \quad (8)$$

$$\varepsilon = \frac{U_{Consumed}}{U_{Feed}} \rightarrow 0.40 = \frac{7.833*10^{-4}\,\frac{kg\,H_2}{hr}}{U_{Feed}} \rightarrow U_{Feed} = 0.00196\,\frac{kg\,H_2}{hr} \quad (9)$$

Where:

$M_{H2} \equiv$

Mass of hydrogen needed per hour for an ideal fuel cell.

$U_{Feed} \equiv$ *Mass of hydrogen needed for a fuel cell with 40% efficiency*

8.0 CONCLUSION

From the foregoing discussion, it can be concluded that the Solar/Battery/Hydrogen power-plant can be achieved, but at present is very costly. Batteries present a problem in that if one battery goes faulty it will have a detrimental effect on the rest of the batteries. Any shade on the solar panels can reduce the output of the cells with 90% (Figure 5) and should be avoided at all costs. It is also important to keep the cells clean to ensure that the output is not affected. The management system was tested and found to be measuring accurately all the input and output variables as seen from Figures 2, 4-7 (solar panel control, battery panel and inverter).

9.0 ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support they received from Telkom, Mtech, TFMC, Meds International and GM Graphix.

10.0 REFERENCES

El-Shatter, TH.F. Eskandar, M.N. El-Hagry, M.T. *Hybrid PV/fuel cell system design and Simulation*. Electronics Research Institute, Dokki, Giza, Egypt. 21/11/2000.

Kotze, IA. (1997). *Renewable energy activities in South Africa – PV and Rural electrification*. In: Proceedings of the Third OAU/STRC Inter-African Symposium on new, renewable and Solar Energies, 22-24 October 1997, Pretoria, South Africa, Department of Minerals and Energy, pp 10-16, Pretoria.

Kotze, IA. (2000). *The South African national electrification programme*: Past lessons and future prospects. In: Proceedings if the African utility Project: Seminar on Rural Electrification in Africa (SEREA), April 2000,

Lisa, K. *DME set to power-up non-grid image in SA*. Engineering News 06/08/1999. [Online]. Available at: <http://www.engineeringnews.co.za/topic/nongrid-electricity>. Accessed 12/02/2008.

WENTZEL, M. *Delivering electricity to South Africa's rural areas*. Energy division, Palmer development consulting. February 2004.