Cost Analysis of Hydrogen Production for Transport Application

Deborah A. Udousoro¹* and Cliff Dansoh¹

¹Faculty of Science, Engineering and Computing, Kingston University, London, UK.

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 DC managed the analyses of the study. Author DAU managed the literature searches. Both authors read and approved the final manuscript.

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(1) Dr. David Dotse Wemegah, Kwame Nkrumah University of Science and Technology, Ghana.

(1) Etienne Rivard, Canada.

(2) Paolo De Filippis, Sapienza University of Rome, Italy.

(3) Essam El Shenawy, National Research Centre, Egypt.

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ABSTRACT

One of the challenges faced in the United Kingdom energy market is the need to supply clean energy at affordable prices. Hydrogen can be used as an energy carrier and has been applied as fuel for automotive engines. Several technologies exist for the production of hydrogen fuel but their acceptance is dependent on the cost and impact on the environment. Steam methane reforming is an established hydrogen production process in the UK. Currently there are 8 fuel cell buses that run on hydrogen fuel but the hydrogen used is produced via steam methane reforming. Production of hydrogen through solar powered electrolysis is a cleaner option but at what economic cost? In this paper, cost analysis is conducted to compare the cost of producing the amount of hydrogen needed to run the RV1 fuel cell buses at Lea Interchange bus garage through steam methane reforming of natural gas to solar powered water electrolysis. From the analysis it was discovered that levelised energy cost of solar powered electrolysis system is 15 times the levelised energy cost of steam methane reforming of natural gas. Thus, the production of hydrogen is not economically feasible through solar powered water electrolysis system.

Keywords: Steam methane reforming; electrolysis; hydrogen; cost.

*Corresponding author: E-mail: deborahu6@gmail.com;
1. INTRODUCTION

Hydrogen gas serves as a flexible energy carrier that has been proposed for use in the transport sector towards reduction of greenhouse gas emissions [1,2]. Although hydrogen fuel does not contribute to greenhouse gas emissions when used, the technology adopted in producing it emits greenhouse gases. Several technologies exist for the production of hydrogen fuel including coal gasification, steam methane reforming, electrolysis and biological processes. The cost of producing hydrogen from coal gasification and steam methane reforming is favourable compared to electrolysis and biological processes, which are considered more sustainable and ecofriendly [3,4].

In the United Kingdom there is a commitment to reduce the total greenhouse emissions from transport systems through the use hydrogen fuel cell buses [5]. One of the challenges faced in the United Kingdom energy market is the need to supply clean energy at affordable prices. At present the bulk of hydrogen used in the UK is being produced through steam methane reforming of natural gas. In order to avoid such increase in UK greenhouse gas emissions, new methods of hydrogen production have to be adopted for the fuel cell buses [6]. Some hydrogen production stations in the UK now use electrolysis of water to produce hydrogen gas using electricity from the grid or wind energy [7].

In general, the cost of hydrogen production depends on the type of technology applied to produce and convert hydrogen to electric, the cost of transportation and storage [8]. Electrolysis of water for hydrogen production is powered by electricity which can come from power plant, solar plants and wind plants. The device used for this operation is known as an electrolyzer. There are several types of electrolyzer, with the more efficient once which can be used with fluctuating energy input from renewable energy sources and can be used for grid balancing, having to add to the overall capital cost of the system [9]. Fuel cell technology which converts the chemical energy (hydrogen) to electrical energy does not also come cheap.

From the environmental standpoint, hydrogen has been touted as the storage energy form for the future, as it can be produced from renewable energy sources [3,10]. All the same, the development of fuel cells and hydrogen technology is still evolving [8]. There are currently 8 fuel cell buses in London that operate within the RV1 route which use hydrogen gas generated from steam methane reforming of natural gas and transported to the bus stations via trucks. In this paper, cost analysis is conducted to compare the cost of producing the amount of hydrogen needed to run the RV1 fuel cell buses at Lea interchange bus garage through a modeled solar powered electrolysis system to steam methane reforming of natural gas.

2. 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 of hydrogen 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 technical features of selected PV modules and Table 2 shows the technical features of selected battery.

2.1 Cost Analysis

The following cost analysis was done to compare the economic feasibility of the photovoltaic systems and the proton exchange membrane water electrolysis system. The photovoltaic system was compared to electricity from the grid and the modelled solar electrolysis system was compared to steam methane reforming of natural gas. The method used in comparing the cost analysis of these various systems is the levelised cost of energy method.

In order to determine the levelised cost of electricity for the solar system, the following formula is used [11].

$$ LEC = \frac{I + \sum_{n=0}^{N} AO}{\sum_{n=1}^{N} Qn (1 + d)^{-n}} $$

Where, LEC is the levelised energy cost, I= capital investment, AO= Annual operations and maintenance expenditures in the year n (fixed and variable), Qn= Energy generation in the year n, d = discount rate, n= life of the system.
Table 1. Technical features of selected photovoltaic generator

| Parameter                                                                 | Value          |
|---------------------------------------------------------------------------|----------------|
| 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 m²     |

Table 2. Technical features of selected battery

| Battery type                                      | Lithium ion batteries |
|--------------------------------------------------|-----------------------|
| Nominal bank capacity                            | 136629kwh             |
| Cell nominal voltage                             | 3.6V                  |
| Cells in series                                  | 96 cells              |
| Depth of discharge                               | 80%                   |
| Battery volume                                   | 272.6m³               |
| Specific energy volume                           | 501.25Wh/L            |
| Strings in parallel                              | 175707                |

3. RESULTS AND DISCUSSION

Results in Table 3 show the monthly electricity required for the production of 160 kg of hydrogen per day. The energy required to produce 160 kg of hydrogen per day 359.2 kW [10]. Fig. 1 shows electricity production from battery, PV and grid. Table 3 shows monthly hydrogen production from electrolysis and the amount of hydrogen required per month.

As shown in Table 3 and Fig. 1, the PV system is able to supply the total electrical load required per year and still have 117757 kWh of electricity which can be added 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. The battery pack serve to store electricity during period of excess production.

The Table 4 shows that the electrolysis system is able to generate 60862 kg of hydrogen gas on a yearly basis of which only 58400 kg of hydrogen is required. The remaining 2462 kg of

Table 3. Monthly electricity production

| Months     | Electrical load required (kWh) | PV system energy (kWh) |
|------------|--------------------------------|------------------------|
| January    | 237187.2                        | 126364                 |
| February   | 214233.6                        | 128196                 |
| March      | 237187.2                        | 198072                 |
| April      | 229536                          | 314333                 |
| May        | 237187.2                        | 377074                 |
| June       | 229536                          | 351652                 |
| July       | 237187.2                        | 390299                 |
| August     | 237187.2                        | 356851                 |
| September  | 229536                          | 279558                 |
| October    | 237187.2                        | 185554                 |
| November   | 229536                          | 128719                 |
| December   | 237187.2                        | 73772.6                |
| Total      | 2792688                         | 2910445                |
hydrogen can be stored and used to fill the fuel cell buses during the maintenance period of the hydrogen plant.

The capital investment was calculated using the system advisor model (SAM) which gave a value of $90651528 and yearly output of 2910445kWh. The operation and maintenance cost was taken to be $16/kW with a 10% discount rate.

\[ AO = 2980kW \times $16 = $47680 \]

Table 5 shows the calculated value of annual operation and maintenance cost and also energy generation for the photovoltaic system using a period of 25 years.

Table 6 shows the financial parameters of steam methane reforming [12] while Table 7 shows the financial parameters of solar powered electrolysis system [13,14].

In order to compare the levelised energy cost between steam methane reforming of natural gas and solar powered electrolysis an annual load of 58400 kg of hydrogen gas was used to perform this analysis as seen in Table 8. The levelised energy cost was done using a period of 20 years.

From the equation above the levelised energy cost of producing hydrogen via SMR is a lot lesser than producing it via SPE.

The cost analyses were carried out to compare the economic feasibility of steam methane reforming and proton exchange membrane water electrolysis. From the analysis it was discovered that levelised energy cost of proton exchange membrane water electrolysis system is 3 times the levelised energy cost of steam methane reforming of natural gas. The levelised energy cost (LEC) for steam methane reforming was calculated to be $1.51 while the LEC for proton exchange membrane electrolysis was calculated...
Table 5. Annual operation and maintenance cost and energy generated for 25 years

| Year (n) | \( \sum_{n=0}^{N} AO \) | \( \sum_{n=1}^{N} Qn \) |
|---------|----------------|------------------|
| 1       | $43345          | 2645859 kWh      |
| 2       | $39404          | 2405326 kWh      |
| 3       | $35822          | 2186660 kWh      |
| 4       | $32566          | 1987873 kWh      |
| 5       | $29605          | 1807157 kWh      |
| 6       | $26914          | 1642870 kWh      |
| 7       | $24467          | 1493518 kWh      |
| 8       | $22243          | 1357744 kWh      |
| 9       | $20220          | 1234313 kWh      |
| 10      | $18382          | 1122103 kWh      |
| 11      | $16711          | 1020093 kWh      |
| 12      | $15192          | 927357 kWh       |
| 13      | $13811          | 843052 kWh       |
| 14      | $12555          | 766411 kWh       |
| 15      | $11414          | 696737 kWh       |
| 16      | $10376          | 633397 kWh       |
| 17      | $9433           | 575816 kWh       |
| 18      | $8575           | 523469 kWh       |
| 19      | $7796           | 475881 kWh       |
| 20      | $7087           | 432619 kWh       |
| 21      | $6443           | 393290 kWh       |
| 22      | $5857           | 357536 kWh       |
| 23      | $5324           | 325033 kWh       |
| 24      | $4840           | 295484 kWh       |
| 25      | $4400           | 268622 kWh       |
| Total   | $432793         | 26418226 kWh     |

\[ LEC = \frac{\$9065.1528 + 432.793}{26418226 \text{ kWh}} = 3.4 / \text{kWh} \]

Table 6. Financial parameters of steam methane reforming (SMR)

| Parameter                  | Unit cost | Actual cost |
|----------------------------|-----------|-------------|
| Capital cost               | $569/kgH\text{\textsubscript{2}} | $91040      |
| Operation and maintenance cost | 5.92% of capital cost | $5389       |
| Feed stock cost            | $5.15/1000 scf | $127311     |
| Other variables            | 8% of capital cost | $7283.2     |
| Transport cost             | $0.96/kgH\text{\textsubscript{2}} | $153.86/kgH\text{\textsubscript{2}} |

Table 7. Financial parameters of solar powered electrolysis (SPE) system

| Parameter                  | Unit cost | Actual cost |
|----------------------------|-----------|-------------|
| Capital cost               | $300/kW   | $107780     |
| Operation and maintenance cost | $0.20/kgH\text{\textsubscript{2}} | $32         |
| Electricity cost           | $0.16/kWh | $1379.33    |

to be $4.75 and the capital cost for both hydrogen production methods are $91040 and $107780 respectively.

More research should also be done to eliminate the need for hydrogen dryers and compressors. Research should be done in order to ensure there is no permeation of moisture or water vapor into the generated hydrogen and oxygen gas; This will eliminate the need for dryers. Research should also be done to allow efficient pressure increase in electrolyses without the risk oxygen gas contaminating hydrogen gas and vice versa. This will eliminate the need for catalytic recombiners and compressors.
### Table 8. Annual operation and maintenance cost and energy generated for 20 years

| Year (n) | Steam methane reforming | Solar powered electrolysis | Annual load |
|----------|-------------------------|---------------------------|-------------|
| 1        | $4899                   | $13714                    | 53090 kg    |
| 2        | $4453                   | $12468                    | 48264 kg    |
| 3        | $4048                   | $11334                    | 43876 kg    |
| 4        | $3680                   | $10304                    | 39887 kg    |
| 5        | $3346                   | $9367                     | 36261 kg    |
| 6        | $3041                   | $8515                     | 32965 kg    |
| 7        | $2765                   | $7741                     | 29968 kg    |
| 8        | $2514                   | $7037                     | 27244 kg    |
| 9        | $2285                   | $6398                     | 24767 kg    |
| 10       | $2077                   | $5816                     | 22515 kg    |
| 11       | $1888                   | $5287                     | 20468 kg    |
| 12       | $1717                   | $4806                     | 18608 kg    |
| 13       | $1561                   | $4369                     | 16916 kg    |
| 14       | $1419                   | $3972                     | 15378 kg    |
| 15       | $1290                   | $3611                     | 13980 kg    |
| 16       | $1172                   | $3283                     | 12709 kg    |
| 17       | $1066                   | $2984                     | 11554 kg    |
| 18       | $969                    | $2713                     | 10503 kg    |
| 19       | $881                    | $2466                     | 9548 kg     |
| 20       | $801                    | $2242                     | 8680 kg     |
| Total    | $45879                  | $128439                   | 49719 kg    |

\[
LEC_{SMR} = \frac{91040 + 49719}{49719} = 0.55 + 0.96 = 1.51/kg
\]

\[
LEC_{SPE} = \frac{107780 + 128439}{49719} = 4.75/kg
\]

In order to optimize the electrolysis system feed water used for the electrolysis process can be used as the heat exchanger medium in the after coolers in the dryers so as to increase the temperature of the feed water and increase the efficiency of the electrolysis process.

Incentives should be given to electrolysis process as they do not add to the global warming potential of the environment. The incentives will also help in reducing the cost of installing an electrolysis process and encourage people to invest in water electrolysis rather than in steam methane reforming of natural gas.

More research should be done in reducing the electricity requirements of electrolysis process so as to reduce the cost of the electricity used for the system. Low electricity demand will make it easy for renewable energy technologies such as photovoltaic modules to function properly without the use of batteries or the national grid.

### 4. CONCLUSION

The use of solar powered electrolysis of water for hydrogen production is highly functional and beneficial as a renewable system. However, production of hydrogen is not economically feasible through solar powered electrolysis system. More research still need be done to cut down the cost of producing hydrogen via solar powered electrolysis.

### COMPETING INTERESTS

Authors have declared that no competing interests exist.

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