PROCEEDINGS OF ECOS 2023 - THE 36TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
25-30 JUNE, 2023, LAS PALMAS DE GRAN CANARIA, SPAIN

Sustainability Assessment of Typical Energy Storage Technologies for Peak Shaving Scenarios Based on the Full Life Cycle

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Abstract:

With more renewable energy sources (RES) which are inherent intermittent and unpredictable connecting with power grid, various stability problems occur, among which the peak load regulation is the most prominent. Energy storage systems (ESSs) are essential for buffering the electricity grid. Selecting the most suitable energy storage technology among various alternatives is of great importance. In this work, the sustainability of typical energy storage technologies was studied with respect to four aspects for peak shaving scenarios, including technical (i.e. maturity, energy density, round-trip efficiency, duration ranges, life cycles, lifetime and position flexibility), economic (levelized cost of energy, net present value), environmental (i.e. global warming, damage to human health, damage to ecosystems, damage to resource availability) and social (public acceptance) based on the full life cycle. This study evaluated the soft criteria including maturity, position flexibility and public acceptance by Analytic hierarchy process (AHP). Life cycle assessment (LCA) and life cycle cost (LCC) methods were combined to study the life-cycle environmental and economic performance. Technique for order preference by similarity to an ideal solution (TOPSIS) was applied for determining the sustainability prioritization of energy storage technologies. The sensitivity analysis was carried out to investigate the effects of control and economic input parameters on environmental performance and economic performance. In addition, the effects of criteria weights, electricity sources and number of daily cycles were conducted on sustainability ranking of ESSs. The results showed Lithium iron phosphate battery (LIPB) and pumped hydro storage (PHS) had good sustainability performance, which could be the most suitable energy storage technologies for peak shaving scenarios.

Keywords:

Energy storage; Life Cycle Assessment; Life Cycle Cost; Peak shaving; Sustainability prioritization.

1. Introduction

More renewable energy sources (RES) have connected with power grid, but RES is inherent intermittent and unpredictable, which result in various stability problems in which the peak load regulation is the most prominent. Energy storage systems (ESSs) are essential for buffering the electricity grid [1]. There are various ESSs which have different properties and performances. Selecting the most suitable energy storage technology for specific scenario when facing various conflicting criteria is of great importance for the decision-makers [2].

A few studies are available that evaluate the performance of different ESSs in the specific application by multi-criteria decision making approach [1-8]. Vo T.T.Q et al. [1], Ren J.Z et al. [2] and Raza S.S. et al. [3] evaluated the energy storage technologies considering the economic, technical and environmental impacts. Walker S.B.et al.[4] and Petrillo A.et al.[5] assessed the Power-to-Gas technologies and a compressed air energy storage system respectively in technological, economic and social aspects. The performance of 27 energy storage alternatives which were classified into fast response and long-term clusters were assessed by Rostami F. et al. [6] considering the economic, environmental and social indicators using data envelopment analysis. Baumann M. et al. [7] and Cellura S. et al. [8] combined the environmental and economic assessments for batteries and flywheel energy storage, respectively. Davies D.M. et al. [9] assessed the batteries by combining economic and technological evaluation. However, the considered evaluation criteria are not comprehensive in these above studies, the disregarded aspects often also have a certain impact on the sustainability performance.

There are some literatures assessing the sustainability performance of ESSs in terms of comprehensive aspects including environmental, economic, technical and social categories [10-17]. Ilbahar E. et al. [10] proposed a methodology to evaluate the hydrogen energy storage systems. Baumann M. et al. [11] evaluated the overall performance of batteries for four grid services. Seven energy storage technologies including lead-acid batteries, Li-ion batteries, super capacitors, hydrogen storage, compressed air energy

https://doi.org/10.52202/069564-0255

storage, pumped hydro, and thermal energy storage for ten scenarios were evaluated by Albawab M. et al. [12]. Balezentis T.et al. [13] presented a novel multi-criteria utility analysis approach for ranking hydrogen storage, HPS, CAES, Li-Ion batteries, lead acid batteries, flow batteries, and molten salt energy storage. Lin R.J. et al. [14] studied the overall performance of energy storge technologies by innovative indices of sustainability efficiency and super-efficiency. Evaluation of PHS, CAES and NaS for integration with wind power in the Pacific Northwest region of the US was conducted by Turgrul U.D. et al. [15]. The sustainability prioritization of four alternatives including pumped hydro, compressed air, lithium-ion, and flywheel were assessed by Ren J.Z.et al. [16]. Acar C. et al. [17] analysed the sustainability performance of energy storage systems including Pumped hydro, conventional batteries, high-temperature batteries, flow batteries, and hydrogen for residential applications. In these literatures, the considered index are often hard criteria which have exact data and the assessments often rely on existing literatures without considering the varying of the input parameters such as round-trip efficiency, electricity sources in different scenarios.

In addition, the available literatures generally study the economic performance in terms of energy cost and power cost [13,17] or capital and operating cost [12,14-16] and study the environmental performance in terms of CO_2 which are both obtained from the previous literatures or the engineering reports. Mostafa M.H. et al. [18], Hunter C.A. et al. [19] and Chen X.J. [20] point out that levelized cost of energy, payback period and internal rate of return should be used to evaluate the life cycle economic performance of ESSs. Researchers [21-26] often conduct life cycle environmental assessments of different ESS to choose the best environment-friendly alternatives from the aspects of cumulative energy demand, global warming potential, ozone layer depletion potential, marine aquatic ecotoxicity potential, acidification potential, damage to human health, damage to ecosystems and damage to resource availability et al. Moreover, few literatures such as [11] analyze the sustainability of ESSs from the perspective of life-cycle aspect. In consequence, there is a lack of comprehensive assessment of different ESSs that consider not only the life-cycle costing but also quantifying the soft index from the aspects of technical, economic, environmental and social performances.

This study aims at tackling these gaps by providing a comprehensive sustainability assessment of different ESSs. The studied ESSs are pumped hydro storage (PHS), compressed air energy storage (CAES), lithium iron phosphate battery (LIPB) and vanadium redox flow battery (VRFB) which are applicable for the peak shaving scenarios. The soft criteria of technical and social categories are quantified by Analytic hierarchy process (AHP), and life-cycle assessment (LCA) and life-cycle cost (LCC) are adopted to evaluate the environmental and economic performance parameters based on the full life cycle of ESSs.

2. Methodology

2.1. Assessment framework

The sustainability assessment which can incorporate both hard and soft criteria was conducted with respect to technical, economic, environmental and social categories for peak shaving scenarios based on the full life cycle, in order to select the most suitable energy storage option, assessment framework of this study is shown in Figure 1. The technical category included round-trip efficiency, energy density, duration range, life cycles, lifetime, maturity and position flexibility. The environmental category included global warming (GWP), damage to human health (DHH), damage to ecosystem (DE) and damage to resource availability (DRA). The economic category was mainly levelized cost of energy (LCOE) and net present value (NPV). The social category mainly considered public acceptance.

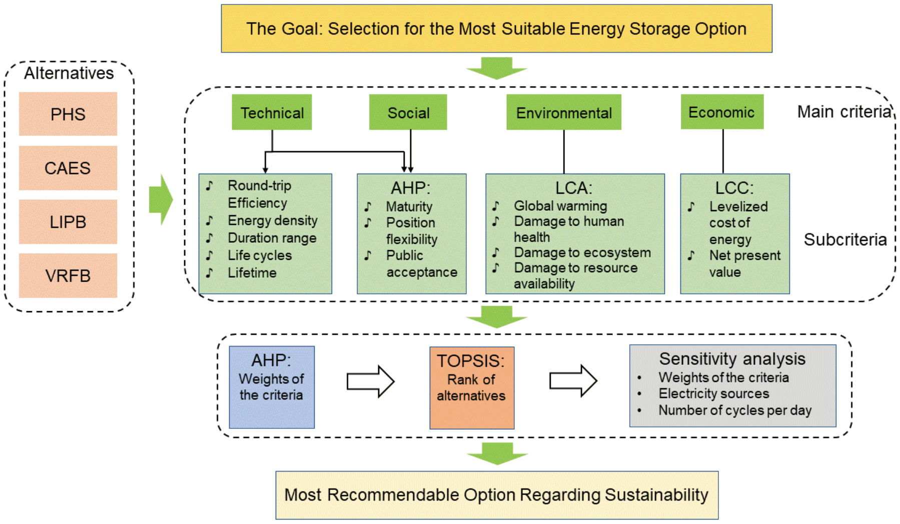


Figure. 1. Overview of the assessment framework.

AHP was applied to evaluate the soft criteria including maturity, position flexibility and public acceptance, it was also employed to determine weights of main criteria and subcriteria in each category. Environmental and economic performance were quantified by Life cycle assessment (LCA) and life cycle cost (LCC) methods, and they have the same system boundary including the raw materials extraction and processing, manufacturing, usage and disposal or recycling stage of ESSs. Technique for order preference by similarity to an ideal solution (TOPSIS) which can rank the alternatives was applied for sustainability prioritization of energy storage technologies. The effects of criteria weights, electricity sources and number of daily cycles on environmental performance, economic performance and sustainability order were conducted in the sensitivity analysis.

The technical and social performance assessment is based on the technology data about ESSs from literature, survey and interviews, and calculated by AHP method and interval approach for uncertainties [2]. Environmental performance assessment is calculated by Recipe endpoint approach in Simapro software whose life cycle inventory data (LCA input) is from literature and engineering reports. Economic performance assessment is conducted by the LCC model which is established by the author in which the life cycle cost inventory is from literature, survey and engineering reports.

2.2. Quantifying the soft criteria and determining the criteria weights

Maturity, position flexibility and public acceptance are important for the alternatives to evaluate the sustainability performance, but they are soft criteria whose data cannot be obtained directly, it is hard to be compared between different alternatives in the TOPSIS process [2], so it is essential to quantify the soft criteria.

AHP method was generally employed to determine the weights of considered four categories as well as that of the subcriteria in each category [13], it could also be used to assess the relative performance of the energy storage alternatives with respect to soft criteria. Table 1 shows the linguistic terms and their corresponding numbers for the pair-wise comparison in the analysis.

Table 1. Linguistic terms and corresponding numbers for the pair-wise comparison.

Numbers	Linguistic terms	Numbers	Linguistic terms
1	Equally important	7	Strongly more important
3	Slightly more important	9	Absolutely more important
5	More important	2,4,6,8	Intermediate values between the two adjacent judgments

2.3. Life cycle cost

Two economic indicators are conducted to compare the economic performance of different energy storage alternatives, namely levelized cost of energy (LCOE) and net present value (NPV) which are important index that be studied by many researchers [18-20]. Figure 2 shows the life-cycle cost of ESSs, it is worth mentioning that costs associated with the environmental impacts were not considered for avoiding the duplication among LCA and LCC indicators. The LCOE and NPV were calculated as equations (1) and (2).

$$LCOE = C_{investment} + \frac{\sum_{t=1}^{T} \frac{(C_{o\&m} + C_c + C_{rc} + C_{dr}) \cdot (1+r_{if})^{t-1}}{(1+r_d)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r_d)^t}} \tag{1}$$

$$NPV = -p \cdot C_{investment} + \sum_{t=1}^{T} \frac{(C_{prof} - C_{loan} - C_{o\&m} - C_{rc} - C_{dr}) \cdot (1+r_{if})^{t-1}}{(1+r_d)^t} \tag{2}$$

Where $C_{investment}$ represents the investment cost, $C_{o\&m}$ is the sum of fixed and variable operation and maintenance cost, C_c is the charging electricity cost, C_{rc} is the replacement cost, the replacement time of ESSs is related to the maximum number of cycles, C_{dr} is the disposal and recycling cost, T is lifetime of the power station, r_d is the discount rate which is set as 5.49%[27], r_{if} is the inflation rate which is set as 2%[27], E_t represents the annual power generation, p is the proportion of initial investment which is set as 30%[20], C_{prof} is the annual profit considering the peak valley price difference of power grid, C_{loan} is the annual repayment of debt. E_t and C_{prof} are calculated as equations (3) and (4).

$$E_t = Q_E \times (1\text{-}\eta_{self}) \times SOC \times \theta_{DOD} \times \eta_{dis} \times N_y \tag{3}$$

$$C_{prof} = E_t \cdot (p_s - p_p / \eta) \tag{4}$$

Where Q_E is the designed capacity of ESSs, η_{self} is the self-discharge efficiency, SOC represents the average proportion of capacity over ESSs' lifetime considering the decay rate, θ_{DOD} is the discharge depth, η_{dis} is the discharge efficiency, and N_y is the average number of cycles per year, p_s and p_p are the electricity prices for sale and purchase, η is the round-trip efficiency.

The lifetime of energy storage power station is considered as 20 years, which is inconsistent with the life of ESS, so it may face the problem of replacement of battery and equipment during the operation of power station. The replacement time is related to the number of cycles, number of daily cycles and the calendar life of ESS, the market price change of energy storage components (especially the battery cell) is also considered at the replacement time. Replacement cost C_{rc} is calculated as equation (5).

$$C_{rc} = c_{rc} \cdot (1 - r_b)^{t_r} \cdot Q_E \tag{5}$$

Where r_b represents the cost reduction rate of energy storage components, which is 7.78% for LIPB [20], c_{rc} is the unit replacement cost, t_r is the replacement time.

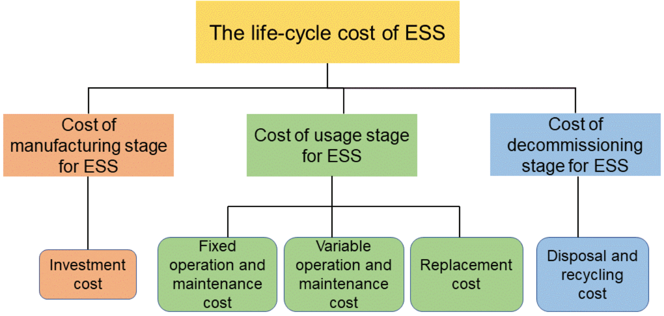


Figure. 2. The main elements of life-cycle cost of energy storage systems.

3. Results and discussions

3.1. Weights

As mentioned above, weights of considered indicators were calculated by AHP method. For the main criteria weights, environmental criteria were assumed to be the most important, followed by economic, technical and social criteria [11, 15], the maturity and position flexibility were the most important, which are followed by round-trip efficiency, duration ranges, life cycles, lifetime and energy density for the technical subcriteria, GWP and DHH were the most important, followed by DE and DRA for environmental subcriteria, the results were shown in Figure 3. The weights of environmental, economic, technical and social indicators were 0.46, 0.28,0.16 and 0.10, respectively. The maturity and position flexibility had the biggest weights which were 0.27, GWP and DHH had the biggest weights which were 0.35.

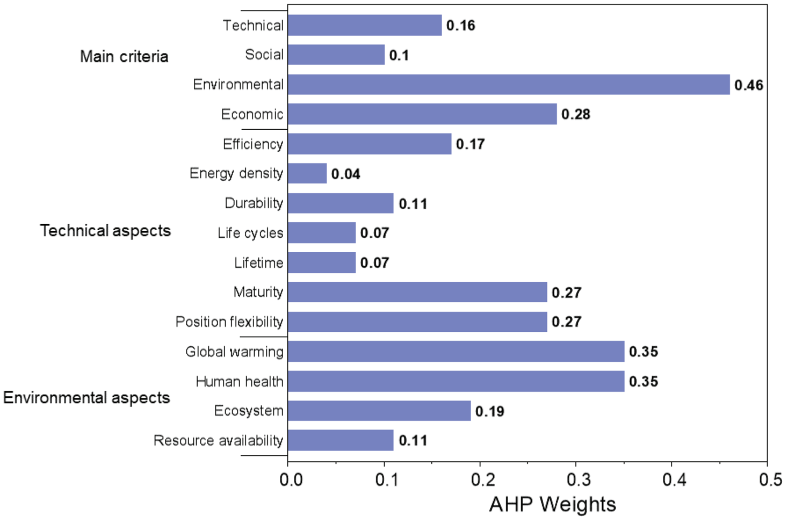
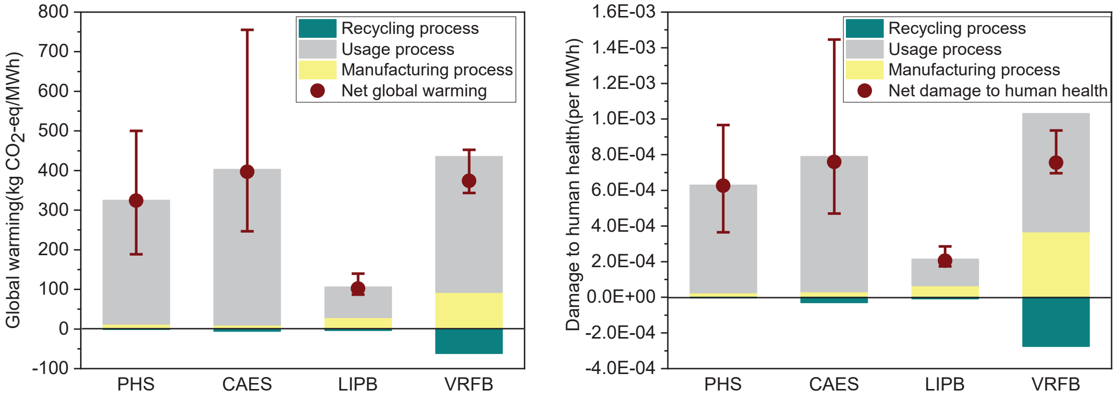


Figure. 3. The weights of the evaluated criteria.

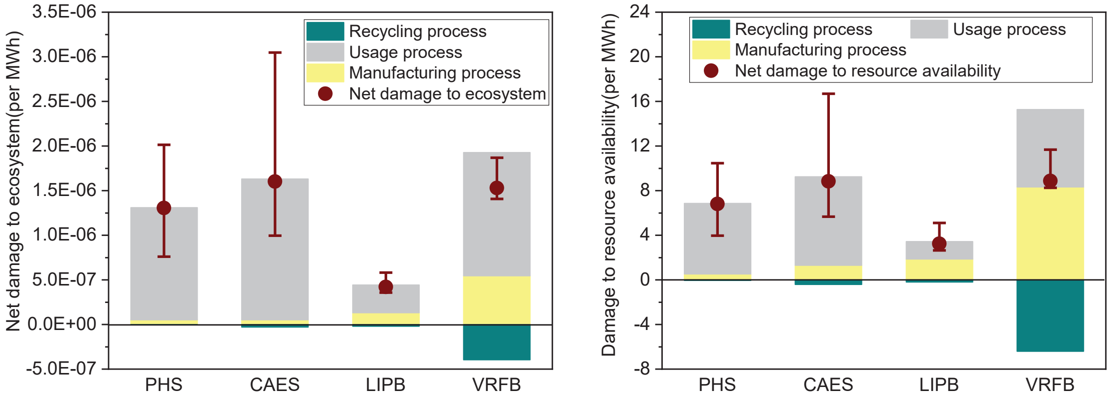
3.2. Environmental aspects

A cradle-to-grave LCA model [21-25] was adopted for evaluating the environmental impacts of typical energy storage technologies, ReCiPe method was applied for the assessment which provides midpoint as well as endpoint indicators by using SimaPro 9.2 software. With the proposal of carbon peak and carbon neutral goal, researchers pay more attention to the contribution of ESSs to this goal, thus GWP was selected as a separate index. The functional unit was set to one megawatt-hour of electricity delivery over the entire lifetime. The life cycle inventory (LCI) was mainly based on specific engineering reports. The environmental results of LIPB and VRFB were partly based on the previous work [26].

Figure 4 shows the environmental performance of ESSs, including the impacts of GWP, DHH, DE and DRA. Median results are provided including positive and negative whiskers for the 25% and 75% quartiles in Figure 4(a), and the author mainly analysed the median results in the work. What needs to point out is the electricity mix used in the usage process of baseline scenario throughout this work was the Chinese electricity mix in 2020.



(a) Global warming *(b) Damage to human health*



(c) Damage to ecosystem *(d) Damage to resource availability*

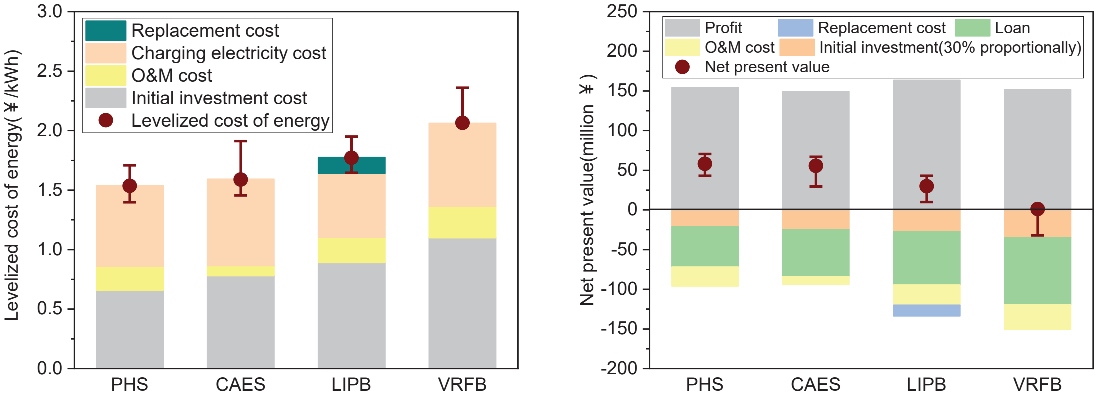
Figure. 4. The environmental performance of energy storage systems in the life cycle. The indicated whiskers in (a) represent 25% and 75% quartiles.

It can be observed that net GWP of PHS, CAES, LIPB and VRFB were 188.4-324.1-500.1, 246.6-397.0-755.4,86.9-102.3-139.8,343.5-374.1-452.4 kgCO$_2$-eq/MWh. LIPB had the best global warming performance, followed by PHS, VRFB and CAES. In general, the basically same trend was observed for the other three environmental impacts which was not demonstrated here. For the life cycle of ESSs, the usage process had the most impacts of GWP, DHH, DE and DRA, and the proportion of four environmental impacts of LIPB was 75.7%,73.0%,73.7% and 48.5%, respectively. The recycling process had the negative environmental impacts for the recycled materials were beneficial for the environment. Compared with PHS, CAES and LIPB, the recycling process of VRFB provided the greatest environmental benefits.

3.3. Economic performance

Levelized cost of energy (LCOE) and net present value (NPV) for PHS, CAES, LIPB and VRFB were displayed in Figure 5 in which median results are provided including positive and negative whiskers for the 25% and 75% quartiles. It should be noted that LIPB needed to be replaced once.

Figure 5(a) showed LCOE of PHS, CAES, LIPB and VRFB were 1.40-1.54-1.71,1.46-1.59-1.91,1.65-1.77-1.95 and 2.04-2.06-2.36 ¥/kWh, respectively. The performance of LCOE from the best to the worst was PHS, CAES, LIPB and VRFB, the rank results were consistent with the literature [11,18-20]. Take LIPB for example, the proportion of initial investment cost was 50.2%, the charging electricity cost was 30.2%, the O&M cost was 12.1% and the replacement cost was 7.5%. It can be found that initial investment cost and charging electricity cost contributed most to LCOE. Figure 5(b) showed NPV of PHS, CAES, LIPB and VRFB were 43.1-58.1-70.6,29.5-55.6-67.0,10.1-29.8-43.0 and -31.9-1.1-2.5 million ￥, respectively. The NPV performance of PHS was best and that of VRFB was worst which was same to the LCOE results. LIPB had the least charging electricity cost for LCOE and the biggest profit for NPV, followed by PHS, VRFB and CAES, it was mainly related to the round-trip efficiency which were 95%, 75%,73% and 70% for LIPB, PHS, VRFB and CAES, respectively.



(a) Levelized cost of energy *(b) Net present value*

Figure. 5. The economic performance of ESSs. The indicated whiskers represent 25% and 75% quartiles.

3.4. Technology and social aspects

The results of quantified soft criteria with respect to maturity are presented in Table 2. The maturity of PHS, CAES, LIPB and VRFB were mature, developed/commercial, demonstration and demonstration, while the corresponding scores were 0.45, 0.26, 0.14 and 0.14, respectively. For the performance of position flexibility, PHS and CAES had strict restrictions, LIPB and VRFB had no special restrictions, so the scores were 0.13, 0.13, 0.38 and 0.38. For the performance of public acceptance, PHS has been accepted, CAES was developing, LIPB and VRFB depended on the station scale, so the public acceptance scores were 0.45,0.26,0.14,0.14. It can be found that the better the performance, the higher the score.

Table 2. The relative performances of ESSs with respect to maturity.

Maturity		PHS	CAES	LIPB	VRFB
PHS	Mature	1	2	3	3
CAES	Developed/ Commercial	1/2	1	2	2
LIPB	Demonstration	1/3	1/2	1	1
VRFB	Demonstration	1/3	1/2	1	1
Relative performances		0.45	0.26	0.14	0.14

In addition to the above soft criteria, the other technical indicators of ESSs were basically not definite values, but were in the range, it was also impossible to be compared directly in the TOPSIS process. Therefore, the interval approach for uncertainties proposed by Ren [2] was used to evaluate the technical performance of ESSs, the results were shown in Figure 6. Round-trip efficiency of PHS, CAES, LIPB and VRFB were 65%-85%, 54%-80%, 93.5%-96% and 70%-75%, while the corresponding scores were 1.77, 1.15, 3.5 and 1.58, respectively. Lifetime of PHS, CAES, LIPB and VRFB were 30-60 years, 20-40 years, 7.5-20 years and 10-20 years, while the corresponding scores were 3.3, 2.7, 0.94 and 1.06, respectively. It can be observed that best performance with higher scores of round-trip efficiency, life cycles, lifetime, duration range and energy density were for LIPB, PHS, PHS, CAES and LIPB.

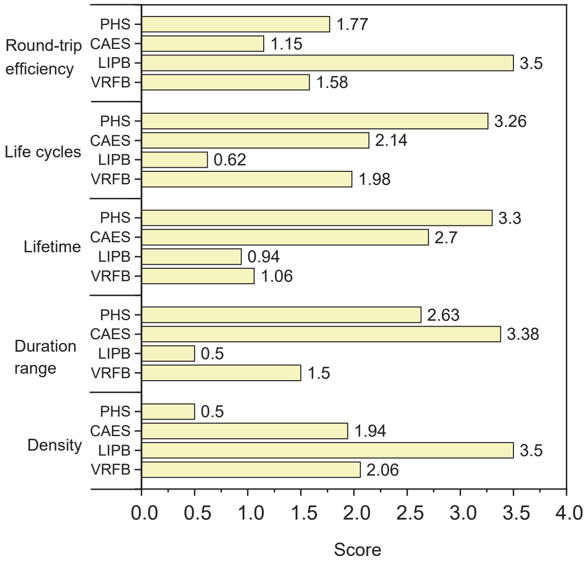


Figure. 6. The technical performance of ESSs.

3.5. Indicative scores and rankings

The considered technical, economic, environmental and social criteria have the inconsistent character, so the results can't be directly comparable, thus a single score was calculated by TOPSIS for multi-criteria decision analysis for sustainability assessment of typical ESSs. The rankings and sustainability scores of ESSs are shown in Figure 7. For environmental aspects, the performance which ranked from 1 to 4 was LIPB, PHS, VRFB and CAES. For economic aspects, the performance of PHS, CAES, LIPB and VRFB ranked from 1 to 4. And PHS performed best, CAES performed worst for technology aspects. The sustainability performance of PHS, CAES, LIPB and VRFB were 0.50, 0.30, 0.64 and 0.13. It was found that LIPB was best for sustainability performance, and VRFB was worst.

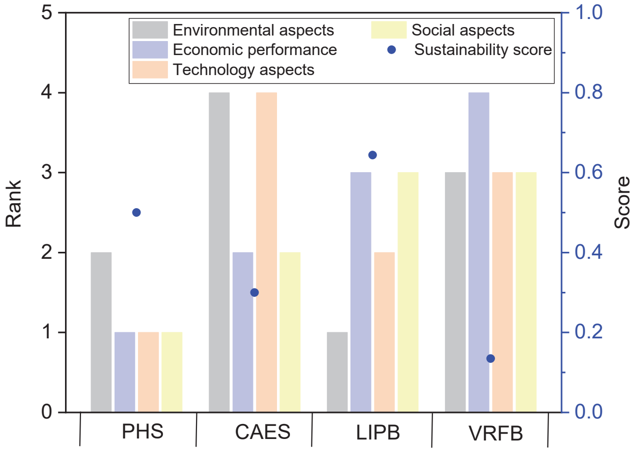


Figure. 7. The ranking and sustainability score of ESSs.

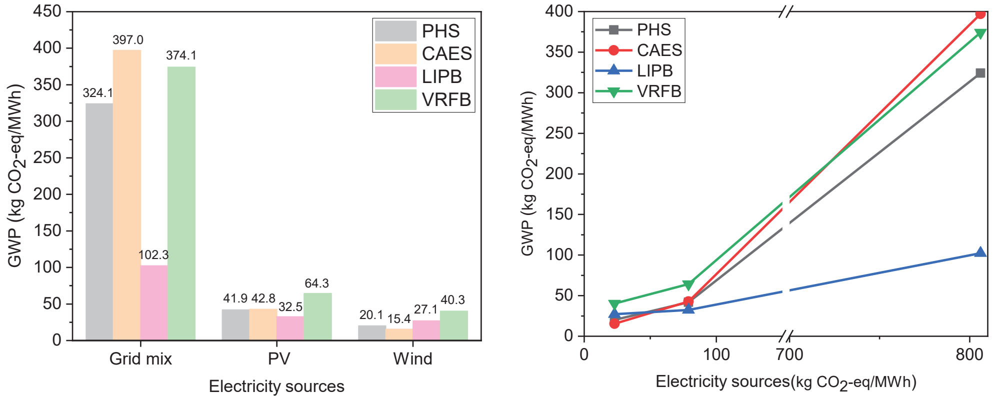
3.6. Sensitivity analysis

3.6.1. Sensitivity analysis of environmental impacts

Sensitivity analysis of electricity sources, discharge depth, round-trip efficiency and number of daily cycles on environmental impacts were conducted. Sensitivity analysis result of GWP was displayed here, the variation trend of DHH, DE and DRA were the same with that of GWP. Figure 8 shows the effect of changing the electricity sources on GWP including solar photovoltaic (PV) and wind, it is quite evident that PV and wind scenarios drastically reduced the environmental impacts compared with the grid mix scenario. The GWP for PV and wind scenario was reduced to as little as less than 31.8% and 26.5% of the impacts of grid mix scenario, respectively. Moreover, the relative ranking of the four ESSs changed and CAES became more

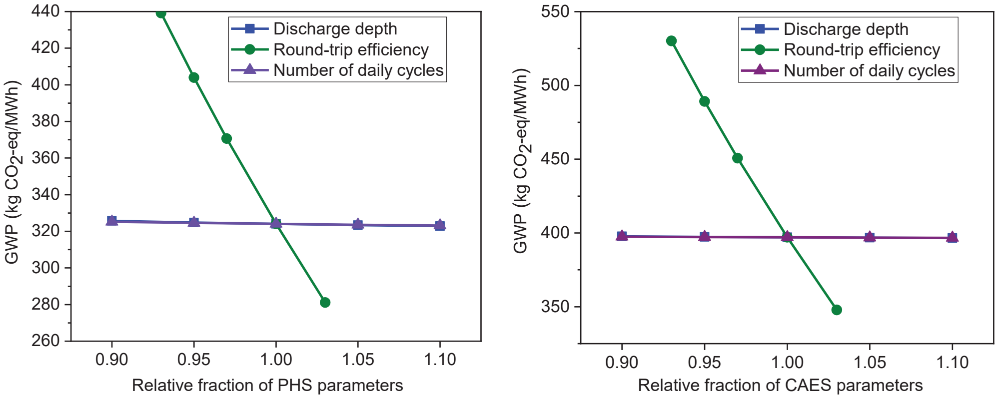
https://doi.org/10.52202/069564-0255

competitive in the wind scenario. Figure 8(b) shows the variation of GWP impacts of ESSs with the variation of the GHG emissions of the electricity sources. The GHG emissions of grid mix, PV and wind are 806, 79 and 23 kg CO2-eq/MWh, respectively. Considering the grid mix as the reference scenario, a decrease of one percentage of electricity sources' GHG emissions will lead to a corresponding decrease in GWP impacts of 0.97%,0.99%,0.76%,0.92% for PHS, CAES, LIPB and VRFB, respectively.

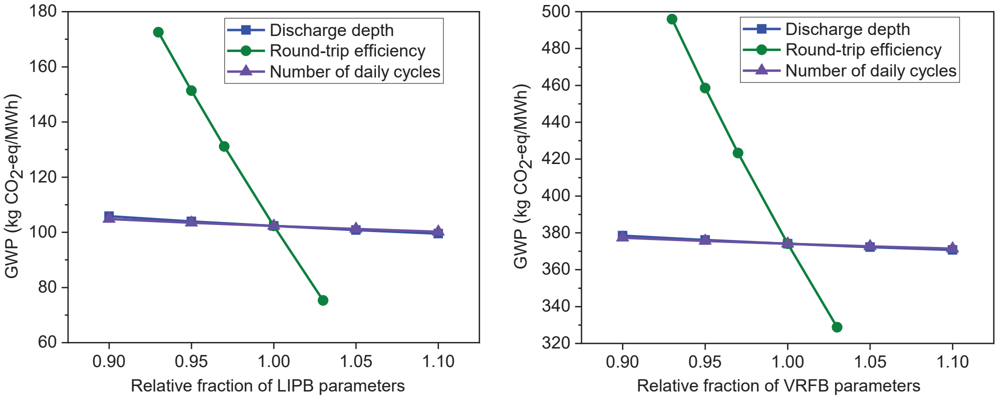


(a) *(b)*

Figure. 8. GWP impact of changing the electricity sources.



(a)GWP impact of PHS *(b) GWP impact of CAES*



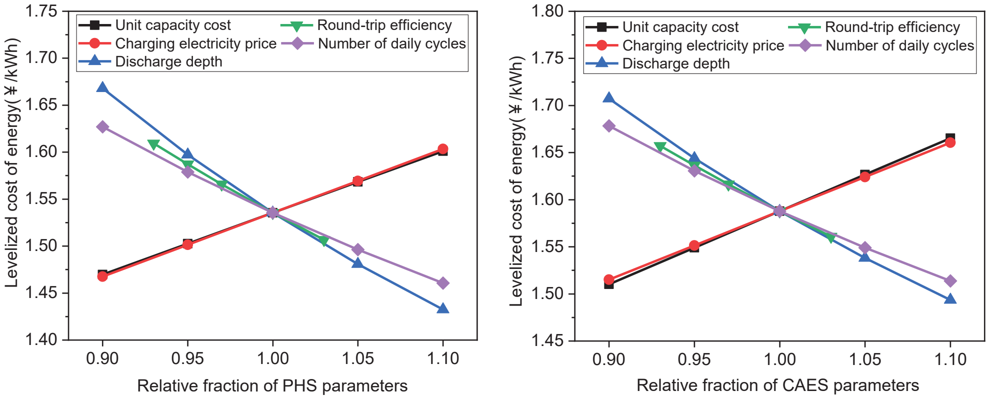
(c) GWP impact of LIPB *(d) GWP impact of VRFB*

Figure. 9. Sensitivity analysis results of changing the discharge depth, round-trip efficiency and number of daily cycles on GWP impact.

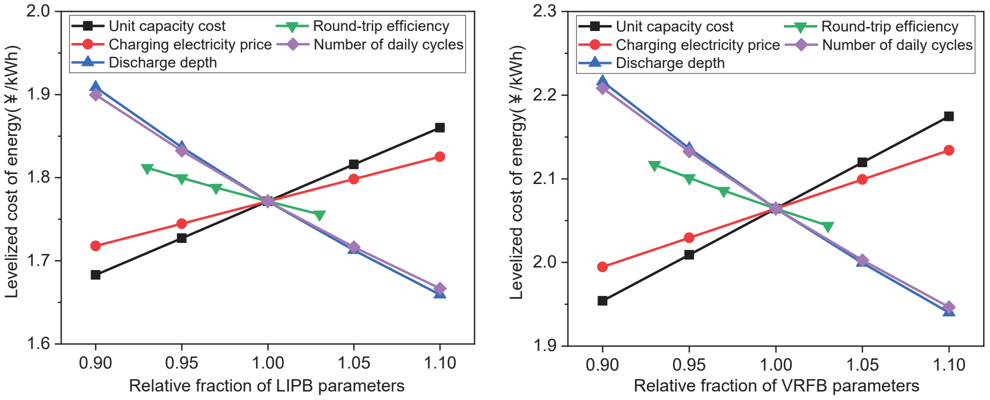
The variation of GWP impact when the discharge depth, round-trip efficiency and number of daily cycles vary from the 0.90 to 1.10 times of reference value are shown in Figure 9. The reference round-trip efficiency values were 75%, 70%,95% and 73% for PHS, CAES, LIPB and VRFB, respectively. It can be found that an increase of one percentage of round-trip efficiency will lead to a corresponding decrease in GWP impacts of 4.8%,4.5%,9.4%,4.4% for PHS, CAES, LIPB and VRFB, respectively. And the reference discharge depth and number of daily cycles values were 80% and 300 cycles per day for four ESSs, the variation of GWP impact was not changed evidently when the two input parameters varied. Therefore, electricity sources and round-trip efficiency had important impacts on the environmental performance of ESSs.

3.6.2. Sensitivity analysis of economic impacts

The effects of control and economic parameters on LCOE were conducted which is shown in Figure 10. In terms of control parameters, discharge depth, round-trip efficiency and number of daily cycles were selected for analysis, and the economic parameters of unit capacity cost and charging electricity price were analysed. LCOE increased with the increasing of economic parameters and the decreasing of control parameters. For LCOE of LIPB, an increase of one percentage of unit capacity cost and charging electricity price will lead to a corresponding increase of 58.1% and 28.3%. In addition, an increase of one percentage of discharge depth, round-trip efficiency and number of daily cycles will lead to a decrease of 72.1%, 29.3% and 67.3%, respectively. It is illustrated that the control parameters had more influence to LCOE than economic parameters, and LCOE was more sensitive to the discharge depth which was consistent with the literature [20].



(a)LCOE of PHS *(b) LCOE of CAES*



(c) LCOE of LIPB *(d) LCOE of VRFB*

Figure. 10. Sensitivity analysis results of control and economic parameters on LCOE.

3.6.3. Sensitivity analysis of rankings

Sensitivity analysis was carried out to investigate the effects of electricity sources, number of daily cycles and criteria weights on sustainability score and rankings.

The variation of sustainability score of ESSs under different electricity sources is displayed in Figure 11, it can be noticed that the sustainability score and ranking varied while the electricity sources varied from grid mix to renewable energy (wind and solar PV), PHS changed its ranking from two to one and changed the score from 0.50 to 0.82 and 0.74, respectively. Figure 12 shows the sensitivity analysis under different number of daily cycles, the ranking did not change in a qualitative manner yet the sustainability score of ESSs changed, as the number of daily cycles increased, the superiority of LIPB was improved.

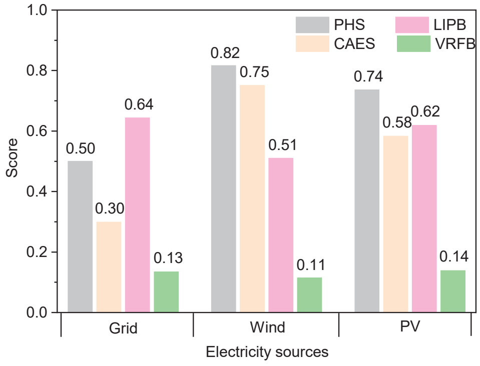


Figure. 11. Sensitivity analysis under different electricity sources.

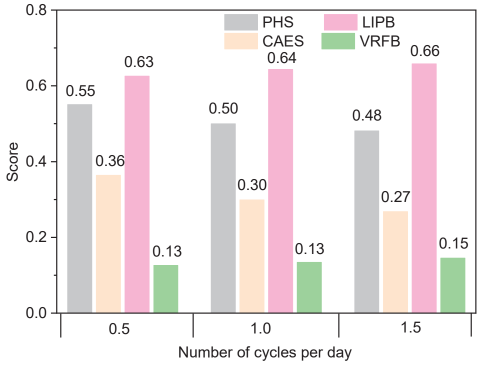
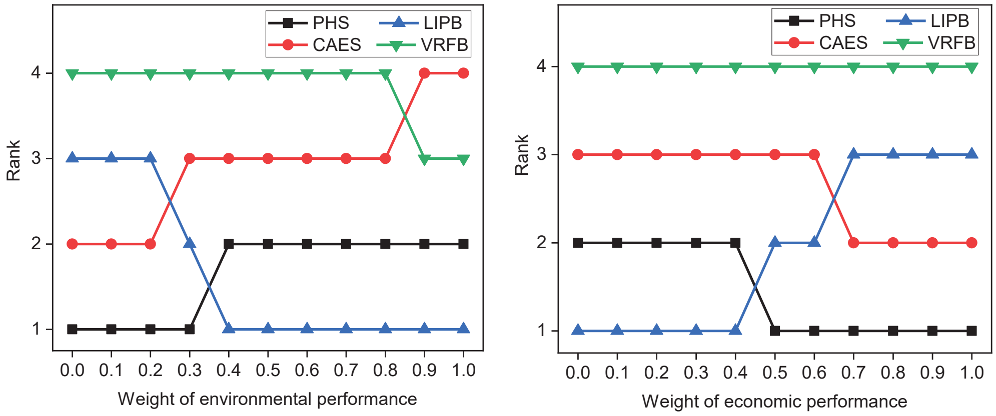
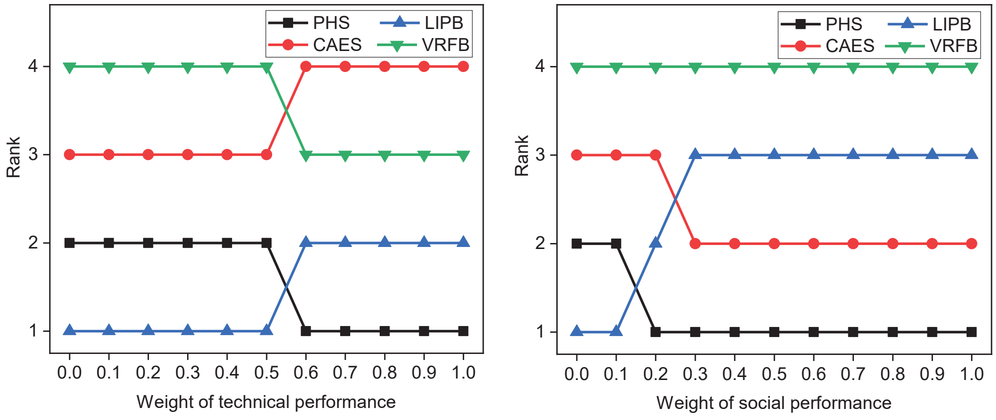


Figure. 12. Sensitivity analysis under different number of daily cycles.

Criteria weights were altered from 0 to 1 by increasing its value 0.1 at a time as shown in Figure 13. When the weight of one criterion was changed, the weights of the remaining three main criteria were kept the same proportionally. As can be noticed from all parts of Figure 13, the ranking varied noteworthily with varying weights of main criteria. For example, LIPB changed its ranking from three to one when environmental weight was given higher weights. As a whole, PHS and LIPB were the most sustainable energy storage option.



(a)environmental *(b)economic*



(c)technical *(d)social*

Figure. 13. Sensitivity analysis of varying the main criteria weights.

4. Conclusions

This study provides a sustainability assessment of typical energy storage systems for quantifying the considered environmental, economic, technical and social criteria for peak shaving scenarios, the studied alternatives include pumped hydro(PHS), compressed air energy storage(CAES), lithium-ion phosphate battery(LIPB) and vanadium redox flow battery(VRFB). A combination of life cycle assessment, life cycle cost, quantifying the soft criteria and TOPSIS methodology were applied based on the full life. The conclusions were:

(1) For PHS, CAES, LIPB and VRFB, environmental indicator of GWP for were 324.1, 397.0,102.3,374.1 kgCO$_2$-eq/MWh, economic indicator of LCOE were 1.54, 1.59, 1.77 and 2.06 ¥/kWh, NPV were 58.1, 55.6, 29.8 and 1.1 million ￥, the sustainability performance score were 0.50, 0.30, 0.64 and 0.13.

(2) The sensitivity results point out discharge depth are the main drivers of life cycle cost (LCC), while for the environmental performance, the electricity sources and round-trip efficiency are of paramount importance. The sustainability rank of ESSs depends on the weight of main criteria and electricity sources, PHS and LIPB are the most sustainable alternatives in the sensitivity analysis.

Acknowledgments

This work was supported by the Natural Science Basic Research Plan in Shaanxi Province of China (No.2023-JC-YB-444), the Fundamental Research Funds for the Central Universities [No.xtr012019001], and the Innovative Scientific Program of CNNC.

Nomenclature

Abbreviations:

AHP	analytic hierarchy process
CAES	compressed air energy storage
DE	damage to ecosystem
ESSs	energy storage systems
DHH	damage to human health
DRA	damage to resource availability
GWP	global warming potential
LCA	life cycle assessment
LCC	life cycle cost
LCOE	levelized cost of energy
LIPB	lithium iron phosphate battery
PHS	pumped hydro storage
RES	Renewable energy sources
TOPSIS	technique for order preference by similarity to an ideal solution
VRFB	vanadium redox flow battery

Greek symbols

C_c	charging electricity cost
C_{dr}	disposal and recycling cost
$C_{investment}$	investment cost
C_{loan}	annual repayment of debt
$C_{o\&m}$	operation and maintenance cost
C_{prof}	annual profit
C_{rc}	replacement cost
E_t	annual power generation
N_y	average number of cycles per year
Q_E	designed capacity of ESSs
SOC	average proportion of capacity
T	lifetime of the power station
p	proportion of initial investment
p_p	the electricity prices for purchase
p_s	the electricity prices for sale
r_d	discount rate
r_{if}	Inflation rate
η	round-trip efficiency
η_{dis}	discharge efficiency
θ_{DOD}	discharge depth

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