Techno-economic comparison of lead-acid and lithium-ion batteries in residential PV systems: A multi-location study of Abuja, Beijing, and Washington DC

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Abstract

This study presents a comparative techno-economic assessment of residential solar photovoltaic (PV) systems integrated with lead-acid and lithium-ion battery storage across three representative global locations: Abuja (Nigeria), Beijing (China), and Washington D.C. (United States). PV system performance was simulated using PVsyst, while economic evaluation was conducted using life-cycle cost analysis over a 25-year project lifetime. The analysis incorporated location-specific solar resources, market-based component prices, and electricity tariffs, and evaluated system performance using capital expenditure (CAPEX), levelized cost of electricity (LCOE), net present value (NPV), and a weighted techno-economic performance index (WTPI). The results show that Abuja has the highest solar resource (GHI ≈ 2,042 kWh/m^2/yr), followed by Beijing (1,564 kWh/m^2/yr) and Washington D.C. (1,503 kWh/m^2/yr). However, Beijing achieves the lowest LCOE (≈ 0.112–0.121 USD/kWh), outperforming Abuja (≈ 0.139–0.160 USD/kWh)and Washington D.C. (≈ 0.276–0.301 USD/kWh). The lead-acid system is economically viable in Abuja (NPV ≈ $384), while all systems in Beijing and Washington DC yield negative NPVs (down to ≈ –$4,673 for Washington DC). Lead-acid systems outperform lithium-ion systems in Abuja and Beijing, whereas lithium-ion systems exhibit slightly better economic performance in Washington DC. Sensitivity analysis identifies discount rate as the most influential parameter affecting LCOE. Overall, the results demonstrate that PV–battery system performance is strongly location-dependent and driven more by market conditions than solar resource alone.

Keywords: Solar photovoltaic, Battery storage, Levelized cost of electricity (LCOE), Net present value (NPV), PVsyst, Global electricity markets

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1. Introduction

The increasing global demand for clean and reliable electricity has accelerated the deployment of renewable energy technologies, particularly solar photovoltaic (PV) systems [1,2]. Solar PV has emerged as one of the fastest-growing renewable energy technologies due to declining costs, technological improvements, and supportive policy frameworks across many countries [3,4]. However, the intermittent nature of solar energy presents operational challenges for electricity systems, especially in residential applications where demand may not coincide with PV generation periods [5,6]. To address this limitation, energy storage systems, particularly battery storage, are increasingly integrated with PV systems to improve energy reliability, enhance self-consumption, and reduce dependence on grid electricity [7,8].

Battery energy storage systems play a critical role in enabling the effective utilization of distributed renewable energy by storing excess electricity generated during peak solar production periods and supplying it during periods of low generation or high demand [9,10]. The integration of PV and battery storage has therefore become an important strategy for improving energy security, reducing electricity costs, and facilitating the transition to low-carbon energy systems [11,12].

Among the various battery technologies available for stationary energy storage, lead-acid and lithium-ion batteries remain the most widely deployed in residential PV systems [13,14]. Lead-acid batteries have historically dominated stationary storage applications due to their relatively low upfront cost, technological maturity, and widespread availability [15–17]. However, they suffer from limitations such as lower energy density, shorter cycle life, and lower depth-of-discharge compared with newer battery technologies [18–20]. In contrast, lithium-ion batteries offer higher efficiency, longer operational lifetimes, and improved energy density, although their initial investment cost is typically higher [21,22].

Recent studies have investigated the techno-economic performance of PV systems combined with different battery technologies. For example, Kebede et al. conducted a techno-economic analysis of lithium-ion and lead-acid batteries integrated into a grid-connected PV system and found that lithium-ion batteries can provide lower lifetime costs due to their longer lifespan and higher efficiency, even though their initial capital cost is higher [23]. Similarly, Carroquino et al. compared the economic performance of these battery types across several demand scenarios and emphasized that the optimal battery technology depends strongly on system configuration, electricity tariffs, and load characteristics [24].

Other techno-economic analyses of PV-battery systems have also highlighted the importance of site-specific factors such as solar resource availability, electricity price structures, and local equipment costs [25–28]. These factors significantly influence key economic indicators such as levelized cost of electricity (LCOE), net present value (NPV), and payback period [29–32]. Studies have shown that the economic viability of PV-battery systems can vary widely between regions depending on solar irradiation levels, technology costs, and electricity market conditions [33–36].

Despite extensive research on PV–battery systems, most existing studies are limited to single-location analyses or do not incorporate real market-based component pricing across different countries. In addition, limited attention has been given to how battery technology choice interacts with regional electricity tariffs and cost structures to influence system feasibility.

This study addresses these gaps by performing a comparative techno-economic evaluation of residential PV systems using lead-acid and lithium-ion batteries across three distinct global electricity markets: Abuja (Nigeria), Beijing (China), and Washington DC (United States). These locations were selected to represent diverse electricity markets, solar resource conditions, and equipment cost structures. Using system design and performance simulations, the study evaluates the technical and economic performance of the PV-battery systems based on key indicators including system production, solar fraction, capital expenditure (CAPEX), levelized cost of electricity (LCOE), and net present value (NPV).

The main objective of this study is to determine how battery technology choice and regional market conditions influence the techno-economic feasibility of residential PV systems. By comparing results across three geographically and economically distinct locations, the study provides insights into the economic competitiveness of PV-battery systems and highlights the role of local market conditions in shaping investment decisions for distributed renewable energy systems.

2. METHODOLOGY

2.1. Study locations and PV array orientation

The techno-economic performance of residential PV–battery systems was evaluated for three representative locations: Abuja (Nigeria), Beijing (China), and Washington D.C. (United States). These locations were selected to represent diverse electricity market conditions, solar resource availability, and technology cost environments.

Abuja represents a rapidly developing electricity market in Sub-Saharan Africa characterized by high solar irradiation and increasing reliance on distributed energy systems. Beijing represents a major Asian market with extensive renewable energy deployment and relatively lower component costs due to local manufacturing. Washington D.C. represents a developed electricity market with comparatively higher system costs and lower solar resource availability.

Each location was defined within PVsyst 8 simulation software, and system simulations were performed independently. The optimal PV array orientation (tilt and azimuth) for each site was determined using the PVsyst orientation optimization tool to maximize annual energy production.

The geographic coordinates, optimal PV orientation, and solar resource parameters, including Global Horizontal Irradiation (GHI) and Global Irradiation on the Tilted Plane (GTI), are presented in Table 1.

Table 1: *Study locations and available solar resources*

S/N	Location	Country	Coordinates	PV array optimal azimuth/plane tilt	GHI (kWh/m^2/yr)	GTI (kWh/m^2/yr)
1	Abuja	Nigeria	9.0643°N, 7.4893°E	180°/15°	2,042	1,902
2	Beijing	China	39.9078°N, 116.3980°E	0°/22°	1,564	1,874
3	Washington DC	USA	38.8866°N, 77.0327°W	0°/58°	1,503	1,683

2.2. Residential load profile

A representative residential load profile corresponding to a three-bedroom household without air conditioning was used in this study. The load includes typical household appliances such as lighting, refrigerator, fans, television, and small electronics.

The estimated daily energy consumption is **10.8 kWh/day**, corresponding to an annual demand of **3,942 kWh/year**. This load level is consistent with reported residential consumption patterns in similar contexts and provides a realistic basis for evaluating PV system performance under moderate demand conditions. The hourly load distribution was defined in PVsyst to simulate realistic consumption patterns. The detailed appliance-based energy demand and load composition are presented in Table 2 and Figure 1.

Table 2: *Load profile and estimated residential energy demand (3-bedroom apartment)*

S/N	Appliance	Wattage/App.	No. of App.	Daily usage (h/day)	Daily energy demand (Wh)
1	Electric Fan	60 W	5	08	2,400
2	Electric Bulb 1	12 W	6	10	720
3	Electric Bulb 2	6 W	8	10	480
4	Fridge/Freezer	2,000 Wh/d	1	24	2,000
5	Blender/Washer/Iron	1,000 W	1	02	2,000
6	PC/TV	100 W	4	08	3,200
				Total E_d	**10,800 Wh**
				Total E_a	**3,942 kWh**

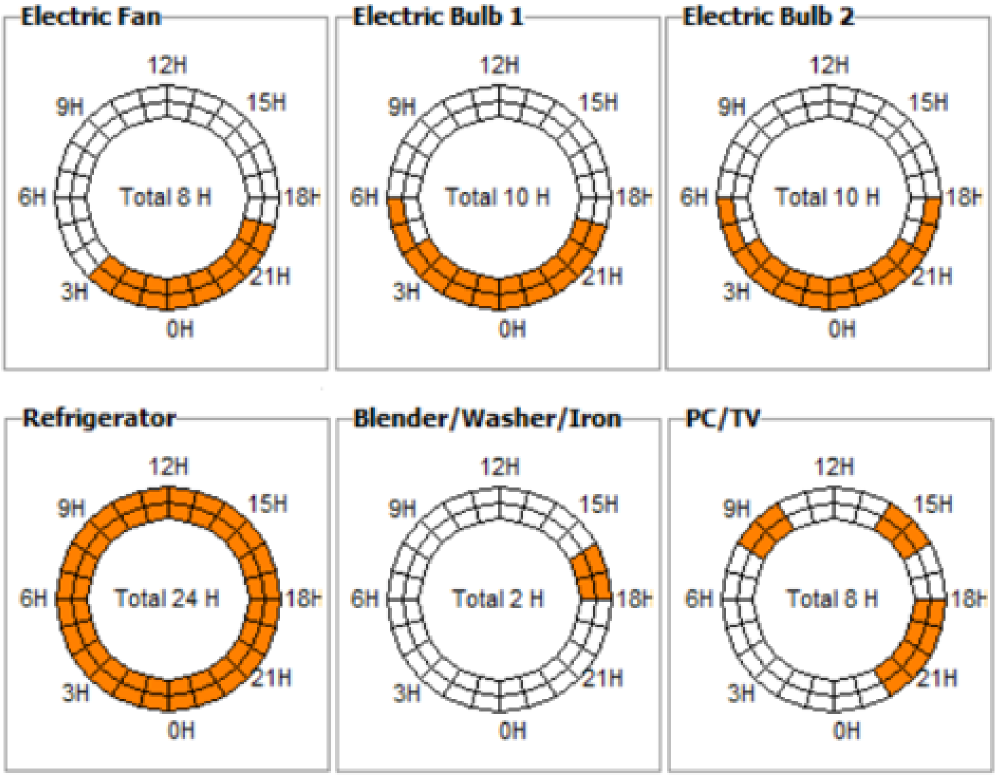

Figure 1: *Household appliances daily energy demand distribution*

2.3. System configuration and design criteria

The system consists of a standalone residential PV system integrated with battery storage and a hybrid inverter. Two battery technologies were considered: Lead-acid battery and Lithium-ion battery ($LiFePO_4$).

The system design was carried out in PVsyst based on predefined reliability and operational constraints, including nominal DC system voltage of **48 V**, maximum allowable loss of load probability of **5%, and** autonomy of **1.5 days**. Using these constraints, PVsyst provided feasible system sizing ranges. The optimal configuration for each battery type was selected based on system reliability and performance.

2.4. PV system simulation

The technical performance of the PV systems was simulated using PVsyst 8. The simulation outputs include Annual energy production (kWh/year), Specific energy production (kWh/kWp/year), Solar fraction, Performance ratio, Battery lifetime and energy throughput. These outputs formed the basis for subsequent economic evaluation.

2.5. Economic evaluation

The economic performance of the PV–battery systems was evaluated using key techno-economic indicators, including Capital expenditure (CAPEX), Operational expenditure (OPEX), Levelized cost of electricity (LCOE), and Net present value (NPV). A project lifetime of **25 years** and a discount rate of **10%** were assumed.

Capital Expenditure (CAPEX): The total capital cost of the system was estimated using equation (1):

$$CAPEX = C_{PV} + C_{inv} + C_{batt} + C_{other} \tag{1}$$

where: C_{PV} = cost of PV modules, C_{inv} = cost of inverter, C_{batt} = cost of battery storage, and C_{other} = accessories, installation, and logistics costs.

The “other costs” category includes mounting structures, wiring, protection devices, installation, transportation, and contractor overheads. Based on established cost analyses from IRENA, NREL, and Fraunhofer ISE, “other costs” typically account for **30–60% of module cost** in residential systems [37–39]. In this study, a base value of **50% of PV module cost** was adopted, with sensitivity analysis performed over the range of **40–60%**. Component prices were obtained from international e-commerce platforms (Jumia, AliExpress, and Amazon) to approximate local market conditions.

Operational Expenditure (OPEX): The yearly operational expenditure comprises repair and maintenance (R&M) costs and yearly provision for battery replacement. The repair and maintenance component of OPEX was assumed to be 1.5% of CAPEX. This assumption is consistent with reported values for residential PV systems [40].

Electricity Tariffs: The unit electricity tariffs for Abuja, Beijing, and Washington D.C. were assumed to be **0.150 USD/kWh, 0.077 USD/kWh**, and **0.160 USD/kWh**, respectively.

Levelized Cost of Electricity (LCOE): The levelized cost of electricity was calculated using equation (2):

$$LCOE = \frac{\sum_{t=0}^{N} \frac{c_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+r)^t}} \tag{2}$$

where: C_t= system cost in year t, E_t= energy generated in year t, r= discount rate, and N= project lifetime.

Net Present Value (NPV): The net present value was calculated using equation (3):

$$NPV = \sum_{t=0}^{N} \frac{B_t - C_t}{(1+r)^t} \tag{3}$$

where: B_t is the benefit from electricity savings, and C_t is the cost in year t. A positive NPV indicates economic viability.

2.6. Weighted techno-economic performance index

To enable an integrated comparison of PV systems with storage battery performance across the study locations, a **Weighted Techno-Economic Performance Index (WTPI)** was developed. The index combines three key indicators representing technical performance, energy reliability, and economic efficiency. The indicators include **Specific PV production (SP)** – technical productivity of the PV system, Solar **fraction (SF)** – reliability of energy supply, and **Levelized cost of electricity (LCOE)**) – economic efficiency. Since these indicators have different units and ranges, they were first **normalized**.

For **benefit indicators** (higher values are desirable), normalization was performed using equation (4a) while for **cost indicators** (lower values are desirable), normalization was performed using equation (4b):

$$X_{norm} = \frac{X_i}{X_{max}} \tag{4a}$$

$$X_{norm} = \frac{X_{min}}{X_i} \tag{4b}$$

where X_i = value of the indicator for location i, X_{max} = maximum observed value, and X_{min} = minimum observed value.

The **Weighted Techno-Economic Performance Index** was then calculated from equation (5):

$$WTPI = w_1 SP_{norm} + w_2 SF_{norm} + w_3 LCOE_{norm} \tag{5}$$

where w_1, w_2, w_3 = weighting factors, and $w_1 + w_2 + w_3 = 1$.

In this study, the following weights were assigned: w_1=0.3,w_2=0.3,and w_3=0.4. The LCOE was given the highest weight because economic performance is often the primary factor influencing investment decisions for residential PV systems.

2.7. Sensitivity evaluation

A sensitivity analysis was conducted to evaluate the influence of key parameters on system economics. The analysis considered variations in battery cost, PV module cost, inverter cost, discount rate, R&M cost percentage, and other cost percentages.

The sensitivity analysis focused on the impact of these parameters on the levelized cost of electricity (LCOE).

3. Results and Discussion

The results of the techno-economic analysis of residential PV–battery systems across Abuja, Beijing, and Washington D.C. are presented and discussed in this section. The analysis considers both lead-acid and lithium-ion battery technologies, with emphasis on their comparative performance under different solar resource and market conditions.

3.1. Solar resource and PV system performance

The solar resource availability for the three study locations is presented in Figure 2 while the specific PV energy production is presented in Figure 3.

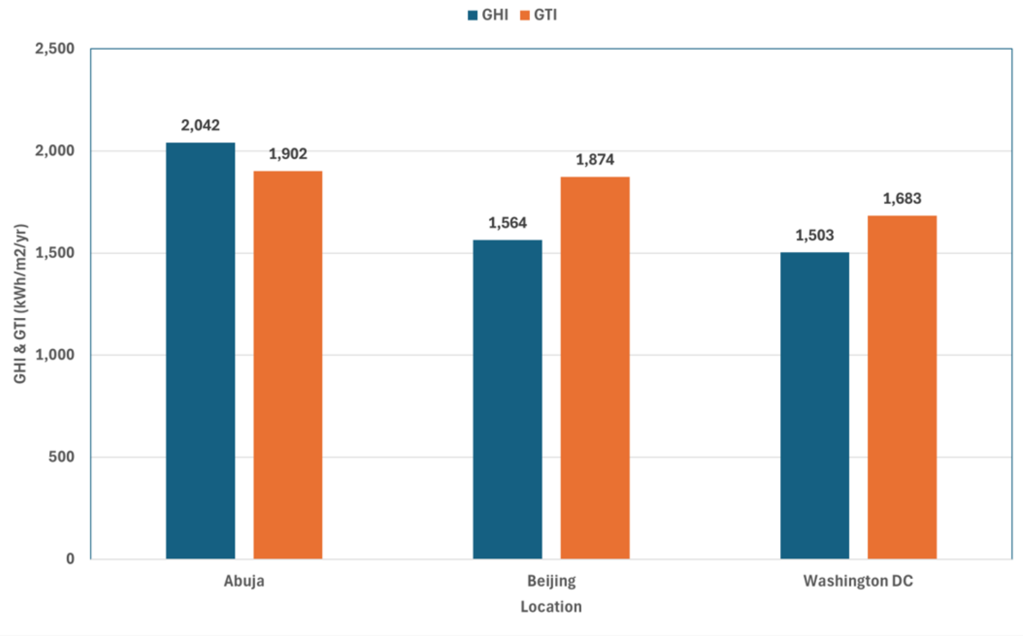

Figure 2: *Solar Resource Comparison*

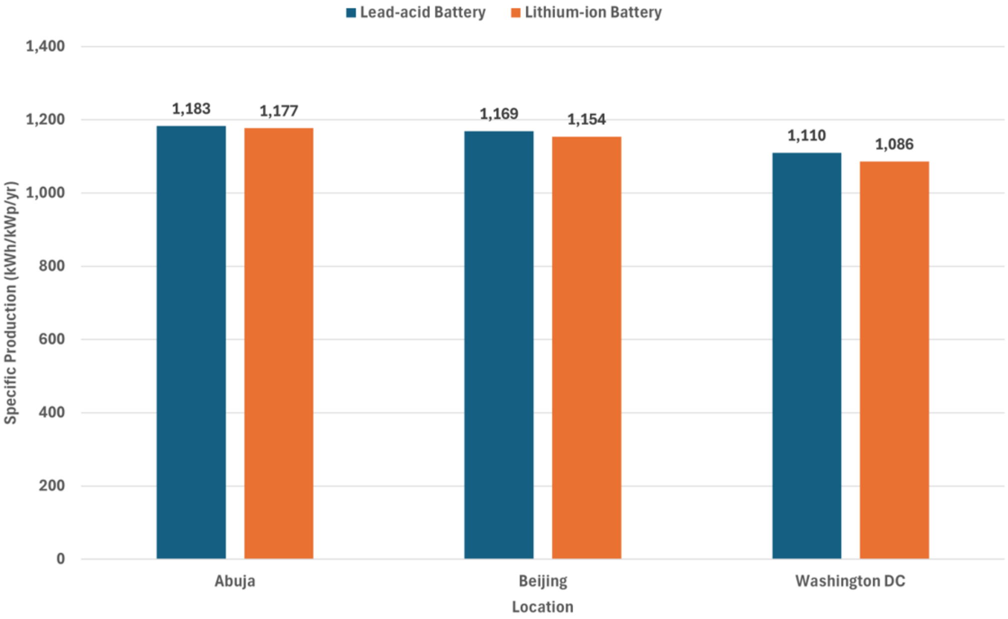

Figure 3: *Specific PV Energy Production*

The solar resource comparison shown in Figure 2 indicates that Abuja has the highest annual solar irradiation among the three locations, followed by Beijing and Washington D.C. This is consistent with their geographical positioning, as Abuja benefits from its lower latitude and more stable solar conditions. The corresponding specific PV energy production presented in Figure 3 follows a similar trend, with Abuja achieving the highest specific yield, while Washington D.C. records the lowest. These results confirm that solar resource availability is a primary determinant of PV system output; however, as shown later in the economic analysis, it is not the sole determinant of system cost-effectiveness.

Across the three locations, the differences in specific production between the lead-acid and lithium-ion configurations are relatively small because both battery systems are coupled to the same PV generator size. Thus, the main distinctions between the two systems arise more strongly in their economic indicators than in their energy output.

3.2. Cost structure and capital expenditure analysis

The average market prices of the major components are presented in Table 3, while the resulting system capital expenditures are shown in Tables 4 and 5 and summarized in Figure 4. For all three locations, the lead-acid system has a lower CAPEX than the lithium-ion system.

Table 3: *Average market unit price of major components*

S/N	Country	330 Wp mono Si solar panel price ($)	12 V/200 Ah gel lead-acid battery price ($)	48 V/200 Ah LFP batteries ($)	3.0 kW/48 Vdc hybrid inverter price ($)	Currency exchange rate (/$)
1	Nigeria	60	210	1,330	350	₦1,400.00
2	China	50	150	900	350	¥6.95
4	USA	250	310	1300	400	$1.00

Table 4: *CAPEX for Solar PV System with lead-acid battery*

S/N	Description	Specification	Qty	Unit	Abuja Total Cost ($)	Beijing Total Cost ($)	Washington DC Total Cost ($)
1	PV Module	330 Wp mono-crystalline Si	10	No	600	500	2500
2	Battery	12 V, 200 Ah sealed gel	8	No	1,680	1,200	2,480
3	Hybrid Inverter	2.8 kW, 48 Vdc / 220 Vac, MPPT	1	No	350	350	400
4	Other Costs	Accessories, Installation, & Logistics	1	Lot	300	250	1250
		Total			**2,930**	**2,300**	**6,630**

Table 5: *CAPEX for Solar PV System with lithium-ion battery*

S/N	Description	Specification	Qty	Unit	Abuja Total Cost ($)	Beijing Total Cost ($)	Washington DC Total Cost ($)
1	PV Module	330 Wp mono-crystalline Si	10	No	600	500	2500
2	Battery	48 V, 200 Ah LFP	2	No	2,660	1,800	2,600
3	Hybrid Inverter	2.8 kW, 48 Vdc / 220 Vac, MPPT	1	No	350	350	400
4	Other Costs	Accessories, Installation, & Logistics	1	Lot	300	250	1250
		Total			**3,910**	**2,900**	**6,750**

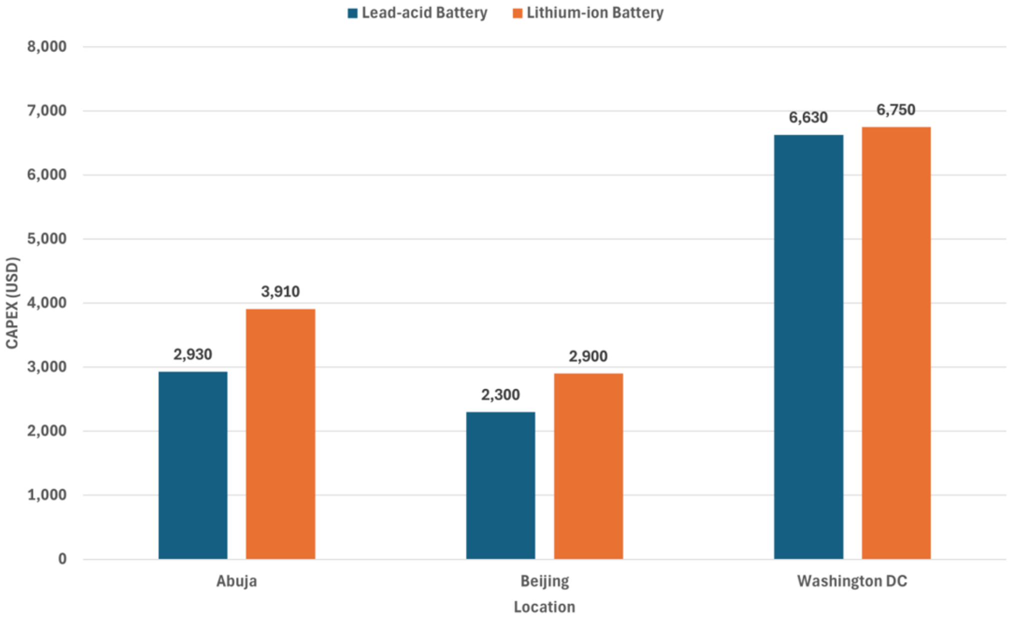

Figure 4: *CAPEX Comparison chart*

For Abuja, the lead-acid system CAPEX is $2,930 compared with $3,910 for the lithium-ion system. In Beijing, the corresponding values are $2,300 and $2,900, while in Washington D.C. they are $6,630 and $6,750, respectively. This pattern is primarily driven by the higher upfront cost of lithium-ion batteries relative to lead-acid batteries.

Among the three locations, Beijing has the lowest CAPEX for both battery options, reflecting lower local component prices. Washington D.C. has by far the highest CAPEX, mainly due to significantly higher module, battery, and installation-related costs. These findings indicate that location-specific market prices exert a strong influence on total system cost, thereby confirming previous findings reported in the literature [31,41]

The lithium-ion systems consistently exhibit higher CAPEX than lead-acid systems due to the higher cost of lithium-ion batteries, although this is partially offset by their longer lifetime and lower replacement costs.

3.3. Operational cost analysis

The annual operational expenditure (OPEX) for both battery technologies is presented in Tables 6 and 7. OPEX includes battery replacement provisions and maintenance costs.

Table 6: *OPEX for Solar PV System with lead-acid battery*

S/N	System Services	Abuja Yearly Cost ($)	Beijing Yearly Cost ($)	Washington DC Yearly Cost ($)
1	Provision for battery replacement	176	142	271
2	Repairs and Maintenance	44	35	99
	Total	**220**	**177**	**370**

Table 7: *OPEX for Solar PV System with lithium-ion battery*

S/N	System Services	Abuja Yearly Cost ($)	Beijing Yearly Cost ($)	Washington DC Yearly Cost ($)
1	Provision for battery replacement	133	99	144
2	Repairs and Maintenance	59	44	101
	Total	**192**	**143**	**245**

The annual OPEX values shown in Tables 6 and 7 indicate that the lead-acid systems incur higher replacement-related costs than the lithium-ion systems, mainly because of their shorter battery life. For example, in Abuja, the lead-acid system has an annual OPEX of $220, compared with $192 for the lithium-ion system. Similar trends are observed in Beijing and Washington, DC.

Although this gives lithium-ion an operational cost advantage, the reduction in OPEX is not sufficient to offset its higher initial capital cost within the economic framework of this study. As a result, the lower OPEX of lithium-ion systems does not translate into superior overall techno-economic performance.

This finding is important because it shows that, under the assumptions used in this study, lower replacement and maintenance costs alone are insufficient to make lithium-ion systems economically preferable.

3.4. Levelized cost of electricity (LCOE)

The levelized cost of electricity (LCOE) for the different system configurations is presented in Figure 5.

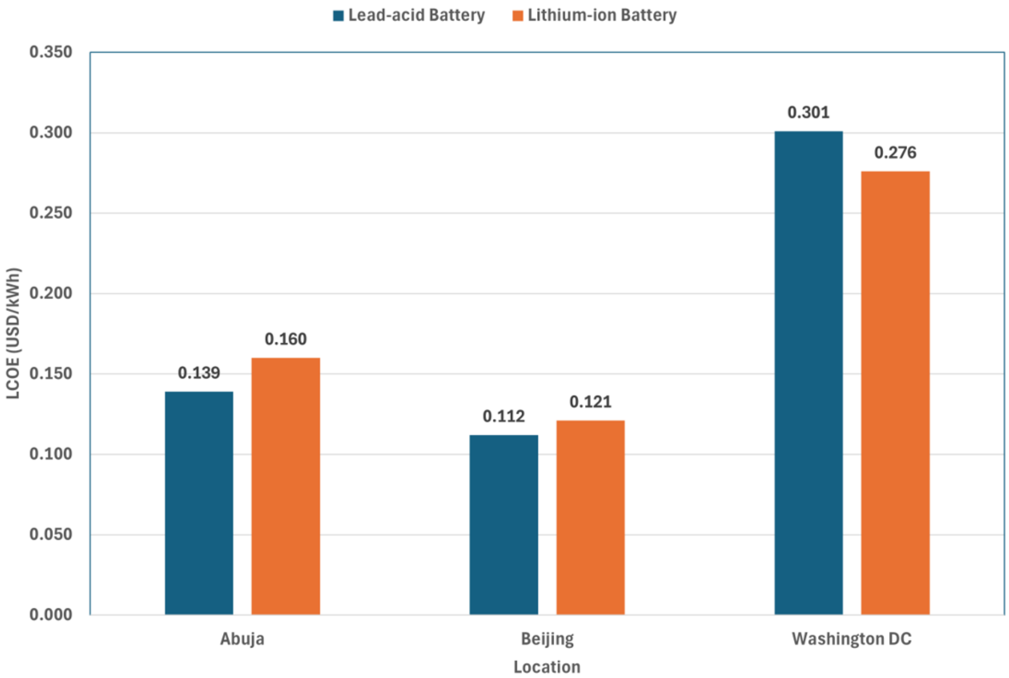

Figure 5: *LCOE Comparison chart*

The levelized cost of electricity results presented in Figure 5 show that Beijing achieves the lowest LCOE values for both battery technologies, followed by Abuja, while Washington D.C. exhibits the highest LCOE.

This result is particularly significant because Abuja has the highest solar resource but does not achieve the lowest LCOE. This indicates that component cost plays a more dominant role than solar resource in determining electricity cost in PV–battery systems.

For both battery technologies, Lithium-ion systems show slightly higher LCOE values than lead-acid systems in Abuja and Beijing, primarily because their higher upfront battery cost outweighs the benefit of longer lifetime. In Washington D.C., however, the lithium-ion system records a slightly lower LCOE than the lead-acid system. This occurs because the battery cost difference between the two technologies is relatively small in Washington D.C., while the longer lifetime and reduced replacement frequency of the lithium-ion battery provide a stronger economic advantage.

3.5. Economic viability (NPV analysis)

The economic viability of the PV–battery systems is evaluated using net present value (NPV), as shown in Figure 6.

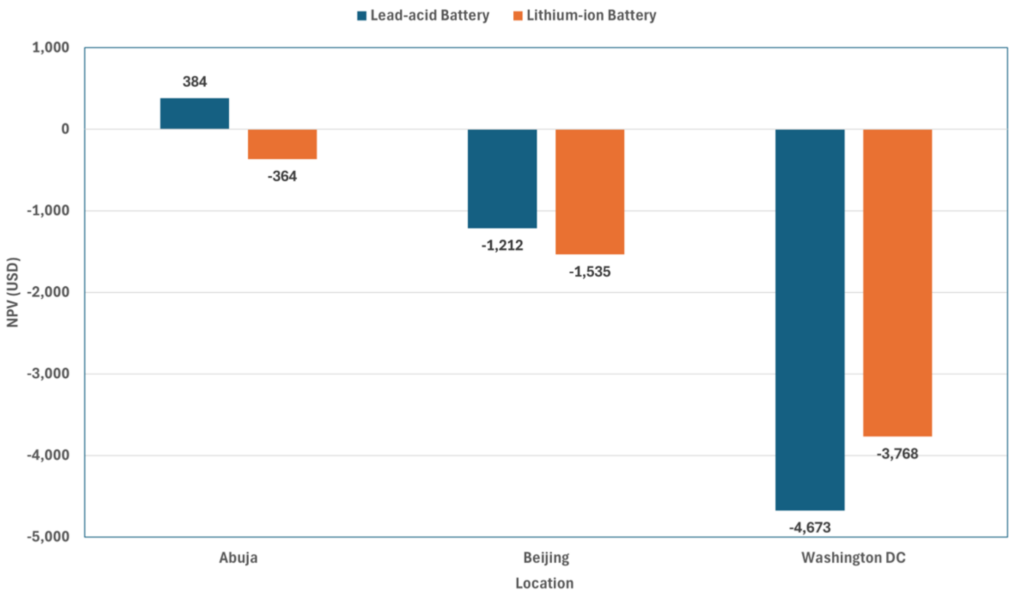

Figure 6: *Economic Viability (NPV) comparison chart*

The NPV comparison presented in Figure 6 provides further insight into the relative economic performance of the two battery technologies. In Abuja and Beijing, the lead-acid configuration yields higher NPV values than the lithium-ion configuration, whereas the reverse trend is observed in Washington D.C., where the lithium-ion system exhibits a slightly higher NPV.

Abuja shows the most favorable economic outcome among the three locations, with the lead-acid system achieving a positive NPV of $384, indicating economic viability under the assumed tariff and cost conditions. The lithium-ion system in Abuja ($NPV = -364$), although closer to economic viability than in the other locations, remains less favorable due to its higher upfront cost. In Beijing, both battery configurations yield negative NPVs, reflecting limited economic attractiveness under the prevailing conditions; however, the lead-acid system still performs better than the lithium-ion system.

Washington D.C. exhibits the least favorable economic performance overall, with both battery systems producing strongly negative NPVs. However, the lithium-ion system achieves a higher (less negative) NPV than the lead-acid system. This outcome can be attributed to the relatively small price difference between lithium-ion and lead-acid batteries in the U.S. market, combined with the longer lifetime and reduced replacement frequency of lithium-ion batteries, which improve its long-term economic performance.

These results indicate that lead-acid batteries provide better economic performance in Abuja and Beijing, primarily due to their lower initial capital cost. However, in markets where the cost gap between battery technologies is reduced, as observed in Washington D.C., the longer lifetime of lithium-ion batteries can offset their higher upfront cost and result in improved economic outcomes. This highlights the importance of local market conditions in determining the optimal battery technology for residential PV systems.

3.6. Battery performance analysis

The operational performance of the batteries is summarized in Tables 8 and 9, while the battery lifetime comparison is shown in Figure 7.

Table 8: *Lead-acid battery operation and performances*

	Abuja		**Beijing**		**Washington DC**	
	U_Batt (V)	**SOCmean**	**U_Batt (V)**	**SOCmean**	**U_Batt (V)**	**SOCmean**
January	50.5	0.68	52.2	0.63	51.5	0.55
February	50.4	0.67	51.9	0.61	50.9	0.53
March	50.3	0.67	51.5	0.66	51.4	0.61
April	50.3	0.67	51.0	0.63	50.6	0.57
May	50.4	0.65	50.8	0.65	50.4	0.53
June	50.5	0.65	50.3	0.62	50.5	0.63
July	50.1	0.56	50.0	0.57	50.0	0.57
August	49.7	0.50	50.4	0.63	50.4	0.65
September	50.0	0.54	50.5	0.61	50.2	0.56
October	50.5	0.65	50.8	0.57	50.3	0.54
November	50.5	0.67	51.4	0.59	50.6	0.51
December	50.5	0.68	51.4	0.53	51.1	0.53
Year	50.3	0.63	51.0	0.61	50.7	0.56

Note: U_Batt = Average Battery Voltage (V), SOCmean = Mean State of Charge, SOC_End = End-of-period State of Charge, Mgass (liter) = Battery gassing losses, EffBatI = Battery Charge Efficiency, EffBatE = Battery Discharge Efficiency

Table 9: *Lithium-ion battery operation and performances*

	Abuja		**Beijing**		**Washington DC**	
	U_Batt (V)	**SOCmean**	**U_Batt (V)**	**SOCmean**	**U_Batt (V)**	**SOCmean**
January	49.3	0.63	49.1	0.56	49.0	0.49
February	49.3	0.62	49.1	0.55	49.0	0.49
March	49.3	0.62	49.2	0.60	49.1	0.55
April	49.3	0.62	49.2	0.58	49.1	0.52
May	49.2	0.60	49.2	0.59	49.1	0.51
June	49.2	0.60	49.2	0.58	49.2	0.59
July	49.2	0.56	49.1	0.55	49.1	0.55
August	49.0	0.46	49.2	0.59	49.2	0.60
September	49.2	0.58	49.2	0.57	49.1	0.53
October	49.2	0.61	49.1	0.52	49.1	0.50
November	49.3	0.62	49.1	0.54	49.0	0.48
December	49.3	0.64	49.1	0.51	49.0	0.48
Year	49.2	0.60	49.2	0.56	49.1	0.53

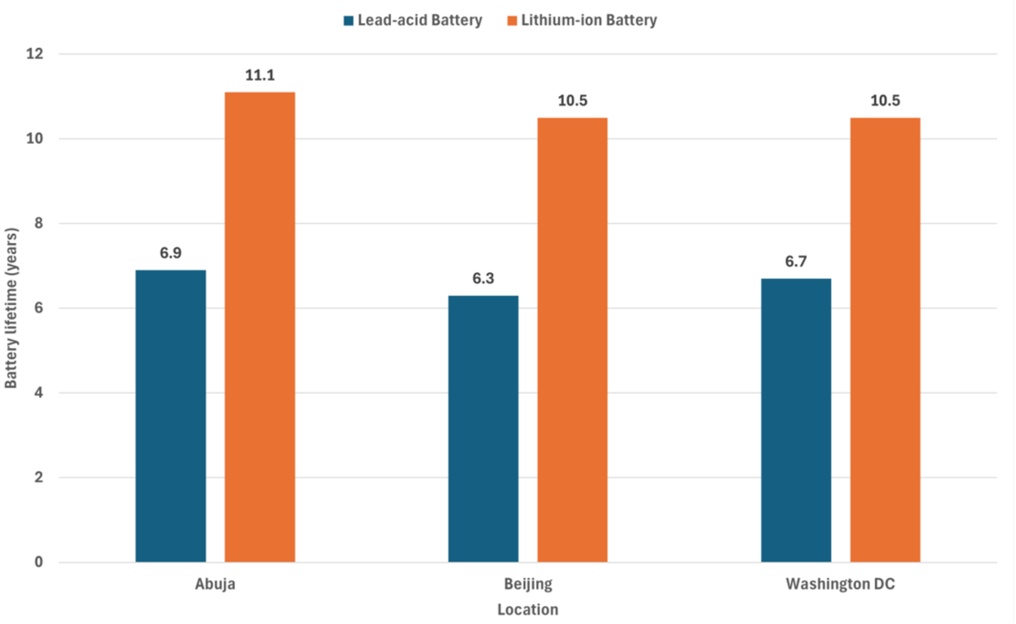

Figure 7: *Battery lifetime comparison chart*

The results show that both battery technologies maintain stable operation across the three locations, with variations primarily influenced by solar resource availability and seasonal conditions.

The mean state of charge (SOC) values indicate that both battery systems operate within acceptable limits throughout the year. For the lead-acid system, the annual average SOC is approximately 0.63 in Abuja, 0.61 in Beijing, and 0.56 in Washington D.C. For the lithium-ion system, the corresponding values are slightly lower, at approximately 0.60, 0.56, and 0.53, respectively. The generally higher SOC values observed in Abuja reflect its superior solar resource, which enables more frequent battery charging, while the lower values in Washington D.C. are consistent with reduced solar availability.

Seasonal variations are also evident in both battery systems, with lower SOC values typically occurring during periods of reduced solar irradiation. Despite these fluctuations, both battery technologies demonstrate reliable performance without significant depth-of-discharge limitations, indicating that the system sizing and design criteria are adequate for meeting the load demand.

The battery lifetime comparison shown in Figure 7 highlights a clear difference between the two technologies. Lithium-ion batteries exhibit a longer operational lifetime than lead-acid batteries across all locations, primarily due to their higher cycle life, deeper allowable depth of discharge, and superior charge–discharge efficiency. In contrast, lead-acid batteries experience more frequent degradation, resulting in shorter replacement intervals.

However, while lithium-ion batteries demonstrate superior technical performance in terms of durability and lifecycle characteristics, this advantage does not directly translate into superior economic performance under the conditions considered in this study. The longer lifetime of lithium-ion batteries reduces replacement frequency and contributes to lower annual replacement costs, but this benefit is offset by their higher initial capital cost, particularly in Abuja and Beijing, where the price differential between battery technologies is significant.

In Washington D.C., where the cost difference between lithium-ion and lead-acid batteries is relatively smaller, the longer lifetime of lithium-ion batteries contributes more significantly to overall economic performance. This explains why lithium-ion systems achieve slightly better

LCOE and NPV values in this location compared to lead-acid systems.

Overall, the results indicate that both battery technologies provide reliable operational performance, but their techno-economic suitability depends on the balance between upfront cost and lifetime characteristics. While lithium-ion batteries offer superior technical performance, lead-acid batteries remain economically advantageous in locations where the cost differential between the two technologies is substantial.

3.7. Integrated techno-economic performance

The overall performance of the PV–battery systems was evaluated using the weighted techno-economic performance index (WTPI), as presented in Figure 8.

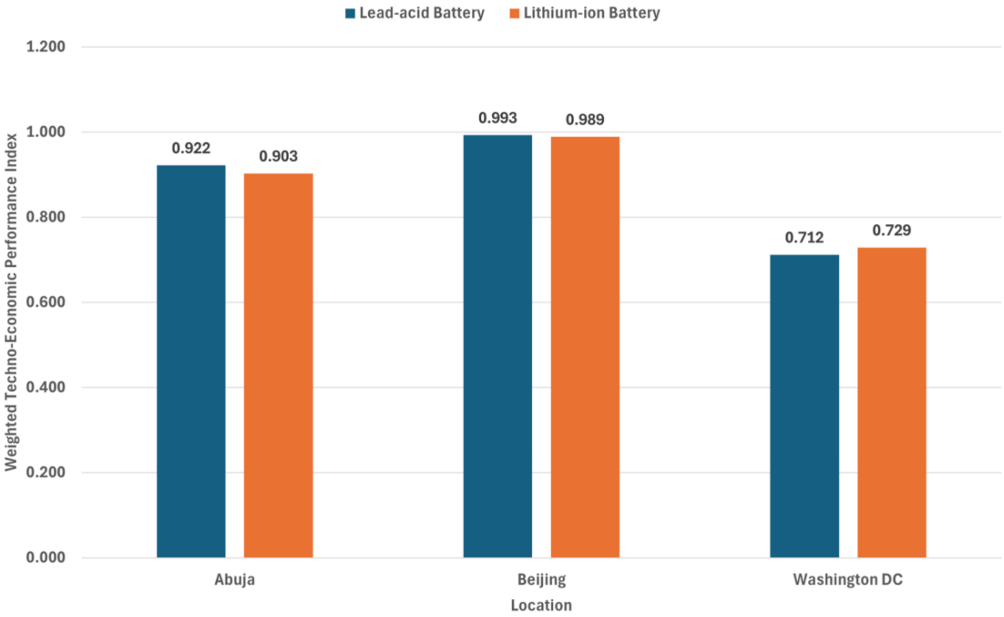

Figure 8: *Weighted Techno-Economic Performance Index (WTPI) Comparison*

The WTPI provides a composite assessment by integrating key technical and economic indicators, including system production, capital cost, levelized cost of electricity (LCOE), and net present value (NPV).

The results show that Beijing achieves the highest WTPI among the three locations, followed by Abuja, while Washington D.C. records the lowest overall performance. The superior performance of Beijing is primarily attributed to its significantly lower component costs, which compensate for its relatively lower solar resource compared to Abuja. This confirms that favorable market conditions can outweigh solar resource advantages in determining overall system performance.

A clear distinction is also observed between the two battery technologies. In Abuja and Beijing, the lead-acid systems achieve higher WTPI values than the lithium-ion systems, reflecting their lower capital cost, lower LCOE, and better NPV performance in these locations. In contrast, in Washington D.C., the lithium-ion system exhibits a slightly higher WTPI than the lead-acid system, consistent with the observed trends in LCOE and NPV. This outcome is mainly due to the relatively small cost difference between the two battery technologies in the U.S. market, combined with the longer lifetime and reduced replacement frequency of lithium-ion batteries, which enhance their overall economic performance.

These findings indicate that the relative techno-economic performance of battery technologies is strongly location-dependent. While lead-acid batteries provide better overall performance in Abuja and Beijing due to their lower upfront cost, lithium-ion batteries become more competitive and slightly superior in environments where their cost disadvantage is reduced and their longer lifetime can be fully leveraged.

3.8. Sensitivity analysis

The sensitivity of the levelized cost of electricity (LCOE) to key economic parameters is presented in Figures 9–11 for Abuja, Beijing, and Washington D.C., respectively.

The tornado diagrams show the relative influence of variations in discount rate, battery cost, PV module cost, inverter cost, OPEX, and other system costs on the resulting LCOE values.

The results indicate that **discount rate is the most influential parameter affecting LCOE** across all three locations and for both battery technologies. This is followed by **battery cost** and **PV module cost**, while inverter cost, OPEX, and other system costs have comparatively smaller effects. The strong influence of the discount rate reflects the long project lifetime of the PV–battery systems and the importance of discounted future costs in determining the overall electricity cost. Since LCOE is calculated on a life-cycle basis, changes in the discount rate substantially affect the present value of both costs and energy outputs.

Battery cost emerges as the second most influential parameter because storage constitutes a major share of total system cost, particularly for lithium-ion systems. Variations in battery price therefore have a direct and substantial impact on system economics. PV module cost is the third most influential factor, reflecting the importance of module pricing in total capital expenditure, especially in small residential systems where equipment cost remains a dominant contributor.

In Abuja, the sensitivity analysis shows that both lead-acid and lithium-ion systems are highly responsive to changes in discount rate, followed by battery cost and PV module cost. The lithium-ion system exhibits stronger sensitivity to battery cost than the lead-acid system because of its higher battery capital cost. This observation is consistent with the earlier finding that lithium-ion systems in Abuja have slightly higher LCOE values than lead-acid systems.

In Beijing, the same ranking of sensitivity factors is observed, although the overall spread of LCOE variation is somewhat moderated by the lower baseline component costs in the Chinese market. Nevertheless, discount rate remains the dominant economic driver, followed by battery and module costs. This suggests that even in lower-cost markets, financing conditions and the cost of capital remain critical determinants of PV system affordability.

In Washington D.C., the sensitivity analysis also identifies discount rate as the dominant parameter, followed by battery cost and PV module cost.

A comparison between the two battery technologies further shows that lithium-ion systems are generally more sensitive to battery cost variations, whereas both technologies are similarly affected by changes in discount rate. This implies that reductions in lithium-ion battery prices, or improved financing conditions, could significantly enhance their economic competitiveness in future residential PV applications.

Overall, the sensitivity analysis confirms that the economic performance of residential PV–battery systems is driven primarily by financial conditions and major equipment costs, with discount rate being the most critical factor, followed by battery cost and PV module cost.

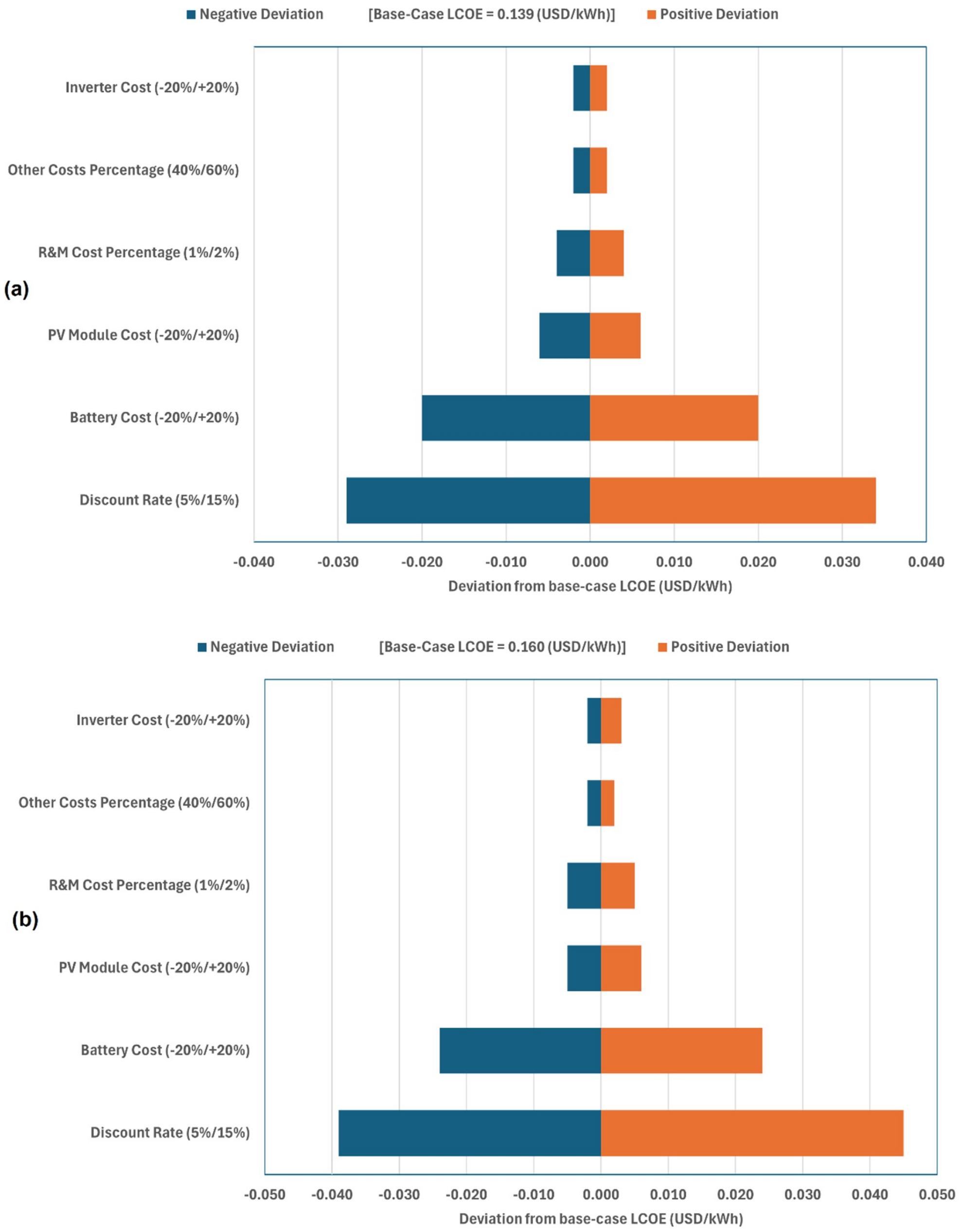

Figure 9: *Tornado diagrams showing the sensitivity of LCOE for Abuja to key economic parameters (a) PV System with Lead-acid Battery (b) PV System with Lithium-ion Battery*

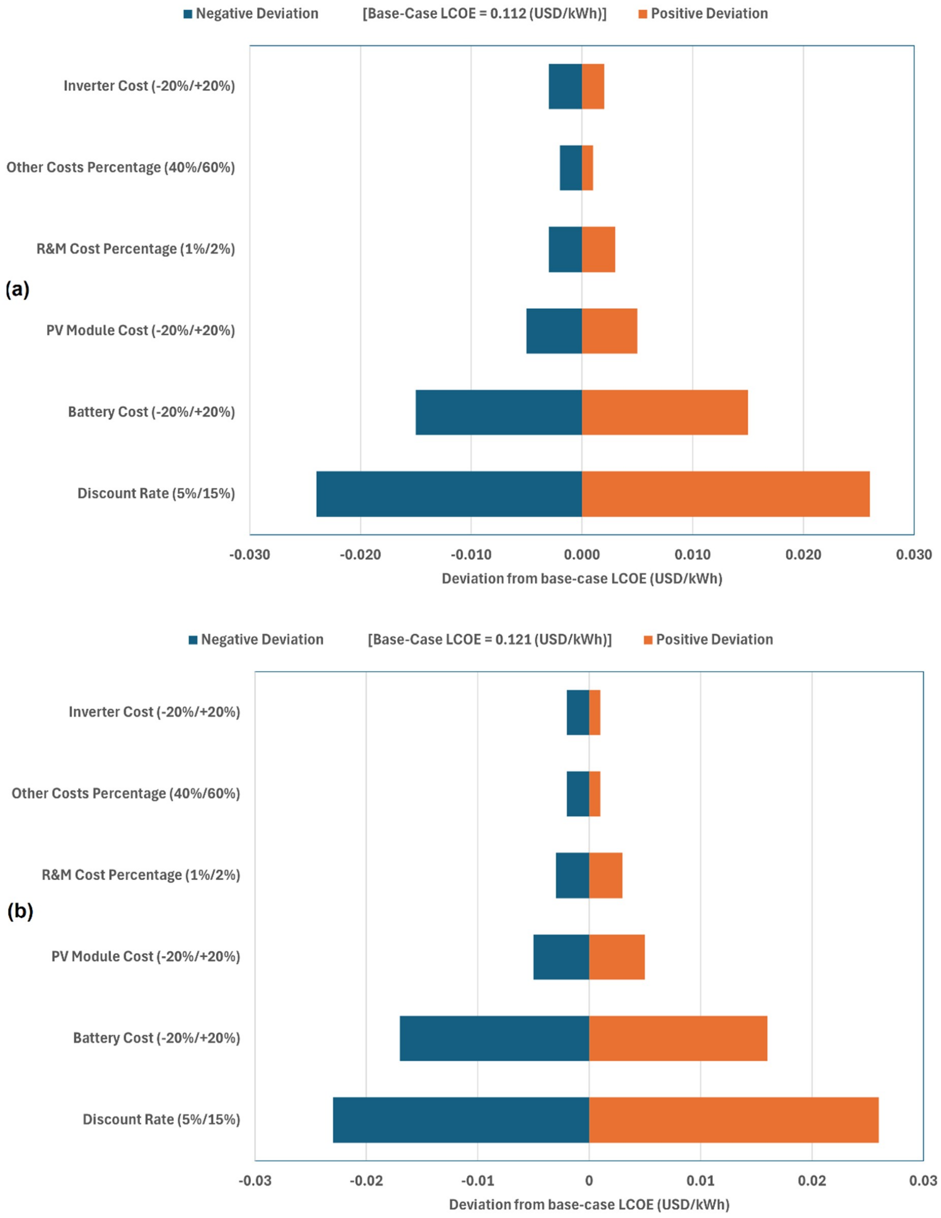

Figure 10: *Tornado diagrams showing the sensitivity of LCOE for Beijing to key economic parameters (a) PV System with Lead-acid Battery (b) PV System with Lithium-ion Battery*

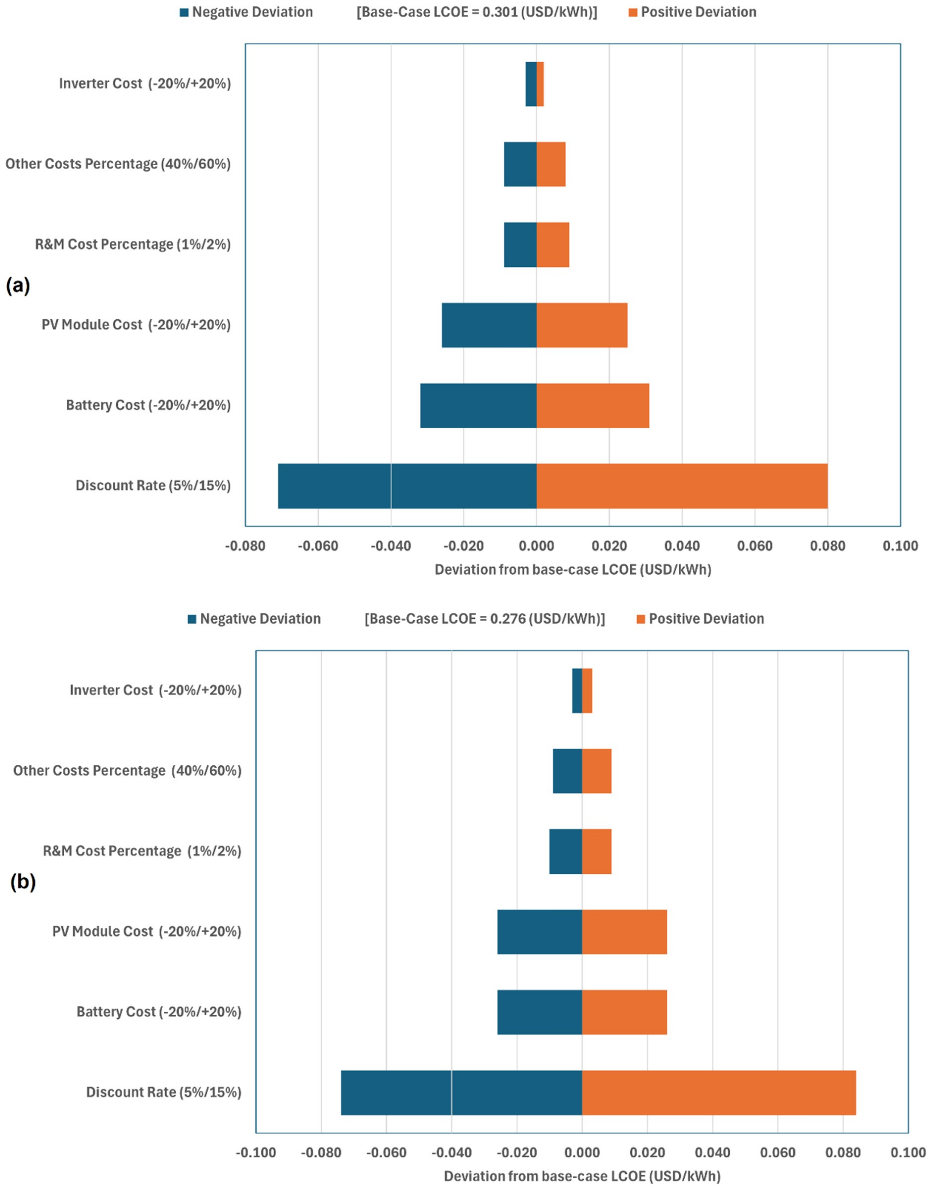

Figure 11: *Tornado diagrams showing the sensitivity of LCOE for Washington DC to key economic parameters (a) PV System with Lead-acid Battery (b) PV System with Lithium-ion Battery*

4. CONCLUSION

This study presented a comparative techno-economic assessment of residential PV–battery systems using lead-acid and lithium-ion batteries across three representative global locations: Abuja (Nigeria), Beijing (China), and Washington D.C. (United States). The analysis combined PV system simulation with life-cycle economic evaluation over a 25-year project lifetime to assess the influence of solar resources, component cost, and battery technology on system performance.

The results show that Abuja exhibits the highest solar resource ($GHI \approx 2,042$ kWh/m^2/yr) and corresponding PV energy production, followed by Beijing ($\approx 1,564$ kWh/m^2/yr) and Washington D.C. ($\approx 1,503$ kWh/m^2/yr). However, Beijing achieved the best overall techno-economic performance due to significantly lower component costs, with CAPEX as low as $2,300 for lead-acid systems compared to $2,930 in Abuja and up to $6,630 in Washington D.C. Consequently, Beijing recorded the lowest LCOE values (≈ 0.112–0.121 USD/kWh), outperforming Abuja (≈ 0.139–0.160 USD/kWh) and Washington D.C. (≈ 0.276–0.301 USD/kWh), demonstrating that economic outcomes are more strongly influenced by local market conditions than solar resource alone.

A key finding of this study is that the techno-economic performance of battery technologies is location-dependent. Lead-acid battery systems demonstrated superior economic performance in Abuja and Beijing, achieving lower CAPEX, lower LCOE, and higher NPV. In Abuja, the lead-acid system yielded a positive NPV (≈$384), indicating economic viability, whereas the lithium-ion system remained less favorable. In Beijing, both battery configurations produced negative NPVs, but the lead-acid system still performed better. In contrast, in Washington D.C., the lithium-ion system exhibited slightly better economic performance, achieving a higher (less negative) NPV compared to the lead-acid system and a marginally lower LCOE, due to the relatively small price difference between the battery technologies and the longer lifetime of lithium-ion batteries.

The weighted techno-economic performance index further confirmed that Beijing provides the most favorable deployment environment, followed by Abuja, while Washington D.C. remains the least favorable. Sensitivity analysis revealed that the discount rate is the most influential parameter affecting LCOE, followed by battery cost and PV module cost, highlighting the critical role of financing conditions and capital cost in determining system viability.

Overall, the findings demonstrate that both local market conditions and battery technology selection are critical determinants of residential PV system performance. While lithium-ion batteries offer superior technical characteristics, lead-acid batteries remain economically advantageous in locations where cost differentials are significant. Conversely, lithium-ion batteries become more competitive in markets where their cost premium is reduced, and their longer operational lifetime can be fully leveraged. These results provide valuable insights for policymakers, system designers, and investors seeking to optimize residential PV–battery system deployment across diverse global electricity markets.

Declaration of interest: The authors declare no conflicts of interest.

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