Energy Conversion and Management 79 (2014) 387–397

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Feasibility study and economic analysis of pumped hydro storage and battery storage for a renewable energy powered island

Tao Ma *, Hongxing Yang, Lin Lu

Renewable Energy Research Group (RERG), Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong

ARTICLE INFO

Article history:
Received 14 November 2013
Accepted 21 December 2013
Available online 11 January 2014

Keywords:
Renewable energy
Pumped hydro storage
Battery
Lifecycle cost (LCC)
Sensitivity analysis
Feasibility study

ABSTRACT

This study examined and compared two energy storage technologies, i.e. batteries and pumped hydro storage (PHS), for the renewable energy powered microgrid power supply system on a remote island in Hong Kong. The problems of energy storage for off-grid renewable energy were analyzed. The sizing methods and economic models were developed, and finally applied in the real project (case study). The results provide the most suitable energy storage scheme for local decision-makers. The two storage schemes were further divided into 4 options. Accordingly, the life-cycle costs (LCC), levelized costs for the renewable energy storage system (LCRES) and the LCC ratios between all options were calculated and compared. It was found that the employment of conventional battery (Option 2) had a higher LCC value than the advanced deep cycle battery (Option 1), indicating that using deep cycle batteries is more suitable for a standalone renewable power supply system. The pumped storage combined with battery bank option (Option 3) had only 55% LCC of that of Option 1, making this combined option more cost-competitive than the sole battery option. The economic benefit of pumped storage is even more significant in the case of purely pumped storage with a hydraulic controller (Option 4), with the lowest LCC among all options at 29–48% of Option 1. Sensitivity analysis demonstrates that PHS is even more cost competitive by controlling some adjustments such as increasing energy storage capacity and days of autonomy. Therefore, the renewable energy system coupled with pumped storage presents technically feasible opportunities and practical potential for continuous power supply in remote areas.

1. Introduction

With growing deployment of renewable energy resources, the high capital cost for high power supply reliability and the need to balance the load demand with supply are attracting substantial interests in the research of energy storage technology [1]. Energy storage is a well-established technology but it is still relatively unexplored [2]. At present, it is one of the greatest technical and commercial barriers to the wide integration of renewable energy applications, especially for those off-grid systems completely powered by intermittent solar or wind energy, because they are available or strong only at certain times of the day.

Energy storage is a topic of great importance for the development of renewable energy, since it appears to be the only solution to the problem of intermittency of its production [3]. Energy storage can ramp the fluctuating output from renewable energy, and ensure that power produced by renewables can be released and dispatched reliably to better fit demand. In addition, it enables energy produced to be held when demand is low, ready for discharge when demand is high, i.e. the function of load leveling and time shifting. Moreover, it can stabilize the power grid with a high penetration level of renewables. To facilitate the renewables becoming completely reliable as a primary source of energy, economical energy storage is therefore a crucial challenge that must be overcome.

Generally energy storage technologies can be classified into four main categories: mechanical process, electrochemical process, electromagnetic process and thermal processes (Fig. 1). The energy storage systems in use for electrical energy usually include the first three types. Hadjipaschalis et al. [4] gave an overview of energy storage technologies used for electric power applications. For distributed renewable energy integration, a review of energy storage technologies was carried out in [5–7]. The characteristics and performance of these storage technologies, such as battery [8,9], flywheel [10,11], fuel cell [12,13], pumped hydro [14,15], have been widely studied. A single energy storage technology may not satisfy all requirements at the same time, therefore the hybrid energy storage system, for instance battery/fuel cell [16], battery/supercapacitor [17], battery/flywheel [18], fuel cell/battery/ultracapacitor [19], battery/flywheel/capacitors [20], are studied in literature. Besides, a novel energy storage technology based on microwave-induced CO_2 gasification was proposed [3].

* Corresponding author. Tel.: +852 2766 5863; fax: +852 2765 7198.
E-mail address: tao.ma@connect.polyu.hk (T. Ma).

0196-8904/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2013.12.047

Nomenclature

Abbreviations

DOD	depth of discharge
LCC	life-cycle cost
LCCA	life cycle cost analysis
LCRES	levelized costs for renewable energy storage system
PHS	pumped hydro storage
PV	photovoltaic
SOC	state of charge

Symbols

ρ	water density
α	portion of energy that from turbine to load
η_p	overall efficiency of pump
η_p	overall efficiency of turbine
$\eta_{array\text{-}motor}$	array mismatch factor
$\eta_{motor\text{-}pump}$	motor/pump efficiency
η_{pipe}	pipe line efficiency
η_{BI}	overall efficiency of battery and inverter

Subscripts

E_{load}	daily energy consumption
E_c	total energy consumption or energy storage capacity
e	overall loss factor and allowance for PV array
C_0	component initial cost
C_{RC}	regular component replacement cost
C_{RV}	residual value at the end of life
C_{PV}	desired PV array installation capacity
g	gravitational acceleration
h	total head
i	year sequence number
I_p	rated current of water pump
I_{PV}	rated current of PV module
n_{day}	number of autonomous days
n	length of study period (25 years)
n_{PV_s}	number of modules connected in series
n_{PV_p}	number of modules connected in parallel
$PV[r, n, C]$	present value of total expenditure with discount rate
r	discount rate
S	total capital cost
T_{ps}	number of peak solar hours per day
U_p	rated voltage of water pump
U_{PV}	rated voltage of PV module
V	volume of the water reservoir
V_0	volume of water which can be pumped per pump per day
V_B	battery rated voltage

Usually, standalone renewable energy systems employ rechargeable batteries to store excess electricity [21]. A good review of batter energy storage for standalone renewable energy systems has been presented in [22] and eight battery technologies in photovoltaic systems have been evaluated in [23,24]. Among those batteries, the nickel–cadmium batteries have been employed in relatively few systems due to its high cost, low cell voltage, low energy efficiency and limited upper operating temperature [25,26]. Lithium-ion battery appears well-suited for the intermittency of renewable energy systems [27], while it is still very plausible in the not-so-distant future although it is predominant in the small portable electronics market [28]. Studies of off-grid renewable systems focus almost exclusively on lead-acid battery, particularly those with deep discharge rate and high cycling stability, as it is the most mature technology and is currently a front-runner for use in renewable energy integration applications [28,29]. However, the lead-acid batteries have well known limitations [4,27,30,31], i.e. high initial investment, especially for large-scale and high capacity systems and relatively short lifespan (usually 1–8 years). Environmental problems in containing toxic substances such as lead can cause problem during shipment, installation, and particularly in ultimate disposal. In addition, they tend to be dangerous with sulfuric acid, in the possibility of explosion.

Pumped hydro storage (PHS) has been utilized for the past hundred years [32] and it remains the most commonly used and most commercially viable electricity storage technology [33]. The accumulated installed capacity accounts for 99% of the total storage capacity globally [1], with a efficiency of 70–85% [4]. This technology is now widely deployed in Western Europe, USA and Japan [34], which is more relevant to renewables integration. George's study [35] shows that wind energy with PHS is considered as the most suitable storage technology for allowing high wind penetration levels. To couple with intermittent renewable energy sources, the PHS capacity is projected to increase by approximately 20% by 2020 in EU [36] and the potential of PHS system begins to be reconsidered by the policymakers in US [37]. Substantial research has demonstrated as well that PHS is an ideal storage option and is being applied to confirm the validity of renewable power sources [14,15]. Some application projects [38–40] have demonstrated the feasibility of PHS for remote renewable energy power supply. However, the challenges for this technology are site availability and possible eco-environmental problems.

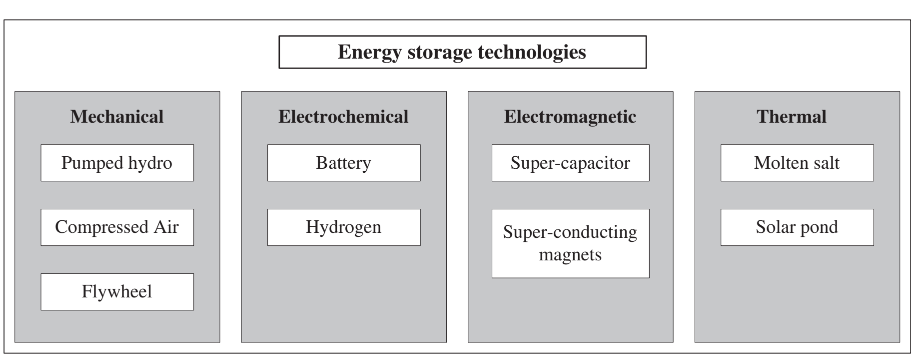

Fig. 1. Classification of energy storage systems.