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Techno-Economic Analysis and Simulation of a Photovoltaic-Wind Hybrid System for Grid-Independent Applications

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ABSTRACT

The utilization of solar and wind energy as alternatives to fossil fuels is gaining increasing significance in the quest for sustainable energy solutions. Hybrid systems, comprising multiple power generation units driven by diverse energy sources, offer enhanced reliability compared to single-source systems. Among these, photovoltaic-wind turbine hybrids have emerged as a promising configuration, capable of meeting extensive and dynamic energy demands. In certain hybrid systems, domestic batteries are employed to counter daily fluctuations, facilitating the conversion and storage of energy for grid-independent applications. The present study conducts a techno-economic analysis of such a hybrid system, employing HOMER software for power supply simulations. Results indicate that the optimal configuration encompasses 10 kW photovoltaic cells, a 10 kW wind turbine, a 4 kW water electrolysis device, a 10 kW converter, a 1 kW fuel cell, and a 1 kg storage tank.

1. INTRODUCTION

The global energy landscape is shifting due to escalating energy demand, rapid depletion of fossil fuel resources, and increasing fossil fuel prices. These factors have driven efforts to reduce reliance on nonrenewable energy sources and promote the adoption of sustainable alternatives [1, 2]. Renewable energy sources, which are virtually inexhaustible, hold the potential to supply more energy than the current global electricity demand and can be harnessed without incurring significant costs [3, 4]. However, the intermittent nature of sources such as wind turbines and stand-alone photovoltaic cells poses challenges for continuous and stable energy generation [5, 6].

To address these challenges, researchers have investigated various hybrid system configurations that combine multiple renewable energy sources to enhance system reliability and performance. Previous studies have conducted comparative cost analyses on grid-connected systems utilizing fuel cells, demonstrating that connected power supplies are more cost-effective than disconnected ones if the distance from the network supply base exceeds 4.4 km [7]. Another study simulated a hybrid system using HOMER software, showing that photovoltaic-wind-battery structures offer economic and environmental advantages [8]. Furthermore, a wind-diesel hybrid system was installed and tested over a year, revealing superior efficiency in wind technology compared to other energy systems [9, 10]. Hybrid power projects have been found to be more stable than independent photovoltaic systems due to the lack of solar radiation in terms of power supply [11]. Technical and economic analyses of off-grid wind energy and fuel cell hybrid systems have indicated that the use of hybrid systems enhances the capacity factor by 2.8 percent [12, 13].

In the present study, four arrays (2, 4, 6, and 8 kW) are analyzed in a grid-independent building with a specific daily load consumption. The size of each energy system required to supply this load is determined using HOMER simulation, taking into account hydrogen storage as an energy carrier in the hybrid system and the increased load resulting from water electrolysis devices and hydrogen compressors. By converting solar and wind energy into electricity, this hybrid system is capable of producing and storing clean hydrogen, which can be utilized in a fuel cell consumer at any time. This research aims to contribute to the ongoing efforts in developing efficient, reliable, and sustainable energy systems for a cleaner energy future.

2. STUDY AREA

Located in the northeastern region of Thailand, Khon Kaen serves as the political and economic hub of the area and boasts the highest population growth rate in the region. This rapid urbanization and economic development have, in turn, led to an increased demand for reliable and sustainable energy solutions. In 1997, the city had a total population of 152,601 residents. Following the Asian financial crisis in 1997, a significant number of people relocated to rural areas, resulting in a decrease of over 12 percent in population the subsequent year [14].

The site for the Khon Kaen energy project lies at a longitude of 102.80873, a latitude of 16.46048, and an elevation of 166 meters above mean sea level. The region receives an average annual solar radiation of 5.4 kWh per square meter per day, making it a suitable location for harnessing solar energy. The data acquired from the anemometer station is based on an annual average wind speed of 3.4 meters per second, indicating the potential for wind energy generation [14]. The selection of this study area showcases the importance of investigating renewable energy solutions in rapidly developing regions, as the successful implementation of hybrid systems in such areas can contribute to a more sustainable energy infrastructure and reduce the reliance on fossil fuels.

3. THE MAIN COMPONENTS OF THE SYSTEM

3.1 Wind turbine

Wind is one of the endless sources of energy in the world, which is caused by thermodynamic differences such as temperature and pressure differences between adjacent areas [15]. One of the best ways to utilize wind energy is to generate electrical energy from wind. A wind turbine converts kinetic energy in the wind into mechanical energy that can be used for a variety of purposes. By placing a wind turbine in the wind direction and transferring the mechanical energy of the turbine to a generator, direct or alternating current is generated directly or through the gearbox with the appropriate conversion ratio [16].

Estimating the amount of energy that can be obtained from a wind site is one of the most important parts of installing and setting up a wind turbine device. Wind energy density is a good way to estimate the amount of potential in the air at a wind site. Wind power density indicates the amount of energy that a wind turbine can absorb from the air. Because air has mass and produces wind when it moves, it has kinetic energy [17]. Wind power is the kinetic energy that passes through level A at a constant velocity V and is obtained from the following equation in which A is the area swept by the wind turbine impeller in square meters, ρ is the density of air and P is the power per sense (Eq. (1)). The rotor diameter and wind speed are the two primary factors that determine the revolutions per minute (RPM) speed of a three-blade turbine. Wind turbine energy curve are shown in Figure 1.

$$P = \frac{1}{2}\rho A V^3 \tag{1}$$

The wind turbines used in this analysis have a capacity of 1 kW and an AC output voltage.

3.2 Photovoltaic module

Photovoltaic systems are an important source of renewable energy that generates direct current using solar energy. The main factors that determine the efficiency of photovoltaic systems are temperature, the efficiency with which energy is converted, solar shadings, the orientation, inclination, and latitude of the location, as well as climatic conditions, operation, and monitoring. Solar panels are made of special photovoltaic cells and are connected to each other. They are usually classified as 12V and more than 12V are available [18, 19]. In this study, 4 arrays in the sizes of (2, 4, 6, and 8) kW have been analyzed. Considering the lifespan of 15-20 years of photovoltaic systems, this technology, as one of the important and efficient tools in the application of new energies, can be a suitable response to provide electricity in areas outside the national grid and difficult to cross.

3.3 Battery

Due to the intermittent nature of the solar wind system, the importance of using energy-saving systems to generate continuous power becomes apparent. Due to the economic importance of this analysis, lead acid batteries were used for energy storage [20]. The cost of lead-acid batteries is significantly lower than the cost of other types of batteries. This is the primary benefit of lead-acid batteries. As a result, the disadvantages of lead-acid batteries include their weight and volume, as well as their low specific energy and stringent charging and discharging requirements.

3.4 Converter

The converter is actually a converter of DC to AC power or vice versa. In this plan, the electricity required for the water electrolysis device is of three-phase current and voltage of 390V. Therefore, the electricity from photovoltaic cells must be provided according to the characteristics and needs of the consumer, so it must be used from direct current to alternating current converter (Figure 2) [21]. The converter converts the DC voltage from the solar module to the AC voltage to supply the energy required by the consumer [22]. In this system, the direct current generated by the modules installed by a proportionate number of converters in the Sunny Boy Model is converted to alternating current. The advantages of selecting these converters include small volume, high efficiency and high operating speed. These converters are available in various capacities and according to the amount of energy of each pilot, the need of each of the desired systems provide. Table 1 presents the technical specifications of the Sunny Boy Model 2500 converter used in this study.

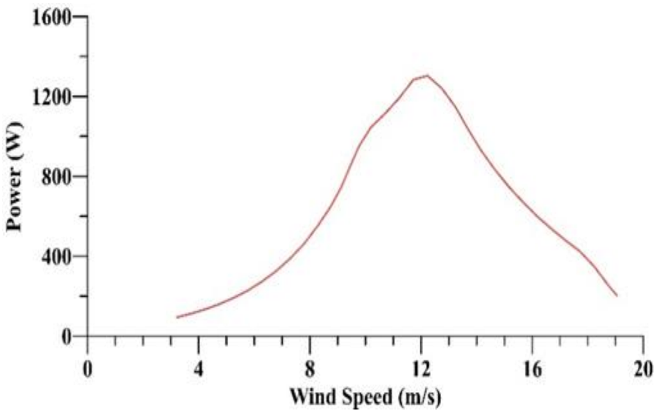

Figure 1. Wind turbine energy curve

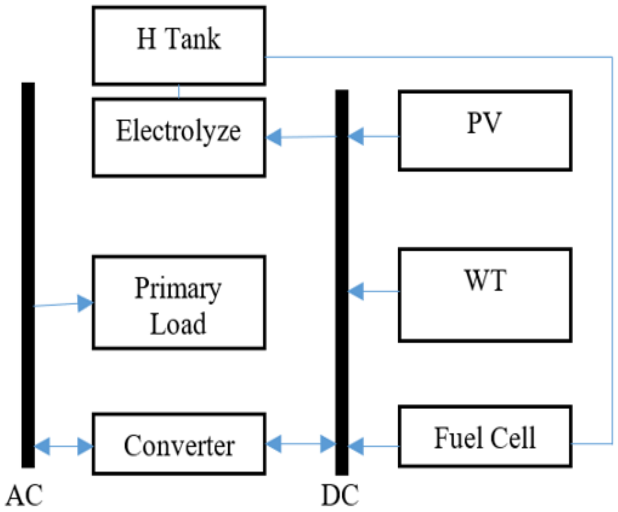

Figure 2. Schematic of photovoltaic/wind hydrogen system

Table 1. Technical specifications of Sunny Boy converters

Sunny Boy type		2500
Input	Recommended max PV-power	3.4 kW_p
	Max input voltage	500 V
	Voltage	220-500 V
	Max input current	10 A
Output	Max AC-power	2.5 kW
	Nominal AC-power	22.5 kW
Efficiency	Max efficiency	93%
Power consumption	Internal consumption in operation	<9 kW
	Internal consumption in standby	0.25

3.5 Water electrolysis device

Water electrolysis is a method of hydrogen production and is considered a clean fuel if the required electricity is provided to decompose water from renewable energy sources [23]. Water electrolysis devise are well adapted to a variety of renewable energies, allowing diffuse hydrogen production systems to manage consumption at peak hours, using stored hydrogen to be used at night in low-capacity fuel cells. To provide to some extent. In the method of electrolysis of water, by passing a direct current of electricity through water, it decomposes it into its constituent components, namely H_2 and O_2 gases [24]. The water electrolysis device model 10/EV05 used in this study is of alkaline type, bipolar and consists of 10 cells and its current is 250 amps in nominal conditions. The water electrolysis device has a capacity of 5 kW and is manufactured by the German company T and is able to produce a maximum of one cubic meter of hydrogen gas per hour under normal conditions. The nominal efficiency of the electrolysis device used in this pilot is 80% [25]. Technical specifications of water electrolysis device are as following:

- Hydrogen Gas Production/h: up to 1000L per hour;
- Oxygen Gas Production/h: up to 500L per hour;
- Pressure: 0-10bars;
- Temperature: 50-80°C;
- Input Voltage: 320VAC;
- Electrolyte: Alkali Solution (KOH, 30wt%).

3.6 Hydrogen storage tank

Hydrogen storage has economic advantages over lead-acid batteries for long-term storage. The energy density of hydrogen per unit mass is very high, but due to the low density of the gas, its energy density per unit volume is very low [20]. Hydrogens energy density per unit volume is very low. However, hydrogen energy per mass of any fuel capability is high. According to this matte, it was requiring the development of advanced storage methods that have the potential for higher energy density. In order to achieve the maximum amount of energy, it is necessary to store a large amount of hydrogen. Hydrogen is stored in solid, liquid, and gaseous form, and gaseous hydrogen storage is one of the simplest, most common, and cheapest storage methods. In this project, a one cubic meter tank has been used to store hydrogen gas up to a maximum pressure of 8 bar [26].

4. PHOTOVOLTAIC/WIND ENERGY SIMULATION WITH HYDROGEN STORAGE

Hydrogens can, along with renewable energy sources, allow energy to store energy and receive appropriate efficiency from these systems. In hydrogen energy implies by converting solar and wind luminous energy into electric nor, hydrogen-electricity is provided, the possibility of producing and storing hydrogen as a carrier of energy, which can be used in consumers after storing at any time and place in consumers [27]. A study showed that the inverter and charge regulator efficiencies in this system are as 90% and 98% respectively [28]. In this technology, the electricity required by the water electrolysis machine is supplied to its constituent components, namely hydrogen and oxygen gases from the photovoltaic and wind turbine cells. The hydrogen produced from the water electrolysis machine is compressed by the hydrogen compressor and is stored in the tank of one cubic meter up to 8 bar pressure to use the fuel cell when needed, and during the hydrogen and oxygen electrical process React and generate electricity.

An analysis of the Photovoltaic/Wind Energy Simulation is presented in the Table 2, in which the costs of the energy system are calculated with twenty years [29]. During the project, water electrolysis, hydrogen storage tank, wind turbine and converts will be used until the end of the project and will not be replaced. In addition, the cost of some of the issues such as installing solar modules, direct current wires, installing modules against the overall cost of the system has been ignored and ignored. To perform technical and economic analysis, this design is sufficient to use the exact information of each component of photovoltaic cells, wind turbine, water electrolysis system, fuel cell system, converts, as well as parameters such as length And the latitude of the site, the useful life span of the project, the average profit and interest rate, the average annual radiation, the daily radiation, the annual wind speed, the spread of environmental pollutants, the amount of energy consumption per day, and the optimum The most suggested plan.

In the simulation process, all possible scenarios and then traces them according to the Net Present Cost (NPC) were simulated, and finally introduces the arrangement achievable by the least NPC as the optimal arrangement. The results of the calculations show that the most optimal energy system proposed consists of 10 kW of photovoltaic cells, 14 kW wind turbine, 5.5 kW water electrolysis device, 10 kW converter, 1 kW fuel cell and a 1.8kg storage tank. 2.5kg of stored hydrogen is used in this design. The results of this system simulation are presented in Tables 2, 3, and Figure 3. As can been seen in the Figure 3, in June, September, and July max power were produced respectively. Wind power in these months were in maximum state. However, PV array power were in maximum state in January. Fuel cell are maximum in December. Daily radiation in July and June was higher than other months in year.

Table 2. Annual electricity consumption of the project

Load	Consumption (kWh/year)
AC primary load	700
Electrolyzer load	21
Total	721

Table 3. Annual electricity generation plan and analysis of the photovoltaic/wind energy simulation

Component	Power production (kWh/year)
PV array	22321
Wind turbine	8016
Fuel cell	5
Total	30342
Component	**Value**
System life cycle cost ($)	125000
Initial investigation ($)	120000
The price of electricity produced ($/kWh)	16.46

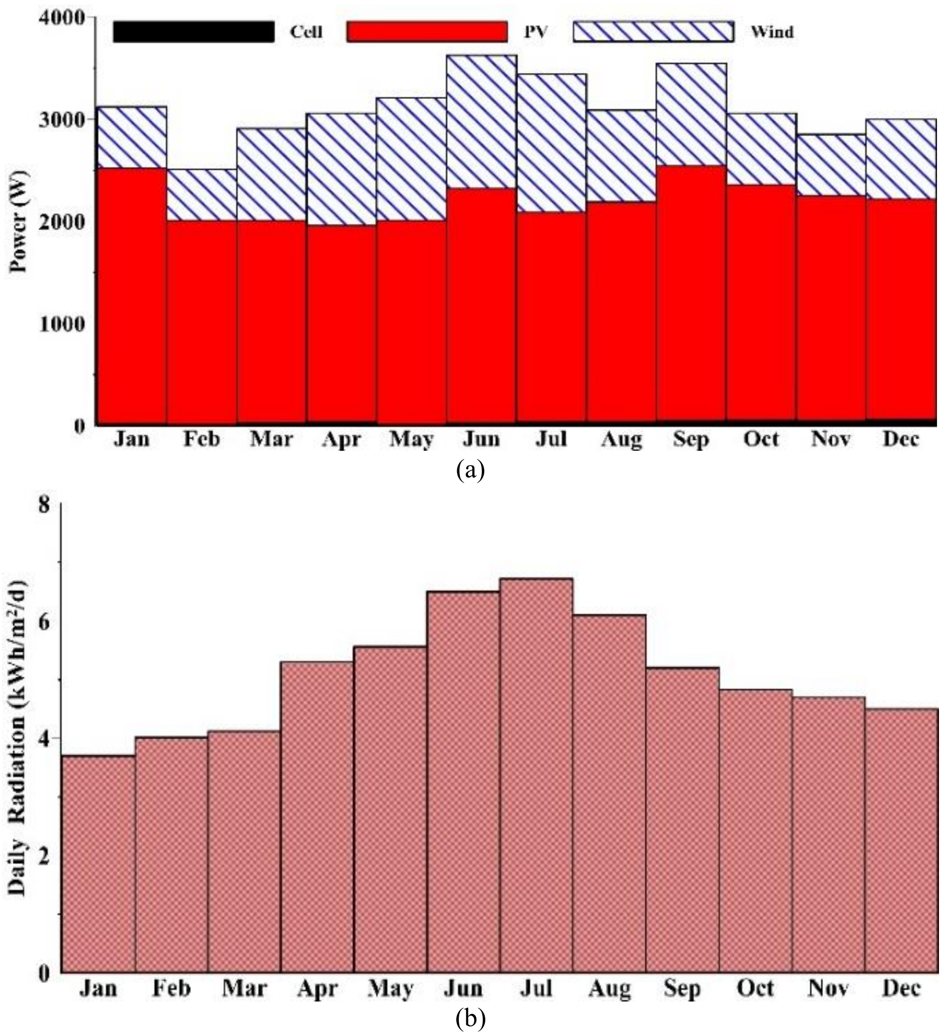

Figure 3. Average amount of a) electricity generated during a year and b) daily sunlight radiation over a year in the study site

5. CONCLUSION

For a detailed study of wind photovoltaic hybrid system with hydrogen storage constant load, here is a network-independent building as well as lighting with a certain daily load consumption and the size of each energy system to provide this load using HOMER simulation. Considering the storage of hydrogen as an energy carrier in this system, hybrid energy as well as increasing the amount of load that is affected by the entry of water electrolysis devices and hydrogen compressors. In this hybrid system, by converting the light energy of the sun and wind energy into electrical energy, it is possible to produce and store hydrogen as a carrier of clean energy, which can be used in the fuel cell consumer at any time and place after being stored in the hydrogen tank.

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