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Performance assessment of a new solar energy-based multigeneration system

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ABSTRACT

In this study, a thermodynamic analysis is conducted on a multigeneration energy system based on renewable energy sources. The proposed system is developed for residential applications, including individual- and multi-building complexes, utilizing solar energy to produce useful outputs, namely electricity, heat, fresh water and hydrogen. Hydrogen is used for the purpose of storing energy to offset the mismatch between demand and supply when dealt with renewables, such as solar energy. The system is modeled thermodynamically to obtain the optimal energy and exergy efficiencies, heat and work outputs for the overall system. Moreover, greenhouse gas emissions caused by conventional energy systems utilized for the same outputs are calculated and compared with the studied systems. A solar collector area of 24 m^2 is considered for the present system and its analysis. The maximum energy efficiency is 36% and the maximum exergy efficiency is 44%. The total work output for electricity is 116 kW, and hence the CO_2 reduction achieved by this system is 476 tons per year. It can produce 0.04 kg/s desalinated water. The optimum number of suites, as an application for a building complex, which can be sustained with the proposed system is determined as 106 suites.

1. Introduction

Energy in the world has become more important over the centuries as we have been striving to develop new technologies which help make our lifestyles much easier and more comfortable. Energy is essentially needed everywhere for almost everything, ranging from transportation vehicles to household appliances, and plays a fundamental role in the world today. Civilization began when people found the fire and learned how to use it effectively for needs. They first started burning wood and obtained high temperatures for melting metals, cooking and heating. Industrial revolution essentially introduced the use of fossil fuels, e.g. oil, coal and gas [1].

There are alternative energy options to fossil fuels, such as solar, geothermal, hydropower, wind and biomass energy. Most energy supplies on earth derive from the sun, which continually warms us and supports plant growth via photosynthesis. Solar energy heats the land and sea differentially causing winds and consequently waves. Solar energy also drives evaporation, which leads to rain and in turn hydropower [2]. Solar energy is a free renewable energy source with no gas emissions. The number of power plants operated partially or completely by solar energy has been increasing significantly [3]. Although the current use of solar energy for electricity generation in the world is about 1% of the global energy consumption [4], several countries have developed country specific programs to enhance the use of renewable energy resources, primarily solar energy and develop and commercialize technologies for the markets. Note that solar energy can be used to obtain electrical power directly through photovoltaic solar cells or indirectly through a solar thermal system.

In order to make an efficient use of energy there is a growing interest in optimizing the design of urban developments by means of the exploitation of natural sources of energy such as solar, wind, geothermal and biomass energy. Research on multigeneration systems has been the subject of increasing interest in the last few decades in order to reduce energy consumption and achieve more sustainable and economic energy generation. A multigeneration energy production process refers to a system with more than three different purposes, and the same sources of input energy, such as electricity, hydrogen, oxygen, cooling, heating, hot water, fresh water and air, synthetic fuels, and chemicals.

Ratlamwala et al. [5] assessed an integrated PV/T and triple

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effect cooling system for hydrogen and cooling production. The study was based on United Arab Emirates weather data; effect of average solar radiation for different months, operating time of the electrolyzer; air inlet temperature and area of the PV module on power; and rate of heat production, energy and exergy efficiencies, hydrogen production and energetic and exergetic COPs. This study provided help for PV/T analysis and hydrogen production sections.

Ozcan and Dincer [6] analyzed and conducted a performance assessment of a solar driven hydrogen production plant running in a Mg–Cl cycle through energy and exergy methods. In the present study, we benefited from the sections on the exergy and energy analyses of hydrogen production using solar energy. Ozturk and Dincer [7] addressed the thermodynamic assessment of a solar-based multigeneration system with coal gasification, involving power, heating, cooling, hydrogen, oxygen and hot water production. The system studied by Ozturk and Dincer is a multigeneration system which has a similar set of useful outputs and provided a based to develop our own in the present study. Chua et al. [8] evaluated the potential of hybridizing renewable technologies to support trigeneration. The developed trigeneration system aimed to be self-sustaining where cooling, heating and power needs of a commercial building are simultaneously fulfilled.

Fresh water shortage is a serious concern especially in third world countries. Available water resources are not suitable for drinking and daily use, as they are strongly mineralized and contaminated. Part of the population live in small villages or settlements without infrastructure, and are not connected to a centralized system of electrification and drinking water supply [9]. The locations experiencing water shortages usually have significant solar energy, which can justify the use of solar energy for desalination purposes. By removing salt from the virtually unlimited supply of seawater, desalination has emerged as an important source of fresh water.

The proposed system is applied to buildings in Toronto, Ontario, because of the available data, although there is sufficient fresh water it can be adapted to other regions. However, it still requires intensive energy, which is the key parameter affecting the cost. The cost of desalination depends on capacity and type of facility, energy use, feed water, location, labor, and concentrate disposal. The most common methods for desalination are reverse osmosis and multi-stage flash distillation (accounting for 85% of production worldwide) [10].

Recent applications on solar desalination processes are small-scale and decentralized. On the other hand, concentrated solar power plants are suitable for large scale desalination. From an environmental point of view, it can be utilized as an alternative source of fresh water to prevent over-exploitation of groundwater (utilizing either a thermal or membrane process, with volumetric flow rates up to several 100,000 m^3/day). It is expected that in twenty years, energy from solar thermal power plants will become the least expensive option for electricity generation (below 4 ¢/kWh) and desalinated water (below 0.4 \$/m^3) [11].

In accordance with the existing climatic conditions of Antalya, Turkey, Yildirim and Solmus [12] investigated the theoretical performance of a solar powered humidification-dehumidification desalination system for various operating and design parameters. They developed the mathematical model of the system and numerically solved governing conservation equations. They also calculated daily and annual yields for different configurations of the system. It is observed that water heating, increasing mass flow rate and feed water mass flow rate positively affects clean water production. Franchini and Perdichizzi [13] developed a computer code to simulate the operation of a low-temperature thermally driven desalination system, based on the HD (humidification-dehumidification) process. The code was used to analyze an HD desalination unit in Abu Dhabi (United Arab Emirates). The unit produces fresh water of about 200 L per hour. The results showed that system performance is strongly affected by the sea water temperature.

Trieb et al. [14] demonstrated the principles utilizing state of the art concentrated solar power technology and explained the option for seawater desalination, using either electricity or steam, generated in such plants. They encouraged Middle East and North Africa governments to establish adequate conditions to support concentrating solar power technology in the region. Sharqawy et al. [15] studied exergy calculations of seawater with applications in desalination systems. They investigated the effect of the system properties as well as the environment dead state on the exergy and flow exergy variation. They found that treating the seawater as an ideal mixture of pure water and solid sodium chloride salt gives unrealistic flow exergy values and a second law efficiency differs by as much as 80% from the correct value.

Li et al. [25] studied a similar co-generation system, using a parabolic trough solar collector system. Their system has an organic Rankine cycle (ORC), and the seawater is desalinated to produce fresh water. The maximum capacity of the ORC cycle is found to be 200 kW by using 4 parallel solar loops. Their system efficiency was found to be greater than 18–20% for a wide value of irradiation values. Their fresh water production rate was about 40 m^3/h.

Astolfi [26] investigated the feasibility of rural electrification of remote areas worldwide and discussed the capabilities of different plant layouts and the use of volumetric screw devices as expander. The results obtained in his study are listed as: the use of well calibrated correlations for the efficiency and the cost of volumetric expander is crucial for thermodynamic and technoeconomic optimizations; the use of two stage tandem expansion can be profitable; the innovative concept of using flash trilateral cycles is promising; the sensitivity analysis on the pressure drops in the solar collectors and on the specific cost of the solar fields highlighted that an increase of pressure drops in solar collectors penalizes all the cycle configurations in a similar way and for a higher cost of the solar field; and flash trilateral cycles are less attractive due to their lower power outputs.

Delgado-Torres and Garcia-Rodrigues [27] studied a solar reverse osmosis desalination based on solar organic Rankine cycles. They provided some design recommendations, such as: the use of a synthetic oil as working fluid in the solar field, importance of analysis of the dependence of the solar ORC performance on the top temperature for a given collector, the use of solar collectors with linear concentrators, selecting the condensation temperature of the ORC as low as possible, and optimization of the design of the reverse osmosis subsystem.

Ferrara et al. [28] presented the thermodynamic analysis of a concentrated solar power plant which works with ORC. They highlighted the construction simplicity of the ORC systems and greater efficiency for lower ratio of the temperature difference.

Freeman et al. [29] presented performance calculations for a small-scale combined solar heat and power system based on an ORC, in order to investigate the potential of this technology for the combined provision of heating and power for domestic use in the UK. A best case average electrical power output of 89 W plus a hot water provision capacity equivalent to 80% of the total demand are demonstrated, for a whole system capital cost of £2700–£3900.

Karellas and Braimakis [30] performed a comprehensive study on thermodynamic modeling and economic analysis of a micro-scale cogeneration system (which is suitable for trigeneration) capable of combined heat and power production and refrigeration, based on the joint operation of an ORC and a vapor compression cycle. In a base scenario, assuming an overall 50kW_{th} heat input and a cooling load of 5 kW_{th}, the net electric efficiency is 2.38%, with electricity output equal to 1.42 kW_e and a heating output of