Low-cost renewable hydrogen production using solar photovoltaic panel

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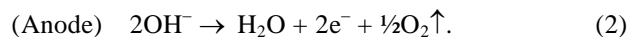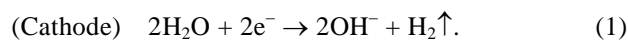
The present work focuses on the use of two coaxial polyvinylchloride (PVC) pipes for the fabrication of an electrolyser. Fine perforations in the lower part of the inner pipe were made for easy movement of ions via electrolytic material between the electrodes. The two electrodes (anodes and cathodes) were kept in the outer and inner pipes respectively. A photovoltaic panel was directly connected to the electrolyser to measure the performance of the electrolyser system at normal room temperature and pressure with 27 wt% potassium hydroxide solution. Water displacement burette flow meter was used for measurement of flow rates of the produced hydrogen and oxygen. The effects of various operating parameters on hydrogen production, variation in open circuit voltage and short circuit current produced by the photovoltaic cell with solar intensity in the daytime and their effect on H_2 flow rate, and utilization of this hydrogen gas in the hydrogen gas stove need to be studied further. The work concludes with an innovative design to prepare a simple and cheap alkaline electrolyser to produce hydrogen gas using solar energy from the photovoltaic panel that can be used in remote areas for cooking purposes.

Keywords: Electrolyser, hydrogen, renewable energy, solar photovoltaic panel.

PROBLEMS of energy crisis and pollutant emission cause serious social concerns, which challenge the traditional energy utilization patterns. There is a need to overcome the problem of non-renewable energy resources by increasing the use of renewable energy resources in order to facilitate development of the society. According to Demirbas[1], about 98% of CO_2 emissions results from fossil fuel combustion, and 30–40% of the world CO_2 emissions is generated by coal combustion among all fossil fuels.

The sun is the ultimate energy source on the earth system and hydrogen production from solar energy is considered to be one of the solutions for sustainable energy[2,3]. Hydrogen as an energy carrier is favoured worldwide due to its highest energy content with the lower heating value at 52,000 BTU lb^{-1} (33.6 kWh kg^{-1}) (ref. 4) and higher heating value of 142 MJ kg^{-1}

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(39.4 kWh kg^{-1}) (ref. 5) as compared to any other fuel. Water electrolysis represents the most important process to produce hydrogen without emitting air pollutants or greenhouse gases[6]. In the process of water electrolysis a direct current is applied to water, splitting it into hydrogen and oxygen through the reactions given below

$$\text{(Cathode)} \quad 2H_2O + 2e^- \rightarrow 2OH^- + H_2\uparrow. \tag{1}$$

$$\text{(Anode)} \quad 2OH^- \rightarrow H_2O + 2e^- + \tfrac{1}{2}O_2\uparrow. \tag{2}$$

$$\text{(Net reaction)} \quad 2H_2O \rightarrow H_2 + \tfrac{1}{2}O_2 + H_2O. \tag{3}$$

It only requires 1.23 V of energy for dissociation of one molecule of water to hydrogen and oxygen. Energy content of hydrogen ranges from 33 to 39 kWh kg^{-1}, whereas the reported energy content of gasoline is about 36 kWh per gallon. A small-scale electrolyser unit can produce about 2.5 kg of hydrogen in a day, whereas larger units have an output of about 25 kg (ref. 7). According to Suffredini et al.[8], zero emission has been reported by hydrogen which is produced by the renewable energy sources such as solar and wind energy after being used in fuel cells for electrical power generation.

A solar photovoltaic (SPV) panel generates electrical energy from the sunlight incident on it. A typical SPV panel generates output voltage up to 30 V direct current (DC). The conventional power control cannot work below 6 V and hence charging of the battery is restricted to the SPV panel output range 6–30 V. In the market, price of SPV panel is Rs 6000 (with battery). For the rural people it is available with government subsidy and can be purchased at Rs 3500 (ref. 9). According to Khan and Iqbal[10], solar–hydrogen system can be used with direct coupling as energy source to the electrolyser system, potentially around US$ 700 kW^{-1} for electronic voltage conversion.

The present study focuses on the fabrication of a cost-effective electrolyser system, its process optimization for hydrogen gas production using renewable solar energy and its utilization as an alternative energy source in remote areas for cooking purposes.

Solar SPV panels were used as renewable direct current source for electrolysis of water. Two SPV panels were obtained from NEDA (Non-Conventional Development Agency), Varanasi, India. Each panel provides maximum of 36 W DC power. Tilt angle of 30° horizontal and south direction are the essential factors required for mounting of the solar panel structure. An electrical DC power supply system was used for comparative studies with the SPV system. The solar radiation intensities from morning till evening were measured with the help of a lux meter (LX-105).

The methodology for fabrication of the electrolyser system was adapted from Prasad[11]. The electrolyser was fabricated in the laboratory using two coaxial PVC pipes,

because they are economical and easily available in the market. The nominal diameters of the outer and inner pipes were 6 and 3.4 cm, and their heights were 20 and 16 cm respectively. Fine perforation in the lower portion of the inner pipe was made boring through a needle of diameter <1 mm. The total number of holes was 739. Sieve electrodes of different materials were used in the experiment. The electrodes were placed in the inner (iron as a cathode) and outer pipes (stainless steel as an anode).

In the electrolyser system the electrodes were connected to the SPV panel through a voltmeter and ammeter using copper tubing. This is used to establish electrical connections between electrodes and also to provide a channel as outlet for hydrogen and oxygen gas separately. Rubber corks were used for leak-proof fitting of the copper tubing and coaxial pipes. Figure 1 shows a schematic diagram of the water electrolyser for PV hydrogen production.

The electrolyser is cost-effective (costing about Rs 60) and sustainably efficient.

Water electrolysis can be carried out using different electrolytes such as potassium hydroxide (KOH), sodium hydroxide (NaOH) and 1-methyl 3-butyl limidozolium tetrafloroborate (BMI.BF$_4$), an ionic liquid salt to study the hydrogen evolution reaction (HER). Electrolytes in the water make it electrically conductive, so that ions can be transported through them during electrolysis. In the present work, KOH solution of different concentrations was prepared in the laboratory and studied. Concentration of the electrolyte was optimized at 3.5 V constant voltage for maximum HER. It was found that 27% KOH by wt% gave the maximum HER. All the experiments were carried in 250 ml electrolyte solution. The flow rate of hydrogen production at the cathode in the inner pipe and oxygen at the anode in the outer pipe was measured using water displacement burette flow meter.

The efficiency of the electrolyser can be calculated as follows

$$\eta = \frac{MC_v}{VI},$$

where η is the efficiency of the electrolyser, M the hydrogen flow rate (g/s), C_v the calorific value of hydrogen (J/S), and V and I are load voltage and corresponding current respectively.

In the electrolyser system the electrolyte can be adjusted to any desired level by adjusting the vertical position of the feeding funnel connected with rubber tubing at the bottom of the electrolyser. A change in the level of electrolyte causes a change in the active surface area of electrodes, and hence the rate of hydrogen evolution reaction can be varied easily to the desired value by manipulation of electrolyte level in the unit. The SPV panel generates DC power that is transferred to the water electrolyser directly as well as through the controller. The

open circuit voltage and short circuit voltage of the SPV panel, and the load voltage and load current of the electrolyser were measured using a voltmeter and an ammeter with accuracies of 0.01 V and 0.001 A respectively. Two reactions take place on passing electric current through the electrolyser system. The negatively charged cathode reduces water to form hydrogen gas. Similarly, at the anode, an oxidation reaction takes place and oxygen is liberated. The rate of hydrogen production at the cathode in the inner pipe and oxygen at the anode in the outer pipe was measured. The liberated hydrogen gas was twice the volume of the produced oxygen gas.

The intensity of solar radiation was measured with the help of a lux meter. Hourly variation of the solar intensity is given in Figure S1 (see Supplementary Material online). The open circuit voltage and short circuit current developed by the SPV panel were measured by a digital voltmeter and ammeter respectively, with hourly variation (Figure 2). The output power of the SPV system remains variable throughout the sampling day and depends on solar intensity on a sample day in March 2011,
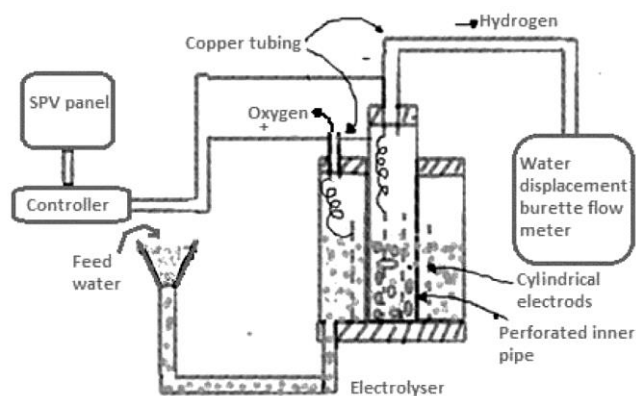

Figure 1. Schematic diagram of the electrolyser system for photovoltaic (PV) hydrogen production.
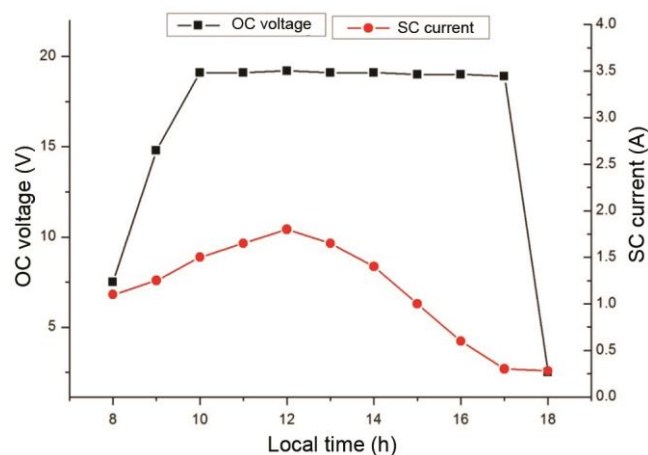

Figure 2. Open circuit (OC) voltage and short circuit (SC) current developed by the PV system on March 2011.

variation of power was recorded from morning till evening. The solar intensity was found to increase from 8.00 am maximum intensity was observed between 12.00 noon and 1.00 pm, and then it decreased gradually till 6.00 pm (Figure S1, see Supplementary Material online).

Electrolysis was carried out at room temperature. KOH electrolyte concentration was optimized to obtain maximum HER. Electrolysis was carried out using solutions of different concentrations ranging from 3% to 36% by weight and hydrogen flow rate was measured (Figure S2, see Supplementary Material online). At 27% KOH concentration, hydrogen flow rate was found to be maximum; thus the optimum concentration of KOH is 27% by weight.

The characteristics of different electrodes were studied using various types of plate and sieve electrodes. Sieves of two mesh sizes, 100 and 80, were used. A plot of current versus hydrogen flow is given in Figure S3 (see Supplementary Material online). It is clear from the plot that flow rate of hydrogen for 100 mesh iron sieve is higher than for 80 mesh iron sieve. This may be because the effective area of 100 mesh size is greater than the 80 mesh sieve. Also, at the same voltage the current drawn is 3.00 A for 100 mesh size and 2.76 A for 80 mesh size (Figure S4, see Supplementary Material online). Thus there is a direct relationship between mesh size and HER, resulting in more hydrogen production. For any sieve mesh size is positively related to HER and HER is positively related to hydrogen production. So if we increase mesh size (area) in the electrolysis, then HER also increases followed by an increase in the rate of hydrogen production.

Water electrolysis powered by solar electricity was carried out while operating at optimized parameters and using the best electrode combination. Data collected on a sample day during March 2011 at Department of Chemical Engineering, IIT (BHU) represents such variation of output open circuit voltage and short circuit current produced by the photovoltaic system (Figure 2). The open circuit voltage rises steeply from 14.2 to 19.2 V from 9.00 to 10.00 am and remains almost constant till 5:00 pm; then it drops suddenly. Similarly, the short circuit current increases in the morning showing a plateau of maximum current about 1.8 A between 11.00 am and 1.00 pm; then it decreases slowly to almost zero around 6.00 pm. Figure 3 shows the relationship between load current and voltage of the electrolyser during the electrolytic hydrogen production by direct connection of SPV panel to the electrolyser on the sample day. A significant decrease in load voltage is observed compared to open circuit voltage. Load current is also found to decrease. The corresponding flow rate of hydrogen production is given in Figure S5 (see Supplementary Material online). It is clear from Figure 3 (Figures S5 and S6, see Supplementary Material online) that hydrogen pro-

duction is significantly related to the electrolyser load current.

For direct coupling of electrolyser to the SPV module, without controller, the relation between solar radiation intensity the time period for a sample day is provided in Figure S7 (see Supplementary Material online). The corresponding electrolyser voltage and time (Figure S8, see Supplementary Material online) and the liberated hydrogen flow rate are also provided (Figure S9, see Supplementary Material online) for the same day. The hydrogen flow rate was found to be directly related to solar radiation intensity. An increase in the electrolyser current increases the hydrogen production flow rate linearly (Figure S10, see Supplementary Material online).

The main advantage of the controller is to adjust the PV current and voltage. Thus, it provides optimum value of voltage and current to the electrolyser for maximum hydrogen production. The relation between solar intensity and time measured in the case of coupling with the controller for a sample day, and the corresponding open circuit voltage and time during the experiments are given in Figures S11 and S12 (see Supplementary Material online) respectively. The hydrogen flow rate in this case is also provided (Figure S13, see Supplementary Material online). It is clear that the system operates with the controller of the SPV panel. The controller increases the system current and accordingly increases the hydrogen flow rate. An increase in the electrolyser current increases the hydrogen production flow rate (Figure S14, see Supplementary Material online).

For comparison, the hydrogen flow rate in case of direct coupling and coupling with the controller in relation to the variation of electrolyser current is shown in Figure S15 (see Supplementary Material online). It is clear that optimization is required for the controller to improve the system performance, which ultimately increases the system current and is responsible for higher
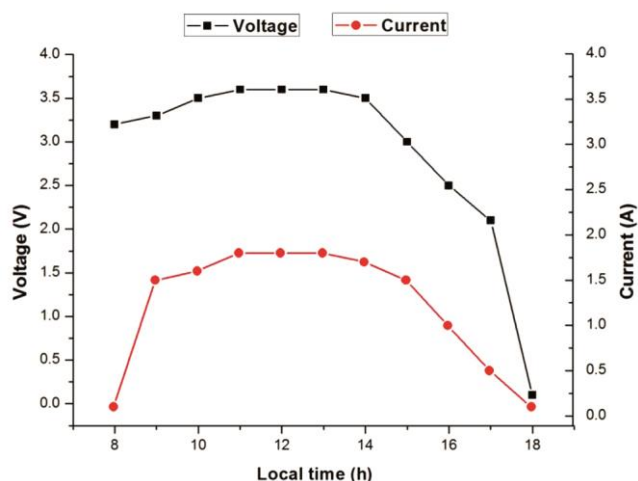

Figure 3. Load voltage and current during electrolysis.

hydrogen production for the same radiation. The average efficiency of the electrolyser was found to be 48% in the first case (direct coupling), and 62% in the second case (coupling with controller) at different load voltages and corresponding currents. The efficiencies of the present electrolyser are comparable to the previously reported values in the literature.

Cell resistance is the ratio of the product of resistivity and distance between the electrodes to area of the electrodes. It is given by the formula

$$R = L/kA.$$

Resistance of the cell increases with an increase in the space between the electrodes; it also increases when the electrodes are placed close to each other. Figure 4 shows that cell current and corresponding hydrogen flow rate increase with distance.
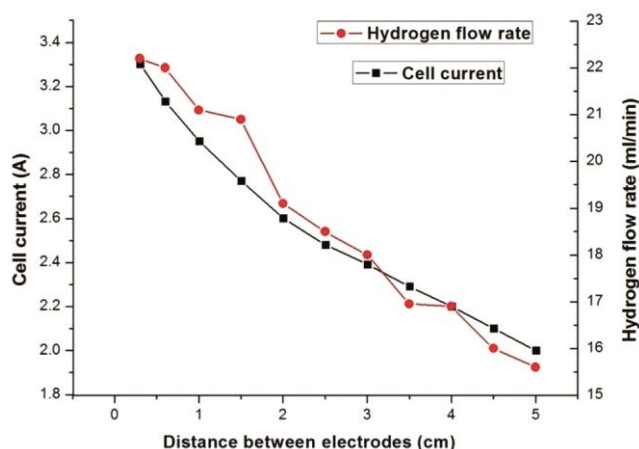

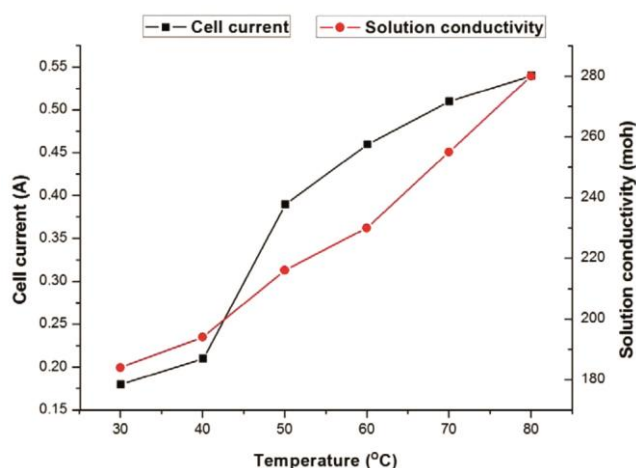**Figure 4.** Variations in hydrogen flow rate and cell current with distance between electrodes.

Figure 5. Increase in cell current and conductivity of the electrolyte with temperature.

On increasing the temperature of the electrolytic solution, ionic conductivity and activation energy of the heterogeneous water for electrolysis also increase[12,13]. Effect of temperature on hydrogen evolution reaction was studied. There was considerable change in energy consumption in water electrolysis and the rate of hydrogen evolution also increased. It is clear from Figure 5 that with an increase in the temperature of the electrolyte, there is a considerable rise in the cell current and correspondingly hydrogen flow rate also increases. This is because, at higher temperature ionic movement increases the conductivity of the electrolyte, consequently increasing hydrogen evolution reaction.

Water electrolysis is one of the easiest methods for hydrogen production, offering the advantage of simplicity. The challenges in the water electrolysis are to reduce energy consumption, cost maintenance and to increase reliability, durability and safety. In this electrochemical reaction process, various barriers are present in the production of direct current. These include electrical resistance of the circuit, activation energy of electrochemical reaction occurring on the surface of the electrode and ionic transfer within the electrolyte solution.

The electrolyser was scaled up to increase hydrogen production, and hydrogen flow rate was measured. The electrode area was increased four times than the previously used in small and electrolyte volume used was 1000 ml, i.e. all parameters wee increased four times.

Unlike, LPG and natural gas stoves where premixed air-fuel mixture is used, no such premixed device is made in the hydrogen stove to avoid explosion. Pure hydrogen is delivered to the burner ports without pre-mixing of air. In this type of stove, the burner is located at the topmost position and there is no opening between the gas knob and burner (primary and secondary openings are absent). This stove has two burners and integral parts made up of cast iron without using galvanized pipe as fumes are realized at high temperature. Pure hydrogen is delivered to the burner ports without primary or secondary air mixing.

The primary end-product of hydrogen combustion is water vapour. If temperature of combustion exceeds the threshold level of about 1315°C, then oxygen and nitrogen present in the air produce unwanted by-products like NO_x which are dangerous to humans and the environment. So, use of a catalyst lowers the temperature of combustion to prevent the formation of NO_x. According to Booth and Pyle[14], the burner is surrounded by the stainless steel wool to prevent mixing of air and hydrogen gas at the burning end. Stainless steel wire mesh can also be used to prevent air mixing. Important functions of the stainless steel wool blanket are:

- It inhibits the mixing of air and hydrogen; but the wire mesh should be thick enough so that the flame remains within the wire mesh.

- Stainless steel also works as an excellent catalyst for hydrogen combustion. If there is not sufficient amount of stainless steel mesh, the catalytic capability and ability to prevent NO_x production could be lost.

A laboratory experiment was conducted to demonstrate hydrogen combustion and measurement of flame temperature (Figure S16, see Supplementary Material online). In this experiment, hydrogen was passed through a Bunsen burner which was open at the top and the closed at the bottom. The flame temperature was measured with the help of a thermocouple and digital temperature indicator, which showed 1315°C. At such high temperature, NO_x is formed as reported in earlier studies[15–17]. Hydrogen and oxygen in the presence of a suitable catalyst may be combined at temperatures significantly lower than flame combustion. This principle was used to design catalytic burners for flameless combustion of hydrogen. To lower the temperature, stainless steel sieve was tied around the burner, which works as a catalyst during flameless combustion of hydrogen and consequently reduces the temperature from 1315°C to 500°C. A mixture is formed in the reaction zone after combustion of hydrogen in the presence of stainless steel catalyst to burn at low temperatures (Figure S17, see Supplementary Material online). The only product of catalytic combustion of hydrogen is water vapour. Due to low temperature of 500°C, no nitrogen oxides are formed.

Thus, hydrogen production from solar energy is considered as a vital example of sustainable energy. There is increasing consensus that hydrogen will replace fossil fuels as the future energy carrier. The production of hydrogen is sustainable and environmentally friendly, because it produces only water and energy at the time of production as well as consumption. Keeping these properties in mind, in the present study a cheap electrolyser has been designed which includes special features like optimum electrolyte concentration at 27% for maximum HER production, maximum and solar intensity recorded between 12.00 noon and 1.00 pm. Moreover, production of hydrogen gas depends upon variables like solar intensity, voltage, current density and mesh size which can affect the rate of production of hydrogen gas. The maximum hydrogen flow rate was observed with 100 mesh iron sieve in the presence of controller with SPV panel from 11.00 am to 1.00 pm. This hydrogen produced can be utilized in remote areas for cooking purposes using hydrogen stove equipped with different types of Booth burners.

The significant advantages of this technology in remote areas are: (1) The designing of the electrolyser is cheap (costing about Rs 60). (2) Hydrogen releases no pollutant at both the ends – production as well as consumption.

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