Imperial College London

Projecting The Future Levelized Cost Of Electricity Storage Technologies

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13 March 2019
International Renewable Energy Storage Conference
Düsseldorf, Germany

Grantham Institute

The future role of storage is still uncertain

Problem

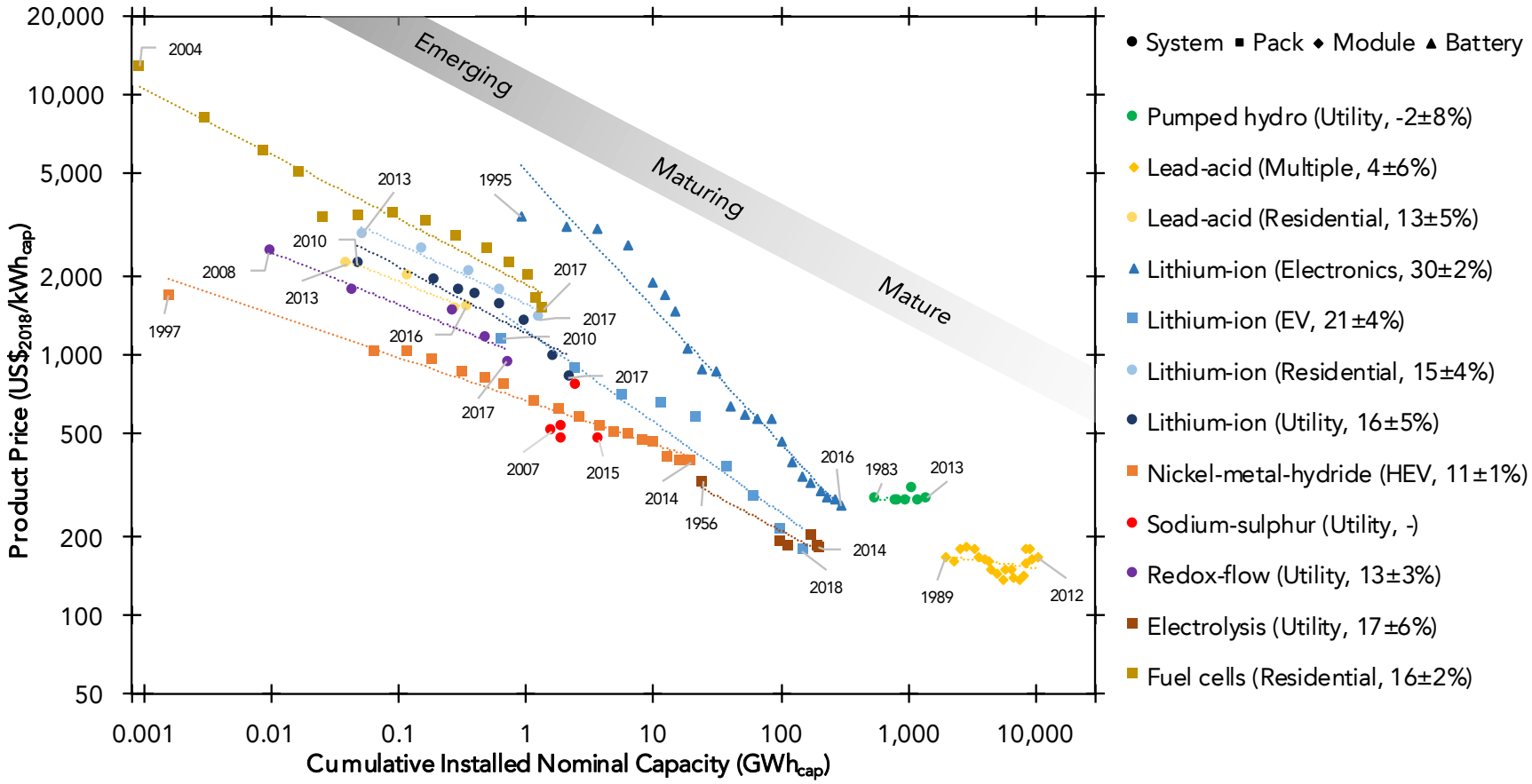
How much will electricity storage cost in the future

?

Which technology will be most cost-effective

Experience curve dataset for storage technologies can predict investment cost

Experience Curve Dataset



But, comparison of technologies must be based on levelised cost of storage (LCOS)

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

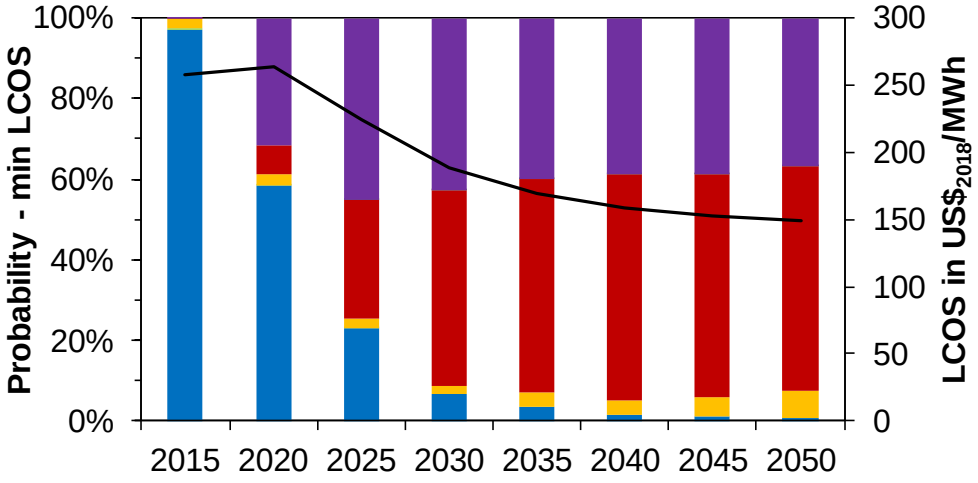
Applications vs Technologies

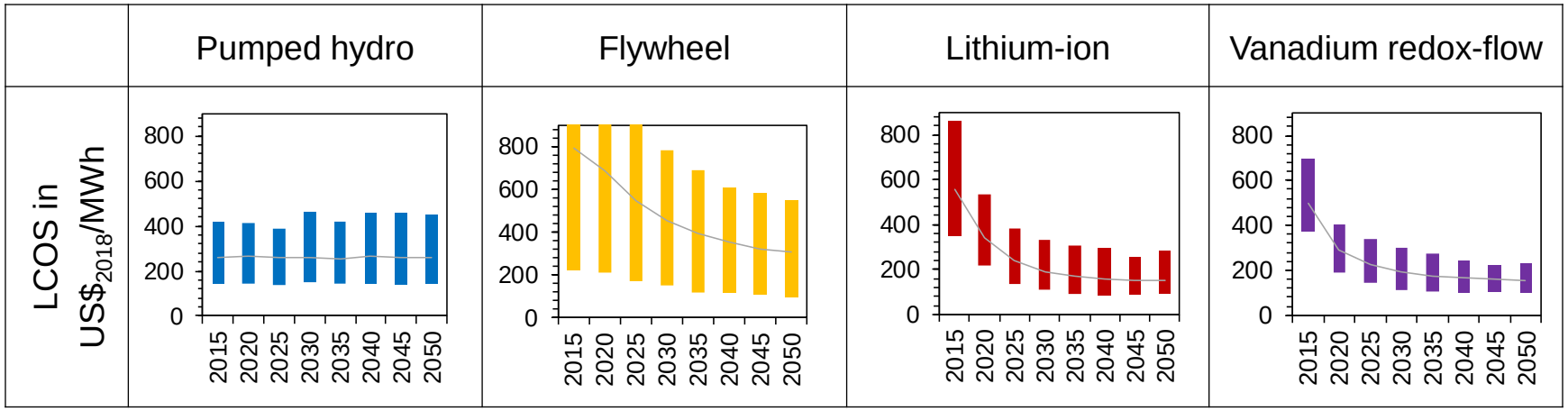
Role	Application	Pumped hydro	CAES	Fly-wheel	Li-ion	Sodium-sulfur	Lead-acid	VRFB	Hydro-gen	Super-cap.
	1. Energy arbitrage	✓	✓		✓	✓	✓	✓	✓	
System operation	2. Primary response			✓	✓	✓	✓	✓	✓	✓
	3. Secondary response	✓	✓	✓	✓	✓	✓	✓	✓	✓
	4. Tertiary response	✓	✓		✓	✓	✓	✓	✓	
	5. Peaker replacement	✓	✓		✓	✓	✓	✓	✓	
	6. Black start	✓	✓	✓	✓	✓	✓	✓	✓	✓
	7. Seasonal storage	✓	✓					✓	✓	
Network operation	8. T&D upgrade deferral	✓	✓		✓	✓	✓	✓	✓	
	9. Congestion mgmt	✓	✓		✓	✓	✓	✓	✓	
Consumption	10. Bill management				✓	✓	✓	✓	✓	
	11. Power quality			✓	✓	✓	✓	✓	✓	✓
	12. Power reliability				✓	✓	✓	✓	✓	

Lithium-ion and vanadium redox-flow will compete for secondary response

③ Secondary Response

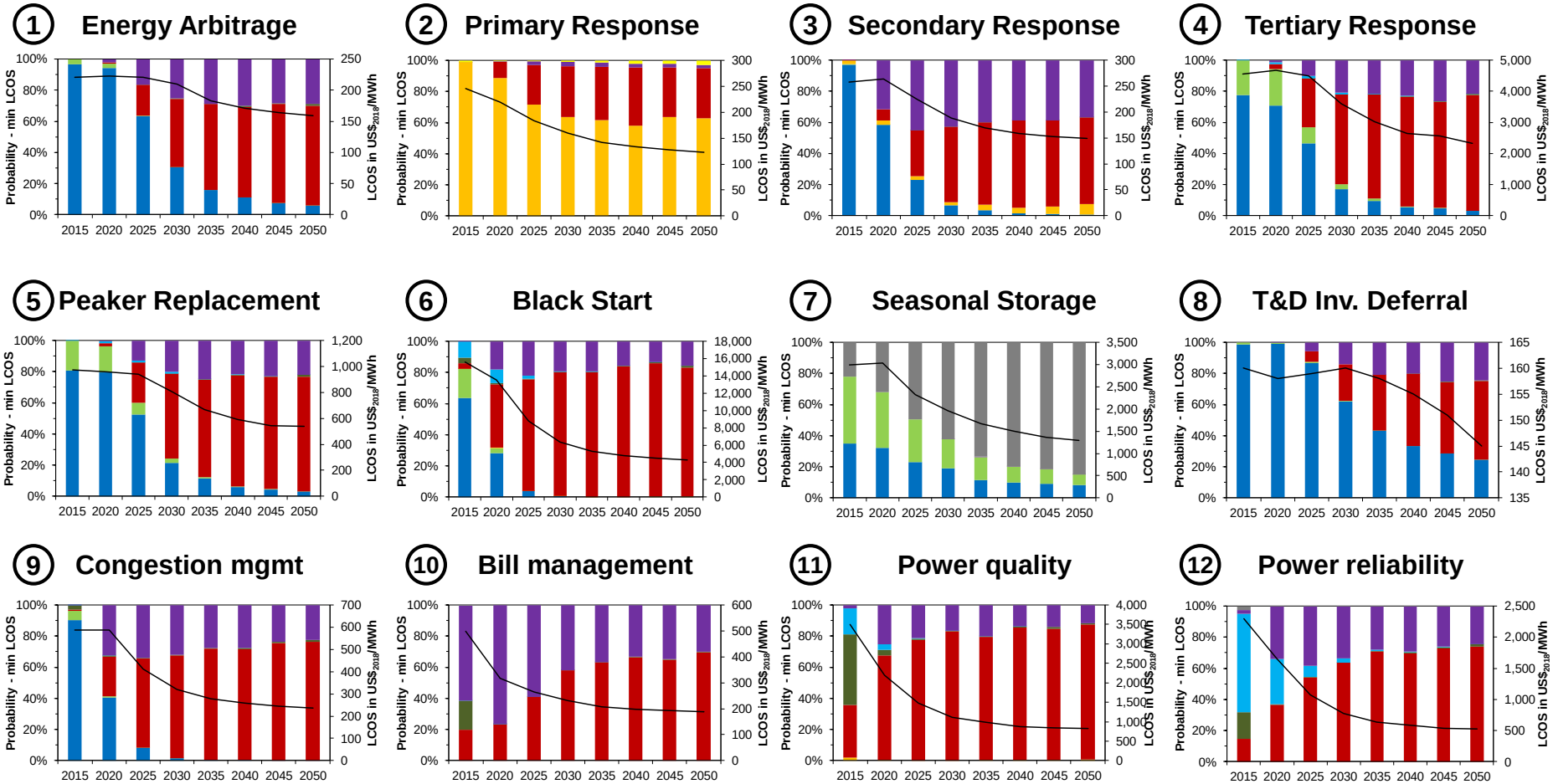
Power capacity	100 MW
Discharge duration	1 hour
Annual cycles	1,000
Response time	>10 seconds
Electricity price	50 $/MWh





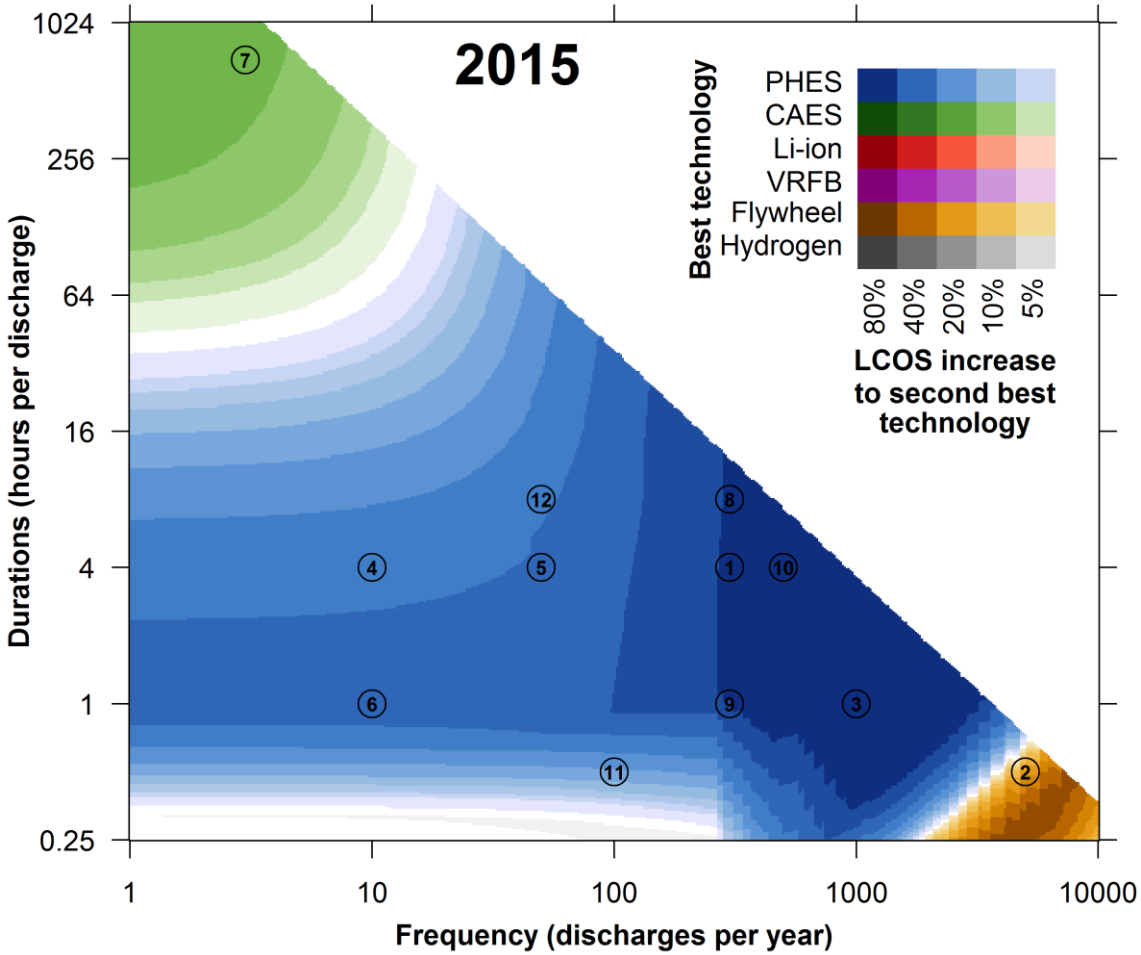
Lithium-ion becomes dominant technology in most applications by 2030

Application overview



Overall, pumped hydro and compressed air give way to lithium-ion and hydrogen

General overview



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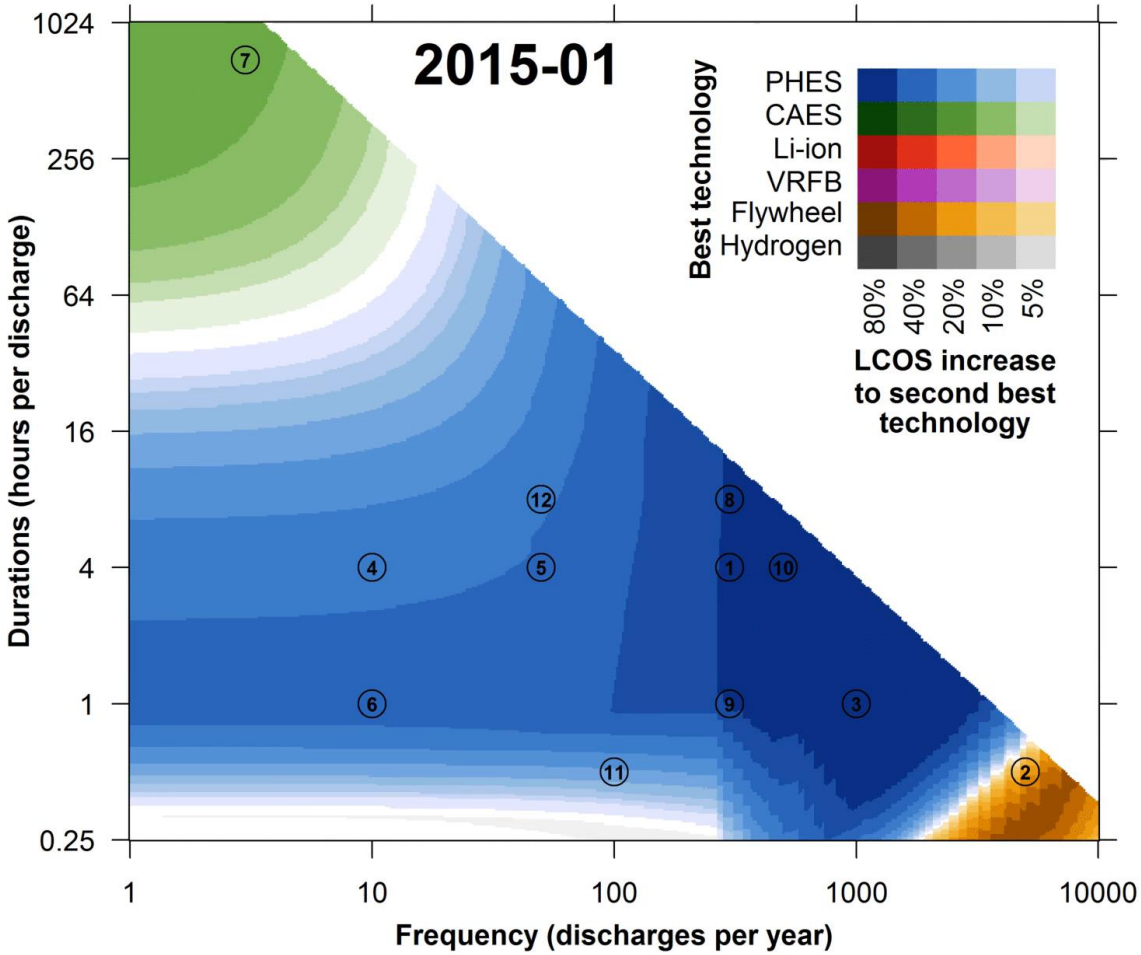
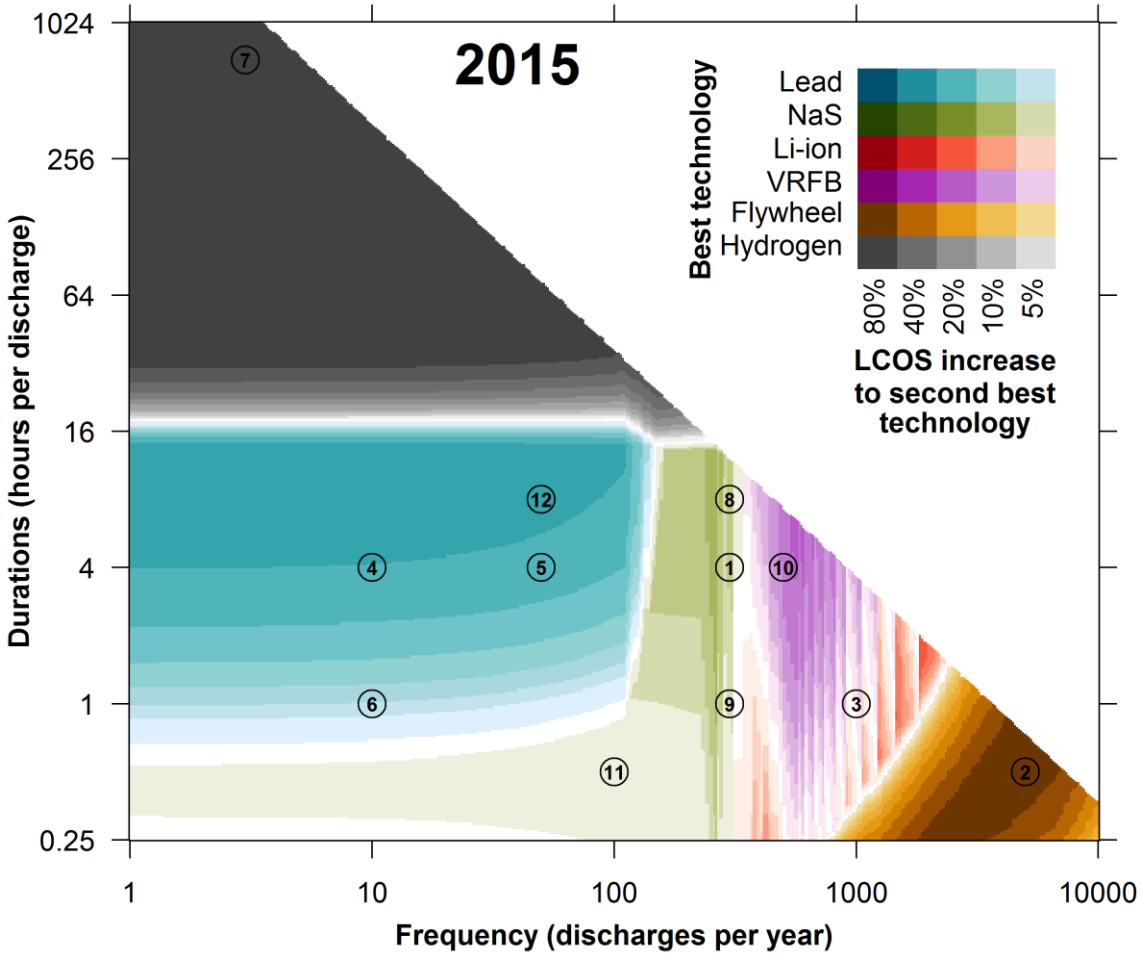


Lithium-ion more competitive than all other battery technologies by 2030

General overview – excl. PHS, CAES



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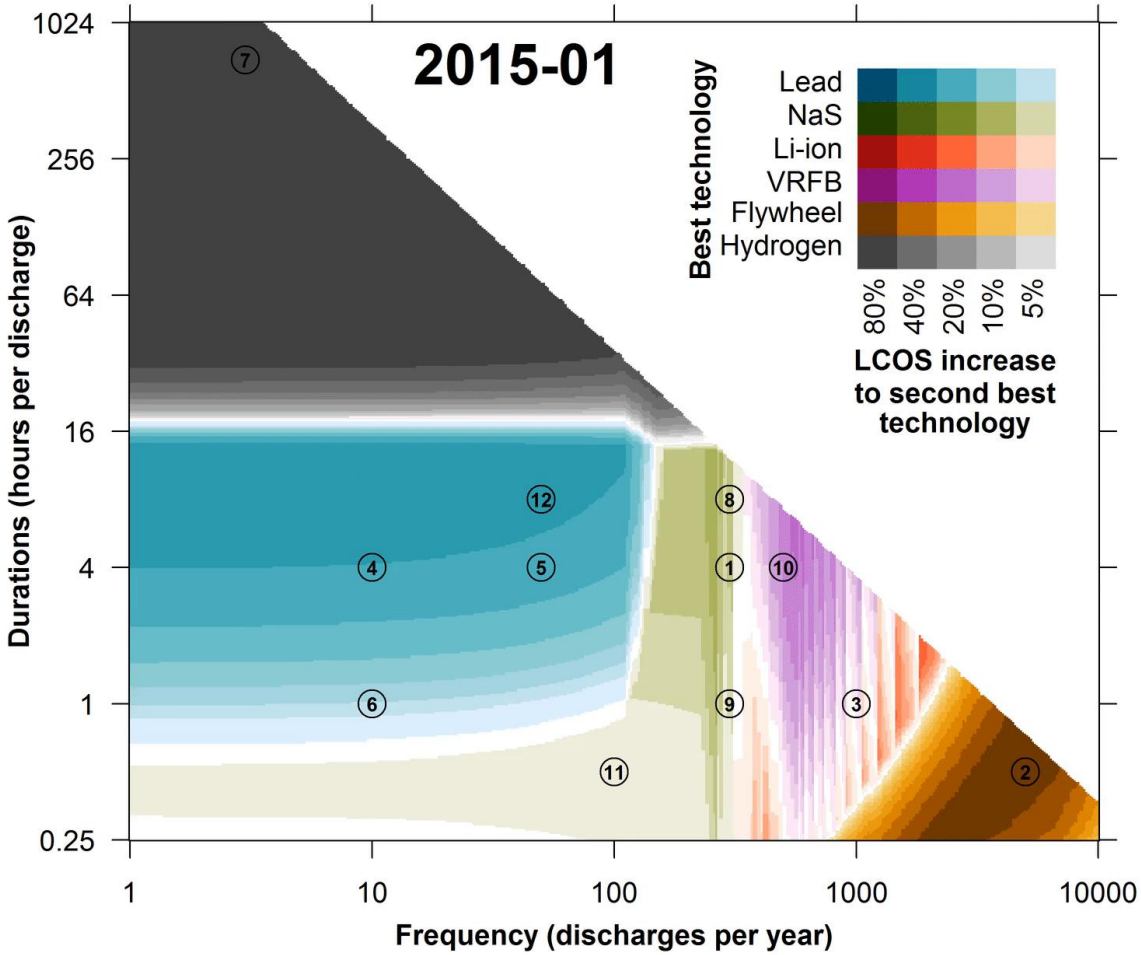
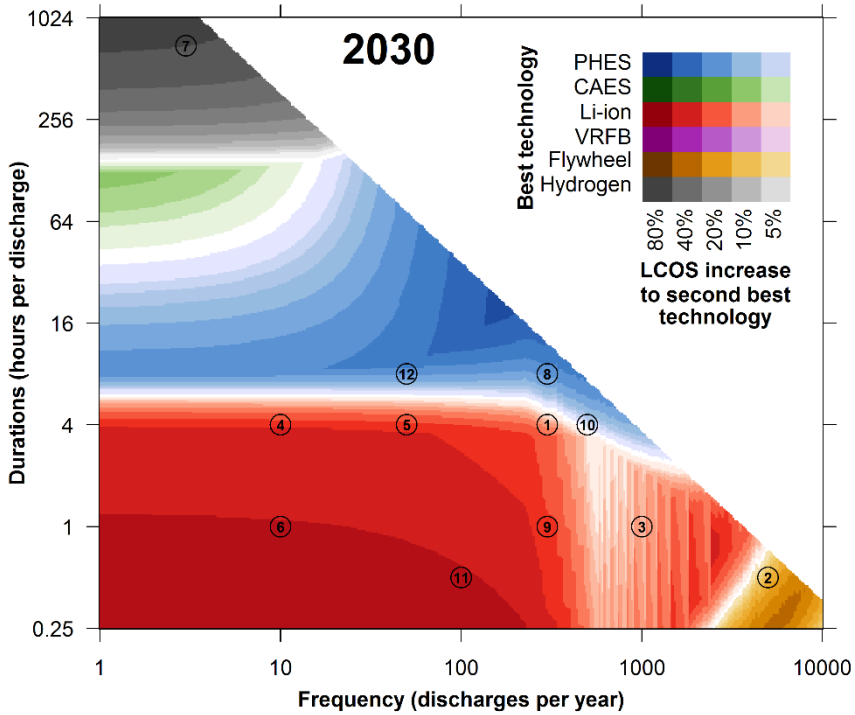


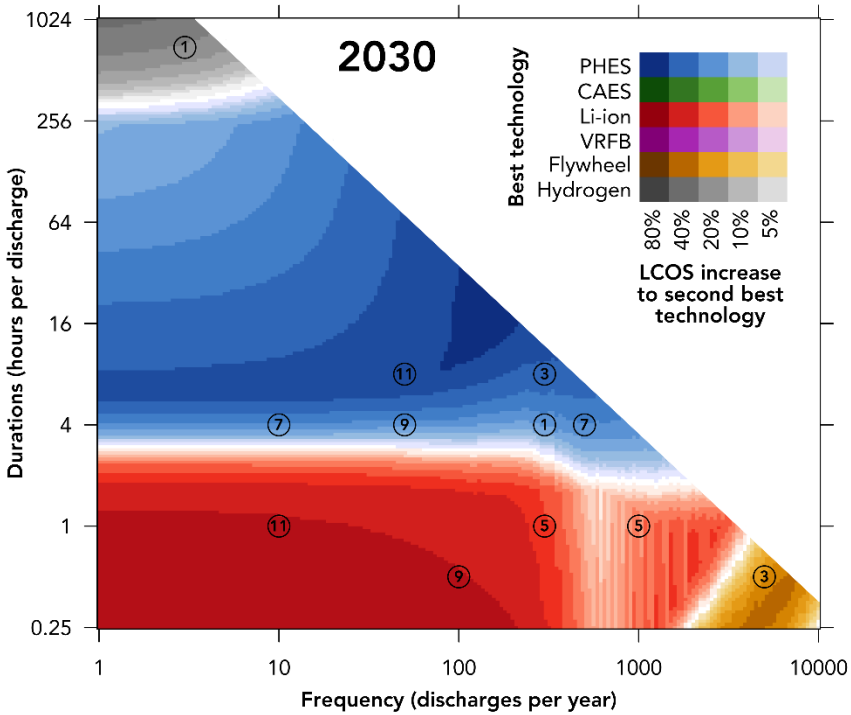
At discount rate of 4% pumped hydro competitive for most applications in 2030

Sensitivity – Discount rate

Discount rate: 8%



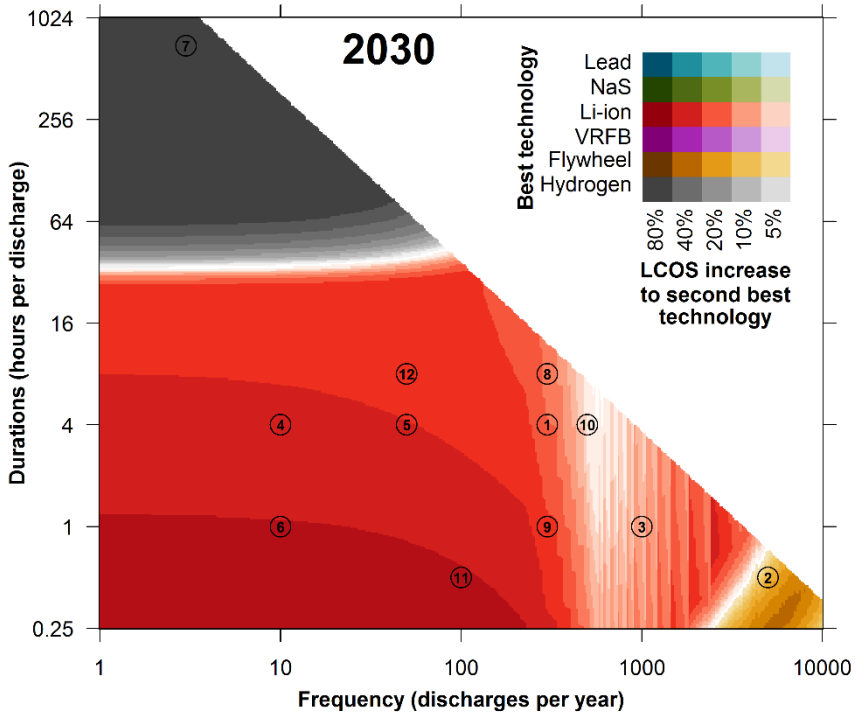
Discount rate: 4%



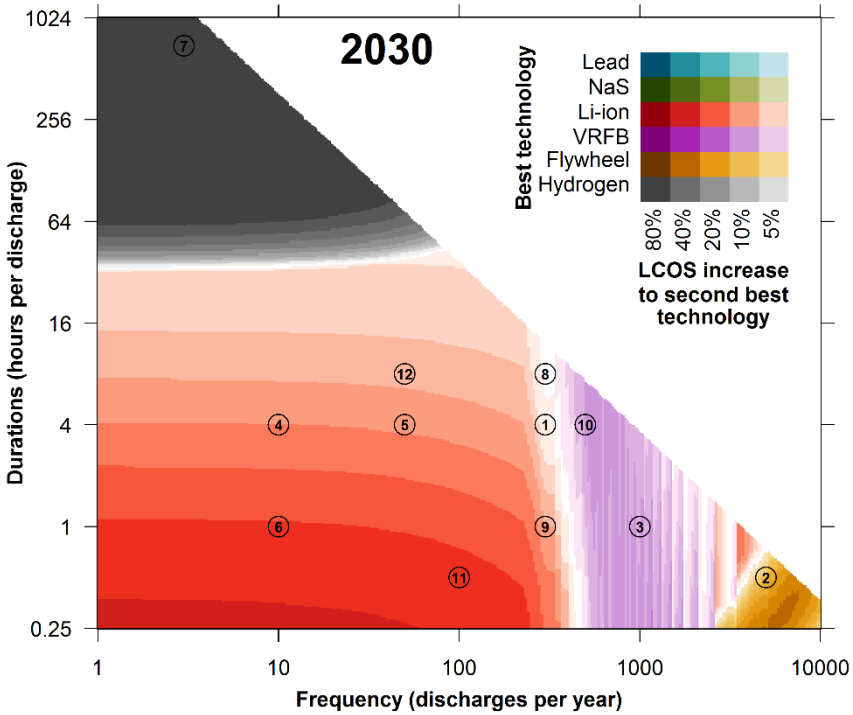
Life improvement of 2.5% p.a. since 2015 means VRFB cheaper than Li-ion in 2030

Sensitivity – Performance improvement

VRFB - Life: **8,300 cycles**
(2015 data) **13 years**



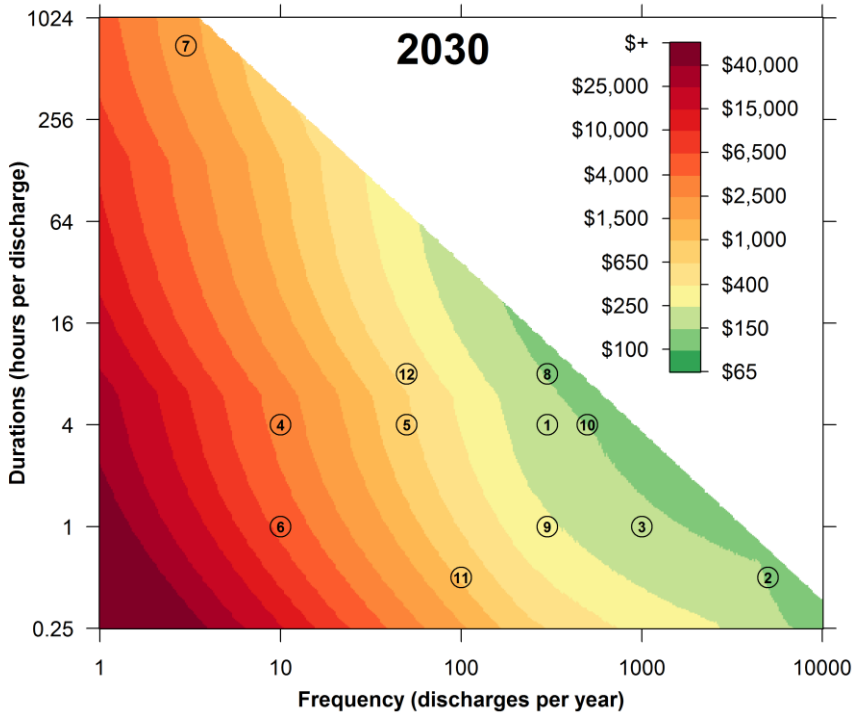
VRFB - Life: **12,000 cycles**
(+2.5% p.a.) **18 years**



Future storage cost is a function of discharge duration and frequency

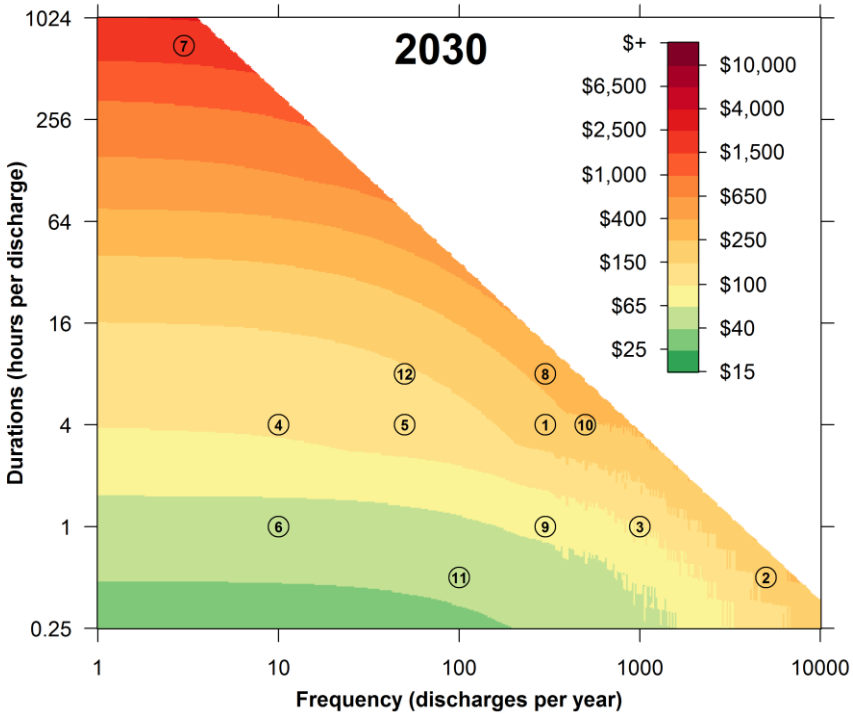
Future cost of electricity storage

LCOS in US$/kWh



ACC in US$/kW$_{year}$

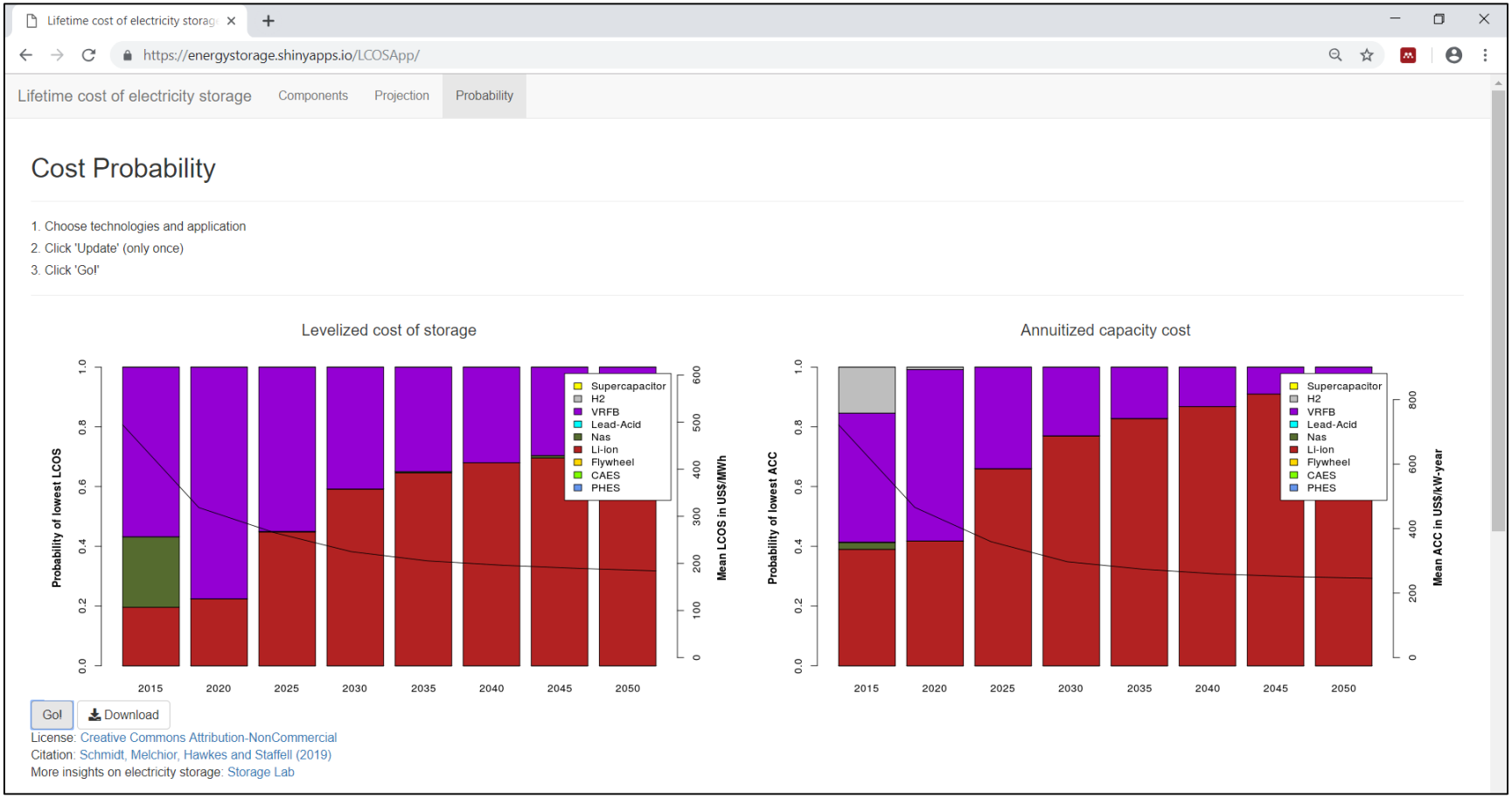
(annuitized capacity cost)



Assumption: Electricity price = 50 US$/MWh$_{el}$

Test your own assumptions on www.EnergyStorage.ninja

Online Tool



Questions & Discussion

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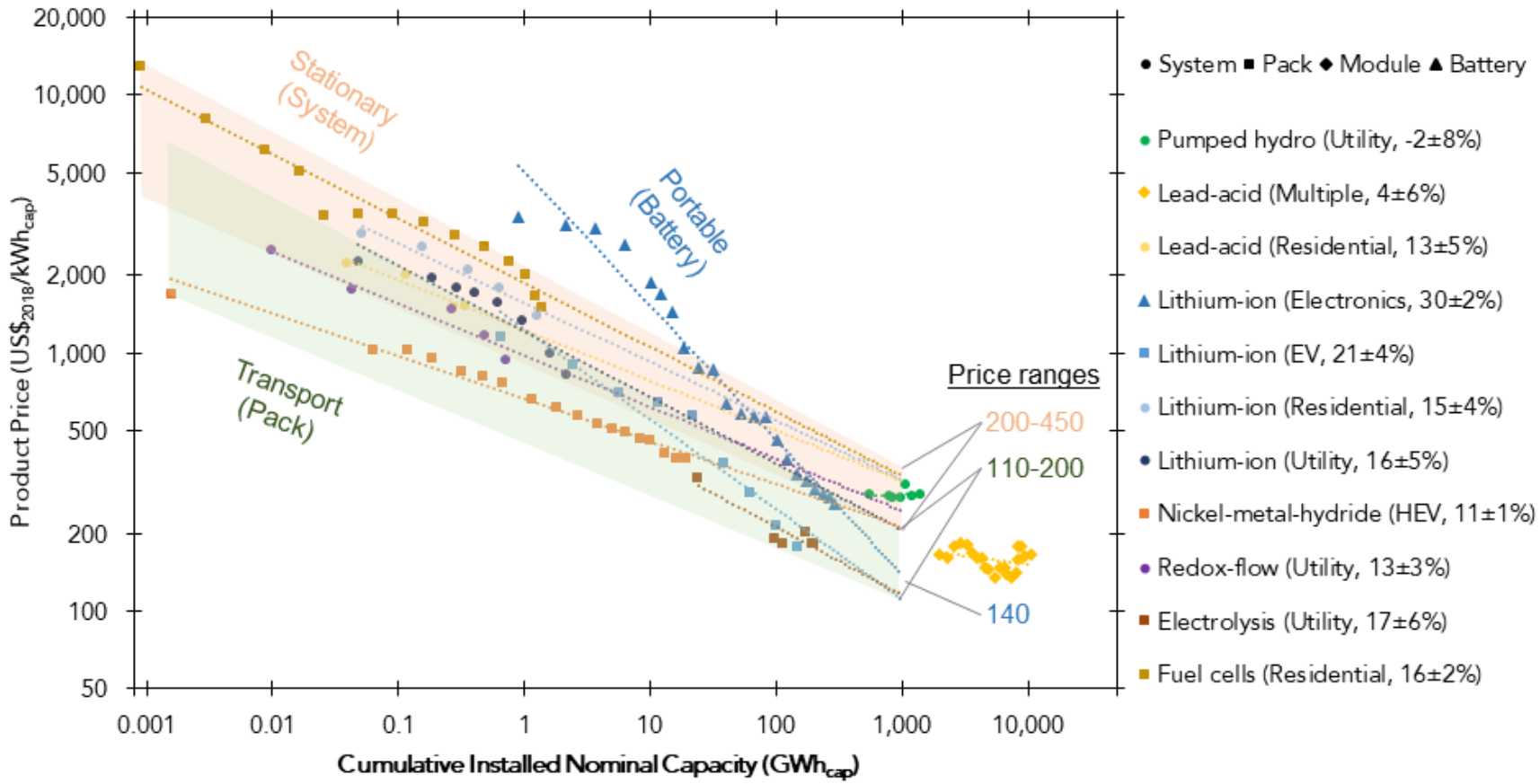
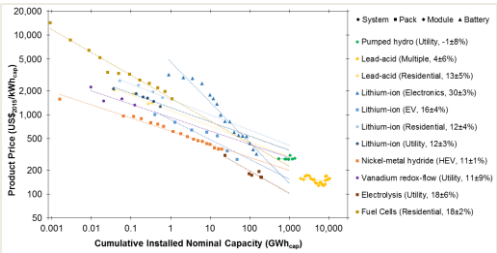
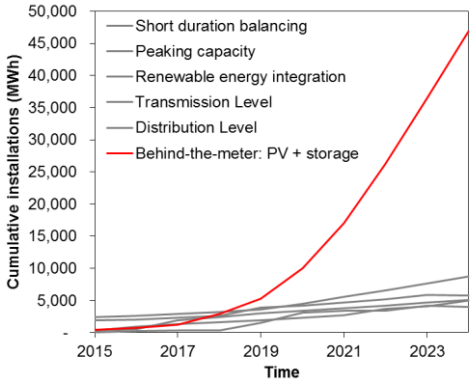
Projection of experience curves to analyze future investment cost

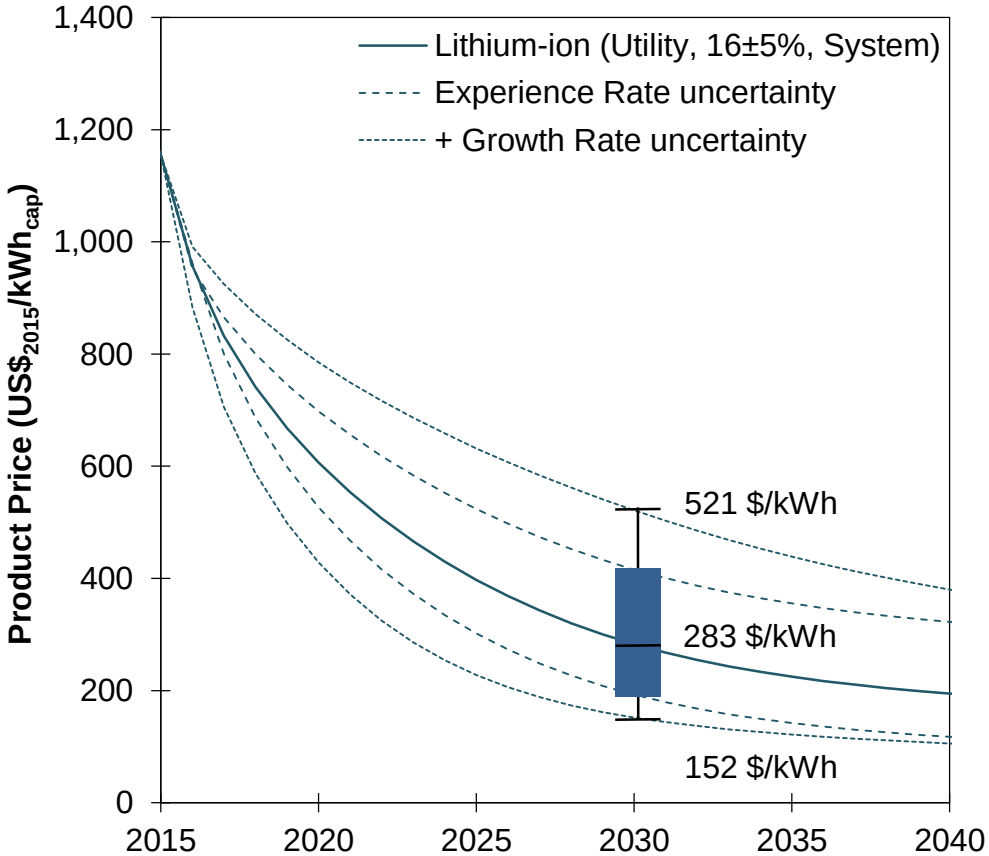


Experience curves combined with market forecasts enable future cost projection

Investment cost – Projection



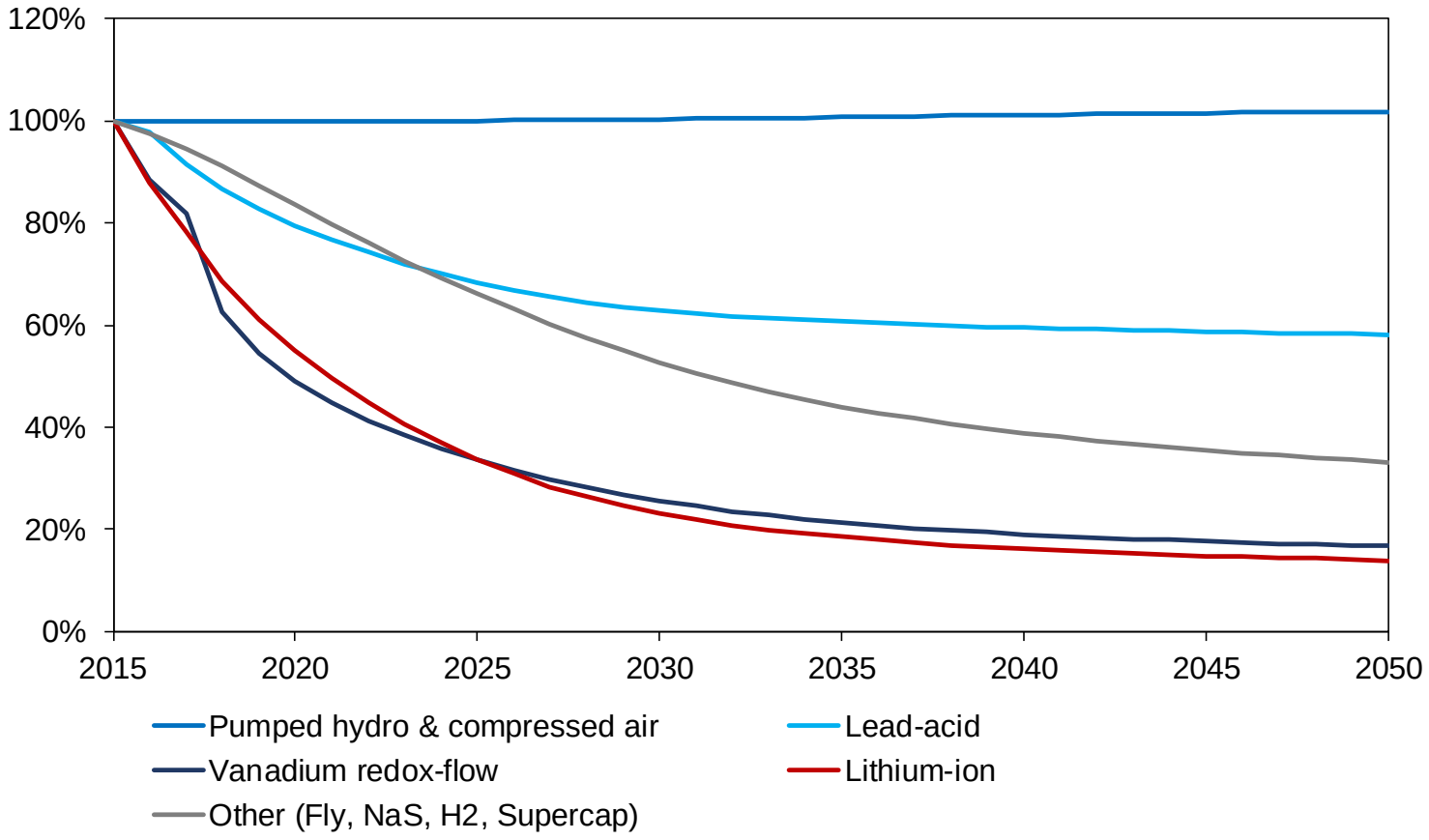




Source: O. Schmidt, A. Hawkes, A. Gambhir & I. Staffell. The future cost of electrical energy storage based on experience rates. Nat. Energy 2, 17110 (2017)

Lithium-ion and vanadium redox-flow investment cost fall to 20%

Investment cost reduction



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

All cost and performance parameters relevant during technology life considered

Technology input parameters

			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	60 (80%)	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	%	η_{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	7,13,14,21–24	7,12–14

Impact of depth-of-discharge on cycle life is considered

Depth-of-discharge

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				25	26	19			

Modelled applications cover entire spectrum of performance requirements

Applications – Detail