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Comparative analysis among three solar energy-based systems with hydrogen and electrical battery storage in single houses

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ABSTRACT

This study investigates and compares the economic analysis of renewable energy-based systems incorporating photovoltaic (PV) panels, electrolyzer, fuel cell (FC), and a hydrogen tank for single houses in North America. Three systems consisting of PV/battery bank, PV/hydrogen, and PV/battery bank/hydrogen are simulated and optimized using the software HOMER. In this study, the electrolyzer produces green hydrogen using to the power obtained by the PV array; the generated hydrogen is stored in a hydrogen tank and powers the FC. Based on the results, the integration of 12 kW PV panels, 2.50 kW FC, 10 kW electrolyzer, 50 kg hydrogen tank, 2 kW converter, and 24 kWh of batteries is found to be the best configuration in Toronto, as it leads to the minimum net present cost (NPC) and levelized cost of energy (COE). Results show that while the battery bank can be used instead of the electrolyzer, FC, and hydrogen tank, the large batteries resulted in the highest NPC due to their high investment cost. Finally, the study is extended to Miami and Washington in the U.S., to check the validity of the conclusions with higher average annual solar radiation and to find their cost-effective configurations.

Keywords: Renewable energy, solar energy, hydrogen, electrolyzer, fuel cell.

Nomenclature

PV	Photovoltaic
FC	Fuel Cell
NPC	Net Present Cost
COE	Cost of Energy

1. INTRODUCTION

Due to the growing population and rapid urbanization levels, the building energy consumption has significantly increased worldwide. Nowadays, fossil fuels are a prominent source of energy supply in electricity production causing increasing risks of global warming, greenhouse effect, and ozone depletion [1]. According to the International Energy Agency, the demand for primary energy sources keeps showing an upward trend with an increase in CO_2 emissions [2], with a trend particularly critical in the building sector [3].

Solar energy is one of the most prominent and reliable renewable energy sources. However, storing solar energy is still challenging [3]. Increasing interest has emerged for hydrogen as a medium to store renewable energy sources. For the production of green hydrogen, water electrolysis is coupled with renewable energy resources as a power supplier. Hydrogen can offer high energy storage capacity, long-time energy storage, and flexibility [4]. The hydrogen can be easily stored in pressurized tanks, and then be sent to fuel cells (FC) to convert back the chemical energy into electricity as needed.

In this study, a recently developed software, named HOMER (Hybrid Optimization Model for Electric Renewables), has been used to investigate the reliability of hybrid systems, including renewable energy sources (e.g., PV, wind, and hydro) with battery or hydrogen storage. Similar comparisons have been recently proposed in other studies, as briefly reported below.

Al-Sharafi et al. considered six systems of PV/battery bank, wind/battery bank, PV/wind/battery bank, PV/FC, wind/FC, and PV/wind/FC, to find the optimum configuration with minimum COE in several Saudi Arabia locations [5]. The results showed that integrating PV/wind/FC gives the minimum levelized COE. In another study, Fazelpour et al. demonstrated five hybrid PV-wind-diesel systems with hydrogen as a diesel generator fuel to supply the electrical requirements for a house and found the wind/hydrogen/battery hybrid system as the most economical configuration [6]. Yunez-Cano et al. [7] showed that an electrolyzer, hydrogen tanks, and FC

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system can be used as a safe, small, and reliable electricity backup system for an house in Mexico. Maclay et al. [8] experimentally investigated a solar-hydrogen reversible fuel cell for residential applications, and found that a significant cost reduction is needed to compete with other conventional energy storage devices.

Despite many studies with almost the same aims, a few of them design and compare these configurations to evaluate the possibility of integrating renewable energy and hydrogen/battery. The present study compares three renewable energy systems with hydrogen storage and battery for a typical house to assess the renewable energy potential in accordance with the most economical design. The systems configurations are performed for Toronto, Washington, and Miami, areas with different weather conditions.

2. METHODOLOGY

2.1 Software adopted in this study

The HOMER software, designed by the National Renewable Energy Laboratory in the U.S., has been widely used to optimize renewable power systems. This tool allows to develop hybrid power systems to achieve the optimum configuration by performing various hourly simulations to find the best possible match between supply and demand. The system configuration with minimum NPC is chosen as the optimal design.

2.2 Systems components

Three renewable energy-based systems are simulated to cover a load demand of a house located in Toronto, incorporating: photovoltaic (PV) array, converter, batteries, electrolyzer, fuel cell (FC) and hydrogen tank. In system 1, the battery bank is used as the storage system (Figure 1). System 2 consists of an electrolyzer, fuel cell, and hydrogen tank (Figure 2). System 3 is the combination of systems 1 and 2 (Figure 3).

Electrolyzer - The electrolyzer is used to break water into hydrogen and oxygen in the process of water electrolysis. The surplus energy generated from the PV array produces hydrogen in the electrolyzer. A generic electrolyzer with capacities of 1, 5, 10, 15, 20, and 25 kW, and 85% efficiency was selected. The capital, replacement, and maintenance costs are US$ 380, US$ 380/kW, and US$ 10/year, respectively.

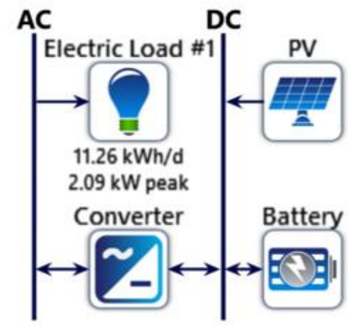

Figure 1. Schematic diagram of system 1 (PV/battery bank).

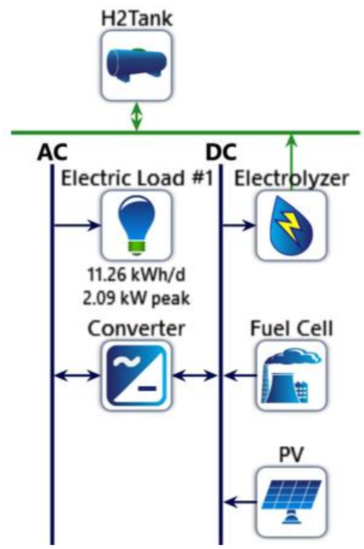

Figure 2. Schematic diagram of system 2 (PV/hydrogen).

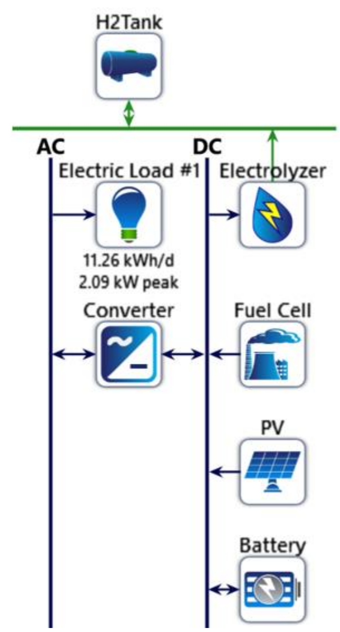

Figure 3. Schematic diagram of system 3 (PV/battery bank/hydrogen).

Hydrogen storage tank - The produced hydrogen is stored in hydrogen tanks.

Battery storage - A Kinetic battery with 1 kWh energy storage is considered in this study to provide electrical storage.

PV arrays - A solar energy system's number of panels is determined by the electrical load demand and the amount of solar intensity available. In this work a flat-plate PV with a derating factor is set to 80% is selected.

2.3 Data for building and location

The considered residential building is a 120 m^2 detached house consisting of two floors above grade and a basement level below grade. The location details and average annual solar radiation of the locations considered in this study (Toronto, Washington, and Miami) are shown in Table 1. Figure 4 illustrates the average monthly solar radiation profile in Toronto taken from the National Renewable Energy Laboratory database into HOMER [[9]. Figure 5 shows the daily average energy demand of the building. The average energy demand is 11.26 kWh/day, and the energy peak demand is 2.09 kW.

Table 1 – Details of the locations.

Location	Latitude	Longitude	Annual solar radiation ($kWh/m^2/day$)
Toronto	43°39.7'N	79°26.5' W	3.53
Washington	38°58.6'N	76°59.5' W	3.99
Miami	25°45.7'N	80°11.5' W	4.79

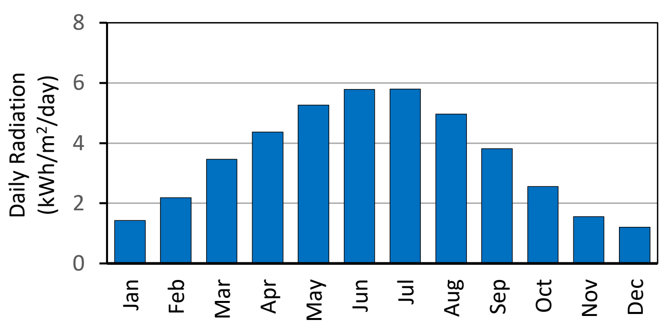

Figure 4. Monthly average solar radiation on horizontal plane in Toronto [9].

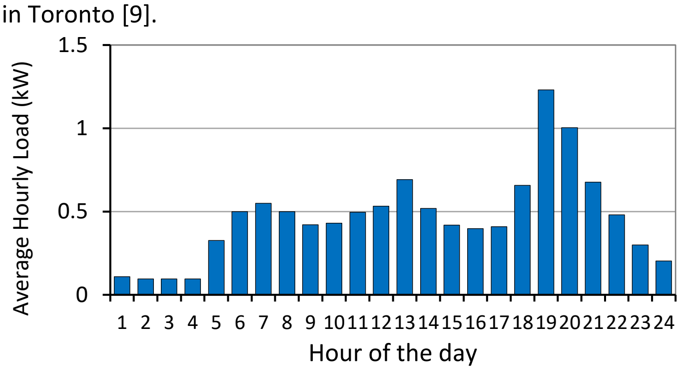

Figure 5. Hourly load profile of the house [9].

2.4 Evaluation criteria

For evaluating the life-cycle cost in HOMER, the total Net Present Cost (NPC) is calculated. An NPC consists of initial set-up, replacement, operations, maintenance, and mixed costs resulting from emissions. NPC is estimated using the following equation [10]:

$$NPC = \frac{C_{TA}}{CRF} \quad (1)$$

C_{TA} = Total annualized cost ($/yr)

CRF = Capital recovery factor which is equal to:

$$CRF = \frac{i(1+i)^N}{i(1+i)^N - 1} \quad (2)$$

i = Annual interest rate (%)

N = Project lifetime (years)

The Cost of energy (COE) is another critical aspect of designing a system and is evaluated as:

$$COE = \frac{C_R + C_I + C_{O\&M} + C_{BE} - C_{SE} - C_{GHG}}{E} \quad (3)$$

E = Annual energy output (kWh/yr)

C_R = Replacement cost ($)

C_I = Annual investment ($/yr)

$C_{O\&M}$ = Operational and maintenance cost ($)

C_{BE} = Annual cost to buy electricity ($/yr)

C_{SE} = Annual income from selling electricity ($/yr)

C_{GHG} = Emission reduction benefits ($).

3. RESULTS

3.1 Optimization Results

3.1.1 System 1: PV/battery bank system

In this system, the photovoltaics modules are provided to power the house, and the battery is considered for storing energy. For any size of the storage system, the size of the PV array is increased until no shortage of the power supply to the load is realized. The range of the PV array size varies from 1 to 20 kW, the range of the batteries varies from 1 to 100 batteries, and the converter size varies from 1 to 4 kW. The optimum design with the minimum COE and covering the load with renewable energy is chosen. Table 2 shows the optimum size of the system components with the total NPC of $78,433.45 and the levelized COE of 1.48 $/kWh. Figure 6 shows the monthly average electric production of the system.

Table 2 – Results of the economic analysis for the systems in Toronto based on HOMER.

	System 1	System 2	System 3
Fuel Cell (kW)	0	2.5	2.5
PV (kW)	12	25	12
Battery (strings)	68	0	24

System Converter (kW)	2.03	3.19	2
Electrolyzer (kW)	0	20	10
Hydrogen Tank (kg)	0	80	50
Total NPC ($)	78,433.45	97,032.97	61,024.09
Levelized COE ($/kWh)	1.48	1.82	1.14

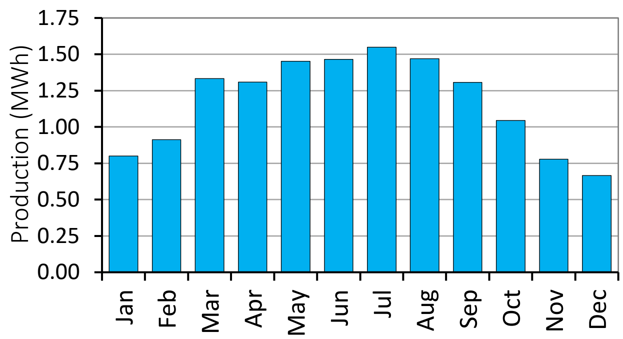

Figure 6. Monthly average electric production of system 1 (PV/battery bank).

3.1.2 System 2: PV/ hydrogen system

The PV array provides load demand, while the stored hydrogen in the tank produces electrical energy through the FC. During the simulations, many configurations are designed to find the optimum one. The size of the PV array varies from 1 to 30 kW; the size of the fuel cell varies from 1 to 5 kW; the size of the electrolyzer varies from 1 to 30 kW; the size of the hydrogen tank varies from 1 to 100 kg, and the size of the converter varies from 1 to 4 kW. Table 2 represents the best configuration for the system, which leads to the minimum levelized COE of 1.82$/kWh and total NPC of $97,032.97. Figure 7 shows the monthly hydrogen production of the electrolyzer, which most of the hydrogen is produced in June and July. The monthly electric production by the PV array and FC is shown in Figure 8. As seen, the PV array produces the most significant amount of electrical energy, 88.5%, while the FC produces only 11.5%.

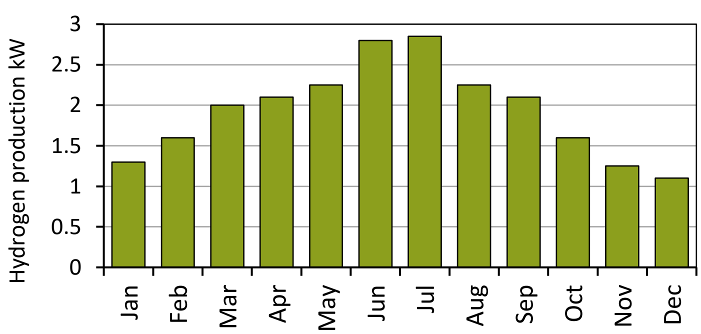

Figure 7. Monthly average hydrogen production of the electrolyzer in system 2.

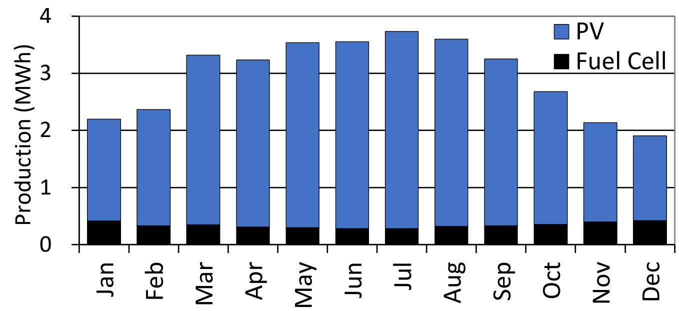

Figure 8. Monthly electric production of system 2.

3.1.3. System 3: PV/ battery/ hydrogen system

This system is the combination of systems 1 and 2. The excess supplied power through the PV panels is sent to the battery and electrolyzer for storage. According to the previous studies in hybrid systems incorporated with hydrogen/battery, hydrogen is appropriate for seasonal energy storage, whereas battery is used for short-term storage [11].

The HOMER software chose the ideal configuration with optimum components size. The size of the PV array varies from 1 to 20 kW; the size of the fuel cell varies from 1 to 5 kW; the size of the electrolyzer varies from 1 to 30 kW; the size of the hydrogen tank varies from 1 to 100 kg, the range of the batteries varies from 1 to 50 batteries, and the size of the converter varies from 1 to 4 kW. Table 2 shows the minimum levelized COE of 1.14$/kWh and total NPC of $61,024.09. Figure 9 shows the monthly average hydrogen production. As seen in Figure 10, 88.2% of electrical energy is produced through PV panels, and FC generates 11.8% of electricity.

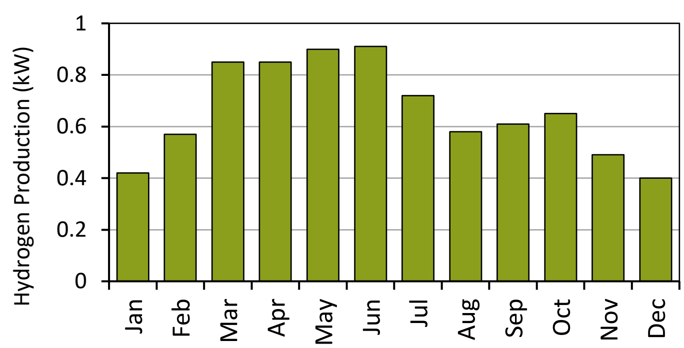

Figure 9. Monthly average hydrogen production of the electrolyzer in system 3.

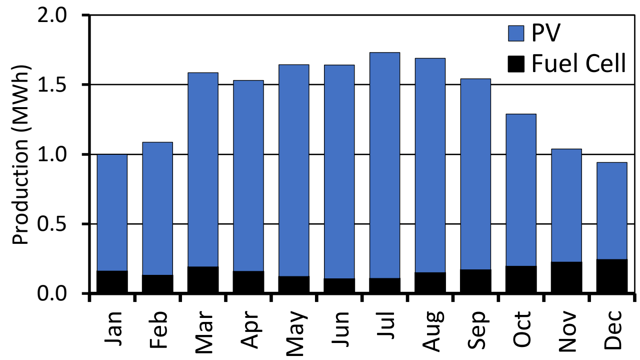

Figure 10. Monthly electric production of system 3.

3.3 Simulation results for Miami and Washington

The simulation has been repeated for Miami and Washington in the USA, with higher annual average solar radiation of 4.79 kWh/m^2/day and 3.99 kWh/m^2/day, respectively, appreciably higher than the yearly average solar radiation in Toronto, which is 3.53 kWh/m^2/day. The difference in weather conditions leads to various system results and components size. The main objective of these simulations is to find the optimum system configurations with the minimum COE and 100% contribution of the renewable energy in each location.

The results show that for Miami (Table 3), system 3 with 4 kW PV panels, 2.50 kW FC, 5 kW electrolyzer, 10 kg hydrogen tank, 1.95 kW converter, and 13 batteries storage bank, has a minimum COE of 0.64 $/kWh. System 3 also has the minimum cost in Washington (Table 4) with 4 kW PV panels, 2.50 kW FC, 5 kW electrolyzer, 12 kg hydrogen tank, 1.88 kW converter, and 14 batteries storage bank and the COE is 0.66 $/kWh. Based on the simulation results, it is observed that in areas with higher solar radiation intensity, renewable energy contribution shows a better potential.

Table 3 – Results of the economic analysis for the systems in Miami (FL, US).

	System 1	System 2	System 3
Fuel Cell (kW)	-	2.50	2.50
PV (kW)	7.42	5.63	4
Battery (strings)	32	-	13
System Converter (kW)	2.35	1.92	1.95
Electrolyzer (kW)	-	4	5
Hydrogen Tank (kg)	-	10	10
Total NPC ($)	41,536	63,112	34,109
Levelized COE ($/kWh)	0.78	1.19	0.64

Table 4 – Results of the economic analysis for the systems in Washington (DC, US).

	System 1	System 2	System 3
Fuel Cell (kW)	-	2.50	2.50
PV (kW)	7.56	5.04	4
Battery (strings)	55	-	14
System Converter (kW)	2.30	1.85	1.88
Electrolyzer (kW)	-	5	5
Hydrogen Tank (kg)	-	20	12
Total NPC ($)	57,028	64,889	35,236
Levelized COE ($/kWh)	1.07	1.22	0.66

4. DISCUSSION

Using renewable energy resources for hydrogen production makes it possible to produce environmentally friendly fuel. Based on the results of systems 1 and 2 (Table 2), replacing the battery bank with an electrolyzer, fuel cell, and hydrogen tank is possible. However, the total cost of the system increases due to the higher costs of the components. Combining the photovoltaic array, battery bank, and hydrogen will minimize the cost of energy and net present cost. This combination causes fewer batteries, a smaller hydrogen tank, and a low-power electrolyzer, leading to a more economical configuration. Hence, system 3 is the most cost-effective configuration among the other systems, with the minimum NPC of $61,024.09 and levelized COE of 1.14 $/kWh. In system 3, PV panels produce 88.2% of electrical energy, while the FC generates only 11.8% of the electricity.

Applying both battery and fuel cell in renewable energy systems allows the battery to use the high PV electricity generation during summer for short-term energy storage and minimizes the need for a fuel cell. In winter, the PV electricity generation declines significantly for several months. Therefore, the surplus power generated in summer causes the hydrogen storage system to be charged. Hence, the fuel cell keeps the system operating continuously by maintaining the battery charged.

It is clear from the results that the renewable energy systems that incorporate PV modules in areas with higher average annual solar radiation have the lowest cost of energy. This result can be seen in Miami, with the highest solar intensity (4.79 kWh/m^2/day) and minimum COE (0.64 $/kWh). These variations in the weather data affect the simulation results and lead to different combinations of the system's components. The best configuration is chosen where the minimum levelized cost of energy is achieved while the renewable contribution is 100%. Thus, renewable energy potential in Miami is better than either Toronto or Washington due to the higher solar radiation potential.

5. CONCLUSIONS

This paper develops and investigates a comparative analysis between three renewable energy-based systems of PV/battery, PV/ hydrogen, and PV/hydrogen/ battery for a house in Toronto. In order to find the optimum configuration with ideal components size and minimum COE and NPC, HOMER software is used. According to the results, the battery bank can be replaced with the electrolyzer, FC, and hydrogen tank; however, the NPC increases due to the high costs of the components. The results show that integration of 12 kW PV panels, 2.50 kW FC, 10 kW electrolyzer, 50 kg hydrogen tank, 2 kW converter, and 24 kWh of batteries storage bank is the best configuration that leads to the minimum NPC of $61,024.09 and levelized COE of 1.14 $/kWh in Toronto. The simulations were repeated for Miami and Washington for each system to compare solar renewable energy potentials in each area. According to the results, system 3 (PV/battery bank/hydrogen) results in the least COE (0.64 $/kWh, 0.66 $/kWh) and NPC ($ 34,109, $35,236) in Miami and Washington respectively. However, Miami and Washington have better renewable energy potential due to their higher solar radiation intensity than Toronto.

The findings of the present simulation provide helpful information about the renewable energy potentials. In subsequent investigations, other renewable energy potential application will studied to cover energy demands all around the year successfully.

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