CHEMICAL ENGINEERING TRANSACTIONS
VOL. 94, 2022

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš, Sandro Nižetić

ISBN 978-88-95608-93-8; **ISSN** 2283-9216

DOI: 10.3303/CET2294059

A Comparative Future Levelized Cost of Storage of Static Electrochemical and Mechanical Energy Storage Technologies in 1-MW Energy and Power Applications

Michael T. Castro, Eugene A. Esparcia Jr., Joey D. Ocon*

Laboratory of Electrochemical Engineering (LEE), Department of Chemical Engineering, University of the Philippines Diliman, Quezon City 1101, Philippines
jdocon@up.edu.ph

Different energy storage technologies have particular applications with advantageous techno-economic characteristics. For this reason, the present and future Levelised Costs Of Storage (LCOS) of commercially mature energy storage technologies have been analysed in the current literature. Emerging energy storage technologies, such as long-duration flywheels, are also vying to capture the energy storage market, but uncertainties linger as to which applications they can capture due to limited and reliable publicly available data. In this work, we determined the future LCOS of a typical 1 MW installation of stationary electrochemical energy storage (lead-acid, sodium-sulphur, and lithium-ion battery) and mechanical energy storage technologies (short-duration flywheel and long-duration flywheel) under different applications from 2020 to 2050 using updated relevant techno-economic parameters. Based on the present costs of energy storage, lithium-ion batteries yield the lowest LCOE across different energy storage applications, corroborating with previous outlooks from different scholarly works. The cost advantage of lithium-ion batteries compared to other storage technologies continues to rise over the years due to their rapid cost decline. In the absence of lithium-ion batteries, long-duration flywheels initially provide the lowest cost for a wide range of applications, but they face stiff competition with sodium-sulphur batteries. By 2040, sodium-sulphur batteries are projected to have a lower LCOS than long-duration flywheels. Promoters and manufacturers of emerging energy storage technologies must find ways to rapidly decrease storage costs to secure their niche in the energy storage market.

1. Introduction

The rising awareness of climate change and the declining costs of renewable energy (RE) technologies, such as solar photovoltaics and wind turbines, have motivated a transition to RE. This is evidenced by the growing installations of RE technologies in the national grid (IRENA, 2021a) and in off-grid areas (IRENA, 2021b). The power output of RE technologies is intermittent, however, so RE installations must be coupled with energy storage systems (ESS), which stores RE when it is in excess and dispatches RE when it is needed.

Electrochemical ESS such as batteries convert electrical energy into chemical energy during charging, and vice versa when discharging. Lithium-ion (Li-ion) batteries are a popular example due to their high energy and power density, commercial maturity, and rapidly decreasing costs (Schmidt et al., 2019). However, geopolitical supply chain risks in Li-ion manufacturing, particularly in the production of lithium and cobalt, have prompted the development of alternative ESS technologies (Olivetti et al., 2017). For instance, the sodium-sulphur (NAS) batteries developed by NGK Insulators Ltd. are made from sodium and sulphur, which are abundant materials (Kumar et al., 2017). Lead-acid (Pb-Acid) batteries are found in uninterruptable power supplies and may be used in RE systems due to their commercial maturity (Dhundhara et al, 2018).

Mechanical ESS, such as flywheels, compressed air, and pumped hydro, convert electrical energy to mechanical energy during charging. For example, short-duration flywheel energy storage (SD FES) stores rotational kinetic energy in a flywheel and can rapidly charge or discharge. SD FES is ideal for high-power applications such as primary response (Schmidt et al., 2019). Recently, long-duration flywheel energy storage (LD FES) has been developed for energy applications. Amber Kinetics has been at the forefront of promoting

Paper Received: 16 April 2022; Revised: 21 June 2022; Accepted: 24 June 2022
Please cite this article as: Castro M.T., Esparcia Jr E.A., Ocon J.D., 2022, A Comparative Future Levelized Cost of Storage of Static Electrochemical and Mechanical Energy Storage Technologies in 1-MW Energy and Power Applications, Chemical Engineering Transactions, 94, 355-360 DOI:10.3303/CET2294059

LD FES by establishing a manufacturing hub in Sto. Tomas city in the province of Batangas, Philippines in 2018 (Cahiles-Magkilat, 2021) and deploying a 1 MW/4 MWh LD FES installation in De La Salle University – Laguna Campus, Philippines (BusinessMirror, 2021). LD FES can be considered a competitor to electrochemical ESS due to its energy-oriented design.

The wide variety of ESS options presents a need to methodically select an appropriate ESS technology for a target application based on technical soundness and economic feasibility. This has led to the conceptualization of the levelized cost of storage (LCOS), a techno-economic metric defined as costs incurred by an ESS divided by its discharged energy over its entire lifespan. Schmidt et al. (2019) conducted a comprehensive study comparing the LCOS of nine ESS technologies under 12 representative use cases from 2015 to 2050. Lazard publishes its annual Levelized Cost of Storage Analysis, with its latest report comparing the LCOS of commercially mature ESS under six use cases (Lazard, 2021).

Existing literature on LCOS has focused on commercially mature technologies, however, and developing technologies such as LD FES are often excluded from the analysis. In this work, the future LCOS of electrochemical (Li-ion, NAS, and Pb-Acid) and mechanical (SD FES and LD FES) ESS technologies were compared for a variety of applications. The LCOS was initially compared using updated techno-economic parameters for the year 2020, while different applications were represented by the charge-discharge cycle time and discharge time. The comparison was then repeated with projected ESS costs from 2020 to 2050. Finally, the LCOS comparison was performed in the absence of Li-ion to simulate a post-Li-ion market.

2. Methodology

First, the LCOS calculation and comparison procedure are outlined. Next, the base case input parameters are presented. Lastly, the method for estimating future costs is discussed.

2.1 LCOS calculation

The LCOS estimates in this study consider the capital, operating, and replacement cost of an ESS installation that accepts 1 MW of power during charging. The size S [kWh] (i.e. energy rating) of the installation is given by Eq. 1, where C is the C-rate [kW/kWh] of the ESS.

$$S = \frac{(1000\ \mathrm{kW})}{C} \tag{1}$$

The total capital cost C_{cap} [USD] of the installation is the product of the per-unit capital cost c_{cap} [USD/kWh] and the size of the installation, as shown by Eq. 2. While the total capital cost is not necessarily a linear function of the size, the ESS in this case study are all rated at 1 MW, so it can be assumed that the total capital cost grows linearly with size due to the similar scales or capacities of the ESS under consideration.

$$C_{\mathrm{cap}} = c_{\mathrm{cap}} S \tag{2}$$

The annual operating cost is the product of the per-unit operating cost c_{op} [USD/kWh·y] and the size of the installation. The total operating cost C_{op} [USD] over the entire lifespan of the project is obtained by adding the discounted costs incurred each year. This is summarized by Eq. 3, where d is the discount rate and N [y] is the project lifespan.

$$C_{\mathrm{op}} = c_{\mathrm{op}} S \sum_{n=1}^{N} \frac{1}{(1+d)^n} \tag{3}$$

Replacement costs C_{rep} are incurred whenever an ESS reaches its lifespan. It is assumed that the per-unit capital and replacement costs are the same. The lifespan of an ESS n_{rep} is either the calendar life n_{cal} [y] or cycle life of the ESS, whichever is lower. The cycle life is defined as the time required until the capacity degrades to 80 % of its initial value, as given by Eq. 5 where t_{cyc} [h] is the time between charge-discharge cycles and D_{cyc} is the capacity degradation per cycle.

$$n_{\mathrm{rep}} = \min\left\{n_{\mathrm{cal}}, \frac{t_{\mathrm{cyc}} \ln 0.8}{\ln\left(1 - D_{\mathrm{cyc}}\right)}\right\} \tag{4}$$

The energy discharged by the ESS throughout its entire lifespan E_{dc} [kWh] is given by Eq. 5, where t_{dc} [h] is the duration of discharge in a charge-discharge cycle, $\mathrm{DOD}_{\mathrm{max}}$ is the maximum allowable Depth Of Discharge (DOD), and η_{RT} is the roundtrip efficiency. This equation assumes that, in each cycle, the ESS is charged by 1 MW of power for a duration of time such that the ESS reaches its maximum DOD at the end of discharge. The energy discharged from each cycle is multiplied by the number of cycles each year (i.e. 8,760 h divided by the charge-discharge cycle time), then annualised using the discount rate.

$$E_{\mathrm{dc}} = (1{,}000\ \mathrm{kW}) \times t_{\mathrm{dc}} \times \frac{(8{,}760\ \mathrm{h})}{t_{\mathrm{cyc}}} \times \mathrm{DOD}_{\max} \times \eta_{\mathrm{RT}} \times \sum_{n=1}^{N} \frac{1}{(1+d)^{n}} \tag{5}$$

The LCOS [USD/kWh] is computed using Eq. 6 by dividing the capital, operating, and replacement costs with the energy discharged by the ESS.

$$\mathrm{LCOS} = \frac{C_{\mathrm{cap}} + C_{\mathrm{op}} + C_{\mathrm{rep}}}{E_{\mathrm{dc}}} \tag{6}$$

2.2 Probabilistic LCOS comparison

The probability that one ESS technology will yield the lowest LCOS was determined using the methodology described by Schmidt et al. (2019). The LCOS of each ESS considered in this study was computed under discharge times of 0.125 h to 4 h and annual cycle numbers of 1 to 10,000. For each combination of t_{dc} and t_{cyc}, the LCOS was computed in 500 instances. In each instance, the per-unit capital and operating costs were perturbed from their base value using a normally distributed random number with a mean of zero and a variance that depends on the ESS technology. The probability that ESS technology A provides the lowest LCOS p_{A} among ESS A, B, C, D, and so on is given by Eq. 7 where $|\mathrm{LCOS}_{\mathrm{A},i} < \mathrm{LCOS}_{\mathrm{X}}|$ is the number of LCOS instances of technology X that were higher than the ith LCOE instance of technology A.

$$p_{\mathrm{A}} = \frac{1}{500^{k}} \sum_{i=1}^{500} \underbrace{|\mathrm{LCOS}_{\mathrm{A},i} < \mathrm{LCOS}_{\mathrm{B}}| \times |\mathrm{LCOS}_{\mathrm{A},i} < \mathrm{LCOS}_{\mathrm{C}}| \times \cdots}_{k\ \text{technologies}} \tag{7}$$

2.3 Base input parameters

The base case input parameters for the LCOS calculations are summarized in Table 1. These parameters reflect the techno-economic specifications of each ESS in the year 2020. Due to the lack of literature on LD FES, its cost variation was assumed to be the same as that of SD FES. The cycle degradation of LD FES was set to 10 times that of SD FES to give it a similar magnitude as electrochemical ESS technologies since LD FES was designed to be discharged at similar rates.

Table 1: Input techno-economic parameters to the LCOS calculations

Parameter	Li-ion	NAS	Pb-Acid	LD FES	SD FES	Ref.
Capital Cost [USD/kWh]	527.0	428.7	352.0	766.0	4,760	[a]
Operating Cost [USD/kWh·y]	7.9050	6.4305	8.8000	11.490	71.400	[a]
Standard Deviation of Cost [%]	24	12	38	17 [*]	17	[b]
Calendar Life [y]	12.5	15.0	3.50	20.0	20.0	[a]
Cycle Degradation [%/cycle]	0.0069	0.0054	0.0182	0.0020 [*]	0.0002	[b]
Maximum DOD [%]	90.0	80.0	50.0	100	100	[a]
C-rate [kW/kWh]	0.500	0.167	0.259	0.250	4.00	[a]
Roundtrip Efficiency [%]	82.5	75.0	65.0	95.0	95.0	[a]

[a] Baxter (2019), [b] Schmidt et al. (2019) [*] Assumed

2.4 Cost projection

A cost projection analysis was carried out to determine how the probability of each ESS yielding the lowest LCOE changes if ESS installation were deferred to a later date. Figure 1 illustrates the cost of ESS technologies relative to their values in 2020. These were obtained from the study of Schmidt et al. (2019), except for the projected costs of LD FES, which was extrapolated from the work of Baxter (2019). The study of Schmidt et al. (2019) presents the uncertainty of their projections, but this information is not available from the work of Baxter (2019). For every 5 y from 2020 to 2050, these relative costs were multiplied with the base case per-unit capital and operating costs, and then the LCOS values were calculated. The probability of each ESS resulting in the lowest LCOE for combinations of t_{dc} and t_{cyc} were then computed using the projected LCOS.

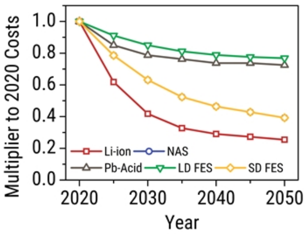

Figure 1: Ratio of capital and operating costs of ESS technologies in the future to their values in 2020. The projected costs of NAS and SD FES are identical.

3. Results and Discussion

3.1 Base scenario

Figure 2 presents the probability of each ESS technology having the lowest LCOS in 2020. Li-ion BESS dominates applications where the discharge time is between 0.25 h to 2 h and the cycles per year are between 1 to 1,000. SD FES has the lowest LCOS for short discharge times lower than 0.25 h and where more than 1,000 cycles/y are required. The results are comparable to those of Schmidt et. al. (2019), where Li-ion BESS has the highest chance of yielding the lowest LCOS for moderate discharge times, while SD FES is most effective when frequent cycling is necessary. LD FES has the lowest LCOE at longer discharge times greater than 2 h. It also competes with Li-ion BESS for applications requiring moderate discharge durations (i.e. 0.25 h to 2 h) and higher cycles per year, since it does not degrade as quickly as electrochemical ESS. Overall, LD FES is a viable ESS technology for applications that need long or frequent discharge. It should be noted, however, that the boundaries between the regions where each technology has the lowest LCOS should not be as sharp as depicted in Figure 2, since this is a result of neglecting the uncertainty of the technical parameters. For instance, uncertainties in the cyclic degradation rate can change the number of allowable cycles, blurring the boundaries between Li-ion BESS and LD FES.

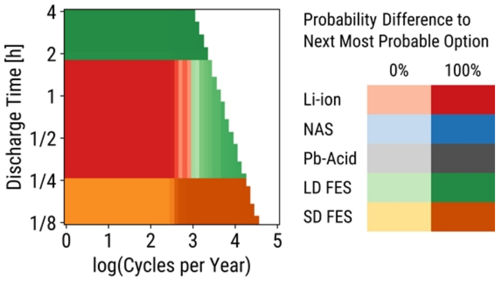

Figure 2: Probability of various ESS technologies having the lowest LCOS in 2020 under each combination of discharge time and cycles per year. The white region on the upper right represents physically impossible scenarios.

3.2 Cost projection

Figure 3 shows the probability of each ESS technology yielding the lowest LCOS from 2025 to 2050. It can be observed that Li-ion BESS supersedes SD FES for discharge shorter than 0.25 h and annual cycles less than 1,000 and LD FES for discharge between 0.25 h and 1 h and annual cycles greater than 1,000. This is also identical to the prediction of Schmidt et al. (2019), that Li-ion BESS dominates all applications except for short-duration high-frequency discharge, where SD FES is more cost-effective, and long-discharge applications, which are satisfied by other ESS technologies. For long discharge applications (i.e. greater than 2 h), LD FES is supplanted by NAS in 2040 since the latter has a faster cost decline. From the results, it can be noted that LD FES quickly loses market traction due to its slow cost reduction compared to other ESS technologies. The manufacturers of LD FES must ramp up production so that the economies of scale will decrease the cost of LD FES. Competing with Li-ion BESS is a highly futile attempt considering its rapid cost decline and how Li-ion has a much greater probability of yielding a lower LCOS than LD FES. It would be more reasonable for LD FES to compete with NAS or long-duration electrochemical ESS technologies due to their slower cost decline. The calculations reveal that the probability of NAS yielding the lowest LCOS is not much greater than that of LD FES.

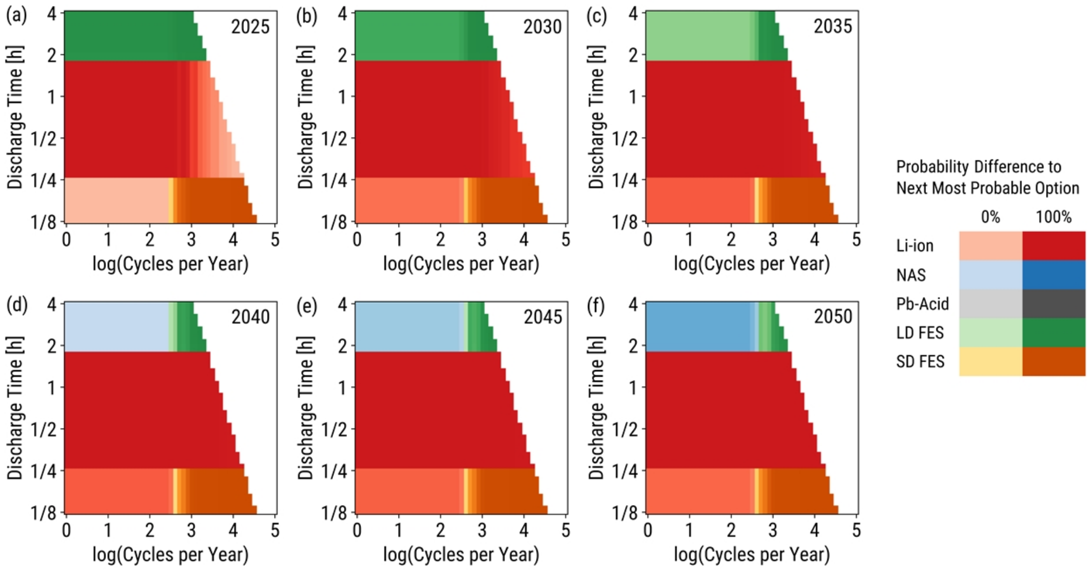

Figure 3: Probability of various ESS technologies having the lowest LCOS under each combination of discharge time and cycles per year from 2025 (a) to 2050 (f) in 5-y increments

Figure 4 shows the probability of each ESS having the lowest LCOS from 2025 to 2050 in the absence of Li-ion BESS. This illustrates a post-Li-ion scenario in which other ESS technologies fill in the excessive demand for Li-ion BESS, since the demand for raw Li-ion battery materials may outgrow the supply (Azevedo et al., 2020). Initially, LD FES is the most cost-effective ESS technology for discharge times above 0.25 h, however, the cost decline of NAS quickly catches up for annual cycles less than 1,000. This also supports our earlier recommendation that LD FES manufacturers should quickly lower their costs to maintain their advantage over NAS. LD FES still retains its dominance over high-frequency discharge cycles, however, due to its lower degradation rate than electrochemical ESS technologies.

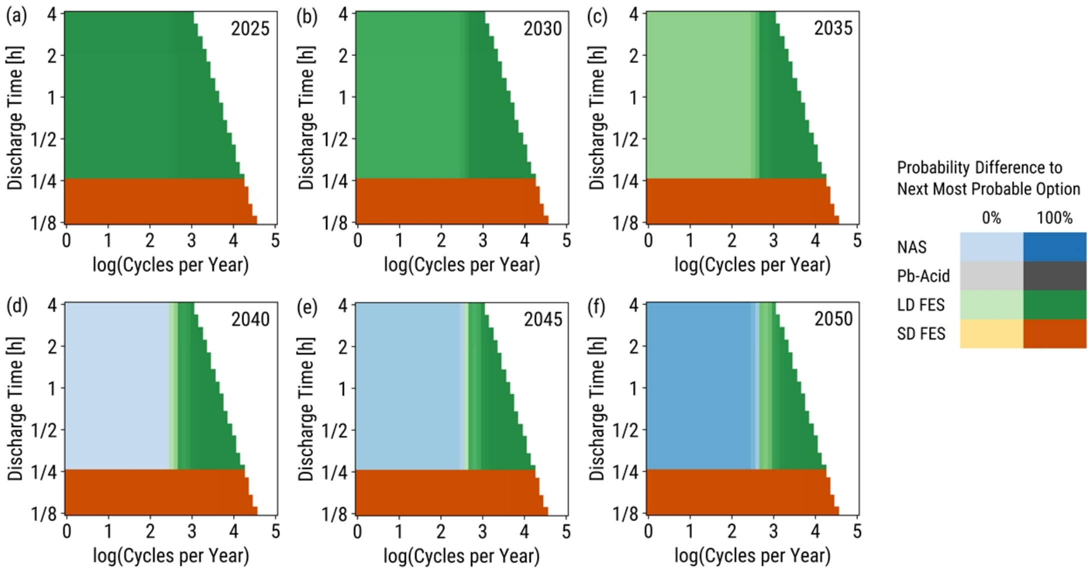

Figure 4: Probability of various ESS technologies having the lowest LCOS under each combination of discharge time and cycles per year from 2025 (a) to 2050 (f) in the absence of Li-ion BESS

4. Conclusions

In this work, the present and future LCOS of electrochemical (i.e. Li-ion, NAS, and Pb-Acid BESS) and mechanical (i.e. LD FES and SD FES) ESS were compared using up-to-date techno-economic parameters. The study demonstrates the identification of potential applications or niches of new contenders in the energy storage market, such as LD FES, and their competition among commercially mature ESS technologies. The comparison of LCOS using costs in 2020 reveals that Li-ion BESS dominates most applications, in particular, discharge times between 0.25 h to 2 h and annual cycles less than 1000. SD FES are cost-effective when short and frequent discharge is needed, while LD FES is advantageous when a longer discharge period is required. The future LCOS of Li-ion BESS is expected to decrease further than the cost of LD FES for discharge times between 0.25 h to 2 h and annual cycles greater than 1,000 and SD FES for discharge times shorter than 0.25 h and annual cycles less than 1,000. The LCOS decline of NAS also overtakes that of LD FES by 2040 for long-duration discharge. In the absence of Li-ion BESS, LD FES initially dominates the ESS market for moderate to long duration discharge but is superseded by NAS by 2040. Players must therefore quickly decrease the cost of their technologies, by ramping up manufacturing to increase economies of scale, for example, to secure a slot in a highly competitive energy storage market. In future work, a more comprehensive study involving more emerging energy storage technologies, such as post-lithium chemistries can be conducted.

Nomenclature

C – C-rate, kW/kWh
c_{cap} – per-unit capital cost, USD/kWh
c_{op}– per-unit operating cost, USD/(kWh·y)
C_{cap} – total capital cost, USD
C_{op} – total operating cost, USD
C_{rep} – total replacement cost, USD
d – discount rate, -
D_{cyc} – cycle degradation, 1/cycle
$\mathrm{DOD}_{\mathrm{max}}$ – maximum depth of discharge, -
LCOS – levelized cost of storage, USD/kWh
n_{cal} – calendar life, y
n_{rep} – lifespan of ESS technology, y
N – lifespan of project, y
p – probability, -
t_{cyc} – charge-discharge cycle time, h
t_{dc} – discharge time per cycle, h
η_{RT} – roundtrip efficiency, -

Acknowledgments

This work is financially supported by the University of the Philippines Office of the Vice-President for Academic Affairs through the ElectriPHI Program (OVPAA-EIDR-C09-01).

Reference

Azevedo M., Goffaux N., Hoffman K., 2020. How clean can the nickel industry become? McKinsey and Company, <https://www.mckinsey.com/industries/metals-and-mining/our-insights/how-clean-can-the-nickel-industry-become>, accessed 17.05.2022.
Baxter R., 2019. 2019 Energy Storage Pricing Survey, Sandia National Laboratories. <https://www.osti.gov/biblio/1765622-energy-storage-pricing-survey>, accessed 11.04.2022.
BusinessMirror, 2021. DLSU and Amber Kinetics launch Flywheel Storage Management System Project with DOST. BusinessMirror, <https://businessmirror.com.ph/2021/07/13/dlsu-and-amber-kinetics-launch-flywheel-storage-management-system-project-with-dost/>, accessed 11.04.2022.
Cahiles-Magkilat B., 2021. US firm to expand energy storage business in PH. Manila Bulletin. <https://mb.com.ph/2021/03/22/us-firm-to-expand-energy-storage-business-in-ph/>, accessed 11.04.2022.
Dhundhara S., Verma Y.P., Williams A., 2018. Techno-economic analysis of the lithium-ion and lead-acid battery in microgrid systems. Energy Conversion and Management, 177, 122–142.
IRENA, 2021a. Renewable Energy Statistics 2021, International Renewable Energy Agency. <https://irena.org/publications/2021/Aug/Renewable-energy-statistics-2021>, accessed 11.04.2022.
IRENA, 2021b. Off-grid Renewable Energy Statistics 2021, International Renewable Energy Agency. <https://irena.org/publications/2021/Aug/Renewable-energy-statistics-2021>, accessed 11.04.2022.
Kumar D., Rajouria S.K., Kuhar S.B., Kanchan D.K., 2017. Progress and prospects of sodium-sulfur batteries: A review. Solid State Ionics, 312, 8–16.
Lazard, 2021. Levelized Cost of Storage – Version 7.0, Lazard. <https://www.lazard.com/media/451882/lazards-levelized-cost-of-storage-version-70-vf.pdf>, accessed 11.04.2022.
Olivetti E.A., Ceder G., Gaustad G.G., Fu X., 2017. Lithium-ion battery supply chain considerations: analysis of potential bottlenecks in critical metals. Joule, 1, 229–243.
Schmidt O., Melchior S., Hawkes A., Staffell I., 2019. Projecting the future levelized cost of electricity storage technologies. Joule, 3, 81–100.