Imperial College London

Future levelised cost of storage in power system applications

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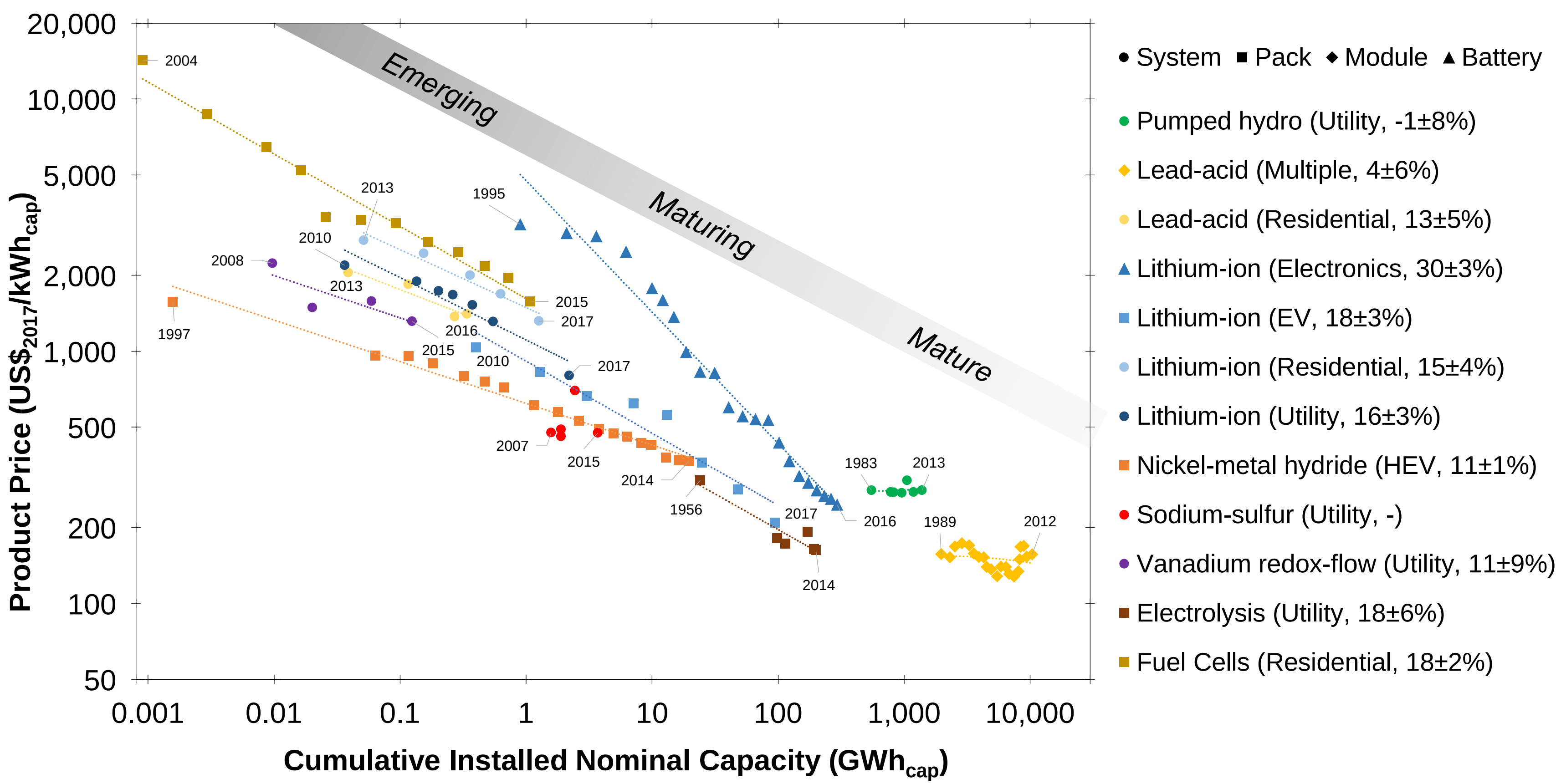
Grantham Institute

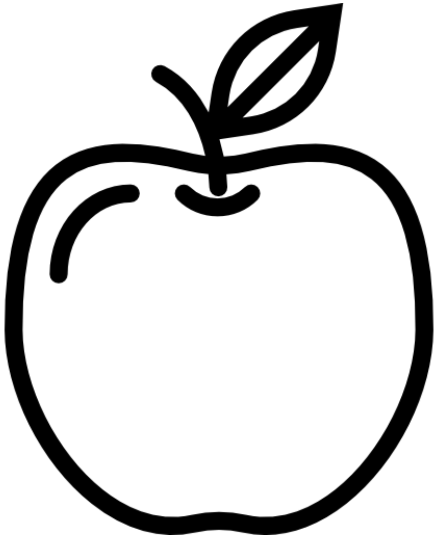
Experience curve dataset for storage technologies can predict investment cost

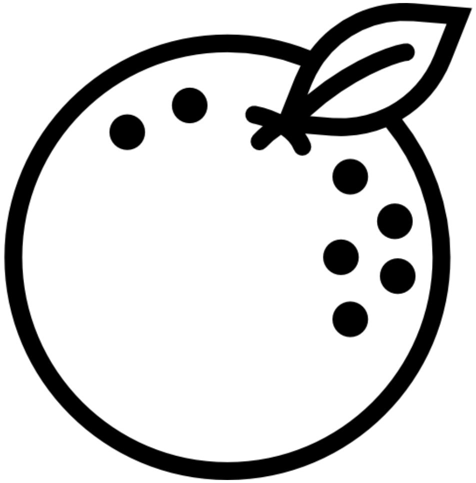
Experience Curve Dataset



Source: Updated from O. Schmidt, A. Hawkes, A. Gambhir & I. Staffell. The future cost of electrical energy storage based on experience rates. Nat. Energy 2, 17110 (2017)

But, Apple ≠ Orange





Levelised cost of storage (LCOS) enable comparison of storage technologies

LCOS Formula

- Investment cost
- Construction time
- Replacement cost / interval

- Charging cost
- O&M cost

$$LCOS\left[\frac{\$}{MWh}\right]=\frac{Investment\ cost\ +\ Operating\ cost\ +\ Disposal\ cost}{Electricity\ discharged}$$

- Round-trip efficiency
- Depth-of-discharge
- Annual cycles
- Cycle life
- Calendar life
- Degradation

- End-of-life cost or residual value

▶ The discounted cost of a “MWh” discharged from the storage device

We model LCOS of 9 storage technologies in 12 power system applications up to 2050

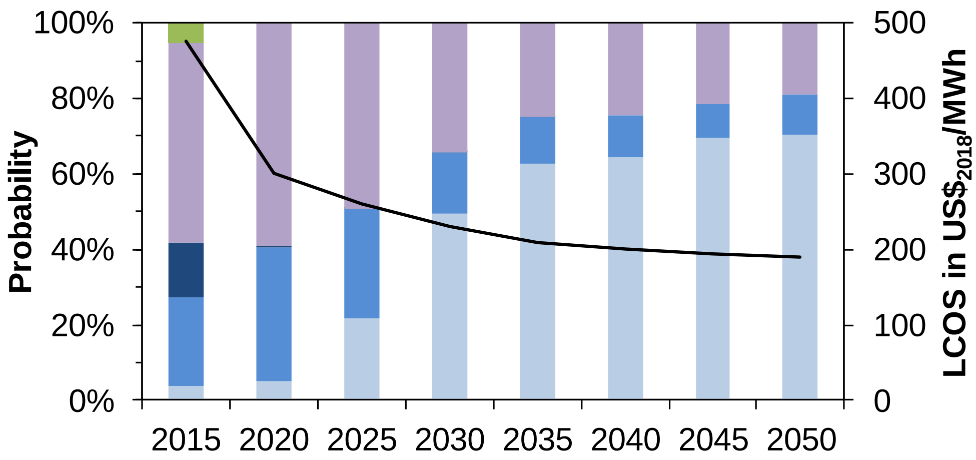
Applications vs Technologies

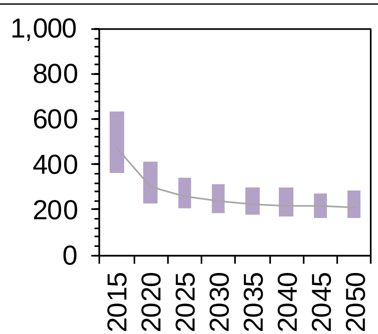
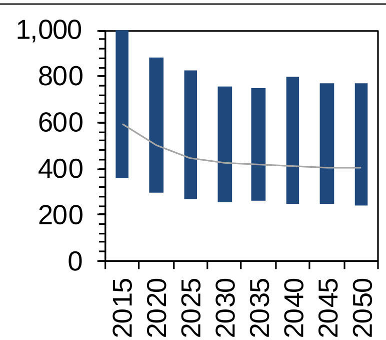
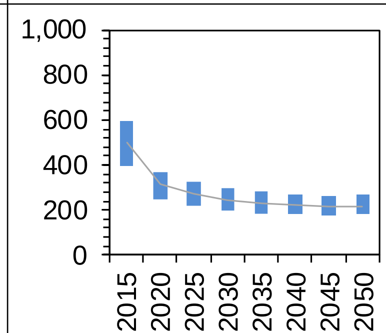
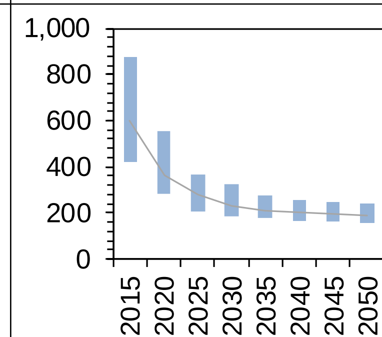
Role	Application	PHS	CAES	Fly-wheel	Lithium-ion	Sodium-sulf.	Lead-acid	VRFB	Hydro-gen	Super-cap.
	Energy arbitrage	✓	✓		✓	✓	✓	✓	✓	
System operation	Primary response			✓	✓	✓	✓	✓	✓	✓
	Secondary response	✓	✓	✓	✓	✓	✓	✓	✓	
	Tertiary response	✓	✓		✓	✓	✓	✓	✓	
	Peaker replacement	✓	✓		✓	✓	✓	✓	✓	
	Black start	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Seasonal storage	✓	✓					✓	✓	
Network operation	T&D upgrade deferral	✓	✓		✓	✓	✓	✓	✓	
	Congestion management	✓	✓		✓	✓	✓	✓	✓	
Consumption	Bill management		✓		✓	✓	✓	✓	✓	
	Power quality			✓	✓	✓	✓	✓	✓	✓
	Power reliability		✓		✓	✓	✓	✓	✓	

Lithium-ion to become more competitive than flow batteries for bill management

LCOS – Bill Management

Power Capacity	1 MW
Discharge duration	4 hours
Annual cycles	500
Charging cost	100 $/MWh

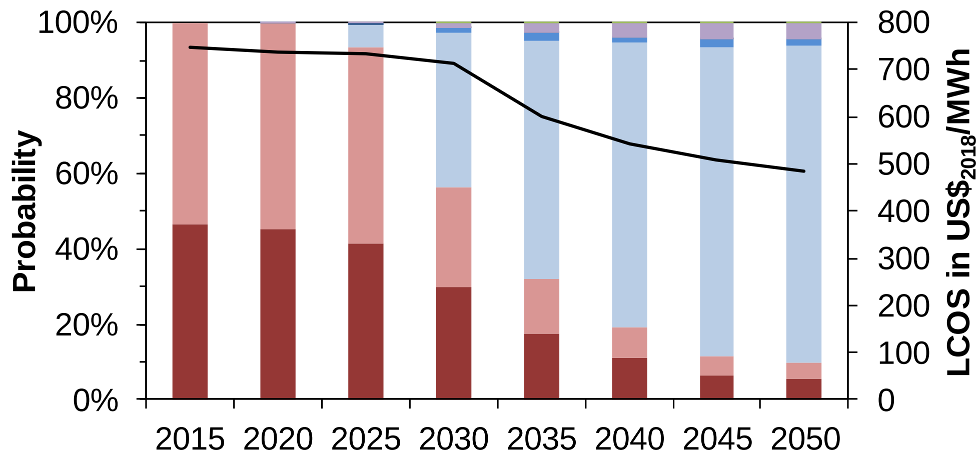


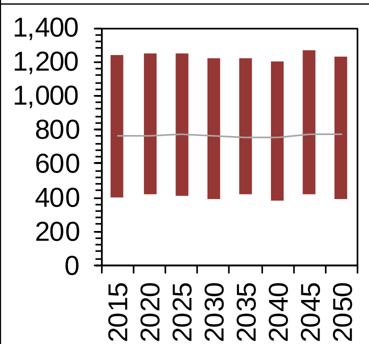
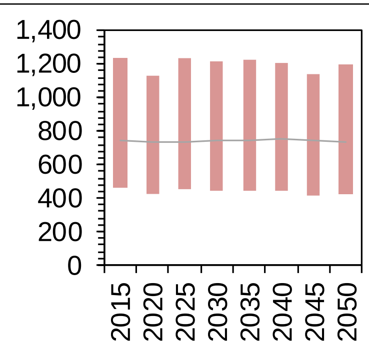
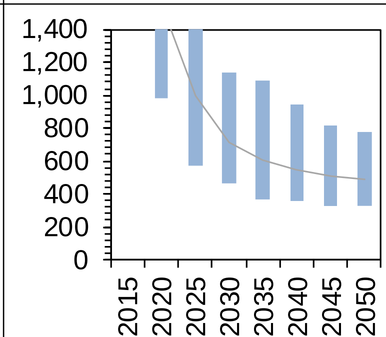
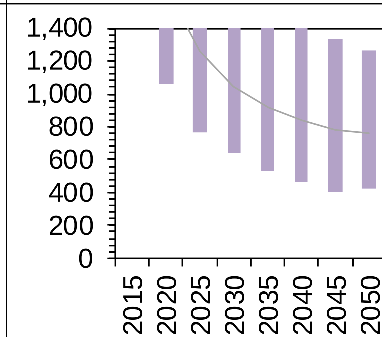
	Vanadium redox-flow	Lead-acid	Sodium-sulfur	Lithium-ion
LCOS in US$2018/MWh				

Lithium-ion to become more competitive than pumped hydro for peaker replacement

LCOS – Peaker Replacement

Power Capacity	100 MW
Discharge duration	4 hours
Annual cycles	50
Charging cost	50 $/MWh

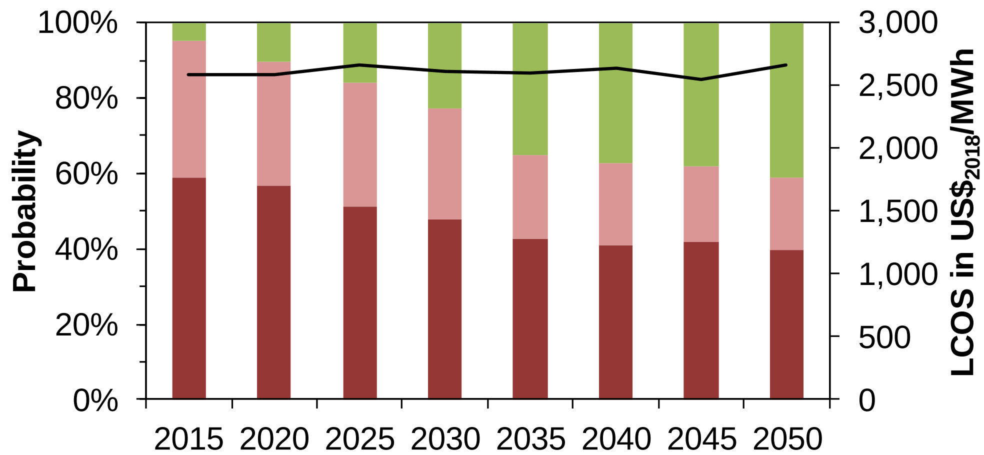


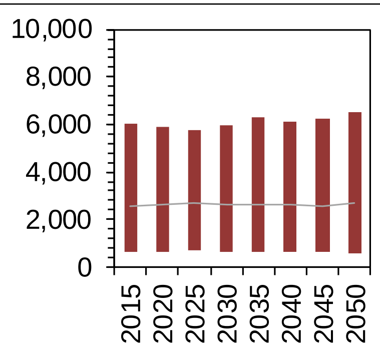
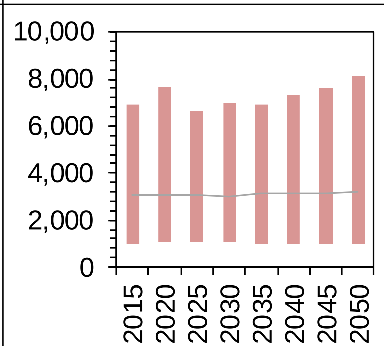
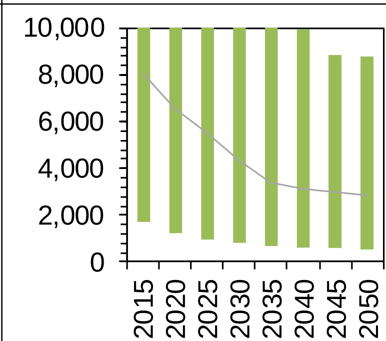
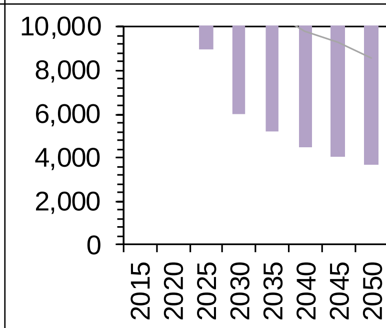
	Pumped hydro	Compressed air	Lithium-ion	Vanadium redox-flow
LCOS in US$$_{2018}$/MWh				

Pumped hydro, compressed air and hydrogen compete for seasonal storage

LCOS – Seasonal Storage

Power Capacity	1,000 MW
Discharge duration	700 hours
Annual cycles	3
Charging cost	50 $/MWh



	Pumped hydro	Compressed air	Hydrogen	Vanadium redox-flow
LCOS in $US\$_{2018}$/MWh				

Overall, increasing dominance of Lithium-ion for majority of applications by 2030

Summary

All technologies

2015

Discharge duration (hours)	1	10	50	100	500	1000	5000	10000
700.00	PHS	PHS						
8.00	CAES	CAES	PHS	PHS	PHS			
4.00	CAES	CAES	CAES	PHS	PHS	PHS		
2.00	CAES	CAES	CAES	CAES	PHS	PHS		
1.00	CAES	CAES	CAES	CAES	PHS	PHS		
0.50	CAES	CAES	CAES	CAES	CAES	PHS	PHS	
0.25	CAES	CAES	CAES	CAES	CAES	PHS	Flywheel	Flywheel

Cycles p.a.

2020

Discharge duration (hours)	1	10	50	100	500	1000	5000	10000
700.00	PHS	PHS						
8.00	CAES	CAES	PHS	PHS	PHS			
4.00	CAES	CAES	CAES	PHS	PHS	PHS		
2.00	CAES	CAES	CAES	CAES	PHS	PHS		
1.00	CAES	CAES	CAES	CAES	PHS	PHS		
0.50	NaS	NaS	NaS	NaS	VRFB	PHS	PHS	
0.25	NaS	NaS	NaS	NaS	NaS	NaS	Flywheel	Flywheel

Cycles p.a.

2030

Discharge duration (hours)	1	10	50	100	500	1000	5000	10000
700.00	PHS	PHS						
8.00	CAES	CAES	PHS	PHS	PHS			
4.00	Lithium	Lithium	Lithium	Lithium	PHS	PHS		
2.00	Lithium	Lithium	Lithium	Lithium	VRFB	PHS		
1.00	Lithium	Lithium	Lithium	Lithium	Lithium	VRFB		
0.50	Lithium	Lithium	Lithium	Lithium	Lithium	Lithium	Lithium	
0.25	Lithium	Lithium	Lithium	Lithium	Lithium	Lithium	Flywheel	Flywheel

Cycles p.a.

Excl. PHS & CAES

2015

Discharge duration (hours)	1	10	50	100	500	1000	5000	10000
700.00	H2	H2						
8.00	Lead	Lead	Lead	Lead	H2			
4.00	Lead	Lead	Lead	Lead	VRFB	VRFB		
2.00	Lead	Lead	Lead	Lead	VRFB	VRFB		
1.00	Lead	Lead	Lead	Lead	VRFB	VRFB		
0.50	Lead	NaS	NaS	NaS	NaS	VRFB	Flywheel	
0.25	NaS	NaS	NaS	NaS	NaS	NaS	Flywheel	Flywheel

Cycles p.a.

2020

Discharge duration (hours)	1	10	50	100	500	1000	5000	10000
700.00	H2	H2						
8.00	Lithium	Lithium	Lithium	Lithium	VRFB			
4.00	Lithium	Lithium	Lithium	Lithium	VRFB	VRFB		
2.00	NaS	NaS	NaS	NaS	VRFB	VRFB		
1.00	NaS	NaS	NaS	NaS	VRFB	VRFB		
0.50	NaS	NaS	NaS	NaS	VRFB	VRFB	Flywheel	
0.25	NaS	NaS	NaS	NaS	NaS	NaS	Flywheel	Flywheel

Cycles p.a.

2030

Discharge duration (hours)	1	10	50	100	500	1000	5000	10000
700.00	H2	H2						
8.00	Lithium	Lithium	Lithium	Lithium	VRFB			
4.00	Lithium	Lithium	Lithium	Lithium	VRFB	VRFB		
2.00	Lithium	Lithium	Lithium	Lithium	VRFB	VRFB		
1.00	Lithium	Lithium	Lithium	Lithium	Lithium	VRFB		
0.50	Lithium	Lithium	Lithium	Lithium	Lithium	Lithium	Lithium	
0.25	Lithium	Lithium	Lithium	Lithium	Lithium	Lithium	Flywheel	Flywheel

Cycles p.a.

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NERC SCIENCE OF THE ENVIRONMENT

Questions?

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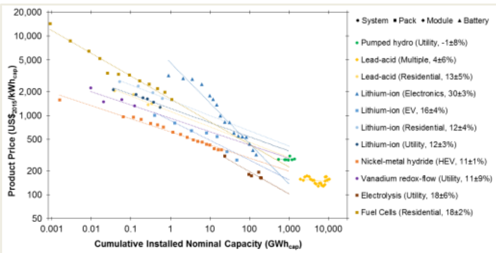
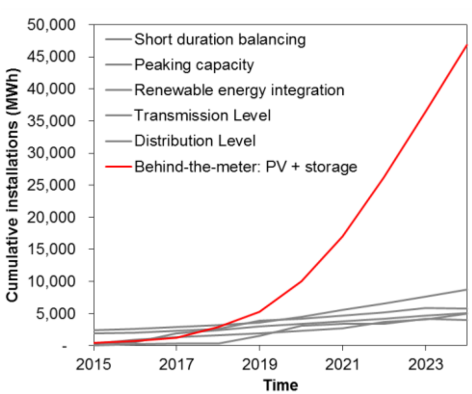
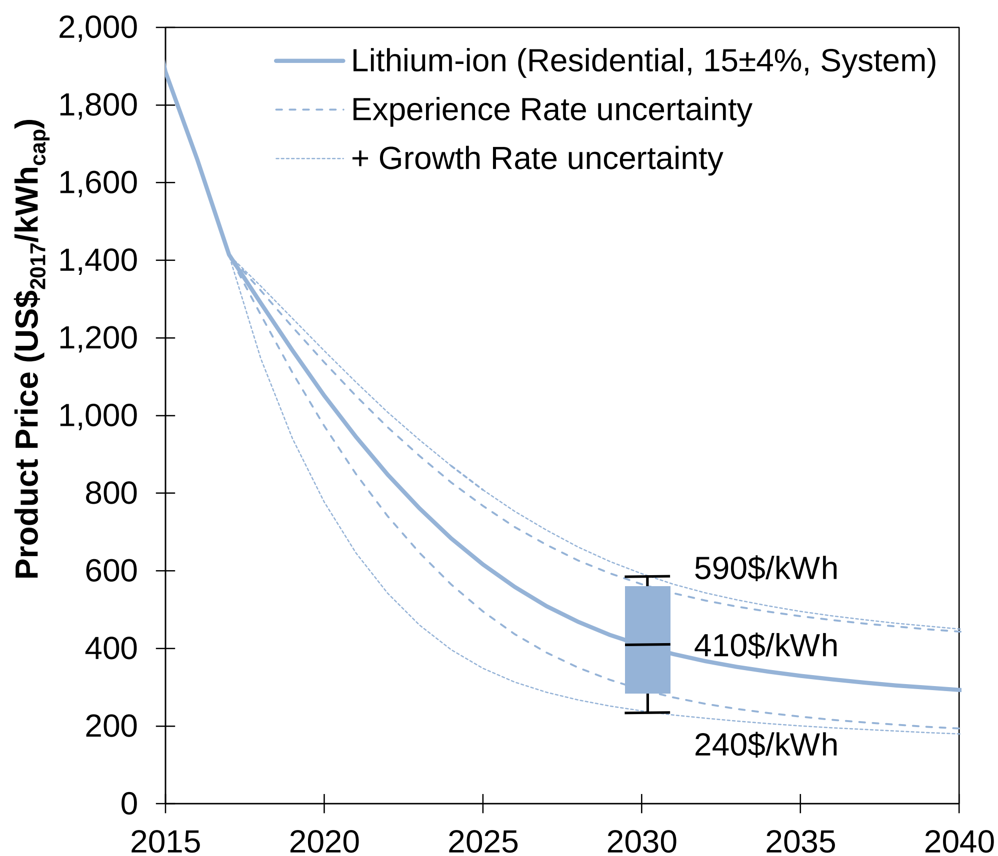
Experience curves combined with market forecasts enable future cost projection

Investment cost – Projection



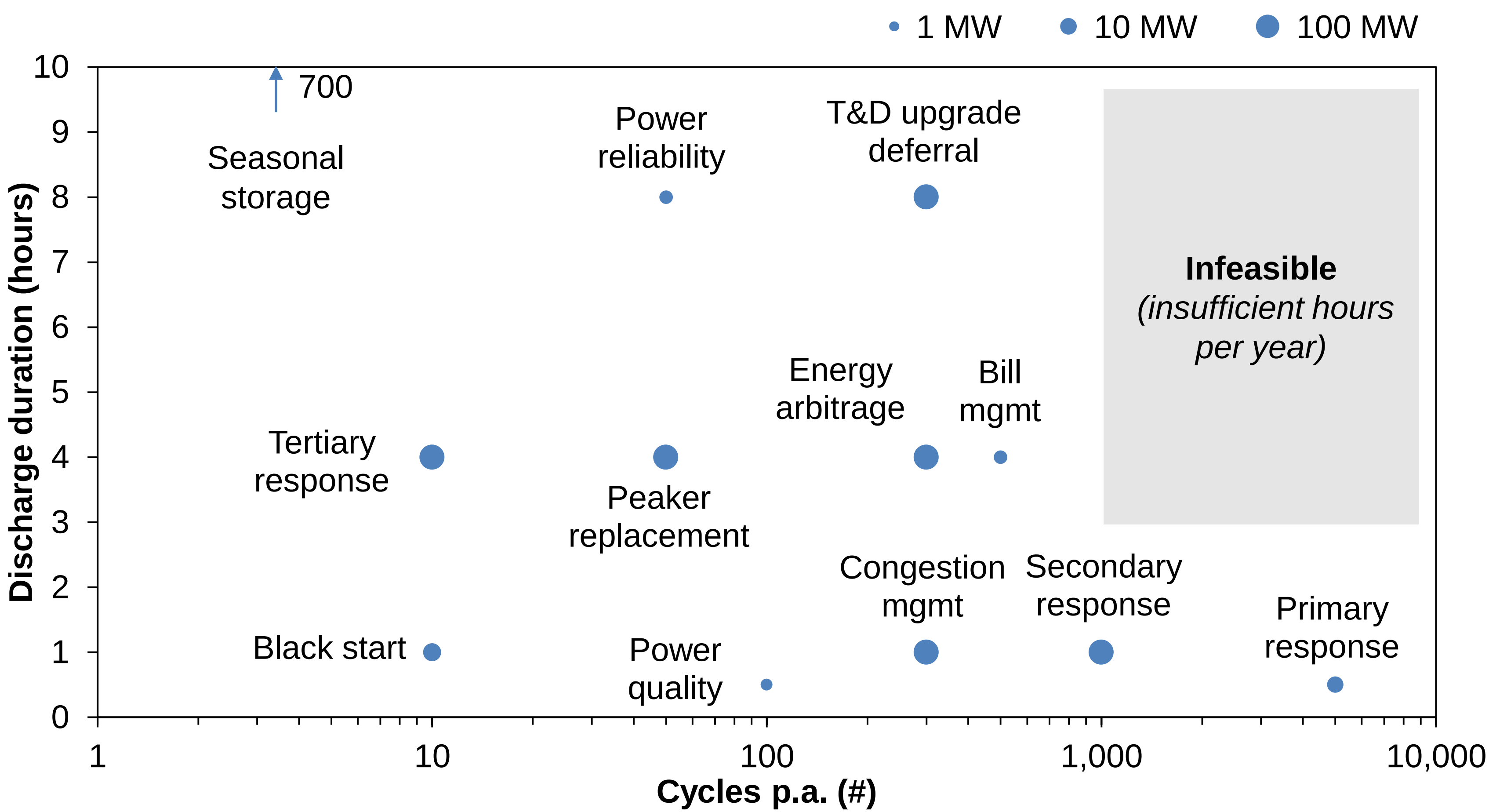




Source: O. Schmidt, A. Hawkes, A. Gambhir & I. Staffell. The future cost of electrical energy storage based on experience rates. Nat. Energy 2, 17110 (2017)

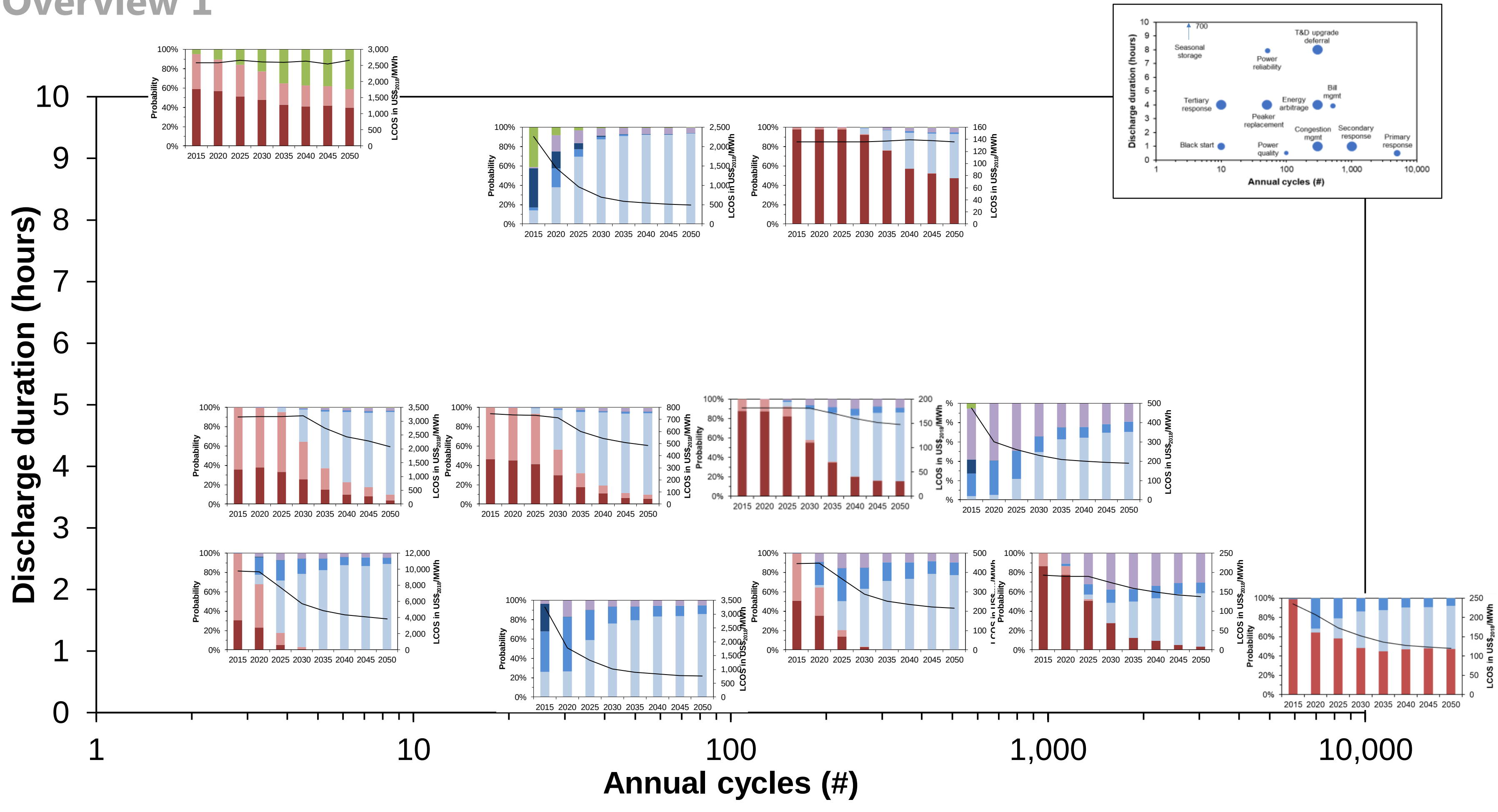
Modelled applications cover entire spectrum of performance requirements

Applications – Detail



LCOS and technology dominance in modelled electricity storage applications

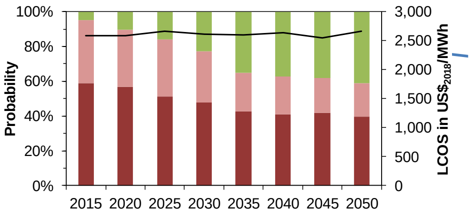
Overview 1



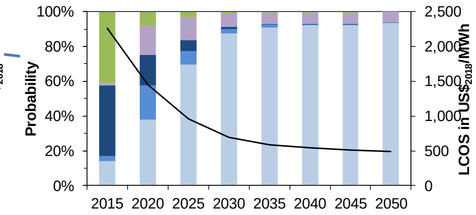
LCOS and technology dominance in modelled electricity storage applications

Overview 2

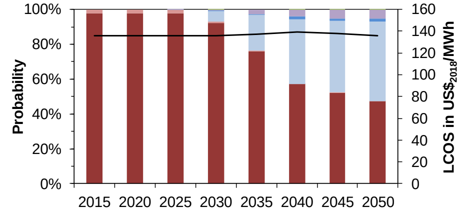
Seasonal storage



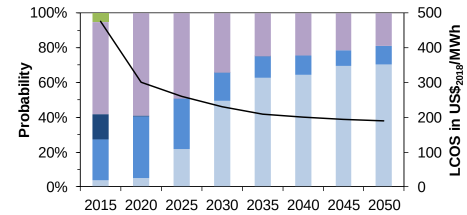
Power reliability



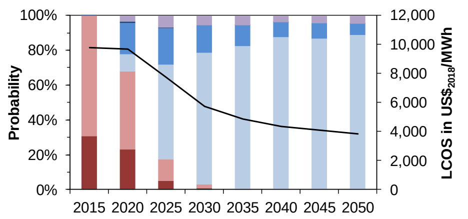
T&D deferral



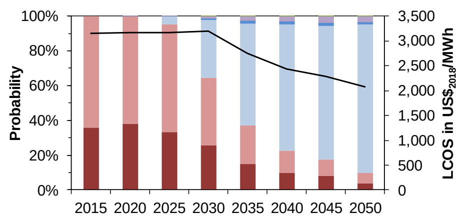
Bill management



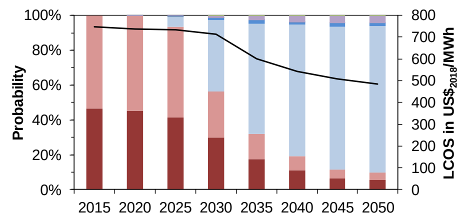
Black start



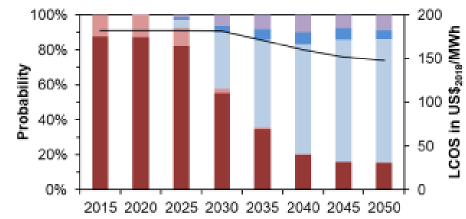
Tertiary response



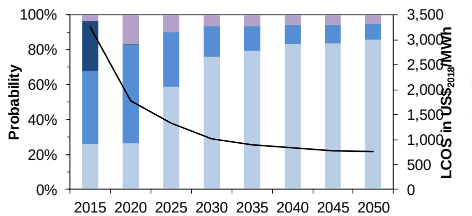
Peaker replacement



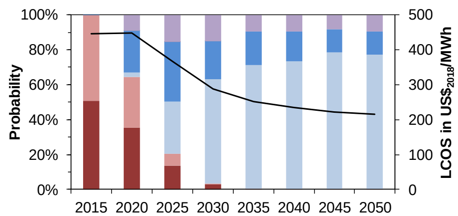
Energy arbitrage



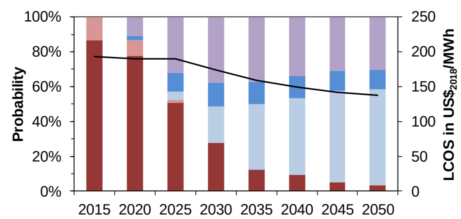
Power quality



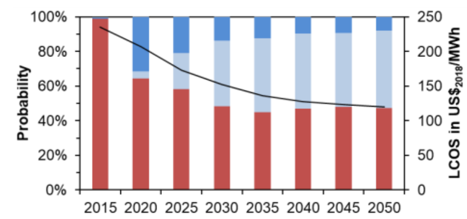
Congestion management



Secondary response



Primary response



Application-specific LCOS account for all relevant cost and performance parameters

Formula – Detail

$$LCOS\left[\frac{\$}{MWh}\right] =$$

$$\frac{Capex + \sum \frac{Capex_R}{(1+r)^{R*T_r}}}{\#cycles * DoD * C_{nom\_e} * \eta_{RT} * \sum_{n=1}^{N} \frac{(1+Deg)^n}{(1+r)^n}}$$

$$+ \frac{\sum_{n=1}^{N} \frac{Opex}{(1+r)^{n+T}}}{\#cycles * DoD * C_{nom\_e} * \eta_{RT} * \sum_{n=1}^{N} \frac{(1+Deg)^n}{(1+r)^n}}$$

$$+ \frac{\frac{Disposal}{(1+r)^{N+1}}}{\#cycles * DoD * C_{nom\_e} * \eta_{RT} * \sum_{n=1}^{N} \frac{(1+Deg)^n}{(1+r)^n}}$$

$$+ \frac{P_{el}}{\eta_{RT}}$$

Capex:	Investment cost ($)
$Capex_r$:	Replacement cost ($)
Opex:	Operating cost ($)
Disposal:	Disposal cost ($)
P_{el}:	Power cost ($/kWhel)
r:	Discount rate (%)
C_{nom_e}:	Nominal capacity (MWh)
DoD:	Depth-of-discharge (%)
N:	Lifetime (years)
#cycles:	Full cycles per year (#)
Deg:	Annual degradation (%)
n:	Period (year)
T_r:	Replacement interval (years)
R:	Replacement number (#)
T_c	Construction time (years)

Note: Construction time and self-discharge not explicitly considered for simplification; these parameters affect capex and period, and discharged energy respectively.

There are many key cost and performance characteristics for electricity storage

Key cost and performance parameters

Cost		Performance	
Investment cost	Cost to construct technology overnight (total vs specific)	**Nominal power capacity**	Maximum amount of power generated
Construction time	Actual duration of technology construction	**Discharge duration**	Maximum duration to discharge energy at maximum power
Replacement cost	Cost to replace technology components	**Nominal / Usable energy capacity**	Maximum amount of energy stored Usable amount of energy stored
Replacement interval	Time interval at which technology component replacement is required	**Depth-of-discharge**	Maximum energy that can be used without severely damaging the store
O&M cost	Cost of operating and maintaining operability of technology	**Cycle life**	Number of full charge-discharge cycles before end of usable life
Charging cost	Cost for energy to technology with energy	**Calendar life**	Number of years before end of usable life (even at no operation)
Disposal cost / Residual value	Cost to dispose of the technology at its end-of-life (can be negative)	**Degradation**	Loss in usable energy capacity
Discount rate	Rate at which future cost / revenues of technology are discounted	**Round-trip efficiency**	Proportion of energy discharged over energy required to charge store