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

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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.

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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].

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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.

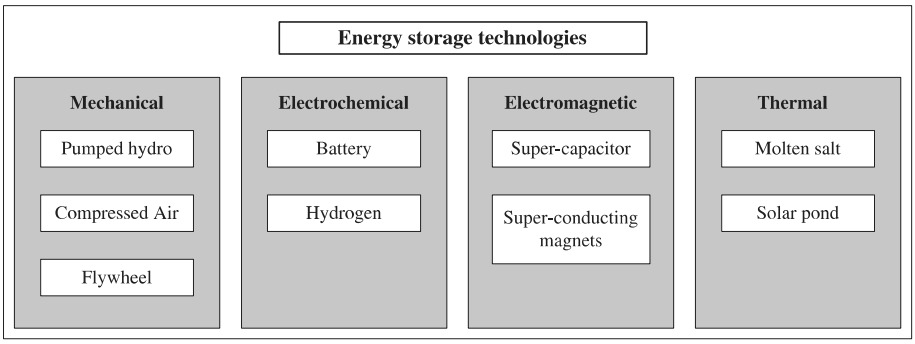

Fig. 1. Classification of energy storage systems.

In this study, two options, i.e. pumped storage scheme and battery storage scheme, have been proposed for a remote island powered by renewable energy. The current research aims at examining the economic performance of the two options. Besides, the problems of energy storage for off-grid renewable energy have been analyzed. The merits and technical challenges of proposed energy storage options have been highlighted as well. The life-cycle costs (LCC) for the schemes were examined to find the optimal design solution.

2. Methodology for study energy storage options

2.1. Project background

This study is part of an ongoing collaborative research project between the Renewable Energy Research Group (RERG) of the Hong Kong Polytechnic University and a local power supply company, aiming at supply power for a remote island in Hong Kong using 100% renewable energy. In Stage 1 of this project, the power supply company installed 99 PV panels with 19.8 kWp capacity [41]. To meet the climbing energy demand of residents on this island and facilitate further expansion, the company plans to increase the total installed PV capacity to meet a daily energy consumption of about 250 kW h in Stage 2. For such consumption the storage capacity should be quite high. A conventional battery storage solution would require high investment, a large storage room, and periodic replacement. Therefore, pumped hydro storage is proposed and the investigation of that solution is described in this study. The feasibilities and economic comparisons between battery and pumped storage schemes are examined in terms of life cycle cost (LCC) and technical viability. The two potential alternatives are further divided into 4 subcategories, which are summarized in Table 1. This study examines all options as detailed below, and finally highlights the optimal one for specific application on this island.

2.2. Basic parameters for comparison

To compare all scenarios utilizing different technologies, some assumptions were made relating to the situation of this island. These basic parameters are summarized in Table 2 and described as follows.

- The daily electricity consumption was estimated as 250 kW h with a peak load at 50 kW, allowing some margin for future to meet the energy requirement of about 100 residents living on the island;
- To guarantee energy security in case of consecutive number of days without renewable energy supply, 5 days of autonomy was ensured in this study so that the system power supply availability is larger than 95% [42];
- The peak sun-hours per day represent the equivalent number of hours per day when solar irradiance intensity averages at 1 kW/m^2. Before this study, an overall evaluation of the solar energy resource on this island has been carried out, and the daily peak sun time was determined at 4.03 h;

Table 1
Summary of potential energy storage options.

Options	Description
Option 1	Advanced deep cycle lead acid battery
Option 2	Conventional battery
Option 3	Pumped storage combined with a small battery bank
Option 4	Pumped storage (no battery)

Table 2
Basic parameters for all options involved in this study.

Items	Unit	Value
Daily energy consumption	kW h	250
Peak load	kW	50
Desired days of autonomy	days	5
Storage capacity	kW h	1250
Peak sun hours per day	hours	4.03
Cost of PV array	$/watt	2
PV module rated voltage (STC)	V	26.2
PV module rated current (STC)	A	7.63
Exploitable height drop	m	80
Discount rate	%	10

- The cost of PV modules fluctuates greatly depending on the market but has declined gradually in recent years. It is also region-specific. For the world market, the up-to-date PV module price is $0.676/Wp [43]. In this study, it was assumed that the cost of PV array as $2/W (including the PV module and array installation costs). The same PV module (STP200-18/Ub-1) from SunTech in Stage 1 of this project in was employed with rated capacity at 200 Wp [41];
- The total hydraulic head can be as much as 100 m on this island. A conservative figure of 80 m was assumed to facilitate upper reservoir construction.
- Other basic common assumptions, such as controllers, the same proportion of PV modules and distribution wires, are not considered in this study.

Quotations for the key components in all options were downloaded from company websites or directly obtained from the suppliers by email (Table 3). The cost information was converted to the common USD unit according to the current exchange rate. Besides, their lifetimes or replacement periods during the 25 years are included in this table.

All calculations were conducted using Microsoft Excel. A different spreadsheet was employed for each option. Economic evaluations on each spreadsheet are automatically recalculated as input parameter values are changed. The detailed sizing procedures adopted for the storage alternatives are illustrated in Section 3.

2.3. Life-cycle cost analysis

The economic performance between different options was compared based on the life-cycle cost (LCC) result, which is known as the total cost of ownership of machinery and equipment. In this study, to build a sound business case for action, life cycle cost analysis (LCCA) is the best way to determine which alternative between battery storage and pumped water storage is the most economically attractive.

The various costs associated with the whole life cycle are usually classified into: initial costs; operation, maintenance, and repair costs; replacement costs; and residual/salvage values [44–46]. In order to add and compare cash flows incurred at different times during the study period, they have to be made time-equivalent [47]. Hence the LCC approach converts all cash flows, whenever they occur, to present equivalent values by use of a selected discount rate. In this study, a 10% discount rate [48] is chosen as the base case study. The LCC analysis period was taken as 25 years (the usual lifetime of PV panels), beginning with the base date, the date to which all cash flows are discounted.

In LCCA, the present value of all capital and recurring costs in the system can be estimated based on the following equations:

Present value calculation:

$$PV[r,n,C] = \frac{C_1}{(1+r)^1} + \frac{C_2}{(1+r)^2} + \cdots + \frac{C_n}{(1+r)^n} = \sum_{i=1}^{n} \frac{C_i}{(1+r)^i} \quad (1)$$

Table 3
Quotation information of the basic components.

Component	Manufactory	Model	Unit price ($)	Lifetime (years)
Battery	Exide/Sonnenschein	Dryfit A600 OPzV	1088.28	5
	Intact/Phaesun	Solar-Power 120 TV	269.15	2
	Victron Energy	BAT412201080	651.48	1 or 2
Inverter	SMA	SMC 10000TL	4070.78	10
	SMA	SI 5048	4480	10
Solar pump	Dankoff	Surface Pump 8243–24	3861	10
	Solartech	PS37 K	5056.39	5
	Yoli	Yoli-400–25	10749.05	5

System total cost during the study period ($C_{RC_0} = C_0$):

$$\begin{aligned} S &= C_0 + C_{RC} - C_{RV} \\ &= C_0 + PV[r, n, C_{RC}] - PV[r, n, C_{RV}] \\ &= C_0 + \sum_{i=1}^{n} \frac{C_{RC_i}}{(1+r)^i} - \frac{C_{RV_n}}{(1+r)^n} \\ &= \sum_{i=0}^{n-1} \frac{C_{RC_i}}{(1+r)^i} + \frac{C_{RC_n} - C_{RV_n}}{(1+r)^n} \end{aligned} \tag{2}$$

Levelized cost for renewable energy storage system (LCRES) i.e. cost per kW h storage capacity [49]:

$$\text{LCRES} = \frac{S}{E_c} = \frac{S}{n_{day} \cdot E_{load}} \tag{3}$$

where r is the discount rate (10% in the base case); n is the length of study period (25 years in the base case); C represents any kind of cost; $PV[r, n, C]$ is the present value of total expenditure during the study period with the assumed discount rate; i is the ith year sequence number (zero represents the initial start time); S is total capital cost; C_0 is the components initial cost; C_{RC} is the regular components replacement cost; C_{RV} is the residual value at the end of the study period; and *LCRES* is the levelized cost of the renewable energy storage system (unit: $ per kW h storage capacity).

2.4. Sensitivity analysis

An economic study for a specific location at a particular time may not be applicable for another location and at another time, because the parameters, such as daily energy demand, peak sun hours, discount rate, PV module prices and storage days, may vary with time and place of application. Sensitivity analysis, a simple way to evaluate the robustness of an economic analysis, can help to identify which of the number of uncertain input values has the greatest impact on the economic evaluation [50]. In this study, the sensitivity analysis approach, as a part of LCCA, is conducted to determine the critical parameter(s) and answer some "what if" questions relating to input uncertainties. By simply altering the input parameters, such as daily energy demand to the upper and lower boundaries and keeping others constant, revised economic results can be generated for different possible scenarios.

3. Sizing and calculation for all options

3.1. Option 1 – advanced deep cycle battery

3.1.1. Battery bank sizing

The necessary battery bank capacity in ampere hours (C_{Ah}) are determined by Eq. (4) [51]:

$$C_{Ah} = \frac{E_c}{\eta_{BI} \cdot \text{DOD} \cdot V_B} = \frac{n_{day} \cdot E_{load}}{\eta_{BI} \cdot \text{DOD} \cdot V_B} \tag{4}$$

where n_{day} is the number of autonomous days powered solely by the battery storage bank; E_{load} is the daily energy consumption; $E_c = n_{day} \cdot E_{load}$ is the summary of energy demand for the continuous number of autonomous days; η_{BI} is the overall battery and inverter efficiency; V_B is the battery rated voltage, DOD is the allowable depth of discharge.

According to the evaluation results of battery performance in Stage 1 [41], the battery bank roundtrip efficiency is approximately 74.3% in 2011. To simplify the calculation, a roundtrip efficiency of 75% was assumed in the whole lifespan of the battery. The other important design criterion for sizing batteries is the depth of discharge (DOD). The deeper the regular discharges the fewer the number of charge/discharge cycles a battery can provider over its service lifetime. In this study, the maximum DOD was taken as 75% depending on the suggestion from a design handbook [52]. With 5 days of autonomy allowed in this study, the actual DOD will often be less than 30% during periods of good sunshine, according to experience from onsite performance evaluation results [41]. The deep-cycle battery (Sonnenschein Exide Dryfit A600 OPzV) used in Stage 1 of the project is still chosen for the current study. According to capacity curve (relationship between DOD and number of cycles) based on IEC 896-2, if the state of charge (SOC) is strictly kept above 25%, the corresponding number of cycles is about 2100, which means that the battery would be replaced approximately every 5 years.

The same PV system configuration in Stage 1 was also adopted in this option, which means it employs two types of inverters. Based on the performance evaluation results of the PV inverter (SMC10000TL) and the bidirectional inverter (SI5048) in Stage 1 [41], the overall efficiency of the inverting process can be estimated as 79%. Thus the efficiency of inverter-battery efficiency η_{BI} is $0.75 \times 0.79 = 0.59$.

Therefore, the total number of batteries in this option is calculated as 1474. However, the number of batteries should be rounded into an integral multiple of 24 since there must be 24 batteries connected in series to meet the voltage requirement of inverter SI5048. Thus the total number is rounded into 1488, with 24 connected in series as one string and with 62 strings in parallel.

3.1.2. PV sizing

To simplify the sizing procedure, the solar PV panel is considered as the sole renewable source without any wind turbine. The sizing of PV array to power the whole system is based on the following equations:

$$C_{PV} = \frac{E_{load}}{\eta_{BI} \cdot T_{ps} \cdot (1 - e)} \tag{5}$$

where C_{PV} is the desired PV array installation capacity, E_{load} is the daily load energy consumption, T_{ps} is the number of peak solar hours per day and e is the overall loss factor and allowance for PV array, such as higher module temperatures, module soiling, possible array shading and production tolerances. This comprehensive loss factor was estimated as 20% [53] in this study.

Therefore the total capacity is calculated as 131.6 kWp, which is equal to 658 PV panels if all are the same modules as in Stage 1 (200 Wp for each module).

3.1.3. Inverter sizing

Following up the specified inverters used in Stage 1 [41], the same models, i.e. the SMC 10000TL and SI5048, are employed in this study. According to the specifications from the manufacturer, the input power of SMC 10000TL is 10 kW. Thus, the total quantity of the SMC 10000TL is 131 kW/10 kW ≈ 13. The charging voltage for SI5408 is 48 V, and the total number is therefore 1488/24 = 62, excluding some standbys.

3.2. Option 2 – conventional battery

In Option 2, two kinds of batteries are compared, which are commonly used in off-grid PV systems. Option 2a uses the Solar-Power 120 TV from Intact, and Option 2b and Option 2c utilize the same model of BAT412201080 from Victron Energy but with different DODs (50% and 100%). The objective of Option 2 is to investigate the capital costs and performances under different cases with batteries from diverse manufacturers, or for the same battery types but with different DODs.

The procedures of sizing and economic evaluation are the same as Option 1.

3.3. Option 3 – pumped storage combined with battery

3.3.1. System schematic and working principle

In Option 3, renewables powered seawater pumped storage scheme is proposed for this island. As shown in Fig. 2, the pumped storage system, which is isolated from the utility-grid system, is powered by an optimized hybrid solar and wind system (to simplify the document and sizing procedure, in this study, the PV panel is considered as the sole renewable source). This proposed system is regulated by a control center, including inverters, transformers, and regulators to manage the whole microgrid system. Another possible benefit is that it can be fully integrated with the local natural conditions by using seawater in the lower reservoir and combining the streams and rain water in the upper reservoir, which can make good use of a renewable solar, wind and hydro combination, also allow renewables to remain renewable.

The work principle of the micro off-grid PV system with pumped storage would be a little more complicated than the conventional PHS due to the intermittent characteristic of PV output. Such a storage system elevates water to a higher storage reservoir using pumps when renewables are available and larger than the demand. The stored water is then allowed to flow back to the lower reservoir enabling discharge of electricity through a turbine/generator during periods of high electrical demand or lower renewable energy resource.

3.3.2. Reservoir

In the traditional PHS for thermal power plants or nuclear plants, two reservoirs are required to be located on the upper mountain and the lower valley. With the technology development, seawater can now also be used for pumped storage purposes, particularly in some remote islands where there might not be enough fresh water. Besides, remote islands are surrounded by sea, and thus often geography and geology are suitable for seawater pumped storage. The feasibility of using seawater for PHS was first examined by Japan [54], and a pilot seawater pumped storage plant was constructed at Okinawa, with a roundtrip efficiency of 77% [55,56].

Based on the geography and condition of this island in this project, a seawater pumped storage is also proposed. Therefore one upper reservoir is only needed. The sizing procedures are given as below.

The efficiency of the micro turbine, generator and pipe line could be estimated as 80%, 80% and 95% according to the engineering practice and manufacturers' specifications. Thus the overall efficiency of turbine mode is determined as $\eta_t = 80\% \times 80\% \times 95\% = 60.8$.

The water stored in upper reservoir should be adequate to meet the power consumption in this island for the several days of required autonomy. The potential energy released from the upper pond can be derived as:

$$E_c = n_{day} \cdot E_{load} = \eta_t \cdot \rho \cdot V \cdot g \cdot h \tag{6}$$

where E_c is the energy storage capacity of a battery bank or water reservoir (Joules); ρ is the density of water (kg/m^3); V is the volume of the water reservoir (m^3); g is the gravitational acceleration (9.81 m/s^2); h is the total head (m).

Then the volume of upper reservoir can be calculated by Eq. (7):

$$V = \frac{E_c}{\eta_t \cdot \rho \cdot g \cdot h} \tag{7}$$

3.3.3. Solar PV powered water pumps

The utilization of solar energy for water pumping was first exploited during the 1980s [57], and significant developments for this technology have been achieved in last two decades [58]. This

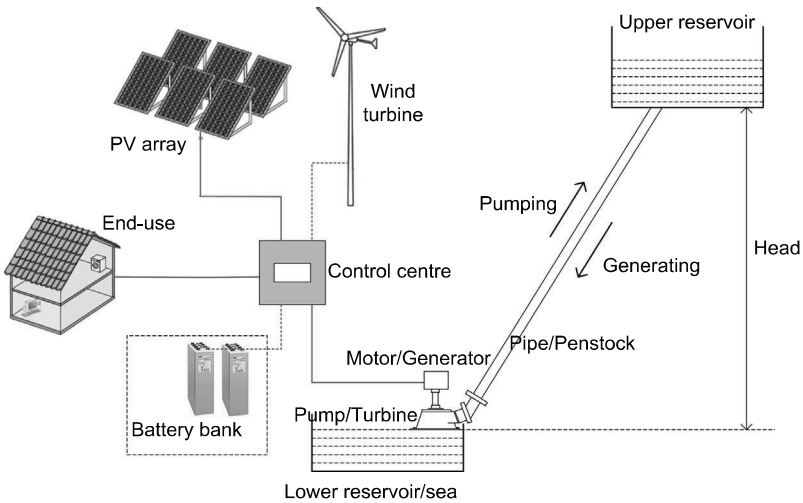

Fig. 2. Schematic of pumped storage for a stand-alone hybrid PV and wind renewable system.

technology presents technically feasible opportunities and practical potential for the solar powered PHS. In Option 3, the DC Surface Pump 8243-24 (801 W) from Dankoff was selected, combined with a small battery bank. The solar pumps are designed to charge the water reservoir with storage capacity E_c in n_{day} days. The total number of pumps needed can be decided by Eq. (8):

$$n_{pump} = \frac{V}{n_{day} \cdot V_0} \tag{8}$$

where V_0 is the amount water which can be pumped per pump per day (m^3/day).

For the pump mode, the overall efficiency η_p includes an array mismatch factor (the rated power of the PV array must be exceeded by the pumps wattage) and motor/pump efficiency, which is given by:

$$\eta_p = \eta_{array\text{-}motor} \cdot \eta_{motor\text{-}pump} \cdot \eta_{pipe} \tag{9}$$

where $\eta_{array\text{-}motor}$ is the array mismatch factor (pump size divided by PV capacity), average at 80%; $\eta_{motor\text{-}pump}$ is the motor/pump efficiency which depends on the reservoir head and the flow rate; η_{pipe} is the pipe line efficiency as affected by friction losses (assumed as 95%).

3.3.4. Turbine sizing

The daily peak load is assumed as 50 kW in this case study. Therefore a micro hydro turbine generator set of at least a 50 kW rating was selected. This study assumed that the micro-hydro turbine and corresponding pipe and controller could be built for $1800 per kW for the pumped storage option. Since seawater is pumped to storage, the turbine generator set was assumed to be replaced every 10-year.

3.3.5. Small battery bank sizing

A small battery bank can play significant roles in scheduling of energy dispatch and managing a pumped storage system, such as balancing demand and supply in generating mode, and balancing renewable sources. The small battery bank capacity can be determined:

$$C_{Ah} = \frac{(1-\alpha) \cdot n_{day} \cdot E_{load}}{\eta_{BI} \cdot DOD \cdot V_B} \tag{10}$$

where α is the portion of energy that flows directly from turbine to meet the load, and $(1-\alpha)$ is the portion that passes through the battery system as short-term storage.In this basic case study, α is assumed to be 70%, and the same battery utilized in Option 1 is employed with same parameters such as roundtrip efficiency, voltage, storage capacity, and maximum DOD. Thus the small battery bank in the combined storage system is calculated as 75 kW h, consisting of 96 batteries.

3.3.6. Overall efficiency of the micro pumped storage scheme

The overall efficiency of the pumped storage scheme combined with a mall battery bank is given by:

$$\eta_{ps} = \alpha \cdot \eta_p \cdot \eta_t + (1-\alpha) \cdot \eta_p \cdot \eta_t \cdot \eta_{BI} \tag{11}$$

The calculated overall system efficiency is 21%, which is approximately 1/3 that of the battery storage scenario. It means that about two times of PV panels are needed for the pumped storage combined with battery system for the same amount of stored energy.

3.3.7. PV sizing

In this scenario, after sizing the pumped storage capacity, the adequate PV array capacity to power the whole system can be determined by:

PV modules in parallel (based on water pump rated current):

$$n_{PV_p} = \frac{I_p}{I_{PV}} \cdot \frac{1}{\sqrt{\eta_{array\text{-}motor}}} \tag{12}$$

PV modules in series (based on water pump rated voltage):

$$n_{PV_s} = \frac{U_p}{U_{PV}} \cdot \frac{1}{\sqrt{\eta_{array\text{-}motor}}} \tag{13}$$

Total number of modules for a single water pump is:

$$n_{PV_{s\times p}} = n_{PV_s} \times n_{PV_p} \tag{14}$$

Total capacity of PV array for this case is:

$$C_{PV} = n_{pump} \cdot n_{PV_{s\times p}} \cdot C_{single} \tag{15}$$

where I_p and I_{PV} are the rated current of water pump and PV module; U_p and U_{PV} are the rated voltage of water pump and module; n_{PV_s} and n_{PV_p} are the numbers of modules connected in series and in parallel, which are then rounded up to the next integer.

Therefore, the total installed PV capacity for Option 3 was determined at 252 kWp with 1230 panels.

3.4. Option 4 – pumped storage scenario without battery

In this scenario, the hydraulic controller, that mechanically adjusts the opening aperture of the penstock valve in response to fluctuations of load [59], is employed to balance supply and demand, instead of the small battery bank of Option 3. Option 4 is further divided into three subclasses based on the types of solar pumps used in this system. The same Dankoff DC Surface pumps in Option 3 (801 W), the Solartech PS37K AC pump (37 kW), and the Yoli-400-25 AC pump (45 kW) are selected for comparative study as Option 4a, Option 4b and Option 4c respectively.

The sizing procedure and system configuration for Option 4 are similar to those for Option 3. Without batteries, the overall efficiency is determined as:

$$\eta_{ps} = \eta_p \cdot \eta_t \tag{16}$$

Therefore the overall pumped storage system efficiency of Options 4a, 4b and 4c are 24%, 14.3% and 21%, respectively. The differences in efficiency among three cases arise from the solar pump performances supplied by different manufactories. Detailed information on these pumps can be seen in Table 5.

4. Results and discussion

To discover the most economical energy storage option, the LCC, LCRES and cost ratio results were derived and compared using the above procedures and quotation information. In the following sections, the results are analyzed and the effects of five key input variables on costs are examined.

4.1. LCC&LCRES results for all options

The total LCC of Option 1 is calculated to be approximate $4.37millon. Fig. 3 provides the cost breakdown of batteries and inverters, which account for 89% and 11% of the total cost, respectively, illustrating that the batteries' cost is the dominating item of Option 1.

The LCC results for the conventional battery (Option 2) are summarized in Table 4. It should be noted that the discrepancies among three subcategories (Options 2a, 2b and 2c) are significant. The LCC of Option 2a using batteries from Intact is lower than those of Option 2b and 2c (Victron batteries), demonstrating the economic differences between two types of batteries. The LCC result for Option 2b with 100% DOD is slightly less than that with

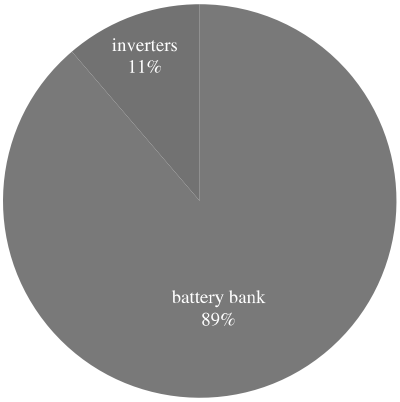

Fig. 3. Components LCC breakdown of Option 1.

the 50% DOD of Option 2c, indicating that the economic performance of the same battery model can be affected significantly by discharging depth. Compared with Option 1, the LCRES results per kW h of capacity for all Option 2 cases are considerably higher, which shows that the advanced deep cycle batteries perform better than the conventional one for long term operation. The findings in Table 4 also reveal that the increase of initial costs incurred in adopting advanced technology can effectively decrease operating and maintenance costs.

Option 3, the pumped storage combined with battery bank scheme, presents attractive results. The total investment cost of Option 3 is about $2.4millon, only 55% of Option 1. The LCC breakdown results for all components involved are presented in Fig. 4. The main reason for the lower total LCC is possibly that extremely fewer batteries (only $0.27millon) are used in this option. The findings in Fig. 4 indicate that the largest weighting of LCC is contributed by the pump (accounting for 59%), followed by the additional PV panels, which take up around 21% due to the relatively low overall efficiency of Option 3, while battery cost only accounts for 11%. The percentages for turbines and the reservoir are minor compared with pumps, at 6% and 2% respectively. Since Dankoff DC solar pumps were employed, the cost for inverters is also reduced with the lowest proportion at 1%.

As for Option 4, a new approach to balance supply and demand is introduced by the use of a hydraulically controlled turbine. The results are summarized in Table 5. The LCC result for Option 4a ($2.1millon) is 12% less than that of Option 3 ($2.4millon) utilizing the same solar pump model. Option 4a, however, needs no inverter and no battery. In Option 4b and 4c, the larger capacity AC solar pumps made by Chinese manufacturers are utilized, and therefore the initial investment significantly decreased, although more frequent replacements are needed. Between these two options, the major cost component is absolutely the additional PV cost due to the lower system efficiency. Improvement in this respect presents significant challenges for both researchers and manufacturers for enhancing solar pump efficiencies so that more energy is conserved and the LCC can be further reduced. The lowest LCRES value among all pumped storage options is provided by Option 4c (about 1029).

A summary of all options' results is presented in Table 6. The cost ratio is the LCC relative rate for the individual option divided by the Option 1 LCC value. A smaller ratio means a lower cost and greater economically feasibility. For Option 2, the cost ratio is much higher than 1, indicating there are no cost advantages for conventional batteries. However, for Option 3 and Option 4 by pumped storage, the economic benefits are significant and the cost ratios decrease to less than 1. The minimum ratio is occupied by Option 4c at a cost of only 29%, and the highest cost pumped storage scheme of Option 3 only costs about 55% of Option 1. Therefore it is obvious that the pumped storage system can be economically competitive with battery solutions for renewable microgrid storage applications. This superiority will be further enhanced when the overall efficiency of micro/medium pumped storage schemes are improved with growing focus of interest in studying it. In

Table 5
Pumped storage option without battery comparison (Option 4).

Pumped storage options	Option 4a	Option 4b	Option 4c
Manufactory	Dankoff	Solartech	Yoli
Pump model	Surface Pump 8243-24	PS37 K	Yoli-400-25
Motor type	DC	AC	AC
Motor rated power (W)	700	37,000	45,000
Array size for each pump (W)	801	65,300	60,000
Array mismatch factor (%)	80	57	75
Turbine model efficiency (%)	52	44	48
Flow rate per pump (m^3/day)	7.69	300.00	403.00
Total number of solar pumps	246	7	5
Desired service life (years)	20	5	5
Cost per pump ($)	3861	5056	10,749
Cost of pumps in 25 years ($)	1,413,348	91,286	138,614
Cost of inverters in 25 years($)	–	249,888	339,721
System overall efficiency (%)	24	14	21
PV array size (kW)	252	464	314
LCC ($)	2,098,784	1,449,609	1,286,855
LCRES ($)	1679	1160	1029

Table 4
Battery storage option comparison (Option 1 and Option 2).

	Option 1	Option 2a	Option 2b	Option 2c
Manufactory	Exide/Sonnenschein	Intact/Phaesun	Victron Energy	Victron Energy
Model/article number	Dryfit A600 OPzV	Solar-Power 120 TV	BAT412201080	BAT412201080
Nominal voltage (V)	2	12	12	12
Rated capacity (Ah)	960	120	220	220
Rated capacity (kW h)	1.92	1.44	2.64	2.64
Maximum DOD (%)	75	50	100	50
Usable power per battery (kW h)	1.44	0.72	2.64	1.32
Desired service life (years)	5	2	1	2
Total number of batteries	1488	3168	816	1608
Initial cost of batteries ($)	1,619,365	852,669	531,610	1,047,584
Total cost of batteries in 25 years ($)	3,877,570	4,500,773	5,357,053	5,529,619
LCC ($)	4,369,635	5,484,343	5,662,458	6,055,016
LCRES ($)	3496	4387	4530	4844

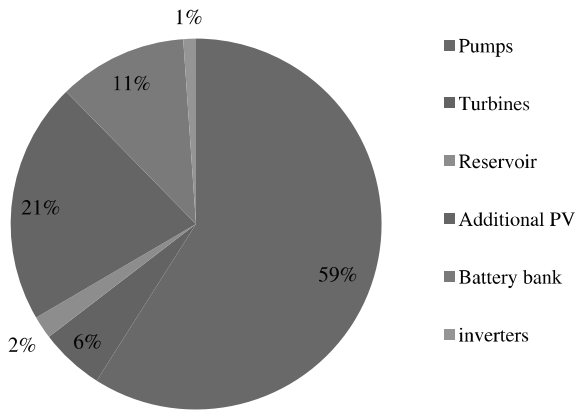

Fig. 4. Components LCC breakdown of Option 3.

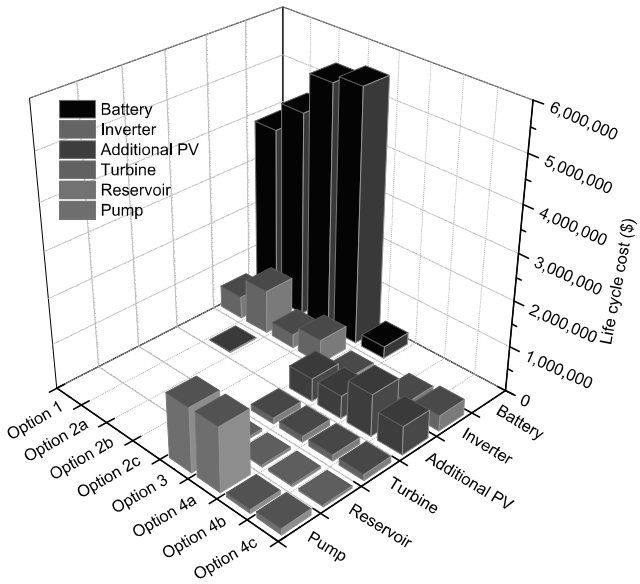

Fig. 5. Breakdown of life cycle cost for all options.

addition, the breakthroughs in PV technology and recent decline in PV panel price along with rising costs of batteries will further enhance the cost effectiveness of pumped storage option.

The LCC results for all options are given in Fig. 5, which provides a breakdown with respect to the six key components involved in this study. A number of significant features exist, particularly the differences in costs of the different components. The battery bank is the major cost item for Options 1 and 2 (battery storage schemes), and the battery costs alone are even greater than the total LCC for Options 3 and 4 (pumped storage schemes). The pump accounts for the largest cost percentage in Options 3 and 4a, which may results from the Dankoff DC solar pumps used. However, Options 4b and 4c, with the AC pumps, need to spend more on additional PV panels in order to achieve the same energy storage capacity and days of autonomy.

The most economical option is quite clear. However, if power supply stability, energy conservation and technology implementability are also considered (not costs alone), the pumped storage combined with battery scheme, i.e. Option 3, would be the optimal one.

4.2. Sensitivity analysis results

Sensitivity analyses are carried out on the five input values which are important to all options, including daily energy consumption, desirable autonomy days, peak sun hours, discount rate, and PV module price. The sensitivity assessment results are provided below.

4.2.1. Daily energy consumption

Daily energy demand is the most critical input affecting option choice, as it directly affects power generation capacity and energy storage capacity needed. The variation in cost ratios is presented in Fig. 6 as the daily energy consumption for the island varies between 10 kW h and 1000 kW h.

It is probably unreasonable to employ the pumped storage for a pico renewable energy system with a daily electricity consumption of 10 kW h, which is about the daily average energy demand for a single home. For this case, the costs of Options 4b and 4c are much higher than that of Option 1 because the solar pump capacity used in this study is quite high and is also costly. For the relatively low storage capacities of 10 kW h and 20 kW h, the chosen sizes of pumps and inverters are also much higher than the daily energy demand, although the reservoir size can be adjusted flexibly. Therefore it is not cost effective to employ pumped storage for the low storage capacity range. However, when daily consumption is greater than 25 kW h (the energy demand of two or more families), the cost ratio for all pumped storage schemes can be kept below 0.8 except for Option 3 with its additional battery costs. As daily energy consumption increases, the cost ratio of 0.8 can be further lowered and the economic benefit of pumped storage becomes more obvious.

4.2.2. Days of autonomy

The results in Fig. 7 indicate that the cost ratio for the pumped storage option is quite sensitive to the number of storage days. However, actually LCC results of battery storage schemes turn out to be more sensitive to storage days than the case with pumped storage. For battery involved Options 1 and 2, as the expected number of storage days decreases, the number of batteries linearly reduces with storage capacity, and thus the cost ratios for Options 2a, 2b and 2c to Option 1 remain almost the same even though the total capital costs are greatly decreased. However, for pumped storage case, the high cost pumps are not related to the

Table 6
Summary of economic cost for options and the cost ratio to Option 1.

Options	Description	LCC ($)	LCRES ($)	cost ratio to Option 1 (%)
Option 1	Advanced deep cycle battery	4,369,635	3496	–
Option 2a	Conventional battery (Intact Solar-Power)	5,484,343	4387	126
Option 2b	Conventional battery (Victron Energy DOD = 100%)	5,662,458	4530	130
Option 2c	Conventional battery (Victron Energy DOD = 50%)	6,055,016	4844	139
Option 3	Pumped storage + battery–Dankoff DC pumps	2,394,901	1916	55
Option 4a	Pumped storage (no battery)–Dankoff DC pumps	2,098,784	1679	48
Option 4b	Pumped storage (no battery)–Solartech AC pumps	1,449,609	1160	33
Option 4c	Pumped storage (no battery)– Yoli AC pumps	1,286,855	1029	29

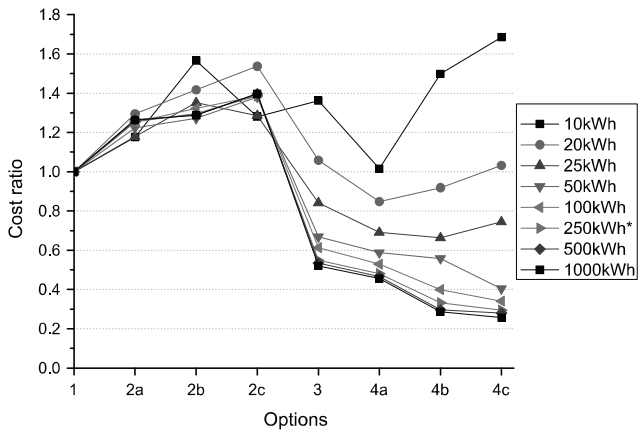

Fig. 6. Sensitivity analysis result on daily energy consumption.

days of autonomy. In Eq. (8), the numerator (the volume of the reservoir) has already taken account of daily energy consumption and the number of autonomy days, while the number of autonomy days is divided out by the denominator term. Therefore, the cost of pumps and inverters which are the dominant cost components remain unchanged. In fact, the overall LCC results for each pumped storage scheme only, vary over a range of 6% as the number of storage days vary from 1.5 to 20 days. The cost ratios, however, fluctuate greatly.

In a word, to achieve a cost effective pumped storage scenario, at least 3 days of autonomy should be deigned. If combined with the result of the sensitivity analysis on daily energy consumption, the conclusion is that a high energy storage capacity, multiplied by daily energy demand and storage days, can enhance the competitiveness of pumped storage.

4.2.3. Peak sun hours

The sensitivity study of the effects of peak sun hour variations mainly relates to the prospects for implementing the technologies in other diverse locations with different mean solar radiation levels, not just for this outlying island and Hong Kong.

As Fig. 8 indicates, the pumped storage option would be more cost effective than the battery storage option for places with 2–7 peak sun hours of solar radiation. Another significant phenomenon is that any increase in peak sun hours further improves the competitiveness of the pumped storage scheme. The result suggests that the pumped storage scenario can be applied widely in any location around the world where the number of peak sun hours exceeds 2.

4.2.4. Discount rate

The discount rate also influences the cost effectiveness of different storage alternatives, as demonstrated in Fig. 9. Eq. (1) reveals that the growth of discount rate decreases the present value of components replacement costs. Therefore, the LCC results of all options are lower at higher discount rates. However, the LCC reduction for the battery options, particularly for the conventional battery, is much greater than that for the pumped storage option because battery replacements are more frequent. Therefore, as shown in Fig. 9, the conventional battery cost ratio falls as the discount rate rises from 2% to 20% whereas the cost ratios for pumped storage options climb. The conclusion is that the decrease in discount rate could improve the relative cost effectiveness of the pumped storage option.

4.2.5. PV module price

The LCC results related to energy storage exclude the PV module price. However, the relatively low overall efficiency of small-scale pumped energy storage means that larger solar arrays are needed to produce the same final unit of output (after storage). Therefore the PV module price does affect the competiveness of pumped storage, as shown in Fig. 10.

It can be seen that the LCC results and cost ratios for the battery option remains unchanged when the PV module price ranges from \$0.5/Wp to \$3/Wp. However, for the pumped storage scenario, as PV module prices decrease the LCC results drop gradually although the reduction of cost ratio is not significant. At present the price of solar PV has declined to below \$1 per installed peak watt (in contrast to rising battery costs), which will further enhance the economic performance of pumped storage, and consolidating the case in favour of this option.

From the above five sensitivity analyses, the uncertainties and economic viabilities of the battery storage and pumped storage options have been evaluated. To sum up, the results suggest that the economic viability of the pumped storage schemes can be further improved when there is a need for higher energy storage capacity, more days of autonomy, when a low discount rate is applicable, and as PV panel prices decrease.

5. Conclusions and suggestions

For a remote island powered by renewable energy, the life-cycle cost (LCC) of battery storage schemes is compared with pumped

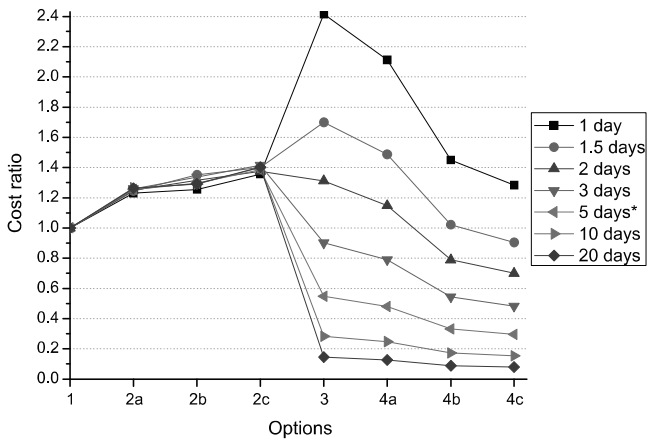

Fig. 7. Sensitivity analysis result on storage days.

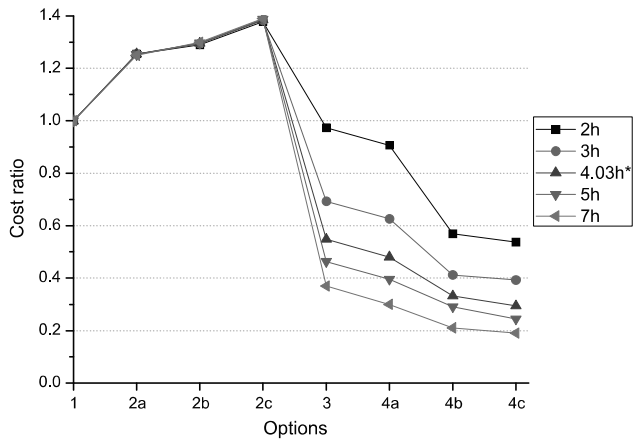

Fig. 8. Sensitivity analysis result on peak sun hours.

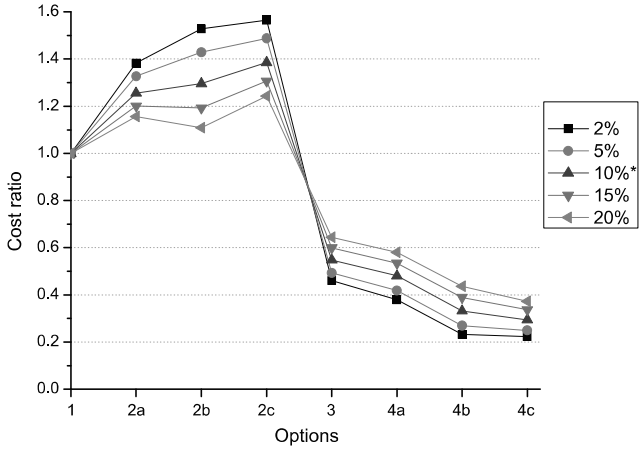

Fig. 9. Sensitivity analysis result on discount rate.

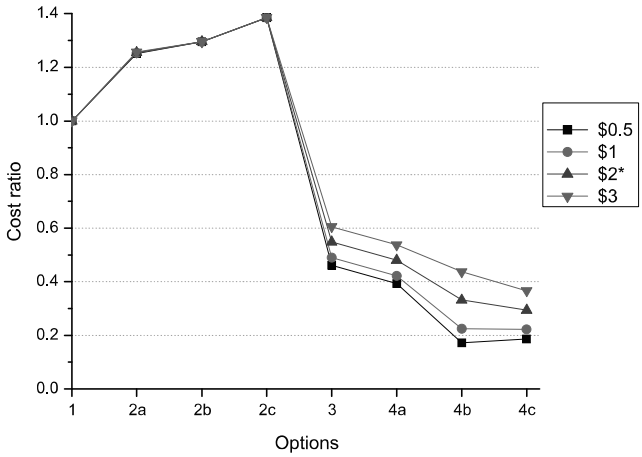

Fig. 10. Sensitivity analysis result on PV module price.

storage schemes. Both schemes, which are further subdivided into the 4 options, serve for a renewable energy powered microgrid energy supply system for an isolated island. The LCC results of all options have been compared in terms of levelized costs of renewable energy storage (LCRES) and cost ratios. The results show that the use of conventional battery (Option 2) has a higher LCC value than the advanced deep cycle battery (Option 1), indicating that use of deep cycle batteries is more suitable for a standalone renewable power supply system. However, the pumped storage combined with battery bank option (Option 3) is only 55% of the cost of Option 1, making this combined option more cost-competitive than the sole battery option. The economic benefit of pumped storage is more significant in the case of storage by pump alone if using a hydraulic controller (Option 4), with the lowest LCC among all options. The sensitivity analysis showed that pumped storage would be even more cost competitive if the parameters of energy storage capacity and days of autonomy were increased. If power supply is stable, energy conservation and technology implementability are also considered and not LCC alone, the pumped storage combined with battery scheme i.e. Option 3 would be the optimal one.

The original idea of this study is to employ the reversible pump-turbine, which is widely used in pumped storage system for conventional power plants. But no off-the-shelf reversible pump-turbines are available for micro renewable energy system with pumped storage. Such a machine would increase system efficiency, decrease machinery cost, and simplify whole system configuration. A suitable pump-as-turbine can perhaps act as a reversible pump-turbine, but it is also not easy to find a mature and well-tested product on the market. However, the innovative idea has been suggested here as worthy of future research.

Some other technological issues, such as control strategy and management of the microgrid system with 100% renewable source and pumped storage, have not been the focus in this study, the concern being primarily with economic issues. If we want to achieve high power supply quality and reliability in remote areas using renewables, such issues could not be ignored, and they would need engineering breakthrough in realizing this emerging technology, remaining big challenges and enormous opportunities as well for the scholars and engineers in this field. A technical feasibility and theoretical simulation study will be conducted and reported by the research group connected with this study in the near future.

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