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Optimal design of solar energy-based hydrogen refueling station: a case study of Touggourt, Algeria

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Abstract

Carbon production is growing globally, with energy-related carbon emissions accounting for two-thirds of global emissions. Generating carbon-neutral hydrogen from renewable energy is a significant achievement toward a circular economy in this industry. Hydrogen can contribute to reducing gas emissions in the future decades, not just as a potential technology for the future but as a successful technology already being implemented globally. Hydrogen is required for the clean transportation sector and multiple different industrial applications. However, the high cost of clean hydrogen production reduces the rapid development of renewable energy projects established on hydrogen production. So, optimizing design is required to choose the optimum solutions for clean hydrogen production. In this context, this short paper aims to investigate a techno-economic optimization of a hydrogen refueling station with a 262 kg/day capacity in Touggourt City, Algeria (latitude of 33° 6.3' N and the longitude of 6° 4.0' E), based on photovoltaic energy resources. The paper analyses the configuration of a

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stand-alone PV system with batteries. The analysis of this arrangement is based on the solar potential at the site, costs of various equipment, electrical load, and hydrogen load. Thus, the study aims to identify the optimized capacity of PV arrays, electrolyzers, batteries, power converters, and hydrogen tanks.

Keywords: Solar energy, Green hydrogen, Hydrogen refueling station, Optimal sizing, Techno-economic, Touggourt region.

1. Introduction

The World's energy need is escalating drastically, and energy production is primarily dominated by oil and coal-based energy generation systems. Fossil fuels are available in limited amounts and cause greenhouse emissions[1]. Moreover, the transportation sector consumes a considerableamount of total fossil fuel and generates vast quantities of carbon dioxide.In the last decades, there hasbeen an increasing need for renewable energy production toreduce greenhouse gas emissions and improve the sustainability of cities[2]. Particularly in the transport industry, using electric, hybrid, and fuel cell vehicles permits considerably reduces gasemissions [3].

Furthermore, population growth hascaused several countries to focus on renewable energies thatare less expensive and sustainable to meet their electrical demands [4].To address these challenges, producing electrical energy utilizingphotovoltaic systemsis being employed to convert solar to electrical energy using PVsystems and solar concentrators, which have been effective in several countries [5]. Other familiar sources of renewable energy that prove high potential includegeothermal, tidal energy, and wind power [6].The applications of renewable energy in different sectorshave been reported, among which electric and green hydrogenvehicles lead to future transportation [7].Green hydrogen (GH_2) is a superb fuel with a high-power storage capacity, and its combustion generates only water without causing ecological pollution.Moreover, H_2 has a cost-effective advantage over batteries storages because it can stock energy for long-term periods [8].

On another note, in recent years, much work has been done on modeling and evaluating renewable energy systems to facilitate their deployment and analyze their behavior and performance in different scenarios. For the modeling and simulation of hybrid systems, several software tools, including HOMER, TRNSYS, RETScreen, and Dymola/Modelica, have been created [9].Hybrid Optimization of Multiple Energy Resources (HOMER) software[10] is one of the software that has found applications in numerous energy feasibilities and optimization analyses. The software has been utilized to conduct feasibility studies of various energy systems, each indicating positive outcomes.Therefore, this paper provides an optimal designand techno-economic analysis of a hydrogen refueling stationbased on a photovoltaic power system in Touggourt (Algeria). HOMER Pro software was used to design and optimize the renewable power system. Thephotovoltaic array was utilized as a critical power source to feed the electric load requirementand supply the electrolyzer for hydrogen production. During the surplus times, additional electrical energy was utilized to recharge the battery series.

2. Location of the study

Touggourt is located in thesoutheast of Algeria at the latitude of 33° 6.3' N and the longitude of 6° 4.0' E and is considered in this study as shown in Fig. 1. The city is approximately 660 km away from the capital city of Algeria. The Touggourt community has significantly high global radiation throughout the year.

Figure1. The geographical location of Touggourt.

3.The load profile

The load assessment of the refueling station (RFS) presented in this section has a daily average load of 13.53 kWh/day for the electric load, whereas the hydrogen load with 262 kg/day.

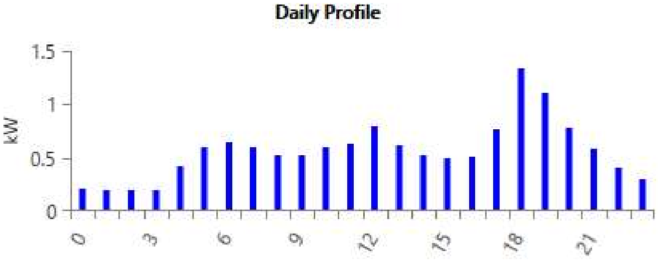

Figure2. Hourly average electric load variations.

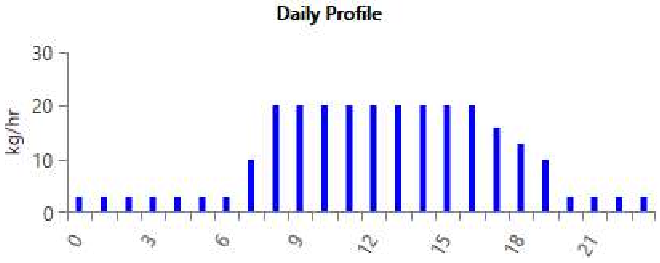

Figure3. Hourly average hydrogen load variations.

As shown in Fig. 3 and 4, the hourly average daily load variations for both the electrical and hydrogen. It is noted that the daily peak electric load occurs at 18 h, where the highest value of hydrogen load was recorded at 8 h to 16 h with 20kg.

4. System Configuration

The proposed system consists of photovoltaic cells, batteries, and an electrolyzer to store hydrogen in a hydrogen tank and a converter. HOMER Pro software was used to model the system to meet the energy needs of the hydrogen refueling station. Fig. 2 shows the schematic of the stand-alone system.

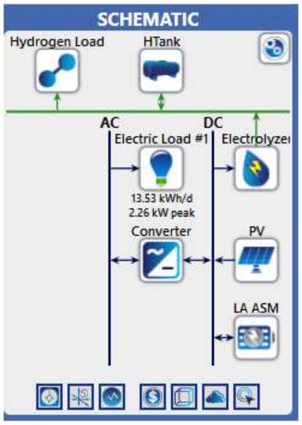

Figure4. Schematic of the proposed system.

The energy management in the system is carried out as follows: the PV feeds the desired load demand and powers the electrolyzer to generate H_2 and stored in the hydrogen tank for refueling station, and charging batteries if the battery's SOC is minimum until the total capacity of the battery is reached, the batteries are required to provide electricity to loads during nights.

5. Optimization results

After the simulation process with Homer software and considering the capacities of different system components, the capacities are obtained and presented in Table 1 presents the optimum configurations. The 100% renewable energy system would have a PV capacity of 28.056 MW, an electrolyzer power capacity of 1.2 MW, a hydrogen tank of 17000 kg, a 2.424 MW power converter, and 2.06 kWh of batteries.

Table 1. Optimized system component sizing.

Component	Size
Generic 1kWh Lead Acid [ASM]	two batteries of 1.03 kWh
Generic Electrolyzer	1200 Kw
Generic flat plate PV	28056 Kw
Hydrogen Tank	17000 kg
System Converter	2.424 Kw

The PV system produces around 52 077,940 kWhper year of electricity with a maximum power of 28 056 kW produced at noon, as shown in Fig. 5. The generated electricity decreases continuously to reach zero at 6.00 pm.

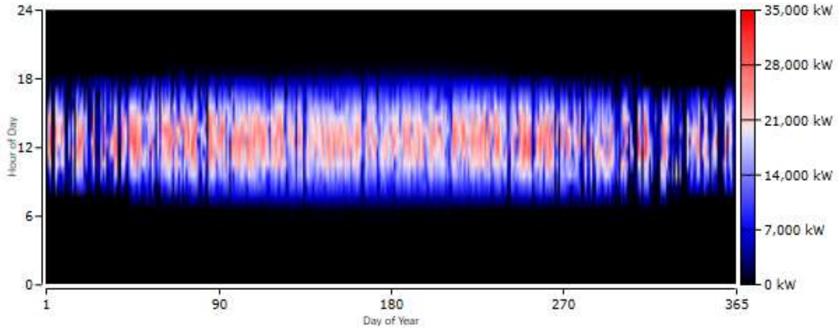

Figure5. PV Power Output.

The electrolyzers consume electricity to produce hydrogen from water.To minimize the cost of green hydrogen production, the electrolyzers are turned on during sunny hours, as shown in Fig. 6, as at this time, the electricity produced by PV panels is available. The electrolyzers are turned off from 6.00 pm to 8.00 am as the PV system provides no green electricity.

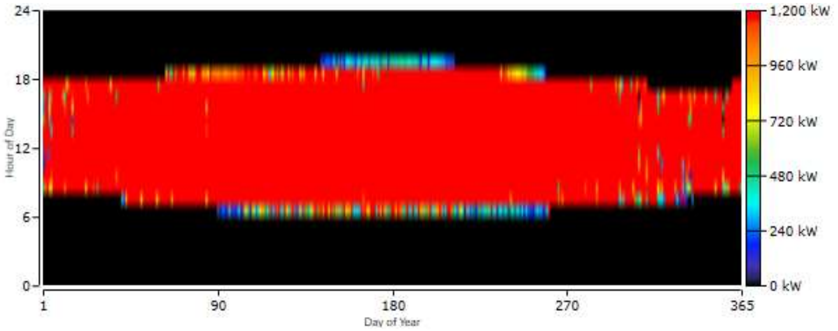

Figure6. Electrolyzer input power.

The monthly hydrogen produced in the electrolyzer is shown in Fig. 7. There is a close agreement between the electricity generated by the PV and the hydrogen produced by the electrolyzer; the amount of hydrogen produced is related to the supplied electricity since electricity is used to initiate the electrochemical process observed during water electrolysis.

Figure 7.The monthly hydrogen produced

The performance of the battery system during the charging and discharging cycles is presented in Fig. 8, where the batteries' daily and hourly State Of Charge is plotted. We noticed that the battery system has the lowest SOC during the autumn and winter.

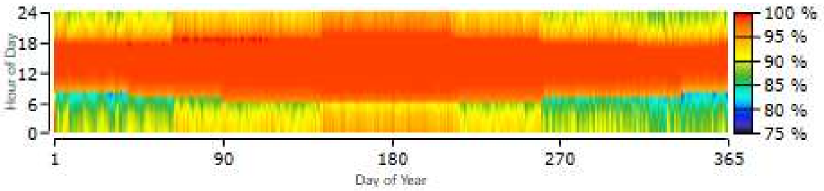

Figure8. State Of Charge.

The hydrogen produced by electrolyzers is stored in special tanks for the refueling station. The hydrogen tank level variation versus the day of the year for a whole year is given in Fig. 9.

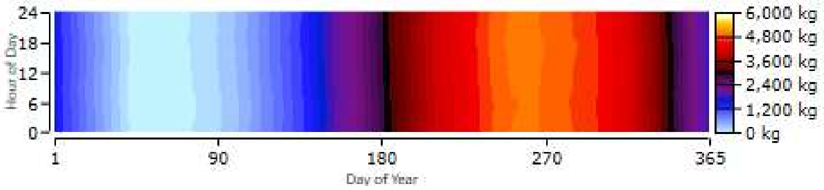

Figure9. Tank Level.

6. Cost optimization

In the price optimization technique, HOMER Pro simulates every system design and shows the possible ones, organized by the Net Present Cost. As defined in Eq (1), the cost of the system (C_S) is the total price of its elements (the cost of the PV system (C_{PV}), the cost of the PEM electrolyzer (C_{Elect}), the cost of theH_2 tank (C_{H_2T})), the cost of batteries (C_B) and the converter cost (C_C)).

$$C_S = C_{PV} + C_{Elect} + C_{H_2T} + C_B + C_C \tag{1}$$

The following formula gives the cost of every part:

$$C_i = N_i[C_{Cap,i} + (C_{Rep,i} + N_{r_i}) + C_{OM,i}] \tag{2}$$

where N_i: is the number of the element of the HES, $C_{Cap,i}$: is the capital cost of each component, $C_{Rep,i}$: is the replacement cost of each component, N_{r_i}: number of replacements suffered, $C_{OM,i}$: the operation and maintenance price of each component [11]. Tab. 2 summarizes the related costs of each system component; the overall COE rate was \$638.03.

Table 2. The cost of the system and its components.

Component	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Total ($)
Generic 1kWh Lead Acid [ASM]	14,400.00	5,532.35	6,205.21	1,746.32	24,391.24
Generic Electrolyzer	2,400,000.00	0.00	465,390.60	0.00	2,865,390.60
Generic flat plate PV	19,639,185.66	0.00	5,077,717.95	0.00	24,716,903.61
Hydrogen Tank	11,050,000.00	0.00	1,098,838.91	0.00	12,148,838.91
System Converter	727,124.02	308,499.69	0.00	58,062.76	977,560.95
System	33,830,709.67	314,032.04	6,648,152.66	59,809.07	40,733,085.31

Fig. 10 displays the Cost summaryof all the components considered in the analysis generated by the HOMER software.

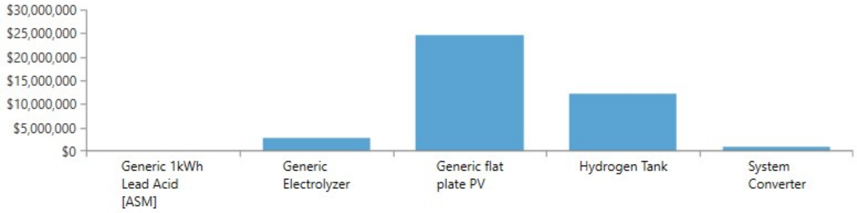

Figure10. Cost summary.

As displayed in Fig. 10,it can be seen that the PV has the highest total cost of $ 24,716,903.61, whereas the battery has the least total cost of $ 24,391.24.

7. Conclusion

This work offered an optimal design of a stand-alone photovoltaic system with battery storage. This configuration fed a hydrogen refueling station of 13.53 kWh/day electric and 262 kg/day hydrogen in Touggourt city. HOMER Pro was utilized to optimize the behavior of the power system. The results were compared to identify the better size of the system based on the least overall Net Present Cost and Cost of Energy. The optimum finding outcomes presented a 28056 kW PV array, two batteries of 1.03 kWh each, a 2.424 kW converter, a 1200 kW electrolyzer, and a 17000 kg hydrogen reservoir was the best choice to equip the hydrogen refueling station. Future work includes adding other renewable energy sources to make a hybrid system for hydrogen refueling stations to minimize the capacity of the PV modules.

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