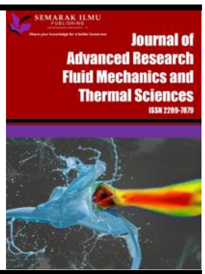
SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879



The Study of Usable Capacity Efficiency and Lifespan of Hybrid Energy Storage (Lead-Acid with Lithium-ion Battery) Under Office Building Load Pattern

Praphun Pikultong[1,*], Sahataya Thongsan[1], Somchai Jiajitsawat[2]

[1] School of Renewable Energy and Smart Grid Technology, Naresuan University, 99 Moo 9, Tambon Tha Pho, Amphoe Mueang Phitsanulok, Chang Wat Phitsanulok 65000, Thailand
[2] Department of Physic, Faculty of Science, Naresuan University, 99 Moo 9, Tambon Tha Pho, Amphoe Mueang Phitsanulok, Chang Wat Phitsanulok 65000, Thailand

ARTICLE INFO

Article history:
Received 25 March 2022
Received in revised form 4 July 2022
Accepted 17 July 2022
Available online 10 August 2022

Keywords:
Hybrid energy storage; usable capacity; lifespan; lead acid battery; Li-ion battery

ABSTRACT

One of the greatest practices in energy management is the Energy Storage System (ESS). ESS can be used for renewable energy control as well as peak shaving in the build-up of a Smart Grid. The cost of a lithium ion battery is more than 200 percent greater than that of a lead-acid battery, which is a significant barrier to project start-up. This paper focuses on the use of a hybrid energy storage system that includes a lithium-ion battery and a lead-acid battery. This work presents the hybrid energy storage using lithium-ion battery and lead-acid battery to reduce costs of the project. However, usability that requires high current power supply considerably affects the usable capacity of a lead-acid battery. Results showed that the ratio 68.63: 31.37 was the most suitable among 7 ratios, compared to the model building installed a 50kW solar power generator on the rooftop, in the worst case scenario when the batter have 85% DoD per cycle. The EOL for hybrid energy storage is about 4 years lifespan with the 0.5C and 0.2C for LFP and AGM respectively. In terms of economic evaluation, hybrid energy storage could initially reduce the project cost by 47.5%.

1. Introduction

Currently, Thailand's economy is growing continuously, resulting in a higher rate of energy consumption. However, Thailand increasingly supports power generation from renewable energy sources but it is not enough to meet demands being a factor to import energy from foreign countries 1.1% increasingly in the first quarter of 2022 [1]. The support on energy generation technology or energy conservation is intangible in the group of office buildings and houses since it is necessary to invest which probably affects overall development of other aspects.

The government has pushed forward the support of renewable energy like solar energy to be installed on the rooftop of designated buildings for a while to reduce energy consumption. However,

* *Corresponding author.*
E-mail address: mr.praphun@gmail.com

https://doi.org/10.37934/arfmts.98.2.6779

due to environmental effects, energy is inconsistent, causing volatility in transmission lines and energy consumption in grids cannot be reduced efficiently. Therefore, in the past 5 years, energy storage system was brought to reduce environmental effects, support the growth of electric vehicle users, and serve preparedness of a transition to smart grids. Though lithium ion energy storage system gains popularity due to its various outstanding features, limitations of the cost make an investment in the country is quite difficult as the total cost to install a lithium ion battery storage system is 1 time higher than the cost of installing lead-acid batteries. Consequently, reduction of the initial cost of energy storage system project for office buildings is a starting point for energy management in an effective manner in response to the growth of electric vehicle users at the household level.

This research aims study usable capacity efficient towards lifespan, which is an important part of economic cost-benefit evaluation of hybrid energy storage system, the collaborative working between lead-acid and lithium-ion batteries. Ratio of the actual capacity of both types of batteries, initial cost, usable storage capacity efficiency, and lifespan of the system were investigated. This research can be used as a case study and a model at the operation level for energy storage system in office buildings and developing further to commercial buildings and houses accordingly.

2. Research Background

2.1 Hybrid Energy Storage System

Hybrid energy storage system consists of two or more types of energy storage technologies to work harmoniously with the goal to bring outstanding features of each energy storage system to reinforce each other [2]. Hybrid energy storage system is perhaps composed of energy storage systems having different characteristics, such as electrical energy storage system-thermal energy storage system, electrical energy storage system- mechanical energy storage system, electrical energy storage system- hydrogen energy storage system, electrical energy storage system-magnetic energy storage system, electrical energy storage system-electrical energy storage system, etc. It can be seen that an electrical energy storage system plays a major part of hybrid energy storage system due to its flexibility in usability, ease of use, and consistency with many operation modes. As for hybrid energy storage system suitable for office buildings, emphasis is placed on battery energy storage system. Arita *et al.,* [3] designed a hybrid energy storage system from lead acid battery and lithium-ion battery using a control system in response to changes in demands of electrical energy consumption and to reduce the fluctuation of electricity generating system from wind power, which can reduce the cost of electrical energy storage system by 40% for areas far away from transmission lines or areas with power system instability. Energy storage system plays a vital role in reducing uncertainty of electrical system by reducing the use of a power generator that relies on fuel consumption. For example, a hospital in South Africa used hybrid energy storage system consisting of lithium-ion and lead-acid batteries, and solar energy for electricity generation as an extra source of energy. Rahe [4] found the model, designed with reference to an experiment, showing that hybrid energy storage system had longer lifespan with a lower cost.

With regard to the application to various approaches as mentioned earlier, hybrid energy storage system, designed to operate with lead-acid and lithium-ion batteries, has points to be studied together, namely, cost and energy management. However, the points to be studied are related to limitations of a lead-acid battery that affect the battery usable capacity when delivering higher electric current, including shorter lifespan [5]. Therefore, the ratio of each type of batteries should be taken into consideration for designing an energy storage system in order to maintain the maximum battery capacity and reduce the initial cost of the system. Jiajitsawat *et al.,* [6] designed a hybrid energy storage system by considering the operating conditions of each battery, the ratio of lead-acid to lithium-ion battery was 70:30. In this study, the ratio of lead-acid battery type: Absorbent Glass Material (AGM) and lithium-ion battery type: Lithium Iron Phosphate (LFP) was examined to reduce the initial cost of energy storage systems by comparing cost and efficiency from the point of view of rated capacitance for testing different levels of current distribution.

2.2 Usable Capacity Efficiency

As the operating conditions require a high current, it strongly results in the usable capacity of lead-acid batteries, having an effect on the operations and design of the size of an energy storage system, including a command menu to control the operations. Therefore, it is important to take the efficiency of hybrid energy storage system in which lead-acid and lithium-ion batteries work together into consideration, in terms of usable capacity efficiency, towards capacity evaluation of the system.

Usable capacity efficiency is the comparison of energy storage system efficiency by referring to usable storage capacity of batteries when tested to deliver electric current compared to the usable storage capacity identified by a manufacturer. Usable capacity efficiency can be calculated from the ratio of discharge capacity and current rated capacity as shown in the Eq. (1).

$$\eta_c = \frac{C_{dis}}{C_r} \times 100\% \tag{1}$$

where

η_c is Usable Capacity Efficiency (%)
C_{dis} is Discharge Capacity (Wh)
C_r is Current Rated Capacity (Wh).

However, an accurate prediction of the battery capacity is strongly depending of the Peukert constant as presented by Eq. (2) [7]. The Peukert equation is an empirical relationship describing the battery discharge capacity. When the Peukert constant is equal to 1, the discharge capacity will be independent of the applied current. When k is higher than 1, the discharge capacity will decrease.

$$t = H\left(\frac{C_r}{IH}\right)^k \tag{2}$$

where

H is the rated discharge time (h)
C_r is the rated capacity at that discharge rate (Ah)
I is discharge current (A)
k is the Peukert constant (dimensionless)
t is the discharge time (h).

Peukert constant is strongly dependent on the battery technology, lead-acid battery had 1.0-1.3 and lithium-ion battery had 1.0-1.28 [8].

Usable capacity efficiency is an important part of economic cost-benefit evaluation of hybrid energy storage system. In this study, AGM and LFP batteries were tested at different capacity-to-usable capacity ratios when drawn at different current requirements.

2.3 Battery Lifespan

IEEE Standard determines an expired battery as at any time a battery cannot produce an electrical current at 80% of the battery capacity expressed in Ampere-Hour (Ah), the battery is considered end of life (EOL). However, EOL value is determined by manufacturers, which most likely ranging from 70-80% of the capacity [9-11]. In a test, it is set to stop delivering an electrical current when the state of charge (SOC) of the battery is lower than the level determined by the manufacturer or some manufacturers determine as electrical energy value across the lifespan of a battery for referring to a test condition of EoL [9]. At the same time, information identified by a test performed by a manufacturer is a battery's cycle life, the number of charge and discharge cycles that a battery can complete before losing performance. For the experiment in this section, each type of battery was tested one at a time by running the discharge current until the specified Depth of discharge (DoD) was reached, and then recharging it to test cycles to examine the remaining capacity compared to the original capacity of the battery.

2.4 Cost of the Project

Based on the expense information and battery lifespan shown in Table 1, the initial cost of the project for pure LFP energy storage system requires higher investment than pure AGM energy storage system; more than 300%, which greatly affects the investment in a large size energy storage system. It can be said that hybrid energy storage system that consists of lead-acid battery and lithium-ion battery can reduce the initial cost of the project. However, due to the problem related to lead-acid battery lifespan, the cost of hybrid energy storage system throughout the lifespan is higher, caused by changing the battery across the lifespan. With the independent operation between each type of batteries, lifespan evaluation is more easily performed, including the battery that will be changed according to the battery's cycle life.

Table 1
Comparison of the specification between lead-acid battery and lithium-ion battery [12-14]

	Lead acid (AGM)	Lithium-ion (LFP)
Energy Density (Wh/L)	100	250
Specific Energy (Wh/kg)	40	150
Battery materials cost ($/kWh)	107	428
Transportation cost ($/kWh)	34.6	12.36
Electric utility cost ($/kWh)	0.15	0.15
Battery installation cost ($/kWh)	0.012	0.012
Battery maintenance	10%	1.5%
Cycle Life	1,000 @ 60% DoD	1,800 @ 60% DoD
Typical state of charge window	50%	80%
Temperature sensitivity	Degrades significantly above 25°C	Degrades significantly above 45°C
Efficiency	100% @20-hr rate 80% @4-hr rate 60% @1-hr rate	100% @20-hr rate 99% @4-hr rate 92% @1-hr rate

3. Experimental Setup

This research focuses on usable capacity efficient towards lifespan, which is an important part of economic cost-benefit evaluation of hybrid energy storage system. The ratio of the actual capacity of

AGM battery and LFP battery were examined. The experiments were classified into two parts namely usable capacity efficiency and economical evaluation.

3.1 Usable Capacity Efficiency

Usable capacity efficiency is the important factor to determine the appropriate ratio of AGM and LFP battery. The experiment was designed to reduce project start-up costs. Test ratio of AGM:LFP batteries was selected in the 90:10 to 50:50 range using 12 V 7 Ah AGM battery pack and 3.2 V 6 Ah LFP pack, grouped for a total of 7 different ratios as given in (Table 2).

Table 2
The ratio of AGM battery to LFP battery in the test

AGM Battery Capacity (Wh)	LFP Battery Capacity (Wh)	Capacity Ratio
168	19.2	89.74 : 10.26
252	38.4	86.78 : 13.22
84	19.2	81.40 : 18.60
168	57.6	74.47 : 25.53
84	38.4	68.63 : 31.37
84	57.6	59.32 : 40.68
84	76.8	52.24 : 47.76

The testing of usable capacity was set up as the diagram in dashed border in (Scheme#1 as illustrated in Figure 1). The testing was performed through programmable resistive load for being able to determine discharge current and measure out for battery voltage and energy discharged. The Power controller was set for both battery types able to work independently and each battery types has BMS circuit to prevent battery damage.

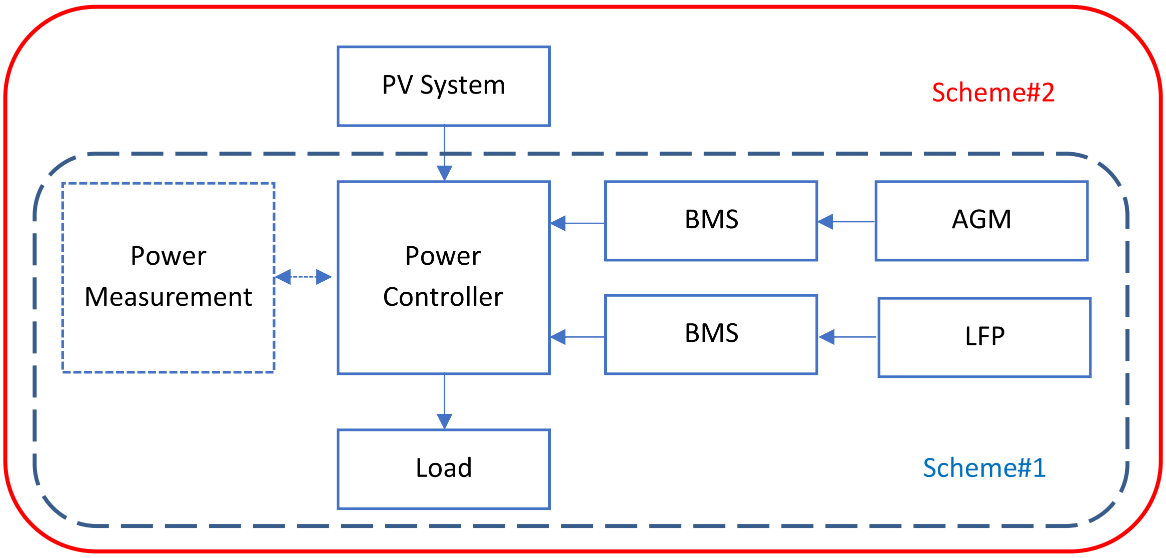


Fig. 1. The overall diagram for system test

3.2 Economic Evaluation

This section contained two parts of the test namely: supply current tests to assess the service life and load response tests of office buildings.

The test in the first section to assess the life of each battery at various discharge rates, which can be seen from Scheme #1 in Figure 1. In this section, each type of battery was connected one by one.

End of discharge voltage was set at 10.5 V for AGM battery and 2.6 V for LFP battery. The details of test parameters can be shown in Table 3. Since usable storage capacity of AGM battery has high variation towards the ratio of electrical current discharged, the actual storage capacity of the battery cannot be seen for consideration of battery EOL. Therefore, the battery's storage capacity is measured based on a 20-hour rate discharge rate according to the storage capacity test information by the manufacturer. Measurement is performed every 50 charge-discharge cycles of AGM battery. The tested cells were rested for 4 hours in every cycle of the discharge before the next cycle of the test shall be started.

Table 3
Details of the battery lifespan test

Factor	Number of Level	Value of Level
Current	2	LFP 0.5C, 1C AGM 0.16C, 0.5C, 1C
Battery Type	2	LFP 3.2V 6Ah, AGM 12V 7Ah
Environment		Atmospheric/Room Temperature
Cycle Life	n/a	1, 100, 200, 300, …
Battery Capacity	n/a	measure

For this section of the office building load response test, the proportion of hybrid energy storage systems had been expanded to a capacity of 100kWh by working with a 50 kW roof-mounted solar power system installation capacity under office building load pattern of Department of Physics, Naresuan University. The test of this section can refer to the diagram in Figure 1 Scheme#2 added with the solar power generation system section, and the Load section can be referenced from the data collected during 11 – 17 November 2019) (before the outbreak of Covid 19) as seen in Figure 2.

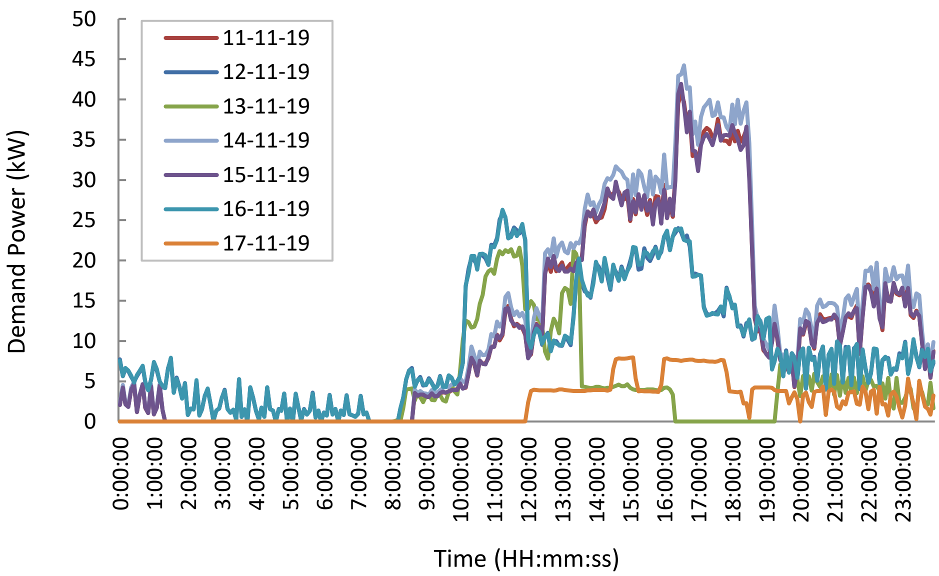


Fig. 2. Office building load pattern of Department of Physics, Naresuan University

In actual response testing, the control system is important to manage the performance of each battery type to match and suit the characteristics of each battery type. The operating conditions of each type of battery can be set as shown in Table 4. The level of importance in the work that the system will choose to work according to the level from a low number (High priority) to high numbers (low priority). Level 0 is the highest priority. However, since the AGM battery has a larger capacity than the LFP battery, the researchers designed the AGM battery to discharge during the day when the demand for electricity is high and the solar energy is low. This is to reduce the burden of LFP batteries to be supplied when solar power is intermittent and to maximize continuity of charging for the solar storage system.

Table 4
Operating conditions for each type of battery and its importance

Condition	AGM	LFP	Priority
Very High-Power Demand	Discharge (do not exceed 90% DoD)		0
Day Peak	Discharge First in cloudy day	Discharge	2
Night Peak	Discharge	Discharge First	2
Solar Fluctuation	n/a	Discharge	1

4. Results and Discussions

4.1 Usable Capacity Efficiency Test Results

Usable capacity efficiency is a parameter that helps evaluate the usability ratio of each type of batteries in the hybrid energy storage system. It is associated with the cost and lifespan of the system so as to be used for evaluating economic cost-benefit of the project.

Table 5 shows overall usable capacity efficiency of the system. A dummy load was used to simulate an electrical load at 3.5 A, 7 A, and 14 A in accordance with battery packs classified by types of batteries and capacity. End of discharge voltage was set at 10.5 V for AGM battery and 2.6 V for LFP battery. Electrical power discharged was measured in this study. Data recorded showed the average value from the 5-time repeated test.

According to the test results of electrical power discharge to find usable capacity efficiency, it was found that the ratio of AGM battery was higher, usable capacity efficiency tended to decrease. Similarly, when the discharge rate of the battery was increased, power discharged from the battery was low. Results implied that high-performance batteries as the LFP are essential to improve the efficiency of the overall energy storage system. However, increasing the ratio of LFP batteries will also increase the cost of hybrid energy storage systems.

Table 5
Usable capacity efficiency of the hybrid energy storage system at different ratios

Battery Ratio (%)		Total Capacity (Wh)	Usable Capacity @ Discharge Current (Wh)			Usable capacity efficiency (%)			Normalized cost by 100% LFP
AGM	LFP		3.5A	7A	14A	3.5A	7A	14A	
89.74	10.26	187.2	134.9	124.5	104.1	72.06	66.51	55.61	0.39
86.78	13.22	290.4	211.9	195.8	164.7	72.97	67.42	56.71	0.41
81.4	18.6	103.2	77.1	71.4	61.6	74.71	69.19	59.69	0.45
74.47	25.53	225.6	173.2	161.9	139.9	76.77	71.76	62.01	0.49
68.63	31.37	122.4	97.9	91.9	79.5	79.98	75.08	64.94	0.53
59.32	40.68	141.6	114.3	108.6	93.3	80.72	76.69	65.89	0.60
52.24	47.76	160.8	132.2	124.8	107.8	82.21	77.61	67.04	0.65

The capacitance efficiency ratio of AGM:LFP is given in Figure 3 and showed that the changing points of the slope occurred at the AGM : LFP ratio 68.63 : 31.37. This behavior was found in all three values of the current supply level as well as shown in the form of the relationship between capacitance efficiency and rated current in (Figure 4). It was found that the data was divided into two groups, with a noticeable point at the AGM:LFP ratio 68.63 : 31.37 showing a marked increase in capacity compared to other ratios, with the change in ratio of LFP batteries only 5.9%. Therefore, in conjunction with the initial cost of the system, it can be said that the ratio of 68.63 : 31.37 was the most suitable out of the seven ratios that were used to design AGM and LFP battery combined energy storage systems, and thus could be summed up in number that was easily calculated or an approximate ratio of 70 : 30.

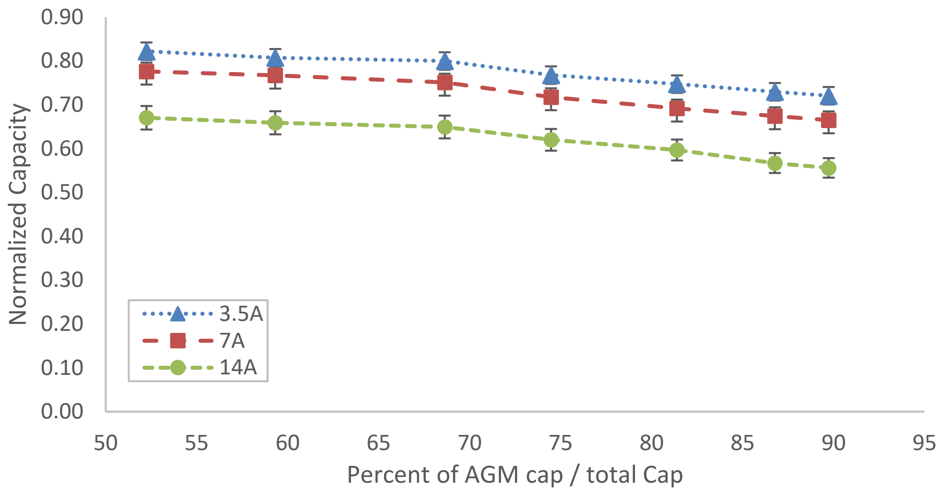


Fig. 3. Normalized Capacity of Difference AGM ratio in various discharge current

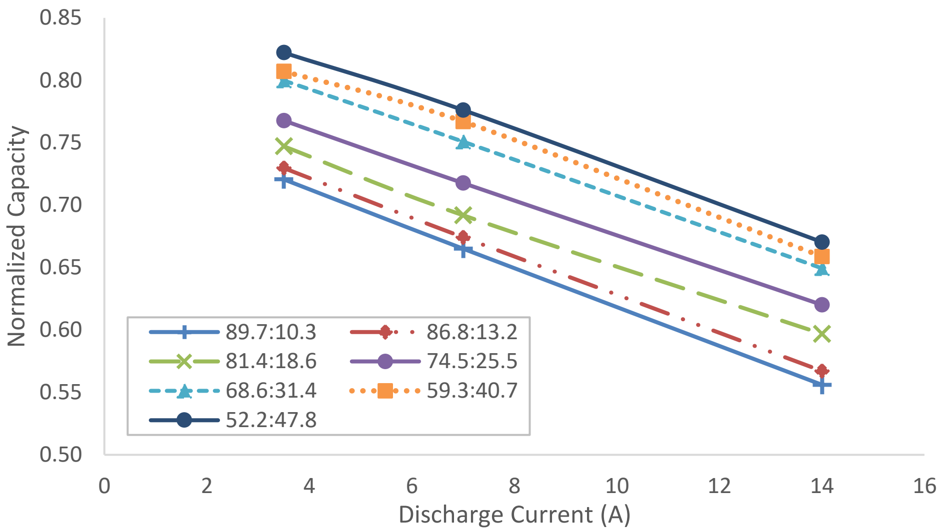


Fig. 4. Normalized Capacity of different discharge current in various AGM:LFP ratio

4.2 Results of Economic Evaluation

Experiments in this section consisted of a test for the life of each battery type and an additional test of system responsiveness when scaled to actual applications in response to office building and workloads integration with the solar power generation system.

Each type of battery was tested separately, discharged at different discharge rates as mentioned earlier in Table 3 with the end of discharge voltage set to 10.5 V for AGM battery and 2.6 V for LFP battery. This test simulates a worst case scenario which the battery is completely drained. The test results in terms of battery capacity decreasing with cycles are shown in Figure 5 and Figure 6 for AGM and LFP batteries, respectively.

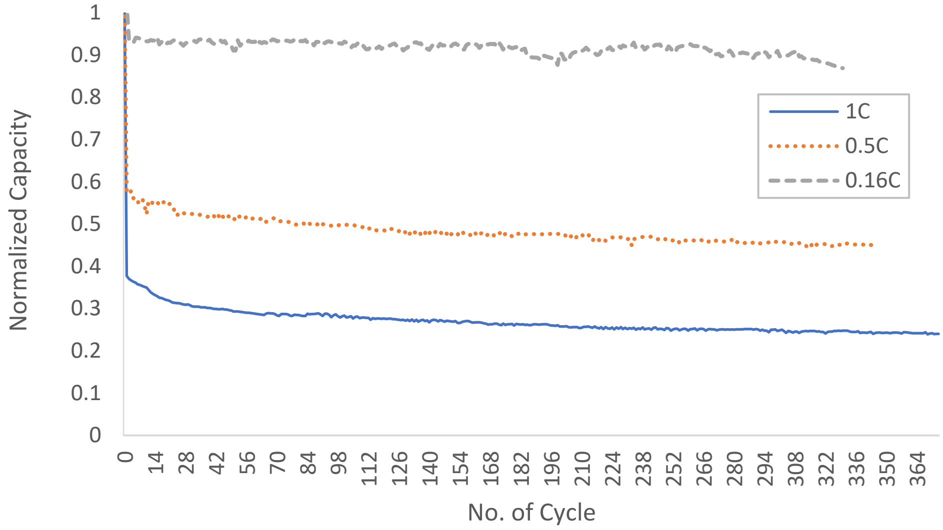


Fig. 5. Test results of AGM battery life span

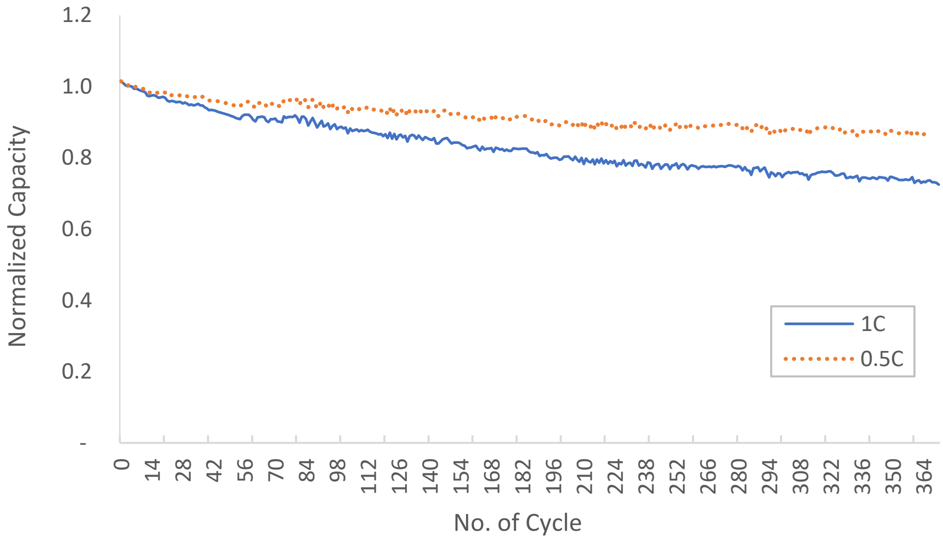


Fig. 6. Test results of LFP batter lifespan

Since usable storage capacity of AGM battery has high variation towards the ratio of electrical current discharged, the actual storage capacity of the battery cannot be seen for consideration of battery EOL. Therefore, the battery's storage capacity is measured based on a 20-hour rate discharge rate according to the storage capacity test information by the manufacturer. Measurement is performed every 50 charge-discharge cycles of AGM battery as seen in Figure 7.

Based on the evaluation of battery lifespan using EOL criterion or the number of cycles the batteries cannot produce an electrical current at 80% of the battery capacity expressed in Ampere-Hour (Ah), it was found that LFP battery had 1 year lifespan with a 1C discharge rate, and its lifespan is longer when a discharge rate is lower. In terms of AGM battery, usable storage capacity shall vary directly to a discharge rate. Consequently, it is necessary to perform a repeated test with reference to the 20hr. rate specified by manufacturers. In this test, the discharge rate was constant at 0.05C in every 50 cycles of the charge-discharge to measure correct usable capacity. Figure 7 shows AGM battery lifespan, 200 cycles (according to EOL conditions). Consideration given to 0.2C used to test usable capacity efficiency at 92% usable capacity found if the discharge rate is limited or the operations are well controlled, its lifespan can be extended about 100%.

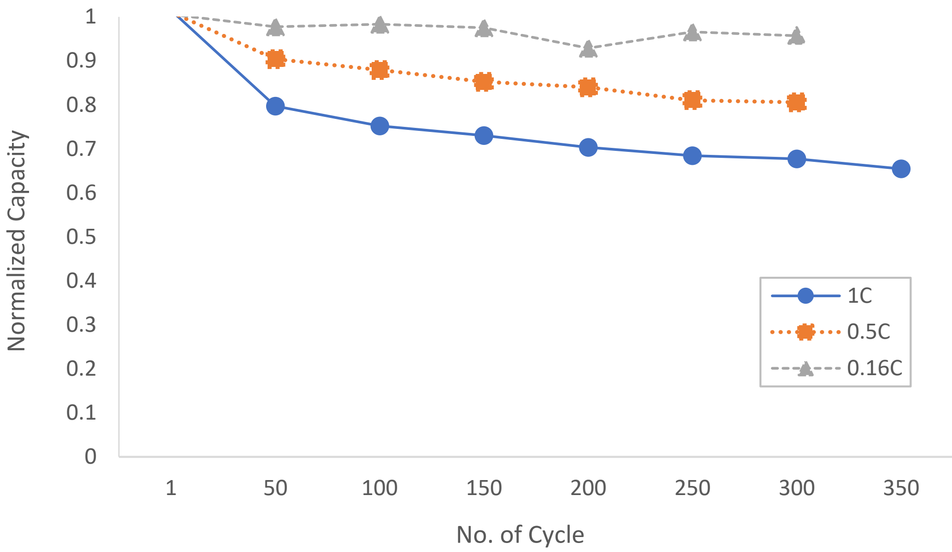


Fig. 7. Test results of AGM battery lifespan from the repeated test based on a 20hr. discharge rate

The above-mentioned tests shall be taken into consideration when a battery has a lower voltage than the end of discharge voltage or compared to a battery that has discharged its full capacity, or DoD is 100% in both types of batteries, contributing to shorter lifespan than normal. When the discharge rate of a battery is controlled, no more than 80% DoD, its lifespan shall be extended. Compared to test results of LFP battery manufacturers, its lifespan is 3,000 cycles, based on a limited discharge rate, and AGM battery lifespan is 2,700 cycles, based on a limited discharge rate. The lifespan can be extended by the limitation of the depth of discharge as well.

As part of the actual response test, the size of the energy storage system and the building's power requirements should be assessed appropriately as the discharge rate and depth of discharge are both factors that affect usable capacity and service life, respectively. Therefore, this research investigated the proportions to a total capacity of 100kWh and to maintain the same 70:30 ratio, 70 kWh AGM batteries and 30 kWh LFP batteries integration with 50 kW rooftop solar power system and office building load pattern of Department of Physics, Naresuan University. The average electrical power consumption of the office building is 253 kWh/day.

However, the operating conditions and the depth of discharge brought about some errors in lifespan estimation. Therefore, the discharge time and energy under operating conditions were determined based on statistical data by collecting solar energy value all day from the 50kW rooftop solar power system at Faculty of Science, Naresuan University with the frequency of 1 minute time series data, throughout 30 days, during 5 June to 5 July 2021 (it is in the rainy season which may most affect electricity generation of the solar power system). The frequency is considered under the condition that electric power changes more than 10% of the installed production capacity in 1 minute, which can be seen in Table 6.

Table 6
Solar power fluctuation within 30 days at Naresuan University

Variables	Solar power fluctuation within 30 days		
	Minimum value	Maximum value	Average
Frequency (time per hour)	4	45	24
Period (minute per time)	1	80	6.5
Decreased electric power (%)	10	90	28
Energy produced per day (kWh)	66	226	184

Based on battery specifications, LFP operation was considered in the day time to maintain stability of electrical energy since there might be fluctuation from the solar power system for electricity generation related to frequency of charge and discharge cycles. According to Table 5, the averaged solar energy lost due to fluctuations was 51.52 kWh per day or calculated to discharge electric power 5.72 kW on the average (9 hrs. day-time). Calculation of the average electrical energy produced per day found there was electrical energy left enough to charge electricity back to the energy storage system. In other words, LFP battery consumed energy around 20% to respond to the fluctuation of the solar power system.

AGM had the lower average lifespan than LFP battery; therefore, it was designed to operate in response to high demands of electrical energy only. Consideration of the average demand of electrical energy of office building at 253 kWh/day when electrical energy was produced 184 kWh on the average, energy needed from the energy storage system was 69 kWh. With such power demands, AGM batteries cannot work alone. In this system, the LFP battery works as an add-on to provide such power by limiting the current for the AGM battery and adjusting the cut-off voltage to stop the supply current.

As the evaluation took place in the situation with high fluctuation of solar power, it was unable to bring electrical energy left from the operations to fully charge the energy storage system, making the situation evaluation per cycle of operation at 10% to 85% DoD per cycle with the 0.5C and 0.2C for LFP and AGM, respectively. When compared to the results of the battery life test in the lab, the lifetime of AGM at 0.2C discharge rate and LPF at 0.5C discharge rate are similar. Compared to manufacturers data for both batteries, life expectancy differs from the technical data sheet of 6% and 10% for LFP and AGM batteries, respectively. Any discrepancies may arise from the temperature during testing. Thus, an initial EoL life expectancy of a hybrid energy storage system can be assessed at 4 years at the assessed operating situation and current rating. When compared to systems that use a 100 percent LPF system, the discharge rate is lower, and the lifespan is projected to be around 7 years.

For the cost comparison, Table 7 shown the comparison of pure LFP system and hybrid system using pure LPF as reference. According to the aforesaid mentioned situation, capacity rating of the hybrid energy storage system at 100 kWh with the ratio of AGM: LFP at 70:30. On the economical view, the levelized Cost of Electricity (LCOE) is the effective factor to compare in term of lifetime costs and energy production. As for cost estimation of electricity generation from solar power system in conjunction with the hybrid energy storage system, it can be estimated from the lifespan of the system at 20 years. The cost of the system across the lifespan including maintenance, system management, and battery replacement cost was 17,050,250.00 THB (at the exchange rate of 35THB / 1USD), generating electricity 1,375,857.81 kWh throughout the lifespan. Deterioration rate of solar panels was 1%. According to a study conducted by Jordan *et al.,* [15], deterioration rate of silicon solar panels was 0.81-0.69% on the average. According to time value of money formula at 7%, electrical energy value was 11.52 baht/kWh. The major advantage of hybrid energy storage is costs which are 47.5 percent less than a pure LFP system to start a project with only 27.8 percent more to calculate lifetime. The fact that project start-up costs can be reduced by almost half that of an LFP-only energy storage system raised concern in the view of operators due to the high cost of energy storage technology, enabling decision-making to implement the system to be easier. However, the preliminary assessment did not assess the cost savings of demand charge and did not take into account the cost of batteries needed to be replaced during the system's lifespan, which can be adjusted downward due to market demand and production technology, as a result, the lifetime cost of a true hybrid energy storage system could be further reduced.

Table 7
Comparison between ESS type on economical aspect

ESS	Starting Cost (ratio)	Lifetime Cost (ratio)	LCOE (THB/kWh)
Pure LFP	1	1	9.01
Hybrid @ 70: 30	0.525	1.278	11.52

5. Conclusion

Usable capacity efficiency was the most influential key factor as it related to the ratio of each type of battery reflecting the start-up cost of the project. The test of usable capacity efficiency of the operating system with 7 ratios of AGM and LFP batteries and a dummy load to simulate electrical load at 3.5 A, 7 A, and 14 A. Results show that increasing the ratio of high-efficiency batteries for LFP would increase the usable capacity efficiency as well. However, when observing the results of the in-depth experiment, a clear segmentation range of active capacitance was found at a ratio of 68.63 : 31.37 or an approximately 70 : 30 ratio. Compared to those with inferior capacity-efficiency groups, this ratio was found to increase the ratio of LFP batteries only by 5.9%, to a ratio which reduced project start-up costs by 47.5%.

Economic cost-effectiveness, consisting of individual battery life test and additional system responsiveness test as it scaled to real applications to respond to office building loads and integrate with solar power generation systems were investigated. In relation to battery lifespan, referred to the office building load pattern with the installation of solar panels on the rooftop and the evaluation was performed in the situation of high fluctuation of solar power, electrical energy left from the operations could not be used to fully charge the energy storage system, the situation evaluation per cycle of the operations was 10% to 85% DoD per cycle. It can be estimated that the EoL for hybrid energy storage is about 4 years lifespan with the 0.5C and 0.2C for LFP and AGM respectively. Discharge rate is lower by comparing systems that use a 100 percent LPF system and the lifespan is approximately 7 years. Hybrid energy storage has low investment cost. Although the initial expenditure is 47.5 percent less than that of a pure LFP energy storage system, the lifetime is 27 percent longer. Furthermore, existing battery costs, the LCOE is too high to invest, government intervention or technology in order to reduce battery costs should be considered government regulation or technological advancements should be focused to reduce battery costs.

References

[1] Ministry of Energy. "Big picture of energy during January - March 2022." *Energy Policy and Planning Office, Ministry of Energy*. Accessed April 10, 2022.

[2] Bocklisch, Thilo. "Hybrid energy storage systems for renewable energy applications." *Energy Procedia* 73 (2015): 103-111. https://doi.org/10.1016/j.egypro.2015.07.582

[3] Arita, Hiroshi, Yohei Kawahara, Shoichi Hirota, and Kenji Takeda. "Large Format Hybrid Energy Storage System for Power Leveling." *Hitachi Chemical Technical Report* (2015): 20-21.

[4] Rahe, Christiane. *Lead-acid Batteries and Lithium-ion Batteries in parallel Strings for an Energy Storage System for a Clinic in Africa*. No. FZJ-2017-02842. Helmholtz-Institut Münster Ionenleiter für Energiespeicher, 2016.

[5] Rand, D. A. J., P. T. Moseley, J. Garche, and C. D. Parker. *Valve-Regulated Lead-Acid Batteries*. Elsevier, 2004.
[6] Jiajitsawat, Somchai, et al. *The Development of Energy Storage System for Photovoltaic System: Research Report*. Enconfund, P-17-50440. 2019.
[7] Peukert, W. "Über die abhänigkeit der kapazität von der entladestromstärke bei." *Bleiakkumulatoren. Elektrotechnische* 27 (1897): 287-288.
[8] Omar, Noshin, Peter Van den Bossche, Thierry Coosemans, and Joeri Van Mierlo. "Peukert revisited-Critical appraisal and need for modification for lithium-ion batteries." *Energies* 6, no. 11 (2013): 5625-5641. https://doi.org/10.3390/en6115625
[9] Tesla. "Tesla Powerwall Limited Warranty (USA)." *Tesla*. April 19, 2017.
[10] SAFT. "Lithium-ion Battery Life: Solar Photovoltaic (PV) - Energy Storage System (ESS)." *SAFT*. Accessed April 18, 2022.
[11] Wood, Eric, Marcus Alexander, and Thomas H. Bradley. "Investigation of battery end-of-life conditions for plug-in hybrid electric vehicles." *Journal of Power Sources* 196, no. 11 (2011): 5147-5154. https://doi.org/10.1016/j.jpowsour.2011.02.025
[12] Albright, Greg, Jake Edie, and Said Al-Hallaj. "A Comparison of Lead Acid to Lithium-ion in Stationary Storage Applications." Altenergymag. December 4, 2012. https://www.altenergymag.com/content.php?post_type=1884.
[13] Avelar, Victor, and Martin Zacho. "Battery Technology for Data Centers: VRLA vs. Li-ion." *International Journal of Science and Innovative Technology* 1, no. 1 (2018): 76-87.
[14] Powertech. "Lithium LiFePO4 vs Lead-Acid cost analysis." *PowerTech*. Accessed May 31, 2022.
[15] Jordan, Dirk C., Sarah R. Kurtz, Kaitlyn VanSant, and Jeff Newmiller. "Compendium of photovoltaic degradation rates." *Progress in Photovoltaics: Research and Applications* 24, no. 7 (2016): 978-989. https://doi.org/10.1002/pip.2744