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Analysis and performance evaluation of a renewable energy based multigeneration system

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A R T I C L E I N F O

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This study proposes a new renewable energy based multigeneration system, which integrates a solar PV/T system and a geothermal energy system to produce electricity and heat for power, heating, cooling, hot water and drying air, and investigates the design, analysis and assessment of this integrated system. The psychometric processes are utilized for obtaining required dry agent from the ambient air, and an air circulation system is used to benefit from the heat transferred from the PV modules to the air, which ultimately increases the PV/T efficiency and hence the overall efficiency. We also assess the performance of the system, through energy and exergy analysis methods, for a selected common case and obtain overall energy and exergy efficiencies of 11% and 28%, respectively. The selected parametric studies investigate the effects of various environmental and operating conditions on the energy and exergy efficiencies of the overall system and subsystems.

1. Introduction

Dramatic increase in human population over the last century and hence the energy demand to support this growth have resulted in important concerns with respect to current energy resources and supply limitations [1,2]. Reducing the usage of carbon based fuels and sources will contribute to decrease level of global warming. Hence, renewable energy based multigeneration systems emerge as an alternative solution.

Renewable energy based multigeneration systems are a dynamic area of research, with many studies proposing various options for alternatives to current fossil fuel based systems. Dincer and Zamfirescu [3] showed that renewable energy-based multigeneration system decreases conventional fuel prices and harmful pollutant emissions, compared to conventional systems. Khalid et al. [4] proposed a biomass and solar integrated based system for multigeneration for power, cooling, hot water, heated air and found the overall system exergy efficiency as 39.7%. El-Emam and Dincer [5] studied on thermodynamic and economic analyses of a geothermal regenerative organic Rankine cycle through energy and exergy concepts. The energy and exergy efficiency values are found to be 16.37% and 48.8%, respectively. The mass flow rates of the organic fluid, cooling water and provided geothermal water are calculated for a net power output of 5 MWe. AlZaharani et al. [6] proposed an integrated system which is comprised of a supercritical carbon dioxide (CO_2) Rankine cycle cascaded by an organic (R600) Rankine cycle, an electrolyzer, and a heat recovery system. It is designed to utilize a medium-to-high temperature geothermal energy source for power and hydrogen production, and thermal energy utilization for space heating. The system provides overall energy and exergy efficiencies of 13.67% and 32.27%, respectively. Ozcan and Dincer [7] conducted a research of trigeneration system which consists of mainly an IRSOFC (internal reforming tubular type solid oxide fuel cell), PTSC (parabolic trough solar collectors) and a two-stage ORC (organic Rankine cycle). They have found the energy and exergy efficiencies of tri-generation as 85.1% and 32.62%, respectively for optimum SOFC stack and environmental conditions. Kanoglu and Bolatturk [8] performed exergy analysis of a binary geothermal power plant using actual plant data to assess the plant performance and pinpoint sites of primary exergy destruction. They found the energy and exergy efficiencies as 10.2% and 33.5%, respectively, based on the heat input and exergy input to the binary Rankine cycle. Al Sulaiman et al. [9] used an exergy model to assess the exergetic performance of a novel tri-generation system using parabolic trough solar collectors (PTSC) and an organic Rankine cycle (ORC). In their system, a single-effect

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absorption chiller is employed to provide the necessary cooling energy, and a heat exchanger is employed to provide the necessary heating load.

Sahin et al. [10] defined a new efficiency which is useful in studying PV performance and possible improvements. They found that exergy efficiencies of PVs, which incorporate the second law of thermodynamics and account for solar irradiation exergy values, are lower than energy efficiencies ranging from 2% to 8%. Bouzguenda [11] conducted a performance evaluation of hybrid systems, including wind turbines, solar systems, and storage batteries backed up with diesel generators, using HOMER software for different locations in Oman. He concluded that hybrid systems offer many advantages such as reducing diesel operating time, fuel consumption, and maintenance. Dincer and Acar [12] performed a review regarding integrated renewable energy based systems. The advantages of multigeneration systems were explained as reliability, better environmental performance by reduction of GHG and other air pollutants' emissions, economic feasibility, and higher efficiencies. Heberle and Brüggemann [13] studied the combined heat and power generation by geothermal resources at a temperature levels lower than 177 °C. Their results showed that using the combined heat and power generation, the exergy efficiency of a geothermal power plant could be significantly improved in comparison to single power production. Tunc et al. [14] analyzed Kizildere geothermal power plant, in terms of exergy, by using organic Rankine cycle. The results of their study showed that the cycle efficiency can vary between 8% and 30% based on the working fluid used. The geothermal data and parameters in their study were based on their earlier studies. Houston et al. [15] evaluated the energy efficiency and renewable energy generation opportunities for small scale dairy farms by making a case study in Prince Edward Island, Canada. They implied that reducing their energy-related operational costs and greenhouse gas emissions can be achieved through taking energy efficiency steps, reducing overall energy consumption and generating energy through renewable energy resources and technologies.

In this paper, a novel multigeneration system based on solar and geothermal renewable energy sources is developed and analyzed. The present multigeneration system is practical and feasible since they employ current technologies and existing systems. Here, the novelty is the integration of these technologies for multigeneration purposes in a more efficient, more cost effective and environmentally-benign manner Therefore, the proposed system will also be practical and applicable after system is verified by testing under various conditions. The specific objectives of this paper are to propose and to assess with energy and exergy analyses a new integrated multigeneration system using geothermal and solar energy, including the determination of overall energy and exergy efficiencies of the multigeneration system and its subsystems; and to conduct a parametric study to determine the effects of various parameters on the overall energy and exergy efficiencies of the multigeneration system and its subsystems.

2. System description

In the designed multi-generation system, solar thermal/photovoltaic and geothermal energy are two independent sources. The system consists of an organic Rankine cycle, heat pump, absorption cooling system, thermal energy storage and drying system. The designed multi-generation system serves for consumers such as large scale dairy farms which are located on a geothermal area. As system schematic is seen in Fig. 1, organic Rankine cycle whose working fluid is isobutane is run by a medium–high temperature geothermal water by giving its heat to Evaporator 1. The inlet temperature of Evaporator 1 is 202 °C and outlet is 150 °C which is utilized by Heat Exchanger 1 to the hot water storage tank. The inlet temperature of the Turbine is 145 °C and steam leaves the turbine with 100 °C which transfers its heat to the generator of the absorption cooling system. This temperature is satisfactory for a LiBr-water absorption cooling system. The turbine is coupled with a power generator to supply the electricity demand of the dairy farm. The condensers of the system, except for absorption cooling system, are cooled by a cold water storage tank which is supplied by ground water through the pump. The temperature of ground water is around 10 °C. The cooling effect provided by the outlet of Evaporator 2 of the absorption cooling system is used to cool the storage of dairy products at around 10 °C. In order to heat the offices of dairy farm, a heat pump with a working fluid of refrigerant R134a is used. Energy supply of heat pump is stored heat in the thermal energy storage system whose temperature is around 58 °C. Refrigerant R134a is chosen to enable low temperature application.

The hot water from hot water storage tank is mixed with the warm water coming from Evaporator 3 in the mixing chamber to keep the temperature of thermal energy storage as high as possible. Some of the hot water is also transferred to hot water storage tank for later use. The working fluid refrigerant R134a leaves the Evaporator 3 with a temperature of 9.5 °C. After compression, it enters to Condenser 3 with 75 °C and leaves at 35 °C. The heat output of Condenser 3 is utilized for office heating purposes. After refrigerant R134a is expanded in the expansion valve, the cold refrigerant with a temperature of 2 °C enters the cooling coils for cooling with dehumidification process. This dehumidified air is then utilized in the drying process. A fan and duct system under the solar PV/T system is used to heat the air needed for drying process. The drying air with the temperature of 55 °C enters dryer for extracting the moisture of milk around 60%. At the end of the drying process, the evaporated milk is obtained allowing long storage conditions for long distance transportation. PV/T systems combine a solar cell, which converts sunlight into electricity, with a solar thermal collector, which captures the remaining energy and removes waste heat from the PV module. The harvesting of both electricity and heat yields these devices to have higher exergy and thus be more overall energy efficient than solar photovoltaic or solar thermal alone. PV/T operating temperatures may reach up to 90 °C [16,17] In the proposed system, solar thermal system reaches up to 75 °C and the hot water is stored in thermal energy storage to have 24 h operation of heat pump. Heating, cooling, electricity and hot water are always needed for users such as dairy farms. By using geothermal energy source and thermal energy storage system, it is guaranteed to have an uninterrupted power generation, heating, cooling and hot water. The drying process is only held during daytime since evaporated milk production is processed between 11.00 am and 3.00 pm within the proposed system.

In a recent research by Alberta Government, a typical 100 cow dairy farm energy consumption is 111,000 kWh [18]. Required power in a dairy farm is distributed into following subsystems: milking, cleaning, waste management, farm house, ventilation, lighting, water pumping and livestock keeping [15]. Milk cooling is held whole year during the nights. Daily milk cooling time is assumed to be around 8 h per day. The output of absorption cooling system is used in milk cooling and storage process. In the day time, produced milk is distributed to the local markets. The heating of the farm house is supplied by the heat pump in the system. Required electricity for whole processes including milking, cleaning, waste management, ventilation, lighting, water pumping etc. is supplied by generated electricity in the organic Rankine cycle. The generated electricity in the PV/T system is used in electricity consumption of fan and circulating Pump 3 which is used in the thermal energy storage. The fan is only used in daytime during the drying process. Pump 3 needs to circulate the water whole day, hence it is run by