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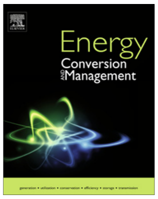

Optimization of Photovoltaic Electrolyzer Hybrid systems; taking into account the effect of climate conditions

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ABSTRACT

Solar energy will make a valuable contribution for power generation in the future. However the intermittency of solar energy has become an important issue in the utilization of PV system, especially small scale distributed solar energy conversion systems. The issue can be addressed through the management of production and storage of the energy in the form of hydrogen. The hydrogen can be produced by solar photovoltaic (PV) powered electrolysis of water. The amount of transferred energy to an electrolyzer from a PV module is a function of the distance between maximum power points (MPP) of PV module and the electrolyzer operating points. The distance can be minimized by optimizing the number of series and parallel units of the electrolyzer. However the maximum power points are subject to PV module characteristics, solar irradiation and ambient temperature. This means the climate condition can substantially influence the MPP and therefore the optimal size of the PV–Electrolyzer (PV/EL) system. On the other hand, system size can affect the levelized cost of hydrogen production as well.

In this paper, the impact of climate conditions on the optimal size and operating conditions of a direct coupled photovoltaic–electrolyzer system has been studied. For this purpose, the optimal size of electrolyzer for six cities which have different climate condition is obtained by considering two solution scenarios, regarding two objectives which are annual energy transfer loss and levelized costs of hydrogen production and then the optimal results for these cities are compared. The results show that the climate condition can strongly affect the size of the electrolyzer, the annual hydrogen production and consequently, both the levelized costs of hydrogen production and annual energy transfer loss. Moreover, it is found out that the solar to hydrogen efficiency of the optimal systems regarding these cities are different based on the solution scenarios, the characteristics of PV output power and the configuration of optimal electrolyzer configuration and placement.

1. Introduction

Renewable energy sources are greatly desired in today's ever-growing, environmentally conscientious society. Solar energy, in particular, is of great interest since it is abundant and ubiquitous throughout the world, and has the potential to provide a solution to the environmental challenges of the day. Solar energy technology includes, but is not limited to, solar heating, solar photovoltaic systems, solar thermal electricity and solar architecture. Solar energy, principally photovoltaic (PV), often requires storage prior to use [1]. In this work energy storage is primarily carried out by the production and storage of hydrogen from the electrolyzer supplied by PV energy.

Although most of the renewable energy technologies are well known, the integration of these technologies has still some issues [2]. The mismatch between the output specifications of PV module and electrolyzer load at different irradiance conditions indicates the importance of the optimal matching of the photovoltaic and electrolyzers [3]. The integration of such a system can be performed indirectly by power controlling devices such as maximum power point trackers which can have high efficiency [4,5] or directly which is independent of controlling devices therefore making the PV-electrolyzer (PV/EL) system more affordable [6]. The direct coupling method, although less costly, lacks efficiency when the PV and the electrolyzer are not properly designed and selected, and as such, the direct coupling method requires more

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Nomenclature

E	open circuit voltage (V)
E_0	open circuit voltage in reference condition (V)
F	faraday constant (C mol^{-1})
G_{eff}	effective irradiation on PV module (W m^{-2})
G_{on}	extraterrestrial radiation
G_{SC}	solar constant
I_D	diode current for the PV system (A)
I_{elec}	operation current for the electrolyzer (A cm^{-2})
I_L	light current for the PV system (A)
I_p	current of parallel resistance (A)
I_{PV}	operation current for the PV system (A)
I_{SC}	short circuit current PV module (A)
I^*_{SC}	short circuit current in standard condition (A)
N_P	number of electrolyzer cells in parallel
N_S	number of electrolyzer cells in series
PV	photovoltaic
PEM	proton exchange membrane
R	universal gas constant (bar m^3 mol^{-1} K^{-1})
R_s	series resistance for the PV-system (Ω)
T_a	ambient temperature (K)
T_c	temperature of solar cell (K)
T^*_c	temperature of solar cell in reference condition (K)
T_{elec}	operation temperature of electrolyzer (K)
V_{act}	activation overvoltage (V)
V_{elec}	operation voltage for the electrolyzer system (V)
V_{diff}	mass transport losses (V)
$V_{OC_{PV}}$	open circuit voltage for the PV-system (V)
$V^*_{OC_{PV}}$	open circuit voltage for the PV-system in reference condition (V)
V_{ohm}	ohmic losses (V)
V_{PV}	operating output voltage of PV (V)
V_t	thermal voltage (V)

Greek symbols

α	electron transfer coefficient
β	slope angle of surface, radian
β_e	anodic transfer coefficient
δ	angular position of the sun at solar noon, radian
$\emptyset$	latitude, radian
ω	hour angle in degrees for the requested time, radian
$\mu_{V_{oc}}$	temperature coefficient of open circuit voltage (V/K)

research [2]. Many literatures have reviewed the direct coupling of PV/EL systems [7–12]. An appropriate operation strategy matching of PV (current–voltage) and performance profile (i.e., voltage - current profile) of the electrolyzer results in energy transfer loss minimization, which is a distance between the operating points of the system and the MPPs of the PV. The results proposed that the PV/El system performance becomes more desirable. Considering the inefficiency of the direct coupling method, Wilhelm and Fowler [13] have compared various solar hydrogen production technologies. Most of the research performed on the subject is aimed toward the optimal design of the PV/EL systems based on the technical criteria. García-Valverde et al. [2] employed a methodology to determine the optimum number of cells in series and Atlam et al. [12] applied a linear method for the optimization of electrolyzer cells in series and parallel based on the minimization of the energy transfer loss between PV and electrolyzer. Maroufmashat et al. [14] employed a particle swarm optimization (PSO) algorithm in order to maximize hydrogen production of a PV/EL system. Energy transfer loss (ETL) was minimized by applying the PSO to optimize the size and operating conditions of a PV/EL system [15]. Note, the optimization of the PV/EL system can also be achieved by implementing different objectives by means of heuristic methods such as Imperialist competitive algorithm in [16,17]. In order to optimally design and operate direct coupling PV/El systems, various optimization algorithms were compared on the basis of their own performance and characteristics [18]. Besides the technical criteria, another crucial objective affecting the design of PV/El systems is economic criteria [19] e.g., the levelized cost of hydrogen produced. Stewart et al. [20] provides an analysis of the “Hydrogen from the Sun” project at the “Ecological House” in northern Italy. The analysis shows the initial cost of hydrogen to be $9.36 per kg and the cost can be reduced to $4 per kg for a large scale optimized system [21]. Ma et al. [22] used an evolutionary based multi-objective algorithm for a pumped storage-based standalone photovoltaic power generation system to minimize system lifecycle cost and maximize power supply reliability at the same time and Dufo-López et al. [23] applied a Multi-objective optimization algorithm to minimize cost and life cycle emissions of stand-alone PV–wind–diesel systems with batteries storage. Likewise Tani et al. [24] developed a method to design a solar hydrogen energy system with the most cost effective way. To the best of authors’ knowledge, the optimal deign of the direct coupling PV/El systems has rarely been done based on economic evaluation.

Geographical location and climate conditions to which the PV/EL system is subjected also greatly impacts the optimal size of such energy conversion and storage systems, and thus consequently system cost and energy conversion efficiency. Chae et al. [25] evaluate the Building Integrated PV (BIPV) system performance in six different climate conditions. Lu et al. [26] studied climate effects on design optimization and optimal control of grid-connected and standalone nearly/net zero energy buildings and Ghribi et al. [27] studied the technical potential of hydrogen production from a PV/EL system in six locations with different climate conditions in Algeria.

1.1. Research contribution

Many works have been performed the optimization of the direct coupling PV/EL systems according to the technical performance as a target. In this paper, in addition to the technical evaluation, the economic criteria have been included to optimally design direct coupling PV/El system. Moreover, despite of the significant effect of climate conditions, it has not been widely investigated before for such optimized systems. In this paper, different efficiencies of integrated systems such as the PV efficiency, the electrolyzer efficiency and the energy transfer efficiency have been studied, whereas in the literature [28–31] mostly the solar to hydrogen efficiency is considered. Taking into account these features, the proposed approach in this paper builds upon the authors’ prior work presented by Maroufmashat et al. [16] along with the consideration of the following points:

1. Optimal design of the direct coupling PV/El systems have been done based on technical objectives such as minimization of energy transfer loss between PV cells and electrolyzers, as well as economic objectives which include the levelized cost of hydrogen.