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# Performance Analysis and Comparison of Batteries Using Off-grid PV System

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**Abstract:** Even though, at present, most of the Indian villages have been known to reach the '100% household electrification' mark, many remote villages in the desert and hilly areas receive electricity supply only for few hours in a day. After an immense awareness programme on usage of freely available solar energy, run by the government throughout the country, villagers have started using solar panels on their rooftops and other open spaces. However, to install a reliable and cost effective off-grid PV system, it is imperative to choose an efficient battery storage system. In this paper, we analyze three different battery types, viz. Advanced Lead Acid, Lithium Ion and Zinc Bromine Flow battery on the basis of their technical and economic performances, when used with an off-grid PV system. From the techno-economic analysis for a domestic load of 250 kWh/day and an agricultural load of 17.91 kWh/day, it was found that the LI batteries are the most favorable option for use with the designed off-grid PV system.

**Key words:** Advanced lead acid battery, lithium-ion battery, zinc bromine flow battery, NPC, state of charge.

## Introduction

It is observed that renewable sources can produce almost 80% of the world's electricity required as per a study done by International Renewable Energy Agency (IRENA) (Renewable Energy Statistics, 2018). Solar power and wind power can contribute to approximately 52% of the total generation. In that case, the energy storage system will serve as the centre of energy transition, serving the entire electricity system. If countries decide to increase the share of renewable energy sources by two times, the estimated electricity storage capacity is likely to triple by 2030.

As the importance and the need of electricity storage technologies has been realized more by the off-grid systems, the industry is working consistently on its cost cutting. The pumped-hydro storage has emerged as the largest single source of energy storage capacity nowadays. There is a minor reduction in the total installed cost as it is site-specific and not as modular as the other electricity storage technologies, which can be scaled down. A major fall of 35% will be seen in the cost of flywheels by 2030. Similarly, the Compressed Air Energy Storage (CAES) could see a cost decline of 17% by 2030. The Indian Energy Storage market growth is estimated to around 70 GW and 200 GWh by 2022 by the Indian Energy Storage Alliance. Out of 70 GW, almost 50% that is 35 GW of demand will come from solar and wind energy systems.

Electro-chemical storage has become the most rapidly developing market segments, though the present installed storage power capacity is about 1.9 GW. The electro-chemical battery storage market is full with lot of options. However, from the 2018 statistics, it was

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found that lithium ion (LI) batteries hold the largest share of the total installed capacity. Other batteries, such as Advanced Lead acid (LA), sodium sulphur and Flow batteries have also shown meager, but important, contributions.

Five different battery types, viz. LA, LI, Sodium-based, Nickel-based and flow, are normally used with the renewable energy systems. Out of the batteries mentioned above, sodium-based and nickel-based batteries are not considered in the study. The reason for this is that the sodium-based batteries, though using non-toxic materials (Kawakami et al., 2010) and having high energy densities, need an extra system required to ensure a high operating temperature, thereby increasing its high annual operating cost. Similarly, nickel-based batteries also suffer from some drawbacks such as the toxicity of nickel, whose decomposition may lead to environmental hazards (Lacerda et al., 2009). Moreover, the battery suffers from the memory effect, i.e. the maximum capacity can be rapidly decreased if it is repeatedly recharged. Therefore in the present work, the performance analysis of three batteries, LA (Achaibou et al., 2008; Mohammedi et al., 2016), LI (Anuphappharadorn et al., 2014; Mariaud et al., 2017) and flow using off-grid PV system is done for a village in the Jaisalmer district in Rajasthan.

## System Modelling

For the practical performance analysis comparison of the three batteries to be used with off-grid PV system, a simple system model shown in Figure 1 has been developed using HOMER software (Homer Energy). The model consists of a PV system with battery backup to be used for remote rural village of Jaisalmer. This village has an excellent annual average irradiance of 5.79 kWh/m$^2$/day. Three different batteries, viz. advanced lead-acid, Li-ion and flow batteries, are used one at a time with the PV system.

For the present loading conditions of 250 kWh/day and 34.99 kW peak load (load factor 0.33) and deferrable load of 17.91 kWh/day, a PV system of 90 kW and a converter of 45 kW is required. Table 1 shows the details of the electrical and agriculture load connected with the off-grid PV system. The performance comparison of the three different batteries is done on the basis of technical and economic metrics. HOMER software works on two optimization algorithms which are used in the present research that helps to obtain the most feasible solution.

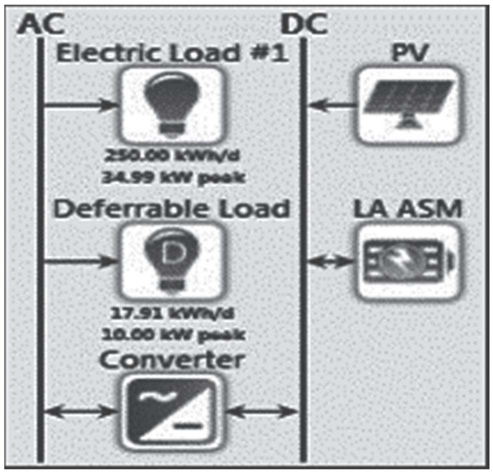


**Figure 1: PV-battery system model.**

The first algorithm, called 'Original Grid Search', checks the system configurations defined by the user and simulates all the feasible system configurations. The second one, called 'Proprietary Derivative Free' algorithm, is used to search for the least cost. Finally, a list of all possible configurations sorted by the Net Present Cost (NPC) is displayed to compare system design options. Three different costs as inputs are used for each component—Capital cost per kW, replacement cost per kW and Operation and Maintenance (O&M) cost per kW.

## Results

During simulation a nominal discount rate of 8% with an inflation rate of 2% and project lifetime of 25 years

**Table 1: Details of Load 1 connected with the off-grid PV system**

| *Load connected* | *Purpose* | *Components* | *Energy requirement* |
|---|---|---|---|
| Electrical load (Electric Load#1) | Domestic | Four LED tube lights (18 Watts each), 2 fans (75 Watts each), point for mobile charging (5 Watts) and a colour T.V. (100 Watts) | 250 kWh/day |
| Agricultural load (Deferrable load) | Water pumping | Three submersible pumps, each having capacity of 0.746 kW and drawing 40,000 litres of water to irrigate about 2.42 hectares of land working for eight hours daily | 17.91 kWh/day |

is considered. The technical and economic metrics are found for the three different battery types.

### Technical Metrics

The technical metrics for assessing the performance of batteries consists of the usable nominal battery capacity, expected lifetime, state of charge, storage depletion, losses, annual throughput and autonomy. Table 3 shows the technical performance metrics for different battery types. It is seen that the state of charge, and hence the expected lifetime, for advanced lead acid batteries is minimum as compared to the Li-ion and ZnBr flow batteries. The performance of Li-ion batteries and flow batteries is found to be superior over the advanced lead-acid battery, since they have a better expected lifetime due to lower storage depletion and losses over the project lifetime as shown in Figure 2. The technical competence of both Li-ion batteries and flow batteries is more or less same, so either can be used after analyzing the cost prospective, as shown in Table 2. Figure 3 shows that the battery capacity (kWh) required in case of LI battery is the least, as compared to the advanced LA and flow batteries. The state of charge for advanced lead-acid batteries is shown in Figure 4, for Li-ion batteries in Figure 5 and for the ZnBr flow batteries in Figure 6. From the figures, it is clear that ZnBr flow batteries have a better state of charge, as compared to Li-ion and advanced lead-acid batteries.

**Table 2: Component cost details for system model**

| *Component* | *Cost (in INR/kW)* | | |
|---|---|---|---|
| | *Capital* | *Replacement* | *O&M* |
| PV | 60,000 | 60,000 | 600 |
| Converter | 16,000 | 16,000 | 0 |
| LA battery | 18,000 | 18,000 | 180 |
| LI battery | 30,000 | 30,000 | 300 |
| Zn Br battery | 50,000 | 50,000 | 500 |

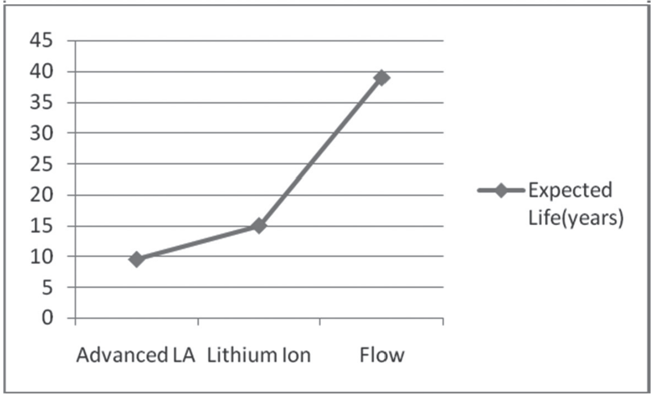


**Figure 2: Expected life in years for three different batteries for a community load of 250 kWh/day.**

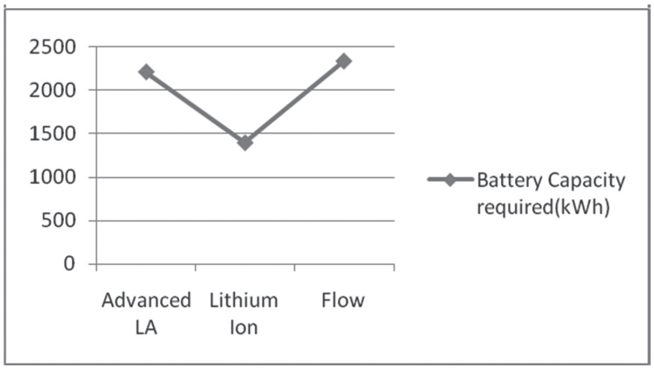


**Figure 3: Battery capacity requirement for a community load of 250 kWh/day.**

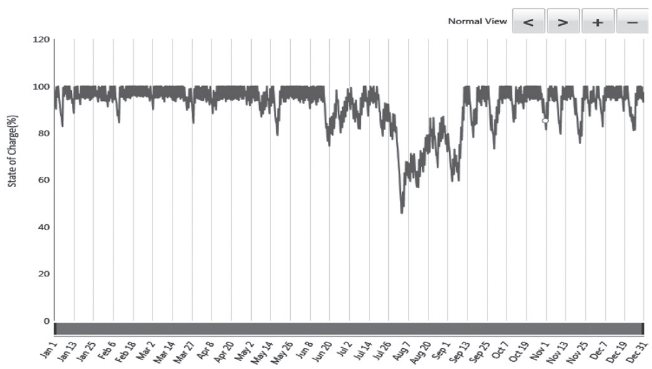


**Figure 4: State of charge for advanced LA batteries used in PV-battery model.**

**Table 3: Technical performance metrics for three different batteries**

| *Battery type* | *Nominal capacity (kWh)* | *Usable nominal capacity (kWh)* | *Expected lifetime (years)* | *Storage depletion (kWh/year)* | *Losses (kWh/year)* | *Annual throughput (kWh/year)* | *Autonomy (hours)* |
|---|---|---|---|---|---|---|---|
| Advanced lead acid | 2,215 | 1,329 | 9.58 | 223 | 8,785 | 55,637 | 158 |
| Lithium ion | 1,399 | 1,115 | 15 | 176 | 4,148 | 53,407 | 87 |
| Flow battery | 2,339 | 2,339 | 39 | 207 | 16,627 | 59,144 | 209 |

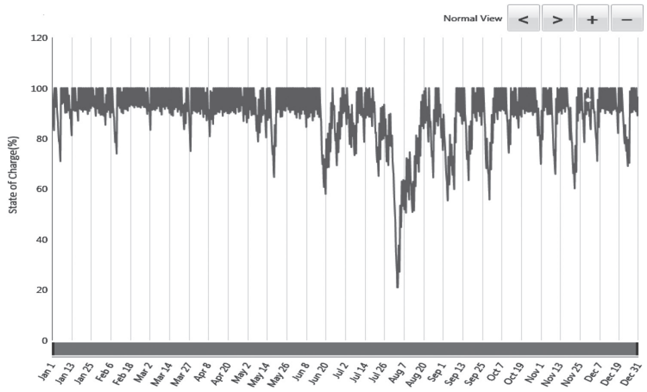


**Figure 5: State of charge for lithium ion batteries used in PV-battery model.**

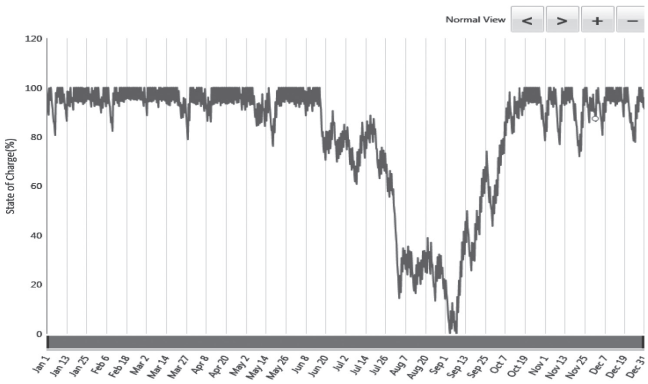


**Figure 6: State of charge for ZnBr flow batteries used in PV-battery model.**

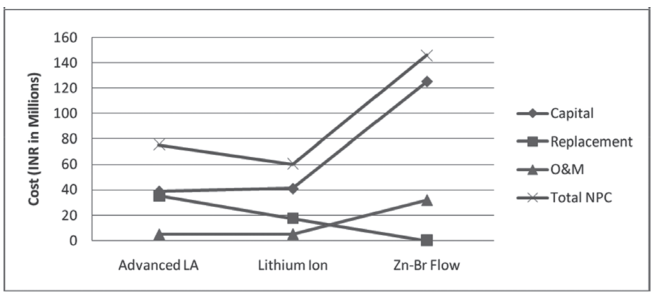


**Figure 7: Cost comparison for the three battery types used in PV-battery model.**

### Economic Metrics

The economic metrics for evaluation of a particular type of battery consists of the capital cost, replacement cost, operation and maintenance cost, and the salvage cost over the project lifetime. As shown in Figure 7, the capital cost for advanced lead-acid batteries is the least among the three battery types. The capital cost for Li-ion batteries slightly exceeds that for advanced lead-acid batteries, but is very less as compared to ZnBr flow batteries. However, since the operation and maintenance (O&M) cost for Li-ion batteries is minimum, the overall NPC for these batteries is low. The overall NPC for ZnBr flow batteries is the highest, and hence it is not recommended for the present loading conditions.

## Observations and Recommendations

From the observations made in the previous section, the following conclusions were derived for the considered load, i.e. a domestic load of 250 kWh/day and an agricultural load of 17.91 kWh/day, for the Jaisalmer district in Rajasthan, based on the technical and economic characteristics of Advanced LA, LI and flow batteries:

### Economics

(a) Flow batteries incur the highest initial capital cost due to the huge expenditure required for cell construction such that the electrodes and electrolytes can be placed separately. Moreover, flow batteries incur the highest O&M cost due to the requirement of pumps, sensors, flow and power management, and secondary containment vessels required for their operation. However, the initial capital cost is the least for Advanced LA batteries, followed by LI batteries. In terms of the O&M cost, both the aforementioned batteries are comparable.

(b) Flow batteries also have the highest total system NPC and LCOE, while the said quantities are the least for LI batteries, followed by Advanced LA batteries.

(c) A comparatively low cycle life (up to 3,000 cycles) as well as a low DoD (up to 60%) contributes to the reason for the advanced LA batteries having the highest replacement cost among the three considered batteries, followed by LI batteries which have a cycle-life of up to 4,000 cycles and DoD of up to 90%. Owing to their high cycle-life (up to 10,000 cycles) and 100% DoD, the flow batteries have the least replacement cost.

In view of the above, from the economics point of view, the off-grid PV system using LI batteries proves to be the most economical option for a domestic load of 250 kWh/day and an agricultural load of 17.91 kWh/day for the Jaisalmer district in Rajasthan.

### Technical

(a) An off-grid PV system using LI batteries was observed to require the least amount of battery capacity due to the high DoD and high cycle life of LI batteries. The battery capacity requirement of an off-grid PV system using advanced LA batteries is higher than that for the system with LI batteries. The battery requirement for HRES using flow battery was found to be the highest due to its lower efficiency.

(b) Flow batteries are found to have the highest battery lifetime (>20 years), followed by LI batteries (up to 15 years), while that for advanced LA batteries is found to be least (<10 years).

(c) LI batteries are found to have the least storage depletion, while that for the advanced LA and flow batteries is very high in comparison. Moreover, LI batteries are found to have the least losses, while that for advanced LA and flow batteries is approx. more than twice that for LI batteries. Hence, LI batteries achieve the highest annual throughput, followed by advanced LA batteries.

In view of the above, from the technical standpoints, LI batteries prove to be the most viable option for use with the designed HRES for the considered domestic and agricultural load for the Jaisalmer district in Rajasthan.

Therefore, it can be concluded from the above techno-economic analysis for a domestic load of 250 kWh/day and an agricultural load of 17.91 kWh/day LI batteries are the most favourable option for use with the designed off-grid PV system.

## Conclusion

In this paper, the performance of three different electrochemical cells, viz. Advanced LA, Lithium Ion and Flow battery, was analyzed and compared for a PV-BT system. To test the performance of the three considered battery types, the PV-BT system model was developed for a small village area in the Jaisalmer district of Rajasthan. Individual optimal sizing of the three considered battery types, to be used in conjunction with the PV model, was done. Further, the considered battery types were compared on the basis of technical and economic metrics. Based on the techno-economic analysis for a domestic load of 250 kWh/day and an agricultural load of 17.91 kWh/day, it was found that the LI batteries had the highest annual throughput, required the least battery capacity and, the lowest NPC and LCOE among the considered battery types. Moreover, LI batteries were tested to have a considerably good battery lifetime. Hence, it was concluded that the LI batteries are the most favourable option for use with the designed off-grid PV system.

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