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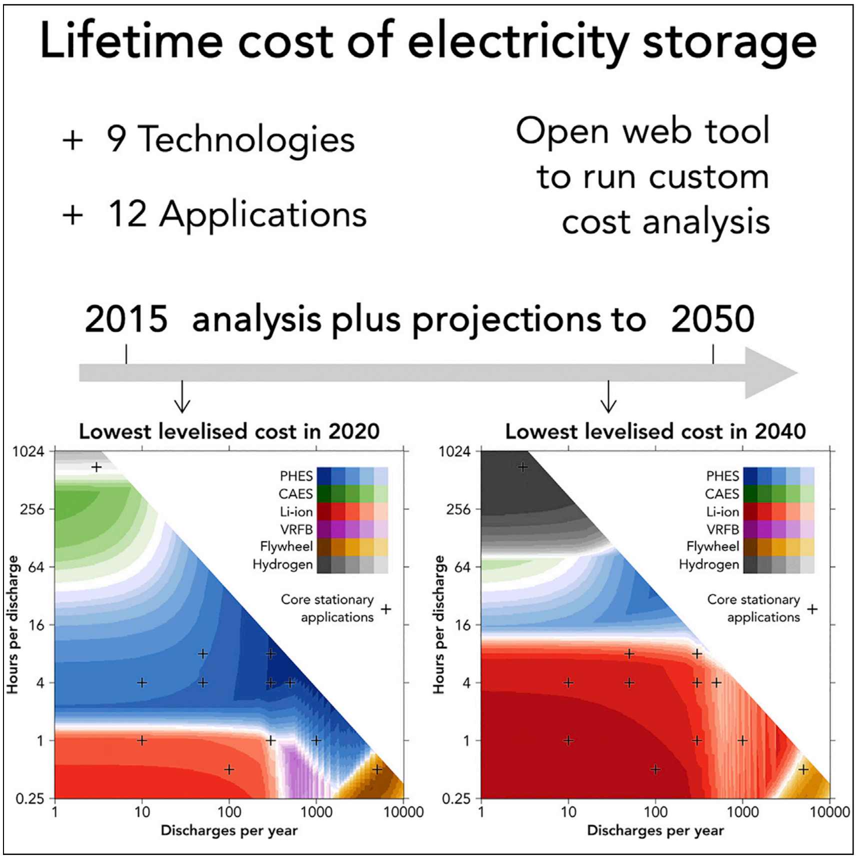
Projecting the Future Levelized Cost of Electricity Storage Technologies



This study determines the lifetime cost of 9 electricity storage technologies in 12 power system applications from 2015 to 2050. We find that lithium-ion batteries are most cost effective beyond 2030, apart from in long discharge applications. The performance advantages of alternative technologies do not outweigh the pace of lithium-ion cost reductions. Thus, investments in alternatives might be futile, unless performance improvements retain competitiveness with lithium ion. These insights increase transparency around the economic viability of electricity storage and can help guide research, policy, and investment activities to ensure cost-efficient deployment.

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HIGHLIGHTS

Lifetime cost for 9 storage technologies in 12 applications from 2015 to 2050

Lowest lifetime costs fall by 36% (2030) and 53% (2050) across the 12 applications

Lithium-ion batteries are most competitive in majority of applications from 2030

Pumped hydro, compressed air, and hydrogen are best for long discharge applications

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Projecting the Future Levelized Cost of Electricity Storage Technologies

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SUMMARY

The future role of stationary electricity storage is perceived as highly uncertain. One reason is that most studies into the future cost of storage technologies focus on investment cost. An appropriate cost assessment must be based on the application-specific lifetime cost of storing electricity. We determine the levelized cost of storage (LCOS) for 9 technologies in 12 power system applications from 2015 to 2050 based on projected investment cost reductions and current performance parameters. We find that LCOS will reduce by one-third to one-half by 2030 and 2050, respectively, across the modeled applications, with lithium ion likely to become most cost efficient for nearly all stationary applications from 2030. Investments in alternative technologies may prove futile unless significant performance improvements can retain competitiveness with lithium ion. These insights increase transparency around the future competitiveness of electricity storage technologies and can help guide research, policy, and investment activities to ensure cost-efficient deployment.

INTRODUCTION

Adequate cost assessments for electricity storage solutions are challenging due to the diversity of technologies possessing different cost and performance characteristics and the varying requirements of storage applications.[1] Recent studies on future costs are limited to investment cost of storage technologies only.[2,3] As a result, the future role of electricity storage is still perceived as highly uncertain,[4] despite remarkable growth in deployment for distinct technologies and applications.[5,6]

The levelized cost of storage (LCOS) quantifies the discounted cost per unit of discharged electricity for a specific storage technology and application.[7] The metric therefore accounts for all technical and economic parameters affecting the lifetime cost of discharging stored electricity. It is directly comparable to the levelized cost of electricity (LCOE) for generation technologies and represents an appropriate tool for cost comparison of electricity storage technologies.[8–11]

Despite an increasing number of LCOS studies,[12–17] there is not yet a common definition of this metric. While some studies neglect cost parameters like replacement or disposal,[13–15] others exclude relevant performance parameters, such as capacity degradation.[12,16,17] Academic publications are often limited to a small selection of storage applications,[7,13–15] while industry reports lack transparency on LCOS methodology.[12,16] Both focus only on current LCOS.[12–17]

In this paper, we present a first-of-its-kind overview of LCOS for 9 electricity storage technologies in 12 stationary applications from 2015 to 2050. We derive a transparent LCOS methodology and review technology parameters and application requirements. The resulting method and data are then used to calculate

Context & Scale

Electricity storage is considered a key technology to enable low-carbon power systems. However, existing studies focus on investment cost. The future lifetime cost of different technologies (i.e., levelized cost of storage) that account for all relevant cost and performance parameters are still unexplored.

This study projects application-specific lifetime cost for multiple electricity storage technologies. We find specialized technologies are unlikely to compete with lithium ion, apart from in long discharge applications. Their performance advantages do not outweigh the pace of lithium-ion cost reductions. These insights could affect business and research strategies for storage, shifting investments to performance improvements for alternative technologies or focusing it on lithium ion. This shows parallels to solar cells where first-generation crystalline cells still dominate, despite significant investments in alternative cell technologies that were expected to be cheaper.

application-specific LCOS. These insights enable us to determine the likelihood of each technology to offer the lowest LCOS in a distinct application and derive patterns of technology dominance along distinct application requirements.

The full input parameters and output results from this work are made available (Supplemental Procedures, Online Data Repository[18]). An interactive version of our LCOS model is available online at www.EnergyStorage.ninja. By increasing transparency of lifetime cost of multiple storage technologies and their competitiveness in diverse applications, this study can help to reduce uncertainty around the future role of electricity storage.

Levelized Cost of Storage (LCOS)

Levelized cost of storage can be described as the total lifetime cost of the investment in an electricity storage technology divided by its cumulative delivered electricity.[8] Delivered electricity can refer to electrical energy or electric power.[9] It reflects the internal average price at which electricity can be sold for the investment's net present value to be zero (i.e., its revenue requirement),[19] and is therefore analogous to the concept of levelized cost of electricity (LCOE) for generation technologies. The LCOS for storage technologies and LCOE for generation technologies can be directly compared; however, different concepts of providing electricity and resulting differences in cost calculation methodology suggest the use of different names. The suitability of the LCOS method to compare storage technologies for specific applications among each other, and to generation technologies, explains the recent increase in LCOS studies.[7,8,12–15]

However, the findings in these studies differ due to varying input data and LCOS methodologies (Procedure S1). Replacement and end-of-life costs are often neglected. Similarly, performance characteristics like cycle life, capacity degradation, and self-discharge are not always considered. Some studies differentiate between net internal costs of storing electricity, which excludes electricity price and storage efficiency, and cost per unit of discharged electricity, which includes both.[14] This lack of common methodology is reflected in the different names that are used to describe LCOS, such as levelized cost of stored energy,[8] life cycle cost,[13,17,19] levelized cost of delivery,[14] or levelized cost of electricity.[14,15]

Equation 1 depicts the approach for calculating LCOS taken in this study. LCOS is defined as the discounted cost per unit of discharged electrical energy, in line with recent publications.[7,12,20]

$$LCOS\left[\frac{\$}{MWh}\right]=\frac{Investment\ cost+\sum_{n}^{N}\frac{O\&M\ cost}{(1+r)^{n}}+\sum_{n}^{N}\frac{Charging\ cost}{(1+r)^{n}}+\frac{End\text{-}of\text{-}life\ cost}{(1+r)^{N+1}}}{\sum_{n}^{N}\frac{Elec_{Discharged}}{(1+r)^{n}}}. \qquad \text{(Equation 1)}$$

The equation incorporates all elements required to determine the full lifetime cost of an electricity storage technology: investment, operation and maintenance (O&M), charging, and end-of-life cost divided by electricity discharged during the investment period. It assumes all investment costs are incurred in the first year and sums ongoing costs in each year (n) up to the system lifetime (N), discounted by the discount rate (r).

For applications that value the provision of active power instead of energy, measuring LCOS per unit of delivered electrical energy is unsuitable.[21] In this

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context, the LCOS in power terms (i.e., annuitized capacity cost) is determined as the discounted lifetime cost per unit of power capacity (Experimental Procedures). Applications that require the provision of reactive power are not considered. A metric measuring lifetime cost per unit of reactive power output would be best suited for these services.

Electricity Storage Applications and Technologies

Electricity storage technologies can be used in numerous applications covering the entire electricity supply chain.[16,21–25] Different technical requirements of these applications determine the suitability of distinct technologies and affect the LCOS of the suitable ones. Therefore, LCOS comparisons should always be application specific.[7,12]

Table 1 describes 12 core applications for stationary storage within the electricity value chain. They amalgamate 25 identified unique-purpose applications based on similar technical requirements and represent a mutually exclusive and collectively exhaustive set of storage applications on that basis (Tables S1 and S2). Table 1 also shows the technical suitability of the 9 most commonly deployed stationary electricity storage technologies for these applications. Technical suitability is determined based on technology characteristics and application requirements (Experimental Procedures).

Pumped hydro and underground compressed air energy storage are characterized by relatively slow response times (>10 s) and large minimum system sizes (>5 MW).[13,16,24] Therefore, they are ill suited for fast response applications such as primary response and power quality and small-scale consumption applications. Flywheels and supercapacitors are characterized by short discharge durations (<1 h)[13,29] and are not suitable for applications requiring longer-term power provision. Seasonal storage requires power provision for months, a requirement that can only be met by technologies where energy storage capacity can be designed fully independent of power capacity.

Note that this analysis considers common application requirements and technology characteristics. Market-specific implementation of these applications can result in a higher number of services and requirements outside the ranges considered in Table S2 (see multiple primary response services in the United Kingdom for example[30]). Similarly, technology characteristics can be engineered outside of the ranges given in Table S3 to meet certain application requirements. However, such deviations are not representative for the majority of existing electricity storage systems.

The key parameters that affect the LCOS of each technology, but are set by respective applications, are nominal power capacity, discharge duration, annual cycles, and electricity price. While the first two affect investment, O&M, and end-of-life cost, annual cycles affect project life and total discharged electricity. In combination with each technology's efficiency, the electricity price affects charging cost. Electricity prices captured during charging will vary between applications, regions, and over both short and long timescales.[31] This study assumes two generic values that are broadly representative of wholesale and retail prices. This is intended to give a price difference that is applicable globally and relevant for network or system applications and behind-the-meter consumer applications, respectively (Experimental Procedures). Readers may test the impact of alternative electricity prices, applications, or technology definitions via the interactive online version of our model at www.EnergyStorage.ninja.

Table 1. Qualitative Description of Electricity Storage Applications and Technology Suitability

Role	Application	Description	Pumped Hydro	Compressed Air	Flywheel	Lithium Ion	Sodium Sulfur	Lead Acid	Vanadium Redox Flow	Hydrogen	Supercapacitor
	1. Energy arbitrage	Purchase power in low-price and sell in high-price periods on wholesale or retail market	✓	✓		✓	✓	✓	✓	✓	
System Operation	2. Primary response	Correct continuous and sudden frequency and voltage changes across the network			✓	✓	✓	✓	✓	✓	✓
	3. Secondary response	Correct anticipated and unexpected imbalances between load and generation	✓	✓	✓	✓	✓	✓	✓	✓	✓
	4. Tertiary response	Replace primary and secondary response during prolonged system stress	✓	✓		✓	✓	✓	✓	✓	
	5. Peaker replacement	Ensure availability of sufficient generation capacity during peak demand periods	✓	✓		✓	✓	✓	✓	✓	
	6. Black start	Restore power plant operations after network outage without external power supply	✓	✓	✓	✓	✓	✓	✓	✓	✓
	7. Seasonal storage	Compensate long-term supply disruption or seasonal variability in supply and demand	✓	✓					✓	✓	
Network Operation	8. T&D investment deferral	Defer network infrastructure upgrades caused by peak power flow exceeding existing capacity	✓	✓		✓	✓	✓	✓	✓	
	9. Congestion management	Avoid re-dispatch and local price differences due to risk of overloading existing infrastructure	✓	✓		✓	✓	✓	✓	✓	
Consumption	10. Bill management	Optimise power purchase, minimize demand charges and maximise PV self-consumption				✓	✓	✓	✓	✓	
	11. Power quality	Protect on-site load against short-duration power loss or variations in voltage or frequency			✓	✓	✓	✓	✓	✓	✓
	12. Power reliability	Cover temporal lack of variable supply and provide power during blackouts				✓	✓	✓	✓	✓	

Applications are grouped by role within the electricity value chain. Selection and description of applications based on review of common electricity storage services.[12,16,21–27] See Tables S1 and S2 for amalgamation of 25 unique-purpose to 12 core applications and their quantitative requirements. Selection of storage technologies represents the most deployed stationary systems by power capacity.[28] Suitability assessment is based on technology characteristics in terms of system size, discharge duration, and response time. See Table S3 for quantitative technology characteristics. T&D, transmission and distribution; Compressed air refers to compressed air energy storage in underground caverns. Hydrogen storage refers to a system with electrolyser, storage tank, and fuel cell.

RESULTS

Projecting Levelized Cost of Storage

We project LCOS for the 9 technologies and 12 applications in Table 1 from 2015 to 2050. Technology cost and performance data and application requirements are based on a review of industry and academic publications and were verified with industry experts (Table S4; Figure S1). Variation and uncertainty in the technology data are accounted for in a Monte-Carlo simulation of the LCOS calculation. Based on the results, a probability for each technology to exhibit the lowest LCOS in each application and year is determined (Experimental Procedures).

Figure 1 shows the results for secondary response. It describes application requirements, projected LCOS for the four most competitive technologies, their probability to be most cost efficient, and the mean LCOS of the technology with the highest probability to be most cost efficient. Uncertainty ranges for projected LCOS are based on the Monte-Carlo simulation. Probability reflects the frequency with which each technology offers the minimum LCOS accounting for these uncertainty ranges.

Secondary response is characterized by short discharge duration and frequent cycles. It can be large-scale and does not require fast response, which makes it suitable for pumped hydro with favourable geographic conditions. Pumped hydro exhibits the lowest LCOS in 2015 (150–400 US$/MWh) due to lifetimes beyond 30 years at 1,000 annual cycles, and despite relatively high power-specific investment cost. Mean LCOS for flywheel storage is much higher than for pumped hydro, however large investment cost uncertainty translates into a small probability for minimum LCOS. The strong anticipated investment cost reductions for battery technologies mean that by 2030 vanadium redox flow and lithium ion are likely to be the most

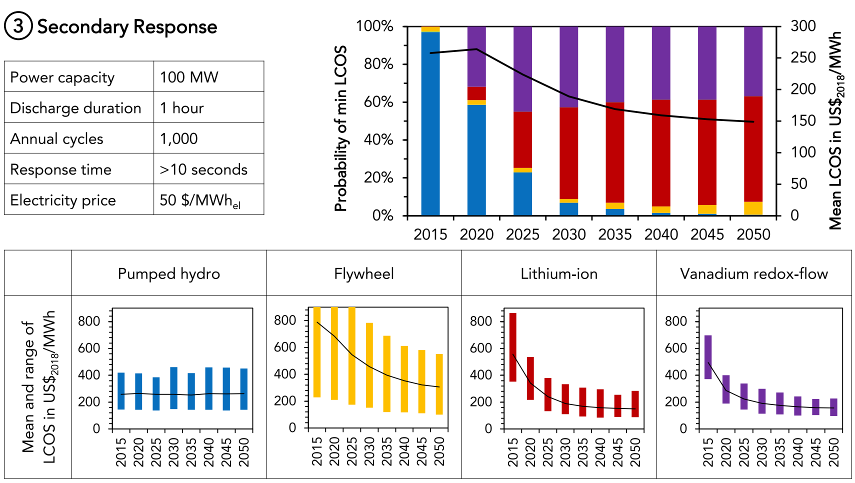

Figure 1. LCOS Projections for Secondary Response

Application requirements (top left), probability of exhibiting lowest LCOS (top right), and explicit LCOS projections for four most competitive technologies, including uncertainty ranges based on Monte-Carlo simulation of LCOS calculation (bottom). Monte-Carlo simulation conducts 500 LCOS calculations per technology and year with random technology input parameter values from an 80% confidence interval of parameter's attributed normal distribution, corresponding to 1.285 standard deviations from the mean. Top-right chart includes mean LCOS of technology with highest probability to be most cost efficient (black line). Probability reflects the frequency with which each technology offers the minimum LCOS accounting for the uncertainty ranges. See Figure 2 for probability charts of other applications and Figure S3 for projected LCOS of all 9 technologies and 12 applications.

cost efficient for this application despite an operating life of only 8 and 13 years, respectively (see Tables S4–S6 for lifetime assumptions).

The mean LCOS of the most cost-efficient technology reduces from 250 US$/MWh in 2015 to 190 and 150 US$/MWh in 2030 and 2050, respectively. Investment costs make up the largest proportion of LCOS across the four technologies, between 65% and 90% in 2015. Reduced investment costs for the two battery technologies mean that this share falls from 80% (2015) to 55% (2030) and 40% (2050). Charging cost represents the second largest contributor for the four technologies at 7% to 25% due to the high annual cycle requirement. Please refer to Figure S3 for projected LCOS of all 9 technologies and 12 applications and cost breakdowns. Note that these LCOS projections are solely based on future investment cost reductions, disregarding potential performance improvements. Figure 2 shows an overview of all technologies' probabilities to exhibit the lowest LCOS, and the mean LCOS of the most cost-efficient technology for all 12 investigated electricity storage applications. In 2015, pumped hydro and compressed air dominate most applications apart from consumption services and primary response, where size and response time requirements make these technologies unsuitable. In consumption service applications, battery systems such as lead acid, sodium sulphur, lithium ion, and vanadium redox flow compete for least-cost, while primary response is dominated by flywheels.

Projected cost reductions for battery technologies limit the competitiveness of pumped hydro and compressed air. Battery technologies exhibit the highest probability of lowest LCOS in most applications beyond 2025. By 2030, lithium ion appears to be most cost efficient in most applications, in particular with <4 h discharge and <300 annual cycles such as power quality and black start. For applications with greater duration and cycle requirements, vanadium redox flow stays competitive, albeit never being the most likely to offer minimum LCOS. These applications are power reliability (>4 h) or secondary response and bill management (>300 cycles). For seasonal storage with more than 700 h discharge, hydrogen storage is likely to become most cost efficient. Primary response with 5,000 full equivalent charge-discharge cycles sees the dominance of flywheels contested by lithium ion.

On average, mean LCOS of technologies with the highest probability to be most cost efficient reduce 36% and 53% by 2030 and 2050 relative to 2015, respectively, across the modeled applications. For applications $\geq$300 annual cycles, LCOS reduce from 150–600 US$/MWh (2015) to 130–200 US$/MWh (2050), for between 50 and 100 annual cycles from 1,000–3,500 (2015) to 500–900 US$/MWh (2050), and applications with $\leq$10 annual cycles never cost below 1,500 US$/MWh. The annual cycle requirement is so important because it affects energy throughput per unit of installed capacity. The lower the amount of capacity deployed to throughput a certain amount of energy per year, the lower the LCOS. This observation is a result of the high share of investment cost in the LCOS.

Another LCOS driver appears to be discharge duration. Applications with longer discharge requirements exhibit lower LCOS than applications with similar cycle and shorter discharge requirements. Examples are minimum LCOS for *T&D Investment Deferral* (150 US$/MWh, 8 h) or the relatively low LCOS for *Seasonal Storage* (1,500–3,000 US$/MWh, 700 h) compared to applications with more cycles but lower discharge duration like black start and tertiary response. This is the result of the energy discharge-focused metric US$/MWh. Any increase in discharge duration for a technology entails a similar increase in modeled energy discharge, but a lower

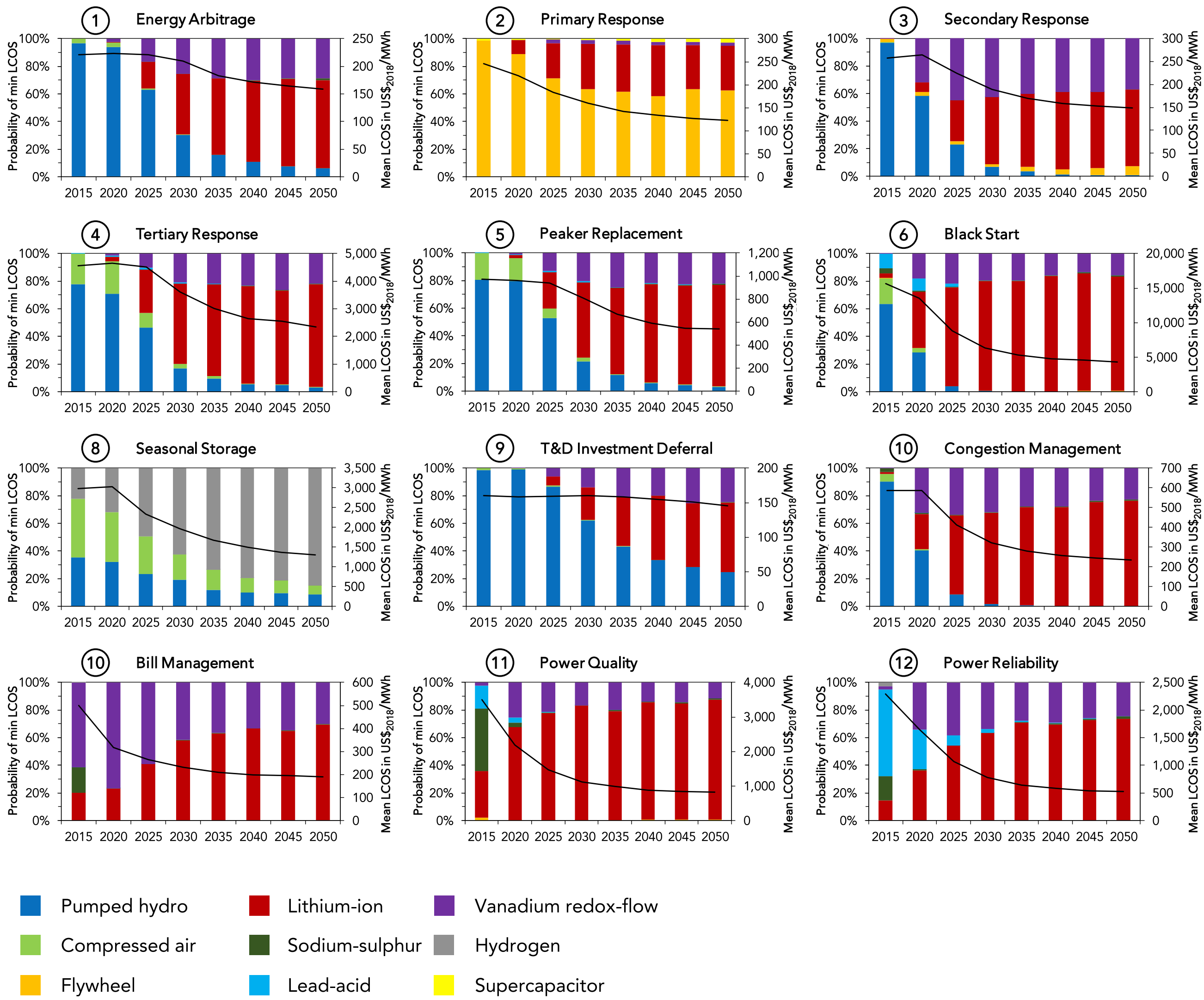

Figure 2. Lowest LCOS Probabilities for 9 Electricity Storage Technologies in 12 Applications from 2015 to 2050

Left-hand axis displays probability that a technology will exhibit the lowest LCOS in a specific application. Right-hand axis displays mean LCOS of technology with highest probability for lowest LCOS. Note there are different scales between panels. Probabilities reflect the frequency with which each technology offers the minimum LCOS accounting for the uncertainty ranges identified with the Monte-Carlo simulation of the LCOS calculation. Circled numbers in panel titles correspond to applications in Table 1. Note that applications like primary response or power quality are usually reimbursed for provision of power capacity, not energy output. Please refer to Figure S4 for probability analysis and projection of LCOS in power terms (i.e., annuitized capacity cost in US$/kW$_{year}$).

relative increase in total investment cost because only energy-related and no power-related cost is affected.

Figure S4 displays LCOS in US$/kW$_{year}$, also called annuitized capacity cost. This metric matters for applications valued for power provision such as primary response or power quality. It reflects the cost at which a technology can provide a unit of power capacity for an entire year or the annual reimbursement it should receive per kW for a net present value of zero. Here, technologies with low round-trip efficiencies like compressed air can be more cost efficient and applications with short discharge and few annual cycles like black start or power quality exhibit lowest cost. This highlights the importance of choosing the appropriate metric, energy- or power-focused when determining application-specific LCOS for economic investment decisions in electricity storage technologies.

Sensitivity to Application Requirements

Figures 3 and 4 explore the sensitivity for most cost-efficient technology relative to discharge duration and annual cycles. While Figure 3 performs this analysis for all modeled technologies, Figure 4 excludes pumped hydro and compressed air, as they have limited geographic suitability.

We find pumped hydro, compressed air, and flywheel energy storage were the most competitive technologies across the entire spectrum of modeled discharge and frequency combinations in 2015. Pumped hydro dominates due to good cycle life combined with low energy- and moderate power-specific investment cost. Compressed air is more competitive above 45 h discharge due to significantly lower energy-specific investment cost. Flywheels are more competitive above 5,000 annual cycles and below 0.5 h discharge due to better cycle life and lower power-specific cost.

Projecting future LCOS based on investment cost reductions indicates that lithium-ion batteries become cost-competitive for low discharge duration applications by 2020, competing with vanadium redox flow and flywheels at high frequencies due to their better cycle life. However, in terms of power-focused annuitized capacity cost (Figure S5), there is a strong cost advantage for lithium ion at high-frequency combinations, relevant for primary response applications, due to considerable cycle life improvement when operating below 100% depth-of-discharge. This finding is supported by the recent uptake of lithium-ion systems for primary response applications.[29]

With continued investment cost reduction, lithium ion could outcompete vanadium redox flow at high frequencies and displace pumped hydro at high discharge durations to become the most cost-efficient technology for most modeled applications by 2030. At the same time, hydrogen storage becomes more cost efficient than compressed air for long discharge applications.

Excluding pumped hydro and compressed air reveals that hydrogen storage is already most cost efficient in 2015 for discharge durations beyond 1 day, and a wider ecosystem of cost-efficient technologies is seen. Sodium-sulphur and lead-acid dominate applications up to 300 and lithium ion, vanadium redox flow and flywheels above 300 cycles per year. Projecting future LCOS confirms that lithium ion becomes cost competitive for most discharge and frequency combinations below 8 h discharge, with a particularly strong cost advantage at frequencies below 300 and above 1,000. The initial increase and subsequent decrease in cost efficiency of vanadium redox flow between 300 and 1,000 cycles shows its possible cost reduction dynamic compared to lithium ion. As a relatively immature technology, flow batteries could realize more significant cost reductions in the near-term[2] (Table S8). The experience curve analysis still reveals stronger cost reductions for lithium ion in the long-term due to a higher experience rate (Figure S2). Lithium ion is thereby likely to replace all other battery technologies by 2030 and dominate all discharge and frequency combinations together with flywheels and hydrogen storage.

The LCOS of the most cost-efficient technology for all discharge and frequency combinations is displayed in Figure 5. Lowest LCOS are achieved by pumped hydro for moderate discharge (~4 h) and frequency (~1,000) combinations. The LCOS range of 100 to 150 US$/MWh in 2015 corresponds to the cost of new pumped hydro

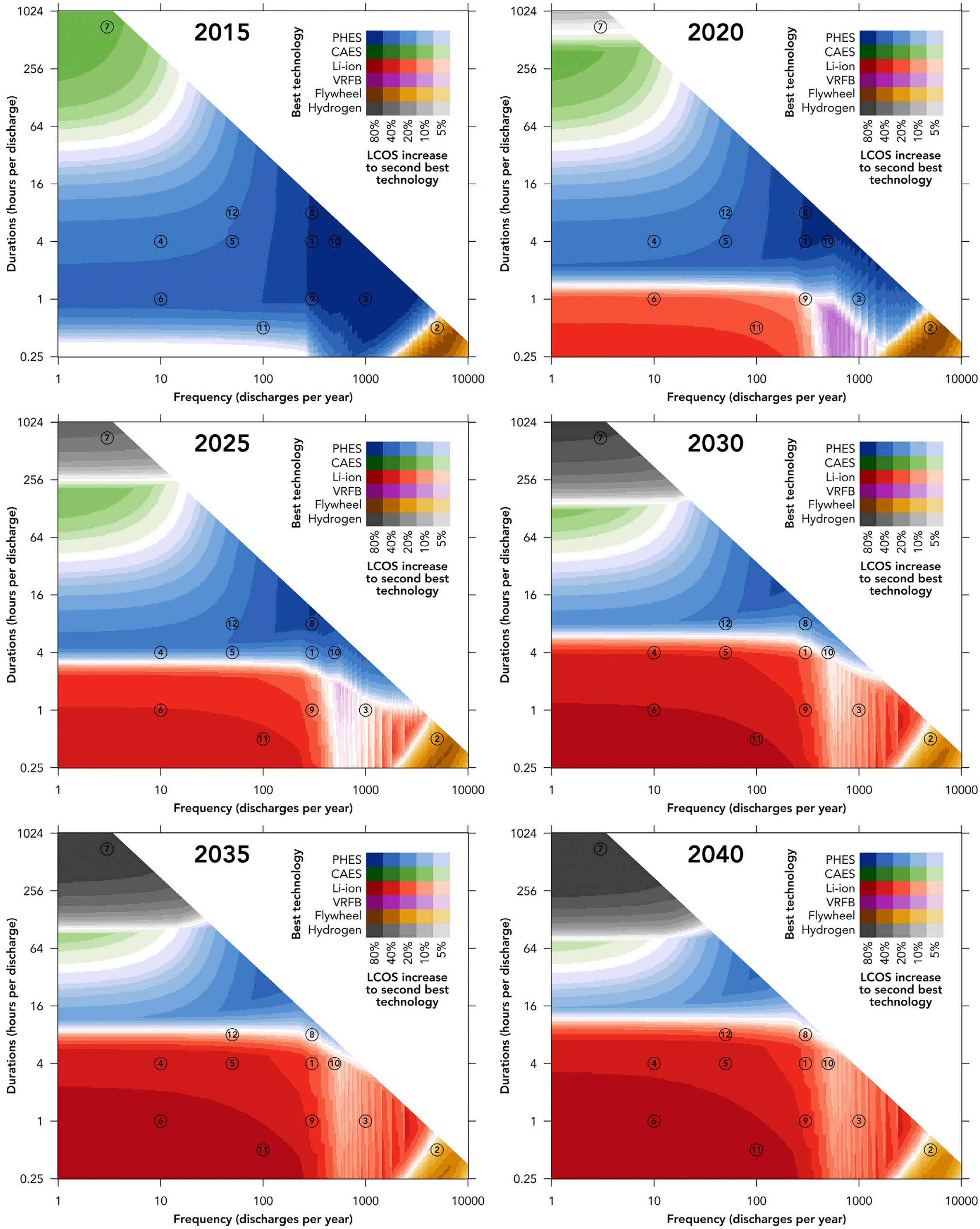
2015
2020
2025
2030
2035
2040
Best technology
PHES
CAES
Li-ion
VRFB
Flywheel
Hydrogen
80% 40% 20% 10% 5%
LCOS increase to second best technology
Durations (hours per discharge)
1024 256 64 16 4 1 0.25
Frequency (discharges per year)
1 10 100 1000 10000
1 2 3 4 5 6 7 8 9 10 11 12

Figure 3. Most Cost-Efficient Technologies Relative to Discharge Duration and Annual Cycle Requirements (All Technologies)

Chart displays technologies with lowest LCOS relative to discharge duration and annual cycle requirements for all modeled technologies from 2015 to 2040. Circled numbers represent the requirements of the 12 applications introduced in Table 1: 1, Energy Arbitrage; 2, Primary Response; 3, Secondary Response; 4, Tertiary Response; 5, Peaker Replacement; 6, Black Start; 7, Seasonal Storage; 8, T&D Investment Deferral; 9, Congestion Management; 10, Bill Management; 11, Power Quality; 12, Power Reliability. Colors represent technologies with lowest LCOS. Shading indicates how much higher the LCOS of the second most cost-efficient technology is, meaning lighter areas are contested between at least two technologies, while darker areas indicate a strong cost advantage of the prevalent technology. White spaces mean LCOS of at least two technologies differ by less than 5%. The sawtooth pattern above 1,000 cycles reflects the marked lifetime reductions at more frequent discharges that affect competitiveness of individual technologies. The modeled electricity price is 50 US$/MWh. See Video S1 for an animated version. All technology input parameters can be found in Tables S4–S8. Refer to Figure S5 for a similar overview of most cost-efficient technologies based on annuitized capacity cost (US$/$kW_{year}$).

facilities.[32] LCOS increase is proportional to the reduction of annual cycles and discharge duration as these determine lifetime energy discharged, the denominator of the energy-focused LCOS metric. The projection of LCOS translates into LCOS reduction across the entire discharge and frequency spectrum without changes in this pattern, despite the changing technologies that achieve this LCOS (Figure 3).

The LCOS share attributed to charging cost is 4% averaged across technologies and discharge and frequency combinations (9% across the 12 modeled applications). A 10-fold increase in electricity price from 50 to 500 US$/MWh increases the relative importance of round-trip efficiency. Consequently, efficient lithium ion would replace pumped hydro at high cycles, which in turn would become more competitive than compressed air and hydrogen storage at high discharge durations. The average share of charging cost in LCOS increases to 19% (35% across the 12 modeled applications) (Figure S7).

Sensitivity to Technology Parameters

Industry projects will use different discount rates for storage technologies reflecting technology and business case maturity. When applying a 4% discount rate to vanadium redox flow and 0% to supercapacitors, their LCOS would reduce on average by 15% and 36%, respectively. In 2030, supercapacitors would displace flywheels as most cost-efficient technology above 5,000 cycles and vanadium redox flow would displace lithium ion between 500 and 1,000 cycles (Figure S8). However, the maturity of pumped hydro and compressed air and recent deployment levels of lithium-ion systems indicate that these technologies are more likely to benefit from lower discount rates, further increasing their cost advantage.[28,33]

Another source of uncertainty is future performance improvements for the investigated technologies that could lead to lower LCOS than displayed in Figure 5. We find that LCOS is most sensitive to round-trip efficiency and cycle and shelf life. For example, a 1% annual round-trip efficiency improvement for vanadium redox-flow batteries, increasing efficiency from 73% (2015) to 85% (2030), would make the technology more cost efficient than lithium ion at high frequencies. An annual increase in cycle and shelf life of 2.5% would have the same effect (Figures S9 and S10). Figures S11–S13 show similar performance improvement requirements for lead-acid, sodium-sulphur, and supercapacitor systems through which these technologies could partially outcompete lithium-ion systems by 2030. Note that these scenarios consider the impact of performance improvements for one technology in isolation. It is more likely that each technology will experience some degree of performance improvement, including lithium-ion and hydrogen storage, which may further improve their cost advantage.[34,35]

It should also be noted that investment cost represents the largest LCOS component for nearly all technologies and applications from 2015 to 2050 (Figure S3). Thus, any

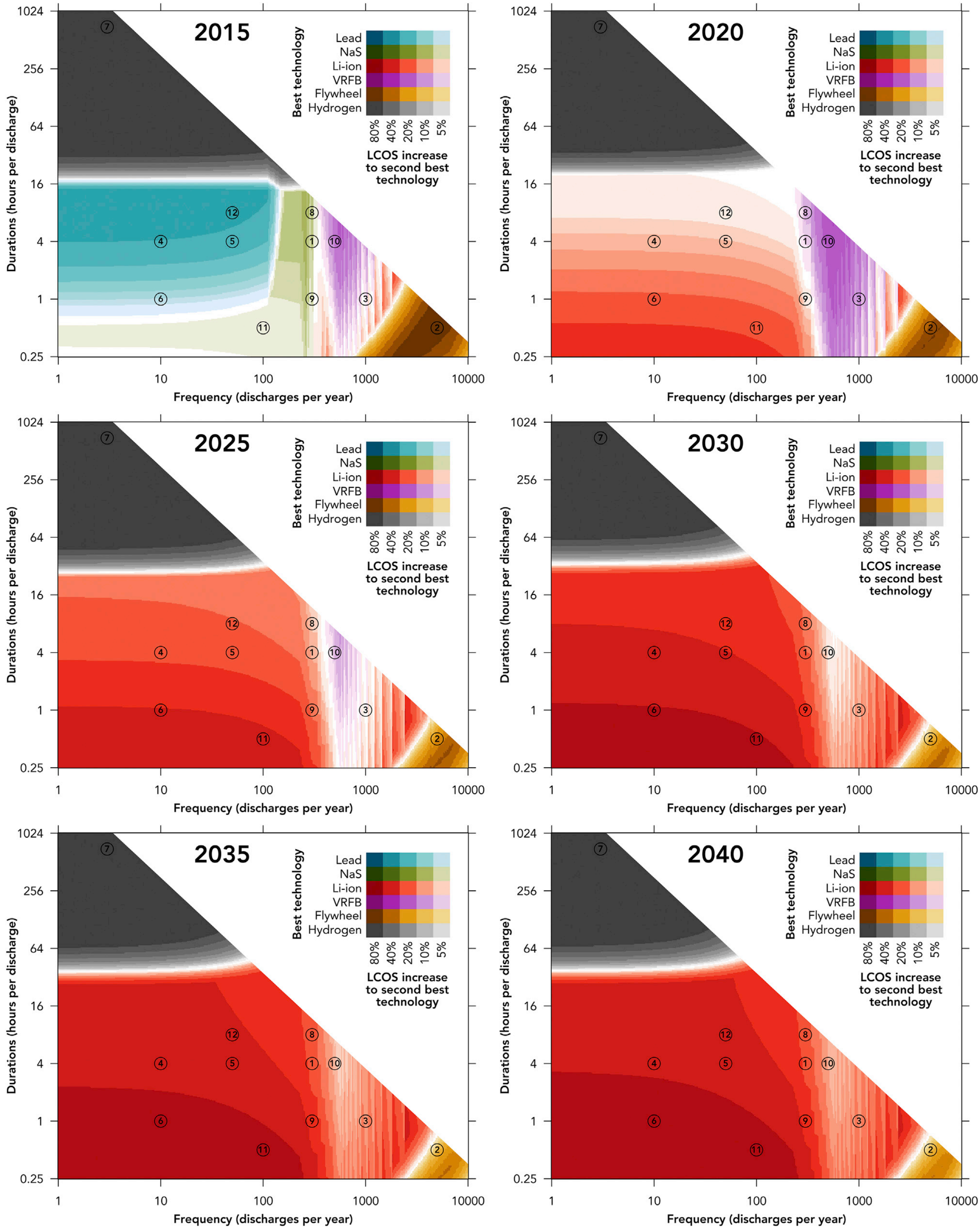
2015
2020
2025
2030
2035
2040
Best technology
Lead
NaS
Li-ion
VRFB
Flywheel
Hydrogen
80%
40%
20%
10%
5%
LCOS increase to second best technology
Durations (hours per discharge)
Frequency (discharges per year)
1024
256
64
16
4
1
0.25
1
10
100
1000
10000

Figure 4. Most Cost-Efficient Technologies Relative to Discharge Duration and Annual Cycles (Excluding Pumped Hydro and Compressed Air)
Chart displays technologies with lowest LCOS relative to discharge duration and annual cycle requirements excluding pumped hydro and underground compressed air from 2015 to 2040. Circled numbers represent the requirements of the 12 applications introduced in Table 1: 1, Energy Arbitrage; 2, Primary Response; 3, Secondary Response; 4, Tertiary Response; 5, Peaker Replacement; 6, Black Start; 7, Seasonal Storage; 8, T&D Investment Deferral; 9, Congestion Management; 10, Bill Management; 11, Power Quality; 12, Power Reliability. Colors represent technologies with lowest LCOS. Shading indicates how much higher the LCOS of the second most cost-efficient technology is, meaning lighter areas are contested between at least two technologies, while darker areas indicate a strong cost advantage of the prevalent technology. White spaces mean LCOS of at least two technologies differ by less than 5%. The sawtooth pattern above 1,000 cycles reflects the marked lifetime reductions at more frequent discharges that affect competitiveness of individual technologies. The modeled electricity price is 50 US$/MWh. See Video S2 for an animated version. All technology input parameters can be found in Tables S4–S8. Refer to Figure S5 for a similar overview of most cost-efficient technologies in annuitized capacity cost (US$/kW$_{year}$).

additional reduction in investment cost that goes beyond the experience curve-based projections used in this study would have the most significant impact on LCOS reduction.

DISCUSSION

We find the projected dominance of lithium-ion technology is the result of good performance parameters, such as high round-trip efficiency and sufficient cycle life, and strong relative investment cost reduction due to a high experience rate coupled with moderate levels of installed capacity for stationary systems. It follows that the development of alternative electricity storage technologies might become futile due to the challenge in matching the cost and performance advancement lithium ion has achieved to date and is expected to achieve in the future. This would mirror the continuing dominance of 1st-generation (crystalline silicon) solar cells despite significant investments in alternative solar cell technologies which were initially expected to be significantly cheaper.[36] Just like crystalline silicon solar cells, "lithium ion" is collective for a range of technologies,[25,37] offering the possibility of chemistry or design improvements that ensure the projected cost reduction for the technology group. A more detailed study could include distinct cost and performance parameters of lithium-ion technology variations.

One possible reason for the high experience rate for stationary lithium-ion systems could be the technology's modularity that enables knowledge spillover from other markets like lithium-ion batteries for electric vehicles.[2,38] On performance, it should be noted that due to the recent research and deployment focus on lithium-ion batteries for portable, transport and stationary applications, the technology might be closer to its performance limits than others,[39] which could suggest that performance improvements offer an avenue for alternative technologies to become more competitive than lithium ion.

We compare application-specific LCOS to recent studies that model LCOS in applications with similar technical requirements.[7,12,13,20] We find that our modeled LCOS are within the ranges identified in other studies for most technologies. Deviations are primarily the result of different investment cost or cycle life assumptions that could not be verified by the literature and experts consulted for this study (see Figures S14–S17 and Procedure S2 for a detailed discussion). While differences in methodology have a minor impact (Procedure S1), the impact of slightly different application requirements among the studies is significant (see Sensitivity to Application Requirements).

A possible route to improving the business case for electricity storage is by providing multiple services with one device and thereby stacking multiple revenue streams[26] (D. Gardiner, O.S., I.S., P. Heptonstall, and R. Gross, unpublished data).

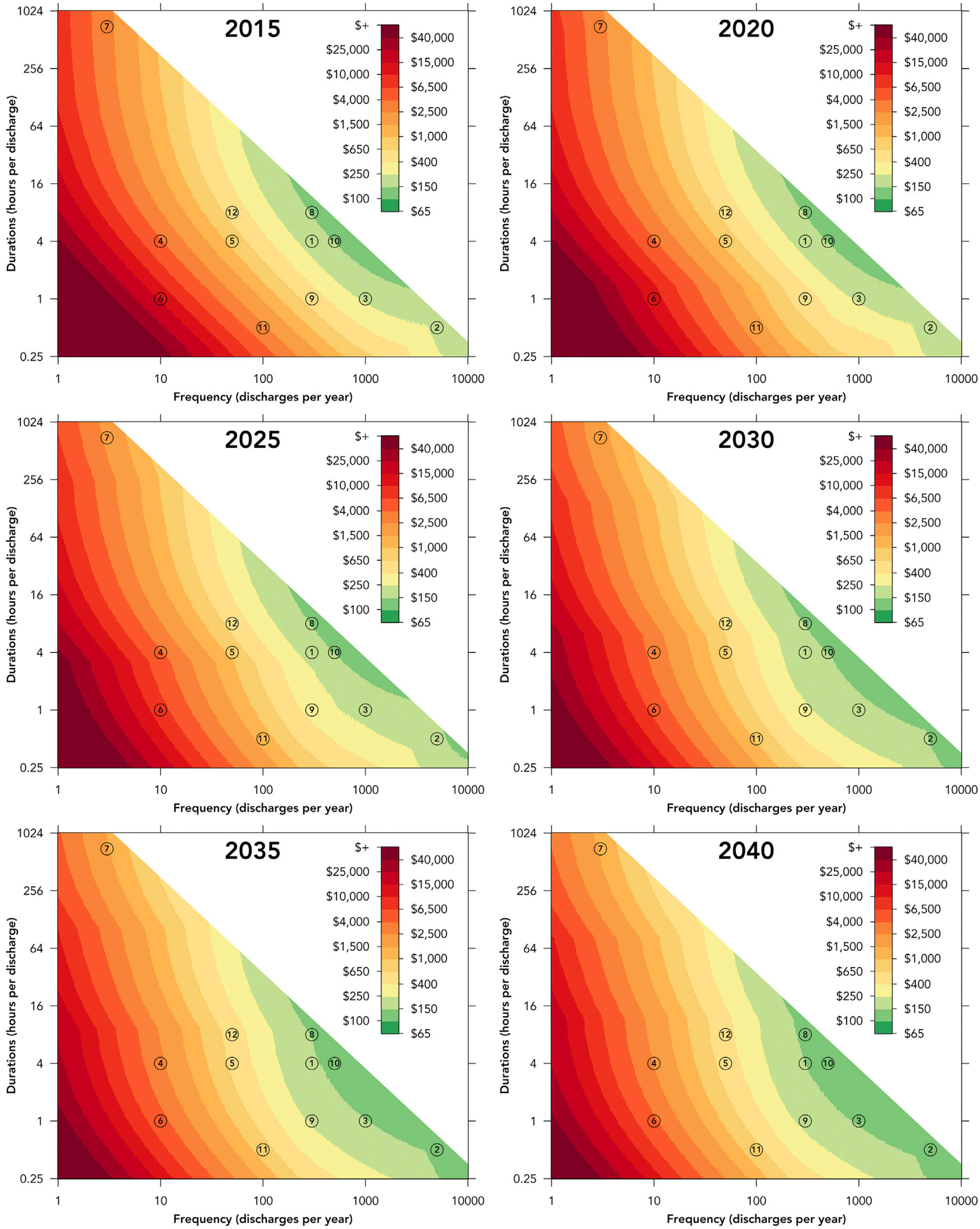
2015
2020
2025
2030
2035
2040
$+
$40,000
$25,000
$15,000
$10,000
$6,500
$4,000
$2,500
$1,500
$1,000
$650
$400
$250
$150
$100
$65
1024
256
64
16
4
1
0.25
Durations (hours per discharge)
1
10
100
1000
10000
Frequency (discharges per year)
1
2
3
4
5
6
7
8
9
10
11
12

Figure 5. LCOS of Most Cost-Efficient Technologies Relative to Discharge Duration and Annual Cycle Requirements

Chart displays LCOS of most cost-efficient technologies relative to discharge duration and annual cycle requirements for all modeled technologies from 2015 to 2040. Circled numbers represent the requirements of the 12 applications introduced in Table 1: 1, Energy Arbitrage; 2, Primary Response; 3, Secondary Response; 4, Tertiary Response; 5, Peaker Replacement; 6, Black Start; 7, Seasonal Storage; 8, T&D Investment Deferral; 9, Congestion Management; 10, Bill Management; 11, Power Quality; 12, Power Reliability. Colors represent LCOS range. The modeled electricity price is 50 US$/MWh. All technology input parameters can be found in Tables S4–S8. Please refer to Figure S6 for a similar overview on annuitized capacity cost (US$/$kW_{year}$) of most cost-efficient technologies.

The presented methodology can also be used to assess LCOS for these "benefit-stacking" use cases by determining application requirements that reflect the provision of multiple services with the same device. Nominal power capacity would be based on the largest service (i.e., sequential stacking) or the sum of all service provided at the same time (i.e., parallel stacking). Discharge duration should reflect the sum of durations required by all services to ensure sufficient energy capacity when all services are required in parallel or directly one after another. Full equivalent cycles also reflect the respective sum for all services provided. Average electricity price could be the sum of prices captured when charging for individual services weighed by the full equivalent cycles attributed to them.

We reiterate that all presented results are subject to the investment cost projections made with experience curves (Figure S2). These are based on historic price reduction trends and are thus uncertain. Another limitation of this study is that the experience-based cost reductions are exogenous, assuming that all technologies take the entire future stationary storage market individually. We thereby explore the full LCOS reduction potential for each technology based on investment cost reductions. In reality, a mix of technologies will be deployed, limiting individual investment cost reductions along experience curves.[40] Modeling this complex dynamic could be attempted in future studies.

Similarly, this study only approximates degradation and lifetime of electrochemical storage technologies in modeled applications. While it accounts for depth-of-discharge, it does not explicitly model mean state of charge, charge rates, and temperature as additional parameters that affect cycle and time degradation and thereby limit cycle and shelf life.[41–43] However, the online version of the presented LCOS model (www.EnergyStorage.ninja) allows the cycle and shelf life values to be modified to account specifically for the named degradation parameters and their variation. The same customization can be applied to all other technology and application parameters.

Our results explore future LCOS potentials for the most widely deployed stationary storage technologies and establish a quantitative foundation for the discussion of storage competitiveness and its drivers. These insights can help guide research, policy and investment activities to ensure a cost-efficient deployment of electricity storage technologies for a successful transition to a secure and affordable low-carbon energy system.

EXPERIMENTAL PROCEDURES

Applications and Requirements

We reviewed reports on electricity storage applications by research institutes,[16,21,24,27,28,44] international organizations,[23] industry,[12,22] and academia[6,26] to identify 27 unique electricity storage applications referred to with more than 100 different names (Table S1). Excluding reactive power services leaves 25 applications. Albeit serving different purposes, these applications often have similar technical requirements. Comparing size (MW), annual cycle (#), discharge duration (h), and response time (s) requirements, we identify 12 core applications that are sufficiently differentiated according to these metrics and display parameter ranges identified from the literature (Table S2). The distinct annual cycle and discharge duration requirements for each application were chosen from within these ranges and such that the entire spectrum for these parameter combinations is represented (Figure S1).

Technology Cost and Performance Parameters

We identified values for 17 cost and performance parameters for 9 electricity storage technologies using 21 sources. Special focus was placed on using industry validated sources that use manufacturer quotes and have a track record of realistic data. The resulting values were cross-checked via e-mail exchanges with 6 industry experts. The final input range is based on the median of all maximum and minimum values of the ranges identified in the literature. Its central estimate and standard deviation are shown in Table S4.

Cycle and temporal degradation parameters (Cyc_{Deg}, T_{Deg}) are modelled as geometric sequences representing degradation of energy storage capacity to an end-of-life value of 80% relative to initial capacity ($Cap_{nom,E}$). For cycle degradation relative to cycle life (Cyc_{Life}):

$$Cap_{nom,E} * \left(1 - Cyc_{Deg}\right)^{Cyc_{Life}} = 80\% * Cap_{nom,E}$$

$$Cyc_{Deg}\left[\frac{\%_{capacity}}{cycle}\right] = 1 - exp\left(\frac{\ln(0.8)}{Cyc_{Life}}\right) = 1 - 80\%^{\left(\frac{1}{Cyc_{Life}}\right)}$$

For temporal degradation relative to shelf life (T_{shelf}):

$$T_{Deg}\left[\frac{\%_{capacity}}{year}\right] = 1 - 80\%^{\left(\frac{1}{T_{Shelf}}\right)}.$$

Where applicable, the relationship between cycle life and depth-of-discharge (DoD) for a technology was taken from recent technical studies and applied to the cycle life value (at 100% DoD) identified in the literature review for each technology (Table S5). We do not model the impact of system size on investment cost of any technology.

Technologies versus Applications

The choice of which technologies to model in each application is based on the match between technical requirement ranges of applications (Table S2) and technical performance ranges of technologies (Table S3) in terms of size, annual cycles or cycle life, discharge duration, and response time. Technology-application combinations without overlap of technology performance and application requirement ranges were not modeled (Table 1).

Modeling Levelized Cost of Storage (LCOS)

The LCOS for each technology in a specific application is calculated using the formula below. r is the discount rate, n a specific year of operation and N the lifetime of the technology. The lifetime is the minimum of shelf life (T_{shelf}) or cycle life (Cyc_{life}) when compared to annual cycles (Cyc_{life}/Cyc_{pa}) and includes construction times.

$$LCOS\left[\frac{\$}{MWh}\right] = \frac{Investment\ cost + \sum_n^N \frac{O\&M\ cost}{(1+r)^n} + \sum_n^N \frac{Charging\ cost}{(1+r)^n} + \frac{End\text{-}of\text{-}life\ cost}{(1+r)^{N+1}}}{\sum_n^N \frac{Elec_{Discharged}}{(1+r)^n}}.$$

Discharged electricity accounts for annual cycles (Cyc_{pa}), nominal energy capacity ($Cap_{nom,E}$), depth-of-discharge (DoD), round-trip efficiency (η_{RT}), cycle degradation (Cyc_{Deg}), time degradation (T_{Deg}), self-discharge (η_{self}), and construction time of the technology (T_c).

$$\sum_n^N \frac{Elec_{Discharged}}{(1+r)^n} = Cyc_{pa} \cdot DoD \cdot Cap_{nom,E} \cdot \eta_{RT} \cdot (1-\eta_{self}) \cdot \sum_{n=1}^{N} \frac{(1-Cyc_{Deg})^{(n-1)*Cyc_{pa}} \cdot (1-T_{Deg})^{(n-1)}}{(1+r)^{n+T_c}}.$$

Investment cost takes into account nominal power ($Cap_{nom,P}$) and energy capacity ($Cap_{nom,E}$), specific power (C_P) and energy cost (C_E), replacement cost ($C_{P\text{-}r}$) and interval (T_r), and number of replacements throughout technology lifetime (rep). Replacement costs are accounted for relative to power capacity. The replacement interval is determined based on full equivalent cycles requiring replacement relative to annual cycles (Cyc_r/Cyc_{pa}).

$$Investment\ cost = C_P \cdot Cap_{nom,P} + C_E \cdot Cap_{nom,E} + \sum_{r=1}^{R} \frac{C_{P-r} \cdot Cap_{nom,P}}{(1+r)^{T_c + rep \cdot T_r}}.$$

O&M cost accounts for power and energy specific operation and maintenance cost ($C_{P\text{-}OM}$, $C_{E\text{-}OM}$) relative to nominal power capacity and annual charged electricity.

$$\sum_n^N \frac{O\&M\ cost}{(1+r)^n} = \sum_{n=1}^{N} \frac{C_{P-OM} \cdot Cap_{nom,P} + C_{E-OM} \cdot (Cyc_{pa} \cdot DoD \cdot Cap_{nom,E}) \cdot (1-Cyc_{Deg})^{(n-1) \cdot Cyc_{pa}} \cdot (1-T_{Deg})^{(n-1)}}{(1+r)^{n+T_c}}.$$

Charging cost account for the electricity price (P_{el}) and round-trip efficiency.

$$\frac{\sum_n^N \frac{Charging\ cost}{(1+r)^n}}{\sum_n^N \frac{Elec_{Discharged}}{(1+r)^n}} = \frac{P_{el}}{\eta_{RT}}.$$

End-of-life costs are calculated as a fraction (F_{EOL}) of investment cost.

$$\frac{End\text{-}of\text{-}life\ cost}{(1+r)^{N+1}} = \frac{\left(C_P \cdot Cap_{nom,P} + C_E \cdot Cap_{nom,E}\right) \cdot F_{EOL}}{(1+r)^{N+1}}.$$

The parameters nominal energy capacity ($Cap_{nom,E}$), discharge duration (DD), annual cycles (Cyc_{pa}), response time, and electricity price (P_{el}) are set for each application (Figure S1). The electricity price assumed in all applications is 50 US$/MWh, except for the behind-the-meter applications bill management, power reliability, and power quality, which use 100 US$/MWh. These generic values are broadly representative of wholesale electricity prices relevant to network and system applications (i.e., front-of-the-meter), and end-customer applications (i.e., behind-the-meter). They are similar to values used in previous LCOS studies and thereby ensure comparability of results.[7,13,17,45]

While the response time requirement only influences which technologies are modeled in each application, all other factors affect the quantitative LCOS results.

Where applicable, depth-of-discharge and thus cycle life is optimized per technology and application to minimize LCOS (Table S6).

Self-discharge (η_{Self}) for each technology and application is approximated by accounting for the daily self-discharge at idle state of the technology, and the application's annual cycle and discharge duration (DD) requirement.

$$\eta_{Self} = \eta_{Self,idle} \cdot \frac{8760\ hours - 2 \cdot Cyc_{pa} \cdot DD}{Cyc_{pa}}.$$

This equation describes the maximum influence of self-discharge, assuming the device is always fully charged when idle between cycles, which are always made at full power. The other extreme of zero self-discharge would occur if the device either remains fully discharged between cycles, or cycles occur gradually to eliminate idle time. As the actual operating strategy of a storage device cannot be known without high-resolution dispatch modeling, we assume the latter for simplicity.

The LCOS in power terms, or annuitized capacity cost, is calculated by dividing annuitized lifetime cost over power capacity ($Cap_{nom,P}$) instead of annual discharged electrical energy ($Elec_{Discharged}$).

$$LCOS\left[\frac{\$}{kW_{year}}\right] = \frac{Investment\ cost + \sum_n^N \frac{O\&M cost}{(1+r)^n} + \sum_n^N \frac{Charging cost}{(1+r)^n} + \frac{End\text{-}of\text{-}life\ cost}{(1+r)^{N+1}}}{\sum_n^N \frac{Cap_{nom,p}}{(1+r)^n}}.$$

The LCOS in power terms is derived by multiplying the LCOS in energy terms by the annual discharged electricity and dividing by power capacity. The result reflects the internal average price at which power capacity can be provided per year for the investment's net present value to be zero (i.e., its revenue requirement).

Future Cost Improvement

The modeled levelized cost of storage projections accounts for future investment cost improvements. These are determined from 2015 to 2050 based on a study of future cost of electricity storage technologies.[2] First, the underlying experience curve data set from reference 2 is updated (Figure S2). Second, the experience curve model including market growth forecasts is used to derive future cost ranges.[46] Third, the resulting relative investment cost reductions and their uncertainty are applied to the 2015 investment cost input parameters identified from the literature (Table S4). To combine the uncertainty of investment cost parameters and relative future reduction, combined standard deviations are derived (Table S7).

$$\sigma_{Combined} = x_{Parameter} \cdot y_{\%Reduction} \cdot \sqrt{\left(\frac{\sigma_{Parameter}}{x_{Parameter}}\right)^2 + \left(\frac{\sigma_{\%Reduction}}{x_{\%Reduction}}\right)^2}.$$

For technologies without experience curve data and resulting cost projections, the relative cost reductions and standard deviation are taken either from a related technology, such as compressed air which follows pumped hydro, or from hydrogen storage, such as for sodium sulphur, flywheel, and supercapacitors. The relative cost reduction for hydrogen storage is chosen as default, because of its moderate character, less aggressive than projections for lithium ion but more than for lead acid. See Table S8 for future cost reduction parameters and respective standard deviations.

Monte Carlo and Probability Analysis

We conduct a Monte Carlo simulation of the levelized cost of storage calculation for each technology and application to account for the uncertainty of technology input parameters, in line with previous studies.[13,15,17] A normal distribution is attributed to a technology parameter (x) based on its central estimate (μ) and standard deviation (σ) (Tables S4 and S7). A normal distribution is assumed to best reflect the variation of input parameters within the value ranges identified in literature sources.

$$f(x; \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{\frac{-(x-\mu)^2}{2\sigma^2}}$$

The Monte Carlo analysis simulates 500 levelized cost of storage calculations per technology and application based on random values from an 80% confidence interval of the attributed normal distribution of the parameter, corresponding to 1.285 standard deviations from the mean.

Probability (P) of a technology exhibiting the lowest levelized cost of storage in each application reflects the frequency with which each technology offers the minimum LCOS accounting for the LCOS uncertainty ranges identified in the Monte-Carlo simulation.

If LCOS for technology A, B and C are {a1; a2; …; a500}, {b1; b2; …; b500}, and {c1; c2; …; c500} respectively, up to N technologies, then

$$P(a_i = min\ LCOS) = P(a_i < b_k, k \in [1; 500]) \cdot P(a_i < c_k, k \in [1; 500]) \cdot \ldots$$

$$P(A = min\ LCOS) = \frac{1}{500^N} \cdot \sum_{i=1}^{500} |a_i < b_k, k \in [1; 500]| \cdot |a_i < c_k, k \in [1; 500]| \cdot \ldots,$$

with $|X|$ the cardinality of set X. Procedure S3 gives more detail on the approach.

Discharge versus Frequency Analysis

The LCOS of each technology is determined for each year between 2015 and 2050 using the central estimate for technology inputs, fixed electricity price (50 US$/MWh), discount rate (8%), and size (10 MW), while varying discharge duration and annual full equivalent discharge cycle requirements. Discharge duration and cycle requirements were varied in 490 steps on a logarithmic scale between 0.25 to 1,024 h and 1 to 10,000 cycles, respectively.

Sensitivity Analyses: Performance Parameters

The most sensitive parameters were identified by comparing the impact of a constant percentage change for each parameter on LCOS. The presented sensitivity results were chosen so that the respective technology becomes competitive with the prevalent technology by varying its most sensitive parameters.

DATA AND SOFTWARE AVAILABILITY

The accession number for the data behind Figures 1–4 in this paper is Figshare: 7330931. The accession number for the future investment cost data based on experience curves is Figshare: 7012202. The accession numbers for the animations of Figures 3 and 4 are Figshare: 7376462, 7376438.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures S1–S3, 17 figures, 8 tables, and 2 videos and can be found with this article online at https://doi.org/10.1016/j.joule.2018.12.008.

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AUTHOR CONTRIBUTIONS

O.S. and I.S. designed the study. S.M. and O.S. collected the data and built the model. I.S. and O.S. analyzed the results. O.S. wrote the draft paper. S.M., A.H., and I.S. edited the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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