Buffer Sizing of Concentrated Photovoltaic Batteries: An Economic Analysis

Yacouba Moumouni and R. Jacob Baker
Department of Electrical and Computer Engineering, University of Nevada, Las Vegas
yacoubam@unlv.nevada.edu

***Abstract*— Energy storage systems are one of the major components in today's grid-tied photovoltaic technology. The most widespread ESSs are the batteries mounted on electric vehicles. Second-life batteries, regardless of the technology, are less expensive than new battery packs. The proper sizing of concentrated photovoltaic buffers and the true economic feasibility need to be investigated thoroughly before any large-scale photovoltaic grid integration. This paper investigates the economic performance of grid-tied concentrated photovoltaics and buffers. Simulation results show that not only is the combined unit capable of connection to the grid during the day at a constant 20 kW, but also was able to shift the less valuable off-peak electric supply to the on-peak supply, where the cost of electricity was higher. This paper addresses 1) techniques behind battery-sizing scenarios, 2) battery-parameter calculations involved in concentrated photovoltaic output smoothing and/or electrical load shifting, and 3) used electric vehicle battery cost estimation. Estimates of the cost effectiveness could be positive if the energy storage system battery pack prices drop to $375/kWh or lower.**

***Index Terms*—Economic Analysis, Energy Storage System (ESS), Electrical Vehicle (EV), Battery, Sizing.**

I. INTRODUCTION

During the last century, the population on Earth has increased at a faster rate than ever seen before. The net global impact has had heavy consequences worldwide. There is, in fact, a global concern that we are running out of energy resources that are either non-regenerative or not replenishing at a fast enough rate on a human scale. In essence, most of our energy supply is not renewable and may be depleted soon. However, appropriate solutions are not only achievable, but are also capable of eliminating the global energy crisis for decades to come.

Hence without the proper buffers, such renewable sources as solar and wind may affect the grid with instabilities that can cause voltage sag, frequency variations, and power-factor corruption. These renewable sources impose unwanted issues in power to the grid operators [1].

In a concurrent paper [2], methods were investigated to mitigate the fluctuations brought to the electric grid by means of used electric vehicle (EV) batteries when a concentrated photovoltaic (CPV) unit was tied to the network. CPVs are highly efficient technology due to their triple junction designs. Additionally, the mirrors and lenses they use are of great advantage compared to the traditional flat-plate technology. Used EV batteries were proposed instead of new batteries for many reasons: 1) primarily for economic feasibility and 2) secondly for environmental concerns [3].

Battery storage system is made up of an assembly of two or more energy storage devices (ESD) in conjunction with the power electronic interface kit [4]. The energy storage system (ESS) aims to support the CPV in putting onto the grid a constant power in the development of short or long weather events (cloud coverage). It also absorbs the less expensive excess power during off-peak hours [2]. More details on used EV ESS assessment were done in [5]. As stated by Tong et al. [6], although the batteries still had 80% or less of the rated capacity, used batteries were good candidates for renewable-energy storage applications for a few more years.

This paper is organized as follows. Sec. II explains the basic battery principles. In Sec. III, the important parameter calculations are performed. Sec. IV emphasizes on the power losses behind the battery charging and discharging phenomenon. The economic implication results are discussed in Sec. V, followed by the conclusion in Sec. VI.

II. BATTERY BASIC PRINCIPLES

Batteries are comprised of a variety of chemical and mechanical devices. Despite the fact that they function on different principles, a battery can be viewed as a device that stores energy in a chemical form, usually different from its original form. Then when needed most, the battery converts the stored energy back to its original form, mainly electrical energy [7]. The round trip conversion is always associated with losses that should be accounted for in any sizing exercise. Batteries can further be categorized into rechargeable, secondary cell and non-rechargeable, primary cell, as opposed to the former.

A. Charging

As a rechargeable battery receives electrical energy, it charges. Hence, there is a fundamental change in the chemical composition of the inner plates. Therefore, the electrolyte is strengthened as it holds many more ions. A voltage is developed that is solely dependent on two factors: the material and type of electrolyte. The reaction of the aforementioned factors produced the chemical energy.

B. Discharging

In a like manner, but opposite direction, when a battery delivers electrical energy, it discharges. Independent of the technology, a battery begins to discharge when an external circuit is completed. A battery can be deeply discharged without the proper measures. Most of the time, the modern ESSs have a control algorithm or include an exceptional circuitry that trips when the battery reaches the DOD of 20%.

III. BATTERY PARAMETERS CALCULATION

In essence, unlike the conventional power generators, batteries do present less significant ramp constraints [8]. Nonetheless, the amount of exchangeable power is limited by either or both of, the power rating and the battery capacity.

A. Battery Sizing

The sizing of a battery bank is a delicate matter that has to be carried out with care, as both load shifting and transient support require relatively expensive battery energy storage. As a matter of fact, the perfect sizing of the battery capacity is vital in order to meet those goals via the avoidance of an under-sized or over-sized battery [9]. Many factors need to be considered in the process of sizing a battery. The most important and crucial ones among those factors will be listed here, such as the anticipated daily kWh of energy consumption and the number of hours or days of autonomy of storage needed.

Basically three types of batteries are considered in this study due to the fact that their advantages outweigh by far their disadvantages, and also they turn out to be the most promising energy storage devices: 1) Lead-acid battery, 2) Lithium ion battery, and 3) Nickel Cadmium battery. Additionally, they present a relatively low initial cost and higher lifespan although they may require frequent maintenance.

Therefore, independently of the type of battery to be used with the PV system, the larger battery would offer more effective net positive aspects. But as a matter of fact, it will become more expensive. Hence, due to the rapid growth in the electric automobile industry, advantage of that will be taken in order to minimize the high initial cost of the batteries. So, in this paper, it is proposed that batteries be inexpensively purchased and added as an option to favor a high penetration to the grid of each CPV unit. Therefore by doing that, the short-term transient phenomena will be solved, as well as the electrical power availability and reliability will be increased.

B. The actual sizing scenario

As in most engineering designs, there are some specifications and assumptions that have to be set forth as a guide.

1) Smoothing the CPV's output

- Load (inverter output) is assumed to be P = 38kW based on the actual performance of the CPV 7700.
- The battery discharge time, t is set to be equal to 1/3 of an hour (≈0.34 hr); the required energy is

$$E = P \cdot t = 38kW \cdot 0.34h = 12.66kWh \quad (1)$$

Where, *E* denotes energy.

- Assume 12% of combined loss such Charging and Discharging and wiring from inverter to load [10].
- Inverter efficiency, ŋ = 88% (assumption); the load on the battery is computed using

$$Load = \frac{12.66kWh}{0.88 \cdot 0.88} = 16.35kWh \quad (2)$$

Where, *Load* denotes the battery capacity.

- Conversion of the above quantity to *Ah* at the battery voltage (assumed to be 24V) is

$$Load(Ah) = 16.35kWh \cdot \frac{1000}{24V} = 681.20Ah \quad (3)$$

The batteries should not deliver more than 80% of their capacity. The factor that accounts for that is 1.25 [11] as seen in Eq. (4) below. This means that if 20% of their capacity is left, the charge controller will shut them off automatically.

$$Total_{Load} = 681.20Ah \cdot 1.25 = 851.50Ah \quad (4)$$

Therefore, the battery size for smoothing out the power intermittencies is 851.50*Ah*.

For simplicity purposes, other factors are neglected in this battery sizing exercise. Furthermore, the energy capacity of the battery bank is to be determined since it will be of great interest in the section reserved for the economic analysis. Hence, knowing the capacity of the battery, the theoretical energy capacity of ESS1 (E_1) is

$$E_1[kWh] = Ah \cdot V = 861.50Ah \cdot 24V = 20.436kWh \quad (5)$$

Having done that, to achieve the above storage capacity, the suitable batteries can now fit in without any problem by connecting them either in series and/or in parallel.

2) Load shifting

The same assumptions apply here at some extent.

The battery discharge time, t is set to be equal to six (6) hours corresponding to the on-peak time frame, i.e. [1pm to 7pm].

- The amount of energy to be shifted is

$$E = P \cdot t = 38kW \cdot 6h = 228kWh \quad (6)$$

The equivalent load on the battery bank is as shown in Eq. (7), where, $Load_{Bat}$ denotes the load on the battery.

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$$Load_{Bat} = \frac{228kWh}{0.88 \cdot 0.88} \approx 295kWh \quad (7)$$

- Conversion to *Ah* at the battery voltage (assumed to be 24V) is

$$Load\ [Ah] = 295kWh \cdot \frac{1000}{24V} \approx 12{,}268Ah \quad (8)$$

The batteries should not deliver more than 80% of their capacity as stated above in order to avoid deep-discharge.

- So, the total load is calculated using

$$Total_{Load} = 12{,}268Ah \cdot 1.25 = 15{,}335Ah \quad (9)$$

Therefore, the battery size required for shifting an equivalent amount of power from off-peak time to on-peak is 15,335*Ah*.

- The energy capacity of ESS2 (E_2) is calculated as follows

$$E_2[kWh] = Ah \cdot V = 15{,}335Ah \cdot 24V \approx 368kWh \quad (10)$$

Having done that, to achieve the above storage capacity, the appropriate batteries can now be adequately fit in without any problem by connecting them either in series and/or in parallel.

The total energy capacity of the combined ESSs, can be easily computed using

$$E_{Total} = E_1 + E_2$$

$$= 20.436kWh + 368kWh \approx 388kWh \quad (11)$$

IV. CHARGING AND DISCHARGING ANALYSIS

A. The round trip losses

During the course of the ESS1's normal operations for the aforementioned energy capacities, the round trip losses are as illustrated in Figure 1. The positive side of the curve in blue is the total loss due to charging and the remaining one in green represents the losses due to the discharging phenomenon. Three things can be remarked in this graph: 1) the minima for both processes occurred in the month of June; 2) the battery was idle, zero loss, and occurred in June, July, and August; 3) the maxima occurred for both phenomena in the month of July, certainly due to the hot weather conditions in Las Vegas.

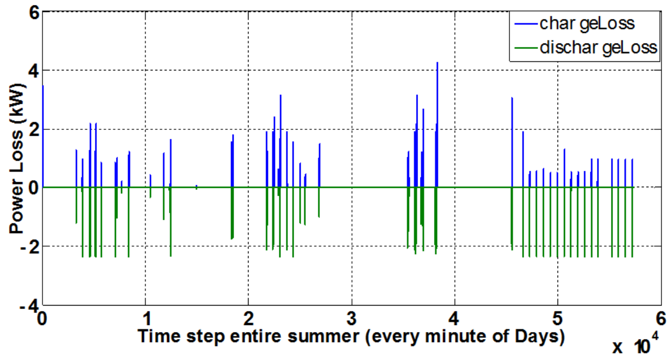

Figure 1- Total charge losses vs that of discharge.

B. Maxima powers charged and discharged by the ESS1

During the course of their operations, the batteries are constantly either charging or discharging except during night or when they are fully charged. Some of the exceptions include when the battery reaches its DOD of 20%. In this latter case, the control algorithm will simply disconnect them from the system for safety purposes. Figure 2 depicts a maximum of 36.03kW of power charged (Blue) occurring in the month of July versus the pattern of power discharged (Green) with a maximum of 22.36kW.

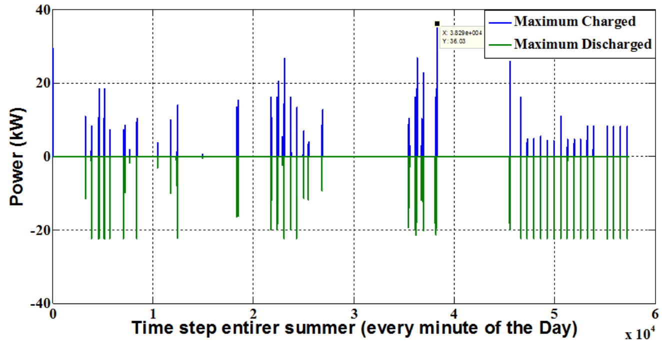

Figure 2- Power charged vs. Power discharged.

The negative signs on the graph have nothing to do with the power quantity itself. In contrast to charging, the discharging is set up to be negative as it is the custom in power engineering, denoting that it is supplying rather than absorbing power.

V. ECONOMIC ANALYSIS

Generally quoted in the forms of $/kWh or $/kW, the costs of energy storage devices are often related to the satisfaction of a particular application, although some systems will have a higher cost/kWh of energy, but obviously a lower cost/kW of power than others, or vice versa. It is shown in [6] that the interdependency of the application and its economic feasibility has a lot to do with the aforementioned assertion. Additional economic benefits of the ESS load shifting applications are treated in [6] for more details. In addition to that, the market structure which is sometimes uncertain and fluctuating also plays an important role in the economics of certain types of storage technology. Despite the fact that some leading battery competitors cost/kWh range from $225/kWh to $300/kWh, the United States Advanced Battery Consortium (USABC) goal is to cut down the cost to $150/kWh in order for the market to grow. Hence, for that to be done, a major breakthrough has to happen in the field of battery technology as a whole. In fact, the US DOE had set for the year 2014 the battery prices for PHEV to be sold at $200 to $300/kWh, which seemingly failed to happen. Obviously, the current prices, ranging from $500-$600 to as high as $1,100/kWh are still prevalent [12].

A. Battery cost estimation

1) Battery price to smooth CPV's intermittency

The battery energy capacity required to smooth the intermittency was found to be 20.436kWh. So, by averaging the price interval, the EV battery could be purchased at a price of $775/kWh. Therefore, the new EV battery would be purchased with a total cost given by

$$Total_{Cost} = \$775/kWh \cdot 20.436kWh \approx \$15{,}878 \quad (12)$$

This is the price that would be paid for each unit if they were to be used with new batteries to smooth out the intermittencies due to the nature of solar source. But the good news is that, used EV batteries will do the job. Therefore, to be able to do that satisfactorily, assume used batteries are purchased either from EV owners or battery leasers. This will cut down the above *cost/kWh* by more than half. Since there are many unpredictable uncertainties as stated earlier, due to the fact that the market is new and anything can happen, such as inflation, deflation or a major breakthrough in the science of batteries. However, for the purpose of this analysis, the buy-down price is considered as a variable. In a similar analysis done in [7], the price range of used EV batteries is assumed to be \$100/kWh to \$170/kWh. Hence the total cost for the second life EV battery would be determined by taking the conservative side as:

$$Total_{Cost} = \$170/kWh \cdot 20.436kWh \approx \$3,475 \quad (13)$$

2) Battery price to shift part of the load

In a similar fashion, if the batteries were to be purchased new, the total price would be estimated as

$$Total_{Cost} = \$775/kWh \cdot 368kWh \approx \$285,200 \quad (14)$$

Finally, the total cost for the second life batteries utilization would be by taking the same side as computed in the following

$$Total_{Cost} = \$170/kWh \cdot 368kWh \approx \$62,560 \quad (15)$$

To sum it up, utilizing second life batteries will dramatically cut down the price of ESS2. The ESS2, coupled to the CPV was able to shift an equivalent amount of power by a factor of 5. Details can be found in our accompanying work [2]. Moreover, the cost benefits estimation of such a single unit (CPV and ESS) seemed to be significant and may not be marketable thus far. But as done in [13], it would have been cost effective when they were aggregated.

Hence, the total energy capacity of 388kWh of combined ESS1 and ESS2 coupled to the system reveals counter intuitive results than what was expected. The findings demonstrated that the efficiency in terms of energy savings and cost-effectiveness is undoubtedly at a much lower value than what was found. Beyond certain limits, the cost of the ESS will be much higher without significantly improving the overall system efficiency. In essence, estimates of the cost-effectiveness through this approach based on the current ESS prices were not conclusive.

VI. CONCLUSION

Large scale CPV grid integration was investigated in this study. Second life EV batteries are proposed instead of brand new ones for both economical and waste disposal issues. The technical feasibility was thoroughly studied and understood as all the major parameters were calculated. The ESS was split into two groups mainly, ESS1 and ESS2, with each group having different functionality. The first category was sized to smooth out the CPV transients so that the latter may put a constant power onto the grid. The second one shifts the less valuable off-peak power to the time when it is mostly needed. The total energy capacity of the combined ESSs was found to be 388kWh.

Furthermore, the economic implications of the ESSs quantities were investigated. Estimates of the cost-effectiveness through this approach based on the current ESS prices were exorbitant. The cost benefits estimation of the system (CPV and ESS) seemed to be significant and may not be marketable thus far. However, it could be cost effective if the ESS battery pack prices drop to \$375/kWh or lower.

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