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Optimal operation of a grid-connected hybrid PV/fuel cell/battery energy system for residential applications

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ABSTRACT

To deal with increasing energy consumption in the residential sector, distributed energy resources including photovoltaic (PV), fuel cell, etc. have been paid more and more attention. In this study, an optimization model is developed for the PV/Fuel Cell/Battery based residential energy system. While guaranteeing reliable system operation, the model may determine the optimal running strategies with annual running cost or annual CO_2 emissions as the objective function to be minimized. In addition, besides the energy flows among the equipments within the hybrid energy system, the economic information including electricity tariff and natural gas price, as well as some policy issues (e.g., buy-back price) are also accounted. As the results of the model, besides the optimal electric and thermal balances, the rational utilization forms of PV module, fuel cell and battery can be also deduced. To verify the viability of the proposed approach, a numerical example is implemented and analyzed. The optimal operating strategies are deduced and compared from different perspectives. Furthermore, the results demonstrate that the PV module mainly contributes to the environmental performance of the assumed hybrid energy system, while the battery may be beneficial from the economic viewpoint.

1. Introduction

Globally, although transportation and industry remain the largest energy consuming sectors, residential energy consumption illustrates obvious increase in recent years and is expected to increase even further. In 2011, the residential sector accounted for 18% of the world's total energy consumption [1]. Also, according to the IEO2013 Reference case, global residential energy consumption will increase by 57% from 2010 to 2040 [2]. To deal with such problems, in recent years, significant efforts have been made to improve the residential energy efficiency in both developed and developing countries.

Besides the development and adoption of domestic energy-efficient equipment, advanced energy supply technologies including some renewable ones have been paid more and more attention. Among which, photovoltaic (PV) systems are widely used as an important alternative energy source for residential application [3,4]. However, due to the intermittent nature of solar energy which is related to the climatic conditions, PV systems should be integrated with other power sources to guarantee stable electricity supply. As an attractive option, the battery can significantly improve the load availability while is insufficient to provide long-term energy requirements [5,6]. On the other hand, though still in early stages of adoption, a fuel cell based micro combined heating and power system (Micro-CHP) is becoming a focus of interest due to its potential for stable energy supply with high overall efficiency, while it may encounter slow dynamics [7,8]. Therefore, to overcome the insufficient nature of either technology, a hybrid energy system composed of PV modules, fuel cells, batteries, as well as residential energy loads can be proposed [9]. By operating either synchronized with the main grid or autonomously, it can supply reliable energy regardless of time overcoming the aforementioned problems faced by single units. In detail, the fuel cell unit will be connected to the PV system in parallel, so as to smooth the output power and expand the PV penetration level. In addition, an electric energy storage unit may be also included to deal with the unbalance problem between the supply and demand sides. The integrated use of PV modules, fuel cell based micro-CHP system and battery banks will realize the interaction and complementation of

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Nomenclature

Parameters

A	available area for PV modules (m^2)
CI^{grid}	carbon intensity of grid electricity (kg/kWh)
CI^{gas}	carbon intensity of city gas (kg/kWh)
D_m	number of days in each month (Days)
$E^{bb}_{capacity}$	rated capacity of the batter bank (kWh)
$E^{fc}_{capacity}$	rated capacity of the fuel cell unit (kW)
$E^{load}_{m,h}$	hourly electric load (kW)
$H^{load}_{m,h}$	hourly thermal load (kW)
$H^{st}_{capacity}$	capacity of the hot-water storage tank (kWh)
HE^{fc}_{ratio}	heat-to-power ratio of the fuel cell unit
M	a large number
P^{grid}_{base}	monthly base tariff rate ($)
$P^{grid}_{m,h}$	volume tariff rate ($)
P^{gas}_{base}	monthly base gas price ($)
P^{gas}_{m}	volume gas price ($)
P^{pv}_{sal}	buy-back price ($/kWh)
$R_{m,h}$	solar irradiation (kW/m^2)
η^{bu}_{t}	efficiency of the afterburner (%)
η^{bb}_{cha}	charging efficiency of the batter bank (%)
η^{bb}_{dis}	discharging efficiency of the batter bank (%)
η^{fc}_{e}	power generation efficiency of the fuel cell unit (%)
η^{st}_{in}	charging efficiency of the hot-water storage tank (%)
η^{st}_{out}	discharging efficiency of the hot-water storage tank (%)
μ	heat loss rate of the hot-water storage tank (%)
φ	module efficiency of PV unit (%)
ϕ	inverter efficiency (%)
ε	self-discharge rate of the batter bank (%)
λ	minimum residue coefficient of the batter bank (%)

Decision variables

C_{total}	total annual energy cost ($)
C^{grid}_{pur}	cost for utility electricity consumption ($)
C^{gas}_{pur}	cost for city gas consumption ($)
C^{grid}_{sale}	revenue from selling surplus electricity to the grid ($)
CO_{total}	total annual CO_2 emissions (kg)
CO^{grid}_{total}	CO_2 emissions from utility electricity (kg)
CO^{gas}_{total}	CO_2 emissions from gas consumption (kg)
$E^{bb}_{m,h,out}$	power discharged from the battery (kW)
$E^{bb}_{m,h}$	available storage capacity of the battery at hour h (kWh)
$E^{grid}_{m,h,self}$	purchased electricity from grid for self-use (kW)
$E^{grid}_{m,h,sto}$	purchased electricity from grid for battery charging (kW)
$E^{fc}_{m,h,self}$	power out of fuel cell unit for self-use (kW)
$E^{fc}_{m,h,sto}$	power out of fuel cell unit for battery charging (kW)
$E^{pv}_{m,h,self}$	power out of PV unit for self-use (kW)
$E^{pv}_{m,h,sale}$	surplus electricity from PV sell to grid (kW)
$E^{pv}_{m,h,sto}$	power out of PV unit for battery charging (kW)
$f^{bb}_{m,h,in}$	0–1 variable indicating the charging state of the battery
$f^{bb}_{m,h,out}$	0–1 variable indicating the discharging state of the battery
$f^{grid}_{m,h,pur}$	0–1 variable indicating the electricity purchase from the grid
$f^{grid}_{m,h,sale}$	0–1 variable indicating the electricity sales out of PV module
$H^{bu}_{m,h}$	heat generation of the afterburner (kW)
$H^{fc}_{m,h}$	recovered heat from the fuel cell unit (kW)
$H^{st}_{m,h}$	available thermal energy in the storage tank at hour h (kWh)
$H^{st}_{m,h,out}$	output of the hot-water storage tank (kW)

different energy supply options in time and space.

Nevertheless, from an operational point of view, running and managing a hybrid energy system with multiple energy sources and energy storage is not an easy task. A well-designed system should not only satisfy the fluctuating thermal and electric demands but also can limit annual energy cost or environmental emissions. Thus, the hybrid system should be optimized by a robust operating strategy based on the cooperation of all technical options, while accounting for the varying energy demands.

A number of researches have been reported on the operation optimization of a hybrid energy system. Originally, size optimization of hybrid renewable energy systems has been the hot topics in this field, by employing both mathematical programming [10,11] and evolutionary algorithms [12]. In detail, Ratnam et al. [13] discussed the influence of net metering on the economic performance of a PV/battery hybrid system. Maleki et al. [14] developed the size optimization model for a PV/wind/battery hybrid system by using particle swarm optimization algorithms. Based on above studies, to ensure sustained and stable power supply especially for the stand-alone application, diesel engine is usually employed to form a hybrid PV-diesel-battery system. For example, Lan et al. [15] proposed an optimal sizing method for a hybrid PV/diesel/ESS ship power system. Malheiro et al. [16] developed a plan and design model for a wind/PV/diesel/battery isolated system. Shin et al. [17] designed the capacity and operation planning of a hybrid power generation system. Merei et al. [18] optimized the PV/wind/diesel system with different battery technologies. Kusakana [19] examined optimal operating schedules of the PV/diesel/battery hybrid systems. Kaabeche and Ibtiouen [20] developed an optimal sizing model for a stand-alone PV/wind/diesel/battery hybrid system.

In recent years, along with the increased attention paid to the thermal energy, the inclusion of CHP units within the hybrid energy system may result in additional difficulty for system design and operation [21,22]. For example, Shah et al. [23] studied and compared the performances of PV/battery/CHP hybrid systems located in different regions. Ondeck et al. [24] studied the optimal operating strategies of a PV/CHP hybrid system. Brandoni and Renzi [25] optimized the size of a hybrid solar mico-CHP system for residential applications. Specifically, as to the hybrid PV/fuel Cell/battery energy system examined in this study, Bigdeli [26] compared various optimal hybrid approaches for the management of the hybrid energy system. Silva et al. [27] demonstrated an economic assessment and optimization of a hybrid PV/fuel cell/battery system through simulations based on HOMER software. Generally, it can be found that most of the previous studies have focused on the examination of hybrid power systems for off-grid application, by employing some existing software tools (e.g., HOMER) [28]. However, in recent years, grid-connecting has become available for the distributed generators, and the smart use of thermal energy is paid more and more attention especially for