Comparative Life Cycle Cost Analysis Of Off-Grid 200 KW Solar-Hydro Power Plant With Pumped Water Storage And Solar Power Plant With Battery Storage Mechanism

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***Abstract*— In this paper, comparative life cycle cost analysis of an off-grid 200 kW solar-hydro power plant with Pumped Water Storage (PWS) and solar power plant with battery storage mechanism is presented. The study was based on the available system sizing data obtained for the two power plants along with some requisite economic data needed for the life cycle cost analysis of the plants. Each of the 200 kW power plants is assumed to have a daily load demand of 4,800 kWh as it supplies power over the period of 24 hours every day. Specifically, the initial investment cost, life cycle maintenance cost, life cycle replacement cost, and unit cost of energy were determined for each of the two power plants. The Simulink model for the life cycle cost analysis for both plants was developed and the analysis was performed using MATLAB software. The results showed the initial cost of investment for the solar-hydro power plant with Pumped Water Storage (PWS) is more than two times that of the solar power plant with battery storage mechanism. Also, the unit cost of energy for the plant with PWS isN34.88 while that of the unit cost of energy for the solar power plant with battery storage is N243.21.In all, the solar-hydro system with pumped water storage PWS gave a unit energy cost that is about 14.3% of the unit energy cost for the solar (PV) power system with battery storage. Essentially, the study demonstrated that it is more economical to implement solar-hydro system with Pumped Water Storage (PWS), especially for bulk energy supply system.**

Keywords— Life Cycle Cost Analysis, Off-Grid Power Plant, Solar-Hydro Power Plant, Pumped Water Storage, Solar Power Plant, Battery Storage Mechanism, Micro-Hydro Power Plant, Unit Cost Of Energy

I. INTRODUCTION

The rapid integration of intermittent renewable energy sources into electrical power generation has raised the interest of scholars in electrical energy storage systems [1,2,3]. The recent report by Sustainable Energy for all Action Agenda, approved by the National Council on Power (NACOP), affirmed that Nigeria's target is to generate 30% share of her energy mix from renewable energy sources by the year 2030 [4]. The International Energy Agency (IEA) in her 2013 World Energy Outlook anticipated substantial growth in the share of renewable energy available in the total electricity generation, from 6.9% in 2011 to 23.1% by 2035 within the European Union (EU) [5]. Correspondingly, the US Department of Energy in collaboration with industry, academia, and government institutions have acknowledged energy storage systems as the key technology, that will increase the reliability, performance, and competitiveness of electricity generation and transmission in the electric grid and in standalone systems [6]. Pumped water storage (PWS) is at the fulcrum of electrical energy storage systems.

Many researchers view PWS as the solution to the challenges associated with high penetration of renewable energy sources (RES) into electrical power generation. Intermittent RES introduce another level of uncertainty to power systems [7]. Deele, Ozuomba, & Okpura [8] asserted that PWS technology is commercially and technically mature to provide a cost-effective solution for bulk energy storage. Furthermore, a wide range of studies address the technical characteristics of PWS and its growing application in balancing the grid for demand-driven fluctuations and balancing generation-driven fluctuations including the contributions by [9,10,11] among others. Kaldellis, Zafirakis, & Kavadias [12] carried out a comparative techno-economic analysis of energy storage systems for autonomous electrical networks for an island. The study investigated the possibility of utilizing appropriate energy storage systems to realize both increased

RES power stations presence and optimal operation of the prevailing thermal power stations. The focus of the study was to, reduced the cost of energy generation through the introduction of RES into the electrical network while maintaining minimal environmental impact.

In any case, technical assessment of large-scale energy storage facility is not always the principal requirement for evaluating feasibility of PWS investment, judging from the investors' perspective. Rather, it is the economic viability and the expected price volatility that is viewed as topmost requirement. PWS is commercially mature storage technology and the only commercially proven large-scale energy storage technology [13]. Economic viability of energy storage systems have been conducted by many scholars but commercial viability of PWS cannot be easily generalized, as it is a site-specific technology [13,14]. Based on the foregoing, there is apparent lack of adequate economic model to establish the commercial viability of PWS in Nigeria. To contribute to addressing this seeming obstacle, this paper provides a comparative life cycle cost analysis of off-grid 200 kW solar-hydro power plant with pumped water storage and solar power system with battery storage mechanism.

Life cycle costs is defined in [15] as "cradle-to-grave" expenditures encapsulated as an economic model of estimating substitutes for equipment and projects. Life Cycle Cost (LCC) of a system (product) is the overall cost of obtaining and utilizing the product over its entire life span. Furthermore, LCC is the total cost of procurement and ownership. The operational, maintenance and disposal cost for repairable systems can vary from10 to 100 times the cost procurement [16].

The huge potential of PWS in Nigeria have been largely untapped perhaps due to absence of a reliable economic model. The focus of this study is to develop an economic model that will stimulate the development and commercial implementation of PWS as well as unmask the economic viability of PWS in Nigeria. This papers demonstrates that PWS is more economical than the battery storage system especially for bulk power generating system.

II. METHODOLOGY

In this paper, the life cycle cost analysis of both solar-hydro power plant with PWS technology and solar power plant with battery storage mechanism are conducted. The life cycle cost and unit cost per kWh of the two systems are evaluated in six simple steps. The steps include;

i. Specification of the life span of each component of the system
ii. Estimate the cost of procurement and installation of the various components
iii. Estimation of the cost of operation and maintenance of the systems
iv. Estimation of the replacement cost of the components
v. Determination of the life cycle cost of the system
vi. Determination of the unit cost per kWh of the system.

Some key economic parameters used in the life cycle cost analysis are as follows:

i. Inflation rate April, 2019 (E_r) = 11.30% (CBN, 2019).
ii. Discount Rate (D_r) = 10.5%
iii. Life cycle period (N). = 50 years
iv. Life span of reservoirs = 100 years [17].
v. Life span of Hydro-Turbine = 30 years [18].
vi. Life span of DC submersible pumps = 15 years [20].
vii. Life span of steel pipe = 70 years [17].
viii. Life span of PV module = 25 years [19]
ix. Life span battery = 5 years [21].
i. Life span inverter = 10 years
ii. Life span charge controller = 10 years

A. LIFE CYCLE COST ANALYSIS OF THE SOLAR-HYDRO POWER PLANT WITH PUMPED WATER STORAGE

The six steps enumerated in the previous section are applied in the life cycle cost (lcc) analysis of the solar-hydro power plant with pumped water storage. the capital investment in the plant with the pws is shown in Table1.

Table 1: Initial investment cost for 200 kW solar –hydro plant with PWS

S/N	Component/Item	Qty	Rate (₦)	Amount (₦)
1	Hydro Turbine 200kW, 230/400V	1	3,240,000	3,240,000
2	PV module 24 Vdc	1960	62,000	121,520,000
3	Reservoir 95 x 95 x 24 m	2	550,000,000	1,100,000,000
4	Pump 168 Vdc, 59.2 kW	10	270,000	2,700,000
5	Steel Pipe 0.7m diameter	65 m	30,000	1,950,000
6	Installation, logistics, support structure etc.15% of the cost components.	lot		184,411,500
	Total	**1,413,821,500**		

Life Cycle Maintenance Cost (LCMC) of the Solar-Hydro System with PWS

Maintenance is important to the life of any turbine/generation primarily to ensure a flawless operation and to enhance the longevity of the system. Life cycle maintenance cost of the solar-hydro system is an amount of money set aside for minor preventive maintenance which is between 1% to 4% of the initial investment cost per annum [5];

The operation and the maintenance cost of the Solar-Hydro System with PWS is given as;

$$\mathrm{LCMC} = \mathrm{ANMC}\left\{\left(\frac{1+\mathrm{E}_r}{\mathrm{D_r}-\mathrm{E_r}}\right)\left[1-\left(\frac{1+\mathrm{E}_r}{1+\mathrm{D_r}}\right)^{\mathrm{N}}\right]\right\} \quad (1)$$

where, LCMC is the life cycle maintenance cost, ANMC is the annual maintenance cost, $E_r$is the escalation rate, D_r is the discount rate, and N is the life cycle period. In this paper, 1.5% of capital cost was assumed for maintenance cost of the system per annum and it is classified as recurring cost. In this paper, the annual maintenance cost(ANMC) is given as;

$$\mathrm{ANMC} = \left(\frac{1.5\%}{100}\right)\mathrm{IIC} \quad (2)$$

Where IIC is the Initial investment cost. According to Table 1, for the 200 kW solar –hydro plant with PWS the IIC is ₦1, 413,821,500, hence;

ANMC = 1.5% x ₦ 1,413,821,500 = ₦ 21,207,322.5

$$\therefore\ \mathrm{LCMC} = 21{,}207{,}322.5 \text{ x } \left\{\left(\frac{1+0.113}{0.105-0.113}\right) \text{ x } \left[1-\left(\frac{1+0.113}{1+0.105}\right)^{50}\right]\right\} = ₦1,281{,}431{,}255$$

Life Cycle Replacement Cost (LCRC) of the Solar-Hydro System with PWS

The life cycle replacement cost for the solar-hydro system with PWS was obtained by the summation of the life cycle replacement cost of the individual component that requires replacement. Considering the life span of each component of the PWS system and the life cycle period, the replaceable components are the PV modules, hydro turbine and submersible pumps. The life cycle replacement cost is given as;

$$\mathrm{LCRC} = \mathrm{ANRC} \text{ x } \left\{\left(\frac{1+\mathrm{E}_r}{\mathrm{D_r}-\mathrm{E_r}}\right) \text{x} \left[1-\left(\frac{1+\mathrm{E}_r}{1+\mathrm{D_r}}\right)^{\mathrm{N}}\right]\right\} \quad (3)$$

where, LCRC is the life cycle replacement cost, ANRC is the annual replacement cost, E_r is the escalation rate, D_r is the discount rate, and N is the life cycle period.

The life span of a good monocrystalline PV module is 25 years. From Table 1, the initial cost of PV modules is ₦121, 520,000, with an inflation rate of 9.8%, the cost for 25 years is ₦133, 428,960. The cost of installation of the PV modules was estimated to be₦ 6,500,000. Then, the annual replacement cost of the panels was calculated as follows:

$$\mathrm{ANRC} = \frac{\text{Replacement cost } + \text{Installation cost}}{\text{Period of replacement}} \quad (4)$$

$$\mathrm{ANRC1} = \frac{133428960+6500000}{25} = ₦5,597158.4$$

A report prepared by Wieland (2010) opined that the average life span of a hydro turbine is about 30 years. From Table 1, the initial cost of a hydro turbine is ₦3,240,000 and with inflation rate as 9.8%, the cost of hydro turbine after 30 years will be 3,557,520. The installation cost of the hydro turbine is₦700,000. Hence;

$$\mathrm{ANRC2} = \frac{3{,}557{,}520\ +\ 700000}{30} = ₦141,917.33$$

Armstrong *et al.* (2017) stated that a well maintained submersible pump has a life span of about 15 years. From Table 1, the initial cost of submersible pump is ₦2,700,000, with an inflation rate of 9.8%, the cost for 15 years is ₦2,964,600. The cost of installation of the pumps is estimated to be₦400, 000.

$$\mathrm{ANRC3} = \frac{2964600+400000}{15} = ₦224,306.67$$

Therefore,

$$\mathrm{ANRC} = \mathrm{ANRC1} + \mathrm{ANRC2} + \mathrm{ANRC3}$$

$$\mathrm{ANRC} = 5,\ 597158.4 + 141,917.33 + 224,306.67 = ₦5,963{,}382.4$$

$$\mathrm{LCRC} = 5,963{,}382.4 \text{ x } \left\{\left(\frac{1+0.113}{0.105-0.113}\right) \text{ x } \left[1-\left(\frac{1+0.113}{1+0.105}\right)^{50}\right]\right\} = ₦360,331{,}418.1$$

Cost per kWh for the Solar-Hydro Power System with PWS

The life cycle cost per kWh of solar-hydro system is given as;

$$\mathrm{LCC.kWh^{-1}} = \frac{\mathrm{CC+LCFC+LCMC+LCRC}}{365(\mathrm{N})(\mathrm{E_d})} \quad (5)$$

where$\mathrm{LCC.kWh^{-1}}$ is the life cycle cost per kWh, CC is the capital cost = ₦1, 413,821,500, LCFC is the life cycle fuel cost = ₦0.00, LCMC is the life cycle maintenance cost = ₦ 1,281,431,255, LCRC is the life cycle replacement cost = ₦360, 331,418.1, N is the life cycle period = 50 years andE_d is the daily energy demand on the power system. In this paper, the 200 kW power plant is expected to operate 24hours every day. As such, the daily energy demand is 24h x 200kW = 4800 kWh per day. Hence,

$$\mathrm{LCC.kWh^{-1}} = \frac{1413821500+1{,}281{,}431{,}255+360{,}331{,}418.1}{50 \text{ x } 365 \text{ x } 4800} = ₦34.88\ \ \mathrm{kWh^{-1}}$$

B. LIFE CYCLE COST ANALYSIS OF THE PV POWER SYSTEM WITH BATTERY STORAGE

The capital investment for the PV system with battery storage is shown in Table 2.

Table 2: Initial investment cost for 200 kW PV Power System with Battery Storage

S/N	Component/Item	Qty	Rate (₦)	Amount (₦)
1	PV module 24 Vdc	763	62,000	47,306,000
2	Deep cycle Battery 200Ah 12 Vdc	5908	80,000	472,640,000
3	Charge Controller	1	1,100,000	1,100,000
4	Inverter 260 kW	1	8,000,000	8,000,000
5	Installation, logistics, support structure etc. 5% of the cost components.	lot		26,452,300
Total				**555,498,300**

Life Cycle Maintenance Cost (LMC) of the PV Power System with Battery Storage

In this paper, 1.5% of capital cost was assumed for maintenance cost per annum of the solar power plant with battery storage and it is classified as recurring cost. Similar to the case of the solar-hydro system with PWS, the operation and maintenance cost for the PV power system with battery storage was computed using Equation 1 (which is $\mathrm{LCMC} = \mathrm{ANMC}\ \left\{\left(\frac{1+\mathrm{E}_r}{\mathrm{D_r}-\mathrm{E_r}}\right)\left[1-\left(\frac{1+\mathrm{E}_r}{1+\mathrm{D_r}}\right)^{\mathrm{N}}\right]\right\}$). Hence, for the PV power system with battery storage;

$$\mathrm{ANMC} = 0.015 \text{ x ₦ } 555{,}498{,}300 = \text{₦ } 8{,}332{,}474.5$$

$$\mathrm{LCMC} = 8{,}332{,}474.5 \text{ x } \left\{\left(\frac{1+0.113}{0.105-0.113}\right) \text{ x } \left[1-\left(\frac{1+0.113}{1+0.105}\right)^{50}\right]\right\} = \text{₦ } 503{,}481{,}439.2$$

Life Cycle Replacement Cost (LCRC) of the PV Power System with Battery Storage:

The life cycle replacement cost for the solar power plant with battery storage is the summation of the life cycle replacement cost of the individual component that requires replacement. Considering the life span of each component of the Solar power plant with battery storage and the life cycle period, all the component part of Solar power plant with battery storage are replaceable. Similar to the case of the solar-hydro system with PWS, the life cycle replacement cost for the PV power system with battery storage was computed using Equation 3 (which is $\mathrm{LCRC} = \mathrm{ANRC} \text{ x } \left\{\left(\frac{1+\mathrm{E}_r}{\mathrm{D_r}-\mathrm{E_r}}\right) \text{ x } \left[1-\left(\frac{1+\mathrm{E}_r}{1+\mathrm{D_r}}\right)^{\mathrm{N}}\right]\right\}$). The life span of a good monocrystalline PV module is 25 years. From Table 2, the initial cost of PV modules is ₦47, 306,000 with an inflation rate of 9.8%, the cost for 25 years is ₦51, 941.988. The cost of installation of the PV modules was estimated to be ₦ 7,000,000. Then, the annual replacement cost of the panels is given as $\mathrm{ANRC_{pv}} = \frac{51941988 + 7000000}{25}$ = ₦2, 357,679.52

Battery Universe Blog, (2017) stated that a well maintained deep cycle battery has a life span of about 5 years. From Table 2, the initial cost is₦472, 640,000, with an inflation rate of 9.8%, the cost for 5 years is ₦518, 958,720. Then, the cost of installation of the battery was estimated to be ₦ 3,200,000. Hence;

$$\mathrm{ANRC_{bat}} = \frac{518{,}958{,}720 + 3200000}{5} = \text{₦}104{,}431{,}744$$

With reference to other works on life cycle cost analysis of PV systems, a life span of 10 years was assumed for both charge controller and inverter. Hence, their annual replacement cost is calculated as follows:

$$\mathrm{ANRC_{cc}} = \frac{1207800 + 310000}{10} = \text{₦ } 151{,}780$$

$$\mathrm{ANRC_{iv}} = \frac{8784000 + 450000}{10} = \text{₦ } 923{,}400$$

Therefore,

$$\mathrm{ANRC} = \mathrm{ANRC_{pv}} + \mathrm{ANRC_{bat}} + \mathrm{ANRC_{cc}} + \mathrm{ANRC_{iv}}$$

$$\mathrm{ANRC} = 2{,}357{,}679.52 + 104{,}431{,}744 + 151{,}780 + 923{,}400 = \text{₦ } 107{,}864{,}603.5$$

$$\mathrm{LCRC} = 107{,}864{,}603.5 \text{ x } \left\{\left(\frac{1+0.113}{0.105-0.113}\right) \text{ x } \left[1-\left(\frac{1+0.113}{1+0.105}\right)^{50}\right]\right\} = \text{₦}6{,}\ 517{,}610{,}803$$

Cost per kWh for the PV Power System with Battery Storage:

Similar to the case of the solar-hydro system with PWS, the life cycle cost per kWh for the PV power system with battery storage is computed using Equation 5 which is ;

$$\mathrm{LCC.\,kWh^{-1}} = \frac{\mathrm{CC} + \mathrm{LCFC} + \mathrm{LCMC} + \mathrm{LCRC}}{365(\mathrm{N})(\mathrm{E_d})}$$

Where CC is the capital cost = ₦555,498,300, LCFC is thelife cycle fuel cost = ₦0.00, LCMC is thelife cycle maintenance cost = ₦503,481,439.2, LCRC is the life cycle replacement cost = ₦6, 517,610,803, N is the life cycle period = 50 years and$\mathrm{E_d}$ is the daily energy demand on the power system. In this paper, the 200 kW power plant is expected to operate 24hours every day. As such, the daily energy demand is 24h x 200kW = 4800 kWh per day. Hence;

$$\mathrm{LCC.\,kWh^{-1}} = \frac{555{,}498{,}300 + 503{,}481{,}439.2 + 6{,}517{,}610{,}803}{50 \text{ x } 365 \text{ x } 1707} = \text{₦}243.21 \text{ kWh}^{-1}$$

The determination of the life cycle unit cost of energy for both the solar-hydro system with PWS and the

PV power system with battery storage is shown Simulink model in Figure 1.

III. RESULTS AND DISCUSSION

A. Results of the life cycle cost analysis of the solar-hydro system with PWS and the PV power system with battery storage

From the result in Table 3, it was observed that, the initial cost of investment for the solar-hydro power plant with PWS is more than two times that of the PV system. Similarly, the 50 years life cycle maintenance cost of the Plant with the PWS is equally more than two times that of the solar power plant with battery storage but the life cycle replacement cost of the Solar power plant with battery storage outweighs the total cost of investment, maintenance and replacement of the PWS system. The replacement cost is surprisingly high because of the short life span of the component parts of the solar power plant with battery storage especially the battery that has to be replaced 10 times within the study period. This fact agrees significantly with the statement of problem which clearly stated that, the relatively short life span of battery has made it unattractive for bulk energy storage.

Furthermore, it was noted that the unit cost of energy for the solar system is more than five times the cost per kWh of the PWS system. This is so in spite of the relatively high initial cost of investment for the PWS system.

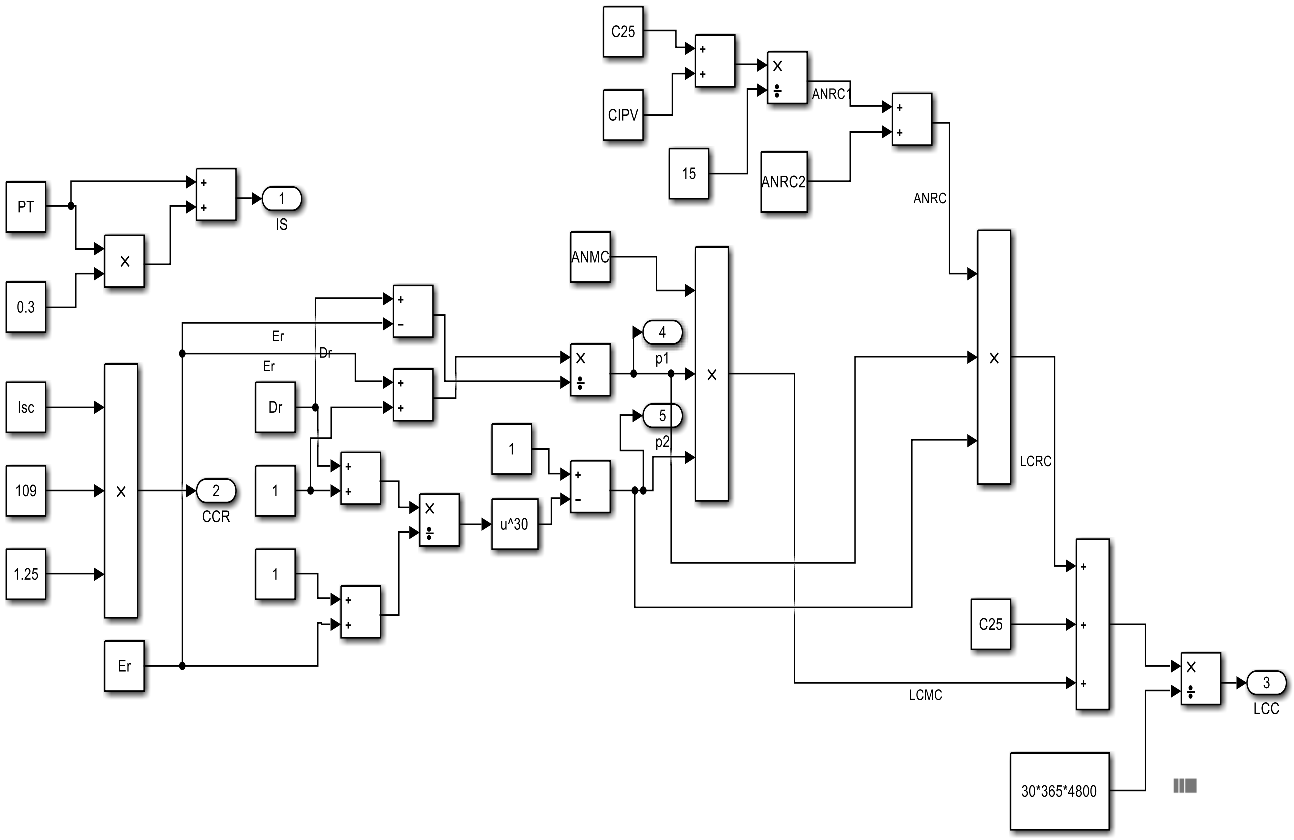

Figure 1: Simulink model for the life cycle cost analysis and unit cost of energy for the solar-hydro system with PWS and the PV power system with battery storage

Table 3: Life cycle cost of the solar-hydro system with PWS and the PV power system with battery storage

S/N	Description	Plant with the PWS (₦)	Solar power plant with battery storage (₦)
1	Initial cost of investment	1,413,821,500	555,498,300
2	Maintenance cost	1,281,431,255	503,481,439.20
3	Replacement cost	360, 331,418.1	6, 517,610,803
4	Cost per unit Kwh	34.88	243.21

The report by [22] agreed with the results displayed in Table 3, wherein it asserted that, pumped water storage (PWS) technology is commercially and technically mature such that for large scale energy storage it can provide cost-effective solution. The PWS technology may have high initial investment, but it relatively long life span (more than 100 years) made it very attractive for bulk energy storage. This is not the same with battery storage, as it has relatively short life span (less than five years). The PSW technology has a low per unit cost of energy (see Table 3) when compared with the battery storage system, because battery storage requires frequent replacement and the cost of replacement is much. This result is consistent with the reports by [23,24,25] adopted similar position after comparing various storage means in terms of ratings came to a conclusion that PWS technology has high discharge time more than 100 hours and suitable for high rated power (400 to 4000 MW). It can take up to five day to discharge a PWS system depending on the reservoir capacity and the volumetric flow rate of the system.

B. Comparison of some Performance Indices between PV/Battery and PV/PWS Systems

Some basic and fundamental components of the two systems were compared within the 50 years study period and graphically presented in Figure 2. The battery and the reservoir perform the same function in the system under review, which is energy storage. The figure shows evidently that, the battery was replaced 10 times within the 50 years study period while the reservoirs where not changed due to its relatively long life span. The efficiency of battery drops to about 80% of its capacity after two years of use unlike the PWS system, similarly the recommended depth of discharge of battery is about 50% while that of PWS is about 20%. This implies that more stored energy is available for use in the case of PWS than battery system. These facts about battery and PWS are consistent with the report present by IHA (2019).

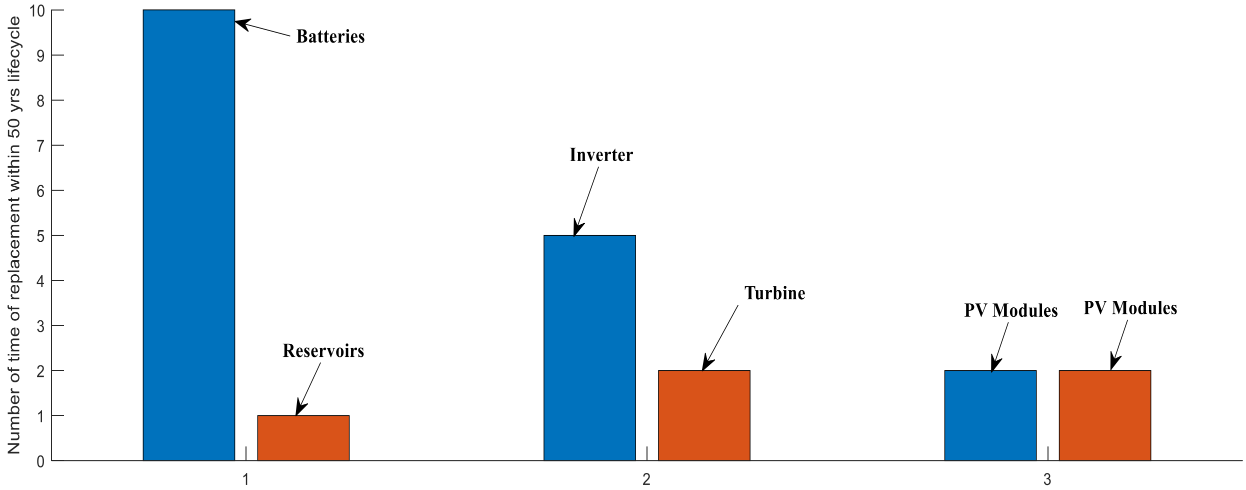

Figure 2: Comparison of three performance indices between battery and PWS systems

The inverter and the hydro turbine compared within the study period, the inverter in the battery system was replaced five times while the hydro turbine in the PWS system, which perform similar function with the inverter was changed only twice. The PV modules were replaced two times in both systems within the study period.

IV . CONCLUSION

Detailed life cycle analyses is presented for two different renewable energy plants, namely, the solar-hydro system with Pumped Water Storage (PWS) and the solar (PV) power system with battery storage. Initial investment cost, Life Cycle Maintenance Cost (LCMC), Life Cycle Replacement Cost (LCRC), cost per unit kWh are determined for each of the two power system. In all, the solar-hydro system with Pumped Water Storage (PWS) gave a unit energy cost that is about 14.3% of the unit energy cost for the solar (PV) power system with battery storage. Essentially, the study demonstrated that it is more economical to implement solar-hydro system with Pumped Water Storage, especially for bulk energy supply system,

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