Applied Thermal Engineering 99 (2016) 169–178

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Energy–exergy and economic analyses of a hybrid solar–hydrogen renewable energy system in Ankara, Turkey

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HIGHLIGHTS

- Uninterrupted energy in an emergency blackout situation.
- System modeling of a solar–hydrogen based hybrid renewable energy system.
- A comprehensive thermodynamical analysis.
- Levelized cost of electricity analysis for a project lifetime of 25 years.

ARTICLE INFO

Article history:
Received 14 February 2015
Accepted 8 January 2016
Available online 21 January 2016

Keywords:
Solar energy
Hybrid renewable energy systems
Energy analysis
Exergy analysis
Levelized cost of electricity

ABSTRACT

A hybrid (Solar–Hydrogen) stand-alone renewable energy system that consists of photovoltaic panels (PV), Proton Exchange Membrane (PEM) fuel cells, PEM based electrolyzers and hydrogen storage is investigated by developing a complete model of the system using TRNSYS. The PV panels are mounted on a tiltable platform to improve the performance of the system by monthly adjustments of the tilt angle. The total area of the PV panels is 300 m^2, the PEM fuel cell capacity is 5 kW, and the hydrogen storage is at 55 bars pressure and with 45 m^3 capacity. The main goal of this study is to verify that the system meets the electrical power demand of the emergency room without experiencing a shortage for a complete year in an emergency blackout situation. For this purpose, after modeling the system, energy and exergy analyses for the hydrogen cycle of the system for a complete year are performed, and the energy and exergy efficiencies are found as 4.06% and 4.25%, respectively. Furthermore, an economic analysis is performed for a project lifetime of 25 years based on Levelized Cost of Electricity (LCE), and the LCE is calculated as 0.626 $/kWh.

1. Introduction

Use of fossil fuels to meet the increasing global energy demand causes rapid depletion of conventional fuel sources, global warming, and other emission related problems. This motivates people to consider alternative resources for energy production. A rational option, which is getting more and more popular, is the use of renewable resources such as wind and sun. These resources, however, are intermittent with daily and seasonal variations. Therefore, in order to ensure the continuity of the supplied electricity, the renewable energy systems need to be coupled with some form of energy storage.

The continuity of the supplied electricity is especially important in health services. Health services should be able to run continuously. Especially after disasters, increased service load and electricity transmission failure may lead to a blackout that needs to be prevented. A common solution is to use a diesel generator as a backup. This solution is not an ideal one because, besides being a fossil fuel, diesel may be hard to find in the aftermath of a disaster. Additionally, in a recent study [1] it is reported that PEM fuel cell systems become economically competitive compared to diesel generator backup systems.

In this study, a solar–hydrogen based hybrid renewable energy system that was built (in order to create an alternative solution to emergency blackout situations) for the emergency room of Kecioren Training and Research Hospital in Ankara is investigated with numerical simulations. The system is expected to provide continuous, off-grid electricity during the period of a whole year without any external electrical power supply. In the system, hydrogen is used as an energy carrier forming an idealized "energy cycle". In the ideal energy cycle, water is split into hydrogen and oxygen using renewable energy sources with an electrolyzer. Then, the hydrogen is stored to be later used in a fuel cell to generate electricity, with water as a by-product to be used in the electrolyzer. The only output of this hydrogen cycle is the electrical energy generated by the fuel cell, and the only input is the renewable energy from the sun.

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http://dx.doi.org/10.1016/j.applthermaleng.2016.01.042

The main purpose of this study is to verify that the stand-alone system meets the electrical power demand of the emergency room without experiencing a shortage for a complete year in an emergency blackout situation. For this purpose, a complete system model including all of the components is formed, and the overall performance of the system is determined through the energy and exergy efficiencies of the hydrogen cycle for a complete year during an emergency blackout.

The energy efficiency alone is not sufficient. It is based on the first law of thermodynamics, thus, gives no information about the quality of the different types of energy involved in the processes. The exergy efficiency (which is mainly based on the second law of thermodynamics), on the other hand, provides both qualitative and quantitative information about the system.

According to the exergy analysis, energy can be degraded in quality, even though it cannot be destroyed or created. Recently, exergy analysis is considered as an important method for evaluating thermal processes and their environmental effects (e.g. in [2]). It is commonly used for achieving effective energy utilization with reduced environmental impact and for obtaining optimal designs and operating systems [3]. Kazim [4] stated that through exergy analysis, it is also possible to obtain a true measure for a system performance. Therefore, here, an exergy analysis is performed together with an energy analysis to obtain a complete thermodynamical analysis of the system. Ni et al. [5] mentioned that detailed thermodynamical analysis is important for optimizing the performance of the PEM based components and identifying the major losses of the system.

The energy and exergy analyses are complemented by a detailed lifetime economic analysis. An analysis method called Levelized Cost of Electricity (LCE) is used.

The levelized cost of electricity is defined in [6] as "*the constant price per unit of energy that causes the investment to just break even*". LCE is an economic estimate of the generated energy. This method is commonly used in the literature for similar systems (among others, in [6–11]). It is also used in designing and sizing of the hybrid renewable energy systems. LCE analysis includes all of the costs related with the system throughout its lifetime. Levelized cost of electricity is also denoted as LCOE in the literature [12–15].

2. System description

The system consists of PV panels, PEM based electrolyzers and PEM based fuel cells, hydrogen and oxygen tanks, controllers, and inverters. The system is modeled using TRNSYS software [16]. In literature, TRNSYS is commonly used in hybrid renewable energy system modeling [17–22].

The simplified model of the system is presented in Fig. 1. The primary function of the PV panels is to supply electricity directly to the emergency room (User). If the power generated by the PV panels is greater than the demand, the excess power is sent to the electrolyzer via power conditioner. The electrolyzer generates hydrogen and fills it into the hydrogen tank. When the generated power is greater than the sum of the demands of the emergency room and the electrolyzer, the extra power is dumped out. On the other hand, if PV power generation is less than the demand of the emergency room, the difference is supplied by the fuel cells utilizing the stored hydrogen. DC/AC inverters are used between the PV panels and the emergency room, and between the fuel cells and the emergency room. The system is controlled by the main control unit (Controller).

The maximum electricity demand of the emergency room is 5 kW. It is assumed that 5 kW is needed between 6 a.m. and 12:00 p.m., while 2 kW is sufficient for the rest of the day (Fig. 2). Variations in the load are neglected for being able to interpret the results more easily. The emergency room has a daily load of 102 kWh and a yearly load of 37.23 MWh. Power demand of the other auxiliary equipment (hydrogen compressor, pumps, water deionizer and controller) is considered as a part of the load profile. Among the auxiliary equipment, only the controller of the system continuously operates; other equipment comes into action when the electrolyzer or the fuel cell is active. Since the demands of the auxiliary equipment are very small compared to the user demand, these fluctuations are neglected in the load profile.

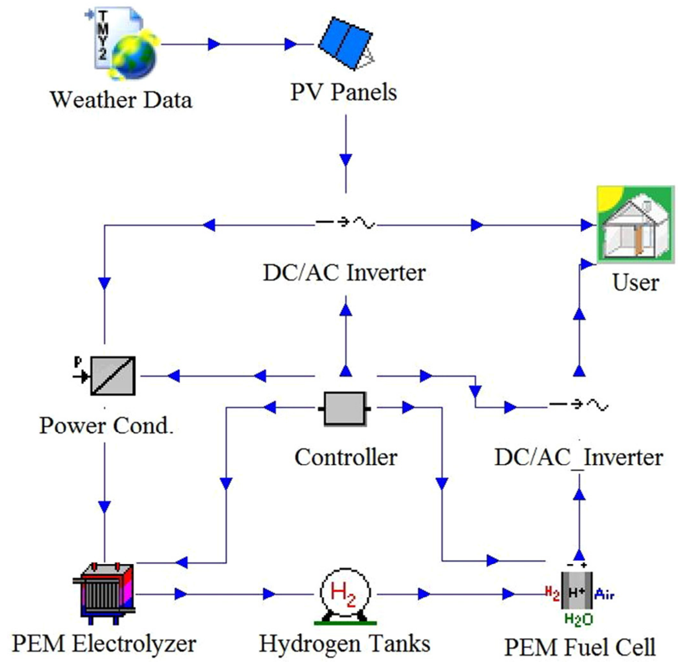

Fig. 1. Simplified TRNSYS model of the system.

High performance Bosch Solar Module c-Si P 60 type PV panels are used in the system. 180 PV panels were mounted in the parking lot of the hospital. The PV panels were directed to south direction. The total area covered by the PV panels is 330 m^2 (the net area is 300 m^2). The total established power of the PV panels is 39.6 kW.

The power output of the PV panels is directly related to the slope of the panels. The PV panels were mounted at the parking lot of the hospital on a tiltable platform to improve the performance of the

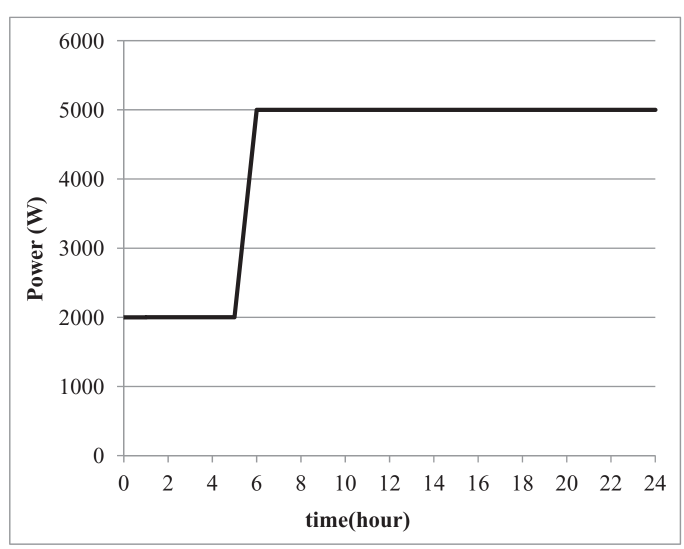

Fig. 2. Load profile of the system, for details refer to [23].