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Development, analysis and assessment of a fuel cell and solar photovoltaic system powered vehicle

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A B S T R A C T

This paper deals with a new hybridly powered photovoltaic-fuel cell - Li-ion battery integrated system and is compared to a base system, consisting of PEM fuel cell and Li-ion battery. It investigates the effects of adding photovoltaic arrays to the base system and further effects on the overall energy and exergy efficiencies and hence hydrogen consumption. These two systems are analyzed and assessed both energetically and exergetically. The study results show that the overall energy and exergy efficiencies become 39.46% and 56.3%, respectively at a current density of 1150 mA/cm^2 for system 1 (fuel cell-battery). Moreover, energy and exergy efficiencies are found to be 39.86% and 56.63% at current density of 1150 mA/cm^2 for system 2 (fuel cell-battery-photovoltaics). Utilizing photovoltaic arrays in system 2 would recover 561 g of hydrogen through 3 h of continuous driving at max power of 98.32 kW, which is approximately 11.2% of the hydrogen storage tank used in the proposed systems. The effects of changing various system parameters on energy and exergy efficiencies of the overall system are also examined.

1. Introduction

The transportation sector is considered the primary cause of both the energy crisis and GHG (Greenhouse gas) emissions, they are responsible for 63.8% of the global oil consumption in 2013, and it will increase the global CO_2 emissions up to 24.6% at 2040. Statistics were taking into consideration applying scenarios for reducing CO_2 emissions [1]. Hybrid and fuel cell vehicles are considered more fuel efficient when compared to conventional vehicles. In addition, fuel cell vehicles are considered carbon-free vehicles, especially if the hydrogen used is extracted from renewable or clean energy sources such as solar, wind and nuclear energy [2]. Lots of contributions have been made by different countries. In 2007, German government started the national hydrogen and fuel cell technology innovation program put a budget of 5 billion dollars for the development of hydrogen energy and fuel cells from 2007 to 2017. In 2001, the Japanese Ministry of Economy, Trade, and Industry recently issued a program to guide the development of hydrogen energy and fuel cell technology [3].

Elnozahy and Salama [4] studied the feasibility of using PV (Photovoltaics) electricity to charge PHEVs (Plug-in hybrid electric vehicles). Results showed the feasibility of using it for a short period as it can fulfill partially the needed energy by PHEVs. However, in the long operating periods, PV arrays will face difficulty to supply the increased demand for energy and storage devices should be implemented to fill the gap. Dinis et al. [5] used a computational application that allows investigating the effect of utilizing photovoltaic panels on board to electric vehicles; it measured the number of km covered by the vehicle and the corresponding amount of emissions of greenhouse gasses associated with power generated by the PV system. Ko and Chao [6] proposed quadratic maximization algorithm to enhance energy harvesting by PVs through the maximum power point tracking method especially during the motion of the vehicle. The results showed a modification in the overall tracking efficiency. The results verified by the experimental data which confirm the feasibility of using QM algorithm.

Kelly et al. [7] tested PV powered high-pressure electrolyzer integrated with Fuel cell system equipped in an electric vehicle. Results showed that the fast irregular alteration of solar power input caused by clouds did not affect the electrolyzer system response. In addition, changing the temperature from day to day did not affect the efficiency significantly. Moreover, the solar energy to hydrogen efficiency, electric to hydrogen efficiency and solar to electric efficiency averaged on 8.2%, 59.7% and13.7%

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Nomenclature

A	area, m^2
a	membrane activity
D^{eff}	diffusion coefficient
E	actual cell voltage, V
E_{act}	activation overpotential, V
E_{ohm}	ohmic overpotential, V
E_{conc}	concentration overpotential, V
$\dot{Ex}$	exergy rate, kW
ex	specific exergy, kJ/kg
F	Faraday constant, C/mol
h	specific enthalpy, kJ/kg
h_c	heat transfer coefficient, W/m^2 K
I	current, A
J	current density, A/m^2
J_L	limiting current density, A/m^2
J_{oa}	exchange current density of the anode, A/m^2
J_{oc}	exchange current density of the cathode, A/m^2
J_0	exchange current density, A/m^2
K	equilibrium constant
$\dot{N}$	molar flow rate, mole/s
n	number of moles
nfc	number of fuel cell cells
P	pressure, bar
R	gas constant, kJ/kmol K
s	specific entropy, kJ/kg K
ST	solar radiation, W/m^2
T	temperature, °C or K
V	voltage, V
v	wind speed, m/s
$\dot{W}$	power, kW
y	molar fraction

Greek letters

α	symmetry factor
δ	element thickness, m
η	energy efficiency
λmem	membrane water content
σmem	membrane conductivity, 1/Ω cm
ψ	exergy efficiency

Subscripts

0	ambient conditions
1, 2, ..., i	state points
an	anode
ca	cathode
Ch	chemical
Comp	compressor
cp	circulation pump
FC	fuel cell
Hex	heat exchanger
Ke	kinetic
m	maximum
PCU	power control unit
Pe	potential
Ph	physical
Pr	pressure regulator
so	solar

respectively. Moreover, the system generated up to 0.67 kg of hydrogen over a sunny and full day of operation. Furthermore, solar battery charging energy usage per mile basis are found to be three times more efficient compared to solar to hydrogen efficiency. Mebarki, et al. [8] introduced a supervisor control unit for an integrated PV- PEMFC- Battery system. Results show the feasibility of the hybrid system production for an electric vehicle.

Zhang et al. [9] developed a PEM fuel cell system integrated with internal combustion engine. The work aimed at recovering the exhaust hydrogen from the fuel cell and high-temperature heat accompanied with exhaust gasses from the internal combustion engine. They recommended that if peak power is demanded instantly not only the flow of the fuel is enough, a mean of integration between both power supplies needed. Sato et al. [10] presented a fuel cell system, consisting of an ethanol dehydrogenation catalytic reactor for producing hydrogen. Supplying both a PEMFC to generate electricity for electric motors and a liquid by-product effluent from the reactor to be utilized as fuel for an ICE engine, or catalytically recycled to extract more hydrogen molecules. They claimed that the system could solve the issues of hydrogen production, distribution, and on board storage.

Andreasen et al. [11] designed a traction power system consisting of a Li-ion battery pack and a high-temperature PEMFC to extend the running range and act as an on board charger to the battery. They used a liquid methanol/water mixture of 60/40% by volume, as fuel instead of compressed hydrogen, enabling a higher volumetric energy density. The system is investigated experimentally, and the fuel cell performed efficiently as a range extender and significantly increases the run time and range of the power system. Martin and Wörner [12] studied using bioethanol and biodiesel to produce hydrogen on board so it can be utilized as a fuel with high-temperature PEM fuel cell. Two types of reformers are used, steam reforming and auto-thermal reforming. They concluded that hydrogen efficiency improved when preheating both feed water and feed air. Using auto thermal reforming option for reforming of bioethanol and biodiesel are found to be better as its less complex. Corbo et al. [13] conducted an experimental investigation for a power system consists of lithium ion polymer battery and PEM fuel cell. The tests conducted using European R47 driving cycle and the system performed in a positive way.

Xu et al. [14] performed a theoretical modeling for a traction power system consisting of a Li-ion battery and PEM fuel cell. Results showed that within the working range of the electric motor, fuel cell output power, fuel cell efficiency, stored hydrogen mass, battery capacity, and average battery resistance will affect the maximum velocity and driving distance linearly. Moreover, accelerating time is influenced by the previous mentioning parameters except for the battery parameters. Moreover, Hydrogen consumption decreases by 14% by increasing PEM efficiency from 48.3% to 55%, braking energy ratio increases from 0% to 28% would lead to a reduction in hydrogen consumption by 16%. Hussain et al. [15] performed energy and exergy analysis on a PEM fuel cell power system for a light-duty vehicle associated with the comprehensive parametric study. Results displayed that increasing current density altered the difference between the gross stack power and net system power. Furthermore, both energetic and exergetic efficiencies of the system increased with increase stack operating temperature and pressure. Moreover, the air stoichiometry does not show a significant effect on energetic and exergetic efficiencies, and the largest exergy destruction rate took place in fuel cell stack.

Ay et al. [16] investigated the effects of changing the cell operating temperature, current density, pressures of anode and cathode and membrane thickness on the PEM fuel cell exergetic performance. The results showed that PEM fuel cell exergy efficiency