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Impact of electric battery degradation on cost- and energy-saving characteristics of a residential photovoltaic system

Akira Yoshida[a,d,*], Tomikazu Sato[b], Yoshiharu Amano[c,d], Koichi Ito[c]

[a] Department of Applied Mechanics and Aerospace Engineering, Waseda University, 3-4-1 Okubo, Shinjuku-ku, 169-8555 Tokyo, Japan
[b] ITOCHU Techno-Solutions Corporation Energy & Infrastructure Business Promotion Department Science & Engineering Systems Division, Kasumigaseki Bldg., 3-2-5, Kasumigaseki, Chiyoda-ku, Tokyo 100-6080 Japan
[c] Research Institute for Science and Engineering, Waseda University, 17 Kikui-cho, Shinjuku-ku, 162-0044 Tokyo, Japan
[d] Japan Science and Technology Agency, CREST, 4-1-8 Honcho, Kawaguchi-shi 332-0012, Saitama, Japan

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ABSTRACT

In Japan, a feed-in tariff scheme has been implemented to promote the use of photovoltaic power generators in combination with electric batteries. Although many researchers have assessed the operation of grid-connected photovoltaic systems with electric batteries, little attention has been paid to the impact of the electric batteries' degradation characteristics. This paper evaluates the operation of a grid-connected photovoltaic/electric-battery system in a house in terms of cost savings and energy savings. We constructed a long-term operational optimization model considering the degradation characteristics of the electric battery. This model contains two objective functions: energy savings and operating costs. We create a scenario of power rates and photovoltaic/battery system configurations. To reveal the optimal operational strategy for the photovoltaic/battery system, the multi-objective optimization problem was solved. As a result, Pareto-optimal solutions were obtained, and trade-off relationships between cost and energy savings are presented. In this study, the utilization of a grid-connected photovoltaic system with an electric battery was expected to be most effective in energy-saving priority operation.

1. Introduction

Over the past several years, interest in solar energy has been growing. In Japan, to encourage the use of photovoltaic power generators (PV), the government established a feed-in tariff (FIT) [1,2] in 2012. Under this system, households that have a PV system of less than 10 kW can sell their surplus electricity using PV-FIT for 10 years after installation; the selling price of this surplus electricity is a fixed initial price such as 38 yen/kWh. This scheme has caused an increase in PV usage. To further expand the use of distributed power sources such as PV, there are plans to reform the electricity systems of Japan based on the Electricity Systems Reformation Subcommittee's report [3]. Several research groups have conducted operational tests of peak shift of electricity demand based on variable power rates. In Japan, if PV output exceeds the entire load in the grid, residential PV is set to shut down by PCU so as to maintain power quality. Therefore, electric batteries (BTs) in grid-connected PV systems are useful, and, as much as possible, all PV power is used on site. The BT system is also useful for shifting the peak electricity demand. For example, one method is to charge the BT when power rates are low, and to discharge the BT when the power rates are high. Another method is to charge the BT using the surplus electricity from a PV system and to discharge the BT when the PV system is not generating electricity. Using a PV system with a BT allows for a variety of operational strategies; therefore, it is necessary to evaluate these systems from both cost- and energy-saving perspectives. In 2012, a residential PV–BT system [4] became commercially available in Japan. This PV–BT system allows the BT to be charged from the grid at midnight, when power rates are lower; the BT is discharged at other times, e.g., in the evening. Moreover, the BT can also be charged using surplus electricity from the PV system.

The optimal operation approach for a PV system with a BT has been studied by many researchers such as Yokoyama et al. [5], using a mixed integer linear programming (MILP) method. Gibson et al. [6] reported on the optimization of charging efficiency from a PV system to a BT in a residential energy system. Lu et al. [7] reported on the short-term scheduling of a BT to utilize the

* Corresponding author at: Department of Applied Mechanics and Aerospace Engineering, Waseda University, 3-4-1 Okubo, Shinjuku-ku, 169-8555, Tokyo, Japan.
E-mail addresses: a.yoshida@aoni.waseda.jp (A. Yoshida), tomikazu.sato@ctc-g.co.jp (T. Sato), yoshiha@waseda.jp (Y. Amano), k.ito8@kurenai.waseda.jp (K. Ito).

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Nomenclature

D	number of days
d	day
e,E	electric energy stored in battery kWh
$\dot{e}, \dot{E}$	electric power kWh/h
F	conversion factor MJ/kWh
J	primary energy consumption J
M	large number
N	number of representative days
n	cycle number cycles
P	power rate yen/kWh
t	time index
T	number of time indexes
X	slope of the DOD degradation characteristics
Y	intercept of the DOD degradation characteristics

Greek symbols

α	cycle degradation rate%/cycle
β	battery degradation rate
γ	DOD degradation rate %/h
δt	sampling interval
ε	weight coefficient
η	efficiency
ξ	depth of discharge

Subscripts and superscripts

BT	battery
buy	purchased
cost	cost
day	daytime
dem	demand
e, ele	electricity
ene	energy
G	grid
in	input
IO	input/output
max	maximum
min	minimum
night	night-time
out	output
PCU	power conditioner unit
PV	photovoltaic
sell	sold
sup	supply

BT for economical operation and control purposes. Thus far, many researches have reported on the operation of PV–BT systems; however, it is important to consider the degradation characteristics of a BT when used in a house. One suitable residential battery type is lithium-ion with graphite anodes and lithium metal oxide cathodes. In terms of the performance fade of a lithium-ion BT, two main aging factors have been found experimentally [8]. One factor is cycle degradation, which is caused by charging and discharging the BT repeatedly. Another factor is calendar degradation, which is caused by holding the BT at a high voltage for a long time. Cycle degradation is related to the depth of discharge (DOD), whereas calendar degradation is related to the state of charge (SOC), meaning the BT storage level. There have been many reports regarding the degradation characteristics of BTs; additionally, empirical model of BT aging concerning capacity fade, cycle number, DOD, temperature of BT, are reported [9–15]; however, little attention has been paid to what the optimal BT operation considering its degradation. When considering the operational planning problem for energy systems

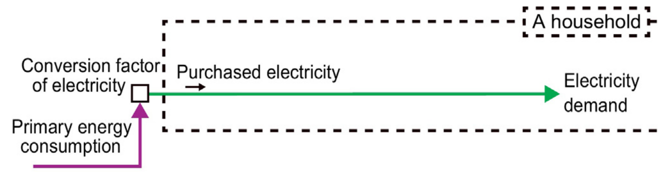

Fig. 1. Schematic diagram of CS.

in the long term, the large problem would become more difficult to solve. In this case, the calculation could be subdivided into segments of several days or of a single day under the condition that the problems would be independent of each other [16]. However, the operation model considering the degradation characteristics of a BT over the long term must be solved as a single problem, because the capacity degradation of a BT generated on a given day will affect all subsequent operation.

This paper discusses the decade-long effects based on a long-term optimal operational planning problem considering the degradation characteristics of a lithium-ion BT in the case of a detached house using a grid-connected PV–BT system. The objective of this paper is also to reveal the impact of the degradation characteristics of BT against the long-term planning problem in residential PV–BT system. We set scenarios of power rates and several configurations of the PV–BT system. A multi-objective optimization problem was solved to reveal the optimal operational strategy of the PV–BT system.

2. Methodology

There are many alternative operational strategies for residential energy systems with BT based on the homeowner's objectives, such as energy savings and economic performance. Therefore, PV–BT system evaluation is formulated as an operational planning problem; the installed system is evaluated for its cost- and energy-saving potentials. The Japanese feed-in tariff program fixes the selling price for surplus electricity for a period of 10 years from the date of installation of the PV system; degradations of the BT informs the operational strategy. Therefore, the planning horizon is set to 10 years, and we must solve the long-term operational planning problems of three targeted systems, which are the conventional grid, the PV system, and the PV–BT system. The demand profile is determined in Section 3.2. The mathematical formulation for MILP, including the degradation characteristics of the BT, is defined in Section 3.3. Then, trade-off analysis between primary energy consumption and operating cost over 10 years is carried out for the three systems. Comparing the results of the numerical investigation, the effect of degradation of the BT capacity on both of the energy-saving case and the cost-saving case is shown.

3. Model of the system

First, we present the three systems of interest: (1) a conventional system (CS), (2) a PV system, and (3) a PV–BT system. The CS, which is the reference system, (illustrated in Fig. 1) is directly connected to the electric power grid. The PV system consists of a PV and a power conditioner unit (PCU) connected to the grid as shown in Fig. 2. The PV–BT system consists of a PV, a PCU, and a BT connected to the grid as shown in Fig. 3. The optimization problem of these systems is calculated over 10 years to minimize either the primary energy consumption or the operating cost. In this study, the electricity capacity of the BT and the quantities of BT degradation are changed. The problem is subject to energy balances and device characteristics constraints, e.g., charging or discharging the BT. The BT can store electricity from the PV and the grid via the PCU.