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Development, analysis and assessment of fuel cell and photovoltaic powered vehicles

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ABSTRACT

This paper deals with a new hybridly powered photovoltaic- PEM fuel cell – Li-ion battery and ammonia electrolyte cell integrated system (system 2) for vehicle application and is compared to another system (system 1) that is consisting of a PEM fuel cell, photovoltaic and Li-ion battery. The paper aims to investigate the effect of adding photovoltaic to both systems and the amount of hydrogen consumption/production that could be saved/generated if it is implemented in both systems. These two systems are analyzed and assessed both energetically and exergetically. Utilizing photovoltaic arrays in system 1 is able to recover 177.78 g of hydrogen through 1 h of continuous driving at vehicle output power of 98.32 kW, which is approximately 3.55% of the hydrogen storage tank used in the proposed systems. While, using the same photovoltaics arrays, system 2 succeeds to produce 313.86 g of hydrogen utilizing the ammonia electrolyzer system 2 appeared to be more promising as it works even if the car is not in operation mode. Moreover, the hydrogen produced from the ammonia electrolyzer can be stored onboard, and the liquefied ammonia can be used as a potential source for feeding PEM fuel cell with hydrogen. Furthermore, the effects of changing various system parameters on energy and exergy efficiencies of the overall system are investigated.

Introduction

In 2014, about one billion light duty vehicles were running worldwide [1], light duty vehicles were responsible for about one-fifth of the EU's carbon dioxide emissions [2]. Moreover, in the US, the transportation sector is responsible for 26% of the GHG emissions [3], and light duty vehicles shares up to 63% of the transportation GHG emissions [4]. While in Canada, the transportation sector is responsible for 27% of the total GHG emissions and road transportation accounted for 69% of the transportation sector [5]. The whole transportation sector is expecting to increase CO_2 emissions up to 24.6% by 2040 considering CO_2 reduction scenarios [6]. Therefore, applying environmental powering options for light-duty vehicles is mandatory to reduce GHG emissions. Using hydrogen as a fuel is one of the promising solutions to replace fossil fuels and eliminate GHG emissions especially if the hydrogen is produced from renewable sources. Hydrogen can be used as a fuel to operate fuel cells, particularly the combination of fuel cells

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and electric motors is highly efficient compared to mechanical combination in conventional vehicles [7].

Many studies included thermodynamic modeling and comprehensive parametric studies on fuel cells fueled by hydrogen for vehicular applications. Ezzat and Dincer [8] developed an integrated system consisting of PEM fuel cell, Li-ion battery and PV arrays. The results showed that the energy and exergy efficiencies were 39.86% and 56.63% respectively. Using Photovoltaics succeeded to recover about 560 g of hydrogen. Hussain et al. [9] investigated PEM fuel cell as main power source for a light duty vehicle energetically and exergetically with a comprehensive parametric study. The results display an increase in energy and exergy efficiencies with the rise of the operating pressure and temperature. Furthermore, the fuel cell stack exergy destruction was the highest compared to the other fuel cell system parts. Mert et al. [10] utilized the energy and exergy approaches to analyze the performance of PEM fuel for transportation purposes. Moreover, the effect of changing some operating conditions such as; membrane thickness, humidity, reference temperature and pressure, operating temperature, operating pressure, an anode, and cathode stoichiometry on the overall energy and exergy efficiencies of the system are considered. Ay et al. [11] conducted a thermodynamic analysis on PEM fuel cell system, and the results assert that increasing membrane thickness and current density would lead to a decrease in the system exergy efficiency, on the contrary, increasing cell operating temperature would increase the system exergy efficiency. Kazim [12] examined the effect of altering fuel cell operating temperatures, air stoichiometric, cell voltages and pressures on the exergetic performance of the fuel cell. The results showed that improving the exergy efficiency of the PEMFC can be achieved by increasing air stoichiometry, cell operating pressure, and temperature. However, hydrogen, as a fuel has some disadvantages. For instance, its low volumetric density which required a large volume of storage, lack of adequate hydrogen distribution infrastructure [13]. Ammonia can substitute hydrogen as fuel efficiently as storing ammonia is cheaper by three times than storing hydrogen, ammonia distribution structure is available, and it can be combusted in an environmentally benign way, and finally any leakage can be detected by a nose in concentrations as low as 5 ppm [14]. Using ammonia as a potential fuel for vehicular applications is addressed in the literature. Dincer and Zamfirescu [15] established a novel system with a unit for ammonia separation and decomposition to acquire hydrogen to fuel a hybrid system using a linear generator with homogeneous charge compression ignition (HCCI); and a direct ammonia high-temperature fuel cell system. The separated nitrogen is used as a cooling agent in the vehicle refrigeration system. Kojima et al. [16] utilized the exhaust heat to separate hydrogen from ammonia followed by storing hydrogen to feed the ICEs along with ammonia into the combustion chamber. Ryu et al. [17] claimed improvement in engine performance and minimization of NOx, HC, CO emissions when using the hydrogen produced by ammonia dissociation catalyst.

Ammonia electrolysis showed promising results due to the low theoretical energy required for the electrolysis process, which consumes 95% lower energy than water electrolysis at standard conditions [18]. Gwak et al. [19] conducted ammonia electrolysis experiments using zero gab cells, and it was proven that ammonia electrolysis technology is more efficient thermodynamically when compared with thermal decomposition. Furthermore, pure hydrogen is generated with energy efficiency of over 80%. Boogs and Botte [20] integrated a micro proton exchange membrane (PEMFC) with ammonia electrolyte cell (AEC), the electricity generated from the PEMFC is utilized to feed the AEC with electricity. The study shows that using 203 L of aqueous ammonia will allow a hybrid fuel cell vehicle to travel 483 km before demanding another ammonia refill. Goshome et al. [21] investigated the electrolysis of ammonia using NH_4Cl as an electrolyte under a current density of 70 mA/cm^2, hydrogen, and nitrogen are generated. Moreover, they successfully generated hydrogen at 20 MPa.

Using solar energy in vehicle applications and implementing it effectively in vehicle powering options was always a promising field of research. ElNozahy and Salama [22] obtained that using photovoltaic (PV) to provide electricity to Plug-in hybrid vehicles (PHEV) will not be sufficient to guarantee a stable supply of electricity for the long operating period. However, using PVs for a short period can partially fulfill the needed energy by PHEV. Dinis et al. [23] calculated the reduction of greenhouse gasses emission per km when utilizing PV panels on board to electric vehicles. Ko and Chao [24] suggested quadratic maximization algorithm that would improve energy harvesting by PVs during the vehicle movement. Kelly et al. [25] equipped an electric vehicle with an electrolyzer coupled with PV and connected the electrolyzer with fuel cell system. The system produced up to 0.67 kg of hydrogen over a sunny and full day of operation. Mebarki et al. [26] developed a master control unit for an integrated PEMFC-PV– Battery system. The energy produced from the integrated system showed to be adequate to run an electric vehicle.

This study aims at introducing a new integrated energy system based on carbon-free fuels; hydrogen, ammonia and using photovoltaics, a renewable power source for a possible powering option for vehicle applications. Two systems are presented in this study for comparison purpose; the first system consists of fuel cell system – Li-ion battery and photovoltaics. While, the second system is consisting of fuel cell system – Li-ion battery-photovoltaics and ammonia electrolyzer. The power from the photovoltaics in the first system is supplied directly to the system power unit. However, the second system will utilize the power produced by photovoltaics to supply ammonia electrolyzer with the electricity required to generate hydrogen onboard. These two systems are examined and evaluated energetically and exergetically. In this regard, the specific goals of the current study are itemized as follows:

- To develop a novel integrated PV– battery - fuel cell based system with ammonia electrolyzer to produce hydrogen onboard and evaluate it in details using the first and second law of thermodynamics by calculating energy and exergy flows for all system streams and determining exergy destructions and losses for the integrated system components.

- To assess the performance of the proposed system by identifying both energy and exergy efficiencies of the entire system.