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Techno-economic comparison between PV and wind to produce green hydrogen in Jordan

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Abstract. The world has begun to move towards searching for the best ways and means to be able to produce hydrogen gas in a healthy and environmentally friendly manner. Especially after manufacturing cars that run on hydrogen, many home appliances in the future would operate using hydrogen. This research paper aims to provide a detailed study and comparison for the potential of photovoltaic energy and wind energy in hydrogen gas production using electrolyzes technology for home applications. In this study, a mathematical model is proposed to predict hydrogen production by means of the two renewable energy sources. Furthermore, the mathematical model computes the electrical energy produced from the fuel cells using the produced hydrogen gas and evaluate its levelized cost. The study was conducted based on the technical specifications based on Jordanian codes and conditions. Results showed that photovoltaic energy system is the best solution compared to other proposed systems which can produce 30,140.5252 kg of hydrogen and produce 1,264,551 kWh/year with the lowest hydrogen levelized cost of 13.262 $/kg.

Introduction

Green hydrogen, a clean energy carrier, is crucial to decarbonization, but its cost is currently high[1]. This is mainly due to the cost of electrolyzers, which split water into hydrogen and oxygen [2]. However, electrolyzer costs are expected to decline significantly in the coming years, making green hydrogen more competitive[2]. Innovation is one of the key factors in reducing electrolyzer costs. This includes developing cheaper electrodes and catalyst materials, and increasing production volumes [2]. By 2030, green hydrogen could be cost-competitive with blue hydrogen in many countries [3]. Another important consideration is the use of renewable energy sources specifically for hydrogen production [4]. This would help reduce the overall cost of green hydrogen. Other challenges include taking into account weather fluctuations and hourly electricity consumption in the system design [5].As well as assessing the environmental impact of the entire production chain, not just the electrolyzers [6]. In addition to incorporating energy storage to manage intermittent renewable energy sources [7]. Research is ongoing to address these challenges and further reduce the cost of green hydrogen. This includes optimizing system design, developing advanced energy storage solutions, and making realistic comparisons of solar and wind energy for hydrogen production [8], [9].

Green hydrogen has the potential to play a major role in decarbonizing the energy sector. Continued research and development efforts are essential to make this a reality. The success of this technology highly depends on the hydrogen production cost per one kilogram [10]. The main idea of this study is to make a real comparison between solar energy and wind energy in hydrogen production and its cost based on Jordanian conditions and policies. The study is done by using mathematical models and using Homer program. This study aims to give a valuable insight that helps policymakers in decision making for selecting and implementing the optimal renewable hydrogen powered home[11].

Methodology
Based on what was mentioned, mathematical calculations and simulations of two different systems will be performed. The first system will be hydrogen production through photovoltaic panels. The second system is hydrogen production through wind turbines.

1) electrical load estimation
Electricity consumption bills for 12 months are used to determine the load of a single house. The energy consumption of different appliances and their operating hours are proposed in table 1.
The total annual home energy consumption for a single house in Jordan is calculated using equation 1.

Table 1 Annual Electricity Consumption for the Electrical Appliances`

DATA	Summer Hours	Winter Hours	Units	Rating (W)	Summer Consum-ption/day	Winter Consum-ption/day	Annual Energy Consumption (kWh)
Small LED Spots	3	5	15	11.5	0.52	0.86	251.9
LED Smart TV	5	5	2	150	1.5	1.5	547.5
Air Conditioner	2	1	1	3000	6	3	1642.5
LED Bulbs	3	5	40	15	1.8	3	876
Phone Charger	3	3	5	25	0.38	0.38	136.9
Laptop Charger	5	5	5	65	1.63	1.63	593.1
Printer	0.5	0.5	1	1.27	0	0	0.23
Suction Fan	0.4	0.5	4	60	0.1	0.12	39.42
Speed Water Heater	0.1	0.4	1	5500	0.55	2.2	501.9
Washing Machine	1.5	1.2	1	1500	2.25	1.8	739.1
Fridge	6	6	2	600	7.20	7.2	2628
Water Pump	0.7	0.4	1	550	0.39	0.22	110.4
Water Cooler	6	6	1	5	0.03	0.03	10.9
Water Heater	0	5	1	1500	0	7.50	1368.8
Food Processor	0.1	0.1	1	250	0.03	0.03	9.1
Grill	0.1	0.4	1	1400	0.14	0.56	127.8
Water Filter (RO)	4	2	1	750	3.00	1.50	821.3

Air Fresher (Suction Duct)	0.2	0.2	1	200	0.04	0.04	14.6
Drying Machine	0	1	1	2700	0	2.7	492.8
Stand Blender	0.1	0.1	1	250	0.03	0.03	9.1

$$Energy\ (kW/h) = Power\ (kW) * Time\ (h) \quad (1)$$

The total annual electricity consumption for each home in Jordan based on the above loads is estimated to be 10921 $\frac{\frac{\text{kWh}}{\text{Year}}}{\text{Home}}$, resulting in a total of 1,092,100 kWh/year for a hundred homes.

2) hydrogen production

The amount of hydrogen production that can satisfy the annual electricity consumption for 100 homes can be calculated from equation 2 [12].

$$Hydrogen\ (kg) = \frac{Electricity\ (kWh)}{Heating\ Value\ \left(\frac{MJ}{kg}\right) * Fuel\ Cell\ Efficiency\ (\%) * Electrochemical\ Conversion\ (\%) * \ Conversion\ Factor\ \left(\frac{MJ}{kWh}\right)} \quad (2)$$

A solid oxide hydrogen fuel cell from Bloom energy company was chosen for this particle study, due to its high efficiency, fuel flexibility and low emissions. The selected fuel cell has a high efficiency and electrochemical conversion of 52 % and 80% respectively. The total amount of hydrogen produced by the selected fuel cell to satisfy the annual electricity of 100 homes is calculated to be 18817.1 kg/year when using hydrogen with a heating value of 119.96 MJ/kg [13].

3) photovoltaic energy system's design

Photovoltaics are an important technology for generating electricity using solar energy[14]. This technology can be integrated in many applications such as greenhouses[15], and battery charging[16]. The photovoltaic system capacity highly depends on the sunny hours. Based on the Energy and Minerals Regulatory Commission (EMRC) in Jordan, the useful sunny hours during the year in Jordan is around 1540 h/year. The power needed to run a 100 house in Jordan can be calculated from equation 3.

$$Power = \frac{Energy}{Time} \quad (3)$$

To generate electricity with a capacity of 709 kW that satisfies the demand. A commercial photovoltaic panel Trina Vertex with a capacity of 555 W is chosen for this application. Trina is considered a well-known and trustable brand that is widely found in Jordanian market. A total of 1273 panels are needed for the one hundred houses.

The price and cost of the selected solar panels are established by the Consolidated Energy and Economic Engineering Company. Table 2 shows the cost of the suggested PV panels, where the cost of each Watt of (Trina Vertex 555W) is 0.27 $/Watt.

Table 2 PV Panel Cost

Capital Cost ($/KW)	Replacement ($/KW)	O&M ($/Year)	System Life Time (Years)	Derating Factor (%)
270	270	10	25	84.8

For the AC side of the whole PV system SMA inverters were used with 1.5 (DC/AC) ratio to ensure the highest number of operating hours for the solar inverters at their maximum power point tracking.

Regarding the cost of the solar inverters, SMA solar inverters are priced also by the Consolidated Energy and Economic Engineering Company and can be presented in table 3.

Table 3 Solar Inverter Cost

Capital Cost (\$/KW)	Replacement (\$/KW)	O&M (\$/Year)	System Life Time (Years)
174	174	5	25

4) Wind energy system's design

The design of wind energy system higly depends on the wind speed. According to Wind Atlas software the average wind speed in Amman-Jordan is 7.12 m/s. The available wind power potential can be calcualted using equation 4.

$$\dot{W}_{Available} = 0.5 * \rho * A * V^3 \quad (4)$$

Where ρ is the density of the air at specific temperature, A is the wind turbine swept area, and V is the average wind speed.

For this specific study Vestas V82-1.65 is selected. The wind turbine is manufactured by Vestas company with a swept area of 5281.01 m^2 and power preformance presented in figure 1.

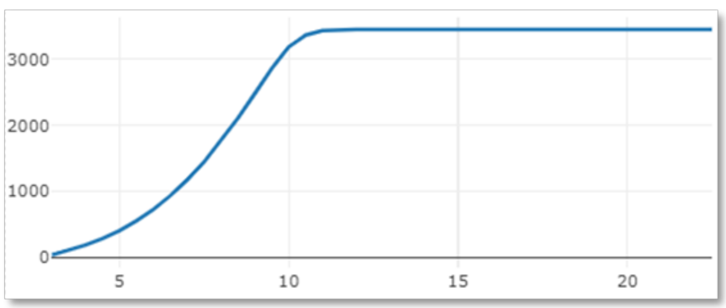

Fig. 1 Vestas V82-1.65 Power Curve

The selected wind turbine was priced by Al-Fujeij Wind Energy Company and summarized in table 4.

Table 4 Wind Turbine Specification and Cost

System Capacity (One Turbine)	Hub Height (m)	Capital Cost (\$/Turbine)	Replacement (\$/Turbine)	O&M (\$/Year)	System Life Time (Years)
1650 kW	100	1,980,000	1,980,000	20,000	20

Results and Discussions

Energy and economic comparison for the two proposed renewable energy systems is done using Homer software [11]. Various results concerning the system potential, costs, and technical specifications are reached and discussed. The first section delves into the results of integrating the system with the PV system. while the other section discusses the results of integrating the system with wind system.

1) PV system

The PV/hydrogen proposed system consists of five main components which are the electrolyzer, PV, inverter, grid, and hydrogen tank. These components relate to each other as shown in figure 2.

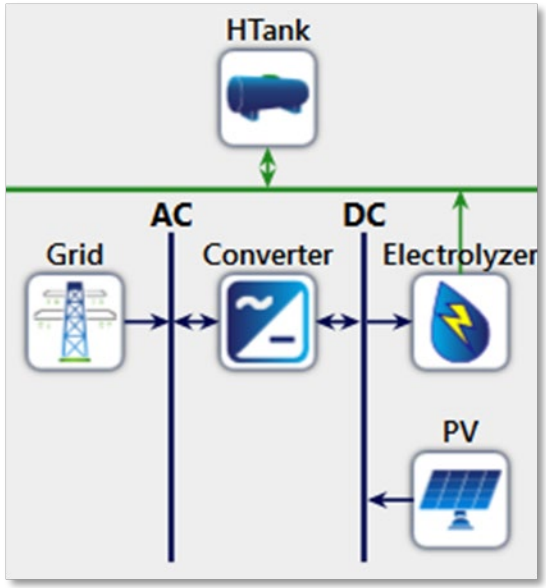

Fig. 2 PV System Schematic Diagram

The results from the mathematical models in the previous section are considered as an input for Homer software [11]. The main idea of these calculations is to reduce the size of the system as much as possible to fit the loads without creating any excess production beyond the energy-consuming facility's need. Important results after running the software can be summarized in table 5.

Table 5 Calculated PV System Output Data

Data	Unit	Value
Net Present Cost	($)	312,062
Levelized Cost of Energy (LCOE)	($/kWh)	0.0104
Payback Period	(years)	1.49
CO_2 Emissions	(kg/year)	388,581
Renewable Fraction	(%)	64.9
Annual PV Production	(KWh/year)	1,264,551
Grid Purchases	(KWh/year)	614,844
Total Hydrogen Production	(kg)	30,140.5252
Hydrogen Produced using PV (Green Hydrogen)	(kg)	21,788.2137
Levelized Cost of Hydrogen	($/Kg)	13.262

Table 5 represents the simulation results of the first experiment of this study, the amount of electrical energy produced from photovoltaic panels is considered appropriate and sufficient to cover the needs of electrical energy consumption in operating the electrolyzers for the purposes of producing green hydrogen while considering the losses during energy transmission, distribution, and losses inside the electrolyzers.

2) Wind Turbines

The wind/hydrogen proposed system consists of five main components which are the electrolyzer, wind turbine, inverter, grid, and hydrogen tank. These components relate to each other as shown in figure 3.

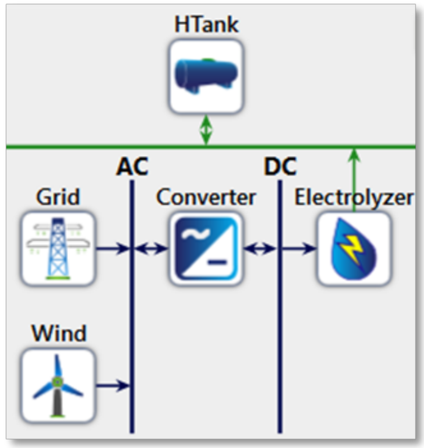

Fig. 3 Wind System Schematic Diagram

A wind farm is suggested to be in Al-Muwaqqar area in Amman, which is known for its low population density. The clean energy from the farm can be used to operate the electrolyzers to produce green hydrogen. The technical specifications and costs of the wind turbines mentioned in previous sections are also considered as an input for Homer software [11]. Different results are obtained and can be presented in table 6.

Table 6 Monthly Electric Production for the Wind System

Data	Unit	Value
Net Present Cost	($)	984,785,100
Levelized Cost of Energy (LCOE)	($/kWh)	0.1379
Payback Period	(years)	1.94
CO_2 Emissions	(kg/year)	63,533
Renewable Fraction	(%)	100
Annual Wind Production	(KWh/year)	552,150,642
Grid Purchases	(KWh/year)	100,527
Total Hydrogen Production	(kg)	9,515,287.625
Hydrogen Produced using Wind (Green Hydrogen)	(kg)	9,513,555.562
Levelized Cost of Hydrogen	($/Kg)	26.7368

It is noted from table 6 that the option of using wind turbines is considered very expensive in terms of the initial cost. Moreover, wind turbines located in Jordanian capital is not considered a good

Approach, as the wind speed inside the region does not exceed 10 m/s which is considered low compared to other locations. The turbine will not reach its natural production capacity. The high cost of producing electricity also leads to a significant increase in the cost of hydrogen.

In terms of levelized cost and hydrogen production the PV/hydrogen system is considered a better option compared to wind/Hydrogen system, where the levelized cost of the first system is 13.5 $/ kg less than of that of wind/hydrogen system.

Conclusion

A techno-economic investigation for hydrogen powered homes in Amman-Jordan based on solar energy and wind energy is presented in this study. The study utilizes mathematical models and Homer software to explore electricity, hydrogen production, and evaluate hydrogen levelized cost. The study is conducted based on Jordanian technical specifications and conditions. Based on the results it is concluded that PV integrated with hydrogen system is a better option than wind turbine integrated with hydrogen system. This is due to the ability of the system to meet the electrical load correctly without causing any disturbances in the network, while also producing 30,140.5252 kg of hydrogen at a low hydrogen levelized cost and payback period of 13.262 $/kg and 1.49 years respectively. The CO_2 emitted from the PV/hydrogen system is considered greater than from Wind turbine/ hydrogen system which was 63,533 kg/year. This high amount of CO_2 emissions is due to the electricity purchase from the grid.

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