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Original Research Article

Design and simulation of hybrid solar high-temperature hydrogen production system using both solar photovoltaic and thermal energy

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ABSTRACT

Hydrogen demand should significantly increase in the next few years due to rapid growth of energy demand, the refinery industry's growing needs and applications such as biofuel production. To meet the demand advanced processes are being developed throughout the world in a sustainability context. Among the most studied ones is high temperature electrolysis of steam using solar photovoltaic and thermal energy. In this work, a large scale hybrid solar hydrogen production system was designed and optimized. The system consists of the solid oxide steam electrolysis system coupled to a Photovoltaic array through a Direct Current converter and coupled to a Parabolic Trough Collector through a heat exchanger network optimized using a Generalized Reduced Gradient algorithm. Under local tropical conditions, the theoretical production rate of hydrogen per second and per day recorded from simulation of interconnected system based on optimum scenario are respectively 0.064 kg/s and 1843.2 kg/day. The exergy efficiency, land used and water consumption of system component was also performed.

Introduction

The rapid growth of energy demand, rising fuel costs along with the fear of the global greenhouse effect has aroused great interest in sustainable energy utilization. At present, many governments are committed to finding a long-term solution to this crisis through the valorization of renewable energy which is fast becoming an increasingly valuable solution for the global energy problem. In pursuance of this goal, Cameroon with an energy sector fully dependent on hydroelectric and hydrocarbon resources is following new policies to improve and develop the sources of energy [1]. Cameroon being a tropical country with a territory spreading itself between the latitudes 2°N and 13°N and between the longitudes 8°E and 16°E, is endowed with sufficient solar radiation that can be effectively harnessed as renewable energy resource. Measurement data indicated an average annual solar irradiance in the range of 4.28kWh/m^2/day to 6.75 kWh/m^2/day and mean annual hours of sunshine per year of over 3000 h [2].

Since renewable sources and solar energy in particular are often variable and uncertain, an energy storage system is a desirable addition in order to accumulate energy when it is overproduced and then to use it when such sources are not enough to meet peak demand (to uncouple the request and the energy production).

Hydrogen is widely considered as the leading candidate as future energy carrier [3] since it has the highest energy content per weight unit and its use either via combustion or fuel cells results in pure water. In order hand Hydrogen demand is already strong. It should significantly increase in the next few years due to the refinery industry's growing needs and new applications such as synthetic fuel or biofuel production. Hydrogen is produced by solar way mainly using thermal processes, photo-electrochemical and electrolytic [4]. Perhaps one of the best methods for the production of hydrogen while using carbon-free, solar energy is the electrolysis of water or steam. High temperature electrolysis of steam (HTE) is expected to consume less electrical energy as compared to electrolysis at low temperature as consequence of the more favourable thermodynamic and electrochemical kinetic conditions for the reaction [5]. A significant part of the energy required for an ideal (loss free) HTE can thus be provided by heat. Several energy sources for water steam production and coupling possibilities was investigated. The energy sources considered in recent works are the nuclear reactors [6–9], biomass and domestic waste incinerators [10], geothermal source [11], and solar thermal collector [12,13]. There are three possible operating modes for

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Acronyme

DC	Direct Current
HEX_NET	heat exchanger network
HPS	hydrogen production system
HTE	high temperature electrolysis
LMTD	Log Mean Temperature Difference
LVH	low heat value
NOCT	nominal operational cell temperature
PRE_HEX	preheated heat exchanger
PTC	Parabolic Trough Collector
PV	photovoltaic
SO_BOILER	solar boiler
SOSE	solid oxide steam electrolyzers

Symbol

A	surface area (m^2)
a	modified ideality factor
Bg	permeability of oxygen
C	concentrating ratio
Cp	specific heat (J/(kg·K)
d	electrode thickness (m)
D	diameter (m)
D_{hy}	Hydraulic diameter (m)
Di	receiver inside tube diameter (m)
Do	receiver outside tube diameter (m)
E	energy or exergy (J)
F	Faraday's number
G	instantaneous solar radiation (W/m^2)
H	enthalpy (J/mol)
h	convective heat transfer coefficient (W/m^2)
I	current intensity (A)
j	current density (A/m^2)
jo	exchange current density (A/m^2)
K	overall heat transfer coefficient
k	Boltzmann's constant
L	electrolyte thickness (m)
P	pressure (Pa)
Q	heat (W)
R	perfect gas constant
S	effective solar radiation absorbed (W/m^2)
T	temperature (K)
U	voltage (V)
WS	wind speed (m/s)

Subscript

a	anode
act	activation
amb	ambiant
c	cathode
co	cold
col	collector
con	concentration
el	electrolyzer
f	fluid
g	glass
ho	hot
m	maximum
mp	maximum power
oc	open circuit
ohm	Ohmic
pv	photovoltaic
R	reflector
ref	reference
rev	reversible
rt	receiver tube
sc	short current
u	useful

Greek letter

α_a	absorber absorptivity
ε	emissivity
η_{act}	activation overpotential (V)
η_{con}	concentration overpotential (V)
η_{en}	energy efficiency
η_{exer}	exergy efficiency
ξ	dynamic viscosity (kg/m·s)
ρ_R	reflector reflectivity
σ	Stefan constant
χ	entropy (J/K)
η_{ohm}	Ohmic overpotential (V)
λ	thermal conductivity (W/m·K)

HTE depending on the energy balance at the electrolyser level: endothermal, isothermal and exothermal. In the exothermal mode, the temperature of the steam increase from the input of electrolyzer to the output. This corresponds to the worst energy efficiency but the best production cost. The exothermal operating mode is best suited for the low temperature source.

The aim of this work is to design, optimize and simulate a hybrid hydrogen production system from solar energy mean high temperature electrolysis of steam. Through the designed system it can possible to evaluate the amount of hydrogen considered as an energy carrier an electrolyzer powered by an 8 MW PV plant can produced in real tropical conditions. The steam entering in the HTE is produced by a cylindrical-Parabolic Trough Collector and superheated by a high temperature heat exchanger network designed and optimized using the reduced generalized gradient method. The HTE is supposed to operate in exothermal mode. The electric power is generated by a large scale PV plant. A simulation of interconnected system is performed under Sudanese sahelian conditions of Sudan type. The performance analysis of each component is conducted and the mass rate of hydrogen and by product oxygen is computed.

1. System description

The system major component and the conceptual flow diagram of the HTES process to produce hydrogen are shown in Fig. 1.

The process consists of the PTC to produce high temperature thermal energy, the PV1 array to generate and supply DC power to the electrolyzer, one solar heat exchangers (solar_boiler) to supply thermal energy to high temperature heat exchanger network (HEX_NET), the high temperature electrolyzer to produce hydrogen from steam, the heat-recuperating condenser (HRC), the hydrogen–water separator (HWS). The high temperature heat exchanger network supplies superheated steam to the electrolyzing cell at a temperature of around 850–900 °C, and a pressure of around 5 MPa. We assumed that the superheated steam introduced into the electrolyzer contains a small portion of hydrogen in order to maintain the reducing conditions at the cathode. The heat of the hot gas product stream exiting the electrolyzer is first recovered in the HEX_NET to superheat the steam exiting the solar exchanger up to operating temperature of the HTE cells. Another fraction of the heat of the hot gas is recovered at the recuperating condenser to raise the temperature of fed water from ambient to