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Transient thermal performance assessment of a hybrid solar-fuel cell system in Toronto, Canada

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ABSTRACT

A comprehensive thermodynamic analysis is reported of a proposed hybrid energy based on solar energy and a fuel cell system. Small-scale solar PV systems equipped with a fuel cell and water electrolysis are suggested for remote combined cooling, heat and power applications. A dynamic simulation of this system is carried out using TRNSYS software. The first law of thermodynamics is applied to model each subsystem and the subsystems are validated to ensure the correctness of the simulation code developed in Matlab software. Exergy analysis is included to enhance the analysis. In order to carry out a case study, climate data for the city of Toronto in the province of Ontario, Canada are used and the solar irradiance during one year are extracted from TRNSYS and applied to the Matlab developed code. The effects of fuel cell current density on exergy efficiency, electricity production and exergy destruction rate are investigated. The overall energy and exergy efficiencies for the hybrid system are found to be 29% and 36%, respectively.

Introduction

Energy usage has grown rapidly during the last decade and fossil fuels like coal, petroleum, and natural gas continue to be widely used despite the problems they cause. One of the major concerns of widespread use of fossil fuels is the greenhouse gases that are emitted to the environment from their use, contributing to global warming. Renewable energy resources are those energy resources that are naturally replenished on a human timescale such as sunlight, wind, rain, tides, waves and geothermal heat. These are increasing in importance, as evidenced by the fact that about 16% of global final energy consumption presently comes from renewable resources, with 10% of all energy from traditional biomass, mainly used for heating, and 3.4% from hydroelectricity [1]. Solar technologies can be characterized as passive or active, depending on the way they capture, convert and distribute solar energy. Active solar techniques include photovoltaic (PV) and solar thermal collectors. Solar energy can be converted to electricity, either directly using photovoltaics or indirectly using concentrated solar power. Concentrated solar power systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small region, and commercial concentrated solar power plants were first developed in the 1980s. Photovoltaics convert light into electric current using the photoelectric effect.

PV systems normally require supplementary devices to meet peak demands or to harvest surplus electricity generation. Producing the energy carrier hydrogen is one method for storing electricity from solar PV systems. Surplus electricity is converted to hydrogen via a process like water electrolysis,

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and the hydrogen can be stored and later used to generate electricity in a fuel cell when required. The fuel cell also can cogenerate heat for district heating or other purposes. In a hybrid system comprised of PV and a fuel cell that operates in a combined heat and power (CHP) mode, both electricity and heat are generated from solar energy.

Numerous studies on hybrid energy systems with various energy sources and components have been reported. Ahmadi et al. [2] conducted energy and exergy analyses of an integrated ocean thermal energy conversion (OTEC) system consisting of a solar collector, a proton exchange membrane (PEM) electrolyzer and an ORC cycle to produce hydrogen as an energy carrier. This OTEC hybrid system exploits the temperature difference between the ocean surface and the colder deep ocean water. They found the energy and exergy efficiencies of this hybrid system to be 3.6% and 22.7%, respectively, and that the hybrid system produced 1.2 kg/hr hydrogen using electrolysis. Yilanci et al. [3] thermodynamically modeled and analyzed a fuel cell powered by solar panels and showed that an increase in current density reduced the energy and exergy efficiencies of the system by about 14%. They also showed that the exergy efficiency is less than the energy efficiency, largely due to irreversibilities in the fuel cell. Dupeyrat et al. [4] assessed the thermal and electrical performance of a PV/T solar collector using TRNSYS software, and showed that PV/T solar collectors are more beneficial energetically and exergetically than a PV solar collector for regions with limited space for collectors. Zhao et al. [5] thermodynamically modeled a hybrid system consisting of an ORC cycle and a PEM fuel cell. The proposed system utilizes the fuel cell waste heat in an ORC cycle to produce electricity. The authors also investigated the effect of several design parameters such as fuel mass flow rate, fuel cell operating pressure and turbine inlet pressure on system performance, and found that hybrid cycle overall efficiency is 5% higher than that for a separate PEM fuel cell system, and that an increase in the fuel cell operating pressure raises the fuel cell and overall cycle efficiency to a point and then reduces it. Ratlamwala et al. [6] modeled a hybrid system consisting of a triple effect water-ammonia absorption chiller and solar panel to produce hydrogen for every month in Dubai. The effect of average solar intensity, inlet solar panel temperature, solar panel area, hydrogen production rate, energy and exergy efficiency of the system and the absorption chiller COP were investigated. The results showed that the energy and exergy efficiencies of the system both increase with average solar intensity, and that the maximum energy and exergy efficiencies of the system occur in March, at 15.6% and 7.9%, respectively. The maximum hydrogen production rate is 9.7 kg/day and occurs in August, and the maximum absorption chiller COP occurs in June and corresponds to a cooling capacity of 15 kW.

In this research, a hybrid system consisting of a solar PV collector, a PEM electrolyzer, a fuel cell and a single effect absorption chiller is dynamically modeling and assessed. Both energy and exergy analyses are included to enhance the analyses. The specific objectives of this study are to improve understanding of the proposed hybrid energy system. The steps undertaken to achieve the objective are: to dynamically model the system using both TRNSYS and Matlab software, to conduct energy and exergy analyses, to assess the effect of several design parameters on the system performance, and to

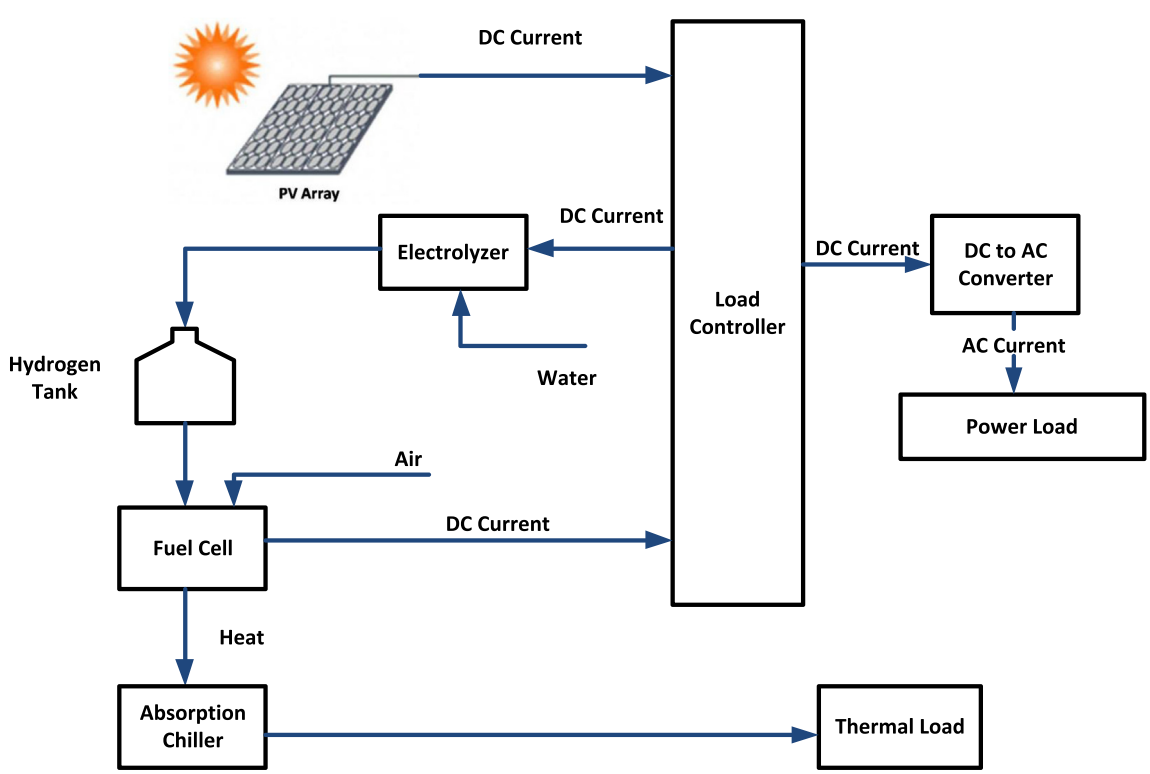

Fig. 1 – Schematic of the photovoltaic-fuel cell hybrid system for residential applications.