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Future cost of electricity storage and impact on competitiveness

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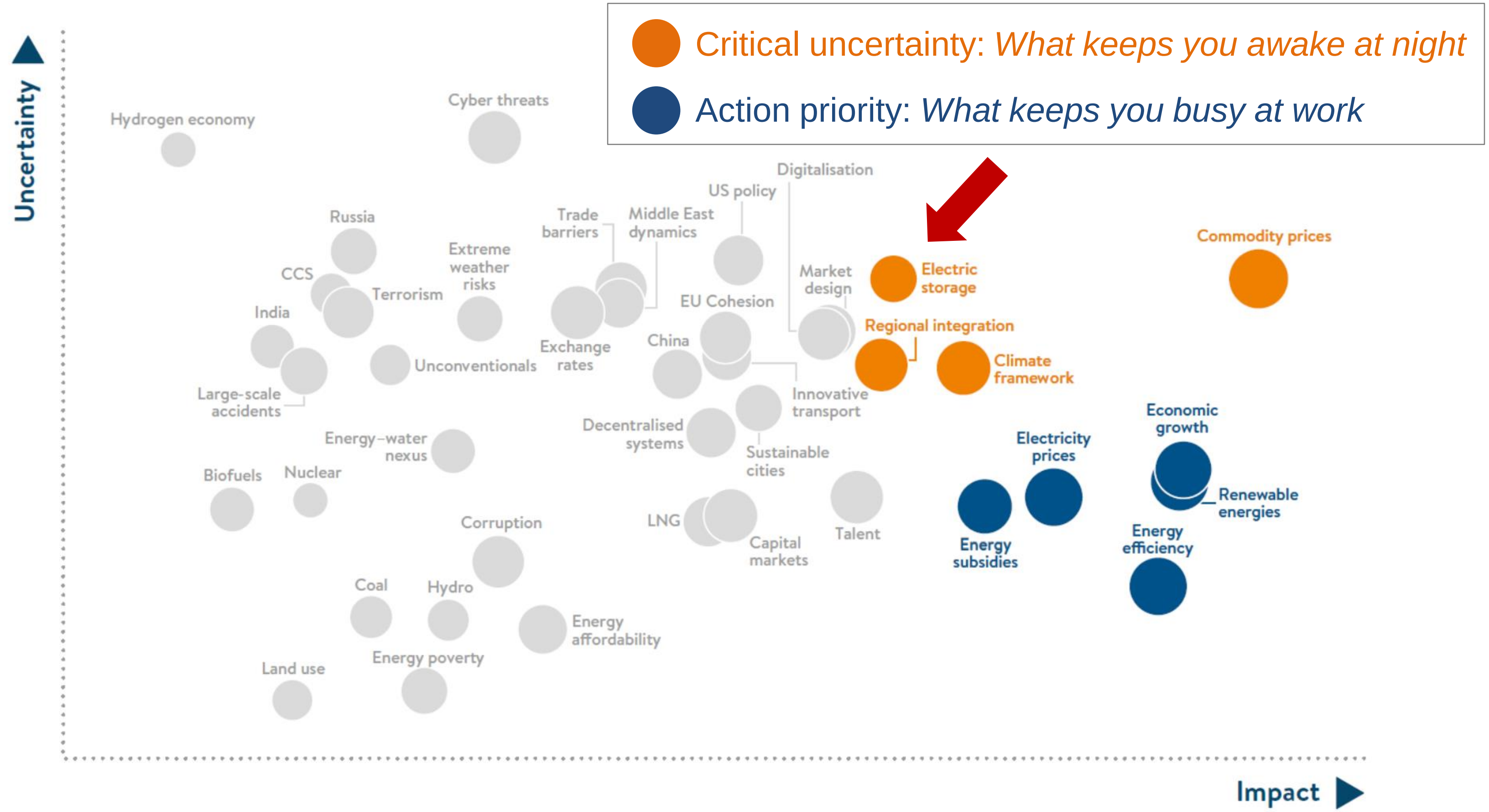
28 June 2018 | EU4Energy Policy Forum
Karven 4 Seasons Resort, Sary-Oi, Kyrgyzstan

Grantham Institute

Storage may have a big impact, but its future role is perceived as highly uncertain

Problem: Uncertainty on role of storage

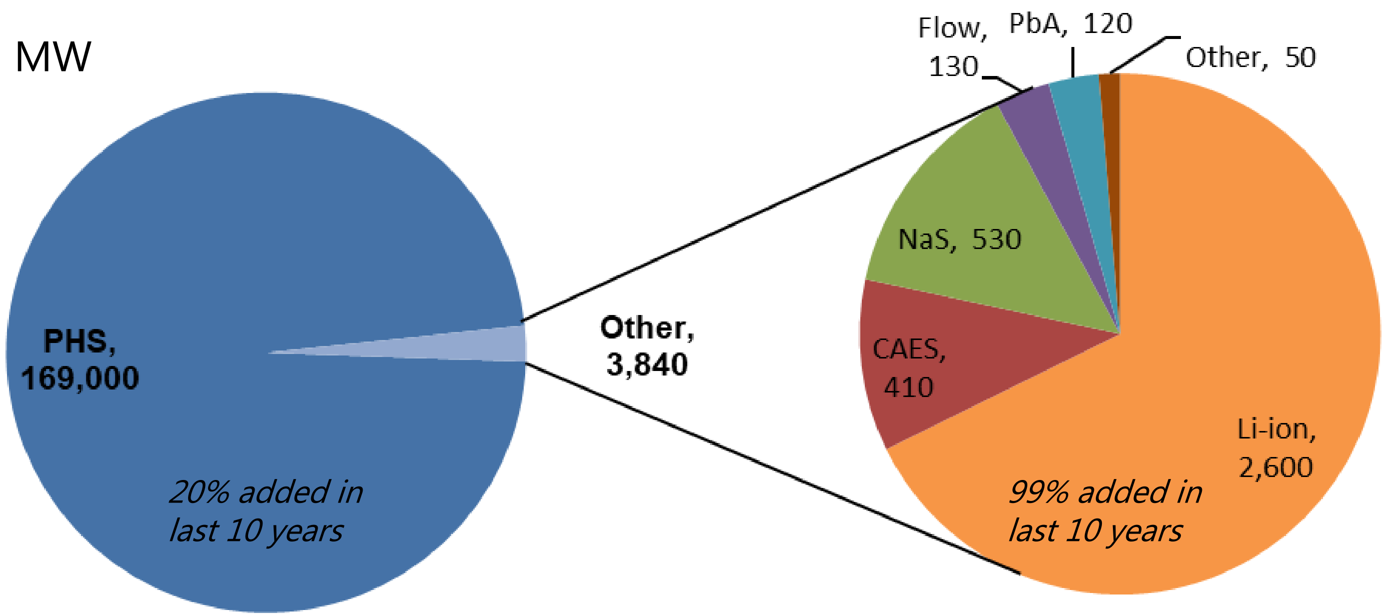


Source: World Energy Issues Monitor 2017 | Exposing the new energy realities. World Energy Council; 2017.

While pumped hydro is the most widely deployed stationary storage technology

Global installed capacity - 2017

All data in MW



PHS – Pumped Hydro Storage
Li-ion – Lithium-ion Battery
CAES – Compressed Air Energy Storage
NaS – Sodium-sulphur Battery
Flow – Flow Battery
PbA – Lead-acid Battery

Source: Energy Storage Database, Department of Energy (2017); Global Energy Storage Forecast, 2016-2024, BNEF (2017); https://www.ngk.co.jp/nas/

Investment costs of lithium-ion batteries have fallen dramatically in recent years

Recent cost developments

Average: 3,000 $\$/kWh_{cap}$

Powerwall 1: 1,100 $\$/kWh_{cap}$

Powerwall 2: 500 $\$/kWh_{cap}$

October 2013

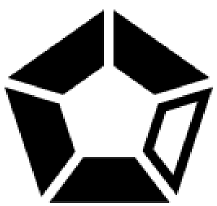
April 2015

October 2016

Sources: Tepper, M. Solarstromspeicher-Preismonitor Deutschland 2016. (Bundesverband Solarwirtschaft e.V. und Intersolar Europe, 2016); www.solarfixni.co.uk/solarpanelsystems/tesla/; www.tesla.com/powerwall

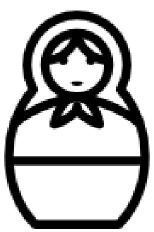
We need a consistent method to project cost for multiple technologies

Approach



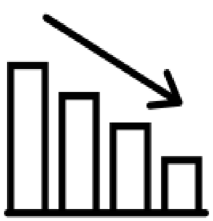
Technology

- Cost analyses are focussed on lithium-ion
- A holistic assessment should cover multiple technologies



Scope

- Cost quotes refer to different technology components
- A transparent analysis should clarify reference scope



Method

- Cost projections are made with varying methods
- An objective and consistent method should be chosen

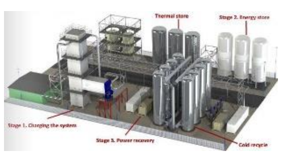
Source: www.flaticon.com

Electricity can be stored in multiple ways

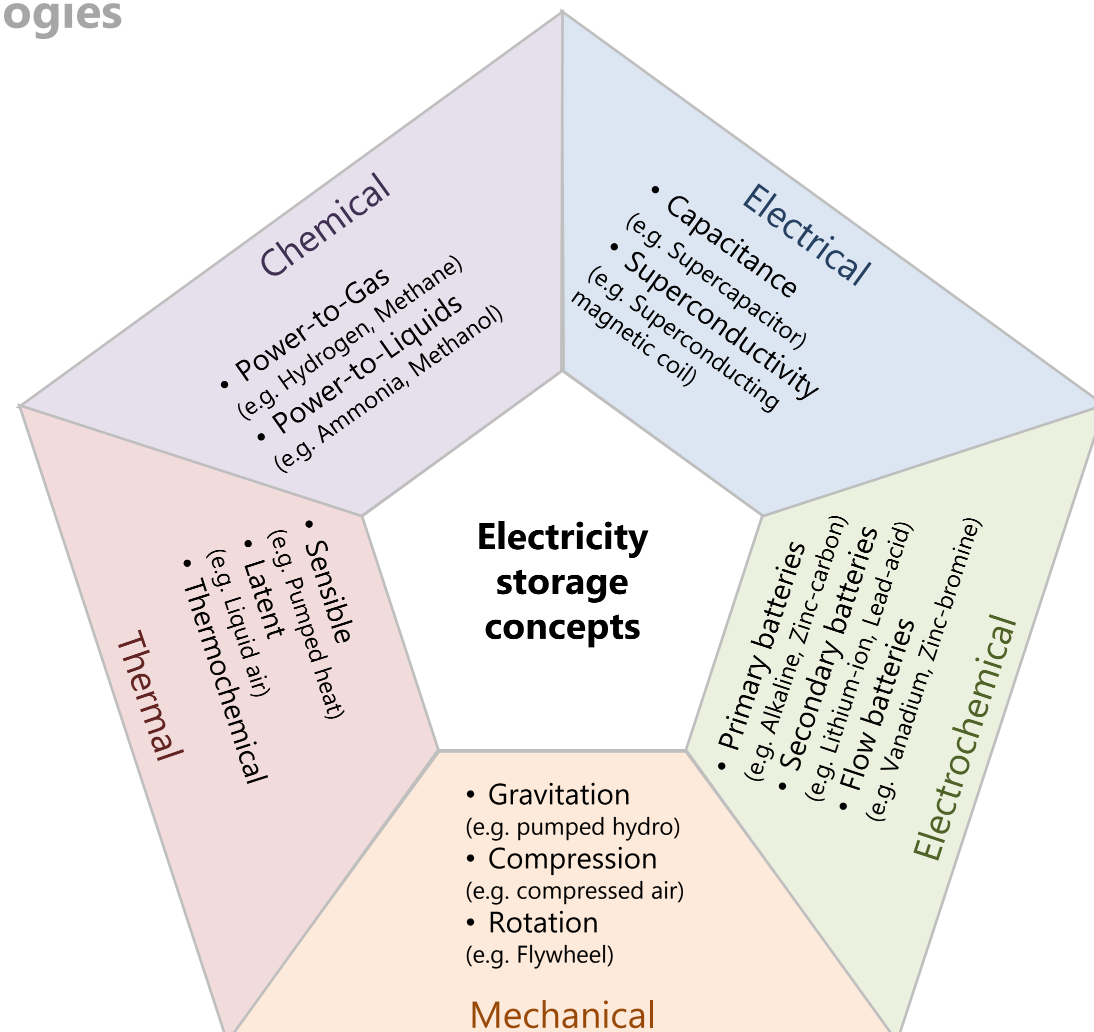
Technologies

Electrolysis

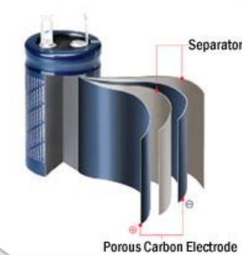
Liquid air



Pumped hydro



Supercapacitor

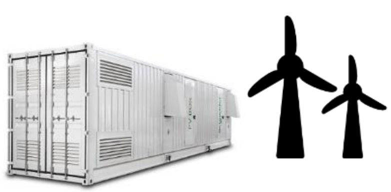


Lithium-ion

Redox-Flow

Cost figures can refer to different scopes containing not all cost components

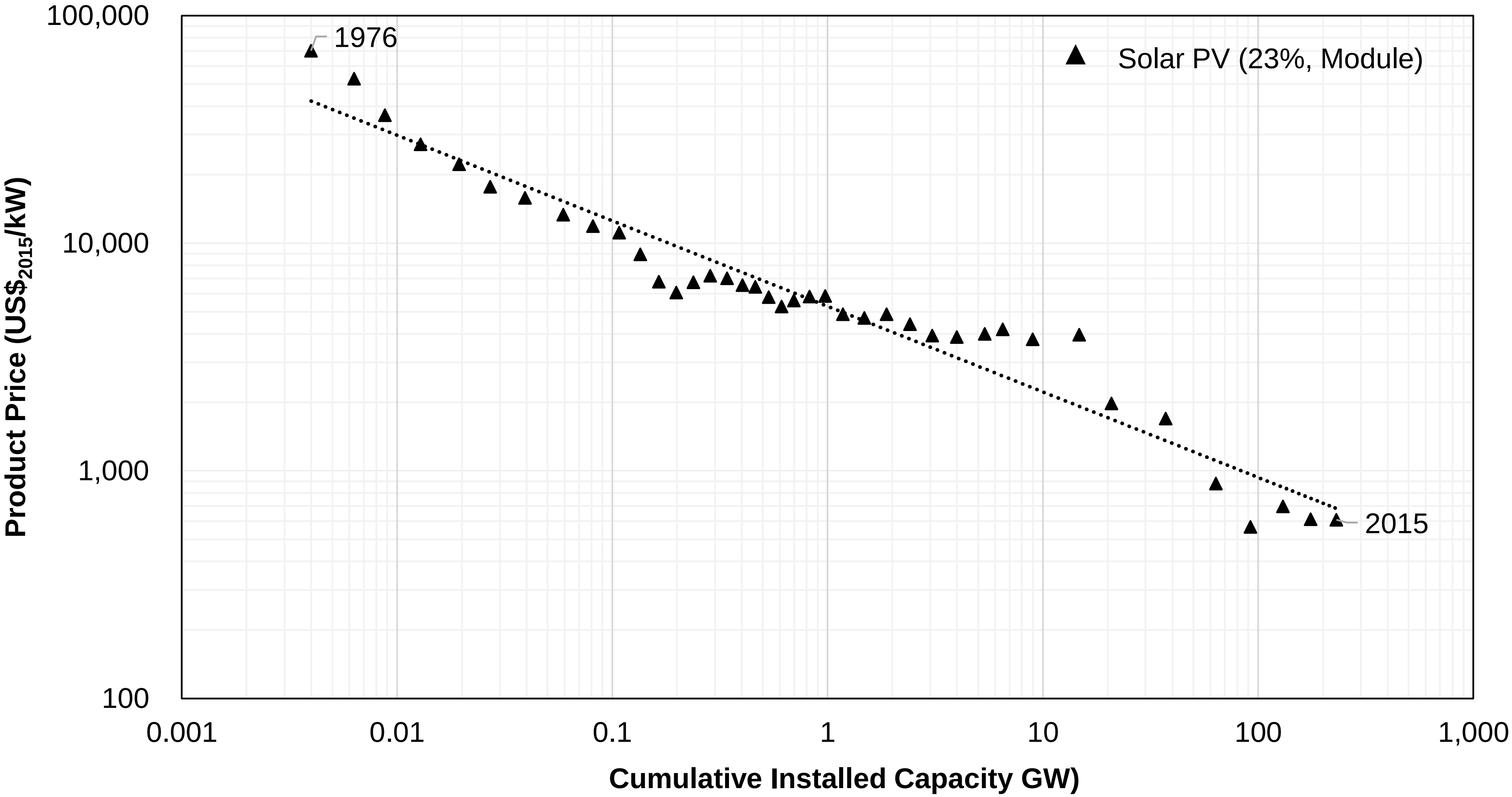
Technology scope

	Cell	Consumer electronics	20% of installed system
	Module	-	-
	Pack	Electric vehicles	30% of installed system
	System (ex-works)	-	65% of installed system
	Installed system	Stationary applications	100%

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)

Experience curves are an objective tool to model cost reductions for technologies

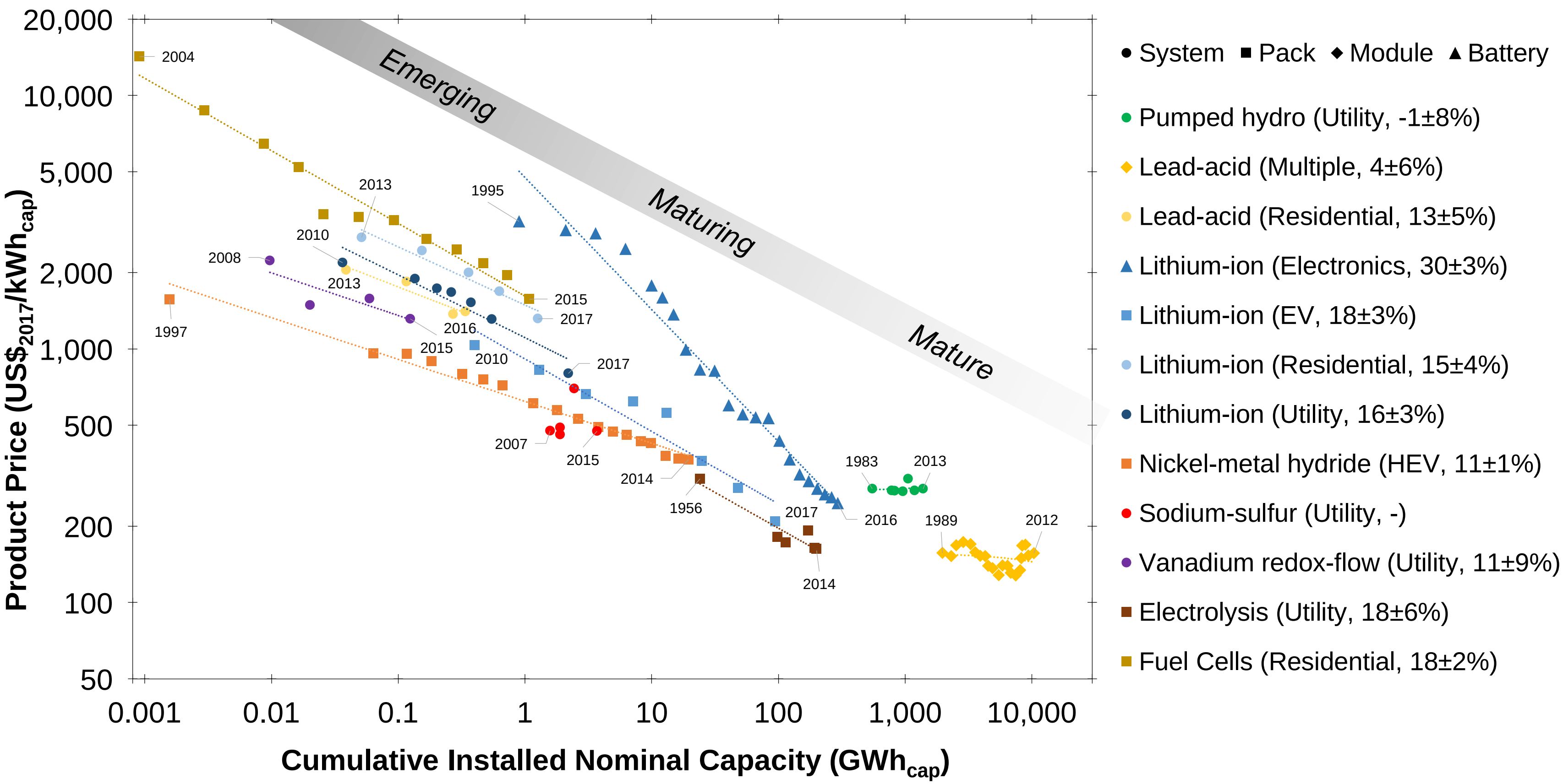
Method



Source: Liebreich, M. Keynote - Bloomberg New Energy Finance Summit 2016. (Bloomberg New Energy Finance, 2016).

The experience curve dataset for storage technologies…

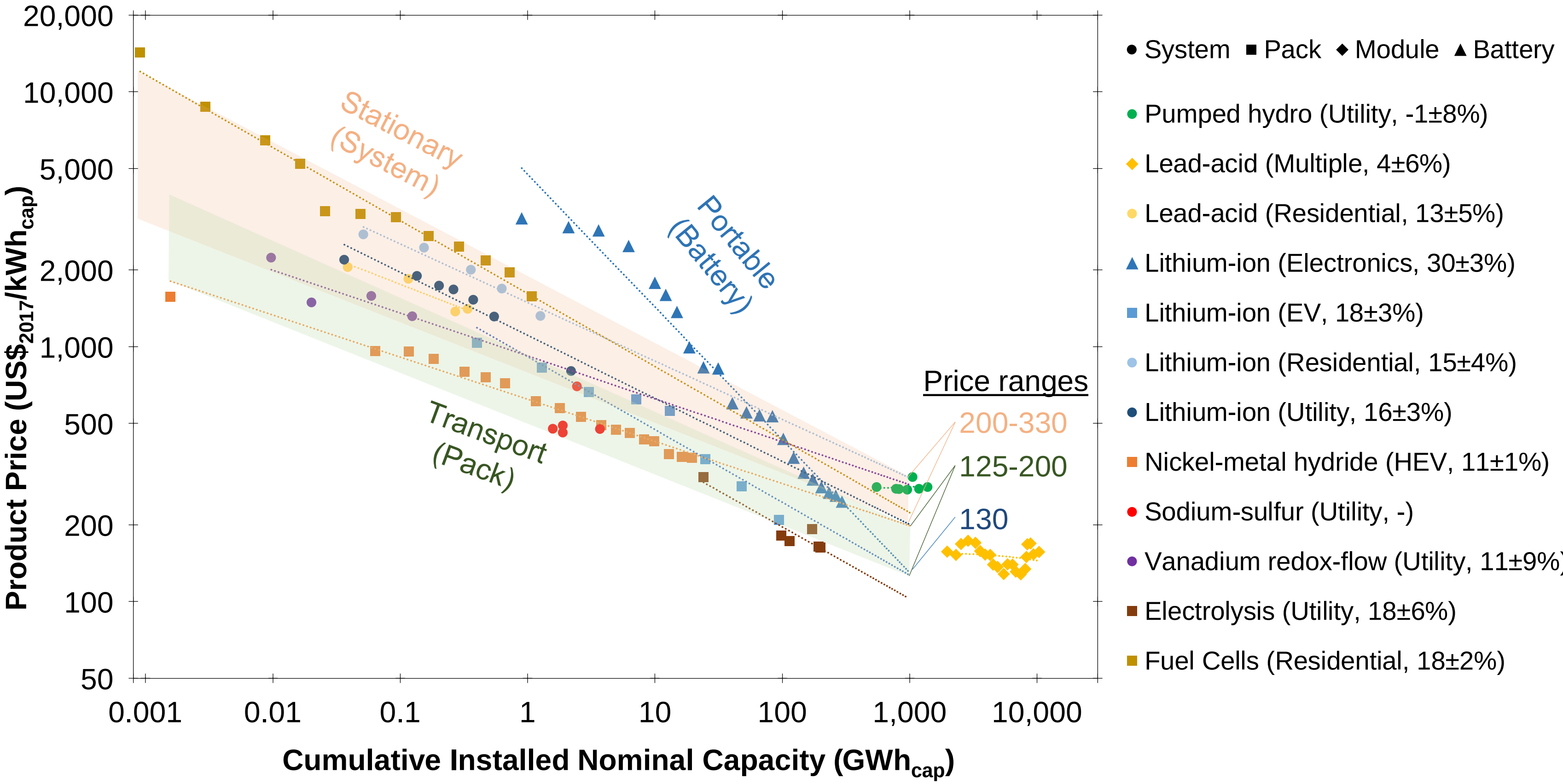
Dataset



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)

... shows that battery storage investment cost will reach cost of pumped hydro

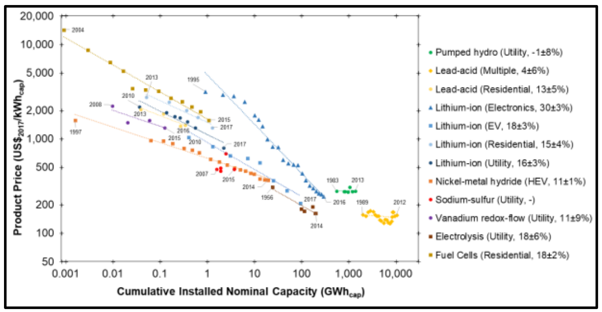
Investment cost projection – Capacity-based

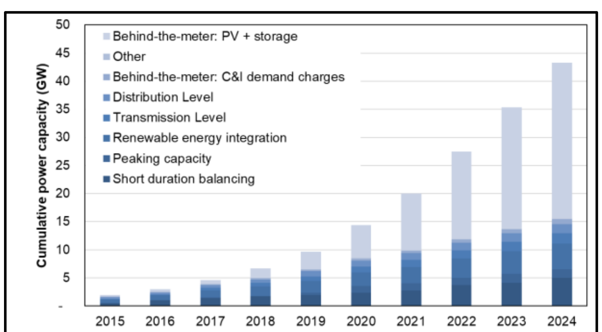


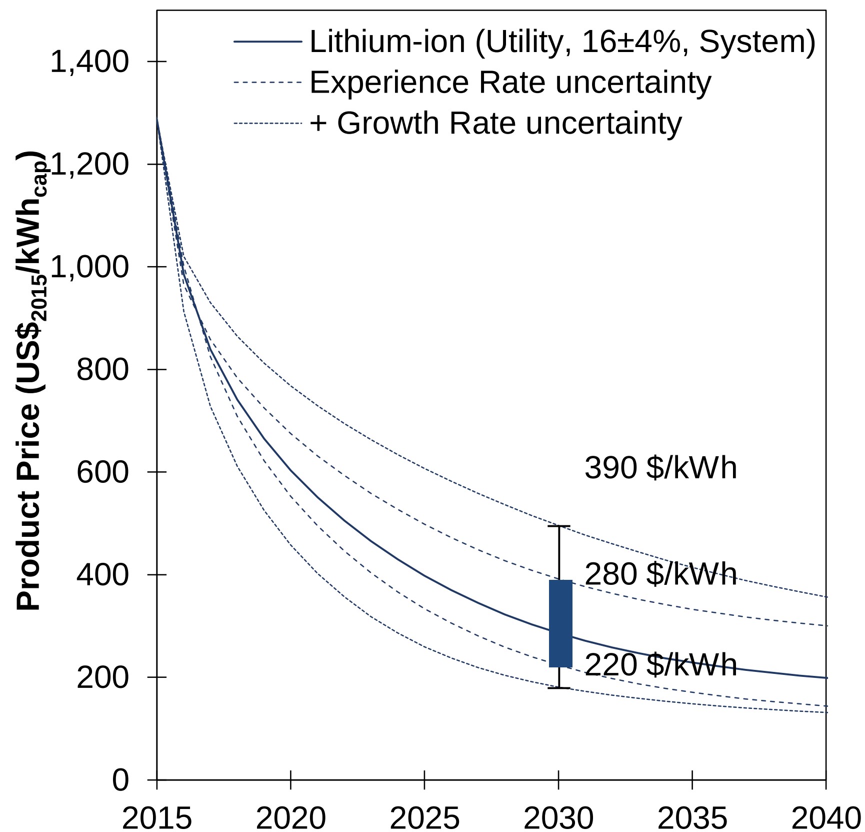
Source: O. Schmidt, A. Hawkes, A. Gambhir & I. Staffell. The future cost of electrical energy storage based on experience rates. Nat. Energy 2, 17110 (2017)

Resulting time-based cost projections could be used to compare technologies, but

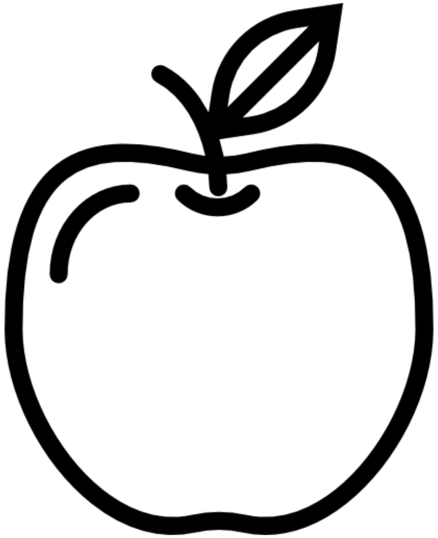
Investment cost projection – Time-based

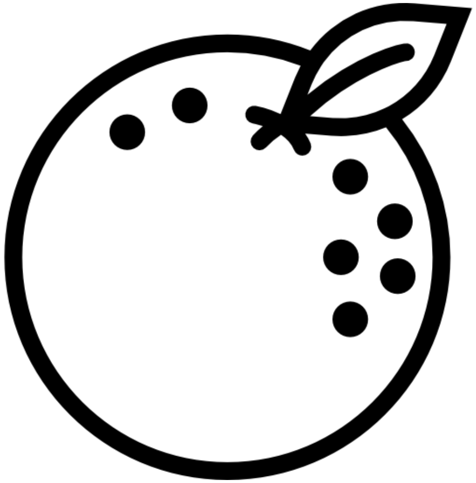






Apple ≠ Orange





Electricity storage technologies differ in many cost and performance parameters

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

Levelised cost of storage (LCOS) consider all cost and performance parameters

LCOS Formula

- Investment cost
- Construction time
- Replacement cost / interval

- Charging cost
- O&M cost

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

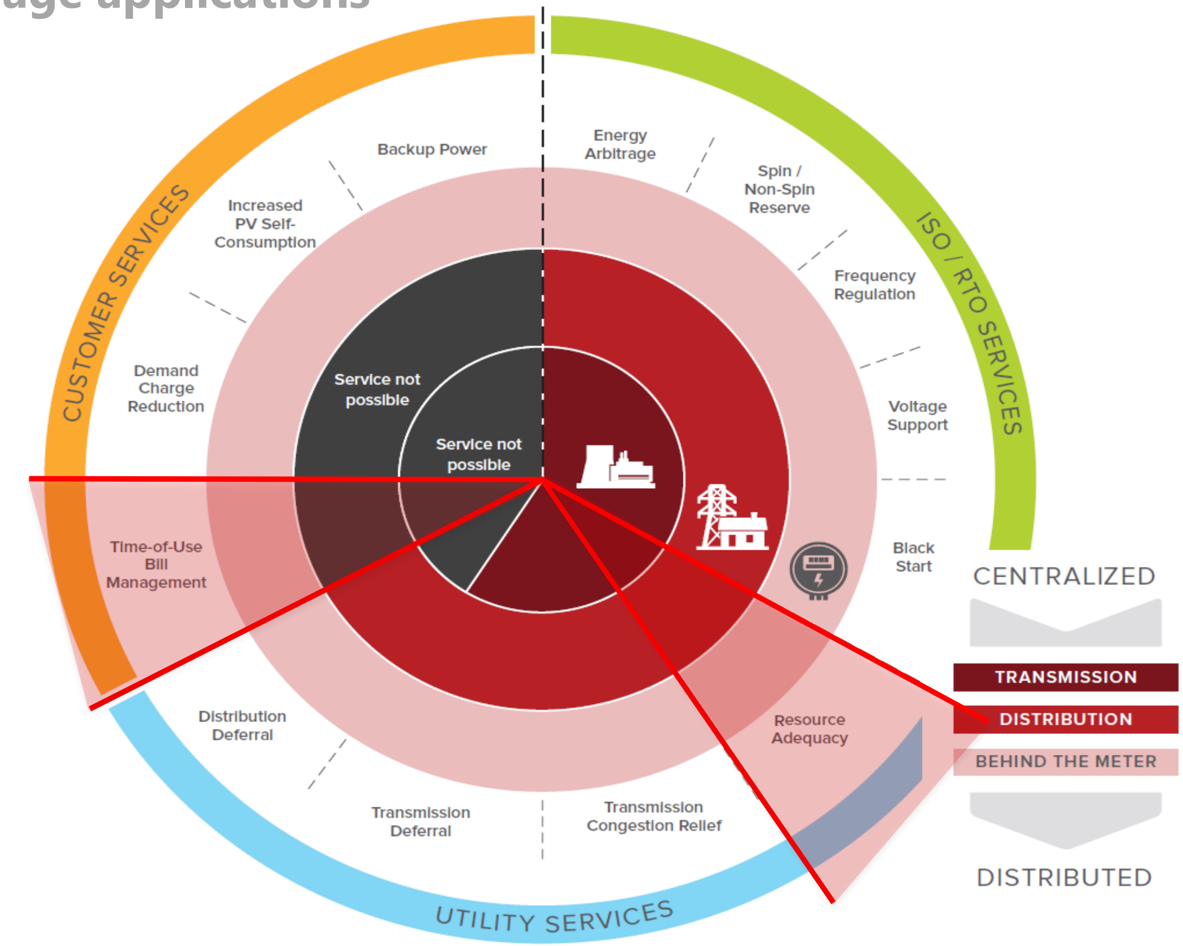
- Round-trip efficiency
- Depth-of-discharge
- Annual cycles
- Cycle life
- Calendar life
- Degradation

- End-of-life cost or residual value

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

Applications affect storage operation, so LCOS analysis must be application-specific

Electricity storage applications

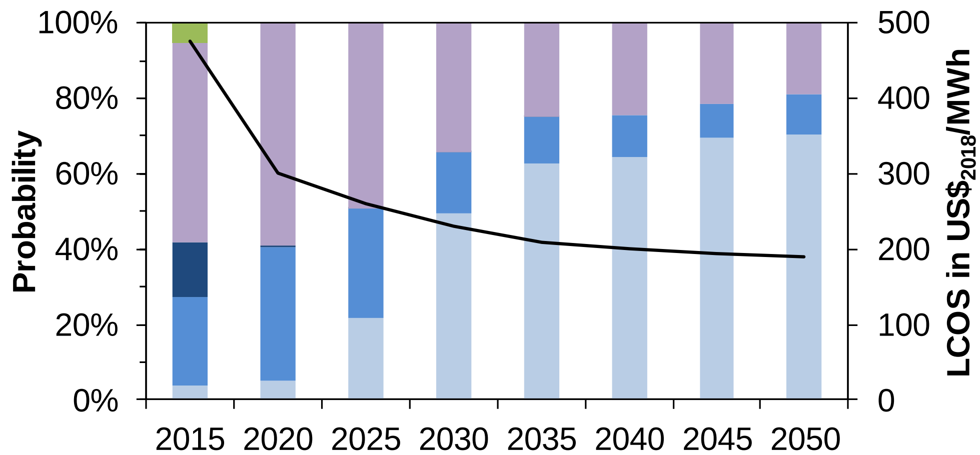


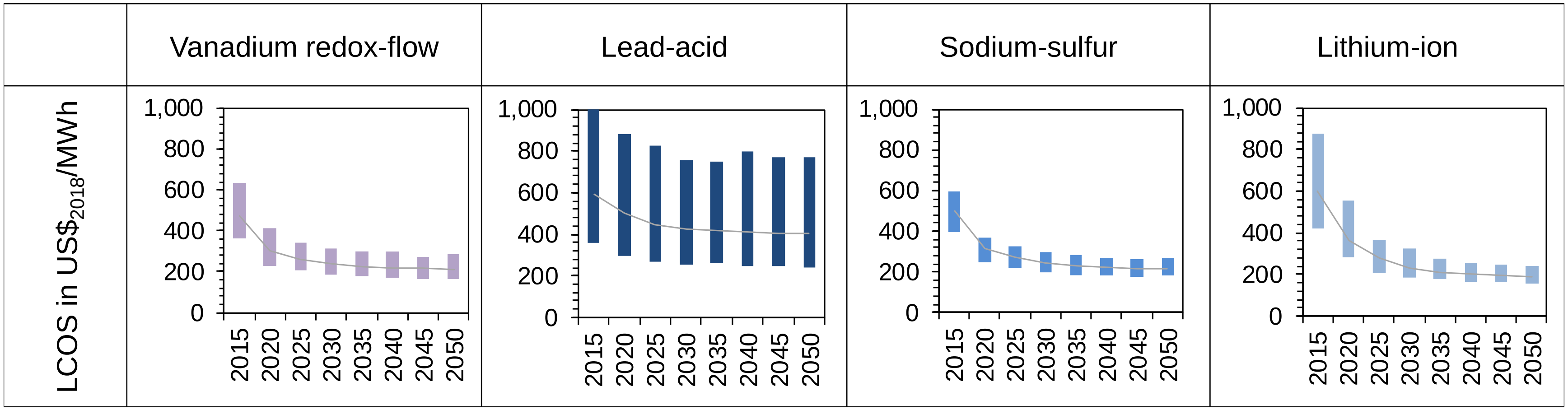
Source: The Economics of Battery Storage, RMI, 2015

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

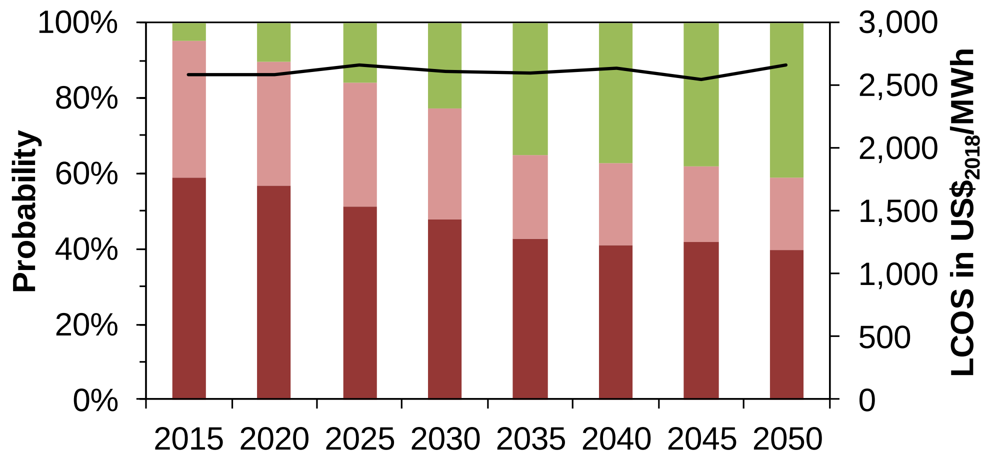


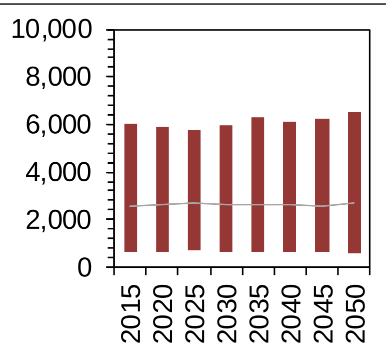
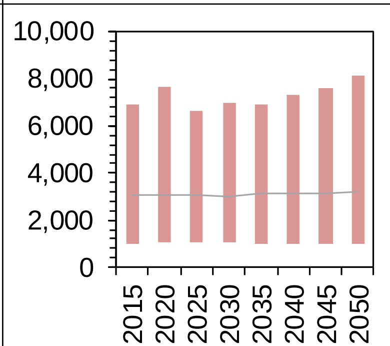
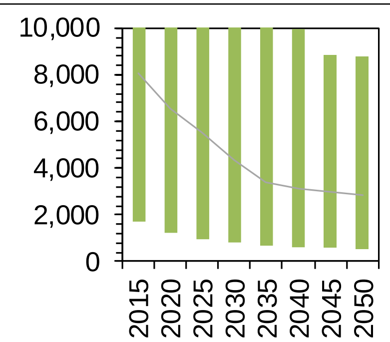
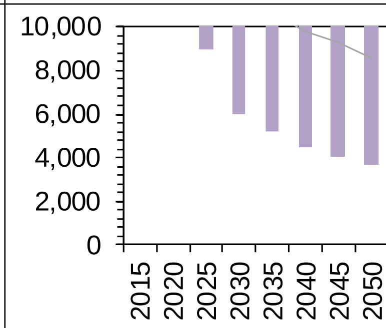


Pumped hydro, compressed air and hydrogen compete for seasonal storage

LCOS – Resource Adequacy (Seasonal)

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

2015

All technologies

Discharge duration (hours)								
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
	1	10	50	100	500	1000	5000	10000

Cycles p.a.

Excl. PHS & CAES

Discharge duration (hours)								
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
	1	10	50	100	500	1000	5000	10000

Cycles p.a.

2020

All technologies

Discharge duration (hours)								
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
	1	10	50	100	500	1000	5000	10000

Cycles p.a.

Excl. PHS & CAES

Discharge duration (hours)								
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
	1	10	50	100	500	1000	5000	10000

Cycles p.a.

2030

All technologies

Discharge duration (hours)								
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
	1	10	50	100	500	1000	5000	10000

Cycles p.a.

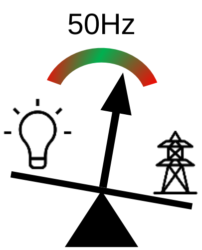
Excl. PHS & CAES

Discharge duration (hours)								
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
	1	10	50	100	500	1000	5000	10000

Cycles p.a.

LCOS analysis also allows analysing competitiveness of electricity storage

Analysis – Competitiveness

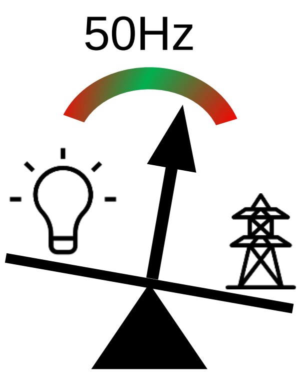


Frequency regulation

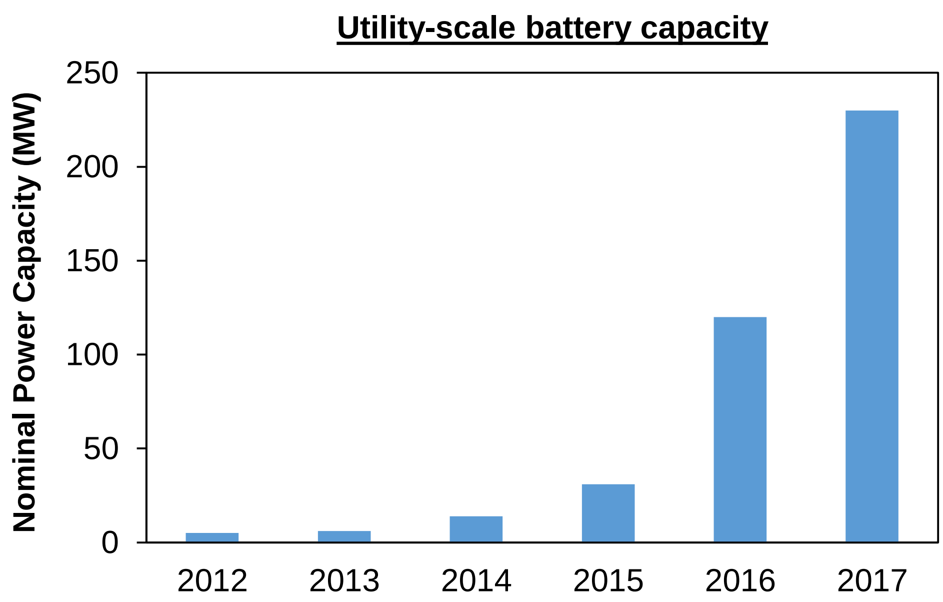
Increased PV self-consumption

Recent investments in storage to provide balancing services show that…

Competitiveness – Frequency regulation



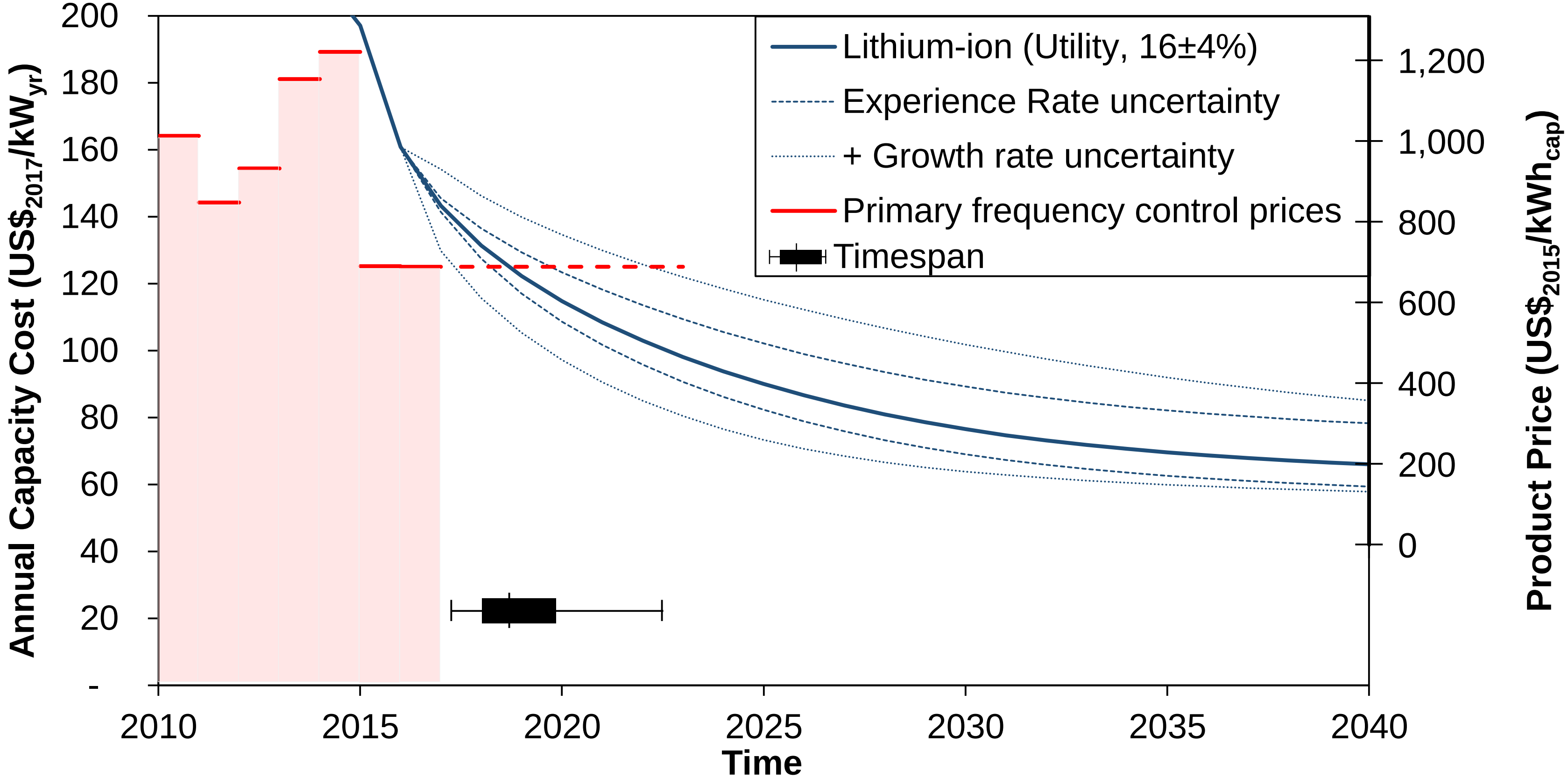
Siemens to deploy market-based grid balancing battery for German utility



Source: https://www.energy-storage.news/news/siemens-to-deploy-market-based-grid-balancing-battery-for-german-utility

… frequency regulation is a business case for electricity storage

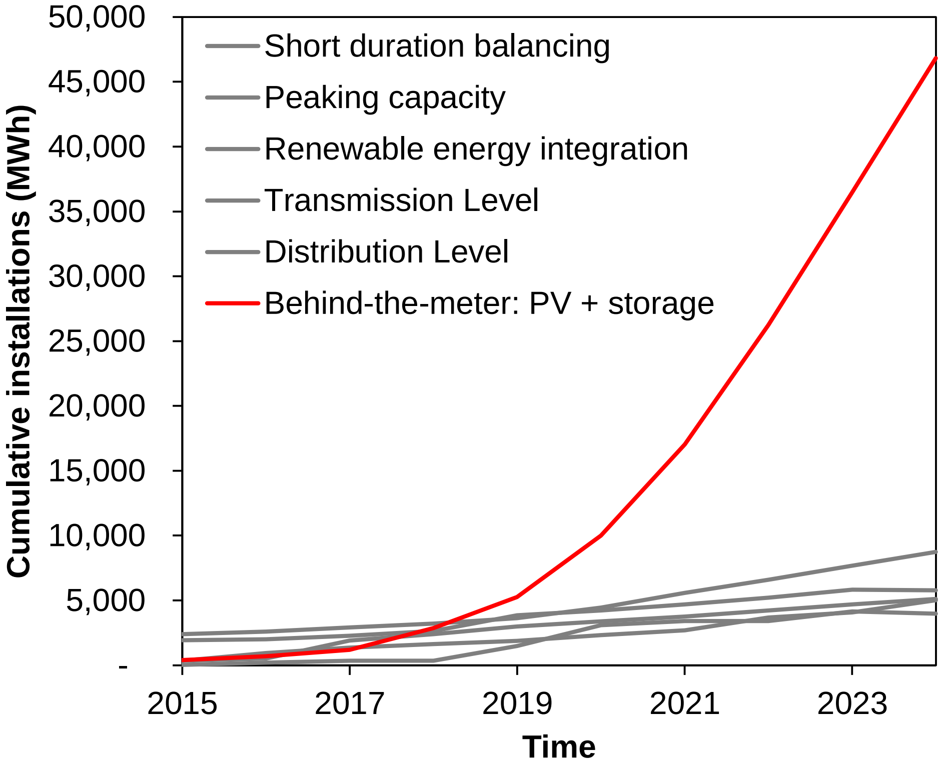
Competitiveness – Frequency regulation



Source: Own Analysis; D.P. Svoboda, D.R. Schemm, M. Bartelt, Aufbruch in den Regelenergiemarkt?, Energ. Manag. (August 2015) 28.

The market for home storage appears poised for growth...

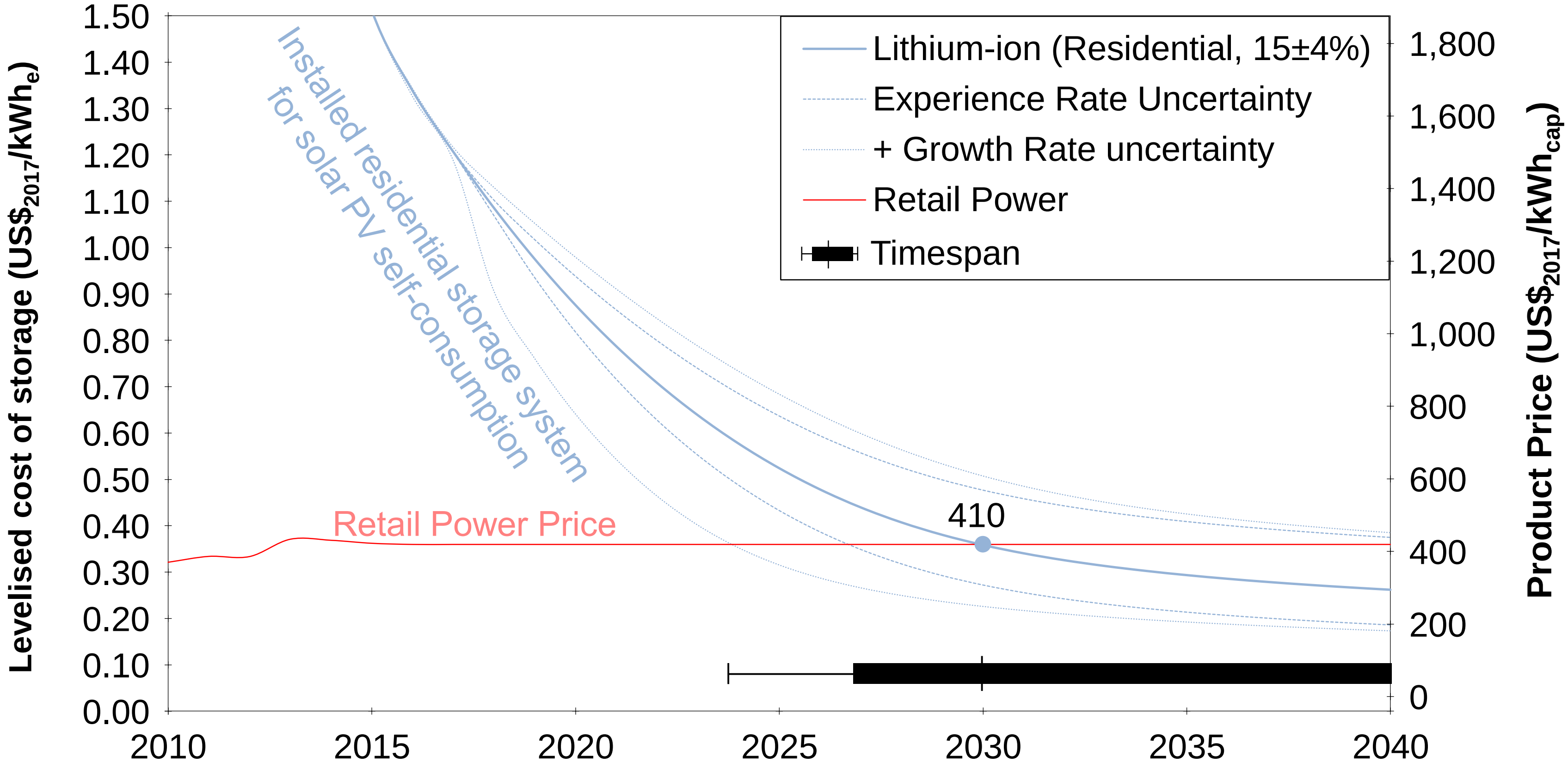
Competitiveness – Increased PV self-consumption



Source: www.tesla.com/powerwall; L. Goldie-Scot, Global Energy Storage Forecast 2016-24, Bloomberg New Energy Finance, 2016.

Still, residential batteries are unlikely to make economic sense in GER before 2030

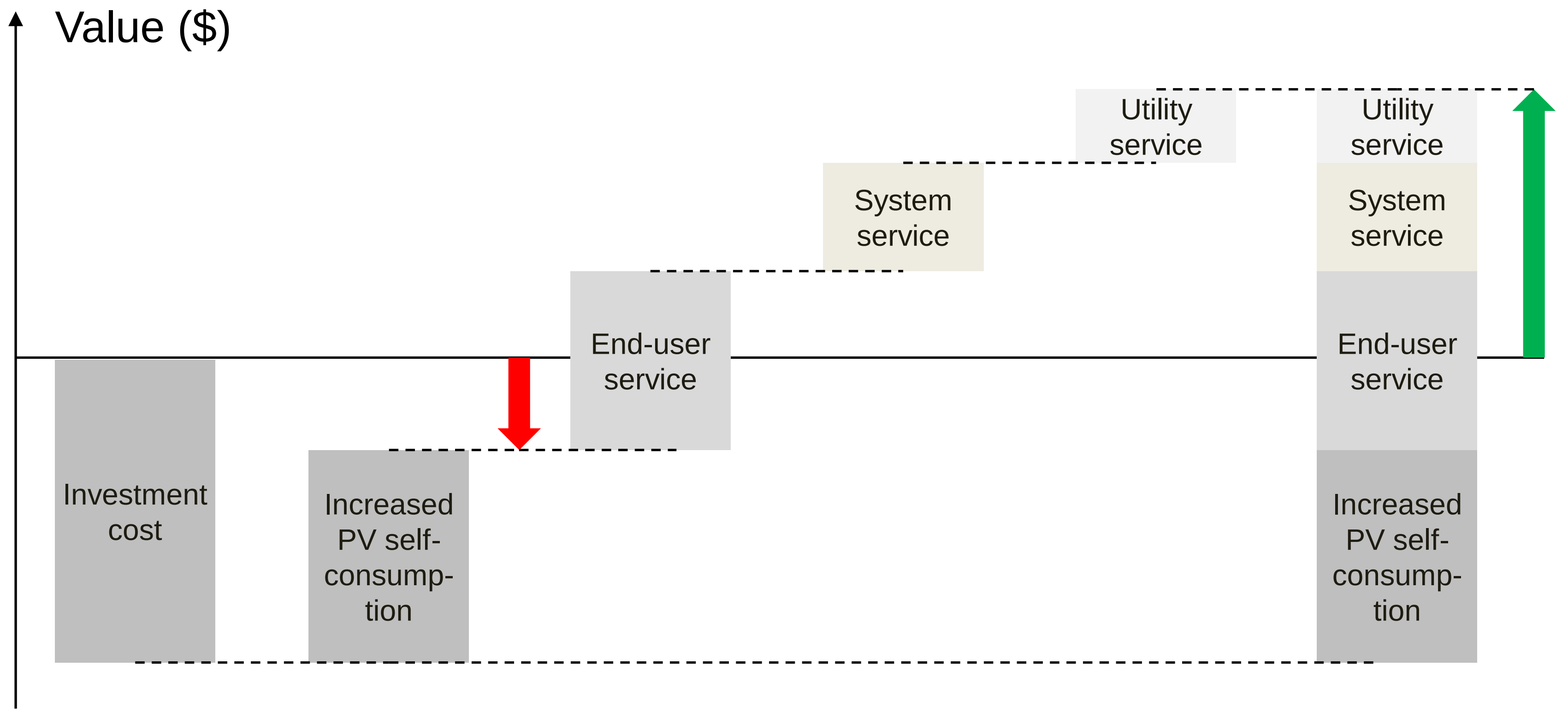
Competitiveness – Increased PV self-consumption



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)

Electricity storage can provide multiple services in parallel, i.e. “benefit-stacking”

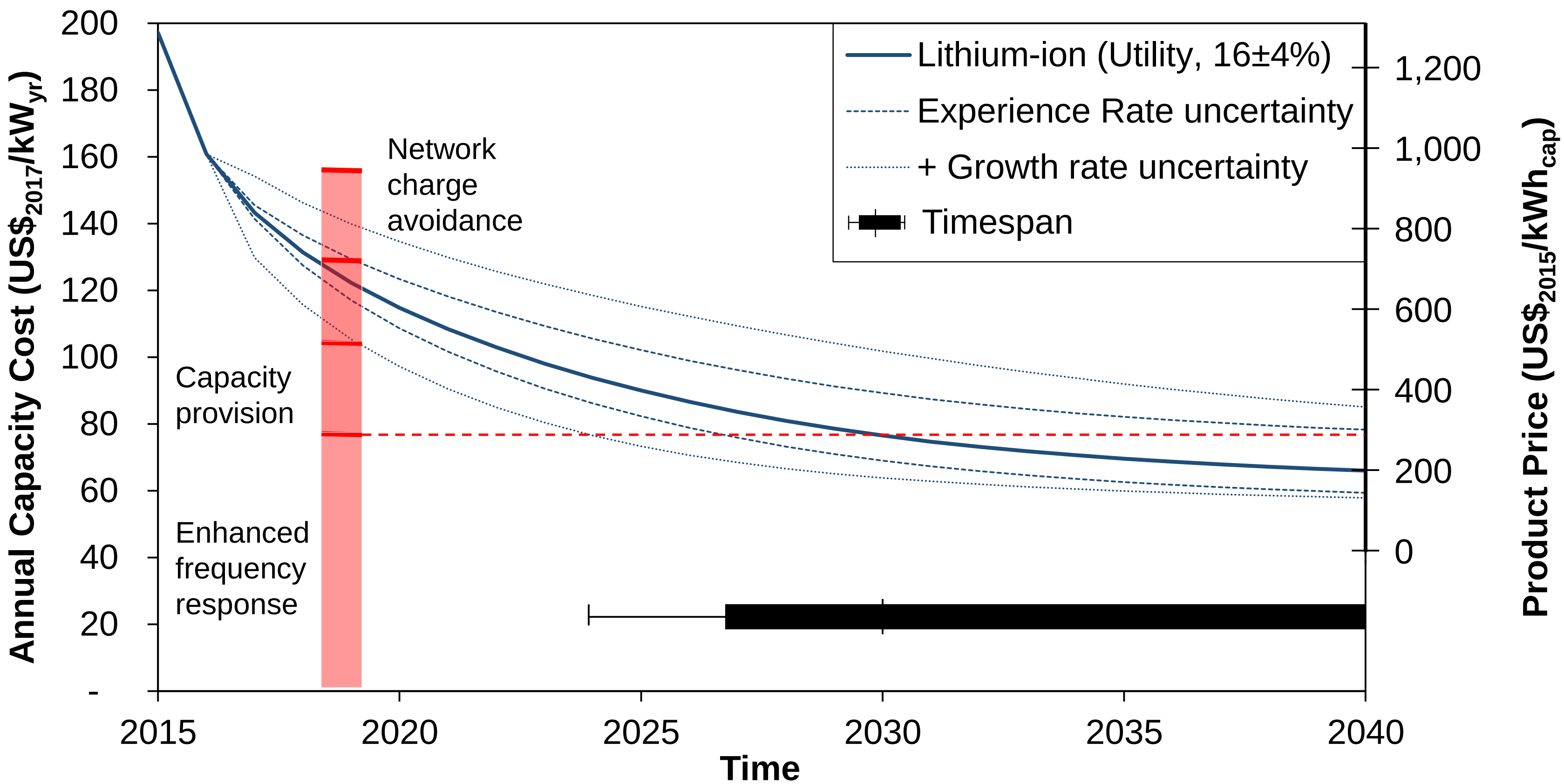
Concept



Source: Own analysis.

Benefit-stacking is a reality for subsidy-free battery projects in the United Kingdom…

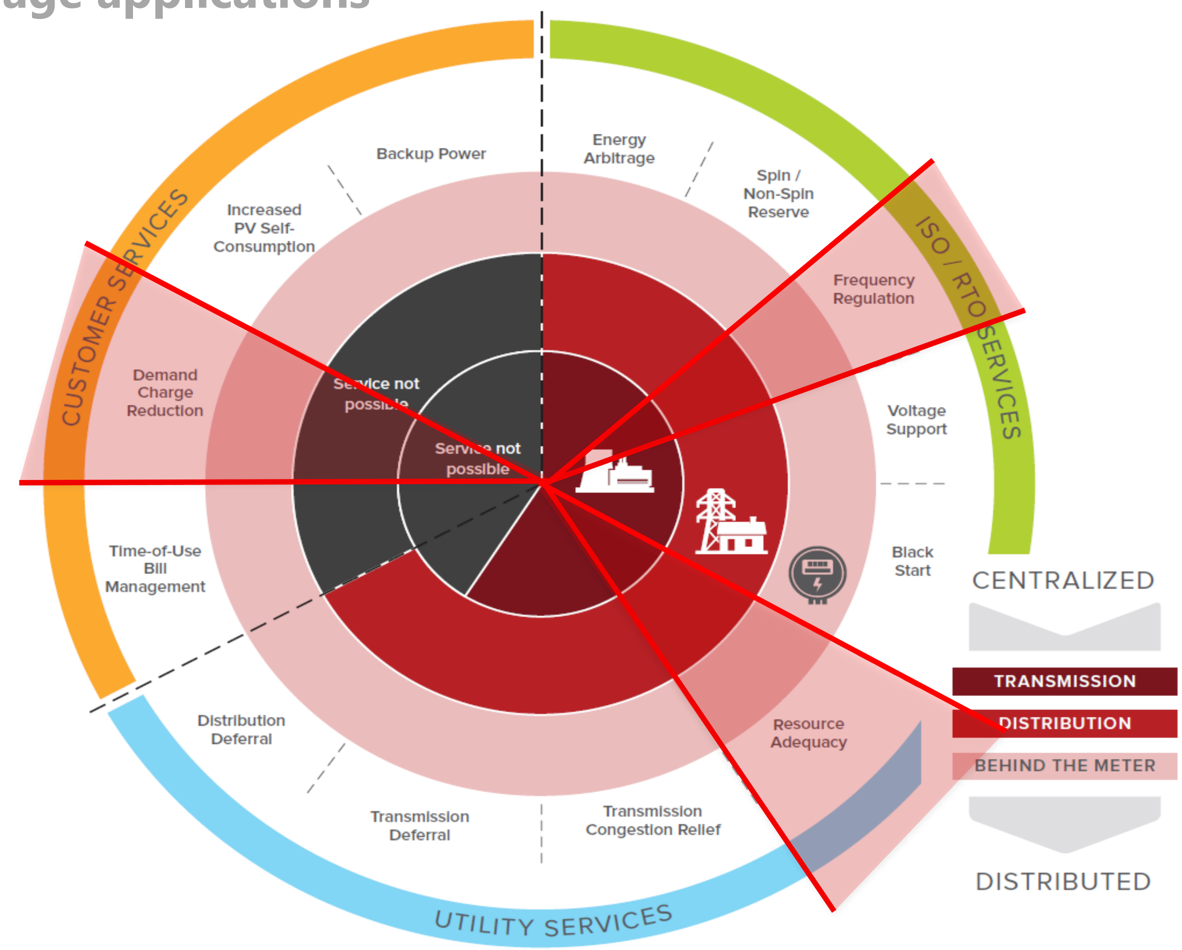
Benefit-stacking in the UK



Source: Own analysis.

...through the combination of three different electricity storage services

Electricity storage applications



Source: The Economics of Battery Storage, RMI, 2015

Low-cost policy measures can enable benefit-stacking

Policy measures

A. Adjust technical standards to open markets for storage technologies
(frequency response: reduce minimum bidding sizes, allow assets operating in dispersed fleets)

B. Amend competition regulation to allow combined value streams
(example: "unbundling" prohibits simultaneous revenues from generation and transmission)

C. Develop consistent legal definition of 'electricity storage'
to ascertain that storage can serve as generation, transmission/distribution and consumption support simultaneously

▶ All three barriers can be removed at low costs

Stephan, A., Battke, B., Beuse, M. D., Clausdeinken, J. H., & Schmidt, T. S. (2016). Limiting the public cost of stationary battery deployment by combining applications. Nature Energy, 1(June), 16079.

Summary

Key messages

1. Investment cost of battery storage technologies will reach cost of pumped hydro.

2. Levelised cost of storage (LCOS) is the metric to be used to compare technologies.

3. Lithium-ion will be most cost-effective in most applications except when long discharge and/or many cycles are required.

4. Electricity storage is expensive, but versatile. Thus, benefit-stacking is the holy grail to profitability and system benefits.

Questions?

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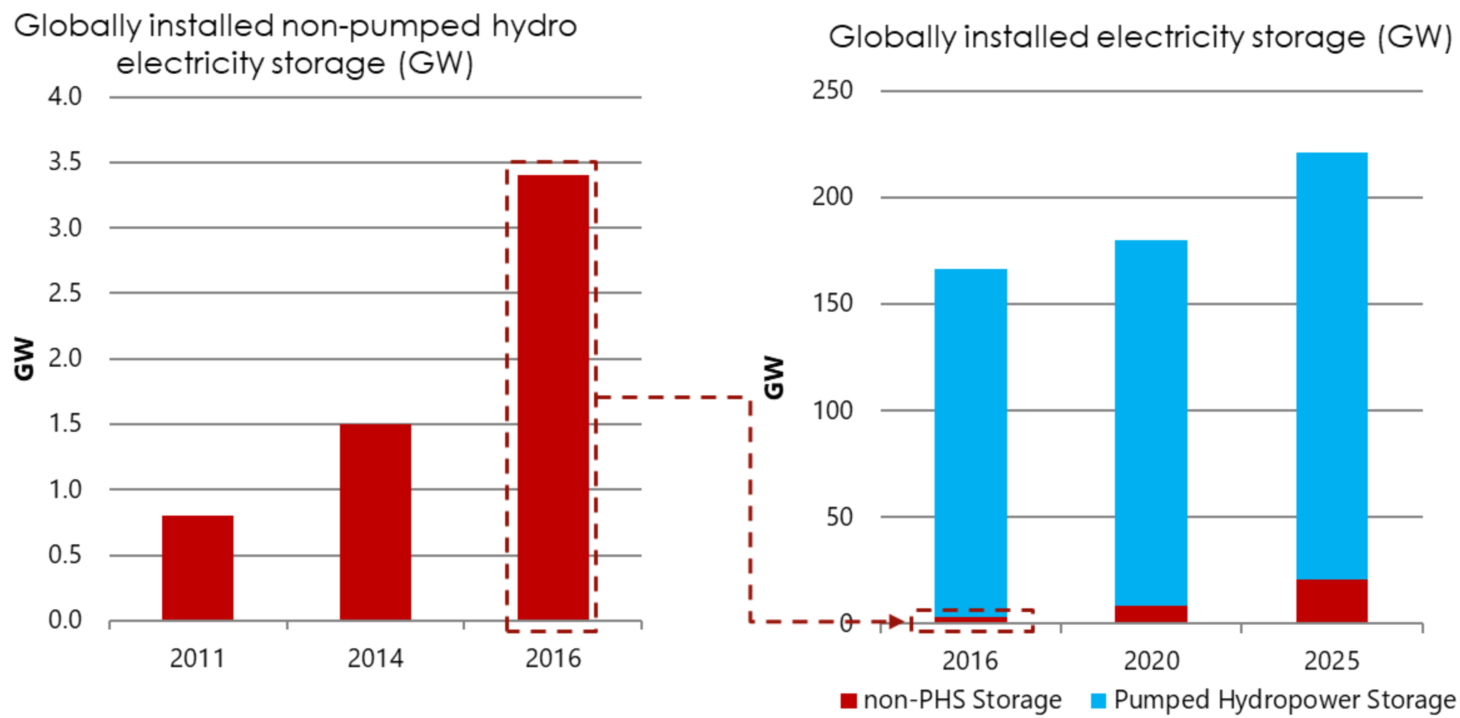
Website: www.storage-lab.com

Global storage capacity is again growing quickly to ensure VRE integration

Non-PHS vs PHS

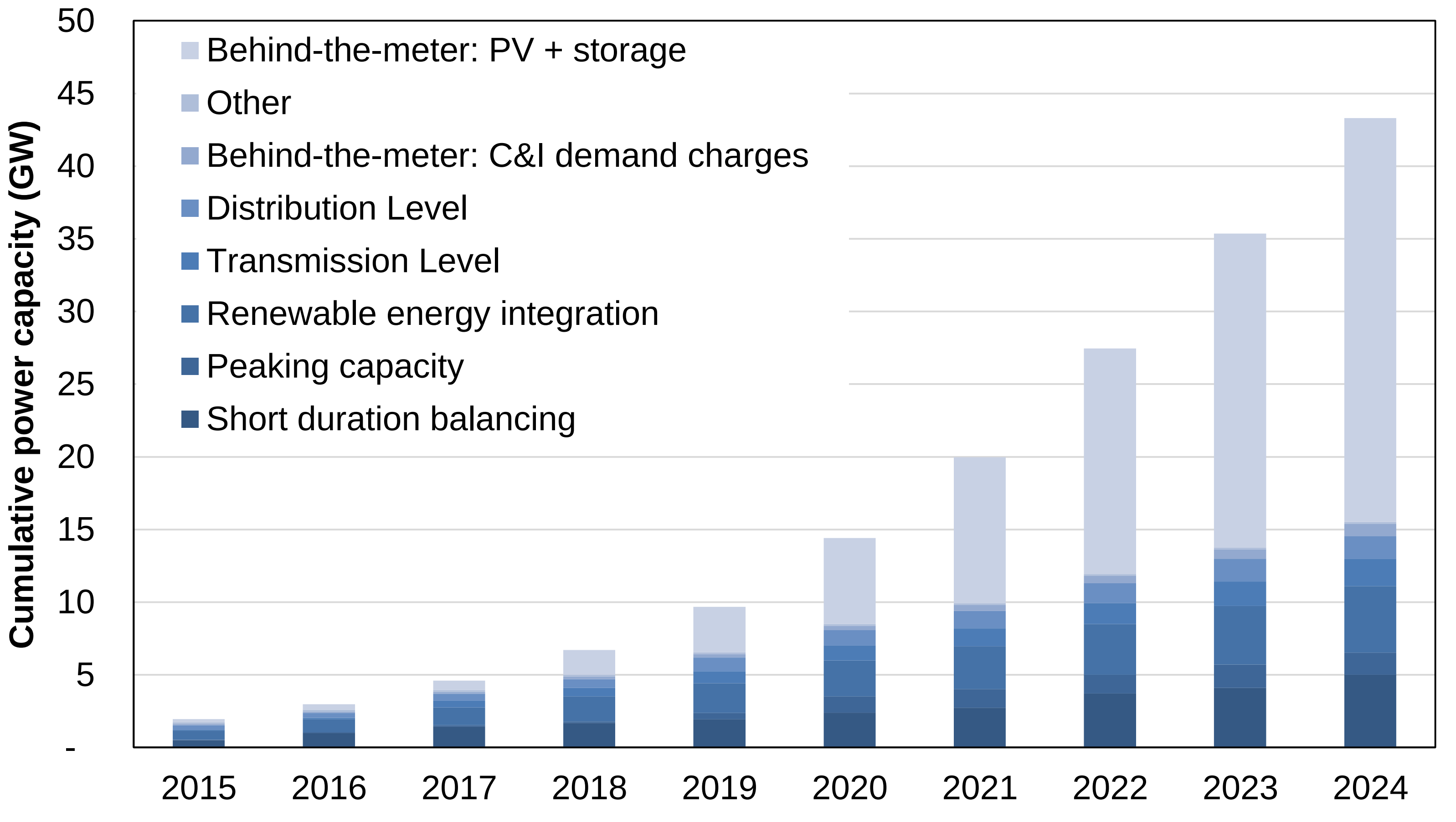


Positive market and policy trends supported annual growth of over 50% for non-pumped hydro storage. Near-term storage needs will remain answered by PHS.

Source: Tracking Clean Energy Progress 2017. International Energy Agency (2017).

Non-PHS capacity growth will mostly be required to integrate self-generated PV

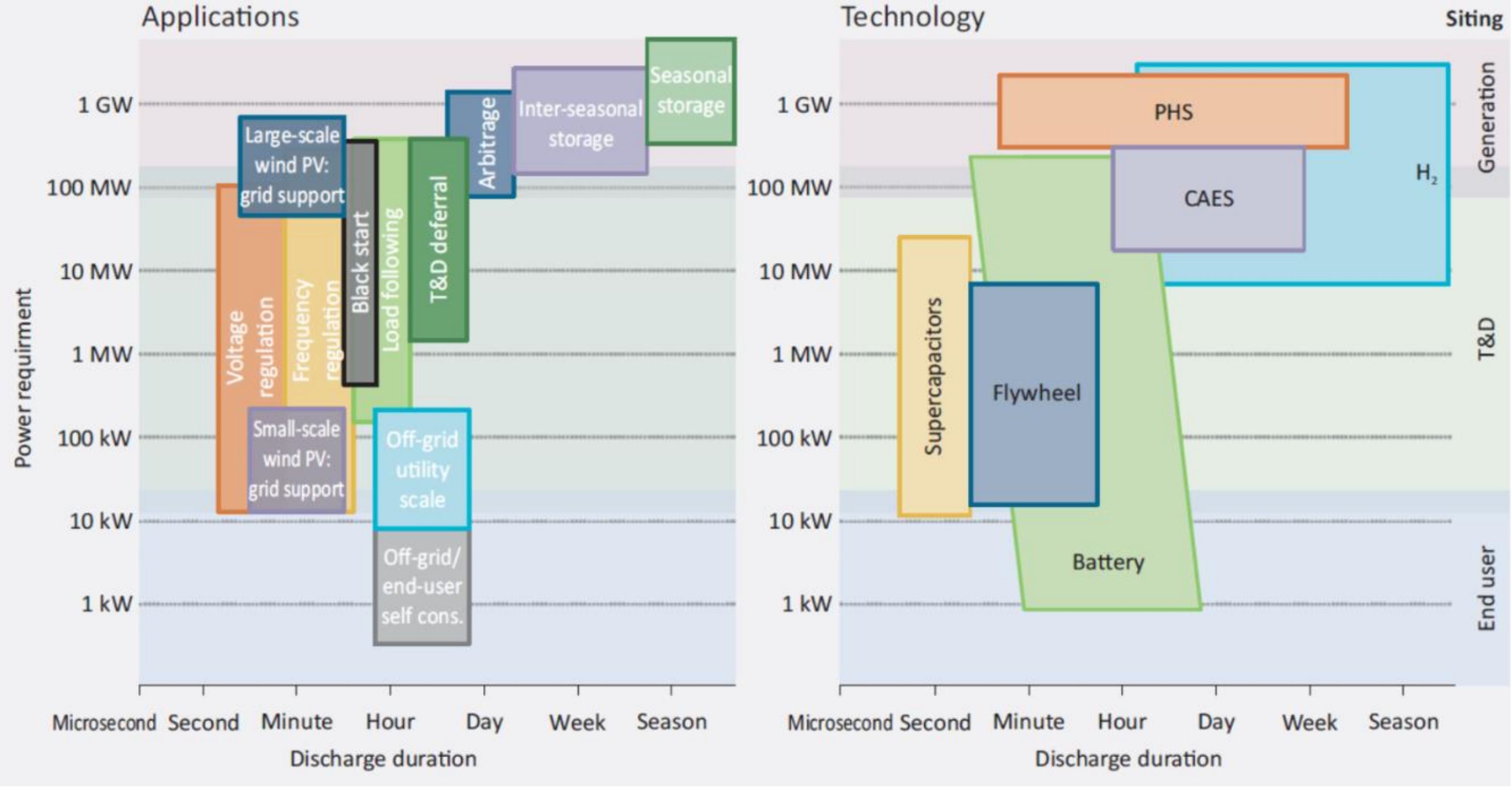
Medium-term outlook for non-PHS storage - Power



Source: Global Energy Storage Forecast, 2016-2024, BNEF (2017)

Application requirements can be met by different energy storage technologies

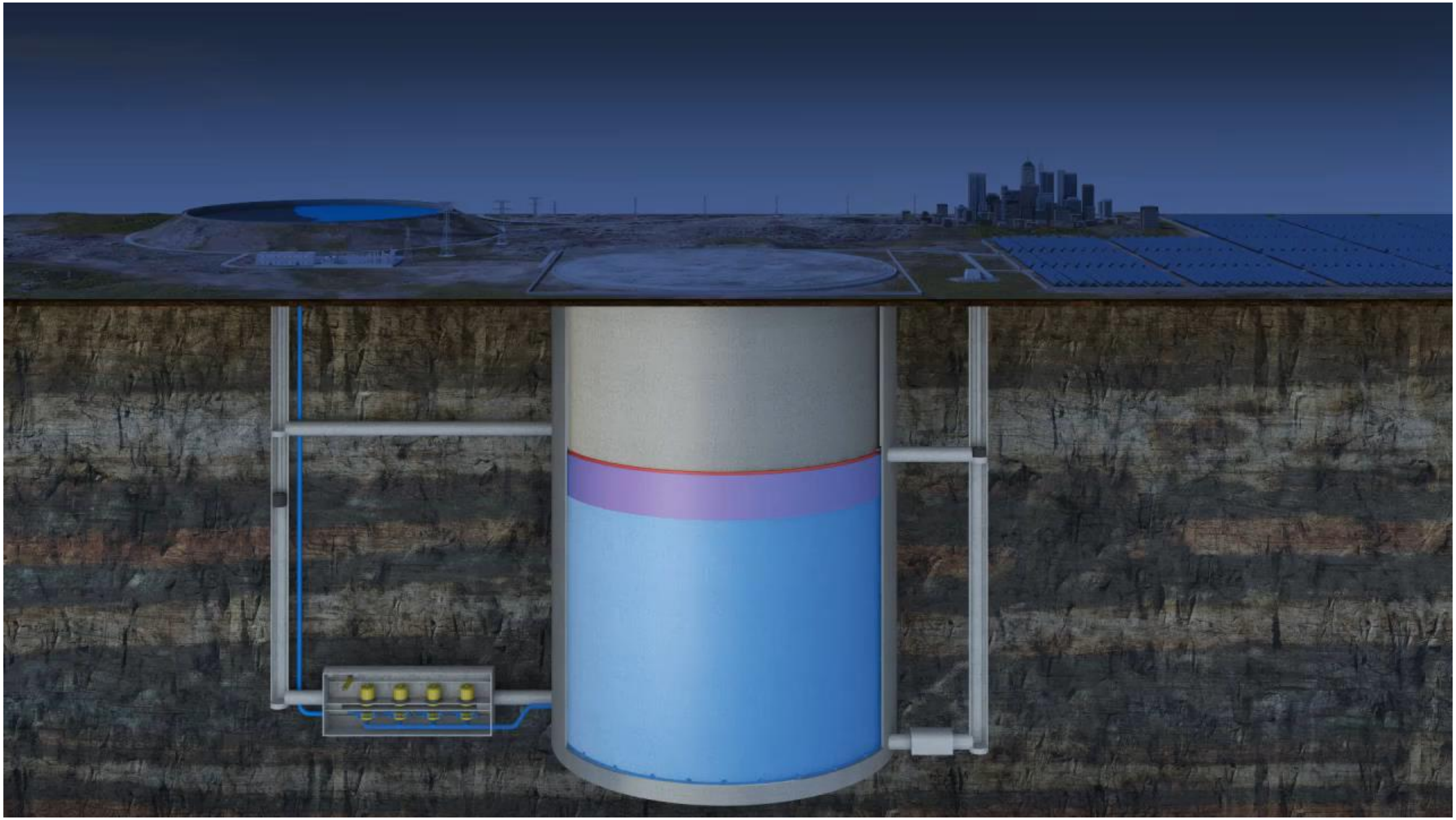
Applications vs Technologies



Source: Energy Technology Perspectives 2014, International Energy Agency (2014).

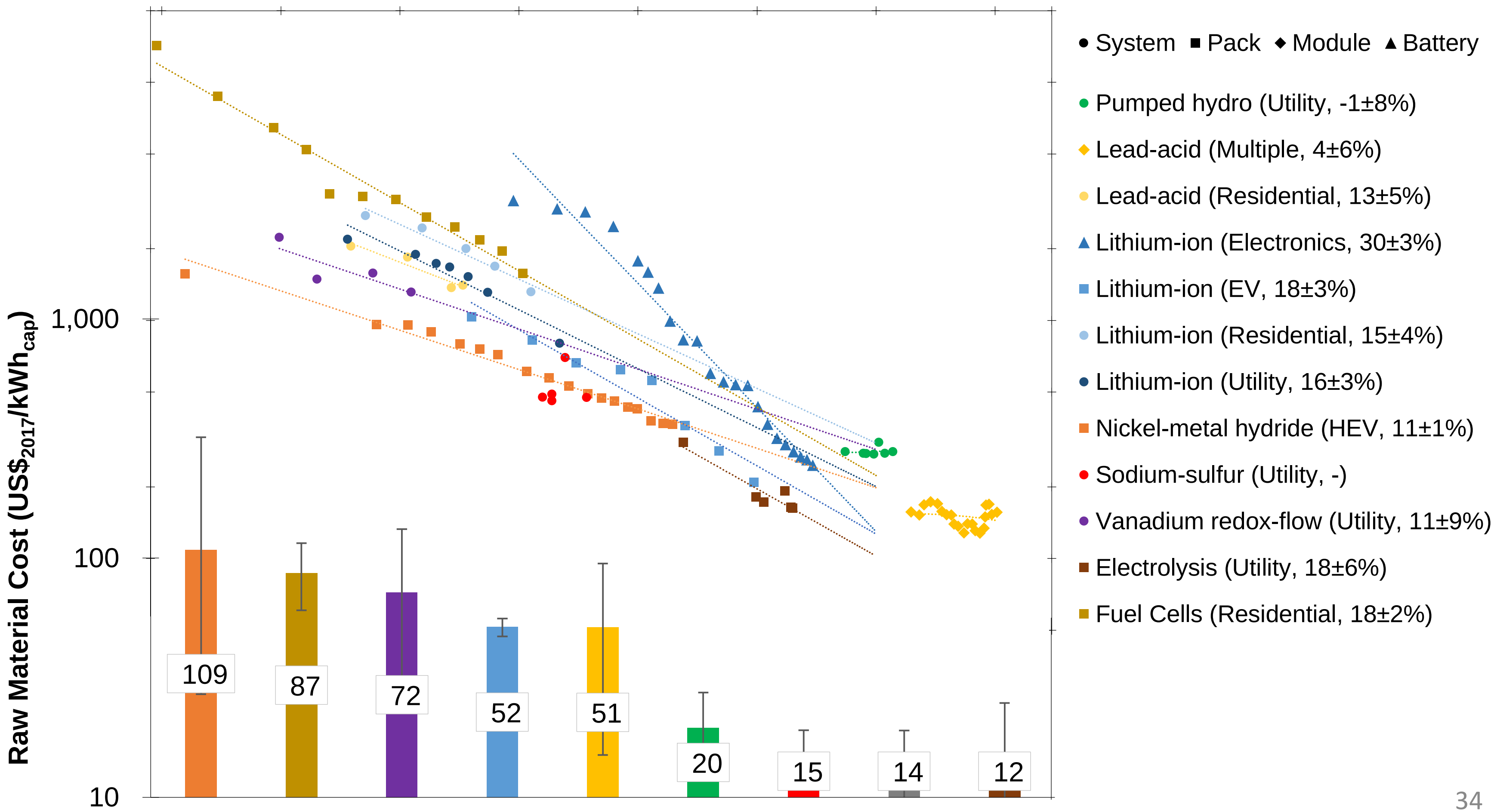
New technologies are constantly being developed

Technologies



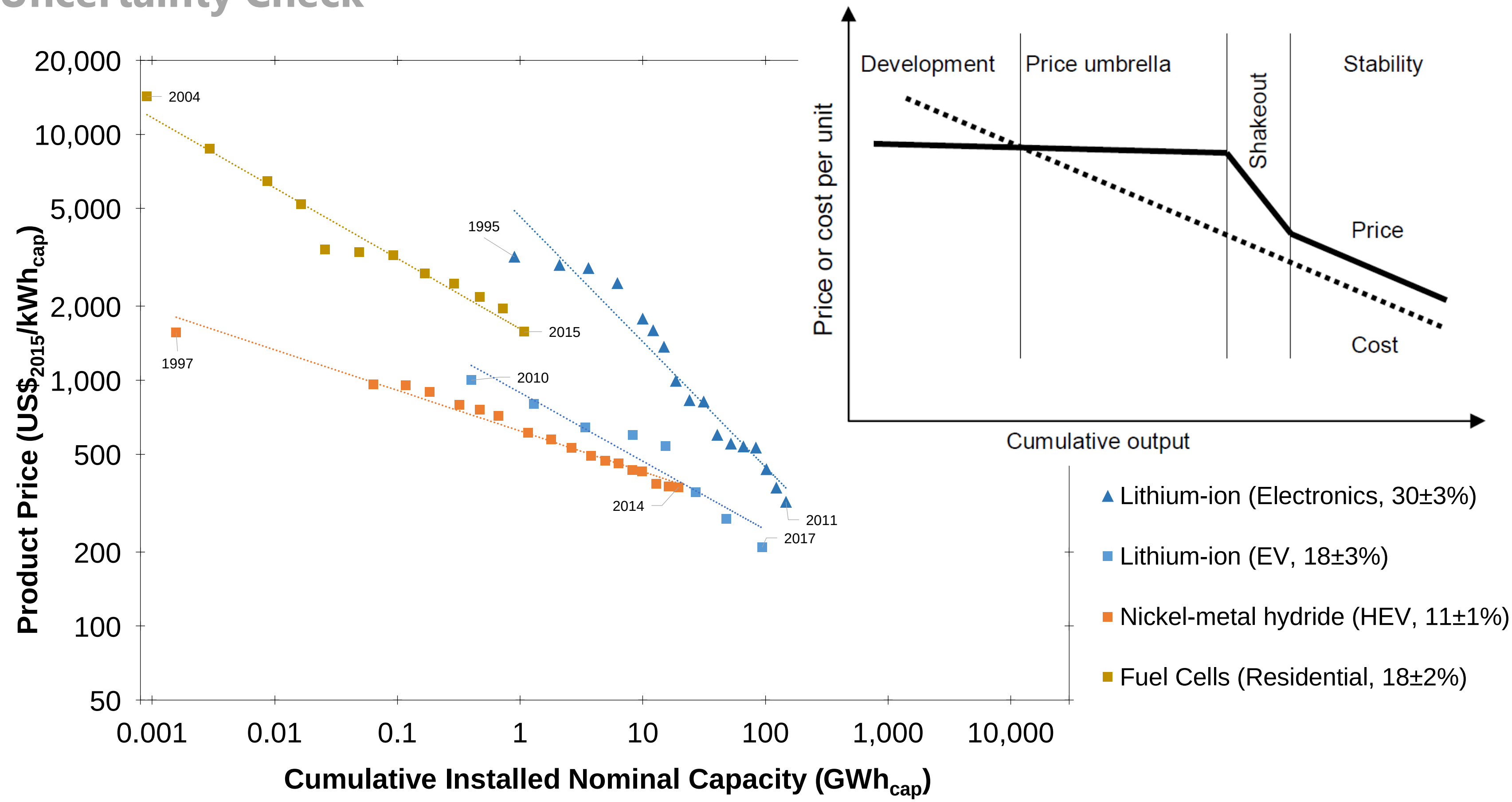
Raw material costs suggest that these cost projections are not infeasible

Sanity Check – Raw material cost



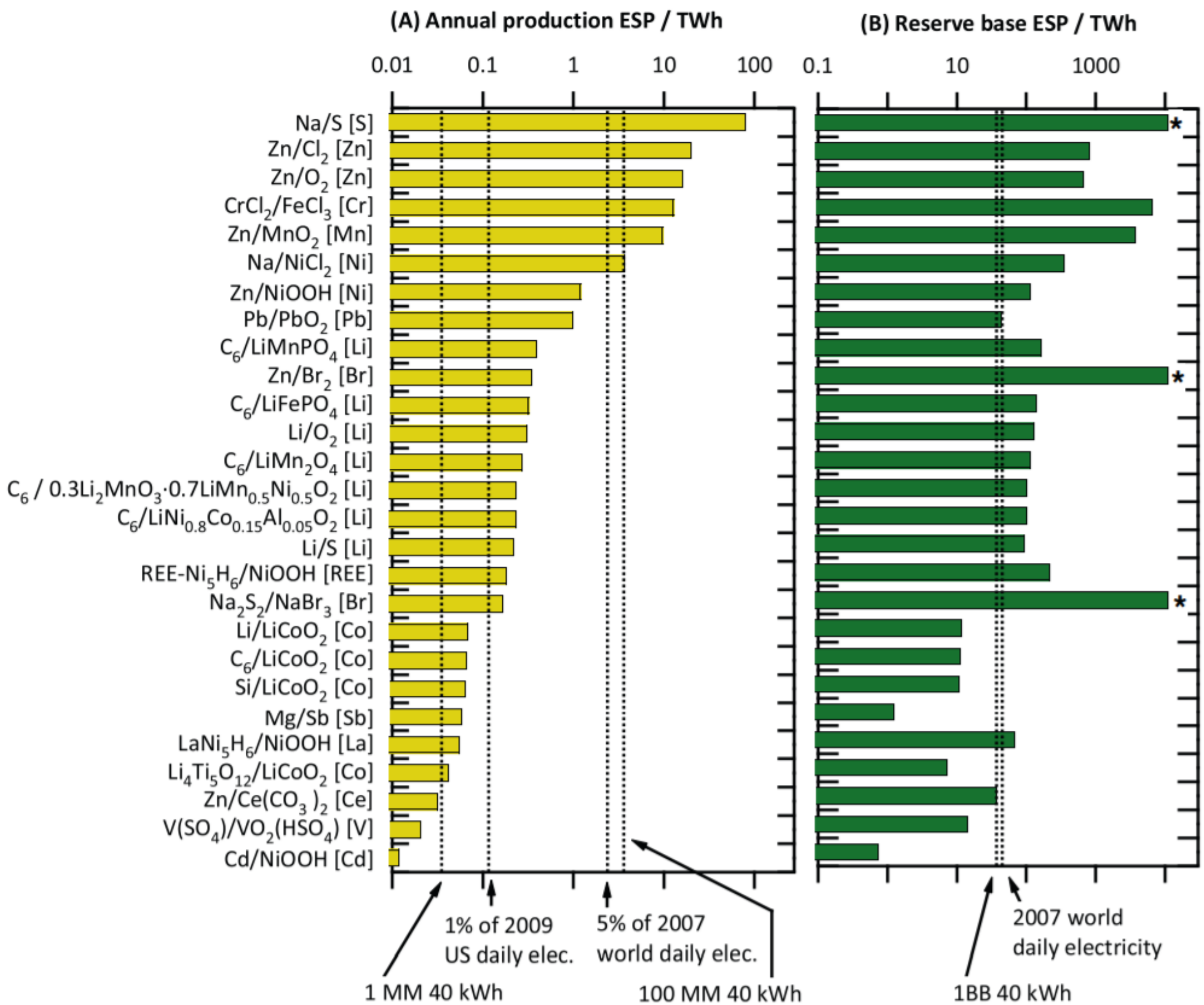
However, experience rates of immature technologies can be highly uncertain

Uncertainty Check



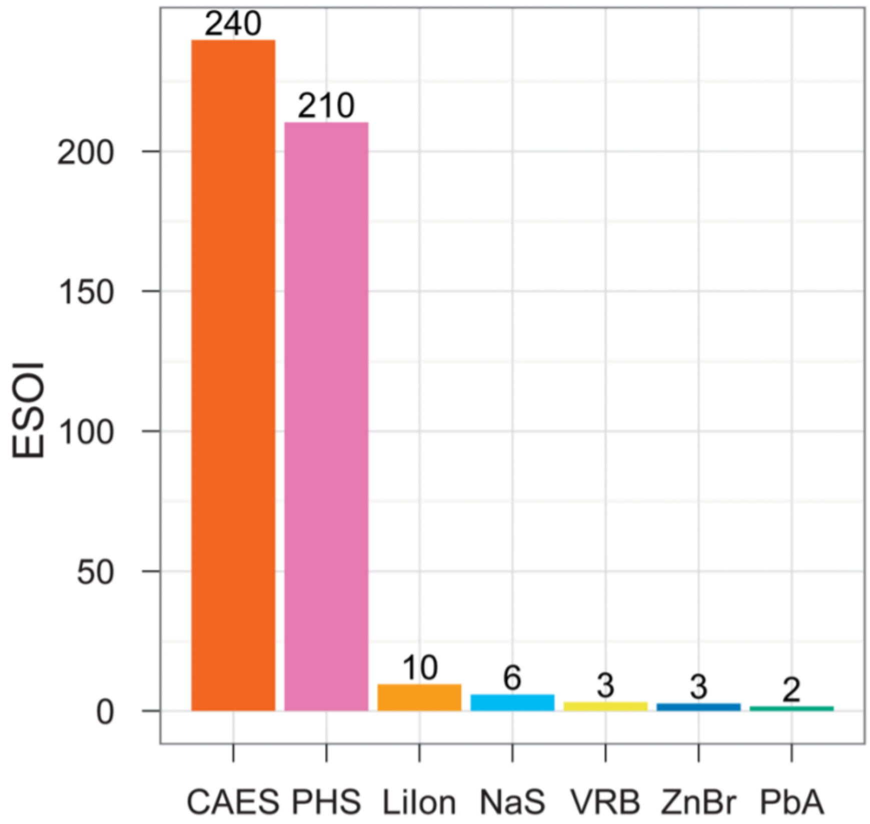
Source: O. Schmidt, A. Hawkes, A. Gambhir & I. Staffell. The future cost of electrical energy storage based on experience rates. Nat. Energy 2, 17110 (2017)

Storage materials – reserve base



Source: Own analysis

ESOI of different storage technologies



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

Formula

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

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

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

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

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

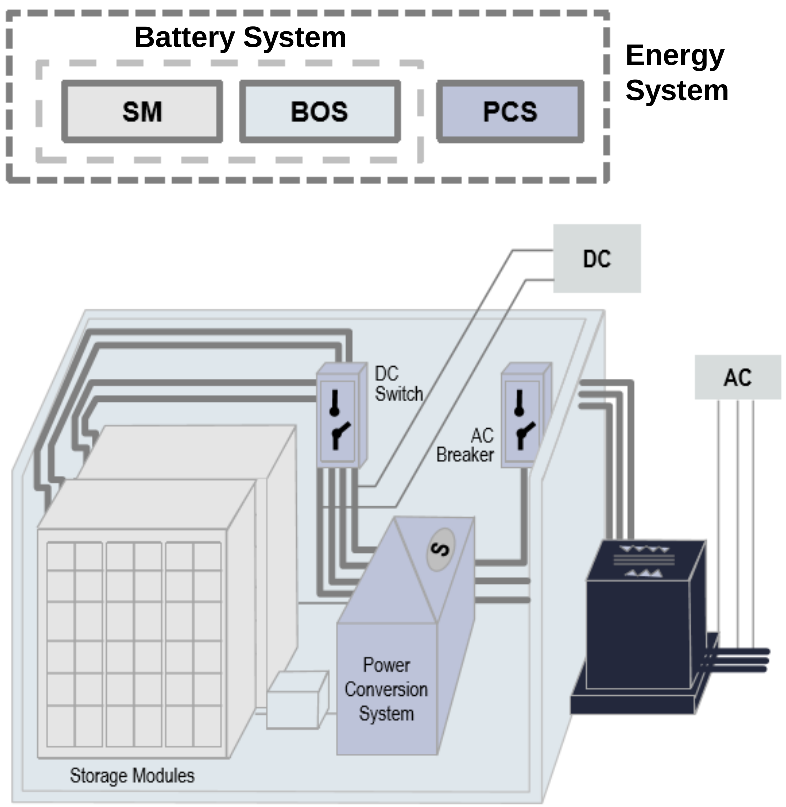
Capex:	Investment cost ($)
$Capex_r$:	Replacement cost ($)
Opex:	Operating cost ($)
Disposal:	Disposal cost ($)
P_{el}:	Power cost ($/kWhel)
r:	Discount rate (%)
C_{nom_e}:	Nominal capacity (MWh)
DoD:	Depth-of-discharge (%)
N:	Lifetime (years)
#cycles:	Full cycles per year (#)
Deg:	Annual degradation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

Energy storage technologies contain a number of components

Technology components

Physical Energy Storage System



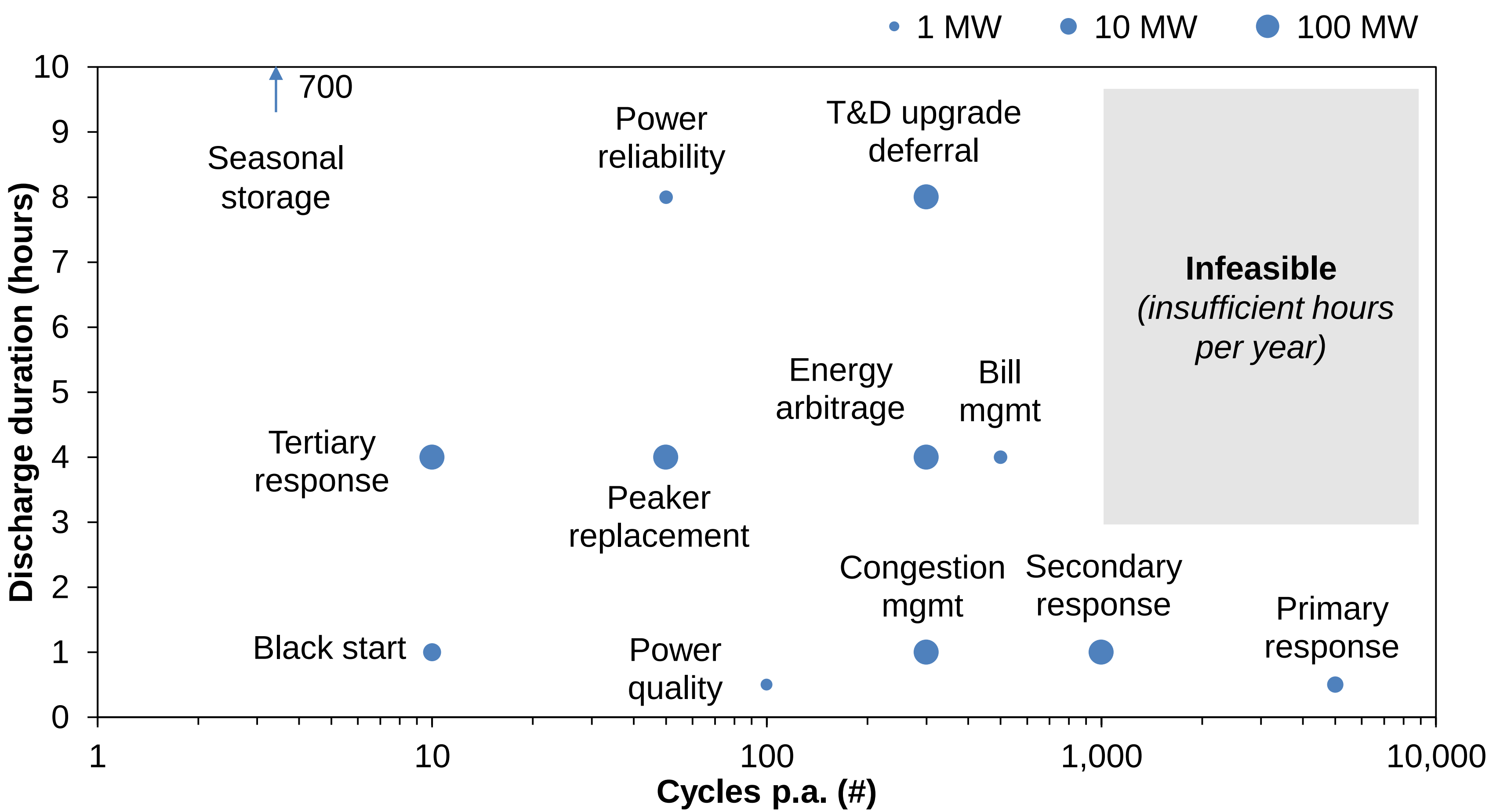
Selected Equipment & Cost Components

System Layer		Component
SM	Storage Module	• Racking Frame/Cabinet • Battery Management System ("BMS") • Battery Modules
BOS	Balance of System	• Container • Monitors and Controls • Thermal Management • Fire Suppression
PCS	Power Conversion System	• Inverter • Protection (Switches, Breakers, etc.) • Energy Management System ("EMS")
EPC	Engineering, Procurement & Construction	• Project Management • Engineering Studies/Permitting • Site Preparation/Construction • Foundation/Mounting • Commissioning
Other (not included in analysis)		• SCADA • Shipping • Grid Integration Equipment • Metering • Land

Source: Lazard's Levelized Cost of Storage Analysis 2017

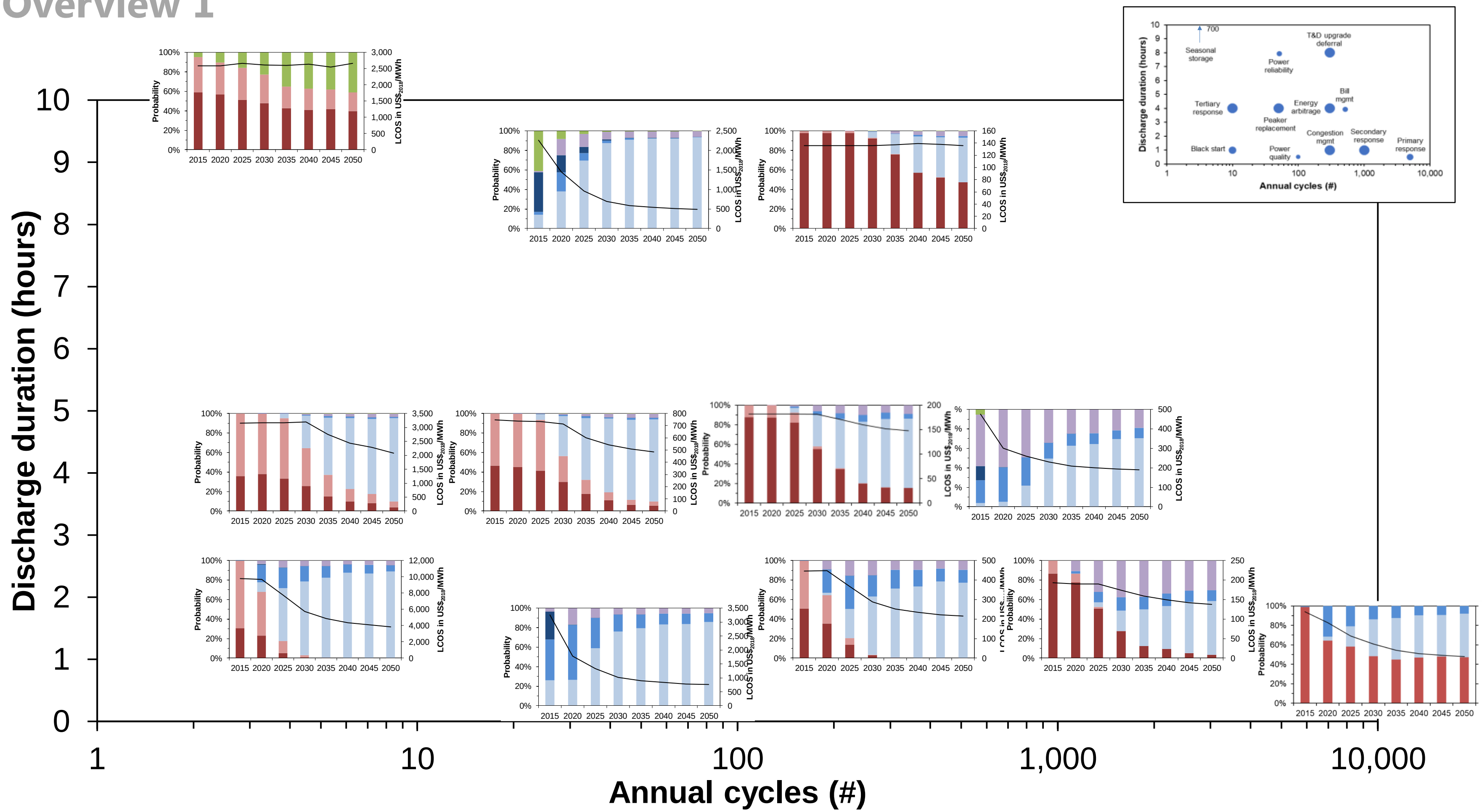
Modelled applications cover entire spectrum of performance requirements

Applications – Detail



LCOS and technology dominance in modelled electricity storage applications

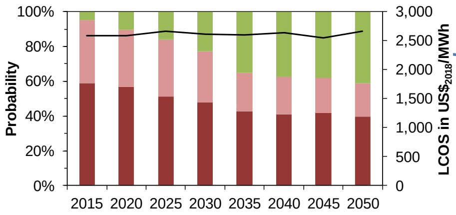
Overview 1



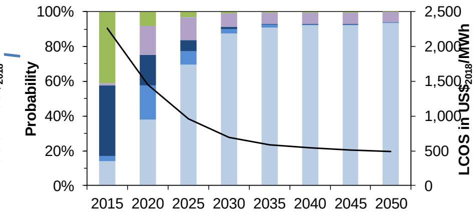
LCOS and technology dominance in modelled electricity storage applications

Overview 2

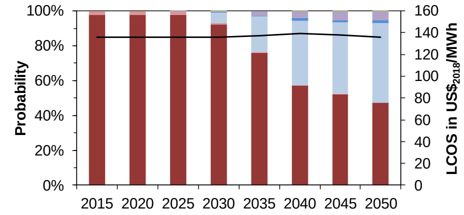
Seasonal storage



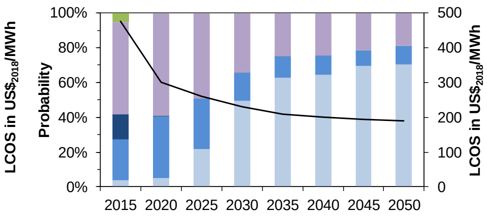
Power reliability



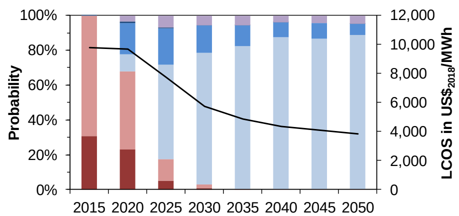
T&D deferral



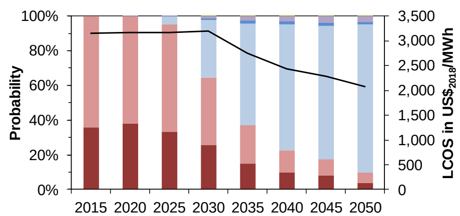
Bill management



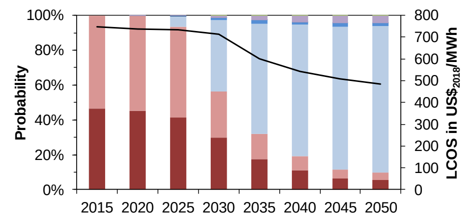
Black start



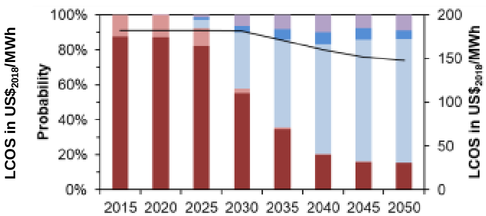
Tertiary response



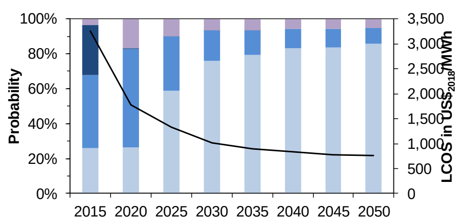
Peaker replacement



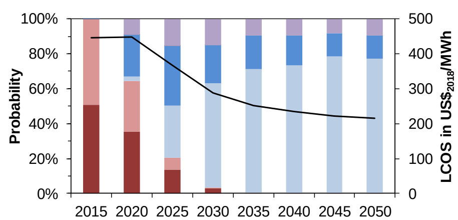
Energy arbitrage



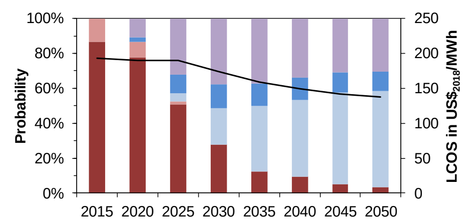
Power quality



Congestion management



Secondary response



Primary response