

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 modelled 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.

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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 applications¹. Recent studies on future cost 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 uncertain⁴, 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 application⁷. The metric therefore accounts for all technical and economic parameters affecting the lifetime cost of discharging stored electricity. It is directly comparable to levelized cost of electricity (LCOE) for generation technologies and represents an appropriate tool for cost comparison of electricity storage technologies⁸⁻¹¹.

Despite an increasing number of LCOS studies¹²⁻¹⁷, there is not yet a common definition of this metric. While some studies neglect cost parameters like replacement or disposal¹³⁻¹⁵, 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 LCOS¹²⁻¹⁷.

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 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 Repository¹⁸). An interactive version of our LCOS model is available online at www.EnergyStorage.ninja. By increasing transparency on 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 electricity⁸. Delivered electricity can refer to electrical energy or electric power⁹. 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 cost 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 both¹⁴. This lack of common methodology is reflected in the different names that are used to describe LCOS, such as levelized cost of stored energy⁸, life cycle cost^{13,17,19}, levelized cost of delivery¹⁴ 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}.

$$LCOS \left[\frac{\$}{MWh} \right] = \frac{Investment\ cost + \sum_n^N \frac{O\&M\ cost}{(1+r)^n} + \sum_n^N \frac{Charging\ cost}{(1+r)^n} + \frac{End_of_life\ cost}{(1+r)^{N+1}}}{\sum_n^N \frac{Elec_{Discharged}}{(1+r)^n}} \quad (1)$$

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 unsuitable²¹. In this 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). This metric also indirectly applies to applications that value the provision of reactive power since reactive power provision requires low active power output from storage devices. A direct metric measuring LCOS per unit of reactive power is conceivable, but not explored in this study. 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 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).

Table 1 – Qualitative description of electricity storage applications and technology suitability. 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 capacity²⁸. 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, PHES – Pumped hydro energy storage, CAES – Compressed air energy storage (underground), VRFB – Vanadium redox-flow battery. Hydrogen storage refers to a system with electrolyser, storage tank and fuel cell.

Role	Application	Description	PHES	CAES	Flywheel	Lithium-ion	Sodium-sul.	Lead-acid	VRFB	Hydrogen	Supercap.
	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				✓	✓	✓	✓	✓	

Pumped hydro and underground compressed air energy storage are characterised by relatively slow response times (>10 seconds) and large minimum system sizes (>5 MW)^{13,16,24}. Therefore, they are ill-suited for fast response applications like primary response and power quality and small-scale consumption applications. Flywheels and supercapacitors are characterised by short discharge durations (<1 hour)^{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 example³⁰). 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 timescales³¹. 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 / 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.

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 and 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 lowest LCOS in each application and year is determined (Methods).

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.

③ Secondary Response

Power capacity	100 MW
Discharge duration	1 hour
Annual cycles	1,000
Response time	>10 seconds
Electricity price	50 \$/MWh _{el}

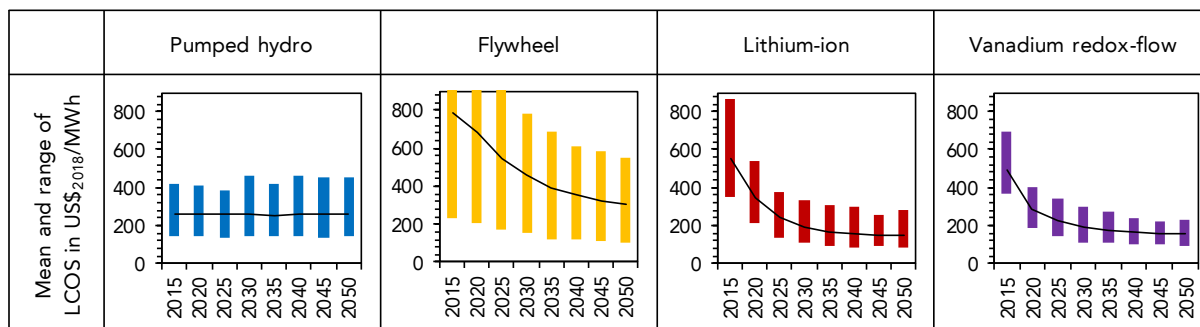
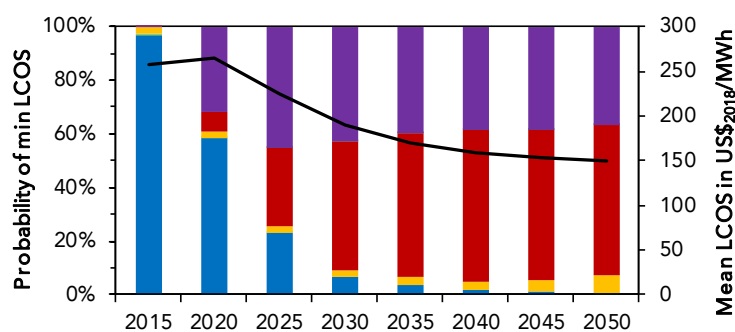


Figure 1 – LCOS projections for secondary response. Application requirements (top-left), probability of exhibiting lowest LCOS (top-right) and explicit LCOS projections for four most competitive technologies, including uncertainty ranges based on Monte-Carlo simulation of LCOS calculation (bottom). Monte-Carlo 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.

Secondary response is characterised 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, 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 most cost-efficient for this application despite operating life of only 8 and 13 years respectively (see Table S4 to 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 cost make up the largest proportion of LCOS across the four technologies, between 65 and 90% in 2015. Reduced investment cost for the two battery technologies mean 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 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.

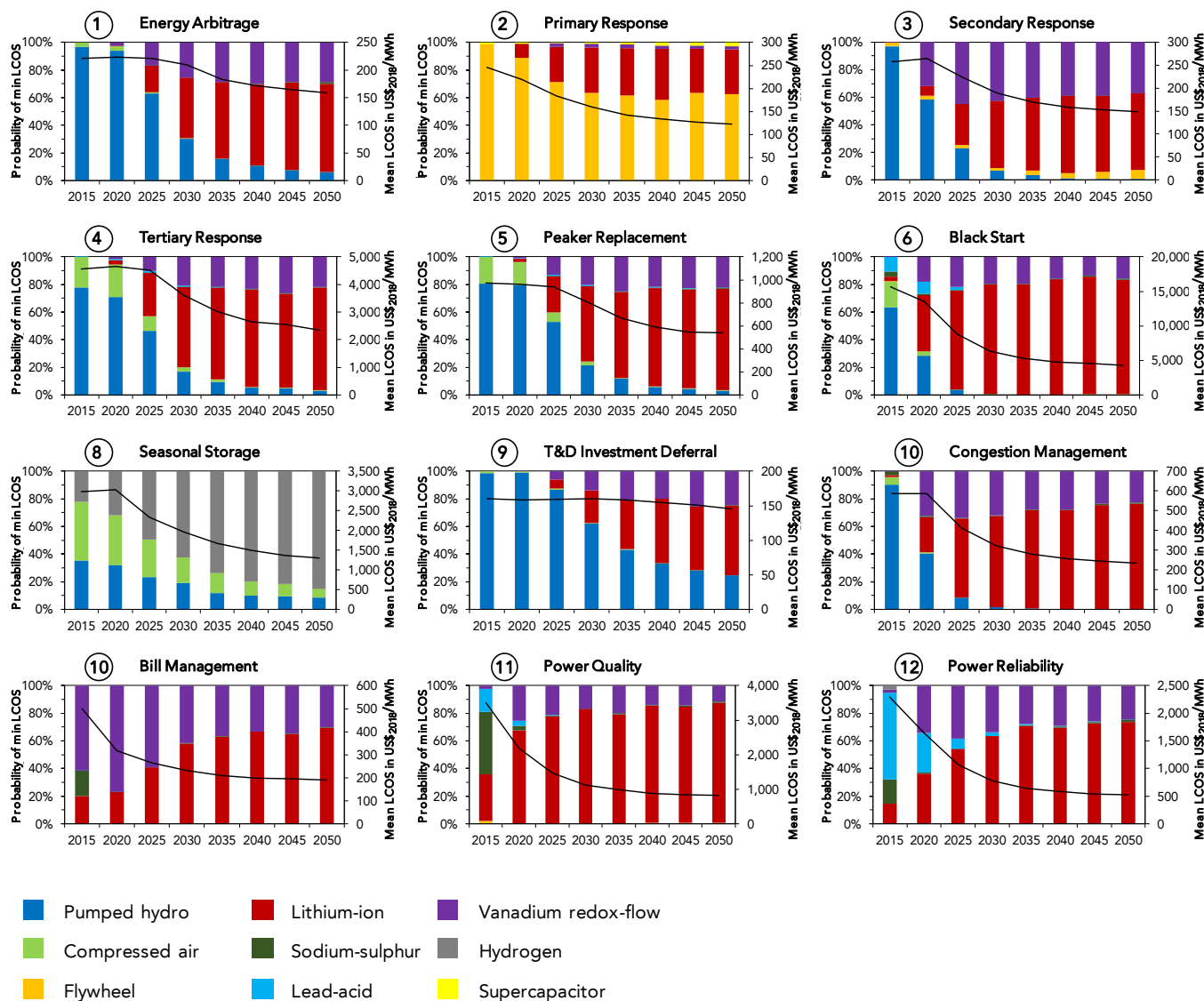


Figure 2 – Lowest LCOS probabilities for 9 electricity storage technologies in 12 applications from 2015 to 2050. Left-hand axis displays probability that a technology will exhibit lowest LCOS in a specific application. Right-hand axis displays mean LCOS of technology with highest probability for lowest 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\$₂₀₁₈/kW_{year}).

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 hours discharge and <300 annual cycles like *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 hours) or *secondary response* and *bill management* (>300 cycles). For *seasonal storage* with more than 700 hours 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 modelled applications. For applications ≥ 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 ≤ 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 hours) or the relatively low LCOS for *Seasonal Storage* (1,500-3,000 US\$/MWh, 700 hours) compared to applications with more cycles but lower discharge duration like *Black Start* and *Tertiary Response*. This is the result of the energy discharge-focussed metric US\$/MWh. Any increase in discharge duration for a technology entails a similar increase in modelled energy discharge, but a lower 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 like *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-focussed, when determining application-specific LCOS for economic investment decisions in electricity storage technologies.

Sensitivity to application requirements

Figure 3 explores the sensitivity of technologies to be most cost-efficient relative to discharge duration and annual cycles. The right-hand panel 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 modelled 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 hours discharge due to significantly lower energy-specific investment cost. Flywheels are more competitive above 5,000 annual cycles and below 0.5 hours discharge due to better cycle life and lower power-specific cost.

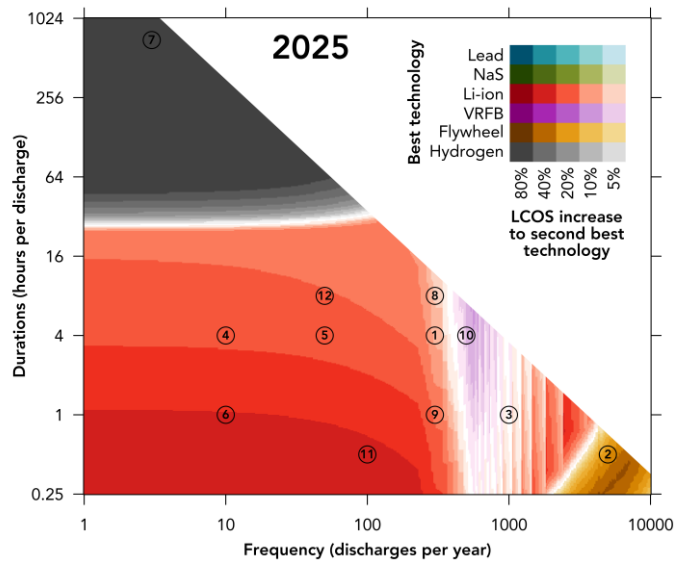
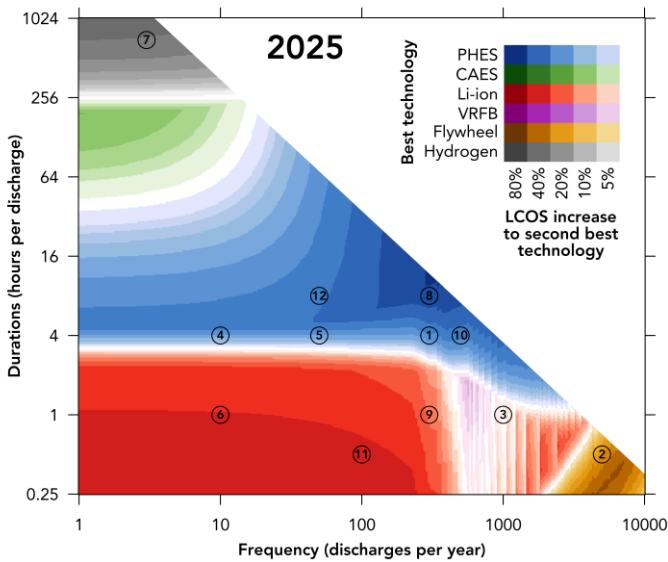
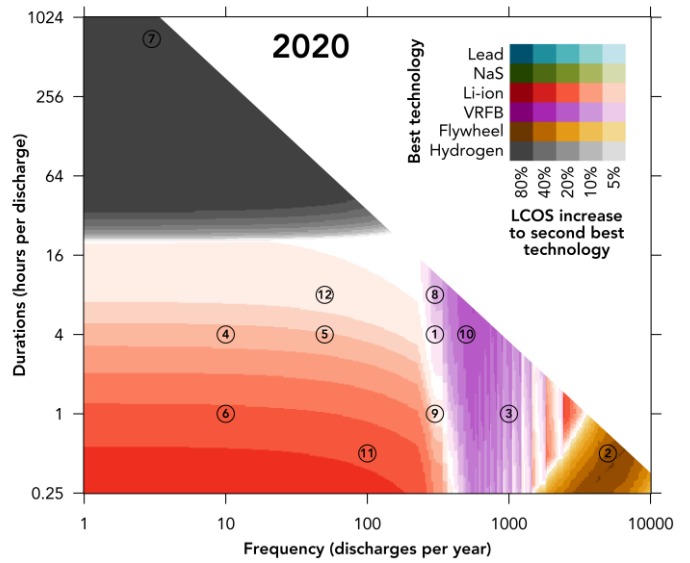
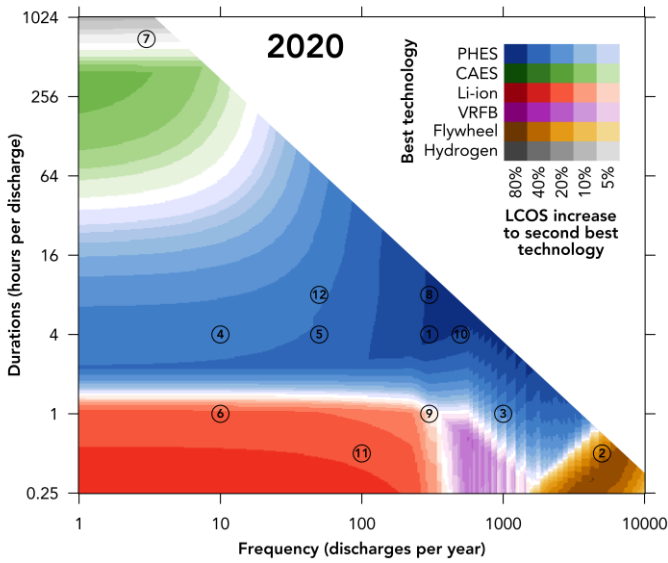
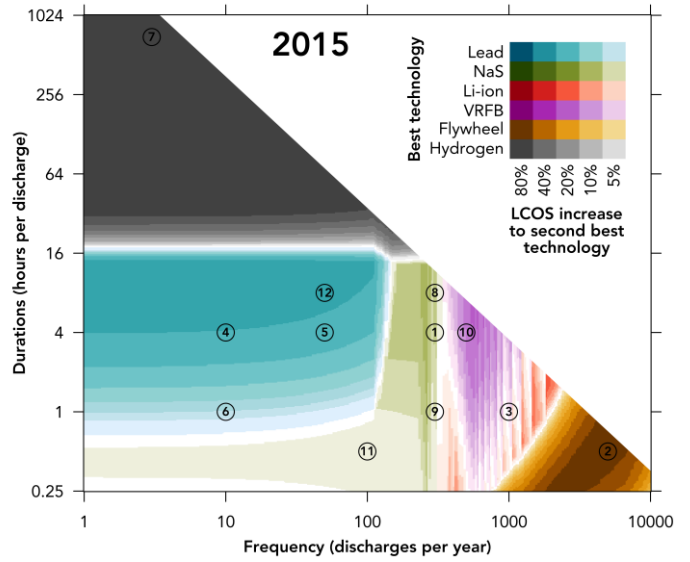
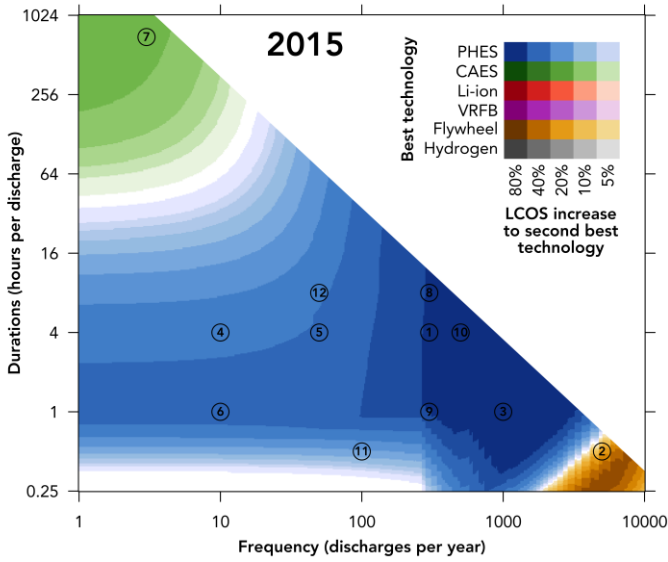
Projecting future LCOS based on investment cost reductions, indicates that lithium-ion batteries become cost-competitive for low discharge duration applications by 2020, competing with vanadium redox-flow and flywheels at high frequencies due to their better cycle life. However, in terms of power-focussed annuitized capacity cost (Figure S5) there is a strong cost advantage for lithium-ion also 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 applications²⁹.

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 modelled 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 hours 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 realise more significant cost reductions in the near-term² (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.

All Technologies

Excluding PHES and CAES



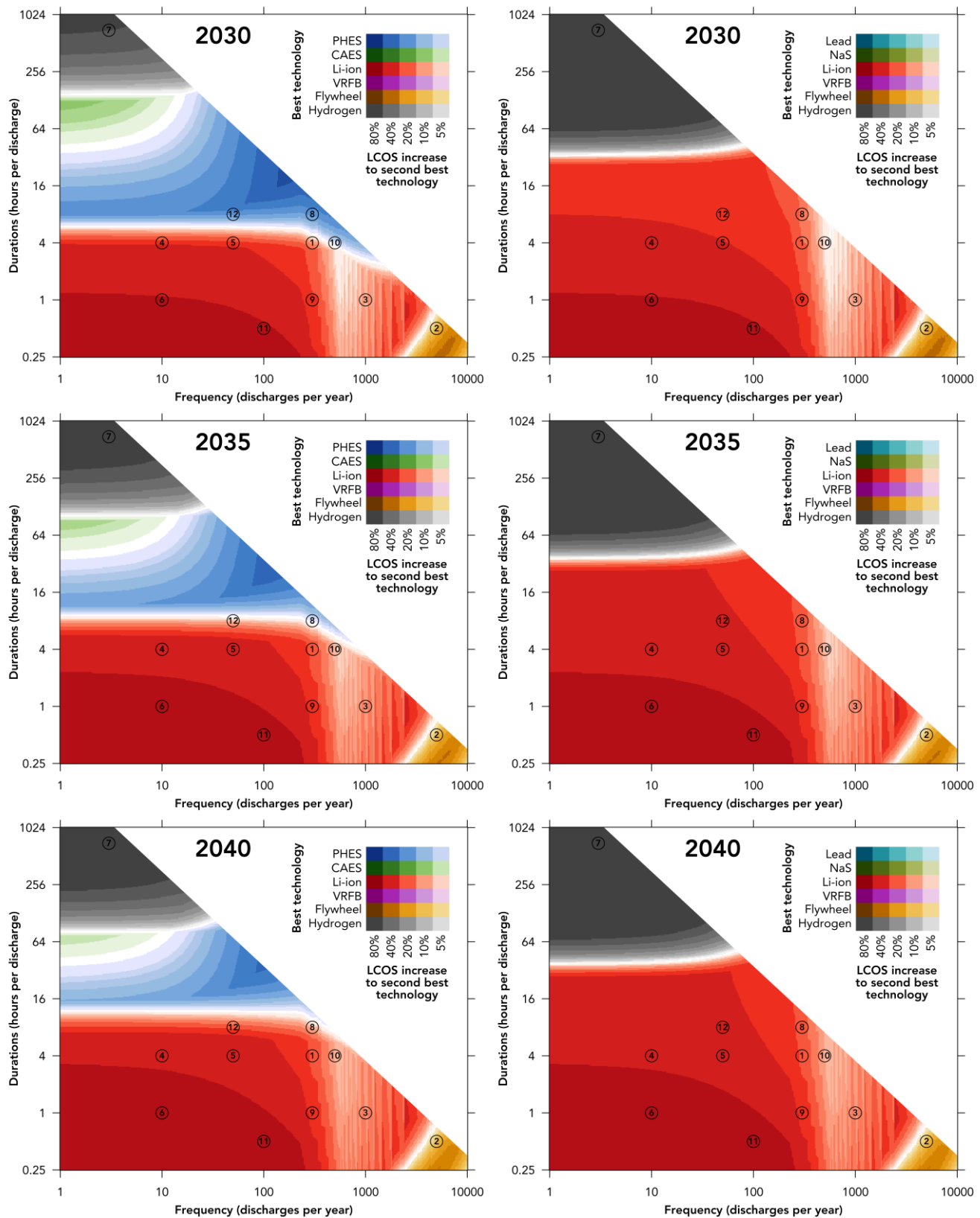


Figure 3 – Discharge duration and annual cycle sensitivity – most cost-efficient technologies. Chart displays technologies with lowest LCOS relative to discharge duration and annual cycle requirements for all modelled technologies (left) and excluding pumped hydro and underground compressed air (right). 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. Colours 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 modelled electricity price is 50 US\$/MWh. See these supplemental videos for animated versions of both charts: [Video S1-All Tech](#), [Video S2-Excl PHEs CAES](#). All technology input parameters can be found in Tables S4 to S8. Refer to Figure S5 for a similar overview of most cost-efficient technologies based on annuitized capacity cost (US\$/kW_{year}).

The LCOS of the most cost-efficient technology for all discharge and frequency combinations is displayed in Figure 4. Lowest LCOS are achieved by pumped hydro for moderate discharge (~4 hours) and frequency (~1,000) combinations. The LCOS range of 100 to 150 US\$/MWh in 2015 corresponds to cost of new pumped hydro facilities³². LCOS increase is proportional to the reduction of annual cycles and discharge duration as these determine lifetime energy discharged, the denominator of the energy-focussed 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 these LCOS (Figure 3).

The LCOS share attributed to charging cost is 4% averaged across technologies and discharge and frequency combinations (9% across the 12 modelled 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 modelled applications) (Figure S7).

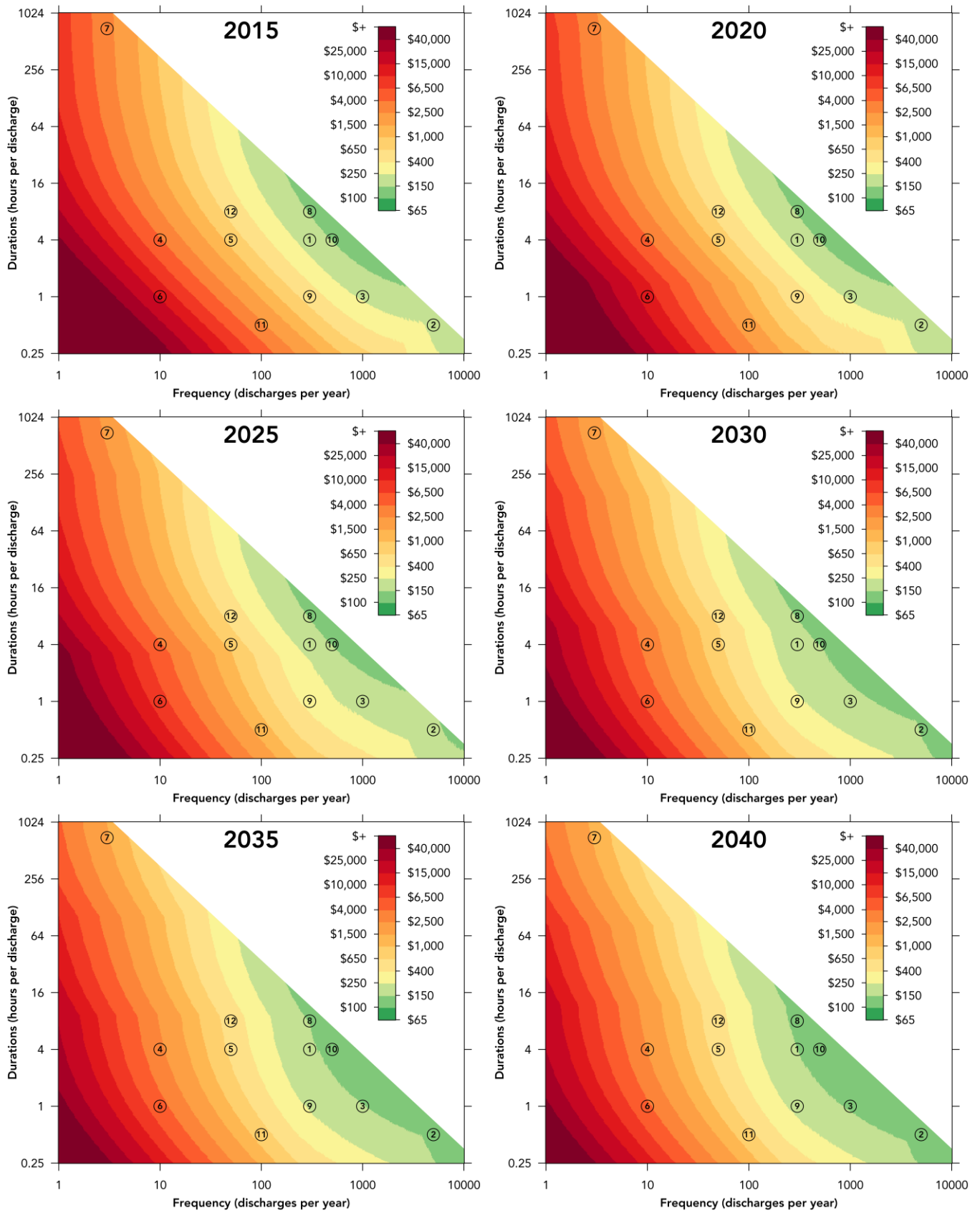


Figure 4 – Discharge duration and annual cycle sensitivity – LCOS of most cost-efficient technologies. Chart displays LCOS of most cost-efficient technologies relative to discharge duration and annual cycle requirements for all modelled technologies. Circled numbers represent the requirements of the 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. Colours represent LCOS range. The modelled electricity price is 50 US\$/MWh. All technology input parameters can be found in Tables S4 to S8. Please refer to Figure S6 for a similar overview on annuitized capacity cost (US\$/kW_{year}) of most cost-efficient technologies.

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 4. 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 (Figure S9 and S10). Figures S11 to 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 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 cheaper³⁶. 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 spill over 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 others³⁹, 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 modelled 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 to 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^{26,40}. 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 curves⁴¹. Modelling this complex dynamic could be attempted in future studies.

Similarly, this study only approximates degradation and lifetime of electrochemical storage technologies in modelled 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 life⁴²⁻⁴⁴. 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 customisation 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^{16,21,24,27,28,45}, international organisations²³, 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 (hours) and response time (seconds) 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}):

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

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 vs 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 / cycle life, discharge duration and response time. Technology-application combinations without overlap of technology performance and application requirement ranges were not modelled (Table 1).

Modelling 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.

$$LCOS \left[\frac{\$}{MWh} \right] = \frac{Investment\ cost + \sum_n^N \frac{O\&M\ cost}{(1+r)^n} + \sum_n^N \frac{Charging\ cost}{(1+r)^n} + \frac{End_of_life\ cost}{(1+r)^{N+1}}}{\sum_n^N \frac{ElecDischarged}{(1+r)^n}}$$

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).

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

Investment cost take 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-r}) and interval (T_r), and number of replacements throughout technology lifetime (rep). Replacement cost 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-OM} , C_{E-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.

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

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

$$\frac{End_of_life\ cost}{(1+r)^{N+1}} = \frac{(C_P \cdot Cap_{nom,P} + C_E \cdot Cap_{nom,E}) \cdot F_{EOL}}{(1+r)^{N+1}}$$

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 / 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^{7,13,17,46}.

While the response time requirement only influences which technologies are modelled in each application, all other factors affect the quantitative LCOS results. Where applicable, depth-of-

discharge and thus cycle life is optimised per technology and application to minimise 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.

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

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 modelling, 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 ($Elec_{Discharged}$).

$$LCOS \left[\frac{\$}{MW_{yr}} \right] = \frac{Investment \text{ cost} + \sum_n^N \frac{O\&M \text{ cost}}{(1+r)^n} + \sum_n^N \frac{Charging \text{ cost}}{(1+r)^n} + \frac{End_of_life \text{ cost}}{(1+r)^{N+1}}}{\sum_n^N \frac{Cap_{nom,p}}{(1+r)^n}}$$

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 modelled levelized cost of storage projections account for future investment cost improvements. These are determined from 2015 to 2050 based on a study of future cost of electricity storage technologies². First, the underlying experience curve data set from Ref. 2 is updated (Figure S2). Second, the experience curve model including market growth forecasts is used to derive future cost ranges⁴⁷. 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).

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

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) (Table 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 $\{a_1; a_2; \dots; a_{500}\}$, $\{b_1; b_2; \dots; b_{500}\}$, and $\{c_1; c_2; \dots; c_{500}\}$ respectively, up to N technologies, then

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

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

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

Discharge vs 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 1024 hours 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.

Supplemental Procedures

Supplemental Information includes Supplemental Experimental Procedures, 17 figures, and 11 tables and can be found with this article online at **XXX**. The raw data of this study is available in the figshare online repository at <https://doi.org/10.6084/m9.figshare.7330931>. The videos supplemental to Figure 3 can be downloaded at <https://doi.org/10.6084/m9.figshare.7376438> and <https://doi.org/10.6084/m9.figshare.7376462>.

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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. analysed 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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