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Modeling of solar photovoltaic-polymer electrolyte membrane electrolyzer direct coupling for hydrogen generation

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ABSTRACT

Hydrogen production by proton exchange membrane water electrolysis (PEMWE) directly powered by photovoltaics (PV) is analyzed by a detailed modeling approach which consists in three parts. The first part is devoted to the quantification of the solar irradiation received on the PV module with the integration of the geographic characteristic of the desired location, weather data, and an estimation of ozone concentration. In the second part, an elaborated mathematical model is presented to estimate the power delivered by PV module, the model include temperature and the amount of solar irradiation. In the third part, an elaborated model of proton exchange membrane water electrolysis was presented. Based on a thorough analysis of the thermodynamic and the electrochemistry of PEMWE, for the first time the efficiency of the PEMWE was well defined. The relevance and the effectiveness have been tested against experimental data with accuracy for each developed models. Then, the complete model, that combine the three parts, has been used to understand the effect of solar irradiation, temperature, pressure, PV electrical efficiency and PEMWE efficiency on the voltage required for electrolysis and hydrogen production rate. Additionally, a multi-objective optimization technic was applied in order to minimize the energy conversion loss, between the PV-PEMWE, and to increase hydrogen production rate. The model presented in this study offers accuracy and flexibility to the analysis of Solar PV-PEMWE system for hydrogen production and helps to analyze the influence of each component on the overall structure, and to develop a decision tool to determine the performance of the Solar PV–PEMWE, to assess the economics of the system and to assist for the deployment of PV-PEMWE technology.

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Introduction

As is well known, fossil fuels such as coal, oil and gas have cradled the childhood of humanity by widely ensuring contemporary energy needs. However, a net imbalance between fossil fuels exploitation and energy consumption has weakened the global economy. Also, the massive exploitation of oil in transportation and heavy industry causes environmental problems, such as pollution and climate change. Efforts are made, by many countries, for developing an alternative energy, capable of competing with the fossil fuels. One of the new emerging technologies, with a global plebiscite, as a clean energy source able to be as effective and efficient as oil or natural gas, and maintaining the integrity of the environment, is based on the duet hydrogen and fuel cells.

Flexible, accessible and reliable sectors of the economy can be attained in all regions of the country by employing hydrogen fuel cells. The hydrogen fuel cell vehicles, solar hydrogen powered residences as well as hydrogen powered fuel cells in mobile phones will be within the reach of all. Prior to shift toward the era of hydrogen and fuel cells, it is important to master the production of hydrogen. Among the different paths to hydrogen production, the one that uses renewable sources such as solar, wind or biomass is of promising future. Although there are several hydrogen production techniques, by far the hydrogen from the electrolysis of water is the simplest option and the only currently practical that drains the enthusiasm of researchers and industry. Current trends in research are channeled towards the production of hydrogen by polymer electrolyte water electrolysis (PEMWE), powered by photovoltaic systems. It consists of a photovoltaic (PV) module that converts solar irradiation into electrical energy, which is connected to the electrolyzer that generates hydrogen. There are different possible configurations of the Solar-PV-PEMWE hydrogen production system. These configurations depend on the operation of the PV modules and whether a converter and a maximum power point tracker are used. It is important, among all kind of configurations, to develop a decision tool to determine the performance of the Solar-PV-PEMWE and to assess the economics of the system. This helps to find the configuration that yields maximum performance and cost effective.

Prior research studies are related to PV–PEMWE. Paul et al. [1] have proceeded to experimental and theoretical investigation on direct coupling of PV array with PEMWE; the authors have demonstrated that using optimization strategy of the series–parallels combination of PV modules, and electrolyzer stacks, yields the highest energy transfer. Even though, the authors have presented a theoretical model of the PV array, there has been no modeling aspect of the electrolyzer. Also, Clarke et al. [2], have conducted an experimental evaluation of energy transfer in a direct coupling of PV array and PEMWE, and studied the system annual energy conversion under the variation of solar irradiation. However, there is no modeling aspect of the electrolyzer. Atlam et al. [3,4] have addressed the issues on the energy transfer mismatch between the PV and PEMWE and highlight the relation between solar irradiation and temperature on the PV performance. The authors have proposed a Matlab/Simulink simulation block for the PV-PEMWE systems, where model used for the PEMWE is a linear relationship between the current and the voltage. The authors have also compared the performance of the optimized and non-optimized system. Maroufmashat et al. [5] have proposed a multi-objective nonlinear optimization methodology to minimize energy transfer loss and to maximize the hydrogen production rate; the model used for the PEMWE was more elaborate than the model proposed by other authors. However, there was no equation used for the estimation of PEMWE efficiency. From the analyzed literature, one of the important issues in PV-PEMWE hydrogen generation systems is the maximum power transfer problem between the two devices (PV and PEMWE).

The present paper presents a detailed modeling of solar irradiation available at a defined geographic location, on an arbitrarily oriented plane, a detailed model for the PV power output and efficiency, a detailed model for PEMWE with the estimation of efficiency. The major outcome of this study is that the design scenario for the direct coupling of the PV-PEMWE was well described and the set of equations proposed are accurate, as we compare our theoretical results with experimental data. The PV model and PEMWE model are generalized, they can be used for different kind of technologies, which is not the case for the models used by others authors, for instance, common models in literature used for water electrolysis generally are suited for alkaline electrolysis, or a semi-empirical approach is used to interpolate the electrolysis behavior device, under different power delivered by the PV module. Our contribution is to propose a generalized model for the PEMWE electrolysis. The approach we have adopted is based on the modeling of each element that makes up the whole system, following by a procedural structure. Thereafter, we developed separate procedural simulation computer software, inherent for the description of the modeled element. This approach provides flexibility to the analysis of individual performance, to modify each module separately without altering the main procedure, to analyze the influence of each component on the overall structure, and finally performing an optimization to determine the connection that will achieve maximum performance of the global PV-PEMWE.

Model development

The idea developed in this paper is to provide a full detailed equations of the solar irradiation received on an arbitrarily surface, the power generated by a photovoltaic module, estimation of hydrogen production rate. In Appendix A, we discuss all the relevant equations. Additionally, in the following section, we test each models with our experimental data for the case of solar irradiation and PV module, and we test the model of PEMWE against published data.

Experimental validation of the solar irradiation model

The solar irradiation model (see Appendix A.1) is tested against measured data in the Algerian site of Ghardaïa (lat. 32° 23′, long. 3°49′ East, altitude 450 m, albedo = 0.3), for clear sky day. Statistics as the adjusted regression factor and the