



Hydrogen Production through a Solar Powered Electrolysis System

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Authors' contributions

This work was carried out in collaboration between both authors. Author DAU designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors DAU and CD managed the analyses of the study. Author DAU managed the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

Production of hydrogen from renewable energy sources is gaining recognition as one of the best energy solutions without ecological drawbacks. The present study reports hydrogen production through a solar powered electrolysis system as a means to curtail greenhouse gas emissions in the United Kingdom. The solar powered electrolysis unit is modeled to provide 58400 kg of hydrogen to run the fuel cell bus fleet in Lea interchange garage in London on a yearly basis. Experiments were conducted to determine the efficiency of the photovoltaic module and the proton exchange membrane electrolyzer. An energy balance of the electrolysis unit was calculated to give 47.82 kWh/kg and used to model a 2.98 MW photovoltaic system required to run the electrolysis process.

Keywords: Solar powered electrolysis; proton exchange membrane; hydrogen.

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1. INTRODUCTION

Climate change is a serious problem that has become more evident as population increases. Due to the manmade industrialization which has led to the emissions of harmful gases, this has led to the depletion of the ozone layer. In order to tackle the effect of greenhouse gases, the Paris 2015 agreement was established which involved 195 countries including the United Kingdom [1].

In the United Kingdom it's been discovered that 21% of its total greenhouse emissions are from transport systems. Due to this reason the mayor of London has committed London to reducing CO₂ emissions within the transport system by 2025 in the climate change mitigation and energy strategy. In order to curtail air pollution from transport systems in London development and uptake of low emission vehicles and technologies have been considered one of the measures to attain this effect. One of the technologies that have been adopted by the London transport system is the hydrogen fuel cell buses [2]. These fuel cell buses operate using compressed hydrogen gas as fuel.

Currently hydrogen is being produced in the United Kingdom via steam methane reforming of natural gas. Although the hydrogen fuel does not emit greenhouse gas emissions when used the process of producing the hydrogen emits 11,888g of CO₂ per kg of hydrogen gas produced and 58400 kg of hydrogen is required to run the bus fleet on a yearly basis. Hence a total of 6942592 kg of greenhouse gases will be emitted into the environment on a yearly basis. If production of hydrogen is continued with this method, in the next 10 years 0.06MtCO₂e of greenhouse gas will be emitted to the atmosphere. Currently the total greenhouse gas emission in the UK is 466MtCO₂e and 119.8MtCO₂e of greenhouse gases is generated from the transport sector. Using these figures in the next 10 years 0.05% of greenhouse gases in the UK transport sector would have been generated from steam methane reforming of natural gas for the fuel cell bus fleet comprising of only 8 buses. These emissions will also increase the UK total emissions by 0.013% in the next 10 years. In order to avoid such increase in United kingdom greenhouse gas emissions, the carbon dioxide being produced during the process have to be captured and stored or a new method of hydrogen production be adopted for the fuel cell buses [3].

Production of hydrogen at very large scale normally requires the use of carbonaceous fuel such as natural gas or coal which emits greenhouse gases to the atmosphere hereby polluting the air and the environment [4]. There are currently 8 fuel cell buses in London and they operate within the RV1 route which ranges from convent garden to tower gateway station. The fuel cell bus garage is the Lea Interchange garage, Leyton. The fuel cell power range is 75 kW and operates 10-16 hours/day. Hydrogen is stored in tanks on top of the buses with a total capacity of 32 kg. The produced energy from the fuel cells are stored in super capacitors before being utilized by the battery system within the bus. The hydrogen gas used by these buses is generated from steam methane reforming of natural gas and transported to the bus stations via trucks. In this research, a solar electrolysis method of hydrogen production was analyzed to deliver the amount of hydrogen needed to run the RV1 fuel cell buses at Lea interchange bus garage.

2. MATERIALS AND METHODS

2.1 Experimental Setup

Analysis was carried out using junior basic hydrogen energy system in order to determine the efficiency of solar panel and proton exchange membrane (PEM) electrolyzers. The junior basic hydrogen energy system consist of a solar panel, PEM electrolyzer, 2 compensation tanks, oxygen and hydrogen tank, a decade resistor, 2 multimeters, a stopwatch, a set of connecting cables and a fuel cell. For this experiment the fuel cell was not taken into consideration. Fig. 1 illustrates the configuration of the hydrogen generation system.

2.2 Efficiency of Solar Panel

The efficiency of solar panel was conducted using natural sunlight with an irradiation of 511 W/m² which was measured using a pyranometer. The solar panel was connected to the decade resistor and at varying values of resistance the current and voltage produced from the solar panel were measured using the 2 multimeters. The solar panel has an area of 90 cm² and an open circuit voltage of 2 V and short circuit current of 0.35 A.

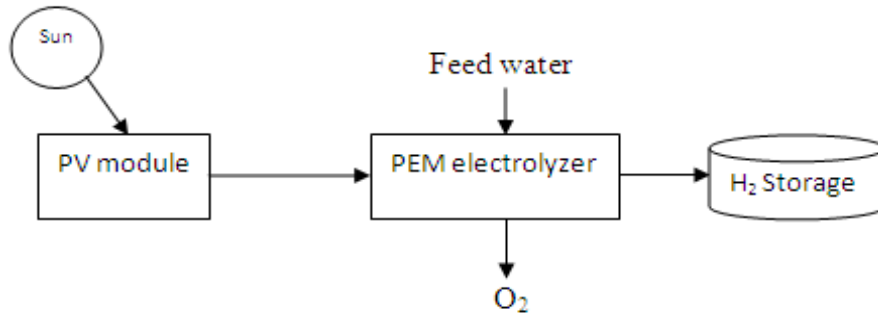


Fig. 1. Schematic of PV-hydrogen generation

2.3 Efficiency of the Electrolyzers

The electrolysis experiment was conducted using an artificial source of light which consisted of 8 bulbs that each had a power rating of 1 kW. The solar panel was connected to the PEM electrolyzer in a series connection. At different time slots the volume of hydrogen produced by the electrolyzer was recorded till the compensation tanks were filled. For the electrolysis experiment distilled water with conductivity of 2 $\mu\text{S}/\text{cm}$ was used to avoid damaging the membrane electrode assembly of the electrolyzer. This experiment was conducted with the distilled water at different temperatures to test the efficiency of electrolysis at varying temperatures.

2.4 Characteristic of the Electrolyzer

In order to determine the IV characteristic of the electrolyzer using the junior basic solar hydrogen system, the system had to operate with a certain amount of resistance in order to increase the voltage of the system. When the voltage of the electrolyzer had increased to 1.65 V it was allowed to run for a minute at that voltage. The resistance was then disconnected and the electrolyzer was short circuit for about a minute. The system was then allowed to run normally with increasing current and voltage, this process was repeated using the resistor to adjust the voltage of the system.

Table 1. Technical features of selected photovoltaic generator

Maximum power output of selected module	170 W
Type of photovoltaic module	Monocrystalline silicon
Maximum power voltage	57.3 V
Maximum power current	5.8 A
Open circuit voltage (Voc)	67.9 V
Short circuit current (Isc)	6.2 A
Total modules per string	6
Total strings in parallel	1397
Total power of Photovoltaic generator	2980 kW
String Voc	408.4 V
String maximum power voltage	343.8 V
Total module area	14502.9 m ²

Table 2. Technical specifications of selected battery

Battery type	lithium ion batteries
Nominal bank capacity	136629 kWh
Cell nominal voltage	3.6 V
Cells in series	96 cells
Depth of discharge	80%
Battery volume	272.6 m ³
Specific energy volume	501.25 Wh/L
Strings in parallel	175707

2.5 Modeling Solar Electrolysis System

Simulation was carried out using the system advisor model (SAM) software package created by National renewable energy laboratories (NREL) in order to determine the amount of solar modules required for the electrolysis process in order to produce 160 kg/day. The modeled system consists of a photovoltaic system, batteries and electrical grid. Using the SAM software a 2.98 MW monocrystalline photovoltaic module was modeled to provide enough electricity to run the system for a year. Table 1 shows the PV modules while Table 2 shows the battery system chosen for this project in SAM.

The battery pack was selected to provide electricity to the electrolysis system during the night time when there is no solar radiation to power the photovoltaic generators. The battery bank capacity was determined using the formula as given in [5]:

$$Ah = \left(\frac{Ah}{day}\right) \left(\frac{days}{D_T D_{ch}(disch)}\right)$$

Where Ah is the battery pack capacity, Ah/day is the corrected load on batteries, days is the number of days of autonomy, DT is the temperature derating factor, Dch is the charge/discharge derating factor and disch is the depth of discharge of battery cells. Days of autonomy represent the number of days the battery can provide electricity to the electrolysis system without being recharge by the solar panels. The days of autonomy depends on the average insolation received at the location. Since the electrolysis system will be operating on a 24 hour basis it is being considered as a critical load. The following formula is used to determine the days of autonomy of the battery pack.

$$D_{crit} = -1.9T_{min} + 18.3$$

Where Dcrit is the days of autonomy and Tmin is the minimum peak sun hours available at the location. The minimum peak sun hours estimated at Lea garage location is 3 hours.

$$D_{crit} = -1.9(3) + 18.3 = 12.6 \text{ days}$$

$$\frac{Ah}{day} = \frac{\frac{kwh}{day}}{voltage} = \frac{7651.2 \text{ kWh}}{343.8 \text{ V}} = 22.25 \text{ Ah/day}$$

Due to voltage drop in wiring and battery efficiency that were estimated to be 2% and 10% losses respectively.

$$\frac{Ah}{day} = \frac{22.25 \text{ Ah/day}}{0.98 \times 0.9} = 25.2 \text{ Ah/day}$$

In order to determine the battery pack capacity, 80% was assumed as the depth of discharge (disch) and unity values were assumed for the temperature derating factor (DT) and the charge/discharge derating factor (Dch).

$$Ah = \frac{25.2 \frac{Ah}{day} \times 12.6 \text{ days}}{1 \times 1 \times 0.8} = 397.4Ah$$

$$= 397.4Ah \times 343.8V = 136628.5 \text{ kWh}$$

Fig. 2 shows the energy generation from the photovoltaic panels, batteries and electric grid. The light blue line represents electricity from the grid. During the winter months more electricity is being generated by the electric grid to power the electrolysis system and during the summer months from the middle of March to September more power is being supplied to the electric grid. The grey line represents the power generated from the batteries to the electrolysis system; electricity provided by the battery is fairly constant throughout the year. The dark blue line represents the electricity generated from the photovoltaic panels to the electrolysis system. In the months of January and December most of the electricity generated is being used to charge the battery pack and the electricity used to power the electrolysis system is gotten from the grid. As seen in the diagram above most of the electricity supplied to the electrolysis system throughout the year is being supplied by the photovoltaic panels. The months of May and July are the peak periods of energy production as they have the highest amount of electricity being sold to the grid.

Fig. 3 shows the energy required in kWh by the system and the energy delivered to the system in one year.

The kWh/kg of hydrogen produced is given as:

$$45.8 \text{ kWh} \times 160 \text{ kg} \times 365 \text{ days} = 2792688 \text{ kWh/yr}$$

During the one-year operation there will be a two-week maintenance period; hence the system was modeled to have hydrogen stored during that time to keep the bus fleet in operation.

As seen in Fig. 2, the excess electricity production during the summer month is used to compensate for the low electricity production

during the winter months. In Fig. 2, the amount of hydrogen required for two weeks is 2462 kg.

$$2462 \text{ kg} \times 45.8 \text{ kWh} = 117757 \text{ kWh/yr}$$

$$\text{Total electricity required annually} = 117757 \text{ kWh/yr} + 2792688 \text{ kWh/yr} = 2910445 \text{ kWh/yr}$$

The PV module to produce this amount of power will require 14502.9 m², which is equivalent to 11.6 acres of land.

As shown Fig. 2, more electricity is produced in April, May, June, July and August which are the summer months and in September, October, November, December, January, February and March there is less production because they are the winter months. The system is able to

supply the total electrical load required per year and still sell 117757 kWh of electricity to the electrical grid. The electrical grid was added to the generation system because of the winter period that have days with just 2 to 3 hours of sunshine, during those times enough electricity cannot be generated to produce enough hydrogen to fuel the fuel cell buses.

2.5.1 Sizing the storage medium

Table 3 shows that the electrolysis system is able 60862 kg of hydrogen gas on a yearly basis and only 58400 kg of hydrogen is required. The remaining 2462 kg of hydrogen stored will be used to fill the fuel cell buses during the maintenance period of the hydrogen plant.

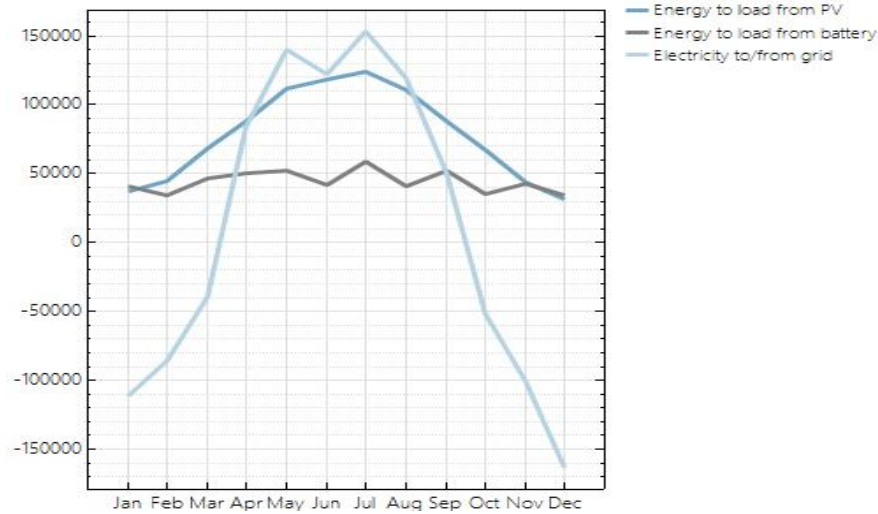


Fig. 2. Electricity production from battery, PV and grid

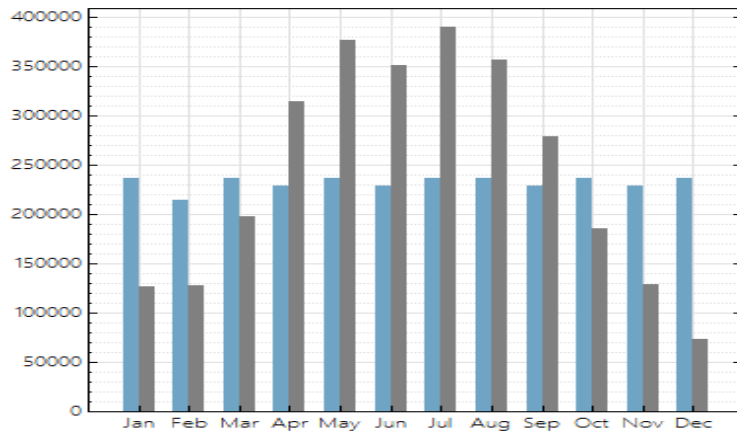


Fig. 3. Energy demand of electrolysis unit (blue line) and energy supplied by PV system (grey line)

Table 3. Monthly hydrogen production

Months	Hydrogen fuel demand (kg)	Hydrogen fuel supplied (kg)
January	4960	2642.5
February	4480	2680.8
March	4960	4142
April	4800	6573.3
May	4960	7885.3
June	4800	7353.7
July	4960	8161.8
August	4960	7462.4
September	4800	5846
October	4960	3880.3
November	4800	2691.7
December	4960	1542.7
Total	58400	60862

Table 4. Technical specifications of high pressure gas cylinder [6]

Tensile strength	2000 MPa
Volumetric density	36 kg/m ³
Total volume of cylinder	320 m ³
Cylinder material	Aluminum
Gravimetric density	13 mass%
Storage temperature	Room temperature at 25 °C

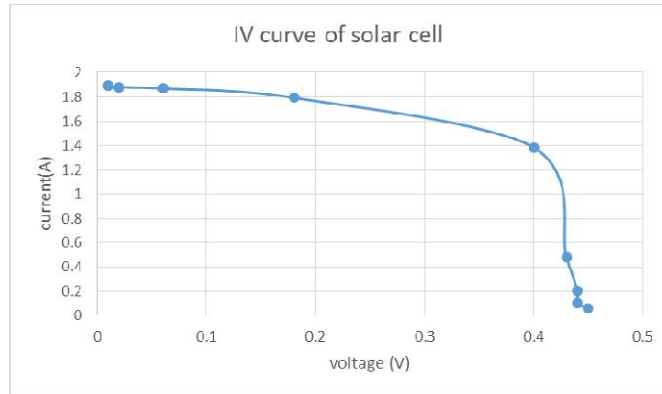


Fig. 4. IV characteristic curve of solar cell

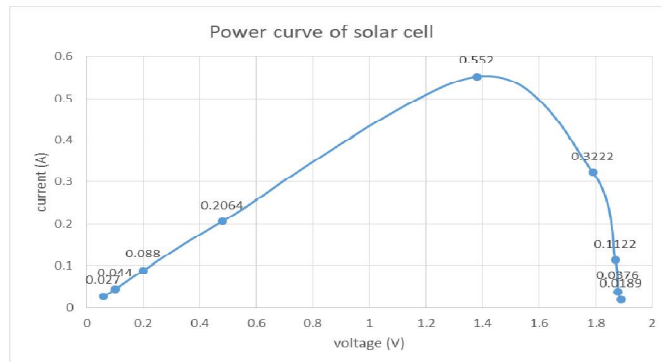


Fig. 5. Power curve of solar cell

As seen in Fig. 2 during the winter months ranging from October to March the electrolysis system is not able to produce enough hydrogen to meet the monthly demand of the fuel cell buses. During those months a total of 11,540 kg of hydrogen gas is needed to meet their monthly demands, for this reason a storage means is required so that excess hydrogen from the summer period can be stored and used during the winter period. During the summer months ranging from April to September the system is able to produce more than required for the fuel cell buses in those months. An excess of 1402.5 kg of hydrogen is produced in these months and this amount is able to offset the amount of hydrogen required during the winter months and still have 2462.5 kg of hydrogen extra. This 2462.5 kg of extra hydrogen gas will be used during the two week shutdown that will occur during the course of the year for annual maintenance of the electrolysis system. The storage medium considered for this project is a high pressure light weight composite gas cylinder with a total volume of 320 m³. Given below are the specifications for the high pressure gas cylinder:

3. RESULTS

3.1 Efficiency of Solar Panels

The IV characteristic curve of the solar cell and the power curve of solar cell are shown in Fig. 4 & 5. The efficiency of the solar cell and the fill factor were calculated using the equation as given in [7] to be 12% and 0.78 respectively.

$$\begin{aligned} \text{Efficiency of solar cell} &= \frac{I_{max} \times V_{max}}{\text{Irradiance} \times \text{Area}} \\ &= \frac{0.40A \times 1.38V}{511W/m^2 \times 0.089m^2} \times 100 = 12\% \end{aligned}$$

$$\begin{aligned} \text{fill factor} &= \frac{I_{max} \times V_{max}}{I_{sc} \times V_{oc}} \\ \frac{0.552}{0.35A \times 2V} &= \frac{0.552}{0.7} = 0.78 \end{aligned}$$

3.2 Efficiency of Electrolyzer

Table 5 and 6 show volume of hydrogen produced per unit time at 23°C and 53°C respectively. Faradays law of electrolysis states that the chemical deposition due to flow of current through an electrolyte is directly proportional to the quantity of electricity passing through it. Using this law the efficiency of the electrolyzer can be determined by measuring the efficiency of current flowing across the cell. In order to determine the faraday efficiency of the PEM electrolyzer in the junior basic hydrogen system the formulas as given in [8] were used as shown in tables (Tables 5 and 6).

Faradays efficiency

$$\eta_{faraday} = \frac{V_{H_2 \text{ experimental}}}{V_{H_2 \text{ theoretical}}} = \frac{V_{H_2 \text{ experimental}}}{\frac{RITt}{FPZ}}$$

Where, R = Universal gas constant = 8.314 J/(mole k); T = Ambient temperature in kelvin; I = Current in ampere; t= time in seconds; P = Ambient pressure=1.013x10⁵ N/m²; F = faradays constant = 96485 C/mole; Z = number of excess electron = 2; V = volume of gas produced.

At 23°C, the theoretical volume of gas produced and the faraday efficiency is as follows:

$$\begin{aligned} V_{H_2 \text{ theoretical}} &= \frac{8.314 \times 298 \times 0.17 \times 807}{1.013 \times 10^5 \times 96485 \times 2} = 17.4 \text{ cm}^3 \\ \eta_{faraday} &= \frac{16 \text{ cm}^3}{17.4 \text{ cm}^3} = 0.91 = 91\% \end{aligned}$$

Table 5. Volume of hydrogen produced per unit time at 23°C

Time (minutes)	Volume of hydrogen (cm ³)	Volume of oxygen (cm ³)	Current (A)	Voltage (V)
4.11	5.0	2.5	0.17	1.73
6.35	7.0	3.5	0.17	1.73
8.45	9.0	4.5	0.17	1.73
9.25	10.0	5.0	0.17	1.73
11.17	13.0	6.5	0.17	1.73
12.31	15.0	7.5	0.17	1.73
13.45	16.0	8.0	0.17	1.73

Table 6. Volume of hydrogen produced per unit time at 53°C

Time (minutes)	Volume of hydrogen (cm ³)	Volume of oxygen (cm ³)	Current (A)	Voltage (V)
1.25	1.0	0.5	0.17	1.73
2.79	3.0	1.5	0.17	1.73
3.46	4.0	2.0	0.17	1.73
4.20	5.0	2.5	0.17	1.73
5.20	6.0	3.0	0.17	1.73
6.35	8.0	4.0	0.17	1.73
7.39	9.0	4.5	0.17	1.73
8.40	10.0	5.0	0.17	1.73
11.30	14	7.0	0.17	1.73
12.02	15.0	7.5	0.17	1.73
12.46	16.0	8.0	0.17	1.73
13.58	17.0	8.5	0.17	1.73
16.14	20.0	10.0	0.17	1.73

Table 7. PEM electrolyzer characteristics

Current (A)	Voltage (V)	Power (W)
0.00	0.93	0.00
0.03	1.30	0.039
0.037	1.3	0.0481
0.048	1.35	0.0648
0.1	1.5	0.15
0.14	1.6	0.224
0.18	1.7	0.306

At 53°C the theoretical volume of gas produced and the faraday efficiency is as follows

$$V_{H_2} = \frac{8.314 \times 298 \times 0.17 \times 968.4}{1.013 \times 10^5 \times 96485 \times 2} = 21 \text{ cm}^3$$

$$\eta_{faraday} = \frac{20}{21} = 0.95 = 95\%$$

The energy efficiency is determined from the ratio of heat energy stored in produced hydrogen and the electric energy used in producing it.

$$\eta_{energy} = \frac{\text{usable energy}}{\text{energy expended}} = \frac{V_{H_2} \times H_0}{\text{voltage} \times \text{current} \times \text{time}}$$

Where H_0 = calorific value of hydrogen = 12.745 x 10⁶ J/m³

At 23°c

$$\frac{16 \times 10^{-6} \times 12745 \times 10^3}{1.73 \times 0.17 \times 807} = 0.85 = 85\%$$

At 53°c

$$\frac{20 \times 10^{-6} \times 12745 \times 10^3}{1.73 \times 0.17 \times 968.4} = 0.89 = 89\%$$

3.3 IV Characteristic of Electrolyzer

The IV characteristics of the electrolyzer are shown in Table 7, while Fig. 6 shows the IV curve. It can be seen that the current varies from 0.00-0.18 A; voltage 0.93-1.7 V and power 0.00-0.306.

3.4 Energy Balance

3.4.1 Sizing the PEM electrolyzer

To estimate the power range of the electrolyzer to produce 160 kg of hydrogen per day, the formula as given in [9] was used:

$$\frac{\text{hydrogen required per day} \times \frac{\text{kwh}}{\text{kg}} \text{ of } H_2}{\text{hours per day} \times \text{efficiency of electrolyser}} = \text{kW of electrolyser}$$

Using the efficiency of electrolysis (85%) that was derived from the above experiment and the higher heating value of electrolysis, the amount of energy required for electrolysis was calculated. Since in this project liquid water is electrolyzed not steam, the energy required to

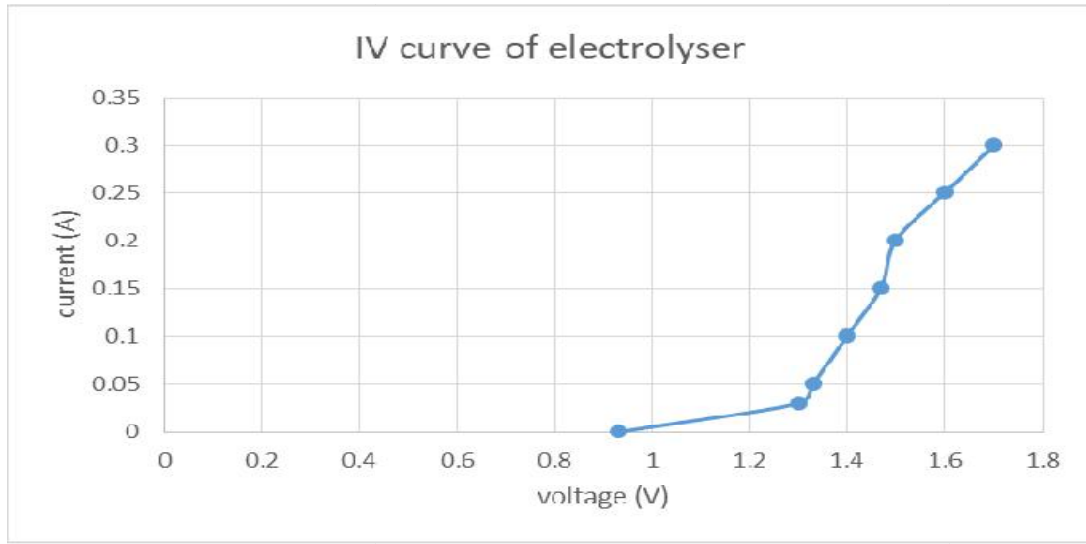


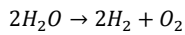
Fig. 6. Current voltage characteristics of PEM electrolyzer

produce hydrogen from water is the higher heating value of hydrogen which is 39 kWh/kg [10].

$$\frac{kWh}{kg} = \frac{39kwh/kg}{0.85} = 45.8 kWh/kg$$

$$\frac{160kg \times 45.8kwh/kg}{24hrs \times 0.85} = 359.2 kW$$

To produce hydrogen via electrolysis water is needed for the reaction to occur as seen in the equation below:



As seen in the equation above, 2 moles of water is required to produce 2 moles of hydrogen, hence 1 mole of water produces 1 mole of hydrogen gas [11]. The molar mass of water is 9 times higher than the molar mass and the mass of a molecule is a function of the mole and molar mass. Thus 9kg of water will produce 1 kg of hydrogen gas as seen in the equation below:

$$\text{molar mass of } H_2 = 2 \times 1g = 2 g$$

$$\text{molar mass of } H_2O = (2 \times 1g) + 16g = 18 g$$

$$\text{ratio of water to hydrogen gas} = \frac{18g}{2g} = 9$$

$$\begin{aligned} \text{daily water feed to produce } 160kg \text{ of } H_2 \text{ per day} \\ = 9 \times 160kg = 1440 kg \text{ of } H_2O \end{aligned}$$

3.4.2 Sizing the heat of compression dryer

Using the equation given in [12] the energy demand required for drying hydrogen gas was derived:

$$\text{specific humidity } (w) = \frac{\text{mass of water vapor in a given volume}}{\text{mass of gas in a given volume}}$$

$$w = \frac{2.18kg}{1kg} = 2.18$$

$$\text{absolute humidity } (x) = 0.622 \times \frac{P_{vap}}{P - P_{vap}}$$

Where P_{vap} = vapor pressure and P =atmospheric pressure (760 mmHg).

The moist hydrogen gas obtained from electrolysis is considered to be fully saturated (relative humidity=100). Vapor pressure was gotten using the pyranometric chart at a temperature of 25°C and relative humidity of 100.

$$x = 0.622 \times \frac{24mmHg}{760mmHg} = 0.02$$

The enthalpy of moist hydrogen gas was used as the energy demand for drying hydrogen gas using the following formula given in [13]:

$$H = (1.01 + 1.97(x))t + 2493(x)$$

$$H = (1.01 + 1.97(0.02))25 + 2493(0.02) = 76 \frac{KJ}{Kg} = 0.02 \frac{kwh}{kg}$$

The energy used in drying 1kg of hydrogen gas is 0.02 kWh.

$$K = \frac{C_p}{C_v} = \frac{14.32}{10.16} = 1.4$$

3.4.3 Sizing the diaphragm compressor

The compressor proposed for this project is a two stage diaphragm compressor. One stage delivers pressurized hydrogen at a temperature for regenerating the silica gel adsorbent while the second stage delivers hydrogen gas at a very high pressure to be used by the fuel cell buses. The temperature for regenerating silica gel is 150 °C.

Where C_p is specific heat at constant pressure and C_v is specific heat at constant volume.

To determine what pressure gives 150 °C temperature required to regenerate the silica gel in the dryer the following formula was used as given in [14]:

$$\frac{T_2}{T_1} = r_p^{\frac{k-1}{k}}$$

In order to determine the pressure that delivers the regeneration temperature the following calculations were used:

Where T_1 is inlet temperature, T_2 is outlet temperature, r_p is ratio of discharge pressure to inlet pressure and K is specific heat ratio. To substitute the formula to get r_p we have

1 kg of hydrogen gas = 423.3 scf, inlet pressure = 30 bar = 435 psi.

$$r_p^{k-1/k} = \frac{T_2}{T_1}$$

$$\frac{k-1}{k} = \frac{1.4-1}{1.4} = 0.286$$

$$160 \frac{kg}{day} = 423.3scf \times 160 = 67728 \frac{scf}{day}$$

The daily flow rate was converted to minute flow rate

$$Q_{line} = \frac{67728scf/day}{24hours \times 60minutes} = 47.03 scfm$$

The mechanical equipment standard used by the gas transmission industry which is at 60°F and 14.7 psia were used. Thus, standard conditions for compression are below:

T_1 is atmospheric temperature = 25°C = 77°F. Due to heat gain during production process of hydrogen an estimate of 80F was used as the inlet temperature

T_2 is discharge temperature = 150°C = 302°F

$$P_2 = 14.7 psia,$$

$$^{\circ}F + 460 = ^{\circ}R$$

$$T_2 = 60^{\circ}F + 460 = 520 ^{\circ}R$$

$$T_2 = 302^{\circ}F + 460 = 762 ^{\circ}R$$

$$T_1 = 80^{\circ}F + 460 = 540 ^{\circ}R$$

$$r_p = \sqrt[0.286]{\frac{762}{540}} = 3.33$$

$$P_2 = r_p \times P_1 = 3.33 \times 449.7psia = 1495 psia$$

The conditions used in this project are given below using an inlet pressure and temperature of 30 bar and 25°C respectively:

$$P_1 = 435 + 14.7 = 449.7psia$$

$$T_1 = 80^{\circ}F + 460 = 540 ^{\circ}R$$

The discharge pressure for the first stage compression in order to regenerate the silica gel adsorbent in the dryer is 1495 psia (102 bar).

$$H_a = Z_{avg}RT_1 \frac{K}{K-1} \left(r_p^{\frac{k-1}{k}} - 1 \right)$$

The flow rate for the compressor is thus:

$$Q_1 = \frac{14.7}{449.7} \times \frac{540}{520} \times 47.03 = 15.31 cfm$$

Where H_a is the enthalpy of adiabatic process, T_1 is inlet temperature, R is specific gas constant and Z_{avg} is assumed to be 1. Universal gas constant is 1545ft.lbf/lb mol. R = universal gas constant/molecular weight =772.5 -lb/lb°R.

In order to determine the specific heat ratio the following formula was used:

$$\frac{K}{K-1} = \frac{1.4}{1.4-1} = 3.5$$

$$H_a = 1.0 \times 772.5 \times 540 \times 3.5(3.33^{0.286} - 1) = 599558.2 \text{ ft} - \text{lb/lb}$$

The enthalpy of the process was converted to power with an efficiency of 79% and a weight flow rate of 0.243 lb/min

$$\text{weight flow} = \frac{160 \text{ kg/day}}{24 \text{ hrs} \times 60} = 0.11 \frac{\text{kg}}{\text{min}} = 0.243 \text{ lb/min}$$

$$\text{power} = \frac{\text{weight flow} \times H_a}{33000 \times \text{efficiency}} = \frac{0.243 \times 599558.2}{33000 \times 0.79} = 5.59 \text{ hp}$$

The power needed for the first stage compression is 5.59hp

For the second stage compression, the inlet pressure is 1495 psia (102 bar) and the outlet pressure is 5091 psia (350 bar). Hence,

$$r_p = \frac{5091}{1495} = 3.4$$

$$H_a = 1.0 \times 772.5 \times 762 \times 3.5(3.4^{0.286} - 1) = 863386.4 \text{ ft} - \text{lb/lb}$$

$$\text{power} = \frac{0.243 \times 863386.4}{33000 \times 0.79} = 8.04 \text{ hp}$$

The total power used in the compression process is

$$\text{Total hp} = 5.59 + 8.04 = 13.63 \text{ hp} = 10163.8 \text{ W} = 10.2 \text{ kW}$$

The power rating of the compressor is 10.2KW. To calculate the energy used per kg of hydrogen compression;

$$\text{energy} = \text{power} \times \text{time} = \frac{10.2 \text{ KW} \times 24 \text{ hrs}}{160 \text{ kg}} = 1.56 \approx 2 \text{ kWh/kg}$$

The total energy used in compressing hydrogen is 2 kWh/kg.

The energy balance of the electrolysis system is presented in Table 8. The total electrical load for this system taking into consideration the electrolyzer, the dryer and the compressor is 47.82 kWh/kg.

4. DISCUSSION

For this project a proton exchange membrane water electrolysis system powered by solar

energy was chosen as a means of producing hydrogen gas for the RV1 fuel cell transport buses in London. This electrolysis method was chosen because it has high current density and it's able to produce hydrogen gas at high pressure. The electrolyzer chosen for this project is a 359.2 KW PEM electrolyzer capable of producing 160 kg of hydrogen on a daily basis and it's able to operate for 24 hours per day with an efficiency of 85%. The total energy required to run the electrolysis system is 47.82 KWh/kg. The electricity needed to run the electrolysis system will be gotten from a 2.98 MW solar photovoltaic system with a total module area of 14502.9 m².

Table 8. Energy balance of electrolysis system

Electrolysis system components	kWh/kg
PEM electrolyzer	45.8
Heat of compression dryer	0.02
Diaphragm compressor	2
Total	47.82

The production of electricity required for the electrolysis system was done using photovoltaics hence this system is a renewable system. The only feed input required for this process is solar radiation and water; both of these inputs are renewable in nature. The total amount of water in UK is 147 km³ and a total solar radiation of 3.66 kWh/m²/day; hence there is a lot of feed to run the system. Since the inputs required to run the system are renewable there are no greenhouse gas emissions from the system. The use of solar electrolysis system is environmentally friendly and an efficient means of reducing carbon emissions [14].

As seen in this study, electrolysis requires a lot of electricity (47.82 kWh/kg) to generate hydrogen gas. Due to the high electricity required and the low solar radiation in the UK (3.66 kWh/m²/day), a lot of photovoltaics will need to be installed to generate the required electricity for the system. This makes the solar electrolysis system very expensive, hence not financially feasible in the UK. Also the PEM electrolyzer is made up of very expensive materials such as platinum and iridium which increases the overall cost of the system [15].

There are not enough lands in the city to contain large scale photovoltaics installation. The photovoltaic system installation required for this project is more than the roof capacity within the Lea interchange bus garage. The total land

capacity required for this project is 14502.9 m², which is equivalent to 11.6 acres of land.

In the experiment conducted to check the energy efficiency and faraday efficiency of the proton exchange membrane electrolyzers results showed that the use of Proton exchange membrane electrolyzers have an energy efficiency ranging from 85%- 89% and faraday efficiency ranging from 91% - 95%. It was also discovered that electrolysis using high temperature distilled water yielded higher efficiency than using distilled water at room temperature. At atmospheric temperature an energy efficiency of 85% was gotten with a faraday efficiency of 91% and at high temperature an energy efficiency of 89% with a faraday efficiency of 95% was gotten.

As seen in the polarization curve of the PEM electrolyzer in Fig. 6, there was no increase in current till a voltage of 1.30V was reached. 1.23 V is the Gibbs free energy voltage of electrolysis, hence for electrolysis to occur the electrolyzer must reach a voltage of 1.23 V. The PEM electrolyzer used in this experiment is not 100% efficient that was why electrolysis occurred at a voltage higher than 1.23 V.

Experiments were conducted to check the efficiency of the solar cell which gave an efficiency of 12% and a fill factor of 0.78. Due to the low efficiency of polycrystalline solar cell gotten from the experiment, a monocrystalline solar cell was modeled for the project.

The balance of plant within this project electrolysis system is heat of compression dryer and a diaphragm compressor. A heat of compression dryer will be used to remove water molecules from incoming hydrogen gas. The amount of energy used by this dryer was calculated to be 0.02 kWh/kg which is very small compared to the energy use of the electrolyzer. The adsorbent used in this drying process will be silica gel and will be regenerated using the heat gained during compression of hydrogen gas. This is an efficient method of drying as it ensures the heat produced during compression is not wasted.

The dryer is a fixed bed process that consist of two towers, while drying of hydrogen gas occurs at one tower regeneration of the silica gel occurs at the second tower. Although the hydrogen gas is used as the regenerating gas, it is not wasted because after it purges all the moisture from the

adsorbent it is sent back to the drying tower to be dried.

The compressor proposed for this project is a two stage diaphragm compressor with a hydrogen flow rate of 15.31 cfm. This compressor was used to compress the hydrogen gas from 30 bar to 350 bar. The first step produces hydrogen at 102 bar with a temperature of 150 °C. Some of the hydrogen produced at this step is used to purge the moisture from the adsorbent in the dryer. The hydrogen produced at the second step is at 350 bar and then it is stored or sent to the fuel cell bus. Since the hydrogen gas has been pressurized in the electrolyzer to some extent before been sent to the compressor it reduces the amount of energy used by the compressor in compressing hydrogen gas. The amount of energy that was calculated for the diaphragm compressor is 2 kWh/kg with an efficiency of 70%.

Hydrogen has a specific energy content of 142 MJ/kg compared to diesel fuel that has a specific energy content of 48 MJ/Kg. this shows that more work is done with hydrogen fuel than the use of diesel fuel [16]. The volumetric density of hydrogen is very low compared to other fuels. However, hydrogen has very low ambient temperature density and will result in a low energy per unit volume, hence hydrogen needs to compress to a high pressure level (350 – 700 bar) in order for it to be used as a fuel [14].

The storage medium required for the solar electrolysis system is a 320 m³ aluminum cylinder to store compressed hydrogen gas during the summer months to be used during the winter months and during the maintenance period of the electrolysis system.

The photovoltaic system to produce energy for the electrolysis system was modeled using the system advisor model (SAM) software (NREL). The photovoltaic system modeled for this project is a 2.98 MW system to produce 29104 kWh per year to the electrolysis system. The photovoltaic system consists of photovoltaic solar panels, lithium cadmium batteries and the national grid. The national grid was introduced to the system because during the winter periods there is not enough sunlight to run the photovoltaic modules and charge the battery systems. The total electricity imported from the grid to the electrolysis system is less than the total electricity exported to the grid. This shows that

the photovoltaic system has compensated for the electricity gotten from the grid and still has spare to sell to the grid and gain profit. The amount of energy gotten from the national grid during the winter period is being offset by the photovoltaic system during the summer period.

Solar electrolysis system is a modular structure and does not take a lot of space. It can be installed onsite in locations with demand for hydrogen fuel hence eliminating the need for transport. Solar electrolysis systems can be installed onsite in the bus stations and this removes the cost for transporting compressed gas via trucks or construction of pipelines [4]. Also, the use of solar electrolysis can be scaled up to produce more hydrogen gas and this can be done by just increasing the amount of photovoltaics to generate more electricity and increasing the amount of electrolysis cells.

5. CONCLUSION

In conclusion the use of proton exchange membrane electrolysis as a form of distributed hydrogen production method is highly functional as it does not require gigantic infrastructure and the feedstock required to run the process is water which is easily accessible. The system also does not emit hazardous gases or loud noises; hence it can be situated within local communities with homes and businesses. Since the system uses electricity from solar energy, the overall process is a renewable system.

This project has analyzed a system to produce the required hydrogen content to run the London fuel cell bus fleet on a daily basis without adding to the carbon footprint of the environment. The total electricity required to run this system is 47.82 kWh/kg of hydrogen gas. An annual load of 2910445 kWh will totally be supplied by solar photovoltaic systems. This system can always be scaled up to produce more hydrogen gas and it's able to function perfectly with the intermittent nature of power supply from photovoltaics.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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