Feasibility Study of Seawater Electrolysis for Photovoltaic/Fuel Cell Hybrid Power System for the Coastal Areas in Thailand

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Abstract. Solar photovoltaic cell and fuel cell are the practicable options to realize as a possible hybrid power system because the power of the sun cannot be utilized at night or cloudy days but hydrogen has been found as an ideal energy carrier for being transportable, storable, and converting energy though fuel cell. Hydrogen storage is chosen for its ability to obtain a clean energy option. Electrolysis, which is the simplest process to produce hydrogen, can be powered by the dc voltage from the photovoltaic cell instead of using the battery as power supply. This paper concentrates on a feasibility study of seawater electrolysis using photovoltaic power integrated fuel cell system for the coastal cities in Thailand. The proposed system composed of photovoltaic arrays, seawater electrolyzer and fuel cell is presented when the 10-kW of fuel cell electrical power is considered. The feasibility study of hydrogen production and energy analysis of this proposed system is also evaluated.

1. Introduction

As the development of renewable energy in Thailand increased gradually and the perspective of Ministry of Energy of Thailand in energy security, economy and ecology to increase domestic renewable energy production has been focused, the Alternative Energy Development Plan (AEDP2015) was developed to set a target of renewable energy sources to replace 30 percent of final energy consumption (in form of electricity, heat and Bio-fuel) by the year 2036 [1]. The target of electricity generation from solar energy is approximately 6,000 MW. In order to reach the goal for developing renewable energy sources, a hybrid power system have been adopted to increase the system reliability and security. Moreover, one of the most promising hybridization approaches is the combination of photovoltaic (PV) panels to other resources [2]. In this paper, we have applied the solar power system via PV to generate hydrogen for energy storage purposes of the hybrid power system. Hydrogen can be produced by a water electrolysis process powered by the electrical energy and thereafter it can be used to produce electricity through fuel cell (FC). The coastal regions, especially in the remote area power supply, are focused to develop the PV/FC hybrid power system using seawater electrolysis. When we consider water as the raw material for hydrogen production, it would be a noticeable advantage to consume these abundant salt water resources for electrolysis, rather than using fresh water. Moreover, the high amount of hydrogen produced from electrolysis of seawater [3-5] or electrolyte added with sodium chloride (NaCl) [6] was observed. Slama [6] found that the addition of NaCl in various types of electrolyte can increase the hydrogen production although
it also increases the consumed electrical power because of higher electrolyte conductivity. Normally, seawater in the world’s oceans has about 3.5% of dissolved salts predominantly NaCl. Many literatures have investigated the hydrogen production via seawater electrolysis integrated solar system, for example to examine the variation of the electric tension and energy consumption of the natural seawater electrolysis comparing with the electrolysis of 15%NaOH solution [4] and to predict the hydrogen production rate in terms of panel temperature, solar irradiation, and current [5]. Abdel-Aal et al. [7] estimated the economic feasibility of a solar-energy stand-alone system including PV modules, water electrolyzer and FC. In addition, it is important to investigate the optimal design of a PV/FC hybrid power system focused on the economical performance [2] and the effects of current, voltage, electrical power on the performance of electrolyzer for hydrogen production [8]. However, a study on the hybrid PV/FC power system integrated seawater electrolysis is limited. As the Phi Suea House project in Chiang Mai, Thailand was introduced as the world’s first 24-hour solar-powered hydrogen storage in a multi-house compound [9], it is a motivation of this work to apply the PV/FC hybrid system by using the electrolysis from seawater as a stand-alone hybrid power system for the coastal areas in Thailand.

In this work, the seawater electrolysis for PV/FC hybrid power system is preliminary investigated as the stand-alone hybrid power system for the coastal areas in Thailand. This paper presents a feasibility study of the PV/FC hybrid power system when seawater electrolyzer is used for hydrogen production when the 10 kW of electrical power of the whole FC stack produced from this hybrid power system is set as the target.

2. System Description

A schematic of seawater electrolysis PV/FC hybrid system is demonstrated in figure 1. The main components are PV arrays, seawater electrolyzer, hydrogen storage and FC. Electricity is firstly generated by PV cells for day time at the appropriate solar radiation. Seawater electrolyzer is then powered by electricity generated from PV to produce hydrogen. The electrode processes at seawater electrolysis [4] are:

- Hydrogen production at cathode, conform to the reaction:
  \[ 2\text{H}_2\text{O} + 2e^- \rightarrow \text{H}_2 + 2\text{OH}^- \]  
  (1)

- Oxygen and/or chlorine production at anode, conform to the reactions:
  \[ 6\text{H}_2\text{O} \rightarrow \text{O}_2 + 4\text{H}_3\text{O}^+ + 4e^- \]  
  (2)

  \[ 2\text{Cl}^- \rightarrow \text{Cl}_2 + 2e^- \]  
  (3)

The produced hydrogen is compressed in the hydrogen storage tank and it could be noted that the high amount of power is utilized for storing hydrogen at high pressures. However, compressor costs are based on the amount of work done by the compressor, which depends on the inlet pressure, outlet pressure, and flow rate. For night time, electricity is produced by FCs when hydrogen is utilized as fuel. FCs also produce fresh water as a by-product. Moreover, oxygen produced in electrolysis process can be utilized, instead of air, in the chemical reaction taking place in the FC. Inside the PEMFC, the reactions that take place at anode and cathode to generate both of the electricity and water can be described as

Anode: \[ \text{H}_2 \rightarrow 2\text{H}^+ + 2e^- \]  
(4)

Cathode: \[ \text{O}_2 + 4\text{H}^+ + 4e^- \rightarrow 2\text{H}_2\text{O} \]  
(5)

Overall: \[ \text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O} + \text{electricity} \]  
(6)

The merits of the hybrid power system are summarized as follows:

- It can supply electricity for day and night use.
- It can utilize availability of hydrogen gas for energy generation using FCs.
- It can supply fresh water as a by-product from the FC.
- It can supply heat source as a by-product from the FC (depending on types of FC).
3. Fuel Cell
Firstly, we considered the electric power production from FC when the produced hydrogen from electrolysis was utilized. In this work, the target of 10-kW electrical power produced from FC for day time or cloudy time was investigated to design the size of electrolysis and numbers of PV panels using in this process. The rate of usage of hydrogen is derived from the basis operation of the FC that there are two electrons from each mole of hydrogen as given in equation (7) and equation (8).

\[ H_2 \text{ usage} = \frac{I}{2F} \text{ moles}^{-1} \]  

(7)

\[ H_2 \text{ usage} = 1.05 \times 10^{-8} \times \frac{P_e}{V_c} \text{ kg s}^{-1} \]  

(8)

Where \( I \) is the DC current, \( F \) the Faraday’s constant (96,484 C/mol), \( P_e \) the electrical power of the whole FC stack, and \( V_c \) is the average voltage of each cell in the stack. In this paper, the using \( V_c = 0.65 \text{ V} \) will give a good approximation [11]. For the 10-kW FC operating for 1 h, at the cell voltage of 0.65 V, the \( H_2 \) usage is \( 1.62 \times 10^{-4} \text{ kg s}^{-1} \) (108.12 liters h\(^{-1}\)); the \( \text{O}_2 \) usage is \( 1.28 \times 10^{-3} \text{ kg s}^{-1} \) and the rate of water production is \( 1.44 \times 10^{-3} \text{ kg s}^{-1} \). This corresponds to an efficiency of 43.9% (using HHV).

4. Hydrogen Production using Seawater Electrolysis
Electrical energy from the PV system is used to split water into hydrogen and oxygen through the process of seawater electrolysis. Hydrogen is an energy carrier and it is stored until the FC utilizes it. The FC will convert the hydrogen back into electrical energy to supply the loads during periods when the PV system is not producing any power.

For the preliminary test for seawater electrolysis, the experiments were set up as illustrated in figure 2 and the seawater electrolysis testing parameters and the hydrogen production were given in table 1. In theoretically, electrolysis at ambient temperature and pressure requires a minimum voltage of 1.481 V and therefore, a minimum energy of 39.4 kWh kg\(^{-1}\)hydrogen [12] whereas this experiment gave the
energy of 190.4 kWh kg⁻¹ hydrogen and efficiency of 41.7%. According to the designed 10-kW FC power output, for about 18 h during periods when the PV system is not producing any power, the hydrogen rate $1.62 \times 10^4$ kg s⁻¹ (108.12 liters h⁻¹) was fed to FC to produce electricity and for the total time of FC operation, the hydrogen of about 2,000 liters was utilized; consequently the hydrogen storage should be sufficiently prepared for support the PV/FC hybrid system. However, the detail of hydrogen storage design and energy consumed for compressing hydrogen will be considered and proposed in the future work because there are many types of hydrogen storage tanks. In the hydrogen production via seawater electrolysis of this work, hydrogen was produced 1 liter h⁻¹ with a power demand of 9.6 W whereas the results from the Phi Suea House project was found that 1 liter h⁻¹ of hydrogen should be produced with a power demand of 4.2 W.

![Figure 2. Seawater electrolyzer used in experiments.](image)

### Table 1. Seawater electrolyzer parameters.

| Seawater electrolyzer parameters | Value |
|---------------------------------|-------|
| Temperature                     | 26 °C |
| Cathode material/area           | 316 SS / 125.6 cm² |
| Anode material                  | 316 SS / 125.6 cm² |
| Electrolyte                     | Seawater at Samut Sakhon Province, Thailand |
| Input voltage                   | 3 V  |
| Electrolysis current density    | 3.974 mA/cm² |
| Hydrogen production rate        | 155.65 ml/h |
| Energy requirement              | 190.4 kWh kg⁻¹ hydrogen |
| Efficiency                      | 41.7% |

### 5. Photovoltaic Cell

There are three basic types of solar PV cells, monocrystalline silicon, polycrystalline silicon and amorphous silicon. The efficiency of different types of silicon based PV cell is shown in table 2. Based on the Phi Suea House project [9], the polycrystalline PV cell is also chosen for this feasibility study. Therefore, the selected PV cell has an efficiency of approximately 15%. According to the initial experiment the power requirement from PV arrays is 12.3 kW. However, PV array site is determined from the availability of space, typically 1 kWp requiring 8 m² of roof/space, that faces south with slope of around 30 – 40 [10]. Figure 3 shows the solar radiation in different areas in Thailand (figure 3(a)) and the monthly average daily solar radiation in Thailand (figure 3(b)). This can be noted that the coastal areas of Thailand are appropriate for using seawater electrolysis integrated PV/FC hybrid system as a stand-alone hybrid power system.

### Table 2. Efficiency percent of different types of silicon based PV cells [10].

| Type/Material of PV cell       | Level of efficiency in Laboratory (%) | Level of efficiency in Production (%) |
|-------------------------------|--------------------------------------|---------------------------------------|
| Monocrystalline Silicon based | 24 (Approximate)                     | 14-17                                 |
| Polycrystalline Silicon based | 18 (Approximate)                     | 13-15                                 |
| Amorphous Silicon based       | 13 (Approximate)                     | 5-7                                   |
6. Summary
The feasibility study of seawater electrolysis for PV/FC hybrid system was investigated in order to investigate the system parameters when the target of 10-kW of FC electrical power generation was evaluated. The appropriate amount of hydrogen produced by seawater electrolysis was calculated for using in FC to produce electricity at night time. In this system, the PV arrays supply the electricity for electrolyzer to produce hydrogen at day time. However, the technical challenge is real time production, the safe and convenient storage and the efficient of the seawater electrolysis for PV/FC hybrid system. The optimal design by using Hybrid Optimization Model for Electric Renewable (HOMER) and the operational control are considered to perform in the future work. Moreover, the economic challenge of this hybrid power system is the reasonable cost of hydrogen production, hydrogen storage and FC system is also considered in the future work as well.

Acknowledgements
Authors gratefully acknowledge Department of Chemical Engineering, Pathumwan Institute of Technology for equipment support.

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