



Sunlight to hydrogen conversion: Design optimization and energy management of concentrated photovoltaic (CPV-Hydrogen) system using micro genetic algorithm



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ABSTRACT

Owing to the intermittent solar irradiance from cloud cover in the diurnal period and unavailability at night time, the practical design of a solar system requires energy backup storage for an uninterrupted supply or for off-grid operation. However, for highly efficient CPV (concentrated photovoltaic) system, the literature is lacking for energy management and optimization algorithm and tool for standalone operation. In this paper, a system with CPV and electrolyser is presented where beam irradiance of sunlight is harnessed to convert the instantaneously generated electricity into useful Hydrogen/Oxygen gas, where they can be stored and re-used for downstream applications such as the fuel cells, etc. The multi-variable design and multi-objective optimization strategies are proposed and presented for a standalone operation of the CPV-Hydrogen system as well as their system performances, particularly electrical rating of CPV based upon the real weather data of Singapore.

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1. Introduction

In recent years, the remarkable share of the renewable energy systems has proved to be a promising solution for global warming [1–4]. Moreover, the renewable energy resources, especially solar energy systems because of highest solar energy potential and easy availability [5], provide suitable option for power supply to remote areas or to the systems with standalone operation. Photoreaction provides simplest method for sunlight to electrical energy conversion [6–8]. Among all the PV (photovoltaic) systems, the CPV (concentrated photovoltaic) system provides highest solar energy conversion efficiency [6–8] as the full solar spectrum is converted into electricity using MJC (multi-junction solar cells) [9–12], under concentration through cheap solar concentrators [13–15]. However, due to intermittent nature of the solar energy in the diurnal period and unavailability at night time, the power output from solar energy systems is not available all the time and not at constant production rate. The steady power production at all load

requirements is the main requirement of any power production system. Therefore, for uninterrupted power supply and standalone operation, solar energy storage is compulsory.

The main objective of the design of the standalone energy systems is uninterrupted power supply all the time at any load requirement over the whole period of operation, at lowest system and operation cost that demand modelling and optimization with regard to the system sizing, control strategies and economics. The design of the standalone energy system goes through three steps. First one is to select the reliable energy storage system. Second one is to select the reliable optimization algorithm with simple implementation and less computational effort, as the system size has to be optimized for multi-objective performance. Third and the most important step is the selection of the main power production system to capture most of the available energy at highest efficiency, and the development of the performance model and control strategy for overall standalone energy system to ensure optimum design and reliable operation.

Regarding the energy storage system, as solar energy systems are designed to operate for long term operation with lifespan of 20–25 years, hydrogen production from the electrolysis of water provides a sustainable, clean and reliable energy storage solution as compared to conventional electrochemical electricity storage

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option i.e. battery which is only reliable for short term operation [16]. Other storage techniques like compressed air, thermal storage, pumped hydro and super-capacitors are suitable for storage of only few days, hours or seconds [17] and their application is not very common and proved to be reliable for solar energy systems especially photovoltaic systems.

For multi-objective optimization, there are many optimization algorithms developed and compared in the literature. The GA (genetic algorithm) provides reliable and simple optimization methodology, motivated by the nature evolution [18,19], to effectively optimize even mixed integer and non-linear problems of complex engineering systems. There are many other algorithms claimed to be as effective as GA, like the recently developed PSO (particle swarm optimization) technique which is competing GA with the same optimal solution. However, there is no benchmark regarding the performance comparison and limitations of PSO over GA as both adopt different searching criteria [20,21]. Some studies claimed to have as efficient solution of PSO as GA but with faster convergence towards the optimal solution [22,23]. It is evaluated that the efficient performance of PSO is only under certain conditions and for certain kind of problems [24–26]. However, the PSO takes overall more computational time for total number of generations than the GA due to time of the particle communications after each generation [27]. In addition, GA is also reported to perform better than PSO [28]. Therefore, the GA (genetic algorithm) is proved to be the reliable optimization technique. However, this simple and conventional GA requires more computational power and convergence time than the other modified GAs like micro-GA and NSGA-II [29]. The micro-GA works on the same methodology like simple GA but with a very small population size [30–32]. The NSGA-II also follows the same methodology of GA but with different selection criteria of individuals [33,34] and with the larger population size than the micro-GA [35]. It must be noted that the both micro-GA and NSGA-II are popular for the multi-objective optimization [36]. But micro-GA showed better performance in terms of computational time [35], 8–12 times faster than NSGA-II and better optimal solution and Pareto front [37]. Therefore, for the current study, micro-GA is used as it provides efficient solution with minimum convergence time and computational efforts.

Now regarding the power production system and the control strategies, there are many studies in the literature for standalone solar energy system optimization based upon size [38], techno-economic optimization with optimum efficiency and control strategy of each component of the system [39,40]. But all of these studies [41] are based upon considering only the conventional flat plate PV systems. The purpose of the techno-economic optimization is to get optimum system size while keeping the overall system cost minimum. However, the cost and the size of the system can be reduced by converting most of the available solar energy into electricity through high efficiency system. Due to low conversion efficiency of the conventional PV, hybrid renewable energy systems like PV + wind-turbine are also considered to capture and utilize most of the available renewable energy [42–44]. Some authors also proposed and analysed PV system in hybridization with the diesel generator system to significantly reduce overall system cost and also the energy storage need [45–48]. However, in this case, the main concern related to green house gas emissions is still there. The main motive of all of these studies is to have larger power output by the primary energy system, which in return reduces overall size of the system with enough storage. In addition, there is also complex control and energy management strategy involved in hybrid techniques due to larger number of subsystems. The CPV system operates at 2–3 times higher efficiency than the conventional PV [49] and without hybridization, CPV alone can provide high capacity system with rather simple overall system configuration.

There are also many commercial tools available regarding the design, analysis and optimization of renewable energy systems. Some of the very popular tools are HOMER (Hybrid Optimization of Multiple Energy Resources) and iHOGA (improved Hybrid Optimization by Genetic Algorithms), which are developed by NREL and University of Zaragoza respectively, especially for the design, hybridization and optimization of renewable energy systems [50,51]. However, for the photovoltaic systems, they only consider conventional PV for overall system analysis. Similarly, combination of TRNSYS and HYDROGEMS libraries (developed at IFE) also provides optimization for renewable energy systems, but only conventional PV system is considered for the photovoltaic systems. Some other tools, HYBRIDS2, INSEL, ARES, RAPSIM, SOMES and SOLSIM can only provide performance simulation of renewable energy systems without optimization [52]. However, none of the available tools have provision regarding consideration of the CPV system. A summary about comparison of these tools is given in Table 1.

The main motive of this paper is that, beside the higher energy conversion efficiency, the literature is lacking for the design optimization and energy management technique for the consideration of CPV as standalone energy system. For the first time, this paper introduces the methodology, modelling and control strategies for the standalone operation of the CPV system to provide uninterrupted electricity to consumer load, with hydrogen production as energy storage. The system is optimized using the micro-GA according to the size, for zero PSFT (power supply failure time), with sufficient energy storage and minimum overall annualize system cost. This study proposes the design methodology of the most efficient standalone solar energy system with simple design and controls as compared to the hybrid or solar energy PV systems alone. Moreover, with the proposed model, the long term performance of the CPV system or CPV-Hydrogen production system is also presented for the weather conditions of Singapore.

2. CPV-Hydrogen system description

The schematic of the proposed CPV-Hydrogen production system for standalone operation is shown in Fig. 1. The CPV system is based upon the concentrated photovoltaic modules, using MJCs (multi-junction solar cells), installed onto the two axis solar trackers, which is one of the main component of the CPV system. CPV (concentrated photovoltaic) modules can be of any type, either Mini-dish Cassegrain reflector type CPV modules or Fresnel lens based refractive type CPV modules, as the developed model considers the concentration of the solar radiations at multi-junction solar cells. Each CPV system is connected to a MPPT (maximum power point tracking) device, in order to ensure the performance of the CPV systems at maximum efficiency. The power output from each of the CPV system is supplied to a main DC line through a DC/

Table 1

Comparison summary of renewable energy system simulation and optimization.

	Optimization	Simulation	Hydrogen energy storage	Analyse CPV?
HOMER [50]	x	x	x	No
iHOGA [51]	x	x	x	No
TRNSYS + HYDROGEMS [52]	x	x	x	No
HYBRIDS2 [52]		x	x	No
SOLSIM [52]		x		No
INSEL [52]		x		No
ARES [52]		x		No
SOMES [52]		x		No
RAPSIM [52]		x		No

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