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RESEARCH ARTICLE

Statistical Analysis of Levelized Round Trip Cost of Grid Scale Electrical Energy Storage in Batteries with Different Chemistries

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Abstract: Electrical energy storage is a crucial component of the clean energy transition for integrating high share of renewable electricity generators into the supply mix. In this study, the round-trip costs of grid scale electrochemical energy storage from 2 up to 24 hours for peak power ratings of 1 MW and 10 MW in lithium-ion LFP, lithium-ion NMC, Pb-acid and vanadium redox flow batteries are compared using their currently projected techno-economic characteristics for year 2030. A statistical approach is used for estimating mean costs and quantifying the uncertainties in these estimates, since many of the techno-commercial features are still evolving and are uncertain. Using Monte Carlo simulations to derive the input parameters, the levelized round trip cost of energy storage is found to vary from Rs 10.73±0.77/kWh(e) to Rs 15.96±1.12/kWh(e) for Li-LFP batteries, Rs 14±1/kWh(e) to Rs 20.3±1.46/kWh(e) for Li-NMC batteries, Rs 19.1±1.39/kWh(e) to Rs 58.3±4.28/kWh(e) for Pb-acid batteries and Rs 18.7±1.37/kWh(e) to Rs 44.2±3.19/kWh(e) for Vanadium redox flow batteries, for the range of input values considered in this study. Through sensitivity analysis and calculation of correlation coefficients, the battery installed capital cost and useful lifetime are found to be the two most influential parameters affecting life cycle electrical energy storage cost.

Keywords: batteries, energy storage, levelized cost, Monte Carlo simulations, Techno-economics, uncertainty analysis

1. Introduction

1.1. Importance of battery energy storage systems

The global clean energy transition will require extensive electrification of various energy end uses. Energy storage will be a crucial component of future electricity systems that will make use of significant quantities of variable and intermittent renewable electricity from solar PV and wind-based power generation assets. This is necessary for managing the variability and intermittency of these generators, which are both diurnal and seasonal. To store excess renewable electricity when available and supply it back during phases of low output, grid scale batteries of various chemistries have to be deployed. As part of the global clean energy transition, the cumulative demand for batteries in stationery applications in the power sector is expected to be about 420 GWh(e) by 2040, while for electric mobility applications, battery needs are estimated to be about 6200 GWh(e) by the same time frame [1]. Batteries are also required to provide a host of ancillary services like peak shaving, grid frequency regulation and black start capabilities, which all facilitate renewable integration and contribute to grid stability when increasing the share of variable renewable generators into the electricity supply mix [2]. However, the specific battery chemistry controls many factors such as energy storage density, initial capital cost, round trip efficiency, cyclic life, depth of discharge and so on. At the system level, all these factors influence the techno-economics of the energy storage and recovery process. This work attempts to represent this influence by calculating a well-known metric known as the levelized round trip cost of energy storage (abbreviated as LCOS), while also considering the uncertainties in the values of the pertinent input parameters by adopting a statistical approach.

1.2. Literature review and gap areas motivating the present study

Given the growing importance of batteries in the clean energy systems and the rapid fall in battery pack costs over the last decade, the economics of battery energy storage systems have gained a lot of attention. The values of levelized cost of energy storage in grid scale batteries have been reported by several researchers and agencies. For example, in a very recent study of utility scale battery energy storage projects in the US, the levelized costs have been found to lie between \$ 222-352/MWh for 100 MW, 1 h storage (i.e., Rs 18.4-29.2/kWh), between \$ 188-322/MWh for 100 MW, 2 h storage (i.e., Rs 15.6-26.7/kWh) and \$ 170-296/MWh for 100 MW, 4 h storage (i.e., Rs 14.1-24.6/kWh) respectively [3]. In a study focused on China, the researchers estimate that the LCOS of lead-carbon batteries at 12 MW power and 24 MWh capacity is 0.84 CNY/kWh (i.e., Rs 9.94/kWh), of lithium iron phosphate batteries with 60 MW power and 240 MWh capacity it is 0.94 CNY/kWh (i.e., Rs 11.1/kWh), and for the case of vanadium redox flow batteries with 200 MW power and 800 MWh capacity, it is 1.21 CNY/kWh (i.e., Rs 14.3/kWh) [4]. Li et al estimate that the LCOS in lithium-ion batteries for 20 MW/40 MWh storage is about \$ 0.314/kWh (i.e., Rs 26.1/kWh), which is lowest among other electrochemical energy storage options like redox flow and sodium sulphur batteries [5].

However, the statistical analysis of the costs and the uncertainties around these estimates have been rarely reported in these studies, even though some broad ranges of cost values have been provided in some of these prior works. Some dedicated studies on uncertainty analysis of energy storage projects under very specific conditions have also been reported recently. For example, Liu et al have used Monte Carlo simulations in connection with techno-economic evaluation of a concentrating solar thermal power plant with different types of thermal energy storage and they determine that the combined sensible-latent heat storage system has levelized costs of \$ 0.1321-0.1852/kWh (i.e., Rs 10.96-15.4/kWh) [6]. In a study of building integrated energy storage system covering different locations of United States with uncertainties in the key techno-commercial parameter values, Chadly et al find that the levelized cost of storage is likely to be between \$ 0.27/kWh and \$0.41/kWh, depending on location; they also state that higher LCOS values are likely for higher battery sizes [7]. Shin and Lee have developed a Least Squares Monte Carlo simulations scheme for determination of optimal investment timing in battery energy systems in the fossil fuel dependent Korean energy system [8].

Studies addressing uncertainties of LCOS of different battery chemistries over different storage durations and peak power ratings are very rare in current literature. This is the gap area which this work attempts to address and forms the novelty of this present study. The work aims to support the initial phases of the battery technology selection process and energy storage project development by evaluating these costs and the associated uncertainties, using known distributions of the values of techno-commercial data for stand-alone battery energy storage projects. This is necessary to ensure that the energy storage system designer is cognizant of a range of possible costs associated with each technology alternative, rather than a deterministic point estimate which is just one of these possibilities that will not be known *a-priori* for a given project.

2. Mathematical Model and Input Data

2.1. Defining levelized round trip cost of energy storage

The mathematical model for levelized round trip energy storage calculations is based on the mapping of life cycle cash flows associated with a battery energy storage project. In doing so, it makes use of projected baseline values of installed capital and operating cost, round trip efficiency, cyclic lifetime, depth of discharge and degradation rates for all the batteries in 2030, from existing compilations in recent literature [9]. The baseline techno-commercial data used in this study are shown in Table 1. Each of these values are assumed to have deviations of ±10% about the corresponding baseline, in the form of a uniform distribution. This means that any value of the parameter between ±10% of the baseline, including the baseline value is taken to be equally likely. These input variables are therefore considered to be random variables, uniformly distributed between -10% to +10% of the respective baseline figures.

These uniform distributions of the parameter values are sampled randomly using a Monte Carlo simulation scheme, details of which are available in the author's prior work [10] and described in Section 2.2. The input data set thus generated for each battery type and storage duration is used to calculate the specific life cycle investments or levelized round trip costs of energy storage incurred for each of them. As the expenditures or cash flows take place at different times during the project life cycle, the accounting for the time value of money is carried out through the project discount rate (which is taken as 5% per annum in this study as a baseline value). The present value of the life cycle costs divided by the life cycle energy storage and recovery gives the levelized round trip cost of electricity storage, as shown in Equation (1) and Equation (2).

$$LCOS = \frac{\sum_0^N \frac{capex_t + replace_t + opex_t + OM_t}{DF(i,t)^{-1}}}{\sum_1^N \frac{Q_t}{DF(i,t)^{-1}}} \quad (1)$$

$$DF(i,t) = \frac{1}{(1+i)^t} \quad (2)$$

Here *capex* represents cash flow associated with the total installed capital cost of the battery given total storage capacity (i.e., power rating multiplied by storage duration), *replace* represents costs due to replacement of battery components, *opex* refers to the operating costs and *OM* indicates any other operational and maintenance charges, including any decommissioning or waste management charges, all in year *t* of the project. Here, replacements have not been considered, so $capex_t$ is assumed to be incurred only at the very beginning of the project. The value of *N* is the total project time in years, which in this study is taken to be the battery life time in years. The symbol Q_t refers to total amount of energy stored and released during the year *t* of the project. The term *DF* is the discount factor, calculated from the project discount rate, that is used to convert any future cash flows into their present value. All cash flows are taken on annual basis. The actual price of electricity that has to be stored in the battery is not included in this analysis, since it is assumed to be available as surplus or excess at zero cost for storage, as it would otherwise have to be curtailed in the absence of adequate demand.

The value of $capex_t$ is calculated using Equation (3), using the data on specific installed capital cost (Sp_{capex}), battery capacity (Cap_b), round trip efficiency (RTE) and depth of discharge (DOD) from Table 1 [9]:

$$capex_t = Sp_{capex} \times 1000 \times Cap_b/(RTE \times DOD) \quad (3)$$

The difference breakdown of the battery capital investment into various components is shown in Figure 1 [9] for the case of the Li-LFP batteries for 1 MW, 2 h storage and 10 MW, 24 h storage respectively, using literature data [9]. The actual storage component or the electrochemical cell stack is seen to make up about 30% of the costs for the first case and 41% in the second case, whereas various other components and system level factors contribute to the rest of the installed capital investment needs in differing proportions. This contributes to the realization of economy of scale in battery energy storage systems. But this also shows that the life cycle costs of battery energy storage are not just limited to the cost of the battery pack; there are several other factors at the project level which add to the cost of energy storage. This study focuses on the system level techno-economics using projections made for 2030.

The levelized cost figure may be considered to be that cost per unit of electricity stored and recovered which exactly balances all the capital and operating expenditures incurred during the lifecycle of the energy storage project. Repeating this calculation process for all the input data sets generated by random sampling of the input data distributions gives the distribution of these costs. Decommissioning and waste management costs have not been included in this assessment, for any of the battery types considered. In this study, 60000 samples have been taken for the levelized cost calculations of each type of battery.

Table 1
Battery techno-commercial characteristics data set

(A) Lithium ion LFP battery								
	1 MW				**10 MW**			
	2 h	**4 h**	**10 h**	**24 h**	**2 h**	**4 h**	**10 h**	**24 h**
Capex installed ($/kWh)	398.98	340.46	302.42	284.63	353.58	311.11	282.83	268.98
Fixed OM ($/kW-y)	2.69	4.28	8.99	19.77	2.37	3.89	8.38	18.65
Round trip efficiency	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Depth of discharge	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Life (y)	16	16	16	16	16	16	16	16
(B) Lithium ion NMC battery								
	1 MW				**10 MW**			
	2 h	**4 h**	**10 h**	**24 h**	**2 h**	**4 h**	**10 h**	**24 h**
Capex installed ($/kWh)	440.85	381.35	342.3	323.69	393.36	349.95	320.72	306.09
Fixed OM ($/kW-y)	2.93	4.75	10.14	22.46	2.6	4.34	9.47	21.21
Round trip efficiency	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Depth of discharge	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Life (y)	13	13	13	13	13	13	13	13
(C) Pb-acid battery								
	1 MW				**10 MW**			
	2 h	**4 h**	**10 h**	**24 h**	**2 h**	**4 h**	**10 h**	**24 h**
Capex installed ($/kWh)	533.64	458.84	410.01	386.84	481.56	423.35	384.63	365.56
Fixed OM ($/kW-y)	3.96	6.09	12.37	26.74	3.47	5.5	11.47	25.13
Round trip efficiency	0.71	0.73	0.78	0.79	0.71	0.73	0.78	0.79
Depth of discharge	0.58	0.68	0.8	0.8	0.58	0.68	0.8	0.8
Life (y)	12	12	12	12	12	12	12	12
(D) Vanadium Redox Flow battery								
	1 MW				**10 MW**			
	2 h	**4 h**	**10 h**	**24 h**	**2 h**	**4 h**	**10 h**	**24 h**
Capex installed ($/kWh)	695.9	486.85	361.42	312.65	634.53	449.55	338.57	295.41
Fixed OM ($/kW-y)	4.99	6.6	11.43	22.7	4.49	6.03	10.63	21.36
Round trip efficiency	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Depth of discharge	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Life (y)	12	12	12	12	12	12	12	12
(E) Other data common to all battery types								
Project discount rate (% p.a.)	5% as baseline value ± 10% uniform variation about baseline							

Currency exchange rate	1 USD = 83 INR
Battery capacity degradation rate (% p.a.)	1% baseline value ± 10% variation about the baseline
No. of daily full charge-discharge cycles	1 (i.e., 365 cycles per year)

2.2. Description of solution methodology

Let each of the input parameters be random variable which are described by a uniform distribution, with the lowest value being a and the highest value being b. The probability density function for any one such variable X is therefore defined as

$$f(X|a,b) = \frac{1}{(b-a)} \; for \; a \leq x \leq b \\ = 0 \; otherwise \tag{4}$$

Let p represent the probability for the random variable X to have a value between x and $x + dx$, given values of a, b. In this study, if c represents the baseline value of the parameters as shown in Table 1, then for ±10% uniform variation about the baseline, the range of the uniform distribution can be specified as $a = 0.9*c$ and $b = 1.1*c$. This therefore defines the input distribution for each parameter value.

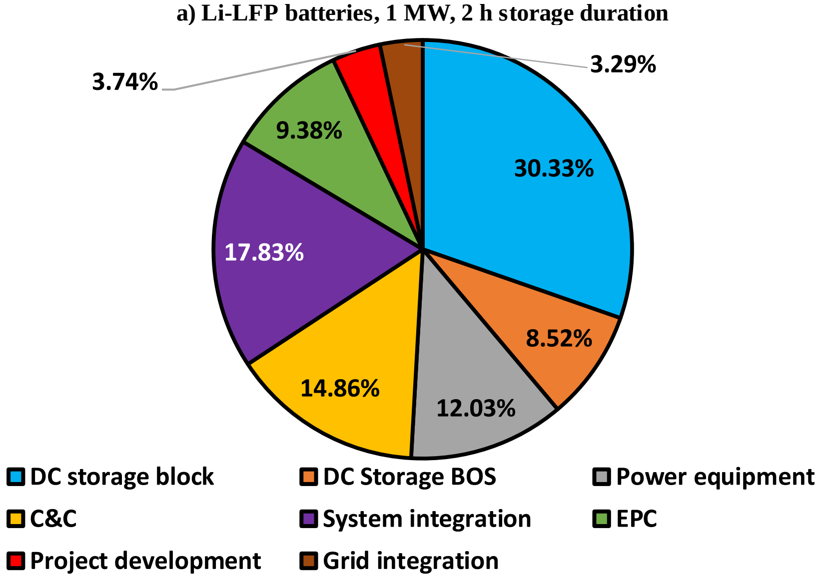
The Monte Carlo simulation technique is then applied to randomly sample the probability distributions representing each of the input parameters and obtain a set of values of each of the parameters concerned. The technique involves generating a random number (which represents a probability of getting a certain value of an input parameter from its given distribution function), assigning its value to p, computing the inverse of the distribution based on Equation (4) to get the parameter value corresponding to p, repeating this sampling process for each input distribution to get all values of necessary inputs. This is followed by determining the LCOS using Equation (1), using the sampled set of values of the parameters.

3. Results and Discussion

3.1. Calculated round trip levelized costs of electrical energy storage

Figures 2a and 2b show the important descriptive statistics of the estimated levelized electricity storage cost values for all the 4 battery chemistries at 8 discrete cumulative installed capacities, ranging from 2 MWh(e) to 240 MWh(e). The figures indicate the mean and standard deviations of levelized round trip energy storage cost respectively and they are reported for all the battery chemistries and capacities. This permits a side-by-side comparison of the techno-economics of energy storage across battery chemistries and storage capacities. The coefficient of variance (i.e., the standard deviation divided by the mean) which is a non-dimensional measure of the spread about the mean value, expressed as a percentage is seen to lie between 6.91 and 7.33% for all the battery types considered.

Figure 1
Apportionment of total installed battery capital cost into various components
a) Li-LFP batteries, 1 MW, 2 h storage duration



b) Li-LFP batteries, 10 MW, 24 h storage duration

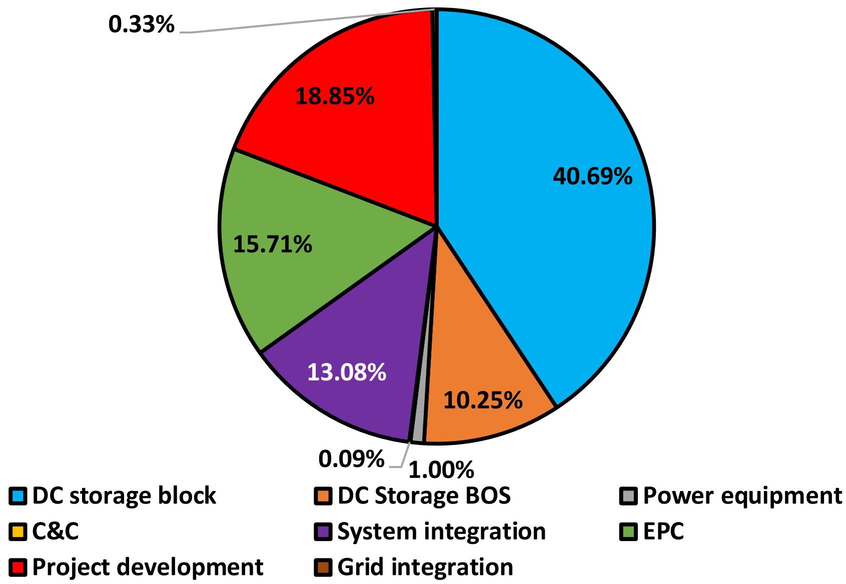


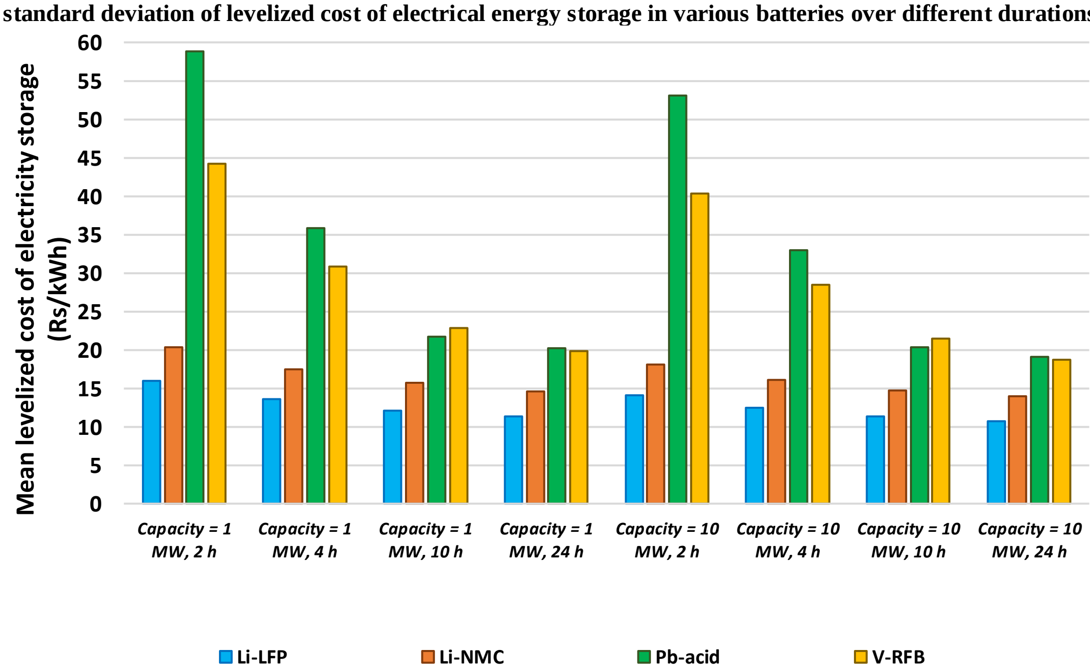
Table 2 shows the normalized mean levelized cost for each battery chemistry at 1 MW and 10 MW power rating and 4 durations. Each value in the table has been derived by dividing the average cost by the least average cost of energy storage in the series of values corresponding to that specific battery chemistry and power rating. These figures are rough indicators of the economy of scale realized in battery storage over different durations and capacities.

Figures 3 to 6 show the calculated distributions of the levelized cost of storage for each battery chemistry at the same capacity of 240 MWh(e) (i.e., 10 MW, 24 h storage duration, which is the highest installed battery capacity considered in this work). The distributions are found to be well approximated as normal distributions, which permits greatly simplified inferential statistics studies to be done, using the properties of the well-known distributions.

Figure 2

a) Estimated mean levelized cost of electrical energy storage in various batteries over different durations b) Estimated standard deviation of levelized cost of electrical energy storage in various batteries over different durations

a)



b)

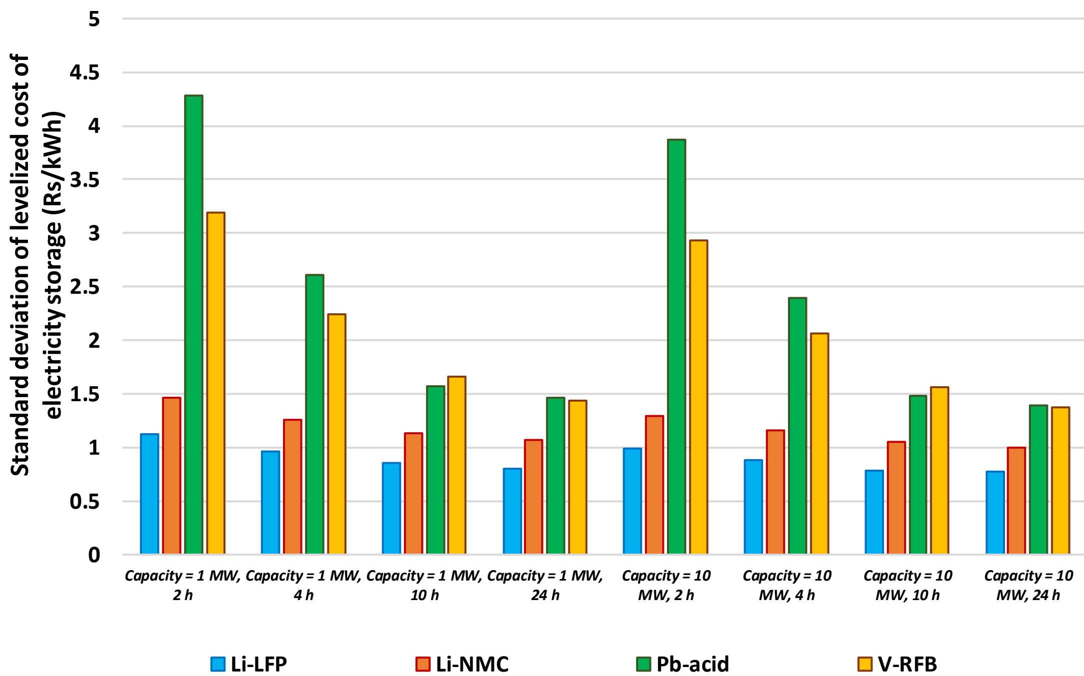


Table 2
Normalized mean levelized round trip cost of electricity storage at 1 MW and 10 MW power ratings and different storage durations and battery chemistries

Capacity	Li-LFP	Li-NMC	Pb-acid	V-RFB
1 MW, 2 h	1.406	1.390	2.911	2.232
1 MW, 4 h	1.198	1.199	1.772	1.561
1 MW, 10 h	1.063	1.075	1.074	1.157
1 MW, 24 h	1.000	1.000	1.000	1.000
10 MW, 2 h	1.319	1.293	2.780	2.155
10 MW, 4 h	1.158	1.150	1.728	1.524
10 MW, 10 h	1.052	1.050	1.068	1.150
10 MW, 24 h	1.000	1.000	1.000	1.000

3.2. Parametric sensitivity analysis

Figures 7 to 10 show scatter plots of the levelized cost of electricity storage as function of battery capital cost, installed cost, life and project discount rate respectively, for Li-LFP and Pb-acid batteries (which are the least and most expensive battery systems identified in the previous section) at the lowest considered and highest considered capacities in this study, respectively. These plots indicate the general direction and strength of the association between the storage cost and each of these input parameters. The association is quantified in Table 3 which reports the statistical correlation coefficients of the cost with each of these parameters, which is calculated as in Equation (5):

$$r_{XY} = \frac{cov(X,Y)}{\sigma_X \sigma_Y}, \tag{5}$$

Here X stands for one of the input parameters from Table a and Y represents the estimated levelized energy storage cost (based on the sampled X values) and r_{XY} is determined in turn for four of the input variables–estimated levelized cost combinations. Higher magnitude represents stronger influence and correlation of the input on cost, while the sign of r_{XY} determines the direction (i.e., increasing or decreasing Y with corresponding changes in the value of X) of this impact.

Figure 3
Distribution of levelized round trip cost of electrical energy storage in Li-LFP batteries (10 MW, 24 h storage duration)

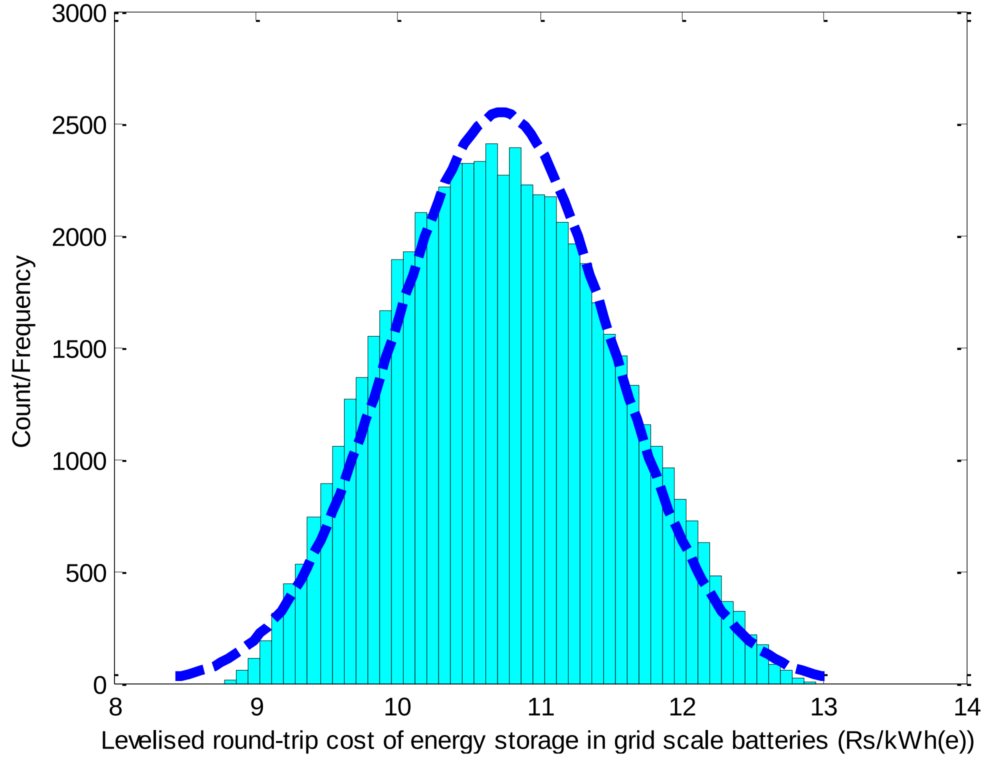


Figure 4
Distribution of levelized round trip cost of electrical energy storage in Li-NMC batteries (10 MW, 24 h storage duration)

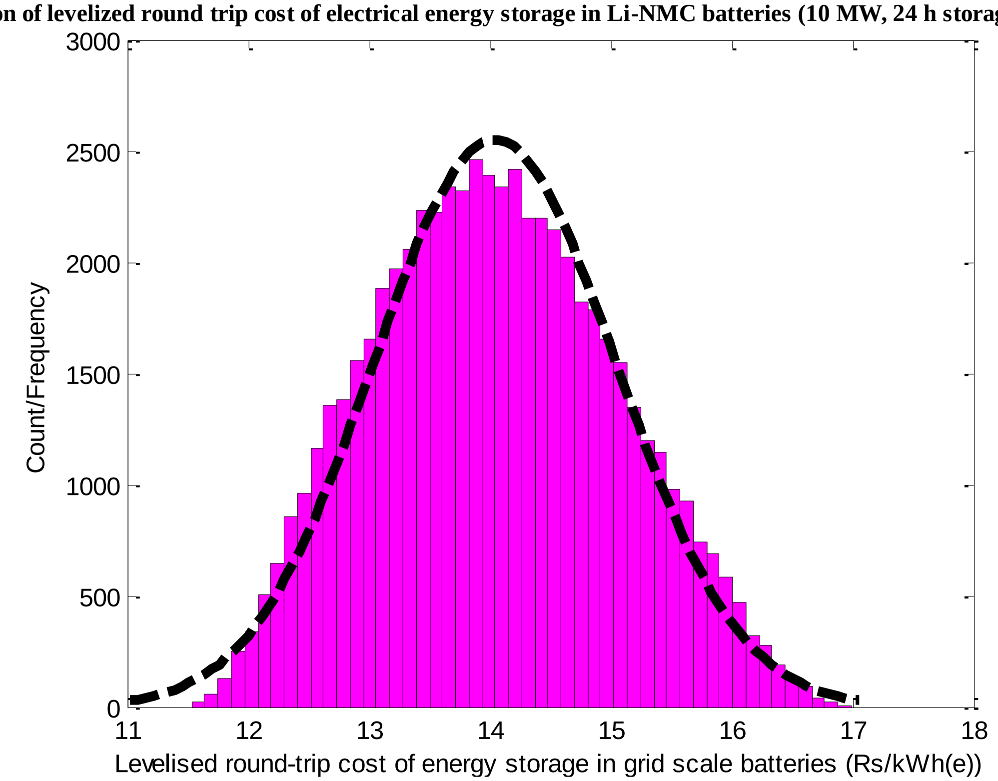


Figure 5

Distribution of levelized round trip cost of electrical energy storage in Pb-acid batteries (10 MW, 24 h storage duration)

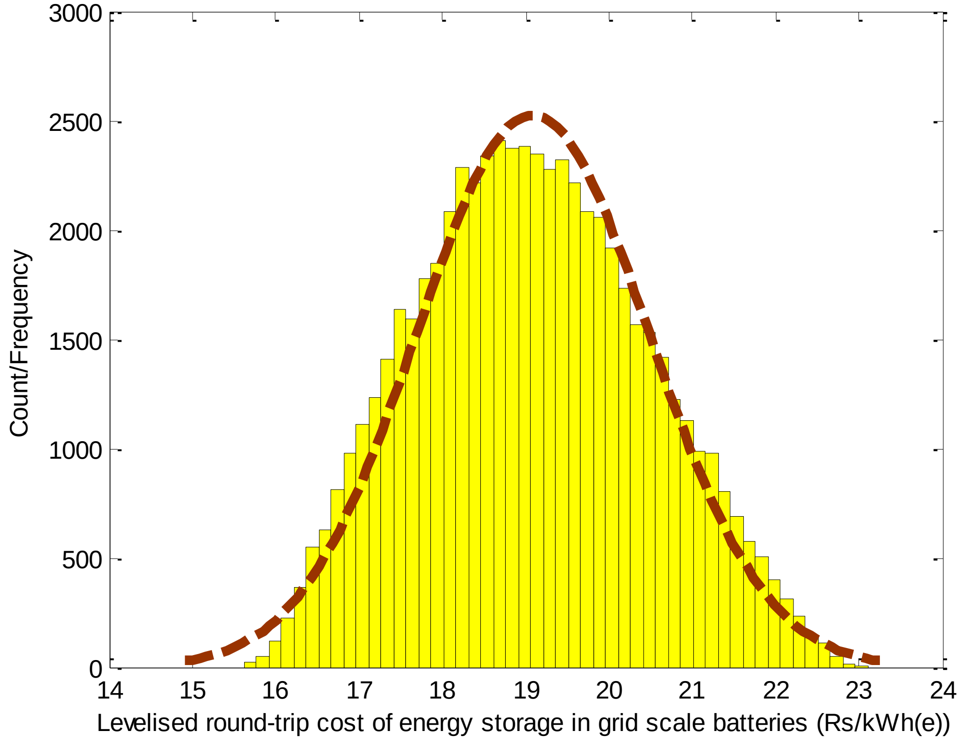


Figure 6

Distribution of levelized round trip cost of electrical energy storage in Vanadium Redox Flow batteries (10 MW, 24 h storage duration)

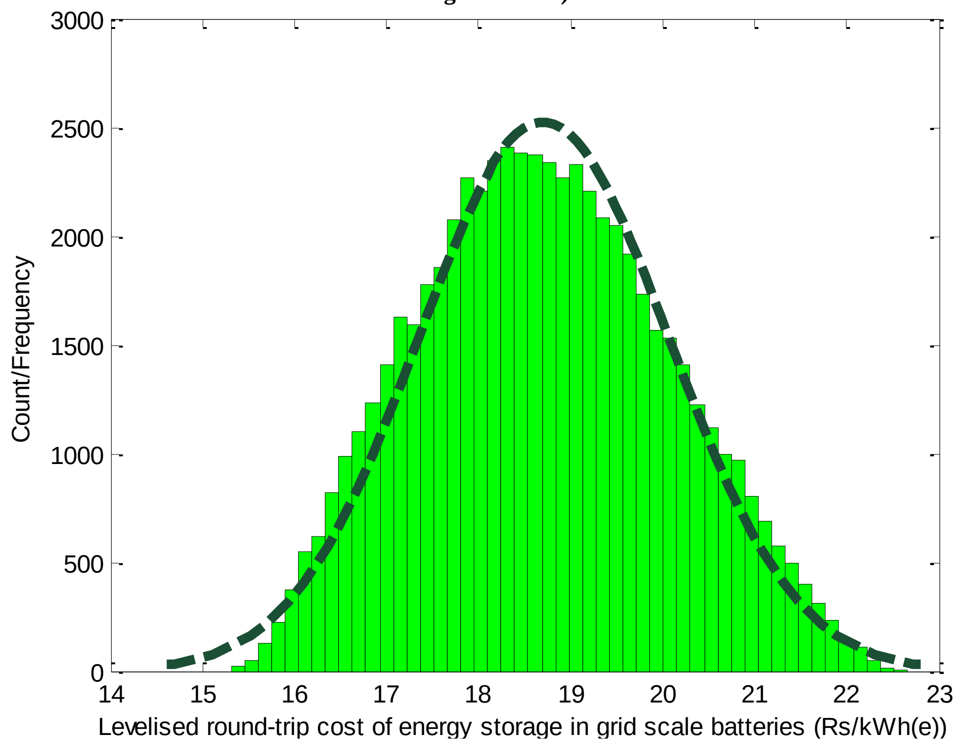


Table 3
Calculated correlation coefficients of levelized round trip cost of electrical energy storage in different batteries chemistries with techno-commercial factors

Battery chemistry	Correlation coefficient between	Battery capacity = 1 MW, 2 h	Battery capacity = 10 MW, 24 h
Li-LFP	Levelized cost, capital cost	0.79798	0.79866
	Levelized cost, operating cost	0.02099	0.0166
	Levelized cost, battery life	-0.52692	-0.53164
	Levelized cost, Project discount rate	0.28614	0.2887
Pb-acid	Levelized cost, capital cost	0.78416	0.78336
	Levelized cost, operating cost	0.01272	0.01146
	Levelized cost, battery life	-0.5789	-0.57838
	Levelized cost, Project discount rate	0.21796	0.22128

Figure 7
Sensitivity of levelized round trip cost of electrical energy storage to various input parameters (Li-LFP batteries, 1 MW, 2 h storage)

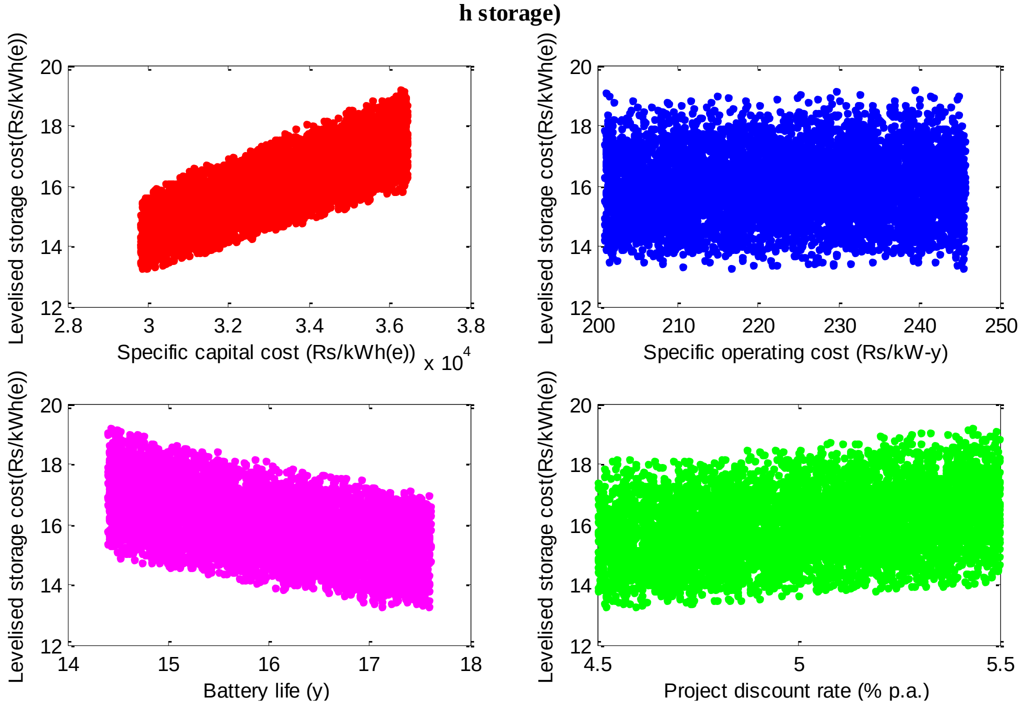


Figure 8

Sensitivity of levelized round trip cost of electrical energy storage to various input parameters (Li-LFP batteries, 10 MW, 24 h storage)

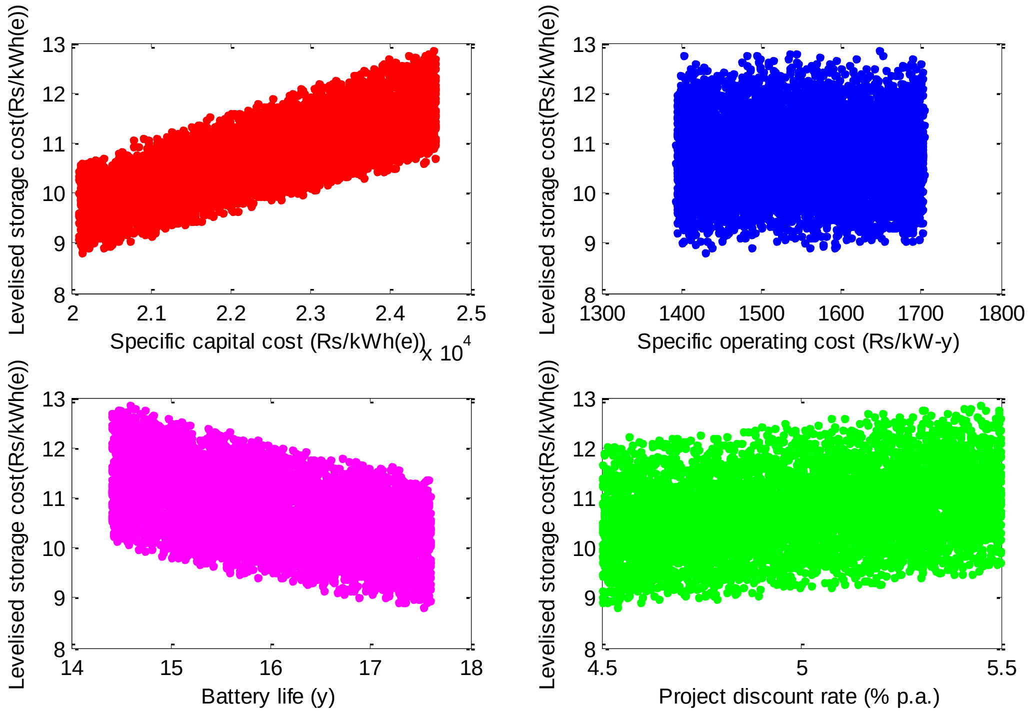


Figure 9

Sensitivity of levelized round trip cost of electrical energy storage to various input parameters (Pb-acid batteries, 1 MW, 2 h storage)

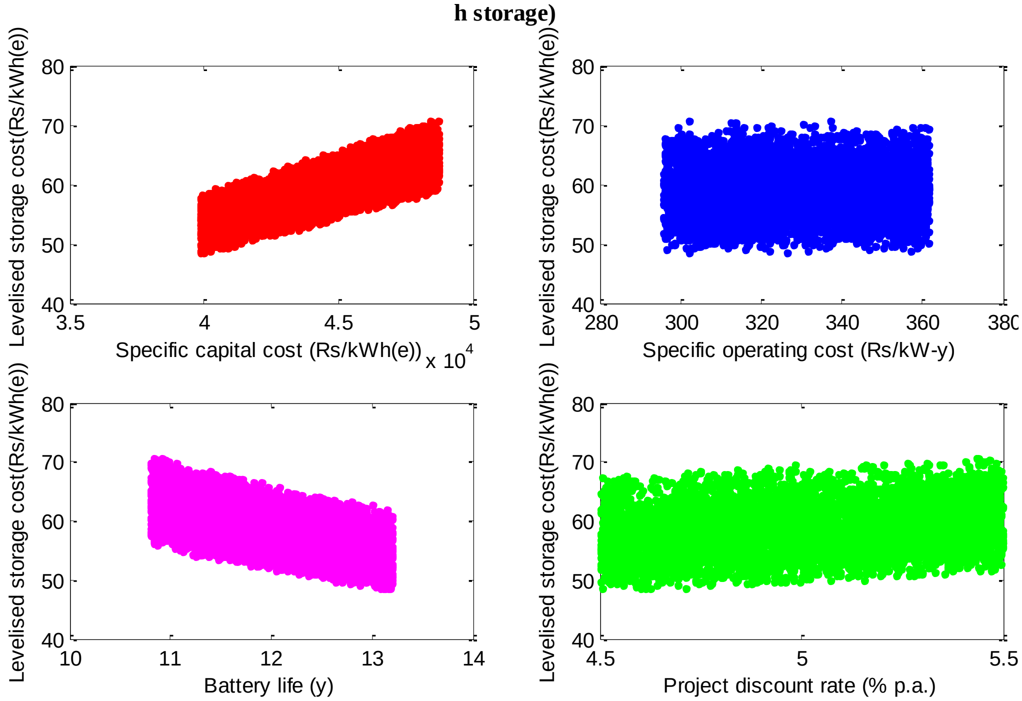
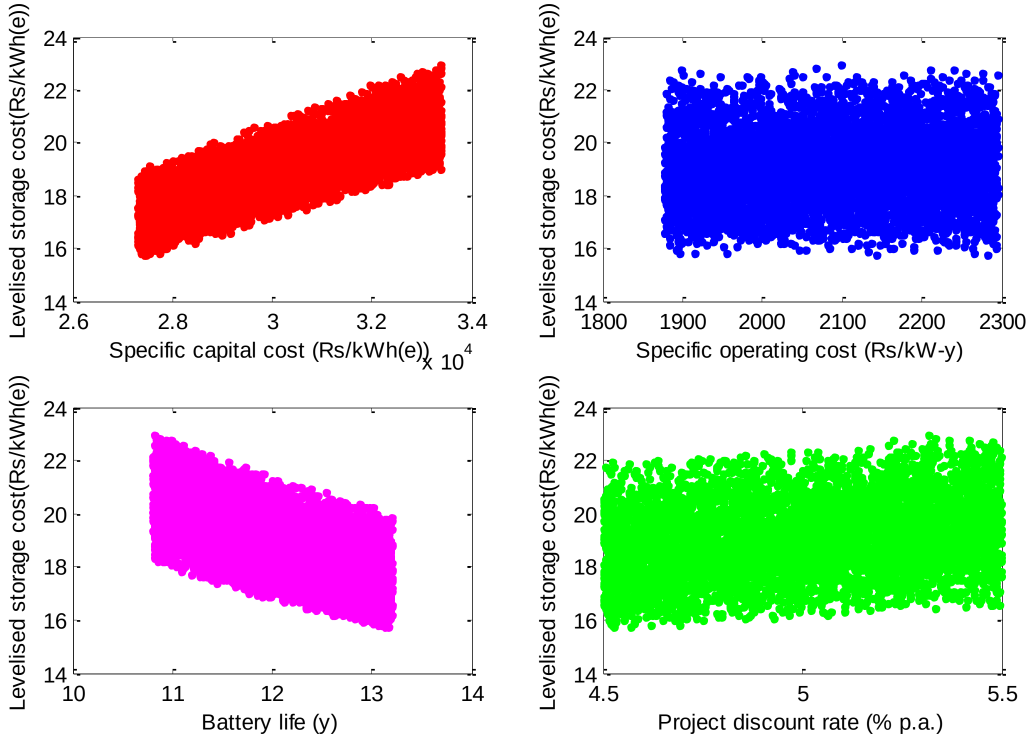


Figure 10
Sensitivity of levelized round trip cost of electrical energy storage to various input parameters (Pb-acid batteries, 10 MW, 24 h storage)



3.3. Sampling distributions of mean and standard deviation of levelized cost of energy storage

The procedure to obtain the distribution of levelized costs is performed multiple times (600 times in this study, with a sample size of 60000 for each run) for each battery type. The values of the mean and standard deviation of levelized cost are obtained from each of these 600 distributions. These values are recorded and shown in the scatter plots of Figures 11 to 14, for Li-LFP and Pb-acid batteries at the lowest considered and highest considered capacities in this study, respectively. These sampling distributions of the two key statistics of the levelized cost distributions are important for deriving metrics related to inferential statistics, such as confidence intervals of the mean and standard deviation for any chosen level of significance.

3.4 Detailed discussion of obtained results

The following key results and observations are drawn from the results in Tables 2 and 3 and in Figures 2 to 14:

a) From Figure 2a and Figure 2b, it is seen that the levelized round trip cost of energy storage varies from Rs 10.73±0.77/kWh(e) to Rs 15.96±1.12/kWh(e) for Li-LFP batteries, Rs 14±1/kWh(e) to Rs 20.3±1.46/kWh(e) for Li-NMC batteries, Rs 19.1±1.39/kWh(e) to Rs 58.3±4.28/kWh(e) for Pb-acid batteries and Rs 18.7±1.37/kWh(e) to Rs 44.2±3.19/kWh(e) for vanadium redox flow batteries, depending on the storage time and peak power rating. These values lie roughly in the range of values discussed in Section 1.2, despite there being different techno-commercial data sets and assumptions used for calculations in different studies. Thus, after this benchmarking, the techno-commercial merit order for these batteries at a given storage capacity, based on levelized storage costs may be expressed as follows:

$$Li - LFP < Li - NMC < V - RFB < Pb - acid \qquad (6)$$

b) From Figures 2a and 2b, it is concluded that for any battery chemistry and power rating, the mean levelized cost of electricity storage decreases with increasing duration. The most relevant figures are for the duration of 2 to 10 hours, since most battery projects round the world are being deployed to cater to peak daily demands over such time frames, with anything longer than 10 h duration being designated as long duration storage [11, 12]. For any battery chemistry and given duration, the levelized cost is found to decrease with increase of peak power rating.

c) From Figures 2a and 2b, it is concluded that out of the 4 battery technologies considered in this study, the Li-LFP battery chemistry has the least levelized cost of energy storage at any duration and power rating. This makes it the best currently available choice for grid scale electricity storage projects.

Figure 11
Sampling distributions of mean and standard deviations of levelized round trip cost of electrical energy storage (Li-LFP batteries, 1 MW, 2 h storage)

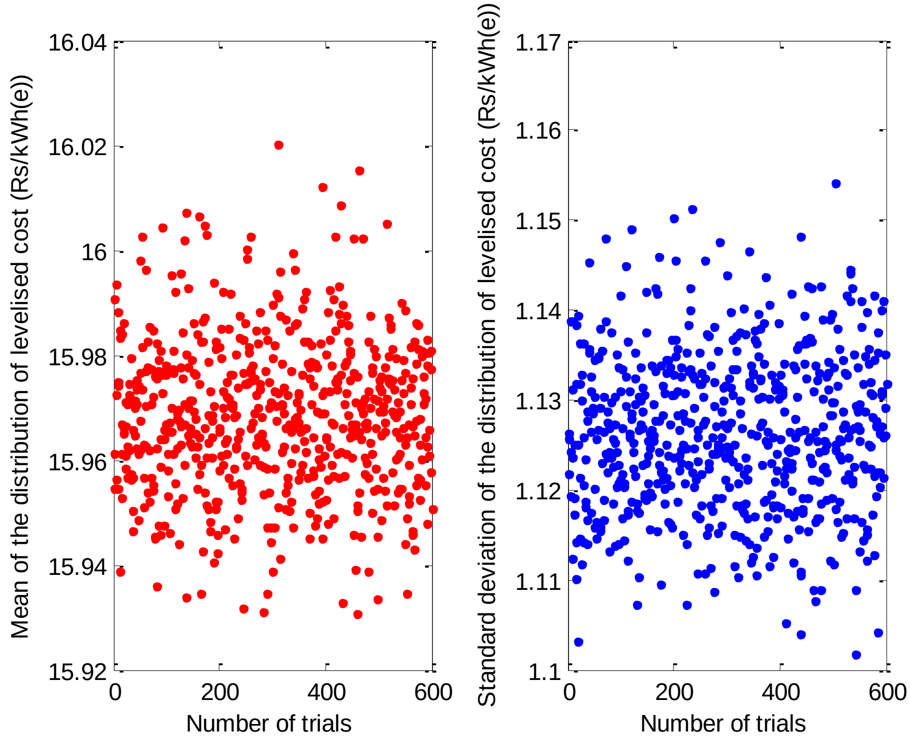


Figure 12
Sampling distributions of mean and standard deviations of levelized round trip cost of electrical energy storage (Li-LFP batteries, 10 MW, 24 h storage)

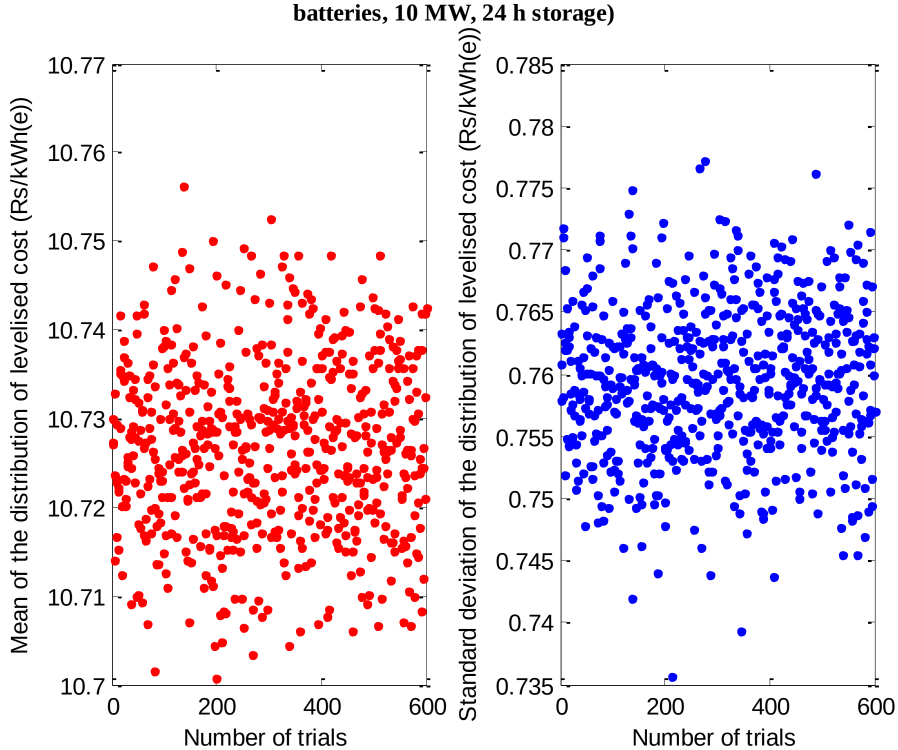


Figure 13
Sampling distributions of mean and standard deviations of levelized round trip cost of electrical energy storage (Pb-acid batteries, 1 MW, 2 h storage)

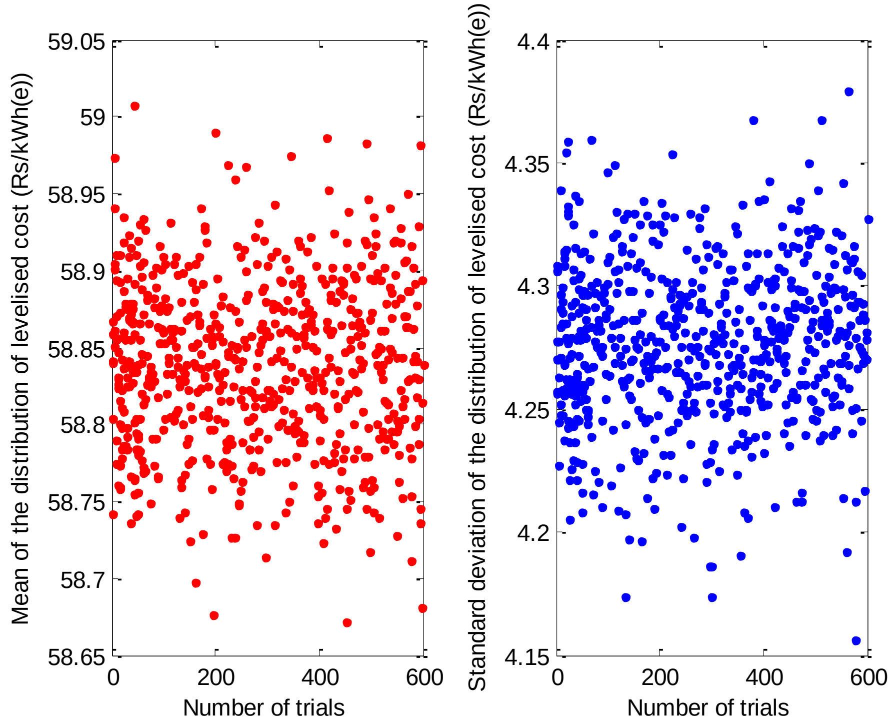
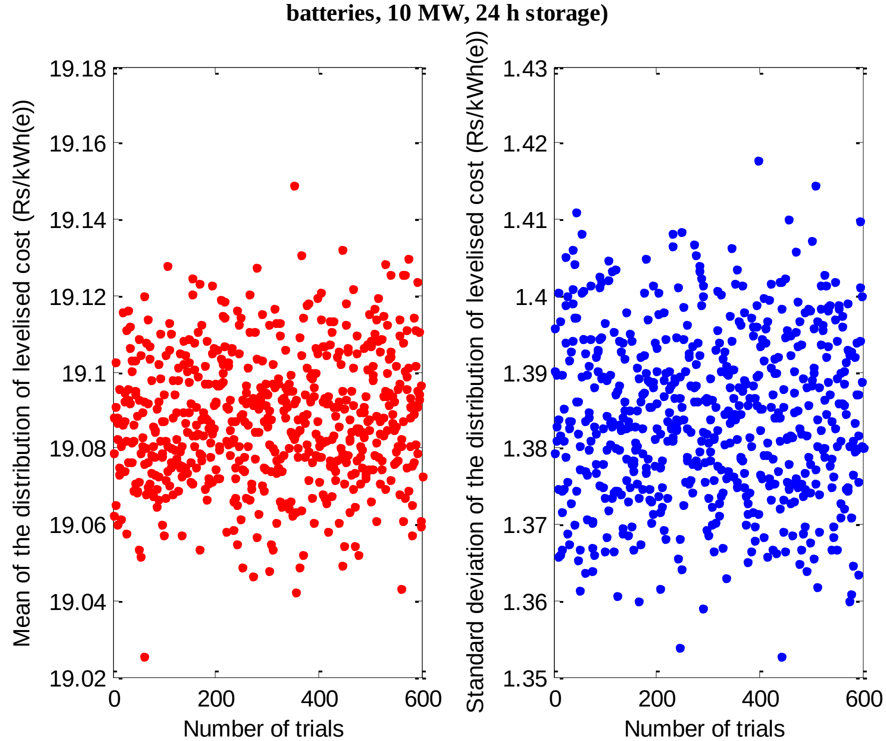


Figure 14
Sampling distributions of mean and standard deviations of levelized round trip cost of electrical energy storage (Pb-acid batteries, 10 MW, 24 h storage)



d) Figure 2 also shows that Pb-acid batteries are the least viable electricity storage option for grid scale energy storage projects. On average, the costs of storage in Pb-acid batteries are seen to be 1.78 to 3.68 times higher than that in Li-LFP batteries of equivalent storage capacity, whereas in terms of total installed capital cost incurred during the start of the project, Pb-acid batteries are only 1.34-1.36 times more expensive than equivalent capacity Li-LFP batteries.

e) Even though Pb-acid batteries have been commercially mature technologies for a long time, they are not economically viable compared to Li-ion batteries for same capacity, due to higher installed capital costs and lower round trip efficiency and depth of discharge. Thus, technological maturity does not automatically guarantee more economical outcomes as other alternatives may have matured faster and reached better technical characteristics compared to an established alternative, exhibiting a steeper learning curve effect.

f) Figure 2b shows that the standard deviation or uncertainty in battery storage cost estimates is lowest for Li-LFP batteries and highest for Pb-acid batteries, at any power rating and duration. The deviation decreases with increase in battery capacity, for any of the battery chemistries considered. This is due to the fact that the batteries are capital cost intensive and capital costs show economy of scale effects. Thus, the impact of capital cost variability on the levelized cost of energy storage is decreased at higher storage capacities.

g) Economy of scale effects are found to be substantial in case of battery energy storage. For example, from the data in Table 2, it can be seen that for Li-LFP batteries with 1 MW rating, there is on average, a 40.6% reduction in levelized storage cost when storage duration increases by 12 times from 2 h to 24 h. However, when storage duration increases by 2.4 times only in going from 10 h to 24 h storage, the storage cost decreases by only 6.3%, showing no major gain in terms of economies of scales. Thus, a plateauing off of the benefits of scaling up battery capacities may be expected at higher capacities. This can be explained by noting that grid scale batteries are modular technologies – higher capacities are realized by adding a greater number of modules of identical capacities and prices, and not by increasing the capacity of an individual module.

h) Table 2 also shows that the most significant economies of scale are observed in the case of Pb-acid batteries and the least impact of scale is seen in the case of Li-NMC batteries. Thus, longer duration and higher capacity storage are somewhat more economical for Pb-acid batteries rather than short duration storage. But absolute costs are still higher for Pb-acid batteries, compared to the other considered battery chemistries.

i) The levelized energy storage cost distributions for the shown in Figures 3 to 6 for the different battery chemistries are very close to normal distributions, despite the input parameters being assumed to vary uniformly about the baseline values. Similar distributions are also obtained for the other cases i.e., storage durations and capacities and their means and standard deviations are shown in Figures 2a and 2b.

Once the nature of the distribution and these two parameters are identified, inferential statistics-based analysis can be carried out for any of the given cases. For example, from Figure 3 and using the well-known properties of normal distributions, it can be stated that about 68% of the battery storage projects of 10 MW, 24 h duration and using the Li-LFP battery chemistries will incur a life cycle round trip storage and delivery cost of Rs 10.73 ± 0.77/kWh(e) i.e., between Rs 9.96/kWh(e) to Rs 11.5/kWh(e). It can also be said that there is less than 1% probability of such a project incurring a round trip cost beyond Rs 13.04/kWh(e), since this figure corresponds to the (mean + 3 times standard deviation) of the cost distribution. It can also be inferred that there is less than 1% probability of such a project incurring a round trip cost less than Rs 8.42/kWh(e) given current state of art and project budgeting should never be less than this figure for this kind of battery. Similar insights can be derived from each of the Figures 3 to 6. These are very useful at the project planning and budgeting stage where single or point values are inadequate and do not reflect all the possibilities.

j) Results from the sensitivity analysis reported in the scatter plots of Figures 7 to 10 are significant as they show how strongly and in which direction the input parameters influence the levelized energy storage costs in different battery chemistries. While the scatter in the data does not allow for a specific mathematical form to be fitted to the points, the value of the correlation coefficient calculated from them provides useful insights. They indicate that in general, the levelized storage cost rises sharply as installed capital cost of batteries increases because of the high positive value of the correlation coefficient, but it is practically insensitive to the operating cost (as seen from the very small value of correlation coefficient) which forms a much smaller share of the life cycle costs associated with the energy storage project. Similarly, improvement in battery life strongly influences the storage cost reduction, while the project discount rate has very little influence on it, at least for the range of its values considered in this study. These results are important for battery manufacturers because it indicates the potential area of further development and cost reduction that they have to target as well as battery storage project developers and energy end users because it indicates to them which aspect of the cost (i.e., initial capex or replacement capex) they should prioritize in project budgeting.

k) The correlation coefficients calculated from the scatter plots of Figures 7 to 10 and reported in Table 3 show that the strongest positive correlation of levelized energy storage cost is seen to be with the installed capital cost of the batteries and the strongest negative correlation is with the battery life. This holds true irrespective of battery capacity or chemistry. Thus, it may be reported that the reduction in capital cost and improvement in battery lifetime are the two strongest levers to bring down the levelized cost of electricity storage.

l) Figures 7 to 10 also prove that the correlation coefficient of cost with battery life is stronger for the Pb-acid battery than for the Li-LFP battery. However, the correlation with capital cost is seen to be almost similar for these two cases. Project discount rate has a higher positive correlation with the cost of storage in Li-LFP batteries compared to Pb-acid batteries, whereas battery lifetime has a stronger negative correlation to cost for Pb-acid batteries.

m) From the sampling distribution of means and standard deviations of the levelized costs of energy storage in different batteries shown in Figures 11 to 14, it is seen that the values lie in a fairly narrow interval for all the cases considered. Thus, substantially high confidence levels for the true population mean and standard deviation can be derived using these distributions with fairly narrow confidence intervals around each descriptive statistic metric. Therefore, the mean values reported in Figure 2 are quite robust and useful for initial project planning and techno-commercial assessments of battery energy storage systems under input data uncertainty. As a large number of trials have been carried out, these sampling distributions of means and standard deviations can themselves be very well approximated as normal distributions, thereby greatly facilitating inferential statistics calculations around them.

n) From Figure 2, the coefficient of variance for the levelized cost of energy storage is seen to lie between 6.91% to 7.33% across all the cases considered in this study. Thus, even though the magnitude of uncertainty in terms of the value of standard deviation is quite different, the percentage uncertainty around the mean is nearly similar for all the battery chemistries, peak power rating and storage durations considered.

3.5 Benchmarking of results against other studies

Comparison of the levelized costs of electrical energy storage obtained in this study against the previous results discussed in Section 1 shows that the present results (i.e., mean costs) are broadly in line with internationally reported levelized cost figures. This study additionally presents the likelihoods of obtaining a certain range of costs for a given type of battery, using the derived probability distributions (e.g., the representative examples shown in Figures 3 to 6). This is not provided in previous studies. Using the levelized storage cost database from PNNL [13], it is seen that their estimate of levelized electricity storage cost in 2030 varies between $ 0.2-0.4/kWh(e) i.e., Rs 16.6-33.2/kWh(e) for the 4 battery chemistries considered here, with storage durations between 2 to 24 h and power ratings between 1 and 100 MW. These values are also encompassed in the distributions derived in the work, showing the validity of this approach and the results of this study.

4. Summary and Conclusions

Grid scale electrical energy storage systems are an important component of future clean energy systems which will integrate a substantially higher share of variable and intermittent renewable electricity generators compared to the present-day scenario in most locations. These technologies are maturing fast and battery cells or cell packs have reported large drops in cost. But considering the relevant system level life cycle cost factors associated with an energy storage project based on grid scale batteries (beyond only the battery cell cost), it is still found to be very expensive today on a per unit electricity stored basis, especially when compared with the cost of renewable electricity generation per unit. In this study based on statistical analysis of life cycle round trip costs of electrical energy storage in different batteries, the Li-LFP batteries are found to be the most commercially viable option for large scale electricity storage at present, given their comparatively lower capital cost, higher life time, greater round-trip efficiency and depth of discharge, while Pb-acid batteries are found to be the least feasible option, despite having a longer track record of technology deployment. Substantial capital cost reductions and useful life improvement are required to improve their viability and the overall cost effectiveness of renewable electricity supply in a round-the-clock manner.

Further work in this direction may be undertaken as follows:

a) The work reported in this paper may be extended to understanding and comparing techno-commercial uncertainties around upcoming battery chemistries such as sodium-ion batteries [14], sodium-sulphur batteries [15], zinc-based batteries [16] or aluminum-air batteries [17], provided a certain level of reliable input data are available about them. This is especially significant in the context of long duration energy storage, for which lithium ion batteries are still far from being cost effective [18].

b) Instead of pre-decided battery capacities as have been taken in this study, battery sizing and costing for management of a given demand-supply situation can also be undertaken with this approach (an example is found in a previous work of the author [19]). Optimal battery sizing exercises under demand-supply uncertainty for various scales and in the presence of other demand side flexibility mechanisms which reduce the need for energy storage can also be undertaken [20, 21].

c) The other elements of life cycle costing such as replacement and end-of-life management with decommissioning of the battery systems can also be included into the calculations, as long as relevant data are available to establish the corresponding cash flows associated with an energy storage project.

d) As the technologies evolve and the fundamental parameters affecting the levelized cost of energy storage change, these calculations must be repeated to reflect the current state-of-the-art to facilitate better intercomparisons at any point of time.

e) The costs of electricity (and hence the cost of charging the batteries) which may vary throughout the day depending on the design of the electricity market can also be included in estimation of levelized energy storage costs to get more decision useful values.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by the author.

Conflicts of Interest

The author declares that she has no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Rupsha Bhattacharyya: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration.

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