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A new solar based multigeneration system with hot and cold thermal storages and hydrogen production

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ABSTRACT

A multigeneration system based on solar thermal energy associated with hot and cold thermal storage is designed and analyzed energetically and exergetically. The system produces electricity, a heating effect, a cooling effect, hydrogen, and dry sawdust biomass as outputs by means of organic Rankine cycles, a heat pump, two absorption chillers, an electrolyser, and a belt dryer. The intermittent behavior of the renewable energy source is addressed through the incorporation of hot and cold thermal storage systems to operate an organic Rankine cycle and provide cooling at night. The performance assessment indicates that the overall (day and night) energy and exergy efficiencies are 20.7% and 13.7%, respectively. The majority of the total exergy destruction is attributable to the sawdust belt dryer, at about 64.0%.

1. Introduction

Various renewable sources can be exploited to obtain environmentally friendly and sustainable products. Many renewable sources are now being utilized despite the dominance of traditional energy forms like fossil fuels. To enhance the commercial potential of renewable energy sources, they are sometimes incorporated into multigeneration energy systems. Such systems usually produce three traditional outputs (electricity, cooling, and heating) and can be expanded to include hydrogen, fresh water, dried products, etc.

A commonly considered renewable source is solar energy. The utilization of solar thermal energy varies with application, amount of heat to be harvested, and desired temperature to be reached. One drawback to solar energy is its intermittent nature. One means of addressing this drawback is storing thermal energy either as sensible or latent heat in (e.g., using molten salts as phase change materials) or via thermochemical storage (i.e., using a chemical substance that can be reconverted into useful energy when needed). Hydrogen storage is an example of the latter type of storage.

Various integrated energy systems have been described and thermodynamically analyzed. Zafar and Dincer [1] proposed a renewable energy system that uses a photovoltaic/thermal solar (PV/T) collector, an electrolyser, and a fuel cell to generate electricity and pure water and to supply heated air to residential buildings. They reported an increase of 3.25% in energy efficiency and 17% in exergy efficiency, when all outputs are considered. The total hydrogen production is reported to be up to 11 kg/hr if more than 90 kW of electrical power is supplied. Pouria et al. [2] assess and optimize a multigeneration system that is supplied with heat from an industrial heat source to produce electrical power, heated water, cooling, and hydrogen and oxygen (via water electrolysis). They reported an efficiency increase of more than 20% for multigeneration compared with generation of only one product (electricity). Pouria et al. [3] investigated a biomass based multigeneration system to produce five outputs including hydrogen. The highest exergy destruction is found to be in the combustor, and the exergy efficiency is reported to be high and the CO2 emission low for the multigeneration system, compared with a single generation system for electricity.

By considering alternative approaches to hydrogen production, Ozcan et al. [4] assessed an Mg–Cl hybrid thermochemical cycle that operates on solar energy and produces electricity and hydrogen. The exergy efficiency of the proposed system is 19.9%. Dincer [5] categorized green methodologies for hydrogen production in terms of inputs (waste heat recovery, nuclear energy, and

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Nomenclature

c_p	Specific heat at constant pressure (kJ/kg K)
ex	Specific exergy (kJ/kg)
$\dot{E}x$	Exergy rate (kW)
HHV	Higher Heating Value
h	Specific enthalpy (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure (kPa)
$\dot{Q}$	Heat rate (kW)
R	Gas constant (kJ/kgK)
s	Specific entropy (kJ/kg.K)
T	Temperature (°C)
t	Storage period (s)
u	Specific internal energy (kJ/kg)
U	Internal energy (kJ)
$\dot{W}$	Work rate (kW)
x	Mass fraction

Greek Symbols

η	Energy efficiency
ψ	Exergy efficiency
ω	Humidity ratio

Subscripts

a	Air
AC	Absorption chiller
CES	Cold energy storage
char	Storage charging
chem	Chemical
cogen	Cogeneration system
comp	Compressor
cond	Condenser
cooling	Cooling effect
d	Dischargeday, Daytime operation
Dehumid	Dehumidification
disch	Storage discharge
evap	Evaporator
gen	Absorption chiller generator
glycol	Ethylene glycol water mixture
H_2	Hydrogen
HES	Hot energy storage
HP	Heat pump
in	Inlet (matter or energy)
Losses	Heat losses
multigen	Multigeneration system
moist	Sawdust moisture
n	Species
night	Night-time operation
orc	Organic Rankine cycle
out	Outlet (matter or energy)
P	Pump
Q	Heat input
single	Single generation system
solar	Solar input
source	Source
tank	Storage tank
TES	Thermal energy storage
trigen	Trigeneration system
v	Vapor
w	Water
0	Reference environment
1 … 32	State numbers

renewable energy), and included further sub-categories based on type of energy conversion (electrical, thermal, photonic, biochemical, etc.).

Beyond hydrogen production, other multigeneration systems have been designed utilizing two renewable sources to provide numerous outputs. Malik et al. [6] proposed a system based on biomass and geothermal energy to obtain five outputs including electrical power, heating, cooling, gas liquefaction through the Linde–Hampson cycle, and dry products by hot air from a combustion dryer. The Energy and exergy efficiencies for the system were found to be 56.5% and 20.3% respectively, and the greatest exergy destructions were found to occur in the combustion chamber and boiler. Suleman et al. [7] proposed a multigeneration system based on solar thermal energy and geothermal energy. The solar thermal energy heats a fluid which in turn heats the system components. The exergy and energy efficiencies were assessed to be 54.7% and 76.4%, respectively. Another geothermal and solar based multigeneration system proposed by Al-Ali et al. [8] also includes a heat transfer fluid feed, and exhibits an energy efficiency of 78.0% and an exergy efficiency of 36.6%.

These multigeneration systems [9–11] suggest the integration of renewable energy sources to provide additional useful products can be advantageous, and merit further investigation. This article builds on the previous work, and the aim is to develop a solar based multigeneration system that includes hot and cold thermal energy storage and hydrogen production, making it suitable to operate during the night, and to assess the system energetically and exergetically (accounting for energy and exergy efficiencies and component exergy destructions). A parametric study is used to determine the change in system performance and outputs as input and assumed parameters vary.

2. System description

The proposed multigeneration system is shown in Fig. 1. The system produces five outputs: electrical power, space cooling, heating, hydrogen, and dry biomass. The system consists of two organic Rankine cycles (ORC1 and ORC2) that operate during the day; two thermal energy storage (TES) systems, a thermal energy storage system to provide heat for an isobutene organic Rankine cycle, and a cold energy storage system charged by an ammonia-water absorption chiller, to provide a cooling effect. Both storage systems are charged during the day, and then discharged at night to drive an organic Rankine cycle during the night and to provide nighttime cooling. Hydrogen is produced by an electrolyser that is supplied with 20% of the net work produced by the daytime-operation organic Rankine cycles. The heat pump incorporated in the system produces heat as an output, used simultaneously for heating the cool dry air used in biomass drying, and heating the water injected into the electrolyser to the operating temperature of 70 °C. The main energy source of the system is solar thermal energy, which is supplied by a parabolic trough collector. The parabolic trough collector is widely used in solar thermal applications and can operate up to a temperature of 400 °C [12,13]. Heat supplied by the parabolic trough collector heats a heat transfer fluid, Therminol-VP1 [14], to an operation temperature up to 400 °C with full chemical stability. As the heat transfer fluid is heated, it interacts with the system's components. These interactions, in which