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Techno-economic Assessment of a Hybrid Off-grid DC System for Combined Heat and Power Generation in Remote Islands

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Abstract

Hybrid renewable energy systems that combine heat and electricity generation is an achievable option for remote areas where grid is uneconomical to extend. In this study, a renewable-based system was designed to satisfy the electrical and thermal demands of a remote household in an off-grid Greek island. A hybrid DC system consisted of a combination of photovoltaic modules, wind turbine, electrolyzer-hydrogen tank, fuel cell and batteries were analysed using HOMER Pro software. Based on the optimal obtained system, it is found that such a system can satisfy both electrical and thermal load demand throughout the year in a reliable manner.

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Keywords: Stand-alone DC power system; renewable energy; Homer; simulation;

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1. Introduction

In the modern society, energy needs are ever-growing and the concerns about the energy demand and the associated environmental pollution resulted from the burning of fossil fuels are becoming more and more serious. With global energy consumption and CO_2 emissions increasing exponentially, the development of efficient alternatives to fossil fuel resources to meet the future energy requirements is of crucial importance. Utilization of hybrid renewable energy systems (HRES) in decentralized off-grid residential households is a very promising approach for their socio-economic development. Particularly, the combination of solar and wind energy technologies with energy storage technologies including batteries and chemical fuel storage as back-up sources have been attracted wide attention because these systems can supply power continuously to households, remote stations or even small villages.

The purpose of this study is to investigate the feasibility of several combined heat and power (CHP) standalone systems for remote areas such as small islands. Particularly, HOMER Pro software was used to design and assess different combinations of photovoltaic modules, wind turbine, electrolyzer-hydrogen tank, fuel cell and batteries that meets the electrical and heat needs of a remote house in Hydra's island, Greece. This software is developed by National Renewable Energy Laboratory (NREL) and it allows the optimal designing and planning of renewable and non-renewable energy systems by carrying out techno-economic analysis for off-grid and grid connected power systems [1, 2]. In the literature, several scenarios have been studied using the same or similar software tools for a variety of networks ranging from small households to big island-wide area [3-9]. Our paper extends the literature by performing a techno-economic analysis where we optimize the electric and thermal load simultaneously of a typical household in Hydra. Finally, the operating cost and cost of energy (COE) factors of different systems were used for comparison throughout a 20-year period.

2. Methodology

Homer Pro 3.10.3 was used to design a hybrid renewable energy system that combines heat and power generation is proposed for an off-grid remote DC household. Hybrid renewable energy system is a combination of different renewable energy sources such as photovoltaic (PV) cells, wind turbines, fuel cell etc. In this particular case, a system was designed with solar PV panels, a small wind turbine and a fuel cell serve as power generators. Apart from electricity, fuel cell generates a large amount of heat which can be utilized to cover a large part of thermal load demands of a house hold (CHP) [10]. Making use of waste heat is the best way to increase the overall efficiency of a system. Apart from the recovery heat system of fuel cell, in this design, a hydrogen boiler was also used to fulfill any remaining amount of thermal load demands. The system was optimized using a controller under the Loading Following (LF) strategy which is the optimal strategy for systems with a lot of renewable power that sometimes exceeds the load.

Table 1: Initial cost, replacement cost and operational & maintenance (O&M) cost of each component [11, 12].

Component	Capital cost (€/KW)	Replacement cost (€/KW)	O & M cost (€/KW/year)	Lifecycle (years)
PV system	2600	2200	10	25
Wind turbine	4000	3467	10	20
Electrolyser	2000	1200	20	15
Hydrogen tank	800/kg	700/Kg	15/Kg	25
Fuel cell	1600	1300	0.002/h	50000 h
Battery	150/battery	100/battery	10/battery	10

PVs, fuel cells, and batteries are all DC. Generally, for a conventional AC powered house, AC/DC power converters are required for power conversion between AC power lines and DC sides of the system. The presence of power converters (AC/DC) not only decrease the overall efficiency of a system but also the capital, operation and maintenance (O & M) cost of the whole system. For a pure DC powered house scenario, there is no need for power converters between AC and DC sides, which will increase the system efficiency and reduce the system cost. Table 1 shows the initial, replacement cost and operational & maintenance (O&M) cost and the lifecycle of each component (DC/DC power converters are included in the related components). In addition, a summary of the available resources of the designed system (Fig. 1) including their characteristics can be seen below:

- PV system: A solar system KYOCERA KU325-8BCA flat plate multi-crystalline silicon PV module with 0.325 kW capacity used for the analysis.
- Wind turbine: a Pika T701 wind turbine with a 3m rotor diameter for a lifecycle of 20 years was used with rated capacity 1.5kW.
- Electrolyzer and hydrogen tank: The excess energy of renewable sources is used to produce hydrogen fuel through electrolysis of water, which is stored in hydrogen tank.
- Fuel cell: A fuel cell converts the stored fuel into electricity to meet the energy demands, replacing the traditional back up power concept.
- Battery: The energy stored in batteries is used when there is insufficiency of solar, wind and fuel cell energy to meet the electrical energy demand. Discover 12VRE-3000TF-L model batteries, with a nominal voltage of 12V, nominal capacity of 245Ah, and maximum capacity of 2.94kWh were chosen for the analysis.
- Hydrogen boiler: Fuel cell was combined with a hydrogen boiler to fulfill the thermal energy load of the proposed household.

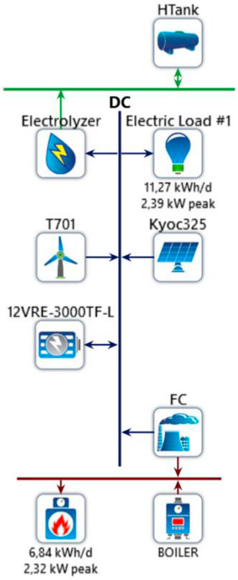

Figure 1. Configuration of a hybrid DC renewable system that covers both electric and thermal load demands

3. Results and discussion

The hybrid renewable CHP system was optimized by varying the capacity of wind turbine, PV cells, fuel cell generator, the number of batteries and the electrolyzer power output. Particularly PV was tested for a capacity range between 0 and 8 kW in the HOMER Pro search space optimizer option. Similarly, wind turbine was varied between 1 and 5 kW, fuel cell generator was varied between 2 and 5 kW while the power input to the electrolyzer ranged from 1 to 5 kW. The electrolyzer generated hydrogen that was stored in a tank (hydrogen storage tank). Storage tank represents the number of units of high-pressure hydrogen cylinders of 1 kg capacity. Several different sizes were used in the simulations ranging from 0 to 100 kg. Although the excess electricity was mainly stored in the form of hydrogen through electrolysis, several battery units were used simultaneously to optimize the energy efficiency of the system and reduce the COE.

An optimized and cost-effective hybrid system design was comprised of a 3.35 kW PV cell, 3 kW wind turbine, 2.9 kW fuel cell, 6 batteries, 4.2 kW electrolyzer and a hydrogen tank of 70 kg. The initial capital for this system was 90520 €, the operating cost was 2254 € and COE was 1.65 €/kW. Although the initial cost of the proposed hybrid system is high, the extension of electricity grid is prohibitively expensive because of the topography of Greek islands. Alternatively, the utilization of a diesel not only is not environmentally friendly but also the transportation of liquid fuels in remote areas increases significantly the overall COE of such a system. Furthermore, a system with Hydrogen-chain (electrolyzer - hydrogen storage tank – fuel cell) without batteries was slightly less cost effective and efficient mainly because the fuel cell operated all year long to cover the electrical energy demands and produced heat, which was not needed during the warm months. In addition, less hydrogen was stored in the tank due to significantly higher amount of fuel cell operating hours.

Monthly average electricity generation from the optimum hybrid system is illustrated in Fig. 2a, where the brown bars represent the electric power produced by wind turbine, orange bars represent the electricity generated by PV panels and green bars represent the generation of electricity by the fuel cell. Particularly, wind turbine produced the largest amount of the electrical power of the system, 55%, followed by the PV cells that generated 40.9% of total electricity. Fuel cell generated only 4.1% of electric power because operated mainly between October and April as a back-up system when there was not solar light or wind. In addition, fuel cell was able to supply power during the warm months when solar cells and wind turbine could not cover the electric load demands while batteries were discharged.

On the other hand, fuel cell fulfilled almost half of the thermal energy load (49.2%) of the household as shown in Fig. 2b, where the orange bars represent fuel cell. The rest thermal energy demand was covered by a hydrogen boiler, which was represented by green bars. As already mentioned hydrogen boiler served as a backup source of heat offering any amount of thermal load whenever necessary. Generally, fuel cell was more cost effective to operate when both heat and electricity generation were required.

Figure 2: Monthly average a) electricity generation, b) heat generation and c) electrolyzer operation for hydrogen production from the hybrid system.

Electrolyzer produced hydrogen only if there was excess electricity and the batteries were fully charged. Electrolyzer produce more amount of hydrogen between November to March (Fig. 2c), although PV module produces more electricity between May and September. However, increased electricity production from the wind turbine between November and March and increased electric power demands during the warm months can justify this trend.

A deeper understanding of the operation of hybrid renewable standalone system can be gained from Fig. 3 in which the power output or input profile for the main components are presented. Specifically, PV module (Fig. 3a) generated electricity during daytime with peak power sun-hours between 11.00 and 15.00. The operation hours of the PV panels ranged from 12 hours during the summer to 9 hours during winter. Furthermore, the simulation results of PV module revealed that there are several days of very low output during the winter due to clouds or fog. On the contrary, wind turbine (Fig. 3b) produce more electricity during the winter months while the operating hours of this module are distributed around the clock. Thus, hybrid systems that use wind and solar energy are very attractive because their peak operating times take place at different times of the day and the year.

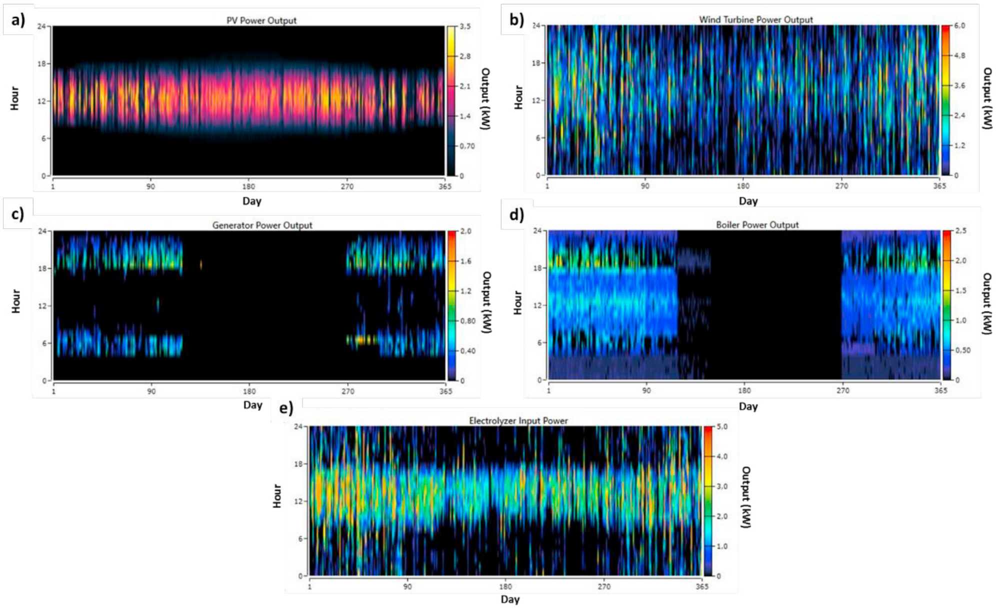

Figure 3: Power output or input profile for the main components of the hybrid renewable standalone system.

For the times when wind turbine or PV module were not generating electricity and the batteries were discharged, fuel cell (Fig. 3c) provides the required electric power. Apart from electricity, fuel cell generated a large amount of thermal power. However, generation of heat from fuel cell was not enough to cover the thermal load demand of the household. For this reason, a hydrogen boiler (Fig. 3d) operated as a heat power backup. Finally, it is shown in Fig. 3e that electrolyzer generated hydrogen only in peak hours of either PV cells or wind turbine.

HOMER Pro software did not allow to use stored hydrogen as fuel for the boiler component. Instead, boiler was supplied with hydrogen fuel that cost 8 €/kg. A realistic price of hydrogen fuel was entered to ensure that boiler module did not serve as a primary heat source but as a backup of fuel cell module. To bypass the aforementioned software limitation, the designed system had a storage tank large enough to store yearly hydrogen boiler consumption which was 59.8 kg. Specifically, the optimum system produced 166.2 kg of hydrogen in a year, from which 106 kg was used in fuel cell module and 60.2 kg were stored in the tank at the end of the year. Therefore, generated hydrogen that was stored in the tank was enough to fulfil fuel consumption of boiler.

The utilization of a 70 kg hydrogen storage tank allowed the detection of annual hydrogen excess, but it was larger than needed. A more realistic system with a hydrogen tank of 40 kg capacity was also simulated. Simulation results showed an identical monthly average electricity and heat generation behavior. However, the hydrogen production profile was significantly different because the electrolyzer could not generate hydrogen when the hydrogen tank was fully loaded. Specifically, electrolyzer was in running order for 4516 hours in a system equipped with a 40 kg storage tank, while in the case of a system equipped with 70 kg storage tank, electrolyzer ran for 5268 h.

Several costs of the designed system could not be included in the model due to software limitations. For instance, the initial capital of boiler is not included. However, in this study, boiler consumes hydrogen that cost 8/kg instead of stored hydrogen. Thus, the gain of zero capital cost of boiler offsets the losses from the cost of hydrogen fuel. In addition, in such a system an oxygen-chain module should also be taken into account. Generally, an electrolyzer can convert water molecules and electric power into hydrogen and oxygen gas. Both can be stored in special tanks and then can be used in fuel cell. Although, the cost of oxygen-chain cannot be introduced directly to HOMER Pro software, it can be incorporated in the costs of electrolyzer, fuel cell and hydrogen tank modules.

4. Conclusions

Expansion of standalone hybrid renewable energy systems to households, monasteries, small villages or telecommunication network stations where connection to the grid could never be possible or viable, has led to an increasing interest in them. Utilization of wind and solar energy technologies in off-grid CHP systems seems even more appealing because in such systems a large amount of energy lost as waste heat can be used to cover thermal load demands. However, diesel generators are still dominate the market of electricity generators for off-grid remote buildings. In this study, it was proposed and analyzed a standalone DC system which was able to cover the energy demand of a de-centralized residential household. Utilizing HOMER Pro, a CHP system based on renewable energy sources was designed, evaluated and optimized. The results obtained from technical and cost analysis showed that the combination of 3.35 kW PV module, 3 kW wind turbine, 2.9 kW fuel cell, 6 batteries, 4.2 kW electrolyzer and a hydrogen tank of 40 kg with initial capital of 66650 €, operating cost of 1802 € and COE of 1.20 €/kW could fulfil both electrical and thermal load demand throughout the year.

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