Energy Conversion and Management 91 (2015) 394–404

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Techno-economic analysis of grid-connected battery storage

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ARTICLE INFO

Article history:
Received 27 April 2014
Accepted 14 December 2014
Available online 30 December 2014

Keywords:
Grid-connected electricity storage
Batteries
Time-of-use tariff
Net present cost

ABSTRACT

This paper presents a methodology to evaluate the technical and economic performance of a grid-connected system with storage under a time-of-use (TOU) electricity tariff. The storage can help smooth demand, reducing peak demand from the grid and, in some cases, also reducing the electricity bill for the consumer. The methodology is valid for any kind of storage, but it has been used for lead-acid or Li-ion batteries, technologies that could be applied in any kind of building (residential, commercial, or industrial). This kind of system could make sense with a TOU tariff: each day, electricity would be bought during off-peak hours (at a low price) to charge the batteries, and during peak hours (at a high price), the batteries would be discharged to supply the whole load or a part of it. We focus on the storage system's profitability for the electricity consumer, analysing the total net present cost (NPC) of a system with storage and comparing it with a system without storage. The results show that even given a Spanish TOU special for electric vehicles (with a great difference between on-peak and off-peak prices of 0.135 €/kW h), at the present cost of battery storage (battery bank + bidirectional inverter + control), the storage system is not profitable for the consumer. For the battery system to be economically profitable, the costs of batteries would need to be reduced to about 0.05 €/kW h_{cycled} in the case of low-efficiency lead acid batteries (with bi–di converter of 700 €/kW) or to 0.075 €/kW h_{cycled} in the case of efficient Li-ion batteries (with bi–di converter of 300 €/kW). The most critical parameters are the acquisition cost of the battery bank and the number of cycles to failure, which determine the acquisition cost of the battery bank per kW h cycled.

1. Introduction

The European Commission, in its energy infrastructure priorities for 2020, has included the need for energy storage systems [1]. Storage technologies can make energy systems more flexible and can also smooth demand, reducing the daily demand variation. Demand smoothing involves charging the battery (or another kind of storage system) during valley demand (usually off-peak hours) and discharging it during peak demand (on-peak hours), bringing such benefits to distribution grids [2] as reduced demand variation (decreased peak demand and increased valley demand), higher capacity in distribution system corridors, and more secure energy supply. From the point of view of the electricity consumer owner of the storage system, demand smoothing can also have economic benefits if the total cost of the storage (capital cost plus operation and maintenance) is lower than the total savings in the electricity bills.

There are various possibilities for electricity storage in grid-connected systems: pumped hydro energy storage (PHES), compressed-air energy storage (CAES), flywheels, supercapacitors, flow batteries (ZnBr, VRB, and PSB), sodium-sulphur batteries (NaS), lithium-ion batteries (Li-ion), nickel–cadmium batteries (Ni–Cd), lead-acid batteries, metal–air batteries, and hydrogen (electrolyser-hydrogen tank-fuel cell) [3–5]. The most frequently used technique for storing electricity is PHES. Storage in PHES and in CAES, however, is suitable only for high amounts of energy, and because of their characteristics they are limited to specific areas. Supercapacitors are more suitable for power quality than for energy management. New batteries (flow batteries, NaS, metal–air), hydrogen, or flywheel technologies are available, but these are not yet mature. Hydrogen has another disadvantage: very low efficiency in the electricity-hydrogen-electricity process. Nowadays, the most suitable storage technologies for demand smoothing to be used in residential, commercial, or industrial buildings are Li-ion, Ni–Cd, or lead-acid batteries, on account of their maturity, high efficiency, low maintenance, and low danger.

In recent years, many authors have studied the economic viability of storage. Many of them have found that storage benefits are usually insufficient to compensate for the capital cost of the

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http://dx.doi.org/10.1016/j.enconman.2014.12.038
0196-8904/

Nomenclature

C_{bat} battery bank (or different kind of storage) capacity (kW h)
$Cost_{bat}$ acquisition cost of the battery bank (€)
$Cost_{bat\_per\_kWh\_cap}$ acquisition cost of the battery bank per kW h of nominal capacity (€/kW h)
$Cost_{bat\_per\_kWh\_cycled}$ acquisition cost of the battery bank per kW h cycled (€/kW h_{cycled})
$Cost_j$ acquisition cost of the rest of the components of the system (*j* = inverter, rectifier, control) (€)
$Cost_{O\&M}$ operation and maintenance annual cost (€/year)
d day of the year (from 1 to 365)
DOD depth of discharge of the batteries (%)
E_{day} total daily average load (kW h/day) ($E_{day} = E_{peak} + E_{mid} + E_{off\_peak}$)
E_{from_batt} daily load covered by the battery bank (during peak hours) (kW h/day)
E_{mid} daily load consumed during middle hours (kW h/day)
E_{off_peak} daily load consumed during off-peak hours (kW h/day)
E_{peak} daily load consumed during peak hours (kW h/day) ($E_{peak} = E_{peak\_direct} + E_{from\_batt}$)
E_{peak_direct} daily load consumed during peak hours obtained directly from the grid (not passing through batteries) (kW h/day).
g_j annual inflation for the cost of the components of the system (*j* = battery bank, inverter, rectifier, control)
$g_{O\&M}$ annual inflation for the O&M cost
g_{Pr_elec} annual inflation for the price of electricity
h hour of the day (from 0 to 23)
h_{off_peak} daily number of off-peak hours
I annual interest rate
$I_{bat}(t)$ current in/out the battery bank (A)
I_{max} maximum current in/out the battery bank without damage (A)
LCOE levelized cost of energy (€/kW h)
$Life_j$ lifespan of the components of the system (*j* = battery bank, inverter, rectifier, control) (year)
$Life_{system}$ system lifetime (duration of the study period) (year)
N_{Cycles} number of equivalent full cycles to failure of the batteries
$N_{Cycles\_80\%}$ batteries' number of cycles to failure at 80% depth of discharge
$N_{Cycles\_DOD\%}$ batteries' number of cycles to failure at DOD (%) depth of discharge
$NPC_{components+O\&M}$ net present cost of the components of the system and the Operation and Management (O&M) (€)
$NPC_{E\_from\_bat}$ net present cost of the load covered by the battery bank during peak hours (€)
$NPCrep_j$ net present cost of replacing the components of the system (*j* = battery bank, inverter, rectifier, control) (€)
$NPC_{with\_storage}$ total cost of the storage system, including all the energy purchased from the AC grid (€).
$NPC_{w/o\_storage}$ total net present cost of the system without storage (all electricity bought from the AC grid at the time when it is used, and no storage) (€).
$NPV_{savings}$ net present value of the savings: difference of the NPC of the energy E_{from_bat} purchased directly from the AC grid at peak price (case without storage) and the NPC of the storage system (components + O&M + load covered by the battery bank) (€).
$Nrep_j$ number of replacements of each of the components of the system (*j* = battery bank, inverter, rectifier, control) during the system's lifetime
P_{bi-di} rated power of the bidirectional converter (W)
$P_{from\_bat}(t)$ load power supplied from the battery during hour *t* of the year (*t* from 0 to 8759) (W)
$P_{load}(t)$ load consumption during hour *t* (*t* from 0 to 8759) (W)
P_{max} maximum power that can be absorbed from the AC grid (limited by the electrical company) (W)
Pr_elec_{mid} price of the electricity at mid-peak times for (TOU tariff) (€/kW h)
$Pr\_elec_{off\text{-}Peak}$ price of the electricity at off-peak times (TOU tariff) (€/kW h)
Pr_elec_{peak} price of the electricity at peak times for (TOU tariff) (€/kW h)
$Pr\_elec_{peak\_needed}$ price of the electricity at peak times (TOU tariff) needed for the storage system to be profitable (€/kW h)
$SOC(t)$ batteries state of charge of hour *t* of the year (*t* from 0 to 8759)
SOC_{max} batteries maximum state of charge (*SOC*) allowed (used $SOC_{max} = 1$)
SOC_{min} batteries minimum state of charge (*SOC*) allowed (per unit)
U_{DC} DC bus voltage (V)
t hour of the year (0–8759)
Δt simulation interval (time step), used 1 h
$\eta_{AC/DC}$ rectifier (AC/DC converter) efficiency
η_{bat_Ch} battery charging efficiency
η_{bat_D} battery discharging efficiency
$\eta_{DC/AC}$ inverter (DC/AC converter) efficiency
$\%NPV_{savings}$ percentage of NPV savings using storage (regarding the case of not using storage) (%)

storage device. In [6] an hourly management method is presented for wind farms using battery storage, concluding that the use of batteries only can be economically competitive if the selling price of battery energy is significantly higher than the average price of the electric market. In another work [7], a review of the electricity storage technologies for large power systems is presented, estimating the economic feasibility of electricity storage, reaching the relevant conclusion that the possible revenue is significantly lower than the estimated costs of an electricity storage system. In [8], it was determined that it is not possible to create a return on investment if the electricity price does not increase more than the inflation for battery storage for houses, considering the subsidy system, the electricity price, and the purchase cost of a PV installation and a battery system. In [9] an analysis of potential supporting schemes for pumped hydro storage facilities in Croatia concluded that a clear regulatory framework is necessary (e.g., applying a feed-in tariff, which guarantees the payment of the capital cost and a reasonable rate of return). [10] proposed a model for the economic feasibility of CAES improves wind power integration and found that given the present conditions on the minute reserve market, no CAES power plant is economically feasible. The Institute for Energy and Transport of the European Commission [11] analysed more than 200 publications on the economics of electricity storage. Relevant information from this document includes the idea that regulation is key to the profitability of electricity storage operating in deregulated markets, and that the grid fees are an obstacle to storage development.

On the other hand, other authors have demonstrated better results. [12] studied the application of two electric energy storage technologies (sodium sulphur batteries and flywheels) in New York