Optimizing Partial Power Processing for Second-Use Battery Energy Storage Systems

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ABSTRACT Repurposing automotive batteries to second-use battery energy storage systems (2-BESS) may have environmental and economic benefits. The challenge with second-use batteries is the uncertainty and diversity of the expected packs in terms of their chemistry, capacity and remaining useful life. This paper introduces a new strategy to optimize 2-BESS performance despite the diversity or heterogeneity of individual batteries while reducing the cost of power conversion. In this paper, the statistical distribution of the power heterogeneity in the supply of batteries is considered when optimizing the choice of power converters and designing the power flow within the battery energy storage system (BESS) to maximize battery utilization. By leveraging a new lite-sparse hierarchical partial power processing (LS-HiPPP) approach, we show a hierarchy in partial power processing (PPP) partitions power converters to a) significantly reduce converter ratings, b) process less power to achieve high system efficiency with lower cost (lower efficiency) converters, and c) take advantage of economies of scale by requiring only a minimal number of sets of identical converters. The results demonstrate that LS-HiPPP architectures offer the best tradeoff between battery utilization and converter cost and had higher system efficiency than conventional partial power processing (C-PPP) in all cases.

INDEX TERMS Battery energy storage systems (BESS), conventional partial power processing (C-PPP), electric vehicles (EV), full power processing (FPP), lite-sparse hierarchical partial power processing (LS-HiPPP), partial power processing (PPP), second-use batteries.

I. INTRODUCTION

Second-use batteries from the exponential growth of electric vehicles (EVs) needed to halt climate crisis represent a challenge. By 2030, there will be 200 GWh per year of used batteries from EVs \footnote{arXiv:2106.11749v1 [eess.SY] 7 Jun 2021} that could be used in the grid storage or other stationary applications. These batteries, when removed from the vehicle, still have approximately 80% capacity and power capability. Reusing these batteries in second-use battery energy storage systems (2-BESS) provides a sustainable solution that adds economic value to EV batteries. There are several economic obstacles to the adoption and deployment of 2-BESS. The price competitiveness of 2-BESS relative to other storage technologies including battery energy storage system (BESS) with new batteries relies on lowering the added costs from repurposing. These include the cost of transportation, inventory, and power converters \footnote{arXiv:2106.11749v1 [eess.SY] 7 Jun 2021}. By using distributed production and a local supply together with just-in-time re-manufacturing, transportation and inventory costs are minimized. However, this production strategy incurs the challenge of a heterogeneous supply. Even with second-use batteries that are identical at the time of original manufacturing and installed in identical vehicles, these batteries, when removed, will exhibit a significant degree of variation because of the different history of drive cycles and temperature cycling.

BESSs are needed to stabilize the grid with a high penetration of renewables \footnote{arXiv:2106.11749v1 [eess.SY] 7 Jun 2021}, support micro and nanogrids \footnote{arXiv:2106.11749v1 [eess.SY] 7 Jun 2021}, and support EV fast charging and reduce the cost of grid upgrades from the high peak power \footnote{arXiv:2106.11749v1 [eess.SY] 7 Jun 2021}. A canonical network for a BESS is illustrated in Fig. 1(a), which is a network of
batteries interconnected with a network of power converters that determine the power flows, and an output to a load.

A typical strategy for BESSs using new batteries, which have a high degree of homogeneity, is to use conventional partial power processing (C-PPP) architectures [6]. Partial power processing reduces the required converter ratings and hence capital cost of converters [6]. Additionally, by reducing processed power, overall system efficiency increases and the cost of thermal management decreases [7]. These architectures can have a pre-determined choice of power converters and power flow topology because of both the high certainty in and homogeneity among the batteries [8]. Fig. 1(b) shows a typical partial power processing topology for batteries in series. Only mismatch power among the batteries and between required load voltage and series voltage of the batteries is processed.

The conventional strategy for BESSs with heterogeneous batteries, e.g. 2-BESS, is to individually process all the power from every battery to adjust for the heterogeneity by individualizing each battery’s power trajectory [9]. Fig. 1(c) illustrates the full power processing (FPP) strategy; the disadvantage to this approach is that the power ratings of the converters must be at least equal to the battery power ratings. Because power converter cost is typically nearly proportional to their power rating, FPP is the costliest option for power conversion. Additionally, the system efficiency will be less than the efficiency of the power converters [10]. For example, a system efficiency of 98% requires power converters with at least 98% efficiency, where the cost of the converters also increases with efficiency [11].

An appealing alternative to FPP for 2-BESS is partial power processing because of the lower cost of power converters, higher system efficiency, and lower cooling requirements. However, heterogeneity among batteries is a challenge. This paper demonstrates the disadvantages of FPP and the challenges of C-PPP approaches in comparison to a new strategy for partial power processing, Lite-Sparse Hierarchical Partial Power Processing (LS-HiPPP). This paper, moreover, presents the formulation and results for the optimization of power capability in LS-HiPPP [11].

The strategy for optimizing 2-BESS presented in this paper uses LS-HiPPP to accommodate for the heterogeneity in the power capability of the individual batteries within a 2-BESS. With LS-HiPPP, the overall output power capability is not heavily compromised as it is with conventional power processing architectures using the same converter ratings. The paper is organized as follows: Section II discusses the Lite-Sparse Hierarchical Partial Power Processing (LS-HiPPP) architecture and optimization strategy, and Section III presents the simulation results of the performance comparisons between LS-HiPPP and conventional power processing strategies.

An energy optimization formulation is also applicable: for example, when optimizing the energy buffering needed for supporting the grid in EV fast charging over a time trajectory. The following was submitted to the IEEE Transactions of Smart Grid and is available as an arXiv preprint [12].

II. OPTIMIZATION OF PARTIAL POWER PROCESSING FOR HETEROGENEOUS ENERGY STORAGE SYSTEMS

An objective often used for optimization in operations research over statistical uncertainties is the ensemble performance in the production of a large number of units, specifically the expected performance [13]. Expected performance metrics are used for optimization and evaluation in the subsequent sections of this paper.

The basic approach for partial power processing in this paper is a topology that is hierarchical, lite, and sparse. Hierarchical partial power processing, as illustrated in Fig. 2, had been previously used to partition the power conversion to optimize the speed of response to disturbances. However in 2-BESS, the speed of power conversion is not typically a critical factor because the time scales required for the typical applications are orders of magnitude slower than that of the power converters. Instead, we use the hierarchy in partial power processing to partition the power converters to take advantage of economies of scale by requiring only a minimal number of sets of identical power converters. This way, only a few types of power converters are needed, which can be purchased in larger volumes. “Lite” refers to low power despite numerous converters, and sparsity refers to few but higher power converters. The combination of numerous lower power converters together with few higher power converters comprise the power processing for LS-HiPPP.

The objectives of the optimization are to: (1) minimize the aggregate power rating of the power conversion; (2) minimize the number of power converters; (3) minimize the different types of power converters; and (4) maximize the overall power capability of the 2-BESS. The optimization is constrained by the statistical distribution of the battery supply. We will illustrate the strategy for a specific architecture within which the power converter choice, interconnection, and power flow will be designed.

The methods discussed in this paper apply not only to battery packs, but also to battery modules (battery packs may be partitioned into modules) and individual battery cells.

A. LITE-SPARSE HIERARCHICAL PARTIAL POWER PROCESSING

LS-HiPPP uses a combination of low-power converters (lite) that are densely connected together with a sparse number of higher power or “heavy converters”. Fig. 2 shows a particular LS-HiPPP interconnection consisting of two power converter layers in a hierarchy. The first is a sparse number of heavy converters that is much fewer than the number of batteries, in contrast to FPP where every battery requires a power converter.

B. MODEL SPECIFICS

There are several model assumptions in our analysis and optimization of 2-BESS in an LS-HiPPP architecture. We investigate the case for a Gaussian distribution in the power capability of the battery supply. The specific energy storage
interconnection for LS-HiPPP that we examine is illustrated in Fig. 2. The topology specifically presented in this paper is a series string of batteries. The following assumptions enable power flow optimization using linear programming methods:

1) Power converters have negligible loss. When each converter processes only a fraction of the power that is extracted from the batteries, the optimization result using this approximation is expected to have only a small deviation from the true optimum.

2) Batteries have negligible loss. The batteries used in practice have a high efficiency. A similar argument can be made that the optimization results using this approximation will deviate by only a small amount from the true optimum.

3) The statistical distribution in power capability for the supply of batteries is Gaussian. While the methods presented in this paper can be used for any distribution, including both discrete and continuous, Gaussian distributions are typically used in analysis and comparisons among technology or configuration options.

4) The voltage mismatch between the battery stack and required bus voltage is regulated and processed by a power converter.

The voltage heterogeneity among the batteries in a series stack results in an aggregate voltage mismatch between the battery stack and the required load voltage. The bus voltage regulator in Fig. 2 is a bidirectional converter that processes only the mismatched power; the power converter functionally in this case can be classified as partial power processing. This bus voltage regulator can output either a positive or negative voltage to the bottom of the of the series stack and can be either non-isolated or isolated.

C. DISTRIBUTION FLATTENING

The method of Distribution Flattening generates a finite set of batteries that represent the expected performance. Fig. 3 shows a particular battery supply distribution for power capability $p(P)$.

The following is directly quoted and equations modified from [12]:

We would like to map this statistical distribution, which is a continuous function, to a finite expected set of batteries of size $N$. In this paper, the statistical distribution of the supply is Gaussian, but this does not necessarily have to be the case.

This expected set is an ordered set. The elements of this set are a particular representation of the expected values for $N$ batteries drawn from this the supply distribution. The set is constructed in the following manner:

1) Divide the distribution into $N$ intervals of equal probability: $[P_1, P_2], [P_2, P_3], \ldots, [P_N, P_{N+1}]$. $P_1$ and $P_{N+1}$ are the lower and upper bounds of battery power capability, respectively. An example is shown in Fig. 3. The $n^{th}$ interval satisfies

$$\int_{P_n}^{P_{n+1}} p(P) dP = \frac{1}{N}. \quad (1)$$
FIGURE 2. Lite-Sparse Hierarchical Partial-Power Processing (LS-HiPPP) for series connected 2-BESS. Layer 1 consists of a sparse set of higher power converters. Layer 2 consists of a dense set of lower power (lite) converters. A bus voltage regulator processes the mismatch between the battery series string and the required bus voltage. Only mismatch power is processed like C-PPP but with fewer power converters and lower converter ratings for the same performance using heterogeneous second-use (2U) batteries.

2) Assign each interval its expected value (1st moment).

\[
\bar{P}_n = N \int_{P_n}^{P_{n+1}} p(P)P \, dP. \tag{2}
\]

3) The finite expected set \( B \) is constructed as \( B = \{\bar{P}_1, \bar{P}_2, \ldots, \bar{P}_N\} \).

In general, each interval can be assigned any measure of central tendency, including those that are functions of the local shape of the interval. For example, one could use a function of the higher moments of the interval. Fig. 3 shows a realization of \( B \) as a series circuit on batteries. In general, \( B \) can be realized into any topology, including circuit topologies.

D. BATTERY STORAGE NETWORK DESIGN

The design of a battery storage network, which can be a BESS, can be defined by the following:

1) Set of batteries whose elements possess the relevant characteristics, for example power capability. Other relevant characteristics can include the statistical distribution of supply, which can be parameterized by their moments, e.g. mean and variance.

2) Interconnection of batteries, which can be represented by a graph or a circuit.

3) Power processing design.

E. POWER PROCESSING DESIGN

The power processing design of a battery storage network (in this paper a 2-BESS) can be defined by the following set, which comprises:

1) Sets of power converters, which can be parameterized by unique set of power converter ratings (e.g. power rating) and number of power converters in the set.
2) Interconnection of power converters to the batteries.
3) Power flows among converters and batteries.
4) Interconnections of input and output ports.
5) Variables of the input and output ports, e.g. voltage, current, and power.

In general, the power flows, and the input and output port variables can be trajectories that change in continuous or discrete time, or in a sampled data space that may or may not be uniform in continuous-time intervals.

In this paper, we specifically discuss the particular 2-BESS in an LS-HiPPP architecture shown in Fig. 2. The circuit interconnection of the batteries is a series string. The set of batteries is drawn from a supply population whose statistical distribution is a Gaussian parameterized by its mean and variance.

The LS-HiPPP structure that we are investigating consists of two layers of bidirectional power converters. Layer 1 is a sparse layer of power converters that is optimized for the realization of expected battery set from the supply population. Layer 2 is a dense layer of power converters, i.e. the number of converters is equal to one fewer than the number of batteries, with each converter’s ports attached to a battery and its adjoining neighbor, as shown in Fig. 2.

The power processing design can be divided into two activities. The goal of the first activity is to pre-determine the sets of power converters that will be used in the production of 2-BESS units. The second activity is the design and construction of a particular 2-BESS unit during actual production.

F. DETERMINING THE POWER CONVERTER SETS

The cost of power converters scales approximately linearly with power rating (i.e. $/kW). There is a penalty in the design as the number of power converter sets increase. In other words, as the number of different types of converters that are needed for the design of a particular BESS product increases, the worse the economies of scale because fewer converters of a particular type are purchased.

The power ratings of both Layer 1 and Layer 2 converters need to be determined. As previously discussed, the structure we choose for LS-HiPPP in this paper has the interconnection of Layer 2 converters is pre-determined. We also stipulate that the Layer 2 converters will be identical. For Layer 1, the number of converters and how they are partitioned into sets of identical converter ratings need to be determined.
FIGURE 3. Distribution Flattening Method maps a statistical distribution to a series string of batteries that represents the expected behavior for that string. The design of the sparse Layer 1 converters uses this series string.

1) Optimization Formulation
In this paper, the objective function is the power utilization of the 2-BESS. The power utilization is defined as the total power delivered from the output port of the 2-BESS normalized by the sum of the power capability of each individual battery in the 2-BESS.

For simplicity, we assume that there is no penalty for power processing in the bus regulation converter. This assumption is homologous to restricting battery sets to contain only batteries with identical voltages. This does not mean that this design method is restricted only to batteries of identical voltages, but rather, the voltage differences do not change the optimization.

The output load is a fixed current source and serves as an optimization constraint.

2) Layer 1 Power Processing Design
The power processing for Layer 1 is designed from the expected set $B$ that is derived from the Distribution Flattening of the battery supply set. The series string of batteries $B_1 \ldots B_9$ are arranged from lowest to highest expected power capability as shown in Fig. 3.

A mixed-integer optimization is performed to maximize the power utilization. For a small number of converters, an exhaustive search can be performed to find the best interconnection. For every interconnection, the optimal power flow is found using linear programming

$$\max \sum_{1 \leq j \leq N} p_{bus}^j$$

subject to

$$-\bar{P}_j \leq p_{bat}^j \leq \bar{P}_j,$$

$$p_{bat}^j = \sum_{i \in K_j^{(1)}} p_{1}^{(1)} + p_{bus}^j,$$

$$p_{bus}^j = I_{string}V_j, \ j = 1, 2, \ldots, N,$$ (3)

where $p_{bus}^j$ stands for the power delivered from $j^{th}$ battery to the bus, $p_{bat}^j$ is the output power of $j^{th}$ battery, $K_j^{(1)}$ is the index set of the Layer-1 converters whose inputs are connected to $j^{th}$ battery. In this optimization problem, the decision variables are the power ratings of $M$ Layer 1 converters, represented by $p_{1}^{(1)} \ldots p_{M}^{(1)}$. The optimization objective (3) is to maximize the total power transferred to the bus (i.e. the summation of the power exchange from each battery to the bus). Constraint (4) is the battery input and output power limitation. Constraint (5) is the power conservation law for each battery. Constraint (6) indicates the direct power transfer from the $j^{th}$ battery to the bus is proportional to its voltage $V_j$ because all batteries share the same string current $I_{string}$.

At the maximum utilization, the converters will have optimal interconnection and power flow. In general, each converter can be processing a different power, which can be described as the optimal set of processed power. The converter ratings for Layer 1 can be partitioned into sets based on the set of different processed power for each converter. For example, for a partitioning that consists of a single converter set, the rating for all the converters will be the highest processed power from the optimal set; for two partitions, the converter with the highest processed power will be one partition and the remaining converters will be rated at the 2nd highest processed power, and so forth for more partitions. This partitioning strategy results in the lowest aggregate rating for the power converters and hence cost. It is worth noting that for a sparse Layer 1, the number of partitions is much fewer than the number of batteries.

3) Layer 2 Power Processing Design
The purpose of Layer 2 is to process the mismatch power from the statistical variation of the batteries. To optimize over statistical variations, Monte Carlo methods are employed. The design of Layer 2 proceeds subsequent to the design of
Layer 1. The interconnection and power ratings of the Layer 1 converters become constraints in the design of Layer 2 as illustrated in Fig. 1. As previously mentioned, the interconnection of Layer 2 is pre-determined and ratings of the power converters are identical; hence, the goal is to determine the optimal rating for the power converters.

The optimization starts by selecting a set of trial power converter ratings. For each converter rating, an optimal set of battery power utilizations is obtained via a set of samples from the statistical distribution of the battery supply. These battery power utilizations are calculated from the optimal power flow by applying linear programming to each sample.

\[ \max \sum_{1 \leq j \leq N} p_{j}^{\text{bus}} \text{subject to } - (P_{j} + \delta P_{j}) \leq p_{j}^{\text{bat}} \leq (P_{j} + \delta P_{j}), \]

\[ p_{j}^{\text{bat}} = \sum_{i \in K_{j}^{(1)}} p_{i}^{(1)} + \sum_{k \in K_{j}^{(2)}} p_{k}^{(2)} + p_{j}^{\text{bus}}, \]

\[ p_{j}^{\text{bus}} = \bar{I}_{\text{string}} V_{j}, \quad j = 1, 2, \ldots, N, \]

\[ p_{k}^{(2)} \leq p_{\text{max}}^{(2)}, \quad k = 1, 2, \ldots, N - 1, \]

\[ p_{i}^{(1)} \leq p_{i}^{*}, \quad i = 1, \ldots, M, \]

where \( K_{j}^{(2)} \) is the index set of the Layer 2 converters whose inputs are connected to \( j \)-th battery. In this optimization problem, the decision variables are the power processed by the \( N - 1 \) Layer 2 converter, represented by \( p_{1}^{(2)} \ldots p_{N-1}^{(2)} \). The optimization objective (7) is to maximize the total power transferred to the bus. Constraint (8) is the battery input and output power limitation. \( \delta P_{j} \) represents the power uncertainty of \( j \)-th battery. Constraint (9) is the power conservation law for each battery. Constraint (10) expresses the direct power transfer from the \( j \)-th battery to the bus. Constraint (11) indicates the power ratings for all Layer 2 converters identical to \( p_{\text{max}}^{(2)} \). Constraint (12) suggests that the Layer 1 converter ratings are kept fixed in the layer 2 power processing design.

The average battery power utilization from the optimal set is designated to that converter rating. Hence, a particular Layer 2 converter rating will have this battery power utilization metric.

G. CONSTRUCTION AND OPERATION OF 2-BESS UNITS

A set of batteries are drawn from a supply. The batteries are sorted from lowest to highest power capability and connected in series. Power converters contribute a significant portion of the cost of a 2-BESS unit. Economies of scale can alleviate this cost and is a directive and, from the perspective of optimization, can be considered an objective. Economies of scale can be accomplished by using fewer types of converters, i.e. using as many converters with the same rating as possible.

This is a goal in Section II-E. In production, both Layer 1 and Layer 2 converters are purchased in mass quantities, which are determined by the prediction of the 2-BESS product demand. Both Layer 1 and Layer 2 power converters are connected according to Section II-F2 and II-F3, respectively.

The production flow of a 2-BESS unit is illustrated in Fig. 5. A battery set for a particular 2-BESS unit is acquired from the battery supply. For a power-intensive application, the batteries are then tested and evaluated for power capability. The assembly of the 2-BESS unit proceeds by sorting and then connecting the batteries so they are ordered from lowest to highest capability. Using the battery capability information from testing, the interconnection of Layer 1 converters (pre-purchased with a specified rating) is determined using the method outline in Section II-F2. Both Layer 1 and 2 converters are then connected to the batteries. Power is optimized for the application. Then, the 2-BESS unit is tested and validated for performance and safety before being delivered to the customer.

The optimal power flows are recalculated using linear programming during operation with the actual battery power capabilities in the 2-BESS unit and the output load as constraints. As we show in Section III, Results, the design method for LS-HiPPP results in a better cost-performance tradeoff as it relates to battery power utilization and aggregate converter rating compared to current state of the art approaches. The LS-HiPPP architecture performs well with a sparse set of Layer 1 converters at moderate power ratings and the dense set of Layer 2 converters at lower power ratings.

III. RESULTS

LS-HiPPP enables tradeoffs in performance and price not previously possible using conventional methods. The LS-HiPPP design methods have tractable complexity in the optimization on the order of \( 10^{4} \) linear programming iterations with 200 variables for nine batteries and three Layer 1 converters, which can be performed on a small computing cluster. The specific LS-HiPPP realization is illustrated in Fig. 2, which consists of nine heterogeneous batteries connected in series with three Layer 1 power converters and nine Layer 2 converters.

The battery power capability was modeled as a Gaussian distribution with a normalized expected power \( \bar{P}_{i} = 1 \) with the power heterogeneity represented by the standard deviation \( \sigma_{p} \) normalized to the expected power. The aggregate converter rating \( \bar{R}_{p} \) is normalized to the aggregate intrinsic battery power \( \bar{P}_{i} \).

\[ \bar{R}_{p} = \frac{\sum_{i=1}^{M} p_{i}^{(1)} + \sum_{i=1}^{N-1} p_{\text{max}}^{(2)}}{\bar{P}_{i}}, \]

\[ \bar{P}_{i} \triangleq \sum_{i=1}^{N} \bar{P}_{i}. \]

With a constant $/kW presupposition, aggregate converter rating is a proxy for converter cost.
Layer 1 Converter Ratings and Interconnection

Set of Battery Samples from Statistical Distributions

Layer 2 Converter Ratings

Battery Supply ~ $N(\mu, \sigma)$

FIGURE 4. Power flow design for Layer 2 power processing is subsequent to the design of the Layer 1 converter ratings and interconnection. In the linear programming formulation for power capability, the ratings for the Layer 2 converters are constraints. From Monte Carlo trials, the Expected Battery Utilization for the 2-BESS can be obtained.

FIGURE 5. Production flow of a 2-BESS unit: (i) Layer 1 and 2 converter ratings are predetermined and purchased in volume; (ii) The batteries are tested and reordered in the series string; (iii) Layer 1 interconnections are optimized; (iv) Layer 2 is connected; and (v) Power flow is optimized. 2-BESS units are optimized for heterogeneity using power converters that are purchased at economies of scale.

### A. BATTERY UTILIZATION

The battery power utilization $\mathcal{U}_P$ is the output power capability $P_{out}$ of the 2-BESS normalized by the summation of each individual power $P_{b,j}$,

\[ \mathcal{U}_P \triangleq \frac{P_{out}}{\sum_{j=1}^{N} P_{b,j}}. \tag{15} \]

1) Partial Power Processing vs. Full Power Processing

A tradeoff between the expected battery power utilization and the normalized aggregate converter rating was investigated using Monte Carlo simulations. We compare LS-HiPPP with two current state of the art approaches for heterogeneous batteries in a 2-BESS: FPP and C-PPP.

We can observe from Fig. 6 that partial power processing architectures perform significantly better even at higher heterogeneity (20%) and low converter ratings (20%). The battery utilization for full processing is very nearly linear to the converter rating; this is the case because all of the battery power must be processed by the power converter, hence making the power converter rating the limiting factor.

Fig. 6 shows the results for a heterogeneity in the battery power capability with a standard deviation of 20% of the mean. Because the maximum output power is equal to the aggregate power converter rating for FPP, the utilization curve increases linearly with converter rating, resulting in the most costly option for converter cost per unit power capability for 2-BESS. One-layer or C-PPP shows a better tradeoff than FPP because only the mismatch power is processed.

FIGURE 6. Comparison of battery utilization as a function of aggregate converter rating $R_p$, for full power processing vs. partial power processing: LS-HiPP and C-PPP. Partial power processing architectures perform significantly better than FPP.
FIGURE 7. Comparison of battery utilization as a function of aggregate converter rating for two partial power processing architectures: LS-HiPPP and C-PPP. LS-HiPPP performs significantly better than C-PPP, needing much lower converter ratings for the same performance. At \( R_p = 15\% \) converter rating and 20% heterogeneity, LS-HiPPP has an battery power utilization of over 95% as opposed to 81% for C-PPP.

2) LS-HiPPP vs. C-PPP
LS-HiPPP shows the best tradeoff for battery power utilization and converter cost. This particular LS-HiPPP design, shown in Fig. 2, uses only three Layer 1 power converters with interconnections and ratings that are optimal for the structure of the statistical distribution of the battery supply. The Layer 2 converters are low power and are designed to accommodate the deviations from the statistical distribution. As a point of comparison in Fig. 7, LS-HiPPP has an expected battery power utilization of 95% with only 15% of the output power processed as opposed to 81% for conventional PPP and 15% for full processing. For the same utilization, LS-HiPPP requires approximately one-fifth of the power converter rating of FPP with the same corresponding reduction in power converter cost, assuming constant $/kW.

3) Effect of Heterogeneity on Battery Utilization
Heterogeneity decreases battery utilization in all second-use BESSs. This is because power converter ratings are selected for a particular design point and pre-manufactured with a directive towards economies of scale. We have observed from Section III-A1 that partial power processing architectures offer the best tradeoff between battery utilization and converter cost.

In this section, we compare the battery utilization for LS-HiPPP with C-PPP as battery heterogeneity increases. As illustrated in Fig. 7 for \( R_p = 15\% \), LS-HiPPP always performs better than C-PPP. The performance of C-PPP falls more drastically at higher battery heterogeneity.

B. SYSTEM EFFICIENCY
The system efficiency is the ratio of the power delivered by the output of the 2-BESS to the sum of the power delivered by each individual battery within the 2-BESS.

\[
\eta_{sys} = \frac{P_{out} - P_{loss}}{P_{out}} = 1 - \frac{P_{loss}}{P_{out}} = 1 - \frac{P_{proc}}{P_{out}}(1 - \eta_{conv}),
\]

(16)

where \( P_{loss} \) represents the converter loss, \( P_{proc} \) represents the processed power by the converters, and \( \eta_{conv} \) is the efficiency of the converters. High system efficiency means lower overall power losses which also means a lower cost of cooling and thermal management. However, high efficiency converters have higher cost. If high system efficiency can be achieved by processing less power or compromising output power capability, then lower cost converters can be used without increasing the cost of cooling. It can be observed from Fig. 9 that as processed power is reduced, system efficiency increases and is less sensitive to converter efficiency.

1) LS-HiPPP vs. C-PPP
In comparing the system efficiency when using low-cost converters with a meager efficiency of 85%, Fig. 10 shows that at \( R_p = 15\% \) converter power rating, LS-HiPPP has a system efficiency of 98.8%, while C-PPP has 97.8% and FPP only 85% (not shown in the figure) because 100% of the power is processed by the converters.

System efficiency has a significant impact on the cost of thermal management. At high efficiencies even a single digit improvement in efficiency is impactful, e.g. at 99%, a 1% decrease in efficiency doubles the requirement for cooling. For example, in a 500 kW BESS operating at 99% efficiency, a 1% decrease in efficiency corresponds to an increase in required heat removal from 5 kW to 10 kW.
FIGURE 9. 3-d plot of system efficiency vs. normalized processed power vs. power converter efficiency. Smaller processed power can result in high system efficiency despite lower power converter efficiency (lower cost power converters).

FIGURE 10. Comparison of system efficiency as a function of aggregate converter power rating $R_p$ for two partial power processing architectures: LS-HiPPP and C-PPP. LS-HiPPP has a higher system efficiency for all cases of heterogeneity and converter rating $R_p$. System efficiency is especially impactful in reducing thermal management and cooling costs.

2) Effect of Heterogeneity on System Efficiency
Battery heterogeneity decreases system efficiency in partial power processing systems. Partial power processing systems are designed to mainly process the mismatch power; heterogeneity increases this mismatch power that the power converters need to process. Fig. 10 shows that as battery heterogeneity becomes higher, the system power efficiency decreases. From Figs. 10 and 11, LS-HiPPP has higher system efficiency than C-PPP in all cases. Fig. 11 illustrates the specific case for $R_p = 20\%$; as battery heterogeneity is greater, the system efficiency decreases.

2. BENEFITS OF LOWER PROCESSED POWER FOR LS-HIPPP
Processed power is the aggregate power flow through the power converters and is normalized by the aggregate intrinsic battery power $\bar{P}_I$

$$\hat{P}_{\text{proc}} = \frac{P_{\text{proc}}}{\bar{P}_I}. \quad (17)$$

The normalized output power is

$$\hat{P}_{\text{out}} = \frac{P_{\text{out}}}{\bar{P}_I}, \quad (18)$$

where $P_{\text{out}}$ is the output power and $\bar{P}_I$ is the aggregate intrinsic battery power.

There are several consequences to having an architecture with low processed power, as illustrated in Fig. 12. The first is lower requirements and subsequently lower cost for cooling. Second, lower processed power means that converters with lower ratings and hence lower cost are required. In comparing

FIGURE 11. Comparison of system power efficiency as a function of battery heterogeneity between LS-HiPPP and C-PPP for $R_p = 20\%$. LS-HiPPP has a higher system efficiency for all cases of heterogeneity. System efficiency is especially impactful in reducing thermal management and cooling costs.

FIGURE 12. 3-d plot of normalized power loss vs. normalized processed power vs. power converter efficiency. Lower processed power results in lower power loss despite lower efficiency (lower cost) power converters. Lower power loss means lower cost of thermal management and cooling.
the two partial power processing architectures, LS-HiPPP and C-PPP, with FPP in Fig. [13]. LS-HiPPP offers the lowest processed power for any choice of converter rating.

In comparing partial power processing architectures in Fig. [14], LS-HiPPP delivers significantly high battery utilization at low processed power. Not only does LS-HiPPP higher battery utilization, but it can also do so at high system efficiency as illustrated in Fig. [15].

**IV. CONCLUSION**

By incorporating the heterogeneity statistics of the battery supply, LS-HiPPP achieves better battery utilization and higher system efficiency for the same converter ratings in comparison to FPP and C-PPP.

At 95% battery utilization, only one-fifth of the power converter rating is needed for LS-HiPPP in comparison to FPP. With the cost of power converters that scale as $/kW, this corresponds to one-fifth of the cost. Additionally, for the same converter power rating, LS-HiPPP has the highest efficiency when compared with C-PPP and FPP.

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