JOUL, Volume *3*

## Supplemental Information

# Projecting the Future Levelized Cost of Electricity Storage Technologies

**Oliver Schmidt, Sylvain Melchior, Adam Hawkes, and Iain Staffell**

## Supplemental Tables

**Table S1.** Review of 27 unique-purpose electricity storage services and allocation to core services based on similar technical requirements

| Application | Description | Alternative name | Core application |
|---|---|---|---|
| **Wholesale arbitrage** | Purchase power in low-price periods and sell in high price periods on the energy wholesale market[1] | Electric Energy Time-shift | Energy arbitrage |
| **Retail arbitrage** | Purchase power in low-price periods and sell in high price periods on the energy retail market[1] | End-consumer arbitrage | Energy arbitrage |
| **Regulating reserve** | Automatically correct the continuous, fast, frequent changes in load or generation within the shortest applicable market interval[2] | Frequency regulation, Frequency control | Primary response |
| **Primary reserve** | Automatically stabilise frequency after rare, sudden change in load or generation[2] | Primary contingency reserve, Frequency response | Primary response |
| **Following reserve** | Manually correct anticipated imbalances between load and generation[2] | Load following, Balancing reserve | Secondary response |
| **Secondary reserve – spinning** | Automatically return frequency to nominal after rare, sudden change in load or generation with operating generator[3] | Spinning reserve | Secondary response |
| **Secondary reserve – non-spinning** | Automatically return frequency to nominal after rare, sudden change in load or generation with non-operating generator[3] | Secondary contingency reserve, Non-spinning reserve | Secondary response |
| **Ramping reserve** | Manually correct for unexpected, severe and infrequent changes in load or generation that are not instantaneous[2] | - | Secondary response |
| **Renewables integration - uncertainty** | Change and optimise output from variable supply resources when generation is out of line with forecasts[4] | Correct for forecasting inaccuracy, Renewables capacity firming | Secondary response |
| **Tertiary reserve** | Automatically replace primary and secondary contingency reserve[2] | Tertiary contingency reserve, Supplemental / Replacement reserve | Tertiary response |
| **Peaker replacement** | Ensure availability of sufficient generation capacity at all times[1] | Electric supply / System capacity, Capacity mechanism, Microgrid | Peaker replacement |
| **Black start** | Restore power plant operations after network outage without external power supply[1] | - | Black start |
| **Seasonal storage** | Compensate longer-term supply disruption or seasonal variability in supply and demand[5] | - | Seasonal storage |
| **Transmission upgrade deferral** | Defer transmission infrastructure upgrades required when peak power flows exceed existing capacity[1] | Transmission support, Network efficiency | T&D deferral |
| **Distribution upgrade deferral** | Defer distribution infrastructure upgrades required when peak power flows exceed existing capacity[1] | Distribution substation, Network efficiency | T&D deferral |
| **Transmission congestion relief** | Avoid risk of overloading existing infrastructure that could lead to re-dispatch and local price differences[1] | Transmission support, Network efficiency | Congestion management |

| | | | |
|---|---|---|---|
| **Bill management** | Purchase power in low-price periods and use during high-price periods[1] | Energy management, Retail ToU charges | Bill management |
| **Demand charge reduction – R** | Reduce demand supplied by the network during periods of highest retail network charges[1] | Peak reduction, Retail demand charges | Bill management |
| **Demand charge reduction – D** | Reduce demand supplied by the network during periods of highest distribution network cost[4] | Peak reduction, Red zone management | Bill management |
| **Demand charge reduction – T** | Reducing demand supplied by the network during periods of highest transmission network cost[4] | Peak reduction, Triad avoidance, Transmission access charges | Bill management |
| **Renewable energy self-consumption** | Minimise export of renewable electricity and increase self-consumption to maximise financial benefits[6] | - | Bill management |
| **Power quality** | Protect on-site load against short-duration power loss or variations in voltage or frequency[1] | - | Power quality |
| **Power reliability** | Fill gap between variable resource and demand[5] | Off-grid, On-site power | Power reliability |
| **Backup power** | Provide sustained power during total loss of power from source utility[1] | Home backup, Emergency supply, Resiliency | Power reliability |
| **Renewables integration - variability** | Change and optimise output from variable supply resources to mitigate output changes and match supply with demand[5] | Off-peak storage, Variable resource integration, On-site generation shifting | Power reliability |
| | | | |
| **Voltage support** | Maintain voltage levels across networks via reactive power supply/reduction[1] | - | - |
| **VAR support** | Maintain voltage levels across transmission network via reactive power supply/reduction[3] | - | - |

**Table S2.** Technical requirements for electricity storage applications

| **Application** | **Size** (MW) | **Duration** (hours) | **Cycles** (per year) | **Response Time** (seconds) |
|---|---|---|---|---|
| **Energy arbitrage** | 0.001-2,000 [1,5] | 1-24 [1,5] | 50-400 [1,3,5] | >10 [5] |
| **Primary response** | 1-2,000 [5] | 0.02-1 [1,5] | 250-15,000 [1,5] | <10 [2] |
| **Secondary response** | 10-2,000 [5] | 0.25-24 [1,5] | 20-10,500 [1,5] | >10 [2] |
| **Tertiary response** | 5-1,000 [2,5] | >1.5 [2] | 20-50 [1] | >10 [2] |
| **Peaker replacement** | 1-500 [1] | 2-6 [1] | 5-100 [1] | >10 [5] |
| **Black start** | 0.1-400 [5] | 0.25-4 [1,5] | 1-20 [1,5] | >10 [5] |
| **Seasonal storage** | 500-2,000 [5] | 24-2000 [5] | 1-5 [5] | >10 [5] |
| **T&D upgrade deferral** | 1-500 [5] | 2-8 [1] | 10-500 [1,5] | >10 [5] |
| **Congestion management** | 1-500 [1,5] | 1-4 [1] | 50-500 [1,5] | >10 [5] |
| **Bill management** | 0.001-10 [1] | 1-6 [1] | 50-500 [1] | >10 [5] |
| **Power quality** | 0.05-10 [1,3] | 0.003-0.5 [1,3] | 10-200 [1] | <10 [1] |
| **Power reliability** | 0.001-10 [3] | 2-10 [3] | 50-400 [3] | >10 [1] |

**Note:** *Cycles* refers to full equivalent charge-discharge cycles. Superscripts refer to references.

**Table S3.** Electricity storage technology performance characteristics

| **Technology** | **Power range** (MW) | **Discharge** (hours) | **Cycle life** (# cycles) | **Response time** (seconds) |
|---|---|---|---|---|
| **Pumped hydro** | 10-5,000 [7] | 1-24 [7] | 20,000-50,000 [7] | > 10 [7] |
| **Compressed air** | 5-400 [7] | 1-24 [7] | >13,000 [7] | > 10 [7] |
| **Flywheel** | 0.01-20 [8] | < 0.5[7] | 20,000-225,000 [1,7] | < 10 [7] |
| **Lead-acid** | 0.005-100 [1] | 0.25-10 [1] | < 5,500 [1] | < 10 [7] |
| **Lithium-ion** | 0.001-35 [9] | 0.25-5 [1] | 2,000-3,500 [9] | < 10 [7] |
| **Sodium-sulphur** | 0.05-50 [7,9] | 0.0167-8 [1,9] | 2,500-4,500 [9] | < 10 [10] |
| **Redox-flow** | 0.02-50 [1] | 0.0167-10 [7] | 5,000-13,000 [7,9] | < 10 [7] |
| **Hydrogen** | 0.3-500 [7] | 0.0167-24 [7] | <20,000 [7] | < 10 [7] |
| **Supercapacitor** | <4 [11] | <1 [11] | >100,000 [7] | < 10 [7] |

**Note:** *Cycles* refers to full equivalent charge-discharge cycles. Superscripts refer to references.

**Table S4.** Technology input parameters for 2015 (standard deviation)

| | | | **Pumped hydro** | **Compressed air** | **Flywheel** | **Lithium-ion** | **Sodium-sulphur** | **Lead-acid** | **Vanadium redox-flow** | **Hydrogen** | **Super-capacitor** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Investment cost - Power | \$/kW | $C_P$ | 1129 (45%) | 871 (35%) | 641 (17%) | 678 (17%) | 657 (27%) | 675 (23%) | 829 (21%) | 5417 (48%) | 296 (31%) |
| Investment cost - Energy | \$/kWh | $C_E$ | 80 (63%) | 39 (58%) | 5399 (67%) | 802 (24%) | 738 (12%) | 471 (38%) | 760 (17%) | 31 (60%) | 13560 (19%) |
| Operation cost - Power | \$/kW-yr | $C_{P\text{-}OM}$ | 8 (26%) | 4 (23%) | 7 (8%) | 10 (35%) | 11 (50%) | 8 (31%) | 12 (52%) | 46 (30%) | 0 (0%) |
| Operation cost - Energy | \$/MWh | $C_{E\text{-}OM}$ | 1 (60%) | 4 (60%) | 2 (60%) | 3 (60%) | 3 (60%) | 1 (60%) | 1 (60%) | 0 (60%) | 0 (60%) |
| Replacement cost | \$/kW | $C_{P\text{-}r}$ | 116 (5%) | 93 (5%) | 199 (44%) | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) | 1637 (48%) | 0 (0%) |
| Replacement interval | cycles | $Cyc_r$ | 7300 | 1460 | 22500 | 3250 | 4098 | 1225 | 8272 | 6388 | 69320 |
| End-of-life cost | % | $F_{EOL}$ | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Discount rate | % | DR | 8% | 8% | 8% | 8% | 8% | 8% | 8% | 8% | 8% |
| Round-trip efficiency | % | $\eta_{RT}$ | 78% (9%) | 44% (16%) | 88% (3%) | 86% (7%) | 81% (6%) | 84% (0%) | 73% (9%) | 40% (13%) | 91% (6%) |
| Self-discharge | %/day | $\eta_{self,idle}$ | 0% | 0% | 480% | 0% | 20% | 0% | 0% | 1% | 30% |
| Lifetime (100% DoD) | cycles | $Cyc_{life}$ | 33250 (43%) | 16250 (20%) | 143402 (30%) | 3250 (38%) | 4098 (29%) | 1225 (35%) | 8272 (13%) | 20000 (0%) | 300000 (67%) |
| Shelf life | years | $T_{shelf}$ | 55 (9%) | 30 (33%) | 18 (14%) | 13 (38%) | 14 (20%) | 10 (50%) | 13 (20%) | 18 (14%) | 14 (33%) |
| Response time | seconds | | >10 | >10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 |
| Time degradation | %/year | $T_{deg}$ | 0.4% | 0.7% | 1.3% | 1.7% | 1.6% | 2.2% | 1.7% | 1.3% | 1.6% |
| Cycle degradation | %/cycle | $Cyc_{deg}$ | 0.0007% | 0.0014% | 0.0002% | 0.0069% | 0.0054% | 0.0182% | 0.0027% | 0.0011% | 0.0001% |
| Construction time | years | $T_c$ | 3 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Sources | | | [1,7,12–15] | [1,7,12–14,16,17] | [1,3,7,12–14] | [7,9,13,14,18] | [1,7,9,13,14,18] | [1,7,12–14,19,20] | [1,7,9,13,14] | [7,13,14,21–25] | [7,12–14] |

**Note:** Cycles refers to full equivalent charge-discharge cycles.

**Table S5.** Technology cycle life relative to depth-of-discharge (DoD)

| Depth-of-Discharge | Pumped hydro | Compressed air | Flywheel | Lithium-ion | Sodium-sulphur | Lead-acid | Vanadium redox-flow | Hydrogen | Super-capacitor |
|---|---|---|---|---|---|---|---|---|---|
| 100% | 33,250 | 16,250 | 143,402 | 3,250 | 4,098 | 1,225 | 8,272 | 20,000 | 300,000 |
| 90% | 33,250 | 16,250 | 143,402 | 4,875 | 4,131 | 1,336 | 8,272 | 20,000 | 300,000 |
| 80% | 33,250 | 16,250 | 143,402 | 6,297 | 4,193 | 1,501 | 8,272 | 20,000 | 300,000 |
| 70% | 33,250 | 16,250 | 143,402 | 8,531 | 4,592 | 1,763 | 8,272 | 20,000 | 300,000 |
| 60% | 33,250 | 16,250 | 143,402 | 10,766 | 5,299 | 2,074 | 8,272 | 20,000 | 300,000 |
| 50% | 33,250 | 16,250 | 143,402 | 14,219 | 6,006 | 2,598 | 8,272 | 20,000 | 300,000 |
| 40% | 33,250 | 16,250 | 143,402 | 18,586 | 7,050 | 3,194 | 8,272 | 20,000 | 300,000 |
| 30% | 33,250 | 16,250 | 143,402 | 24,984 | 8,516 | 4,211 | 8,272 | 20,000 | 300,000 |
| 20% | 33,250 | 16,250 | 143,402 | 35,953 | 10,654 | 6,316 | 8,272 | 20,000 | 300,000 |
| 10% | 33,250 | 16,250 | 143,402 | 60,734 | 21,325 | 13,183 | 8,272 | 20,000 | 300,000 |
| Source | | | | [26] | [27] | [19] | | | |

**Note:** Cycles refers to full equivalent charge-discharge cycles.

**Table S6.** Optimal depth-of-discharge (if applicable)

| Lithium-ion | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Bill Management | 77% | 77% | 77% | 77% | 80% | 80% | 80% | 80% |
| Black Start | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Congestion Management | 92% | 92% | 92% | 92% | 92% | 92% | 92% | 92% |
| Energy Arbitrage | 92% | 92% | 92% | 92% | 92% | 92% | 92% | 92% |
| Peaker Replacement | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Power Quality | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Power Reliability | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Primary Response | 45% | 45% | 45% | 45% | 45% | 45% | 45% | 45% |
| Seasonal Storage | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Secondary Response | 57% | 57% | 57% | 63% | 67% | 67% | 67% | 67% |
| T&D Investment Deferral | 92% | 92% | 92% | 92% | 92% | 92% | 92% | 92% |
| Tertiary Response | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

| Sodium-sulphur | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Bill Management | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Black Start | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Congestion Management | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Energy Arbitrage | 96% | 96% | 100% | 100% | 100% | 100% | 100% | 100% |
| Peaker Replacement | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Power Quality | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Power Reliability | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Primary Response | 64% | 64% | 64% | 64% | 64% | 64% | 64% | 64% |
| Seasonal Storage | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Secondary Response | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| T&D Investment Deferral | 96% | 96% | 96% | 96% | 96% | 100% | 100% | 100% |
| Tertiary Response | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

| Lead-acid | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Bill Management | 80% | 80% | 80% | 80% | 80% | 80% | 80% | 80% |
| Black Start | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Congestion Management | 96% | 96% | 96% | 96% | 96% | 96% | 96% | 96% |
| Energy Arbitrage | 96% | 96% | 96% | 96% | 96% | 96% | 96% | 96% |
| Peaker Replacement | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Power Quality | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Power Reliability | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Primary Response | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Seasonal Storage | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Secondary Response | 61% | 61% | 61% | 61% | 61% | 61% | 61% | 61% |
| T&D Investment Deferral | 96% | 96% | 96% | 96% | 96% | 96% | 96% | 96% |
| Tertiary Response | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

**Table S7.** Combined standard deviations for investment cost parameters

| Investment cost - Power | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Pumped hydro | 45% | 45% | 45% | 45% | 45% | 45% | 46% | 46% |
| Compressed air | 35% | 35% | 35% | 35% | 35% | 36% | 36% | 36% |
| Flywheel | 17% | 17% | 19% | 23% | 29% | 32% | 33% | 34% |
| Lithium-ion | 17% | 28% | 45% | 59% | 65% | 67% | 67% | 68% |
| Sodium-sulphur | 27% | 28% | 29% | 32% | 36% | 39% | 40% | 41% |
| Lead-acid | 23% | 24% | 24% | 24% | 24% | 24% | 24% | 24% |
| Vanadium redox-flow | 21% | 37% | 51% | 59% | 61% | 60% | 58% | 57% |
| Hydrogen | 48% | 48% | 49% | 51% | 53% | 55% | 56% | 57% |
| Supercapacitor | 31% | 31% | 32% | 35% | 39% | 41% | 42% | 43% |
| | | | | | | | | |
| **Investment cost - Energy** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| Pumped hydro | 63% | 63% | 63% | 63% | 63% | 63% | 64% | 64% |
| Compressed air | 58% | 58% | 58% | 58% | 59% | 59% | 59% | 59% |
| Flywheel | 67% | 67% | 67% | 69% | 71% | 72% | 73% | 73% |
| Lithium-ion | 24% | 33% | 48% | 61% | 67% | 69% | 70% | 70% |
| Sodium-sulphur | 12% | 13% | 15% | 20% | 26% | 30% | 31% | 32% |
| Lead-acid | 38% | 38% | 39% | 38% | 38% | 38% | 38% | 38% |
| Vanadium redox-flow | 17% | 35% | 49% | 58% | 60% | 58% | 57% | 56% |
| Hydrogen | 60% | 60% | 60% | 62% | 64% | 66% | 66% | 67% |
| Supercapacitor | 19% | 19% | 20% | 24% | 30% | 33% | 34% | 35% |

**Table S8.** Investment cost projections relative to 2015 with forecast uncertainty

| | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 | Comment |
|---|---|---|---|---|---|---|---|---|---|
| Pumped hydro | 100% (0%) | 100% (0%) | 100% (1%) | 100% (3%) | 101% (6%) | 101% (8%) | 102% (10%) | 102% (12%) | Original |
| Compressed air | 100% (0%) | 100% (0%) | 100% (1%) | 100% (3%) | 101% (6%) | 101% (8%) | 102% (10%) | 102% (12%) | Same as pumped hydro |
| Flywheel | 100% (0%) | 84% (3%) | 66% (6%) | 53% (8%) | 44% (10%) | 39% (11%) | 36% (10%) | 33% (10%) | Same as hydrogen |
| Lithium-ion | 100% (0%) | 55% (12%) | 34% (14%) | 23% (13%) | 18% (12%) | 16% (10%) | 15% (10%) | 14% (9%) | Original |
| Sodium-sulphur | 100% (0%) | 84% (3%) | 66% (6%) | 53% (8%) | 44% (10%) | 39% (11%) | 36% (10%) | 33% (10%) | Same as hydrogen |
| Lead-acid | 100% (0%) | 80% (5%) | 68% (6%) | 63% (5%) | 61% (5%) | 59% (4%) | 59% (4%) | 58% (5%) | Original |
| Vanadium redox-flow | 100% (0%) | 49% (15%) | 34% (16%) | 26% (14%) | 21% (12%) | 19% (11%) | 18% (10%) | 17% (9%) | Original |
| Hydrogen | 100% (0%) | 84% (3%) | 66% (6%) | 53% (8%) | 44% (10%) | 39% (11%) | 36% (10%) | 33% (10%) | Original |
| Supercapacitor | 100% (0%) | 84% (3%) | 66% (6%) | 53% (8%) | 44% (10%) | 39% (11%) | 36% (10%) | 33% (10%) | Same as hydrogen |

## Supplemental Figures

**Figure S1.** Core application with modelled technical requirements

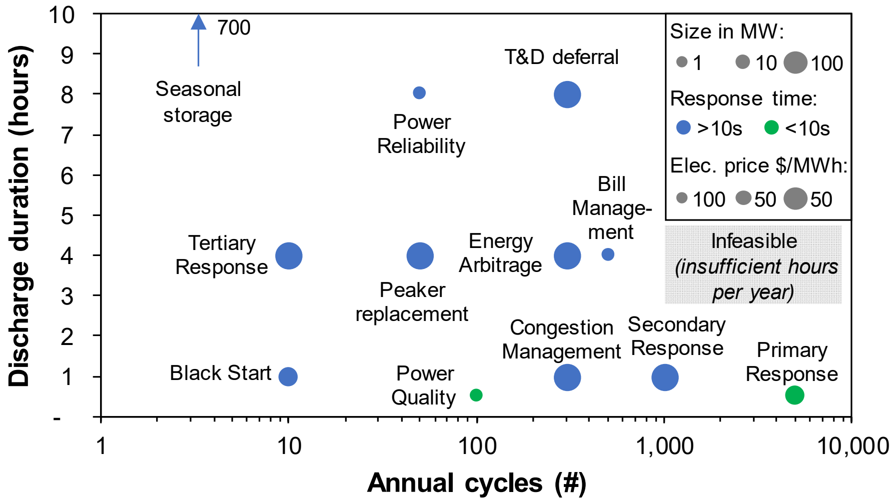


**Figure S2.** Updated experience curve data set

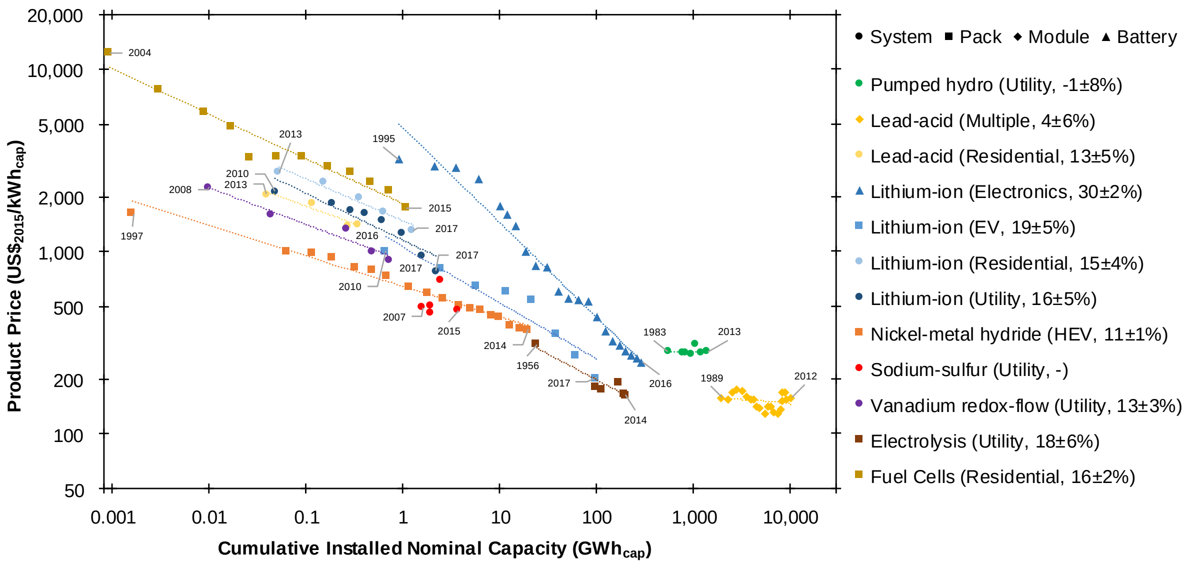
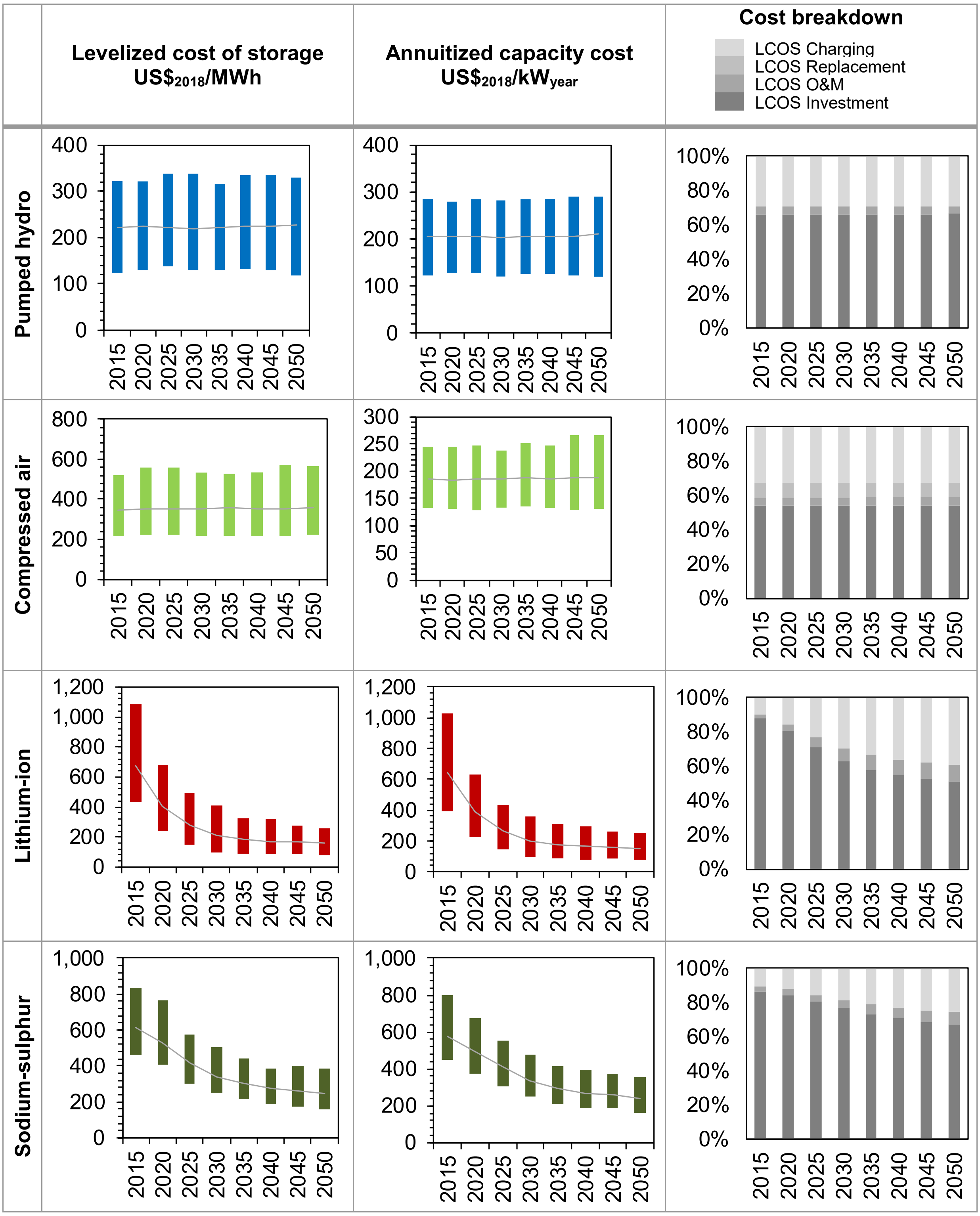
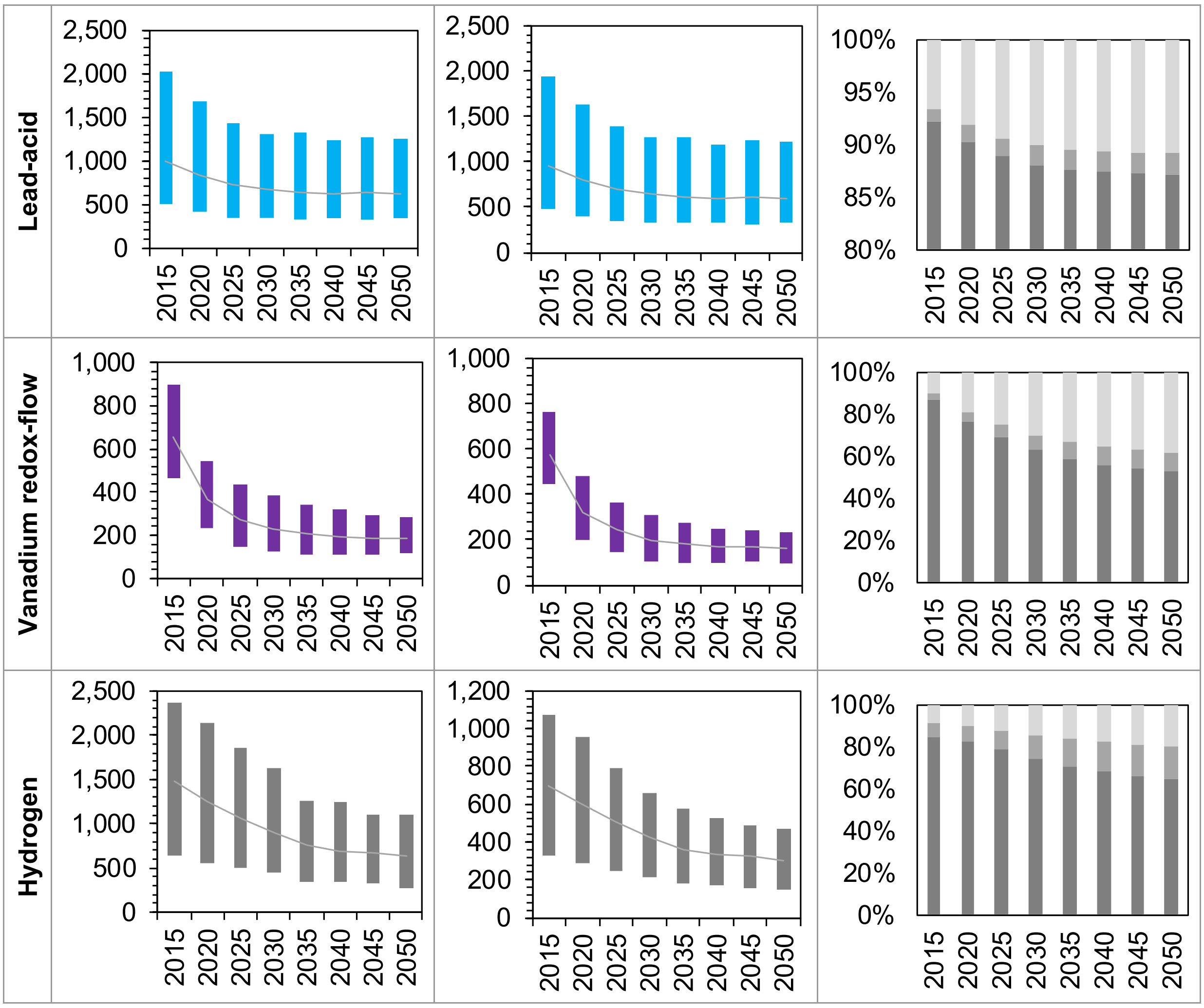



*Figure S2* – *Updated experience curve data set based on Schmidt, 2017[28]. All lithium-ion and redox-flow data sets have been updated to include 2016 and/or 2017 data. The data set including future price projections can be downloaded[29].*

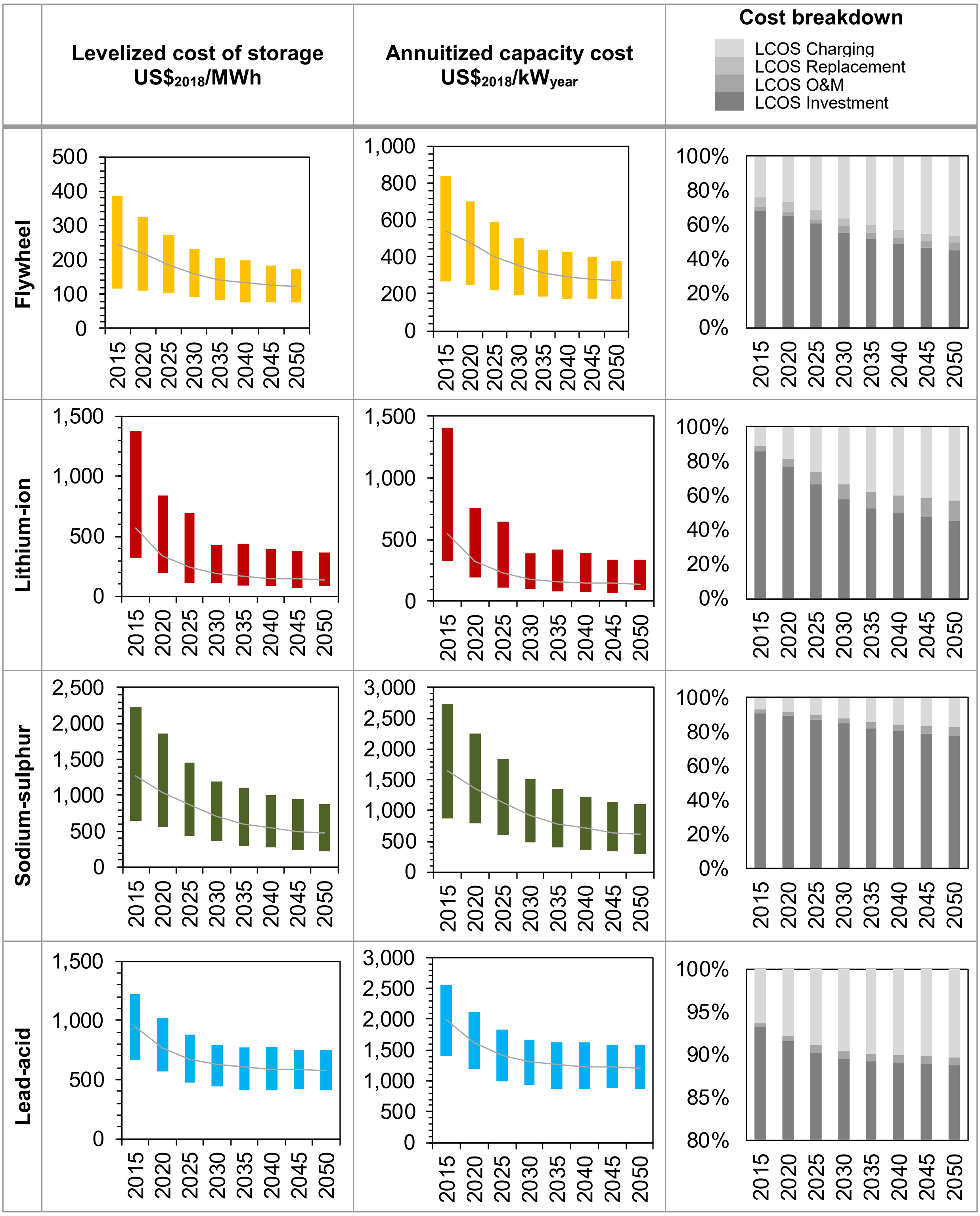
**Figure S3.** LCOS projections and breakdown for 9 technologies in 12 applications

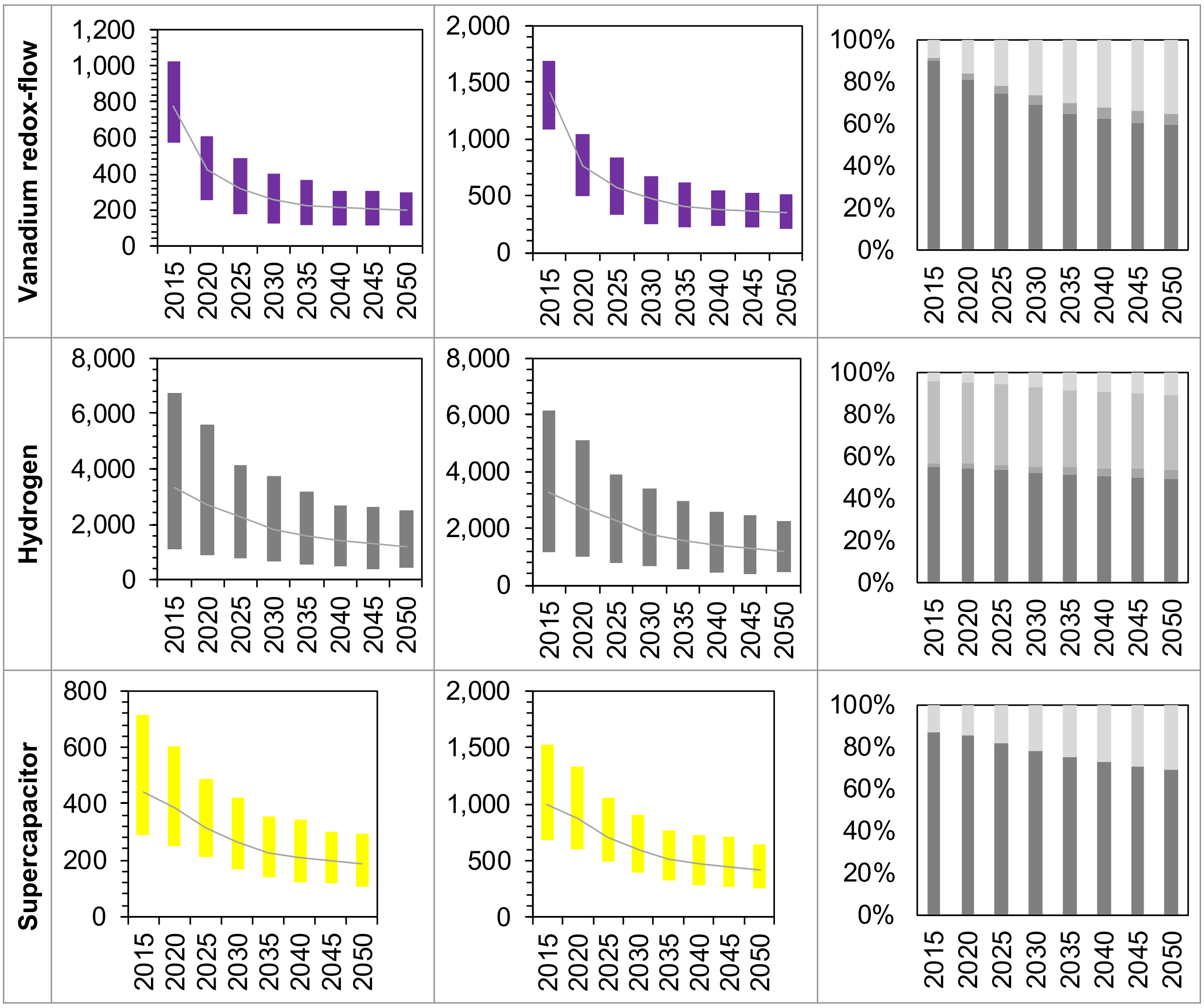
**Application: Energy Arbitrage**



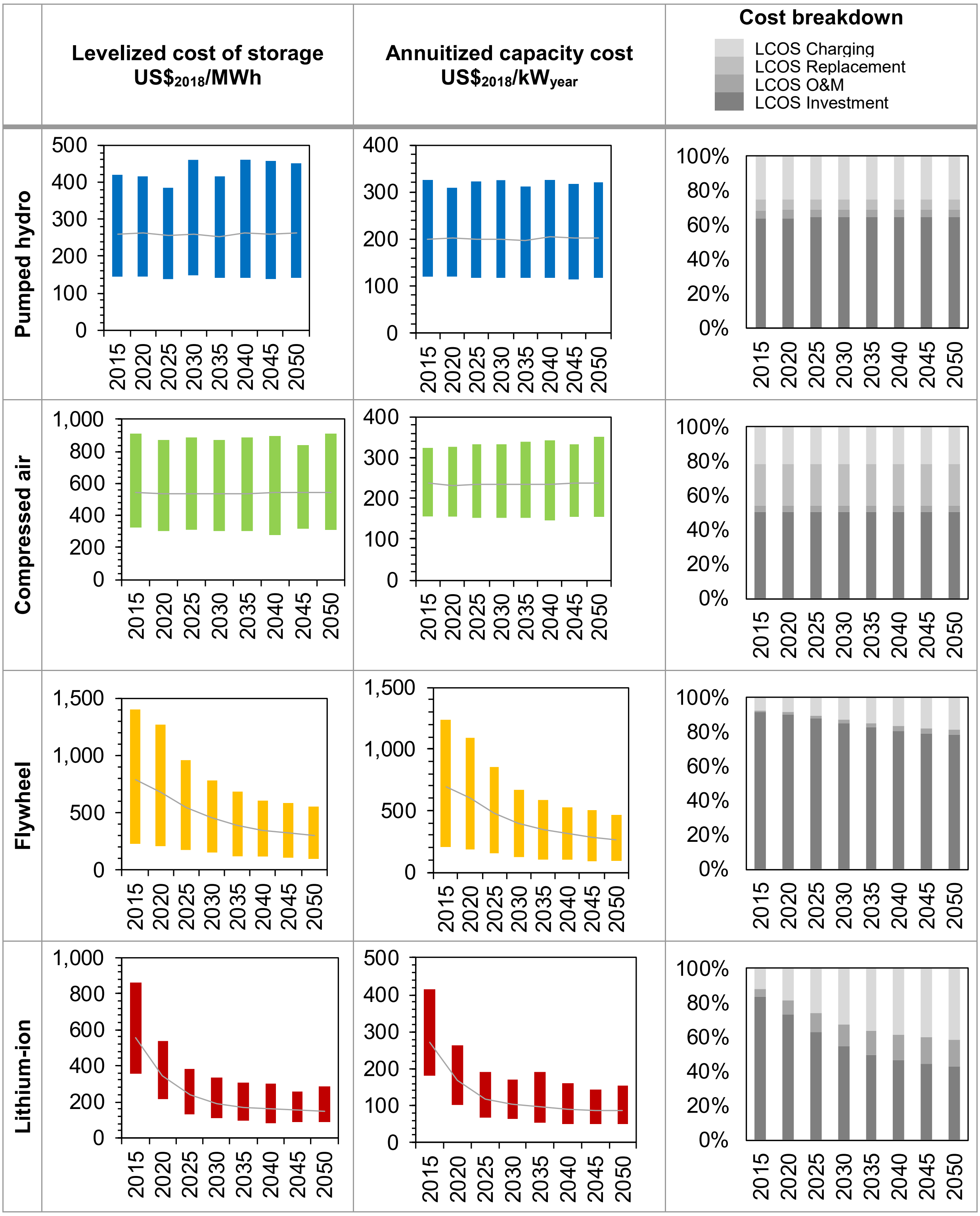

Lead-acid
Vanadium redox-flow
Hydrogen
0
500
1,000
1,500
2,000
2,500
200
400
600
800
1,000
1,200
80%
85%
90%
95%
100%
0%
20%
40%
60%
2015
2020
2025
2030
2035
2040
2045
2050

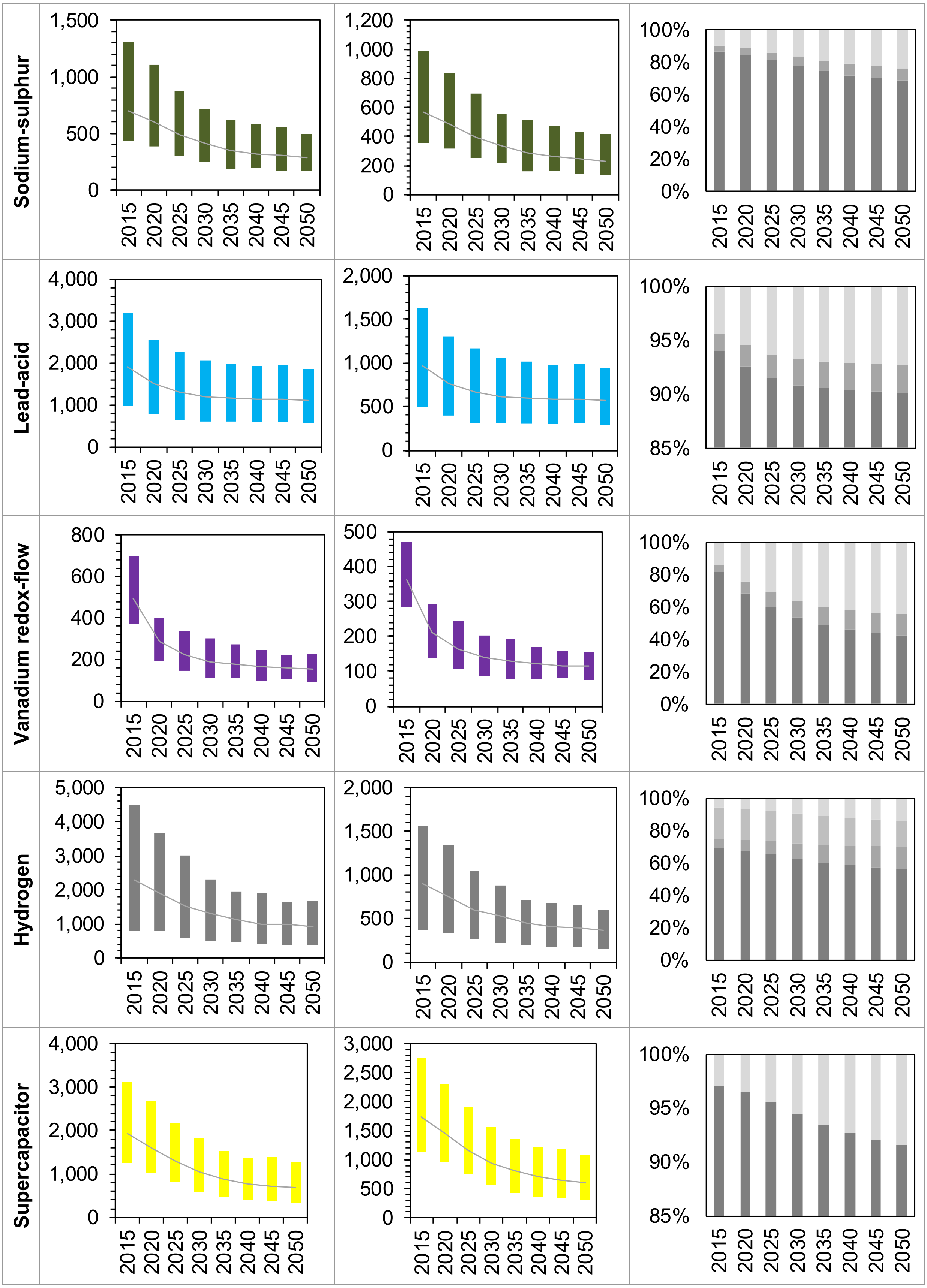
**Application: Primary Response**




Vanadium redox-flow
Hydrogen
Supercapacitor
1,200
1,000
800
600
400
200
0
2,000
1,500
1,000
500
0
100%
80%
60%
40%
20%
0%
8,000
6,000
4,000
2,000
0
2015
2020
2025
2030
2035
2040
2045
2050

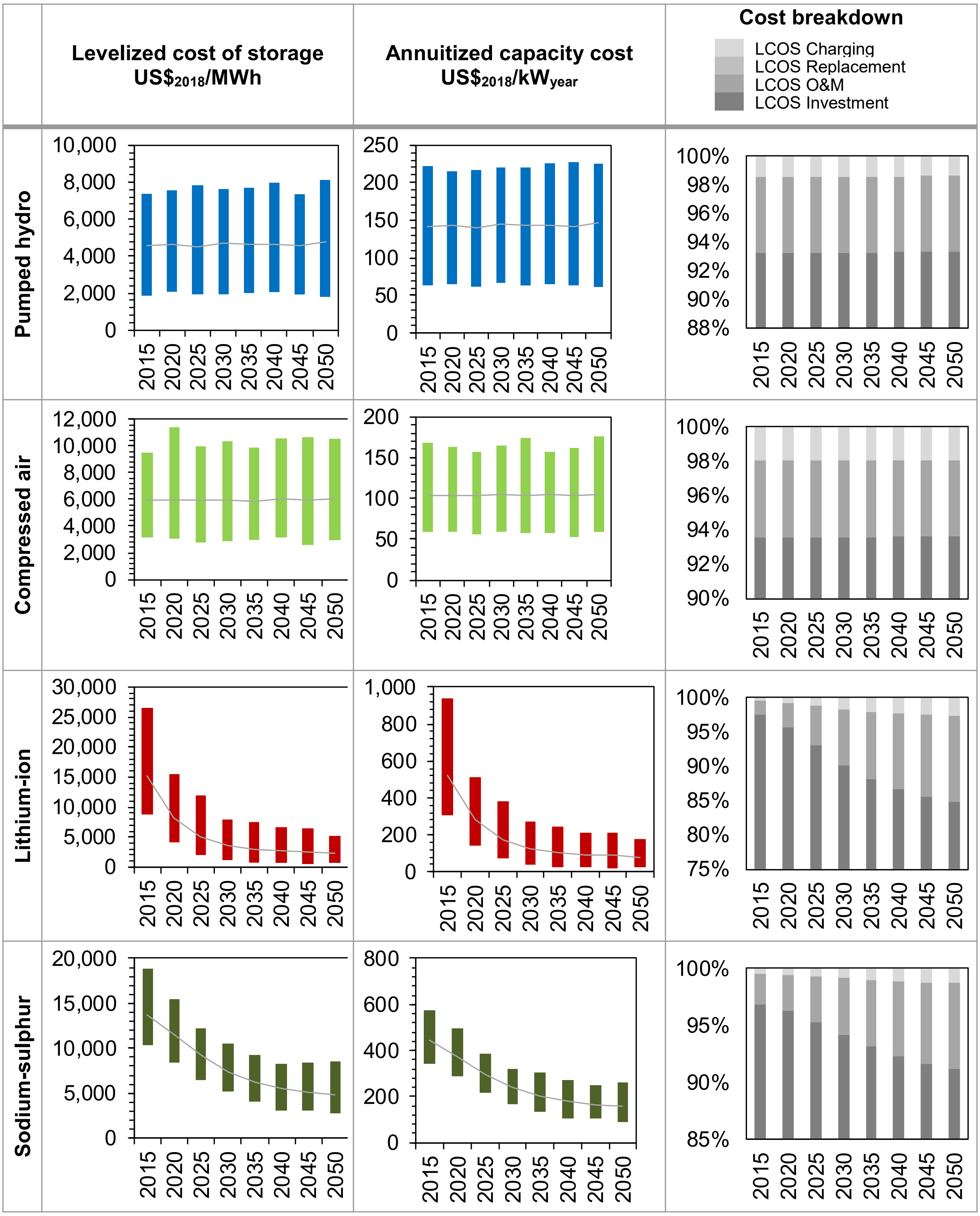
**Application: Secondary Response**

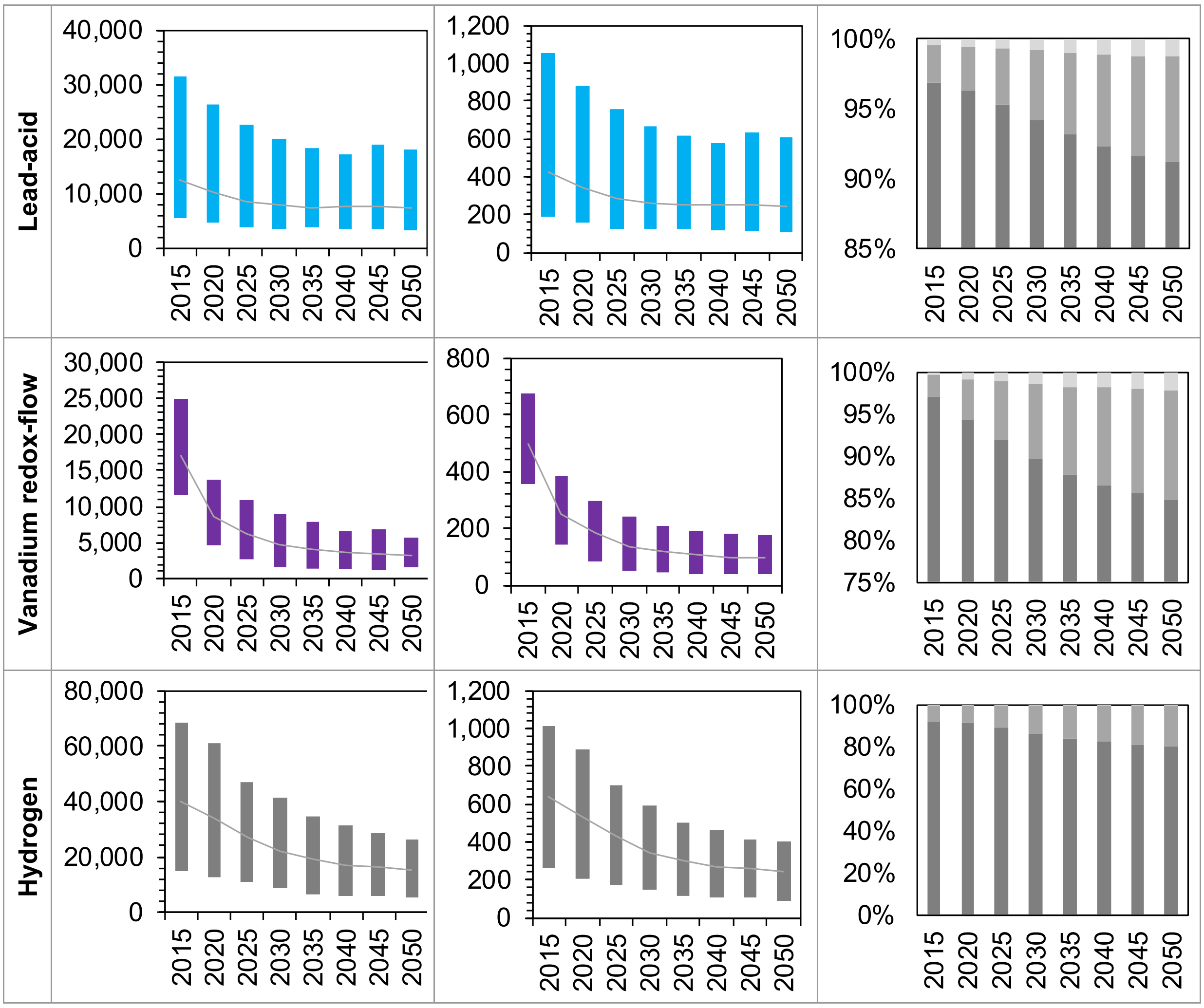




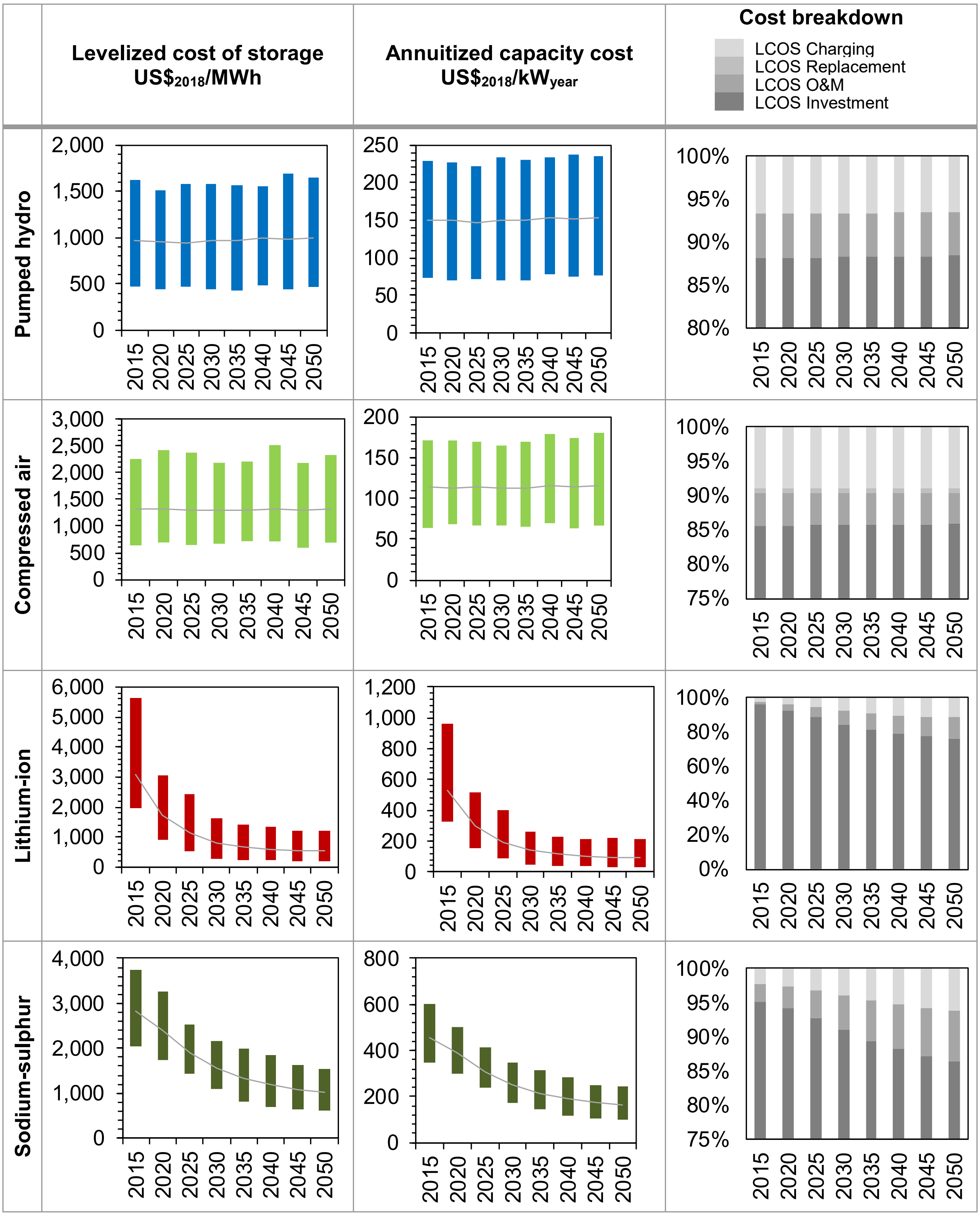
Sodium-sulphur
1,500
1,000
500
0
1,200
1,000
800
600
400
200
0
100%
80%
60%
40%
20%
0%
Lead-acid
4,000
3,000
2,000
1,000
0
2,000
1,500
1,000
500
0
100%
95%
90%
85%
Vanadium redox-flow
800
600
400
200
0
500
400
300
200
100
0
100%
80%
60%
40%
20%
0%
Hydrogen
5,000
4,000
3,000
2,000
1,000
0
2,000
1,500
1,000
500
0
100%
80%
60%
40%
20%
0%
Supercapacitor
4,000
3,000
2,000
1,000
0
3,000
2,500
2,000
1,500
1,000
500
0
100%
95%
90%
85%
2015
2020
2025
2030
2035
2040
2045
2050

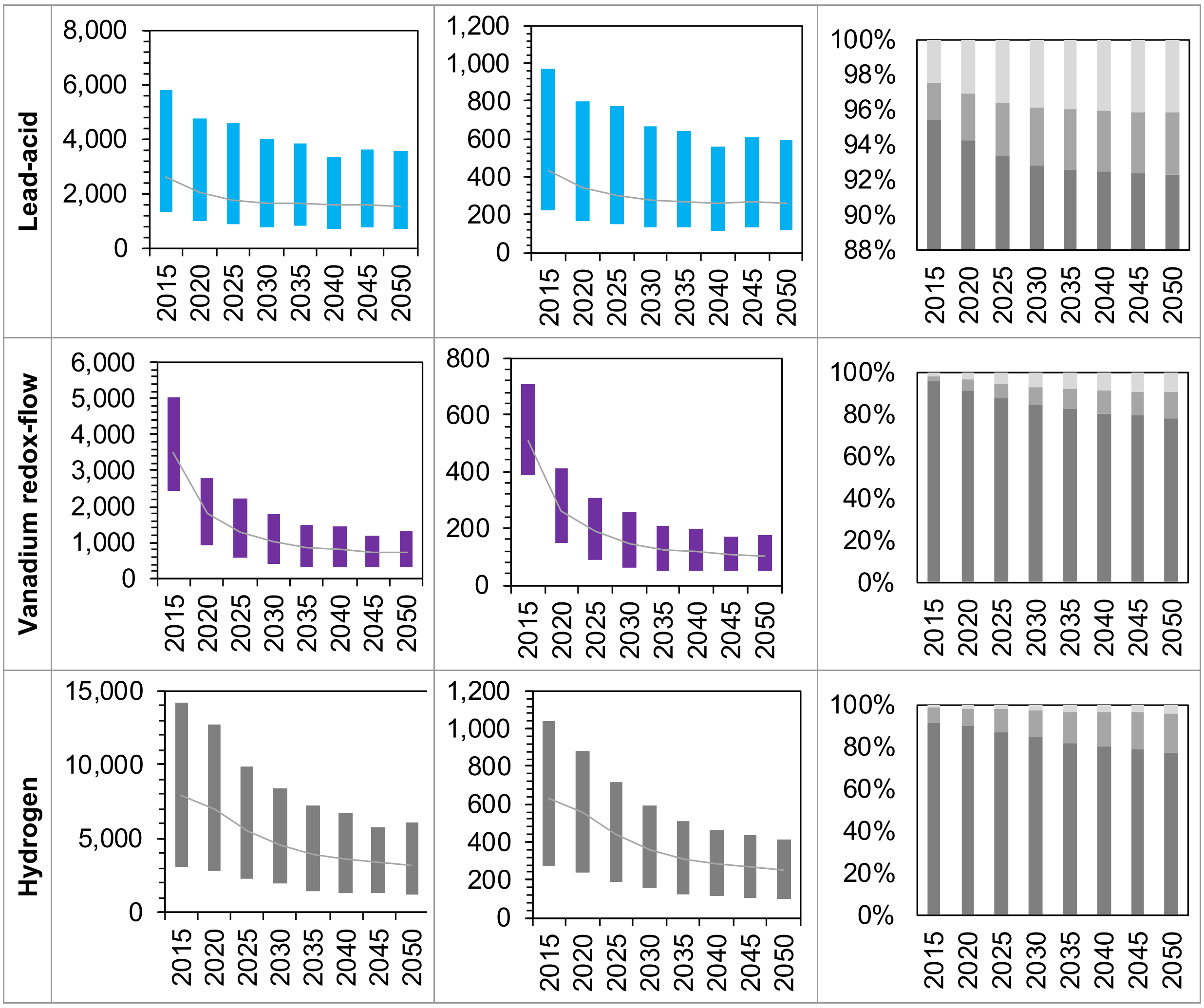
**Application: Tertiary Response**



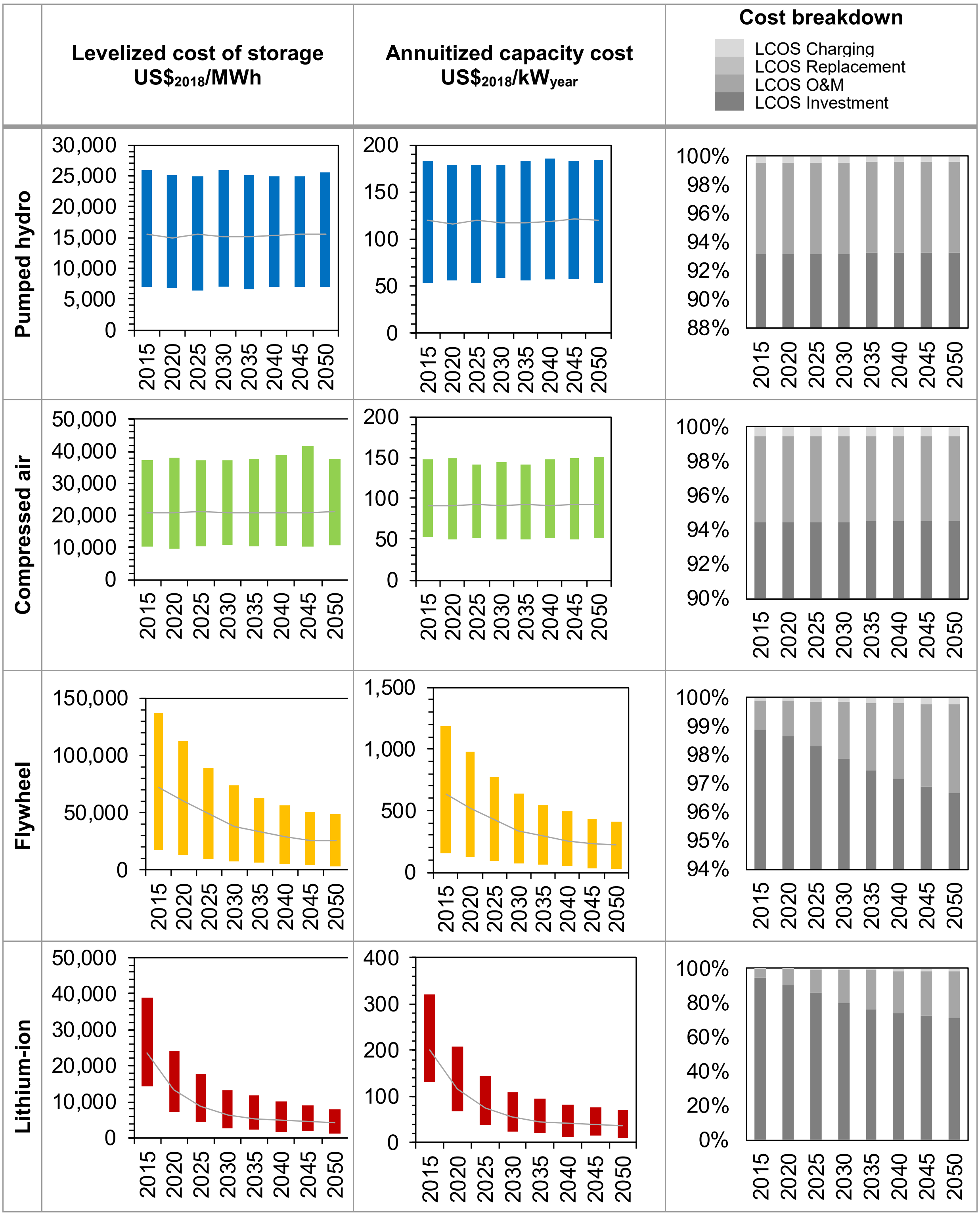

Lead-acid
Vanadium redox-flow
Hydrogen
40,000
30,000
20,000
10,000
0
1,200
1,000
800
600
400
200
0
100%
95%
90%
85%
30,000
25,000
20,000
15,000
10,000
5,000
0
800
600
400
200
0
100%
95%
90%
85%
80%
75%
80,000
60,000
40,000
20,000
0
1,200
1,000
800
600
400
200
0
100%
80%
60%
40%
20%
0%
2015
2020
2025
2030
2035
2040
2045
2050

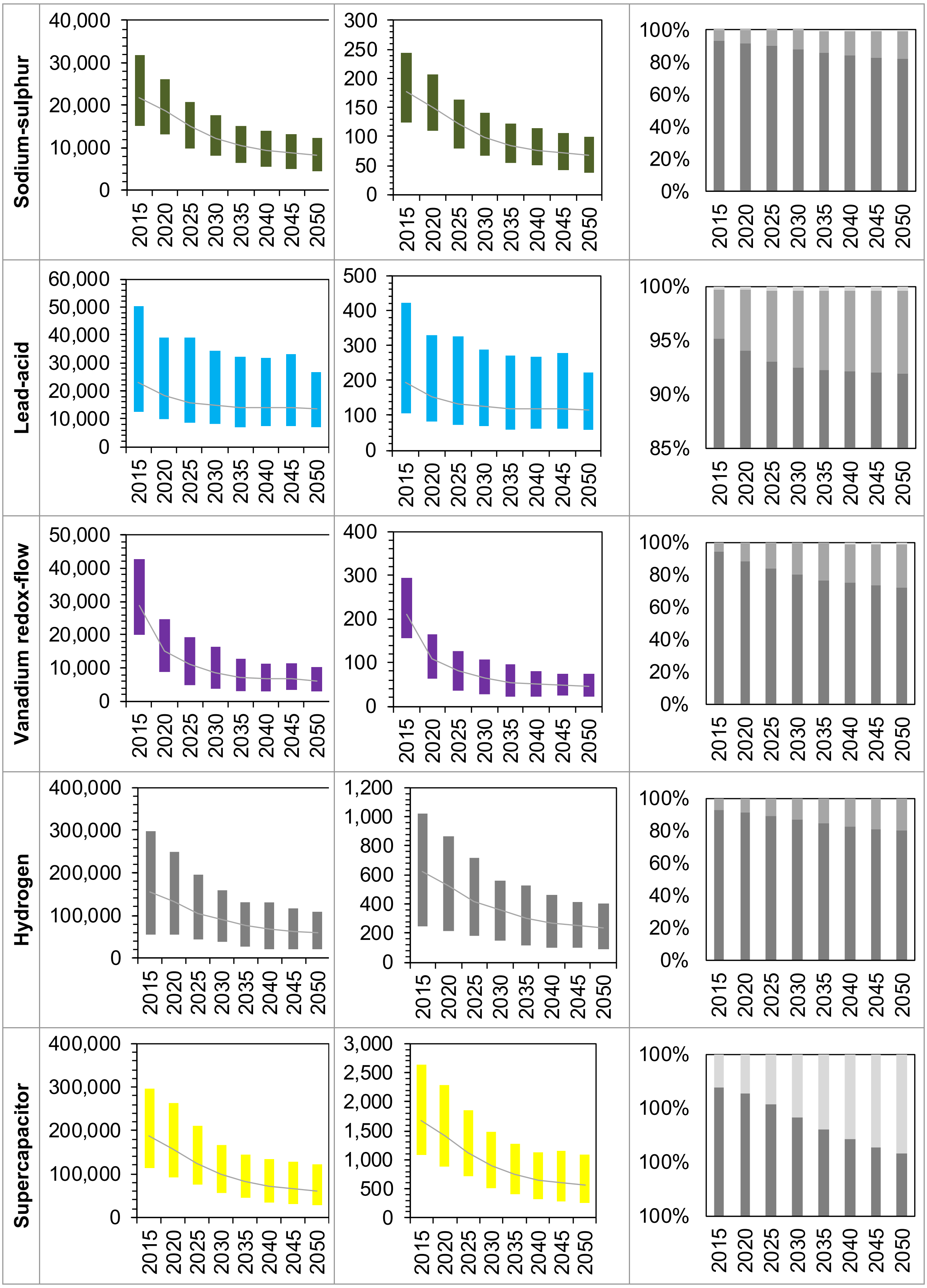
**Application: Peaker Replacement**



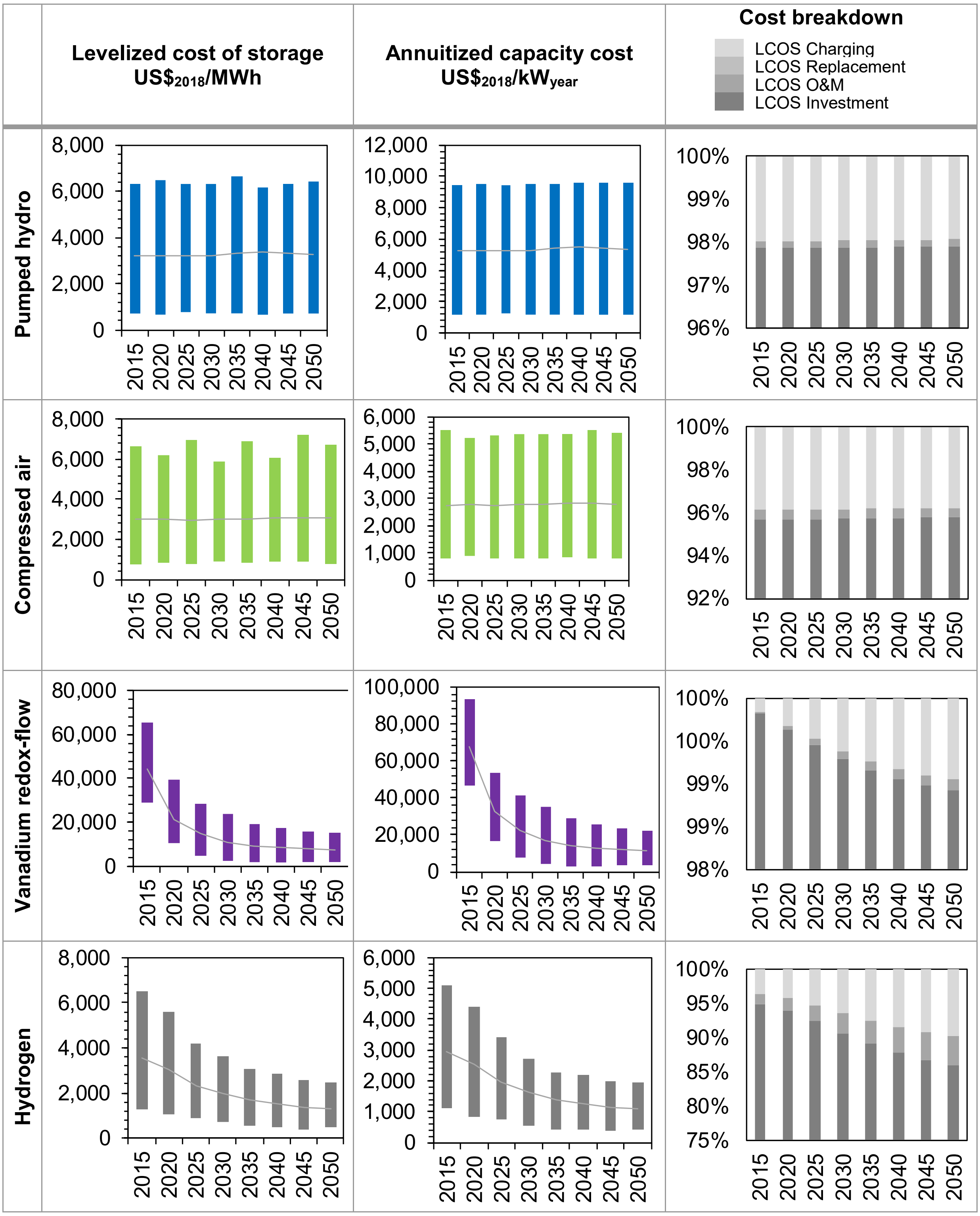

Lead-acid
Vanadium redox-flow
Hydrogen
8,000
6,000
4,000
2,000
0
1,200
1,000
800
600
400
200
0
100%
98%
96%
94%
92%
90%
88%
5,000
3,000
1,000
80%
60%
40%
20%
0%
15,000
10,000
2015
2020
2025
2030
2035
2040
2045
2050

**Application: Black Start**

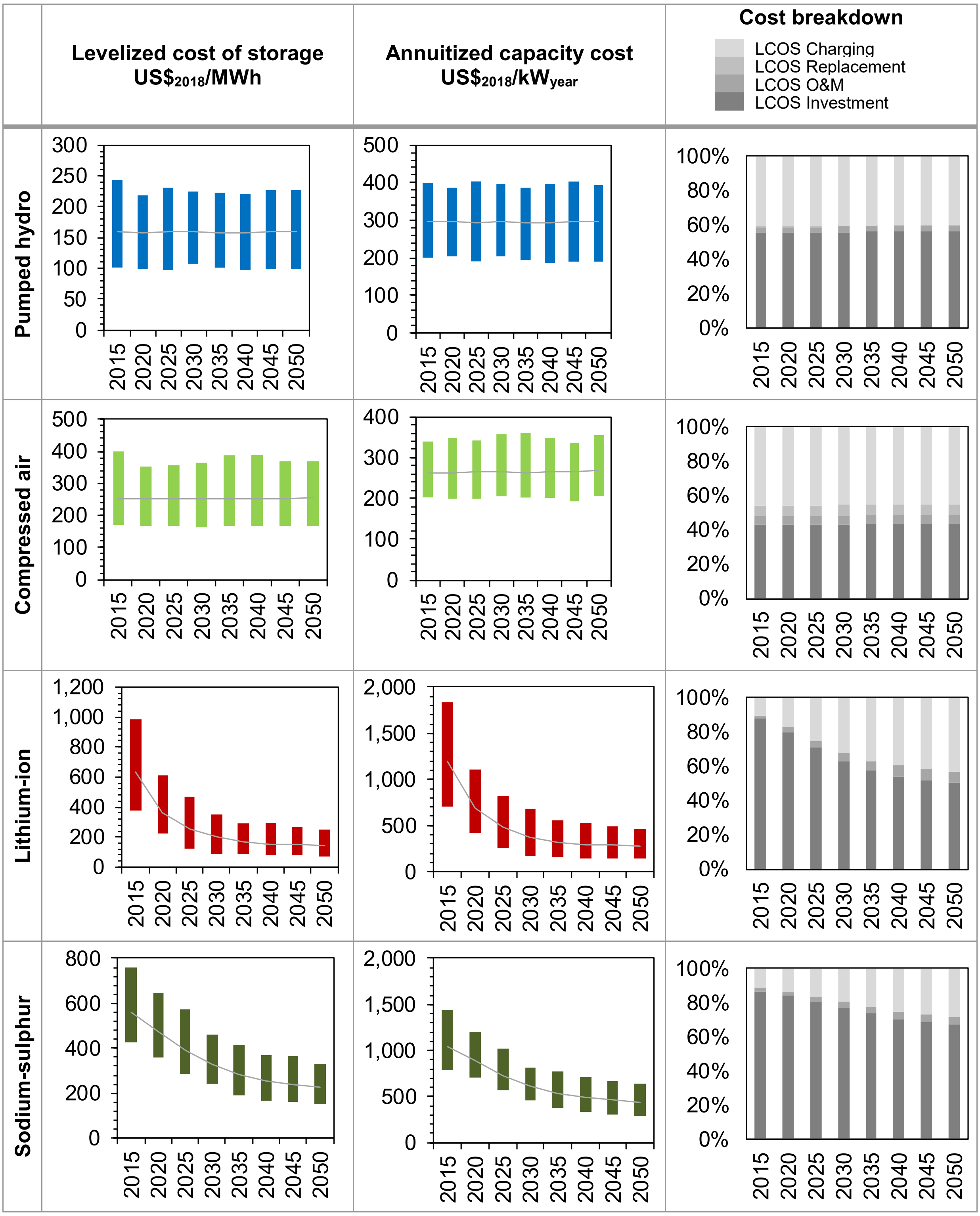


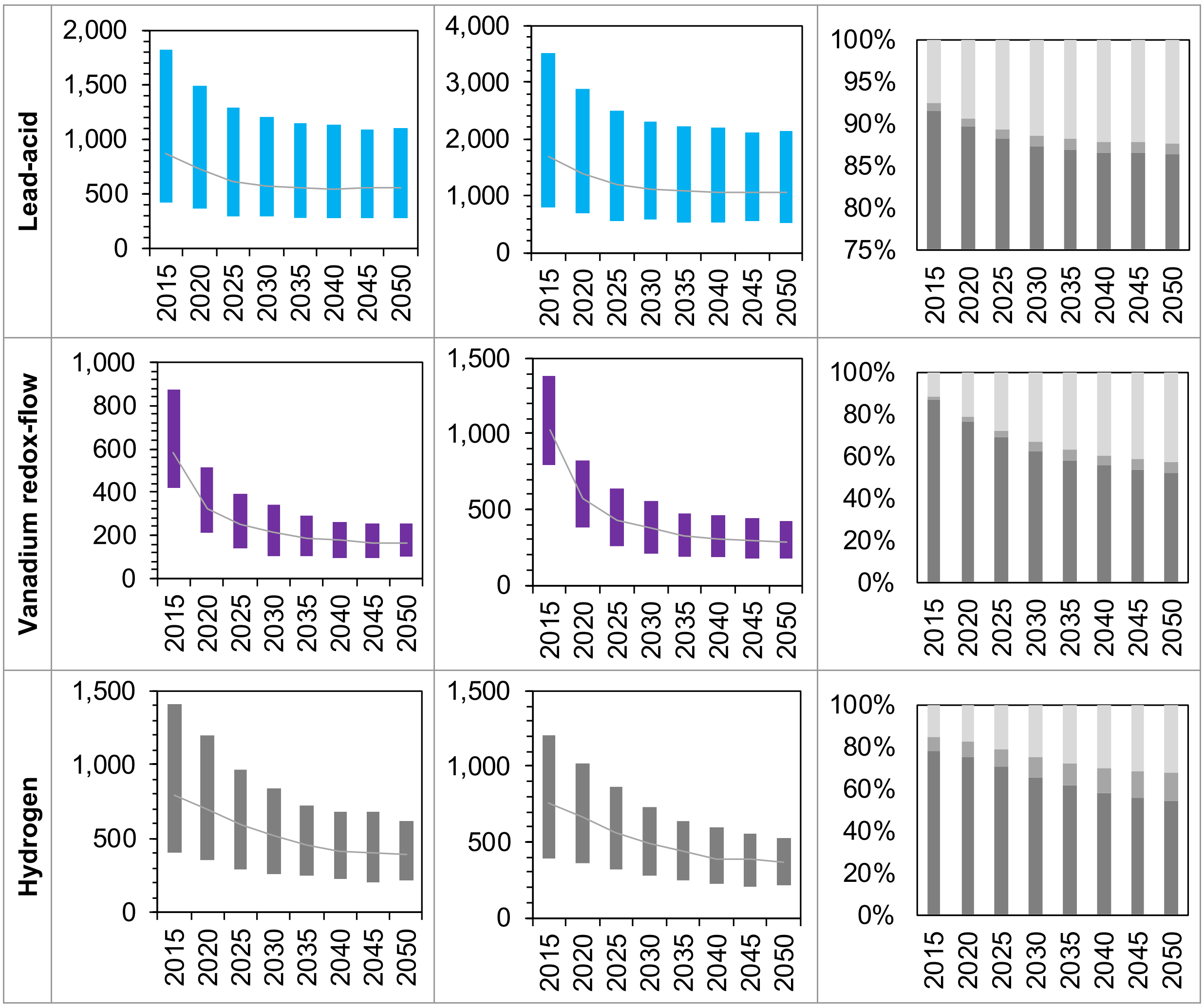

Sodium-sulphur
Lead-acid
Vanadium redox-flow
Hydrogen
Supercapacitor
2015 2020 2025 2030 2035 2040 2045 2050
0 10,000 20,000 30,000 40,000
0 50 100 150 200 250 300
0% 20% 40% 60% 80% 100%
0 10,000 20,000 30,000 40,000 50,000 60,000
0 100 200 300 400 500
85% 90% 95% 100%
0 10,000 20,000 30,000 40,000 50,000
0 100 200 300 400
0 100,000 200,000 300,000 400,000
0 200 400 600 800 1,000 1,200
0 500 1,000 1,500 2,000 2,500 3,000
100% 100% 100% 100%

**Application: Seasonal Storage**



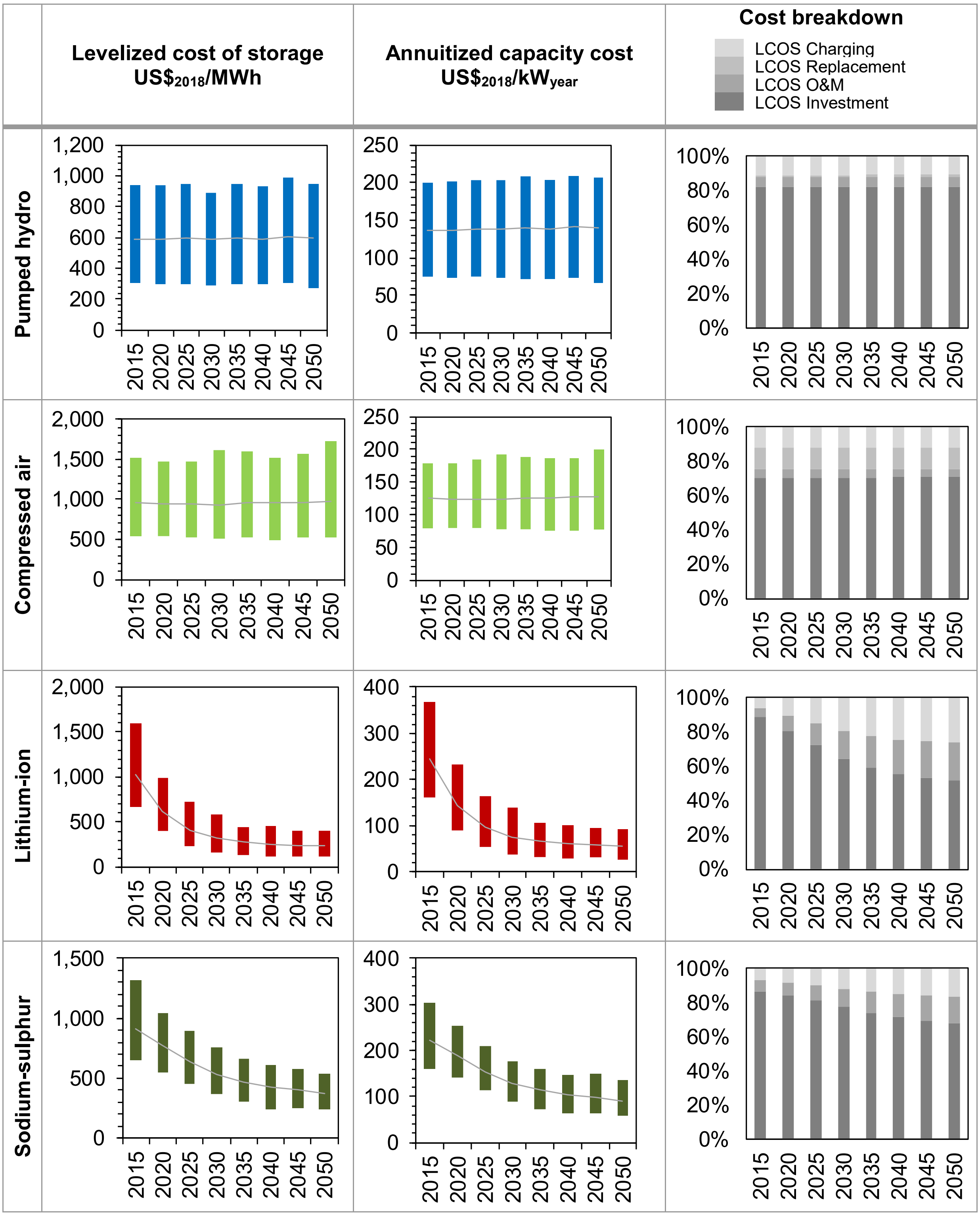
**Application: T&D upgrade deferral**

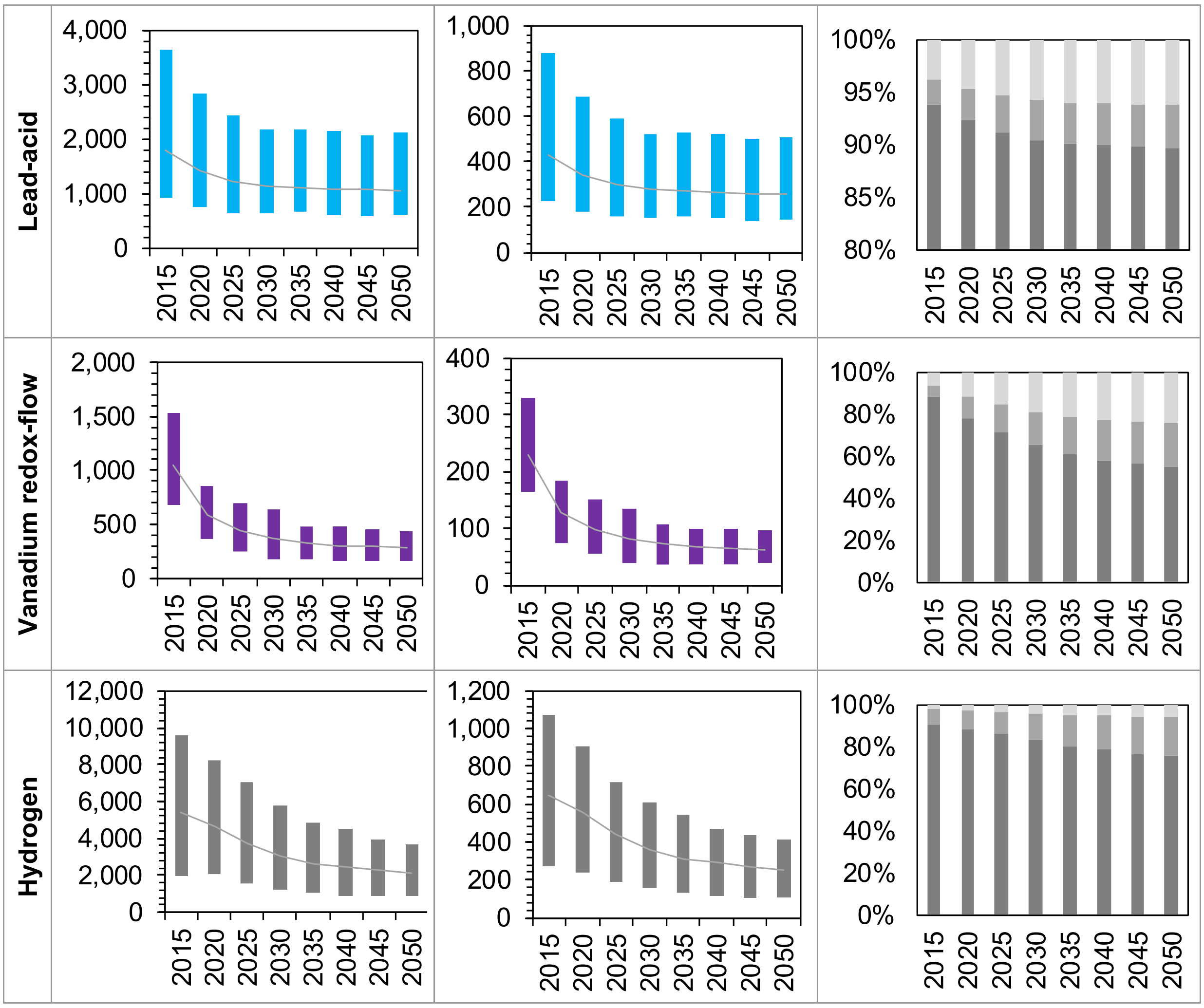




Lead-acid
Vanadium redox-flow
Hydrogen
2,000
1,500
1,000
500
0
4,000
3,000
2,000
1,000
800
600
400
200
100%
95%
90%
85%
80%
75%
60%
40%
20%
0%
2015
2020
2025
2030
2035
2040
2045
2050

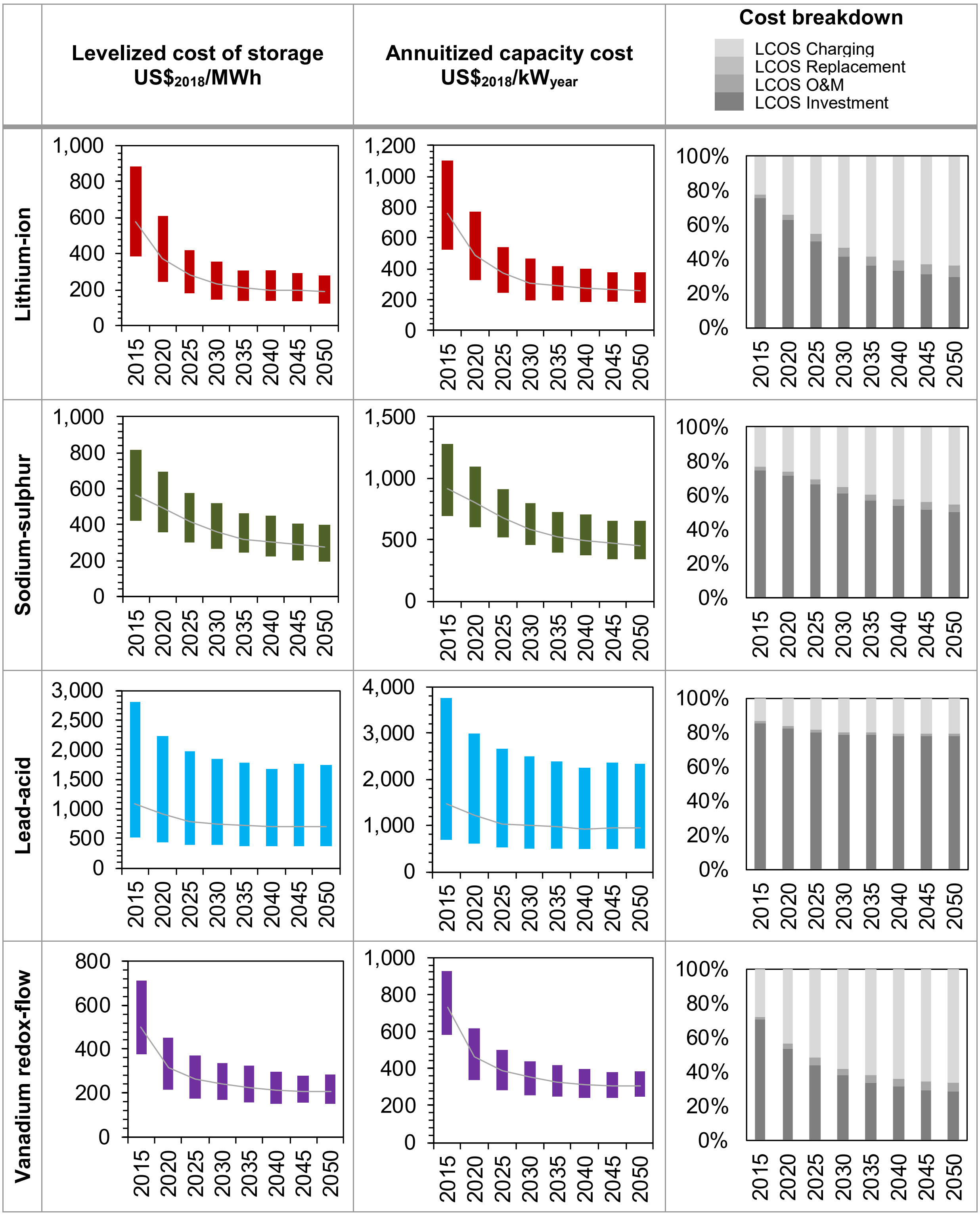
**Application: Congestion Management**



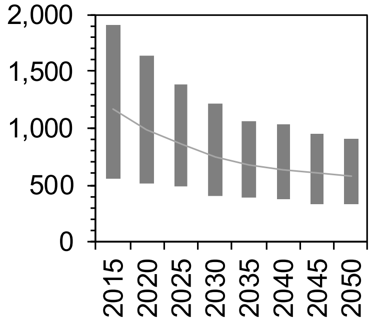


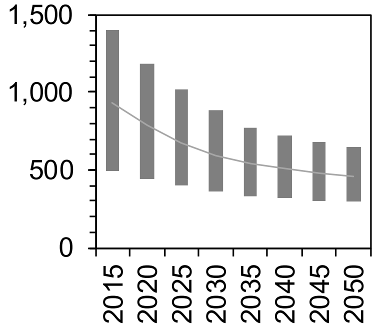
Lead-acid
4,000
3,000
2,000
1,000
0
1,000
800
600
400
200
0
100%
95%
90%
85%
80%
Vanadium redox-flow
2,000
1,500
1,000
500
0
400
300
200
100
0
100%
80%
60%
40%
20%
0%
Hydrogen
12,000
10,000
8,000
6,000
4,000
2,000
0
1,200
1,000
800
600
400
200
0
100%
80%
60%
40%
20%
0%
2015
2020
2025
2030
2035
2040
2045
2050

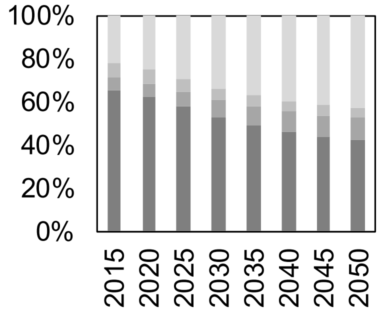
**Application: Bill Management**



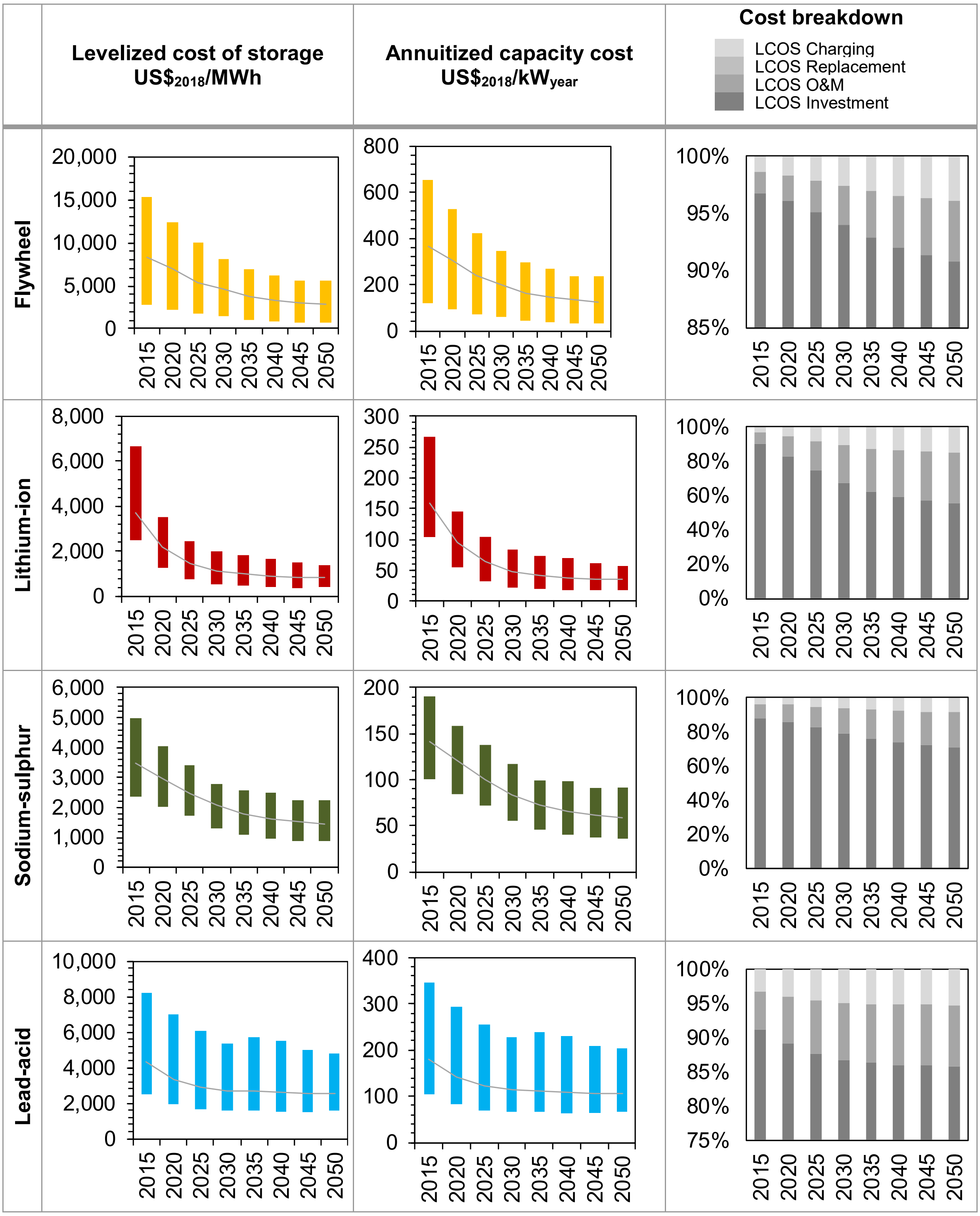
**Hydrogen**

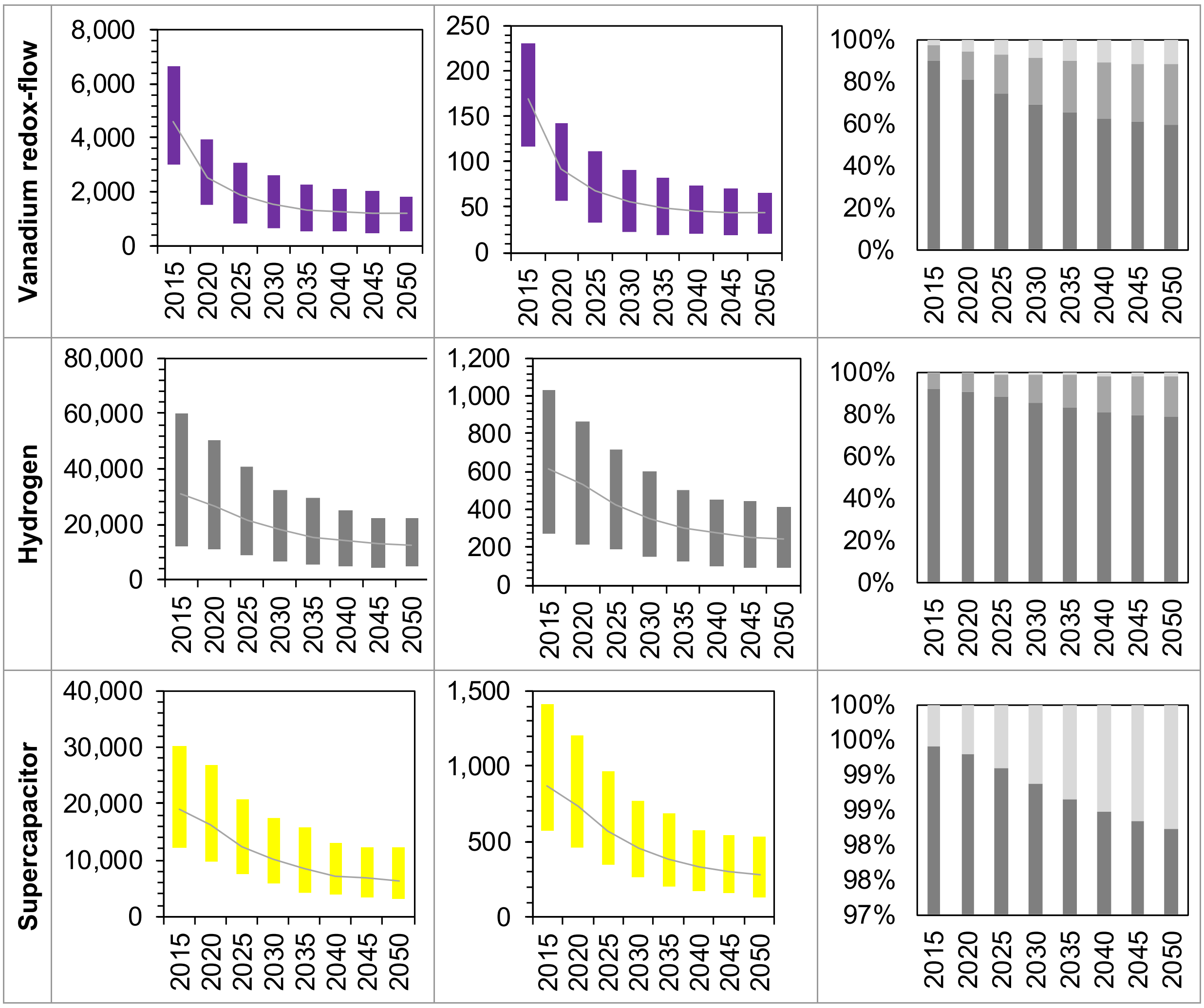

2,000
1,500
1,000
500
0
2015
2020
2025
2030
2035
2040
2045
2050


1,500
1,000
500
0
2015
2020
2025
2030
2035
2040
2045
2050


100%
80%
60%
40%
20%
0%
2015
2020
2025
2030
2035
2040
2045
2050

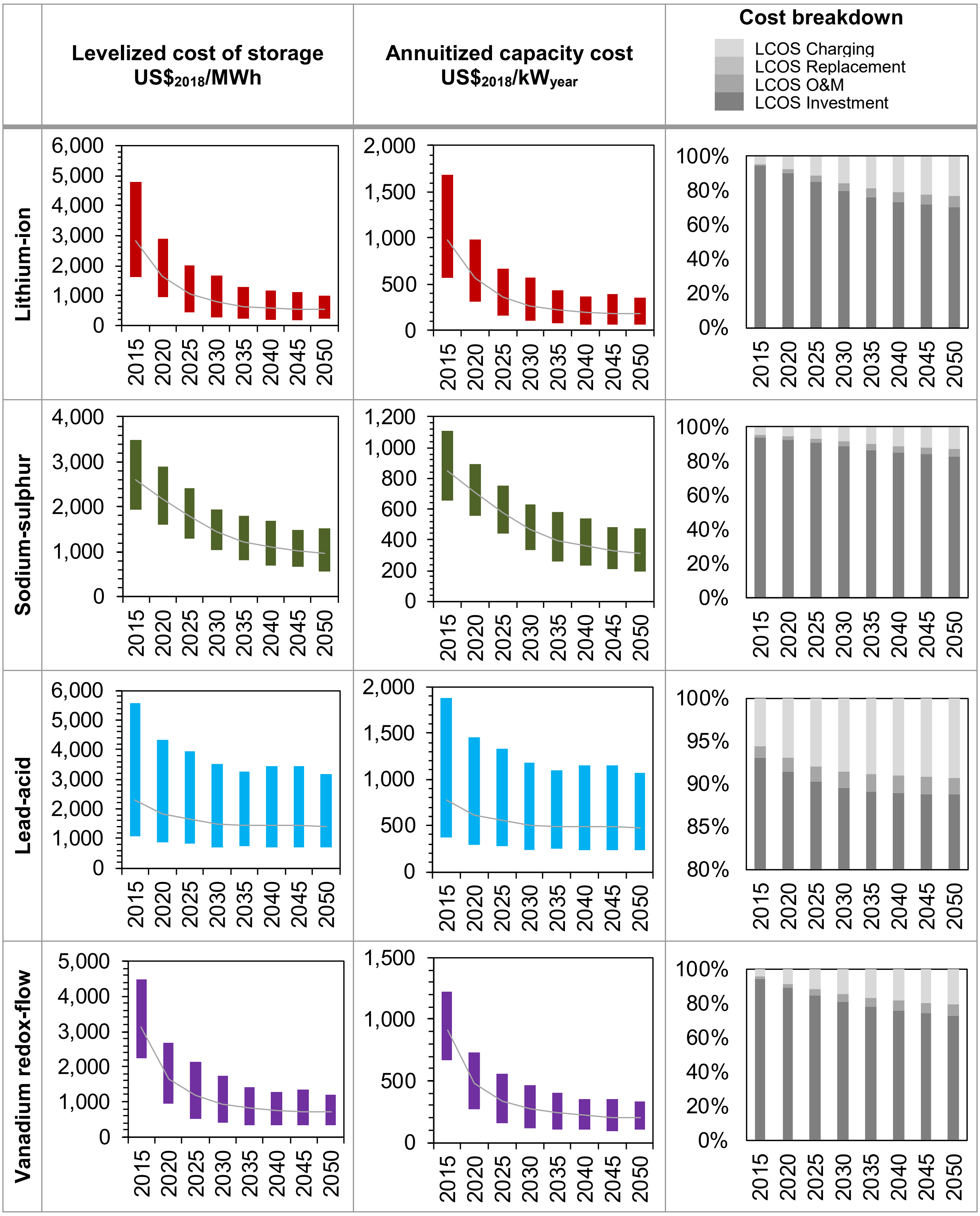
**Application: Power Quality**

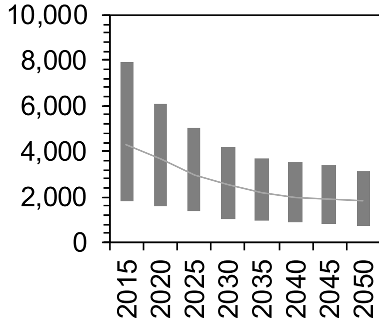
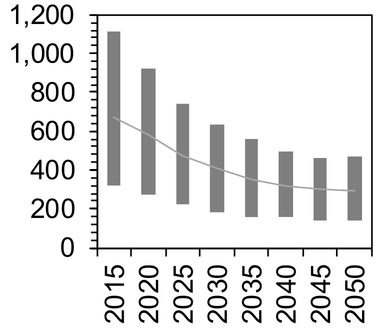
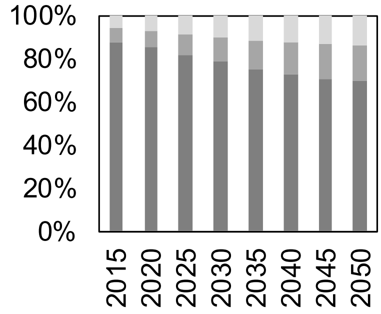




Vanadium redox-flow
8,000
6,000
4,000
2,000
0
250
200
150
100
50
0
100%
80%
60%
40%
20%
0%
Hydrogen
80,000
60,000
40,000
20,000
0
1,200
1,000
800
600
400
200
0
100%
80%
60%
40%
20%
0%
Supercapacitor
40,000
30,000
20,000
10,000
0
1,500
1,000
500
0
100%
100%
99%
99%
98%
98%
97%
2015
2020
2025
2030
2035
2040
2045
2050

**Application: Power Reliability**



| | | | |
|---|---|---|---|
| **Hydrogen** |  |  |  |


10,000
8,000
6,000
4,000
2,000
0
2015 2020 2025 2030 2035 2040 2045 2050



1,200
1,000
800
600
400
200
0
2015 2020 2025 2030 2035 2040 2045 2050



100%
80%
60%
40%
20%
0%
2015 2020 2025 2030 2035 2040 2045 2050

**Figure S4.** Overview of technology probabilities to exhibit lowest LCOS and their mean LCOS in power terms or annuitized capacity cost

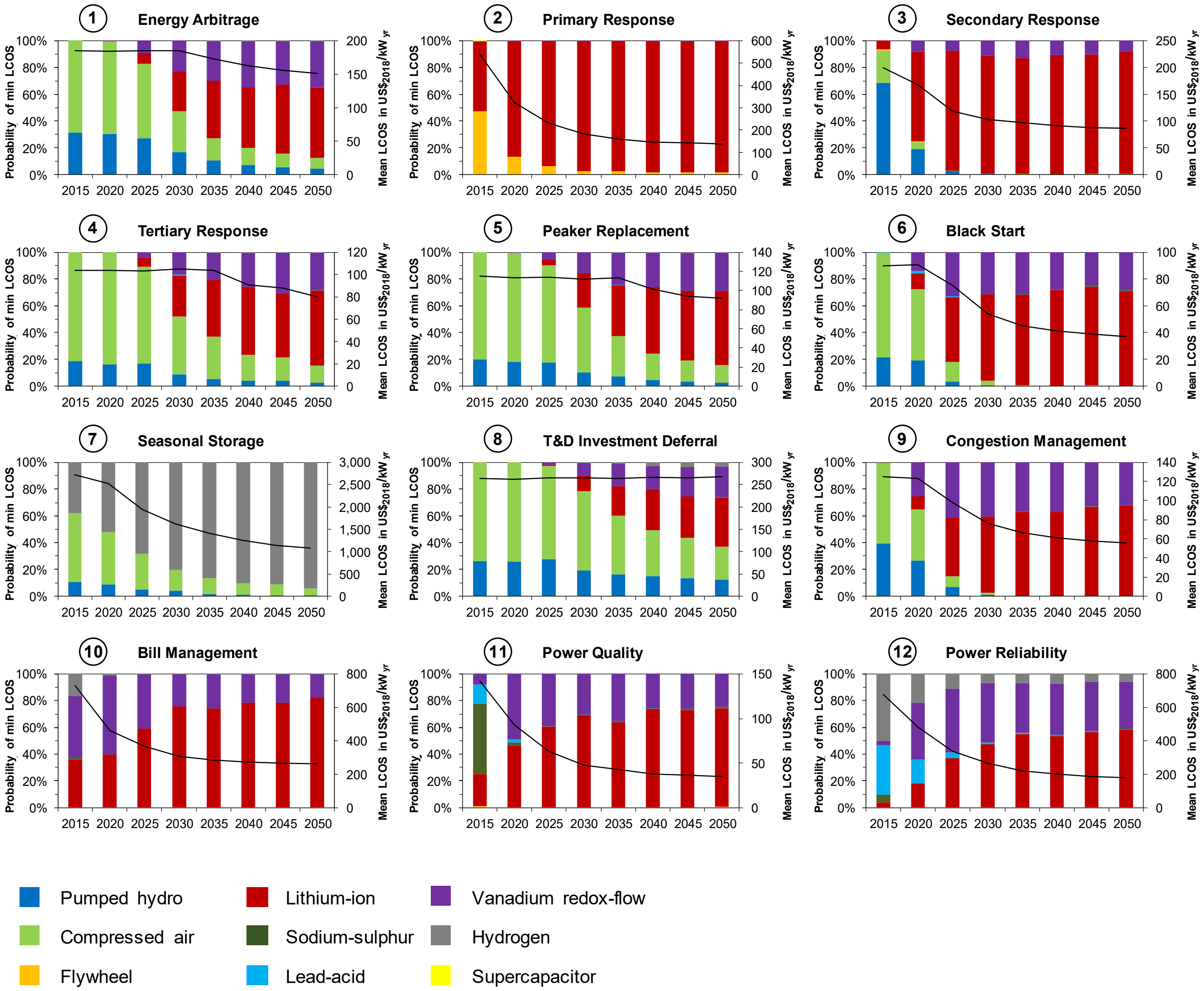
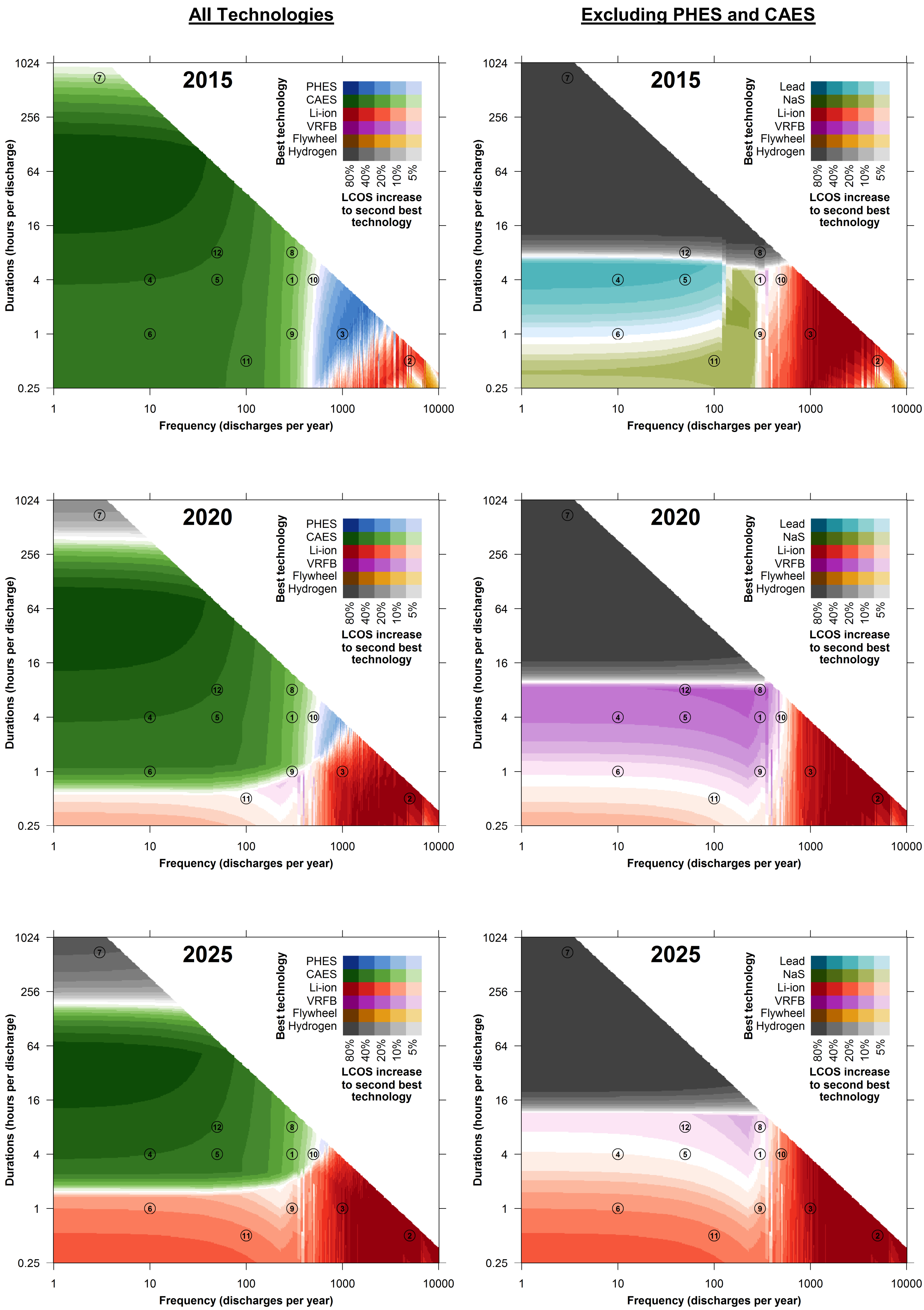


**Figure S5.** Lowest annuitized capacity cost (US$/kW$_{year}$)



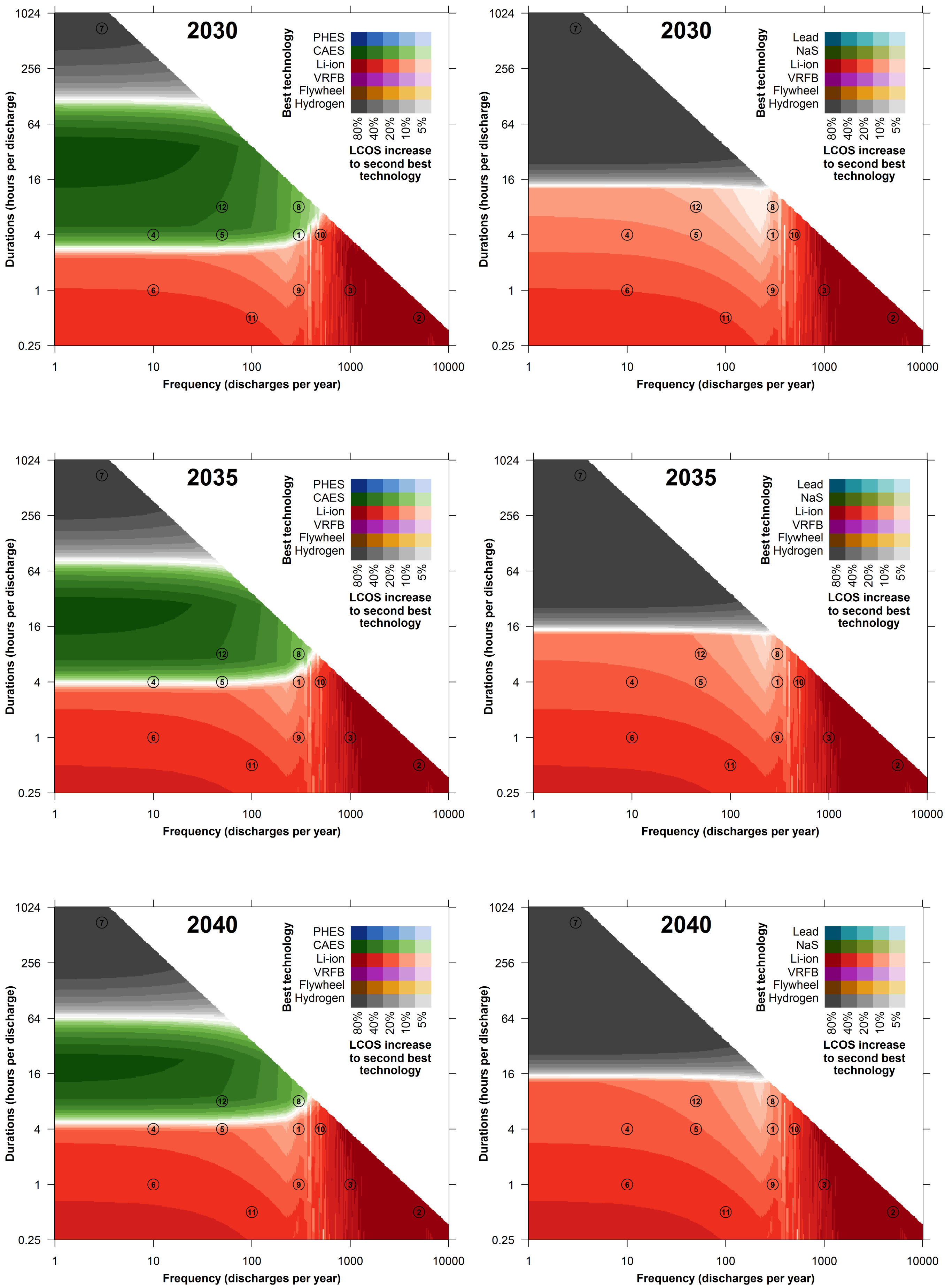

2030
Best technology
PHES
CAES
Li-ion
VRFB
Flywheel
Hydrogen
80%
40%
20%
10%
5%
LCOS increase to second best technology
Durations (hours per discharge)
1024
256
64
16
4
1
0.25
Frequency (discharges per year)
1
10
100
1000
10000
2030
Best technology
Lead
NaS
Li-ion
VRFB
Flywheel
Hydrogen
80%
40%
20%
10%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

**Figure S6.** Annuitized capacity cost (US$/kW$_{year}$) – Most cost-efficient technology

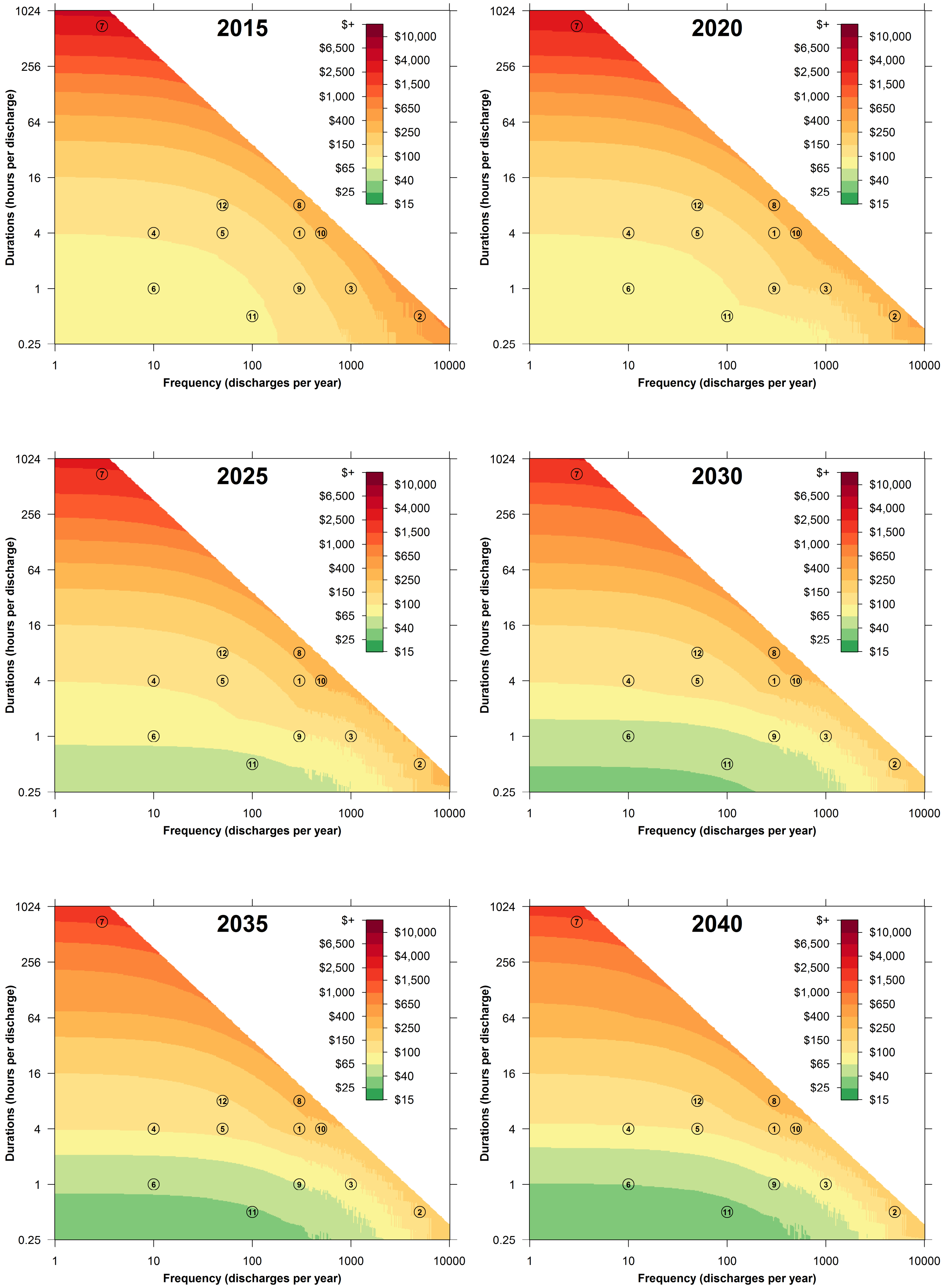


**Figure S7.** Sensitivity to power price

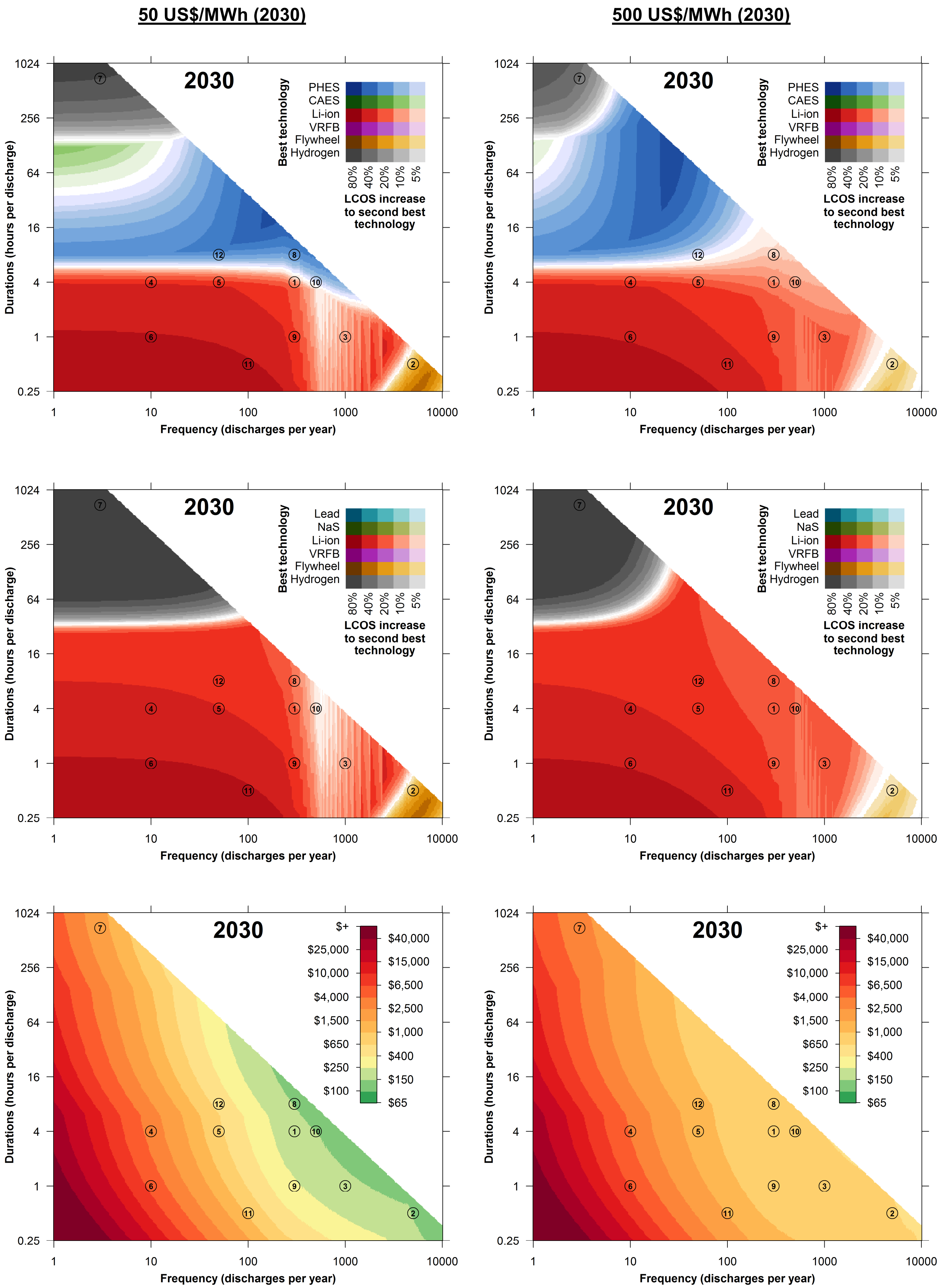


**Figure S8.** Sensitivity to discount rate

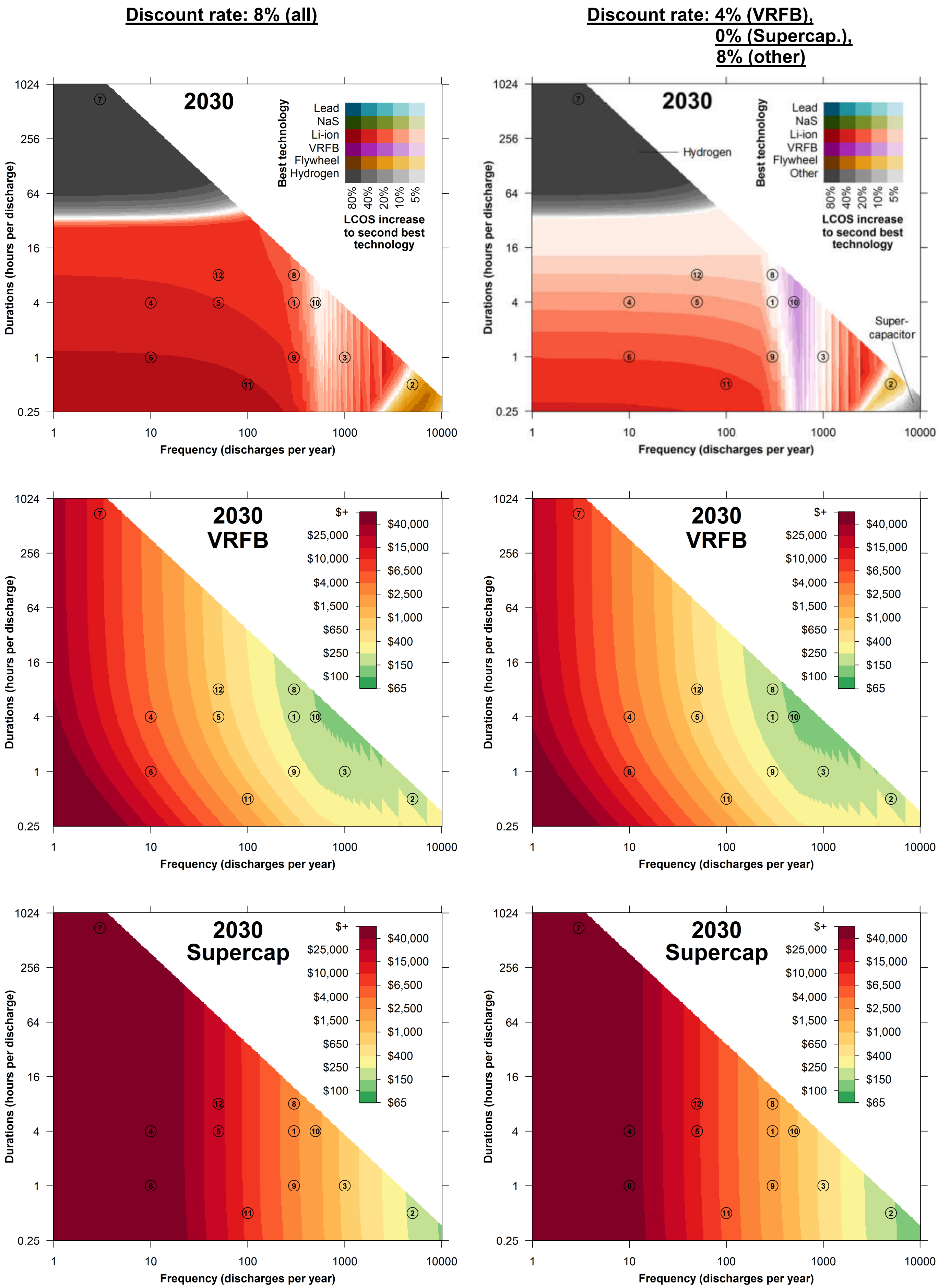


**Figure S9.** Sensitivity of vanadium redox-flow LCOS to efficiency improvement

**Vanadium redox-flow – Round-trip efficiency:** 73%        **Vanadium redox-flow – Round-trip efficiency:** 85%

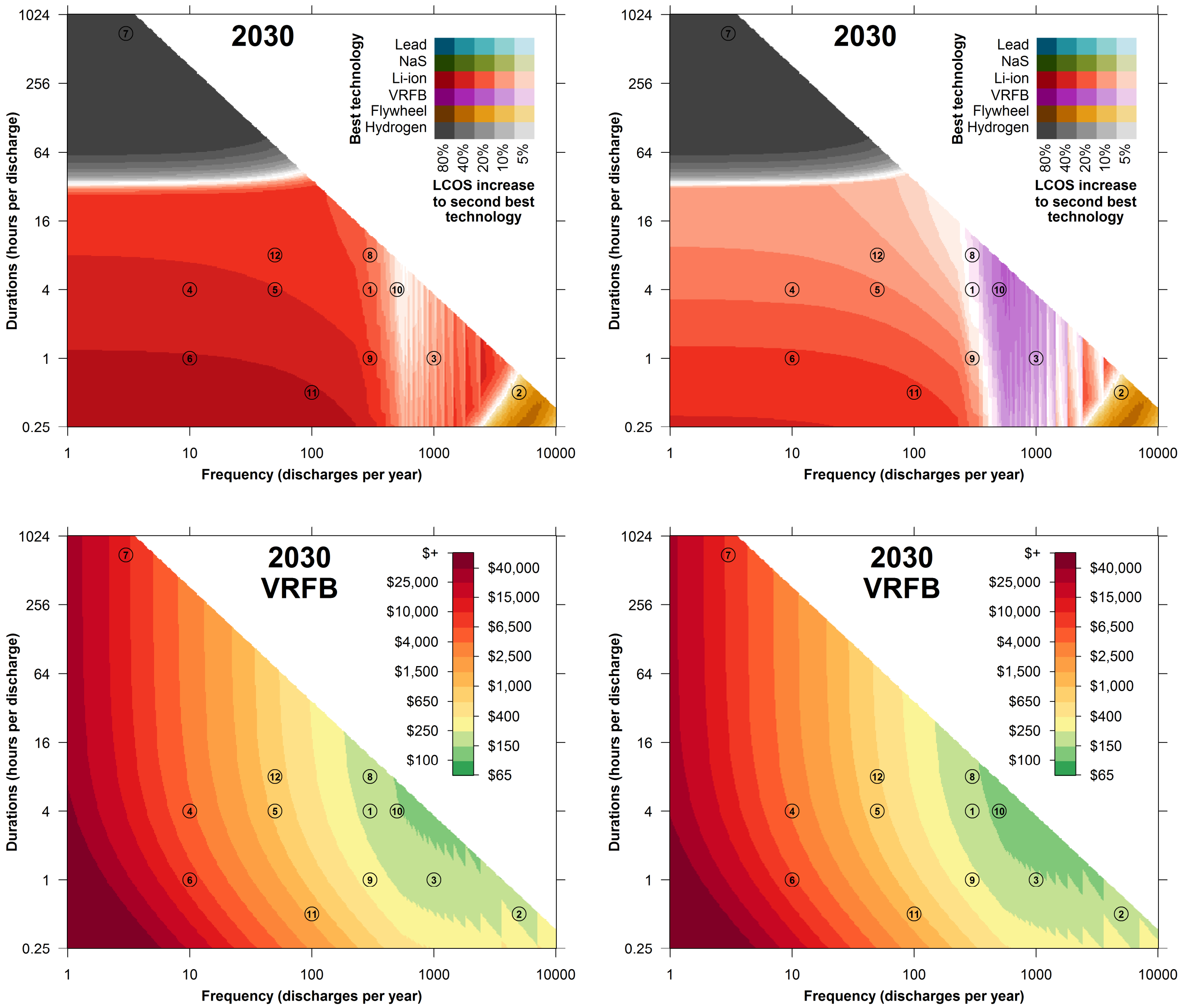


**Figure S10.** Sensitivity of vanadium redox-flow LCOS to lifetime improvement

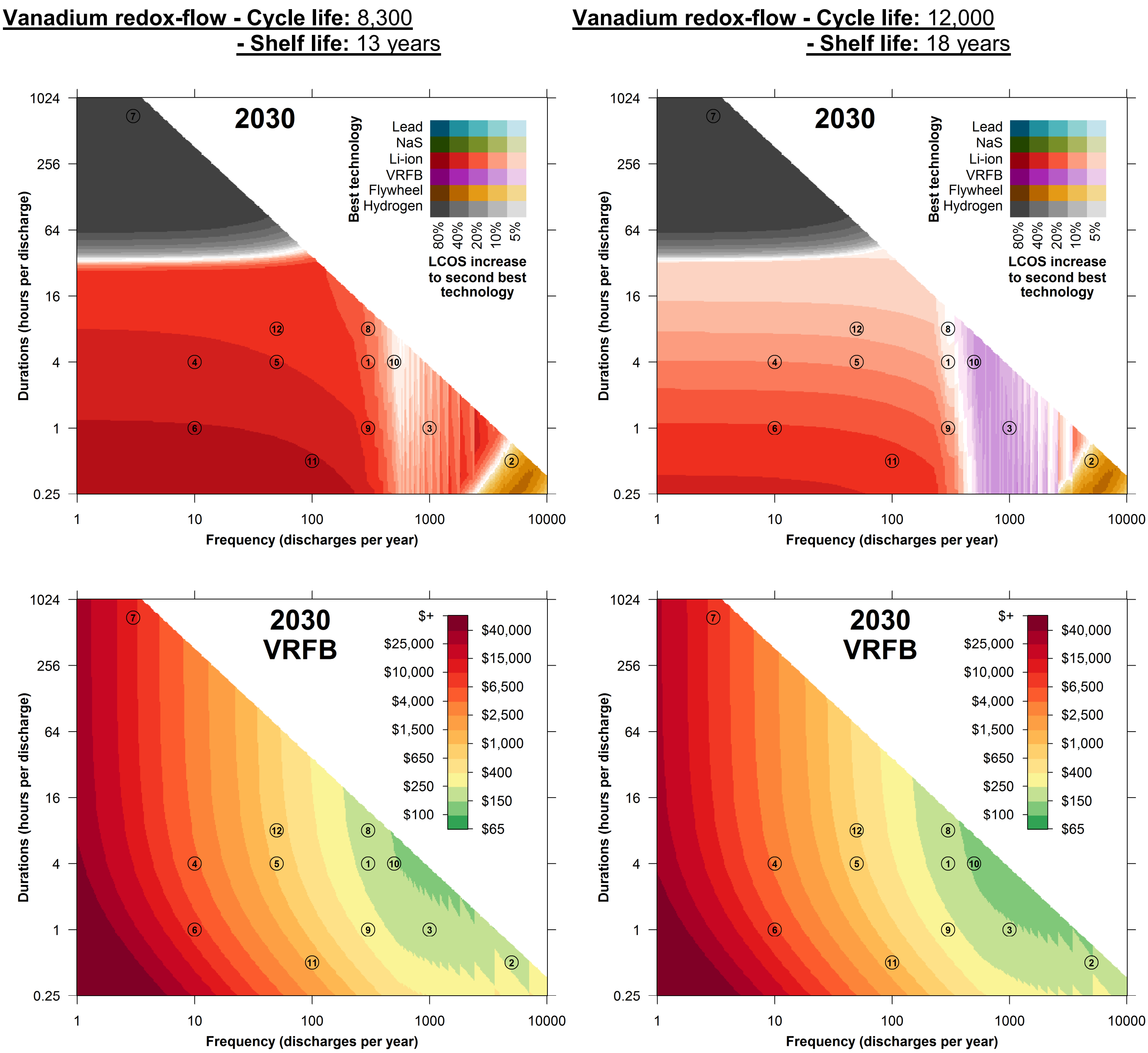


**Figure S11.** Sensitivity of lead-acid LCOS to efficiency and lifetime improvement

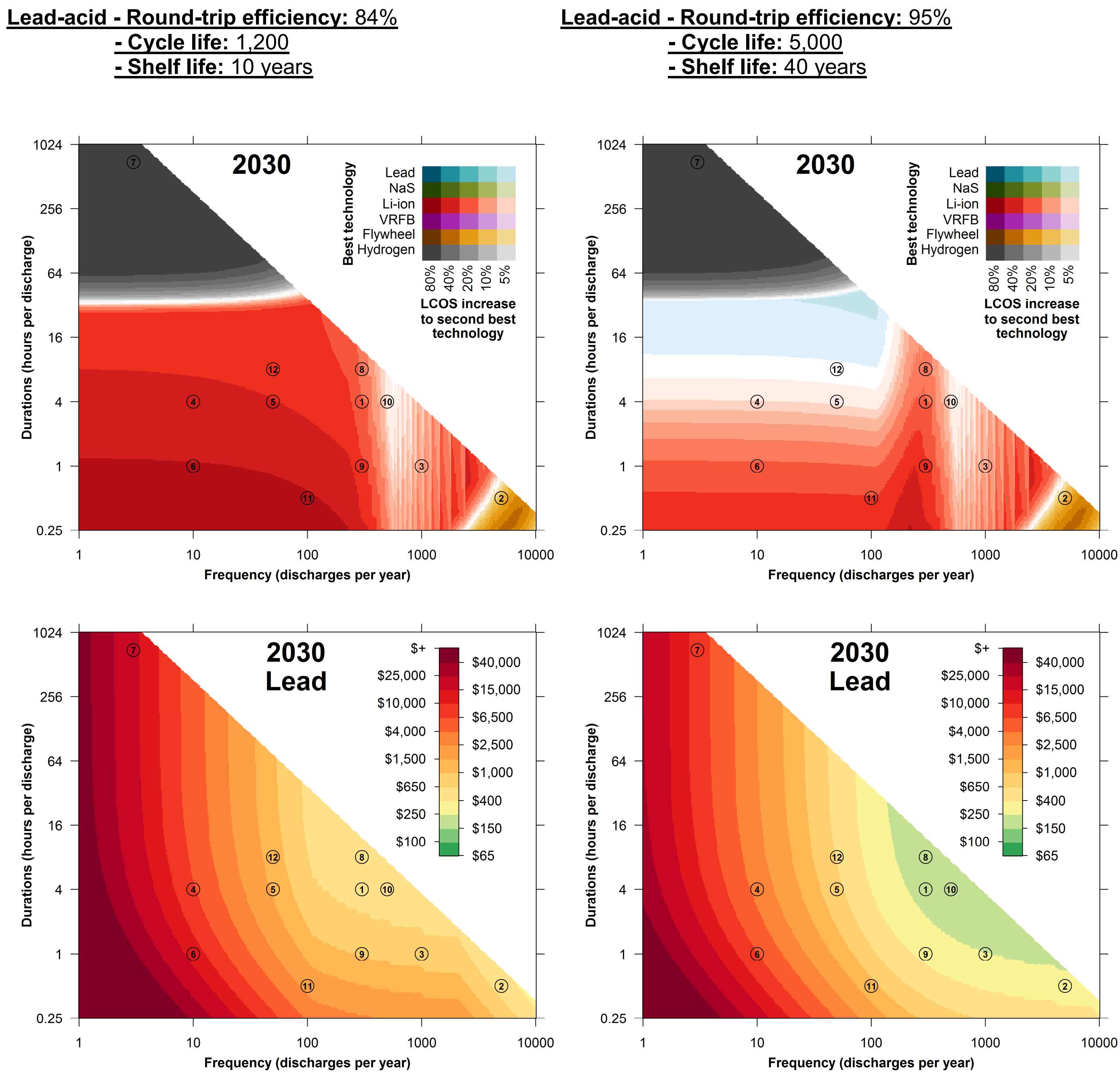


**Figure S12.** Sensitivity of sodium-sulphur LCOS to efficiency and lifetime improvement

**Sodium-sulphur - Round-trip efficiency:** 81%
**- Cycle life:** 4,000
**- Shelf life:** 14 years

**Sodium-sulphur - Round-trip efficiency:** 94%
**- Cycle life:** 17,000
**- Shelf life:** 20 years

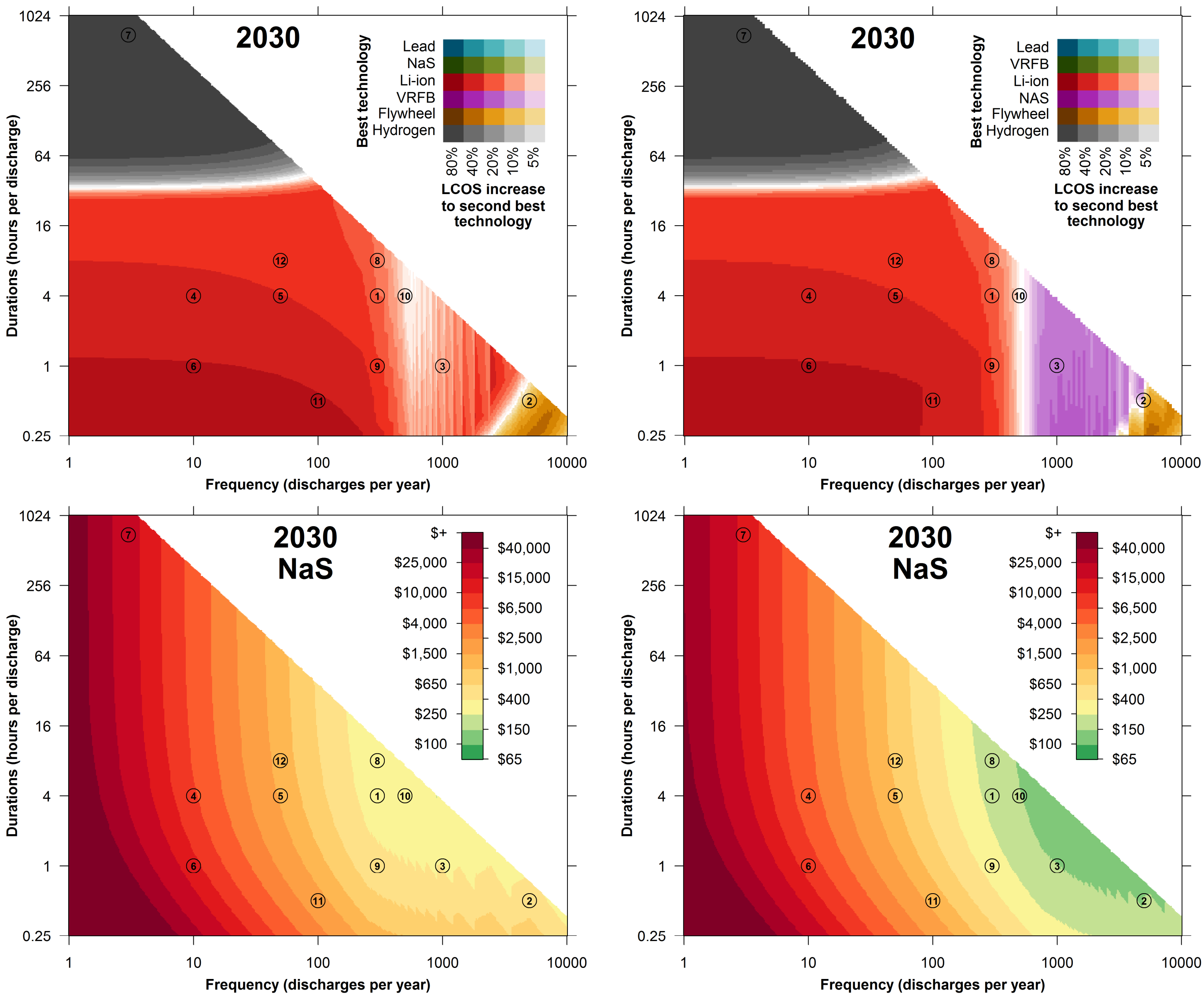


**Figure S13.** Sensitivity of supercapacitor LCOS to efficiency and lifetime improvement

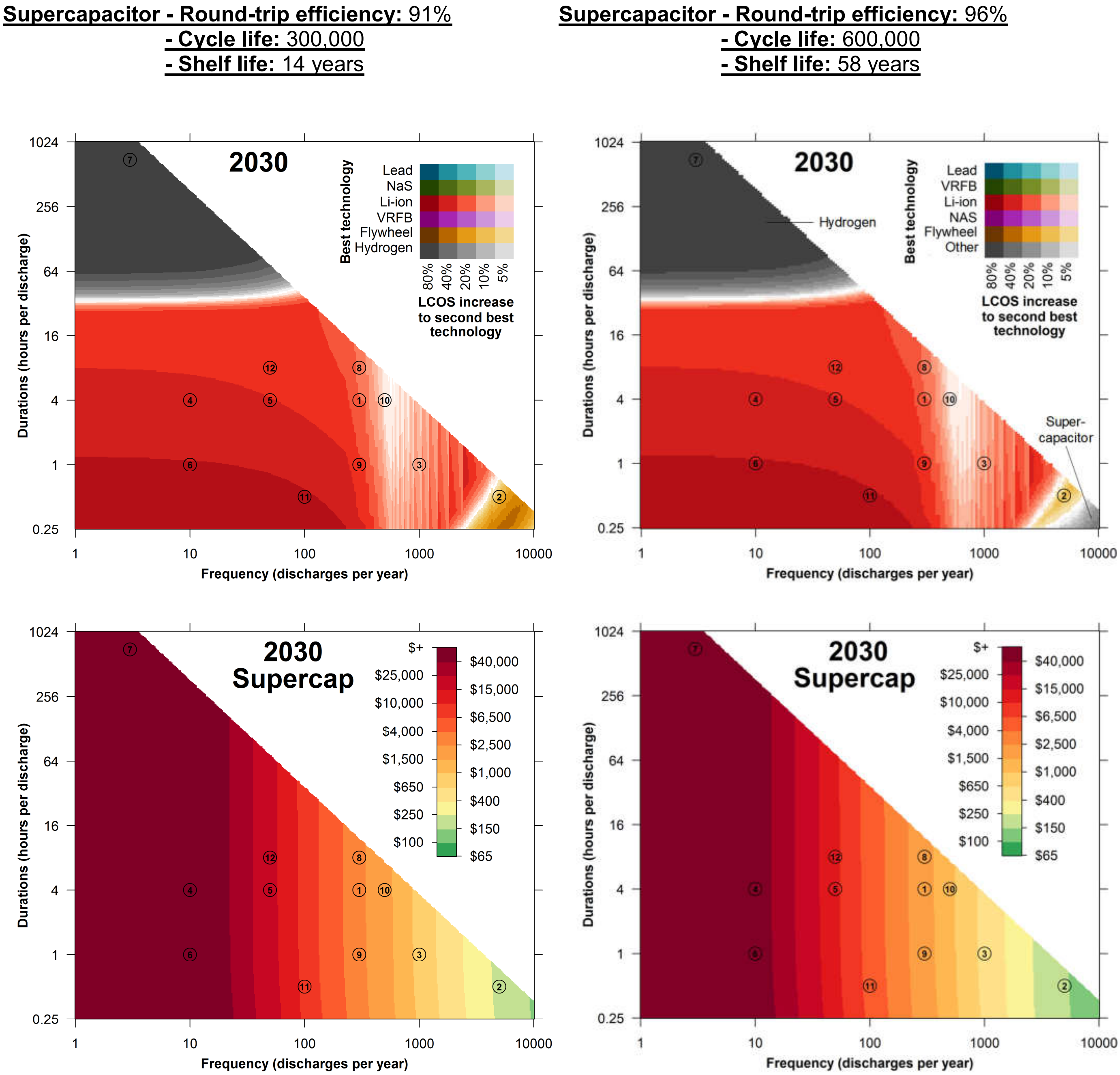


**Figure S14.** Result comparison to other LCOS studies for Energy Arbitrage

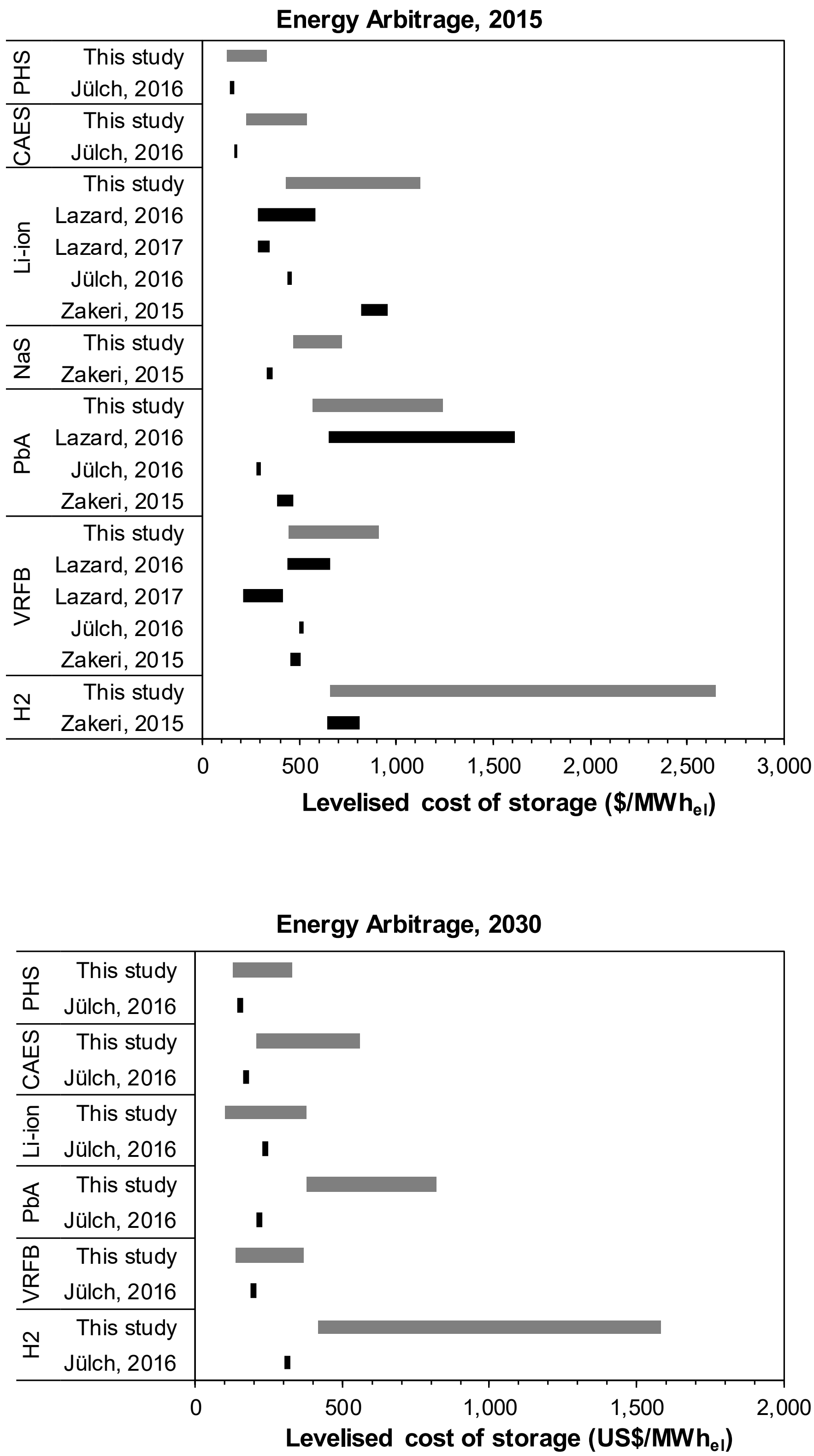


**Figure S15.** Result comparison to other LCOS studies for Primary Response

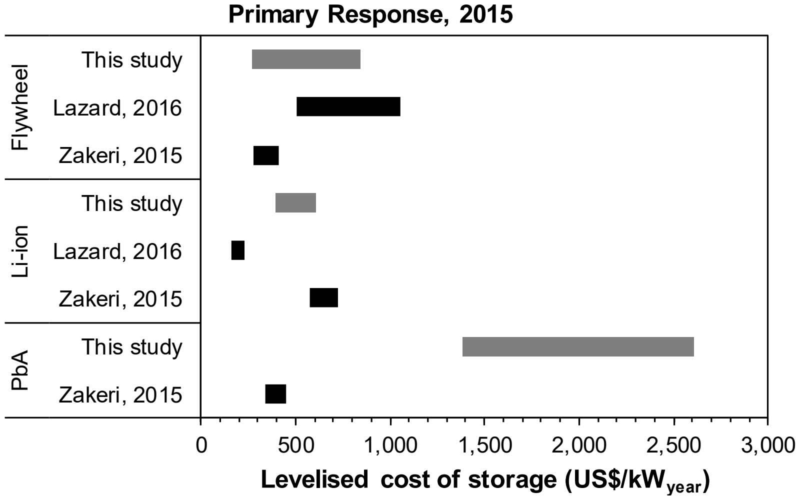
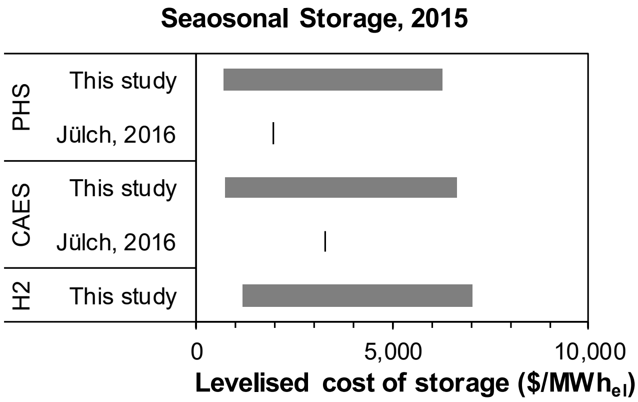


**Figure S16.** Result comparison to other LCOS studies for Seasonal Storage



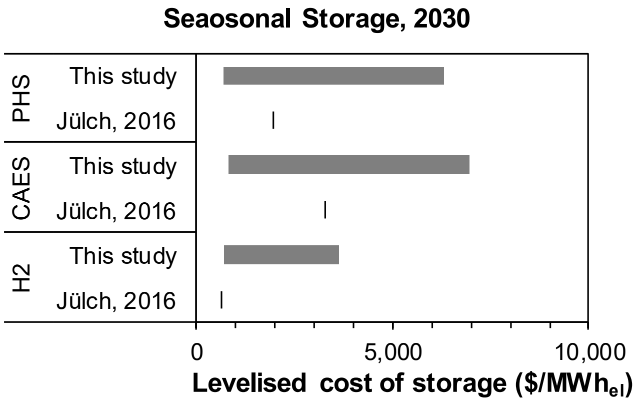
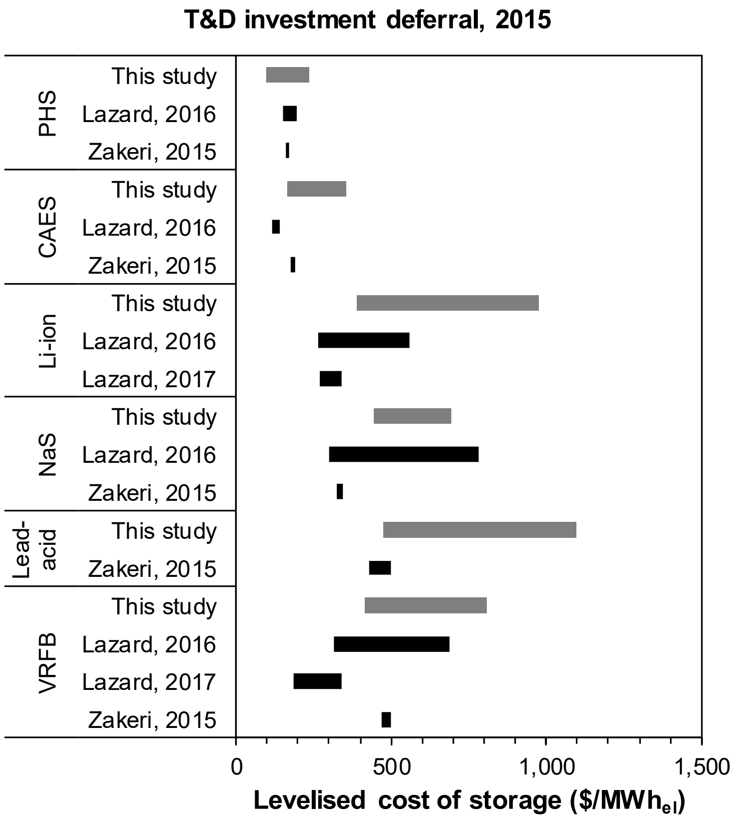



**Figure S17.** Result comparison to other LCOS studies for T&D investment deferral



## Supplemental Experimental Procedures

### **Procedure S1.** Methodological LCOS comparison to recent studies

Recent LCOS studies differ with respect to parameters included in the calculation and their methodological approach.

Investment costs should include overnight investment cost, construction time and replacement cost. While most studies consider overnight investment and replacement cost, they neglect the impact of construction time. In this study, the discounting impact of construction time is accounted for in investment cost, as well as operating and charging costs and electricity discharged. Also, most studies combine operating and replacement cost and thereby annualise replacement cost, which distorts the impact of discounting on this cost element. In this study, replacement costs are fully discounted to the end of each replacement period.

The end-of life cost or potential value of a storage technology at its end of life or end of investment period should also be accounted for, which is not the case for some studies.

Electricity discharged incorporates the technologies nominal charge capacity, depth-of-discharge, efficiency, annual cycles, self-discharge and time and cycle degradation. Some studies neglect the impact of varying depth-of-discharge and most studies neglect the impact of self-discharge and degradation.

Some studies do not explicitly consider the lifetime of the technology, but rather assume a fixed investment period. This approach is suitable for specific project proposals, but ill-suited to compare technologies based on their inherent cost and performance characteristics.

Considering the impact of taxes is important in a country-specific context, but not relevant for location-independent character of this study.

| | **LCOS components** | **Zakeri et al.**[7] | **Jülch et al.**[30] | **Lazard**[31,32] | **Lai et al.**[33] | **Pawel**[34] | **Battk et al.**[35] | **This study** |
|---|---|---|---|---|---|---|---|---|
| Economic | Investment cost | x | x | x | x | x | x | x |
| | Replacement cost | x | x | x | | | | x |
| | Operating cost | x | x | x | x | x | x | x |
| | Power cost | x | x | x | x | x | x | x |
| | End-of-life cost | x | x | | | x | | x |
| | Discount rate | x | x | x | x | x | x | x |
| | Taxes | | | x | | | | |
| | | | | | | | | |
| Technical | Nominal capacity | x | x | x | x | x | x | x |
| | Depth of discharge | x | x | x | | x | x | x |
| | Round-trip efficiency | x | x | x | x | x | x | x |
| | Cycle life | x | x | | | | x | x |
| | Shelf life | x | x | | x | x | x | x |
| | Construction time | | | | | | | x |
| | Degradation rate | | | | x | x | | x |
| | Self-discharge | | x | | | | | x |

In terms of methodological approach, Lai et al.[33] differentiate between the levelized cost of storage, excluding power price and round-trip efficiency, and levelized cost of delivery, including both. All other studies include power price and round-trip efficiency in their lifetime cost assessment of storage technologies, and three of them call this metric levelized cost of storage[30–32]. In this study *levelized cost of storage* is chosen as metric including power price and round-trip efficiency, because the nomenclature is meaningful and different to *levelized cost of electricity,* which is used for generation technologies, and a metric excluding technology round-trip efficiency is considered incomplete.

## **Procedure S2.** Comparison of LCOS studies

Multiple recent academic and industry studies perform LCOS analyses for different electricity storage technologies and applications[7,30–32]. Figures S8 to S11 compare the findings of these studies to the present analysis.

**Energy Arbitrage** (Discharge duration: 4 hours, Annual cycles: 300)

For energy arbitrage, the LCOS values identified by Jülch et al.[30] for "short-term storage" (4h discharge, 365 cycles) are within the ranges identified in this study, although often at the lower end, and for lead-acid batteries significantly below. These deviations have two main reasons. First, annual cycle assumptions differ (365 vs 300). This effect reduces LCOS by 8-15%. More significantly, distinct cycle life assumptions are higher and investment cost assumptions are lower than in the present study (lithium-ion: 7,000 vs 3,250 cycles, lead-acid: 2,700 vs 1,250 cycles; pumped hydro and compressed air: 50% lower investment cost). This also explains why Jülch et al.'s results for 2030 are at the lower end of the ranges identified in this study. Exceptions are lithium-ion and hydrogen storage. Despite the higher cycle life assumption (10,000 vs 3,250), respective LCOS are at the upper end of our range, because of Jülch et al.'s higher investment cost assumptions for 2030. For hydrogen, respective LCOS are below the range identified in this study due to lower investment cost and longer shelf life assumptions. The deviations in investment cost and lifetime assumptions used by Jülch et al. could not be verified in the academic and industry literature used for this study.

In the two LCOS studies produced by Lazard[31,32], the peaker replacement application features similar requirements that we model for energy arbitrage (4h, 365 cycles). The LCOS values are also at the lower end of the results in the present study (Lazard, 2016) or even lower (Lazard, 2017). Again, the slight difference in annual cycle requirement explains part of the deviation. Lower charging cost (30 US$/MWh vs 50 US$/MWh) also has an impact. However, the most significant deviations are found for lithium-ion and vanadium redox-flow due to the significantly lower investment cost assumptions. This can partly be explained with the temporal difference of the studies. Lazard's investment cost values are for 2016 or 2017 and assessed against the 2015 values of this study. Especially these two technologies have experienced significant cost reductions in recent years (Figure S2).

The LCOS values identified by Zakeri et al.[7], are well within the ranges of the present study, apart from sodium-sulphur and lead-acid batteries. For sodium-sulphur this is due to lower investment cost, and for lead-acid due to higher cycle life assumptions. Both could not be verified with recent industry reports. Zakeri et al.'s range identified for hydrogen storage is at the lower end of our range due to investment cost assumptions at the lower end compared to this study.

**Primary Response** (Discharge duration: 0.5 hours, Annual cycles: 5,000)

Lazard[31] and Zakeri et al.[7] also model LCOS for flywheels, lithium-ion and lead-acid batteries for a primary response application, albeit significantly different annual cycle requirements (500 vs 1,000 vs 5,000 cycles). LCOS in power terms or annuitized capacity costs value the provision of capacity instead of discharged electricity. As such, an increase in discharged electricity is not valued and many annual cycles only limit the technology's lifetime. As a result, LCOS are lowest for the study assuming fewest annual cycles (Lazard and Zakeri et al.). Deviations beyond this effect are the result of differing lifetime assumptions (lead-acid, Zakeri et al.; flywheels, Lazard).

**Seasonal storage** (Discharge duration: 700 hours, Annual cycles: 3)

LCOS for seasonal storage were also modelled by Jülch et al.[30]. For pumped hydro and compressed air, the results match with the ranges identified in this study. This is the result of two contrasting effects. Jülch et al. only assume 1 annual cycle, which would mean LCOS should be around 3 times higher than in this study. However, the 50% lower investment cost assumptions for pumped hydro and compressed air and longer lifetime assumptions mean that LCOS fall back into the range identified in this study. For hydrogen storage, the relevant energy-specific investment cost in Jülch et al. are 50 times lower, which explains their LCOS result below the range in this study.

**T&D investment deferral** (Discharge duration: 8 hours, Annual cycles: 300)

Despite slightly differing discharge duration and annual cycle requirements, the LCOS results of T&D investment deferral are compared to the LCOS results of Lazard 2016[31] (application: Transmission), Lazard 2017[32] (application: Distribution substation) and Zakeri et al.[7] (application: Bulk storage). For most technologies there is broad agreement in the LCOS identified in all studies.

An exception is compressed air due to the high efficiency assumption made by Lazard 2016. The low LCOS for lithium-ion and vanadium redox-flow by Lazard are again the result of significantly lower investment cost assumptions, which can be the result of the temporal difference of the studies, given recent cost reductions for both technologies (see above).

Zakeri et al.'s results are lower for lead-acid and sodium-sulphur, which is the result of lower investment cost assumptions. Again, these investment costs could not be verified in the academic and industry literature used for the present study.

In addition, the LCOS ranges identified in this study tend to be slightly higher than the results in the discussed studies due to the differences in LCOS modelling approach (Note S1). The neglection of construction time, capacity degradation and self-discharge artificially reduces LCOS in these studies. However, the effect is marginal compared to the impact of the described differences in investment cost and lifetime assumptions.

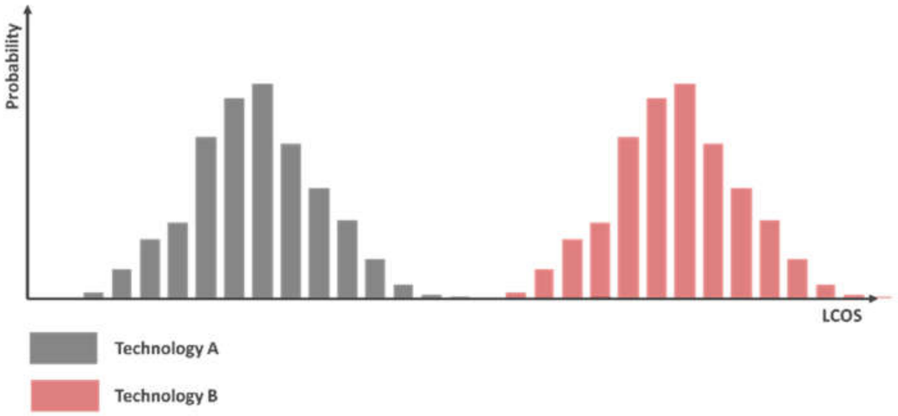
**Procedure S3.** Probability assessment

The Monte-Carlo simulation of the LCOS calculation gives 500 LCOS results for each modelled technology in a specific application. The LCOS results are normally distributed due to the normal distribution associated with the input parameters.

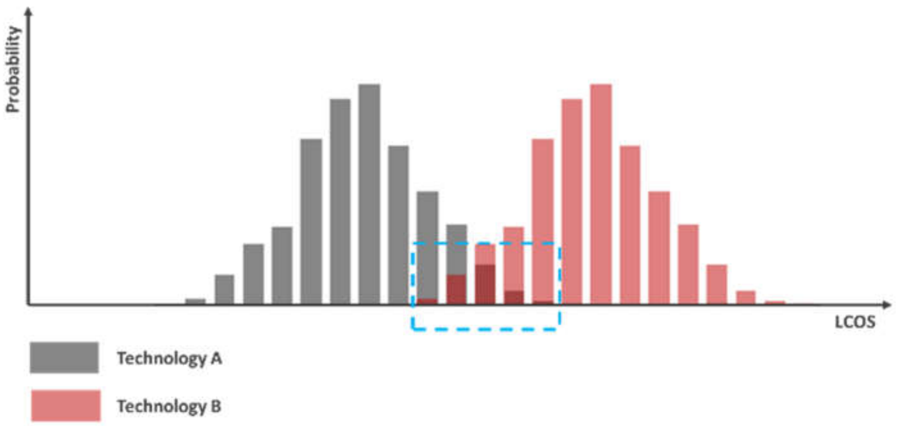
If the maximum of the LCOS distribution for a technology A is below the minimum of all the other technologies, the simulation sets the technology A as the cheapest option with 100% probability (Option 1).

However, if the intersection between the LCOS distributions is not an empty set, the probability is lower (Option 2). The approach then counts the occurrences when technology A exhibits lower LCOS than all other technologies and divides by all occurrences (500^#_technologies) to arrive at the probability for a technology to exhibit lowest LCOS.

**Option 1:** 100% probability




**Option 2:** <100% probability



## Supplemental References


1. Huff, G. *et al. DOE/EPRI 2013 electricity storage handbook in collaboration with NRECA*. *Sandia Report* (Sandia National Laboratories, 2013).
2. Ela, E., Milligan, M. & Kirby, B. *Operating Reserves and Variable Generation*. (2011).
3. Rastler, D. M. *Electric Energy Storage Technology Options: A White Paper Primer on Applications, Costs and Benefits*. (2010).
4. Everoze. Cracking the code: A Guide to Energy Revenue Streams and How to Derisk Them. *Everoze* **25,** 90 (2015).
5. IEA. *Technology Roadmap - Energy Storage*. (International Energy Agency, 2014).
6. Fitzgerald, G., Mandel, J., Morris, J. & Touati, H. *The Economics of Battery Energy Storage: how multi-use, customer-sited batteries deliver the most services and value to customers and the grid*. (2015).
7. Zakeri, B. & Syri, S. Electrical energy storage systems: A comparative life cycle cost analysis. *Renew. Sustain. Energy Rev.* **42,** 569–596 (2015).
8. Luo, X., Wang, J., Dooner, M. & Clarke, J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Appl. Energy* **137,** 511–536 (2015).
9. Kleinberg, M. *Battery Energy Storage Study for the 2017 IRP*. (Pacificorp, 2016).
10. NGK Insulators. NAS is being used throughout the Grid. (2017). Available at: https://www.ngk.co.jp/nas/why/. (Accessed: 29th October 2017)
11. Sandia National Laboratories. DOE Global Energy Storage Database 2017. (2017). Available at: http://www.energystorageexchange.org/. (Accessed: 29th October 2016)
12. Chen, H., Ngoc, T., Yang, W., Tan, C. & Li, Y. Progress in electrical energy storage system : A critical review. *Prog. Nat. Sci.* **19,** 291–312 (2009).
13. Black & Veach. *Cost Report: Cost and Performance for Power Generation Technologies*. (National Renewable Laboratories, 2012).
14. Beresford, J. & Zhu, O. Feasibility of Electricity Storage Technologies on the UK Grid. (2015).
15. Rehman, S., Al-Hadhrami, L. M. & Alam, M. M. Pumped hydro energy storage system: A technological review. *Renew. Sustain. Energy Rev.* **44,** 586–598 (2015).
16. Brix, W. & Elmegaard, B. Efficiency of Compressed Air Energy Storage. in *The 24th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems* (Technical University of Denmark, 2011).
17. International Renewable Energy Agency. *Technology Brief: Electricity Storage*. (2012).
18. Swierczynski, M., Stroe, D. I., Stan, A.-I., Teodorescu, R. & Sauer, D. U. Selection and Performance-Degradation Modeling of LiMO_2/Li_4Ti_5O_12 and LiFePO_4/C Battery Cells as Suitable Energy Storage Systems for Grid Integration With Wind Power Plants: An Example for the Primary Frequency Regulation Service. *IEEE Trans. Sustain. Energy* **5,** 90–101 (2014).
19. Layadi, T. M., Champenois, G., Mostefai, M. & Abbes, D. Lifetime estimation tool of lead–acid batteries for hybrid power sources design. *Simul. Model. Pract. Theory* **54,** 36–48 (2015).
20. Aquino, T., Roling, M., Baker, C. & Rowland, L. *Battery Energy Storage Technology Assessment Platte River Power Authority*. (2017).
21. Schmidt, O., Hawkes, A., Gambhir, A. & Staffell, I. The future cost of electrical energy storage based on experience curves: dataset. *Figshare Digital Repository* (2017). Available at: http://dx.doi.org/10.6084/m9.figshare.5048062.
22. Kurtz, J., Saur, G. & Sprik, S. *Hydrogen Fuel Cell Performance as Telecommunications Backup Power in the United States*. (2015).
23. Kaldellis, J. K. & Zafirakis, D. Optimum energy storage techniques for the improvement of

renewable energy sources-based electricity generation economic efficiency. *Energy* **32,** 2295–2305 (2007).

24. Ramsden, T., Kroposki, B. & Levene, J. *Opportunities for Hydrogen-Based Energy Storage for Electric Utilities*. (National Renewable Energy Laboratory, 2008).

25. Karellas, S. & Tzouganatos, N. Comparison of the performance of compressed-air and hydrogen energy storage systems: Karpathos island case study. *Renew. Sustain. Energy Rev.* **29,** 865–882 (2014).

26. Xu, B., Oudalov, A., Ulbig, A., Andersson, G. & Kirschen, D. S. Modeling of Lithium-Ion Battery Degradation for Cell Life Assessment. *IEEE Trans. Smart Grid* **9,** 1131–1140 (2018).

27. Andriollo, M. *et al.* Energy intensive electrochemical storage in Italy: 34.8 MW sodium–sulphur secondary cells. *J. Energy Storage* **5,** 146–155 (2016).

28. Schmidt, O., Hawkes, A., Gambhir, A. & Staffell, I. The future cost of electrical energy storage based on experience curves. *Nat. Energy* **2,** 17110 (2017).

29. Schmidt, O., Melchior, S., Hawkes, A. & Staffell, I. Update 2018 - The future cost of electrical energy storage based on experience rates:dataset. *Fishare Digital Repository* (2018). Available at: https://dx.doi.org/10.6084/m9.figshare.7012202.

30. Jülch, V. Comparison of electricity storage options using levelized cost of storage (LCOS) method. *Appl. Energy* **183,** 1594–1606 (2016).

31. Lazard. Lazard's levelized cost of storage analysis - version 2.0. (2016). Available at: https://www.lazard.com/media/438042/lazard-levelized-cost-of-storage-v20.pdf. (Accessed: 26th January 2017)

32. Lazard. Lazard's Levelized Cost of Storage Analysis - Version 3.0. (2017). Available at: https://www.lazard.com/media/450338/lazard-levelized-cost-of-storage-version-30.pdf. (Accessed: 31st July 2018)

33. Lai, C. S. & McCulloch, M. D. Levelized cost of electricity for solar photovoltaic and electrical energy storage. *Appl. Energy* **190,** 191–203 (2017).

34. Pawel, I. The cost of storage - How to calculate the levelized cost of stored energy (LCOE) and applications to renewable energy generation. *Energy Procedia* **46,** 68–77 (2014).

35. Battke, B., Schmidt, T. S., Grosspietsch, D. & Hoffmann, V. H. A review and probabilistic model of lifecycle costs of stationary batteries in multiple applications. *Renew. Sustain. Energy Rev.* **25,** 240–250 (2013).