



Online-Appendix

„A Cost-Effective Future for Electricity Storage - An Examination of LCOS Studies on Stationary Applications“

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Appendix

Appendix A. Definition of Important Terms and Concepts

Term or Concept	Definition	Reference
Anode	Positive electrode	Hoff (2022, p. 143)
Balance of system (BOS)	All additional equipment needed to enable a stable operation of the generation/storage system that is not part of the primary generation/storage module	Clark (2023)
Calendrical/cycle life	Shelf life or number of complete cycles after which EES technology requires replacement	Ralon et al. (2017, p. 38)
Cathode	Negative electrode	Hoff (2022, p. 143)
Cryogenic	“[...] stored at very low temperatures [...]”	Unitet States Environmental Protection Agency (2019)
Depth of discharge (DoD)	Percentage of available capacity that is used	Ralon et al. (2017, p. 37)
Discharge duration	Period in which EES system can operate at full power capacity before stored energy is exhausted (energy capacity divided by power rating)	Bowen et al. (2019, p. 2)
Electrolyte	Liquid or solid medium facilitating the movement of ions between the electrodes while impeding the flow of electrons	Hoff (2022, p. 145)
Harmonics	Voltages or currents of higher than usual frequency that cause deviations from the regular waveform	BC Hydro (2023)
Inertia	Tendency of an object to retain its state and direction of movement	Cambridge University Press & Assessment (2023)
Notching	Periodic voltage disruption resulting from regular use of power electronics devices (specific example of harmonics)	El-Eissawi Fathi (2012, p. 11)
Over-/undervoltage	Voltage exceeds/falls below the limit a system was designed for	Maintech Engineering & Supplies Pte Ltd (2019)
Power/energy density	Rated power/energy per volumetric unit	Ralon et al. (2017, p. 37)
Redox reaction	Chemical reaction between reducing and oxidizing substances that respectively gain and lose electrons during this process	National Cancer Institute (2023)
Round-trip efficiency (RTE)	Percentage of charged energy that is subsequently retrievable from an EES technology	Bowen et al. (2019, p. 2)
Separator	Barrier between electrodes that is permeable for ions but not for electrons	Hoff (2022, p. 145)
Time/cycle degradation	Decreasing overall performance (e.g., capacity and power) of an EES technology with increasing calendrical/cycle age	Edge et al. (2021, pp. 8201–8202)
Voltage and current waveform	The pattern of the voltage or current across time (e.g., sinusoidal)	Humane Slaughter Association (2023)

Appendix B. Scopus Queries

Search Date	Scopus Query
4 May 2023	((TITLE-ABS-KEY (stationary AND application*)) OR (TITLE-ABS-KEY (stationary)) OR (TITLE-ABS-KEY ("behind-the-meter")) OR (TITLE-ABS-KEY ("system application*")) OR (TITLE-ABS-KEY ("use case*")) OR (TITLE-ABS-KEY ("grid service")) OR (TITLE-ABS-KEY ("utility-scale")) OR (TITLE-ABS-KEY (stationär*)) OR (TITLE-ABS-KEY (versorgungsunternehmen)) OR (TITLE-ABS-KEY (energievorsorger))) AND ((TITLE-ABS-KEY (energiespeicher*)) OR (TITLE-ABS-KEY ("chemische *speicher*")) OR (TITLE-ABS-KEY ("electrochemische *speicher*")) OR (TITLE-ABS-KEY ("mechanische *speicher*")) OR (TITLE-ABS-KEY (pumpspeicher*)) OR (TITLE-ABS-KEY (batteriespeicher*)) OR (TITLE-ABS-KEY (stromspeicher*)) OR (TITLE-ABS-KEY ("grid energy stor*")) OR (TITLE-ABS-KEY ("stationary energy stor*")) OR (TITLE-ABS-KEY ("electr* batter*")) OR (TITLE-ABS-KEY ("chemical energy stor*")) OR (TITLE-ABS-KEY ("mechanic* energy stor*")) OR (TITLE-ABS-KEY ("electro* energy stor*")) OR (TITLE-ABS-KEY ("stor* electricity")) OR (TITLE-ABS-KEY ("electric* storage")) OR (TITLE-ABS-KEY ("electric* energy stor*")) OR (TITLE-ABS-KEY ("stor* tech*")) OR (TITLE-ABS-KEY ("energy stor*"))) AND ((TITLE-ABS-KEY (lcos)) OR (TITLE-ABS-KEY ("leveli?ed cost* of stor*")) OR (TITLE-ABS-KEY ("leveli?ed cost* of electric* stor*")) OR (TITLE-ABS-KEY ("leveli?e* cost*")) OR (TITLE-ABS-KEY ("cost* of stor* electr*")) OR (TITLE-ABS-KEY (energiespeicher\$kosten))) AND PUBYEAR > 2018 AND PUBYEAR < 2024 AND (EXCLUDE (DOCTYPE , "re"))
5 May 2023	((TITLE-ABS-KEY ("energy stor*")) OR (TITLE-ABS-KEY ("storage tech*")) OR (TITLE-ABS-KEY ("electric* storage")) OR (TITLE-ABS-KEY ("storing electricity")) OR (TITLE-ABS-KEY (stromspeicher*)) OR (TITLE-ABS-KEY (energiespeicher*))) AND ((TITLE-ABS-KEY ("mechanic* energy stor*")) OR (TITLE-ABS-KEY (phs)) OR (TITLE-ABS-KEY (psh)) OR (TITLE-ABS-KEY ("pumped hydro*")) OR (TITLE-ABS-KEY ("pumped-storage")) OR (TITLE-ABS-KEY (caes)) OR (TITLE-ABS-KEY ("compressed air")) OR (TITLE-ABS-KEY (flywheel)) OR (TITLE-ABS-KEY ("electrochemical energy storage")) OR (TITLE-ABS-KEY ("lead-acid")) OR (TITLE-ABS-KEY ("lithium-ion")) OR (TITLE-ABS-KEY ("vanadium redox")) OR (TITLE-ABS-KEY (vrb)) OR (TITLE-ABS-KEY (rfb)) OR (TITLE-ABS-KEY ("sodium-sulfur")) OR (TITLE-ABS-KEY ("sodium-sulphur")) OR (TITLE-ABS-KEY (supercapacitor*)) OR (TITLE-ABS-KEY ("hydrogen storage")) OR (TITLE-ABS-KEY ("chemical energy stor*")) OR (TITLE-ABS-KEY (pumpspeicher*)) OR (TITLE-ABS-KEY ("mechanische* *speicher*")) OR (TITLE-ABS-KEY ("chemische* *speicher*"))) AND ((TITLE-ABS-KEY (lcos)) OR (TITLE-ABS-KEY ("leveli?ed cost* of stor*")) OR (TITLE-ABS-KEY ("leveli?ed cost* of electric* stor*")) OR (TITLE-ABS-KEY ("cost* of stor* electr*")) OR (TITLE-ABS-KEY (energiespeicher\$kosten))) AND PUBYEAR > 2018 AND PUBYEAR < 2024 AND (EXCLUDE (DOCTYPE , "re"))

Appendix C. Digital Appendix

The digital appendix can be found [here](#). Refer to sheet “Master Data” for the complete data extraction table and to “Results” for a detailed overview of the cheapest EES technologies for each study and application.

Appendix D. Overview of Included LCOS Studies

Appendix D.1. Studies With Specifically Defined Applications

Study ID	Author/s (Year)	Regional Focus (Region)	Relevant Considered Applications (Name Used in the Study)	Relevant Considered Technologies (Specific Sub-Type)
2	Battke et al. (2013)	No	Primary Response (Area and Frequency Regulation), Power Quality (Support of Voltage Regulation), Time Shifting (Utility Energy Time-Shift), T&D Investment Deferral	PbA, Li-ion, NaS, VRFB
3	Baumann et al. (2017)	No	Secondary Response (Primary Regulation), Time Shifting (Electric Time Shift (ETS))	PbA (VRLA), Li-ion (Lithium titanate (LTO)), Li-ion (Lithium iron phosphate (LFP)), Li-ion (Lithium manganese oxide (LMO)), Li-ion (Nickel cobalt manganese oxide (NCM)), Li-ion (Nickel cobalt aluminum oxide (NCA)), VRFB
10	Mugyema et al. (2023)	No	Primary Response	FES, PbA, Li-ion, VRFB
11	Nikolaidis et al. (2019)	No	Primary Response (Frequency Regulation), Secondary Response (Spinning Reserve), Tertiary Response (Non-Spinning Reserve), Power Quality (Voltage Regulation), Energy Arbitrage, Energy Shifting (Load Levelling), Peak Shaving, Black Start, UPS, Emergency Backup, Seasonal Storage	PHS, CAES, FES, PbA (VRLA), PbA (Advanced), Li-ion, NaS, VRFB, HES
12	Rahman et al. (2021)	Yes (Alberta, Canada)	Primary Response (Frequency Regulation), Power Quality (Support of Voltage Regulation), Time Shifting (Bulk Energy Storage), T&D Investment Deferral	PbA (VRLA), Li-ion, NaS, VRFB
14	Schmidt et al. (2019a)	No	Primary Response, Secondary Response, Tertiary Response, Power Quality, Energy Arbitrage, T&D Investment Deferral, Demand Charge Management (Bill Management), Black Start, Power Reliability, Seasonal Storage	PHS, CAES, FES, PbA, Li-ion, NaS, VRFB, HES
17	Xu et al. (2022)	Yes (China)	Peak Shaving, T&D Investment Deferral (T&D Application)	PbA (Lead-carbon), Li-ion (LFP), VRFB
18	Zakeri and Syri (2015)	No	Primary Response (Short Duration, Highly Frequent), Power Quality (Short Duration, Highly Frequent), Time Shifting (Long-Duration, Frequent), Secondary Response (Medium Duration, Fast Response), T&D Investment Deferral (Medium Duration, Fast Response)	CAES (Aboveground), CAES (Underground), FES, PbA, Li-ion, NaS, VRFB, HES (Fuel cell, aboveground), HES (Fuel cell, underground), HES (Gas turbine, aboveground), HES (Gas turbine, underground)

Appendix D.2. Studies Without Specifically Defined Applications

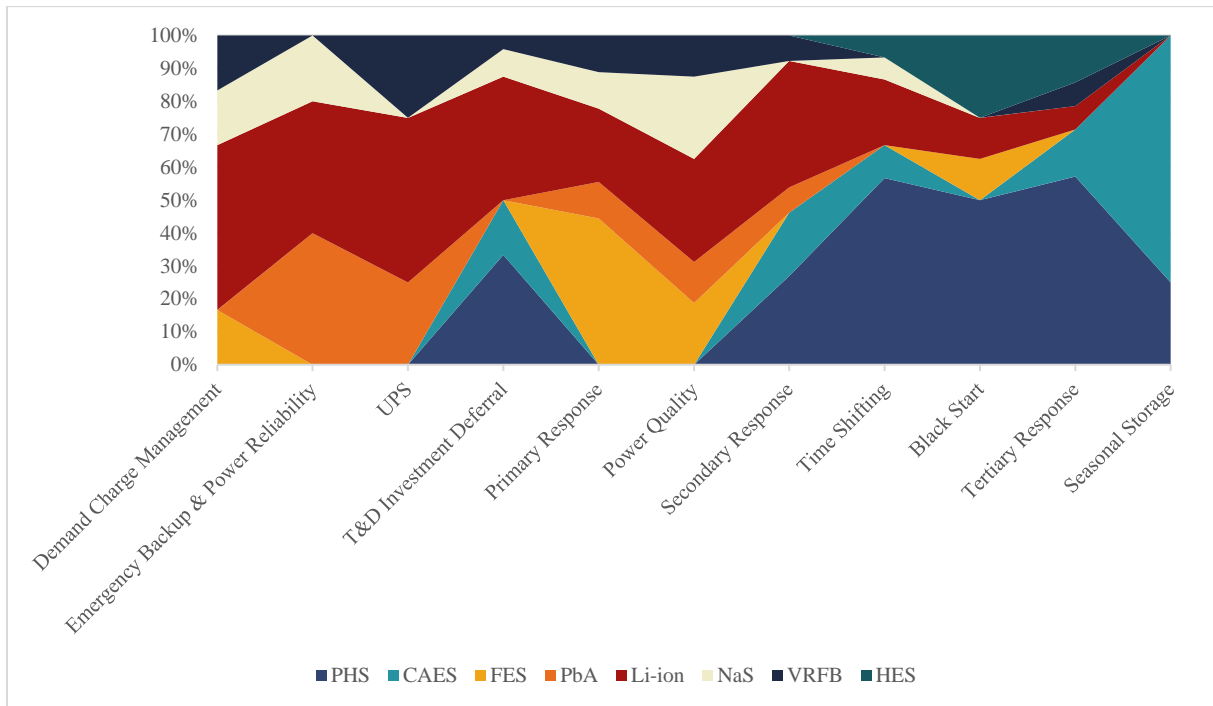
Study ID	Author(s) (Year)	Regional Focus (Region)	Derived Applications (Power, Discharge Duration, Annual Cycles)	Relevant Considered Technologies (Specific Sub-Type)
1	AER (2020)	Yes (Australia)	Secondary Response (100 MW, 4 h, 365), Tertiary Response (100 MW, 4 h, 255), Time Shifting (100 MW, 4 h, 365), T&D Investment Deferral (100 MW, 4 h, 270)	PHS, PbA, Li-ion, VRFB
4	Beuse et al. (2020a)	No	Primary response (N/A, 0.5 h, 1,000), Secondary Response (N/A, 1 h, 618), Tertiary Response (N/A, 3.5 h, 255), Power Quality (N/A, 0.5 h, 1,000), Time Shifting (N/A, 5.4 h 364), T&D Investment Deferral (N/A, 4.8 h, 274), Demand Charge Management (N/A, 4 h, 500), UPS (N/A, 0.5 h, 50), Emergency Backup/Power Reliability (N/A, 6 h, 50), Seasonal Storage (N/A, 39 8h, 4)	PHS, CAES, PbA, Li-ion, NaS, VRFB
5	Castro et al. (2022)	No	Primary response (1 MW, 0.3 h,3,374), Secondary Response (1 MW, 1 h, 618), Power Quality (1 MW, 0.3 h, 1,309), Demand Charge Management (1 MW, 4 h, 500), Black Start (1 MW, 2 h, 7), UPS (1 MW, 0.4 h, 50)	FES (Long-duration), FES (Short-duration), PbA, Li-ion, NaS
6	Cortez et al. (2021)	Yes (USA)	Secondary Response (1 MW, 4 h, 365), Demand Charge Management (1 MW, 4h, 365), Time Shifting (1 MW, 12 h, 365), T&D Investment Deferral (1 MW, 4 h, 365), Emergency Backup/Power Reliability (1 MW, 4 h, 365)	PbA, Li-ion, NaS, VRFB (Flow battery), HES (Underground)
7	Hunter et al. (2021)	Yes (Western USA)	Secondary Response (100 MW, 12 h, N/A), Time Shifting (100 MW, 12 h, N/A), Seasonal Storage (100 MW, 168 h, N/A)	PHS, CAES (D-CAES), CAES (A-CAES), Li-ion, VRFB, HES (Underground and combustion), HES (Underground and fuel cell)
8	Jülch (2016)	No	Secondary Response (100 MW, 4 h, 600), Tertiary Response (100 MW, 4h, 250), Time Shifting (100 MW, 4 h, 365), T&D Investment Deferral (100 MW, 4 h, 250), Seasonal Storage (100 MW, 700 h, 4)	PHS, CAES (D-CAES), CAES (A-CAES), PbA, Li-ion, VRFB
9	Moradi-Shahrbabak and Jadidoleslam (2023)	No	Primary response (Technology-specific, 0.3 h, N/A), Secondary Response (Technology-specific, 1 h, N/A), Tertiary Response (Technology-specific, 3.5 h, N/A), Power Quality (Technology-specific, 0.3 h, N/A), Time Shifting (Technology-specific, 5.5 h, N/A), Black Start (Technology-specific, 2 h, N/A), UPS (Technology-specific, 0.4 h, N/A)	PHS, CAES, PbA, Li-ion, NaS, VRFB, HES

Appendix D.2 (continued)

Study ID	Author/s (Year)	Regional Focus (Region)	Derived Applications (Power, Discharge Duration, Annual Cycles)	Relevant Considered Technologies (Specific Sub-Type)
13	Salvini and Giovannelli (2022)	No	Secondary Response (20 MW, 6 h, 365), Time Shifting (20MW, 6h, 365), T&D Investment Deferral (20 MW, 6 h, 365), Demand Charge Management (5 MW, 6 h, 365), Emergency Backup/Power Reliability (5 MW, 6 h, 365)	CAES (D-CAES), Li-ion, NaS
15	Topalović et al. (2022)	Yes (Western Balkans)	Time Shifting (N/A, 8 h, 364), T&D Investment Deferral (N/A, 8 h, 274)	PHS, PbA, Li-ion, NaS
16	Viswanathan et al. (2022)	Yes (USA)	Secondary Response (100 MW, 2 h, 456), Tertiary Response (100 MW, 4 h, 456), Time Shifting (100 MW, 6 h, 456), T&D Investment Deferral (10 MW, 4 h, 456), Demand Charge Management (1 MW, 4 h, 456)	PHS, CAES, PbA, Li-ion (LFP), Li-ion (NMC), VRFB, HES

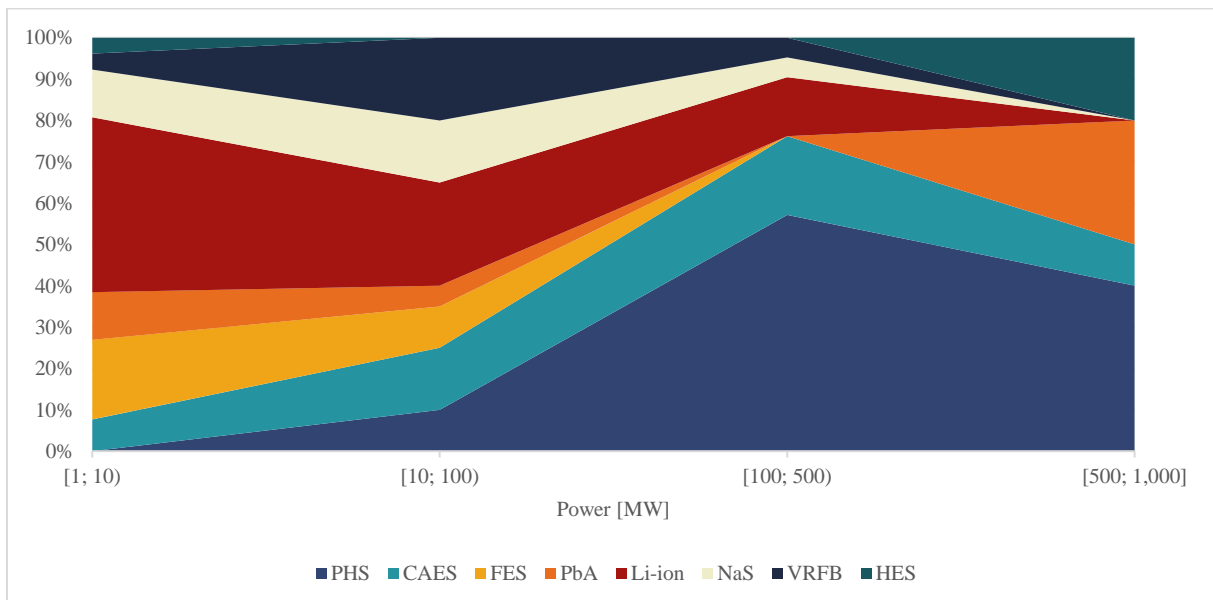
Appendix E. Results Sorted by Power Rating

Appendix E.1. Applications Sorted by Power Rating

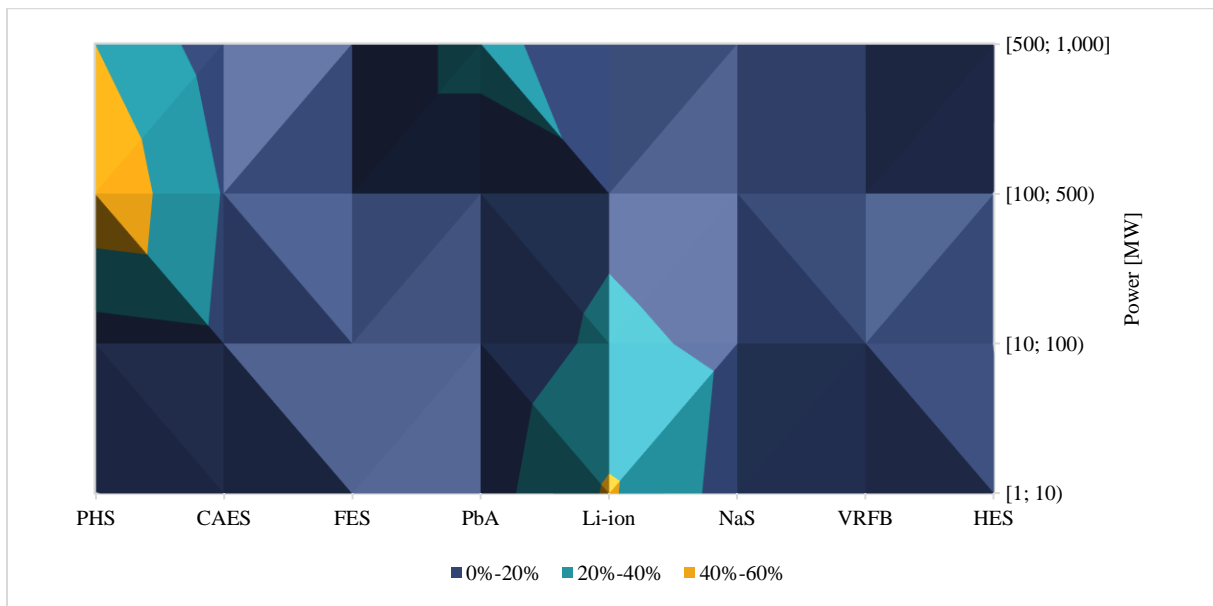


Note. Ascending order from left to right.

Appendix E.2. Shares of Results per Power Interval

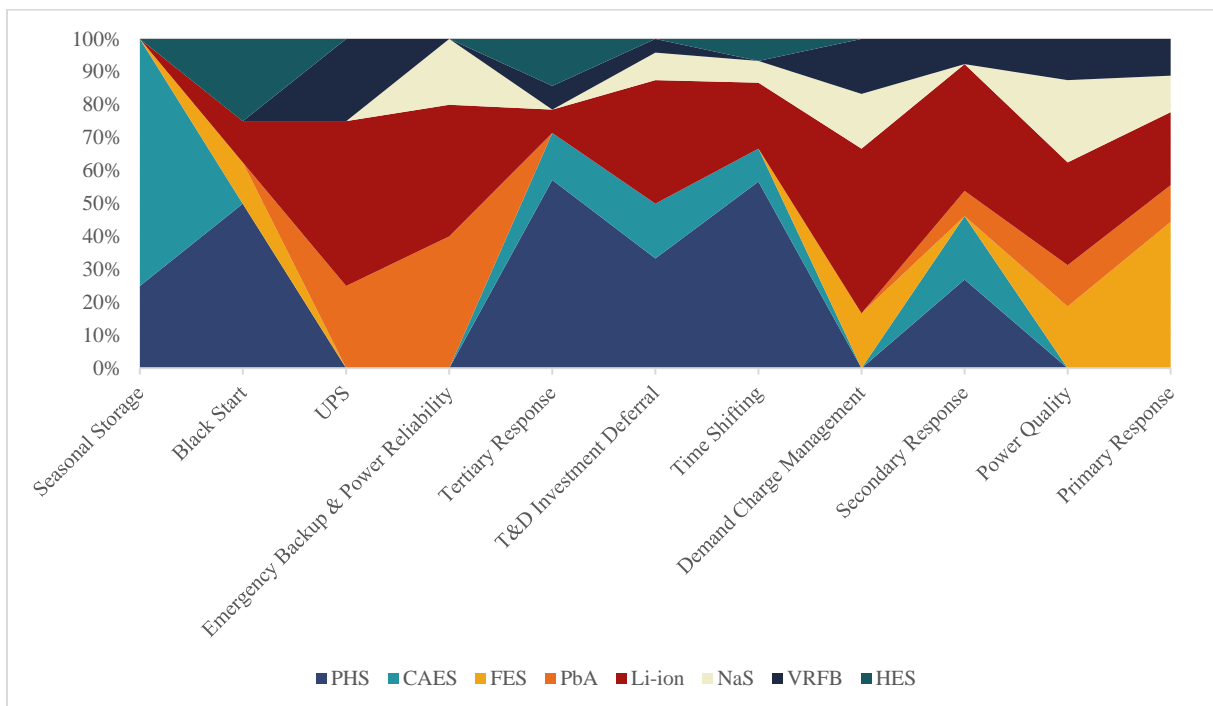


Appendix E.3. Contour Plot of Shares per Power Interval



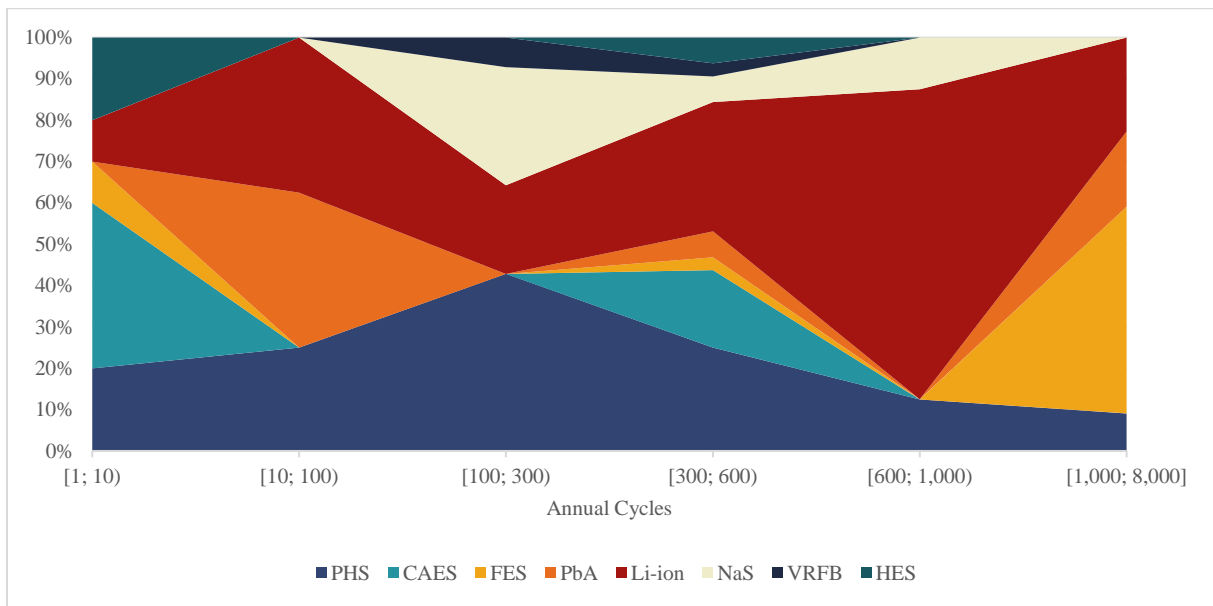
Appendix F. Results Sorted by Annual Cycles

Appendix F.1. Applications Sorted by Annual Cycles



Note. Ascending order from left to right.

Appendix F.2. Shares of Results per Cycle Interval



Appendix F.3. Contour Plot of Shares per Cycle Interval

