https://www.irena.org/-/media/Files/IRENA/Agency/Events/2017/Mar/15/2017_Kairies_Battery_Cost_and_Performance_01.pdf

Battery storage technology improvements and cost reductions to 2030: A Deep Dive

International Renewable Energy Agency Workshop

Düsseldorf, 17.03.2017

Kai-Philipp Kairies, ISEA / RWTH Aachen

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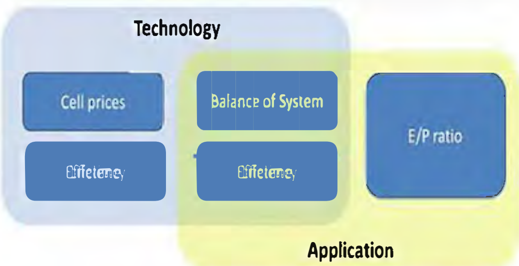
Agenda



- **Battery performance and cost**
  - The current and future cost and performance of battery electricity storage for electric power
- Calculating the cost of service of electricity storage
- Example calculations
  - Load leveling
  - Rural electrification

Overview: Storage Technologies

- Mechanical Storage Systems
  - Pumped Hydro Storage
  - Compressed Air Energy Storage
  - Flywheels
- Lead-Acid Batteries
  - Flooded / VRLA
- High Temperature Batteries
  - NaNiCl / NaS
- Flow Batteries
  - Vanadium Flow / ZnBr Hybrid Flow
- Lithium-Ion Batteries
  - NMC / NCA / LFP / Titanate

Overview: Storage Technologies

- Cost development
  - Energy installation costs [USD/kWh]
  - Power installation costs [USD/kW]
- Electrochemical properties
  - Energy density
  - Power density
  - Power dynamics
- Performance development
  - Cyclic lifetime
  - Calendric lifetime
  - Round-trip-efficiency
  - Self-discharge
  - …

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Overview: Power Conversion Units

- Power conversion units can have a significant influence on the cost of service, depending on the application

- Electric machines
  - PHS / CAES / Flywheel

- Inverter
  - Small scale <= 30 kW
  - Large scale > 30 kW

- No inverter
  - For DC applications

[1]

Overview: Methodology

> 150 literature sources

Expert interviews

[2]

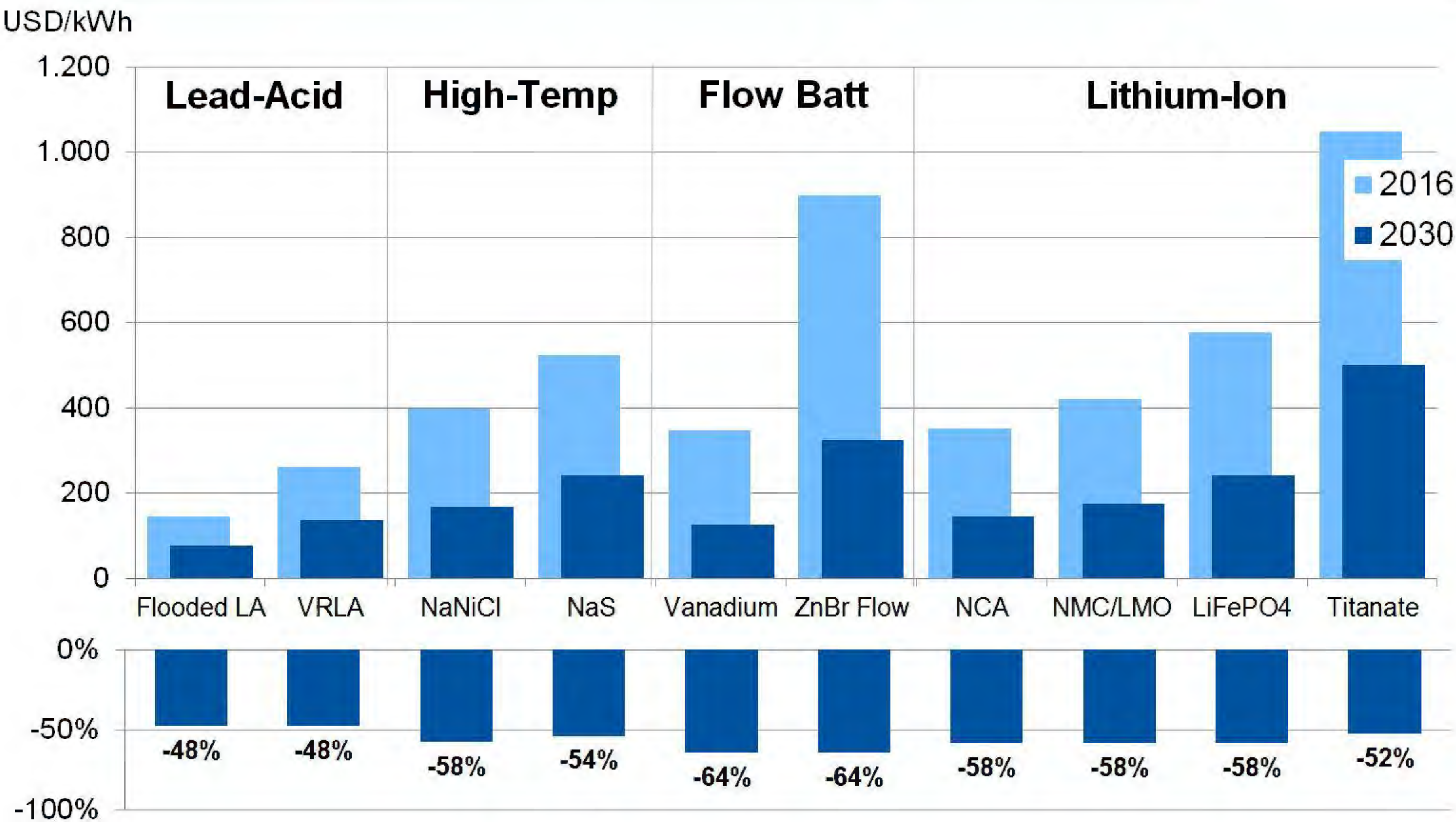
Background report

International Renewable Energy Agency

Events

IRENA event on 'Battery storage cost and market outlook 2030'
15 – 16 March 2017
Düsseldorf, Germany

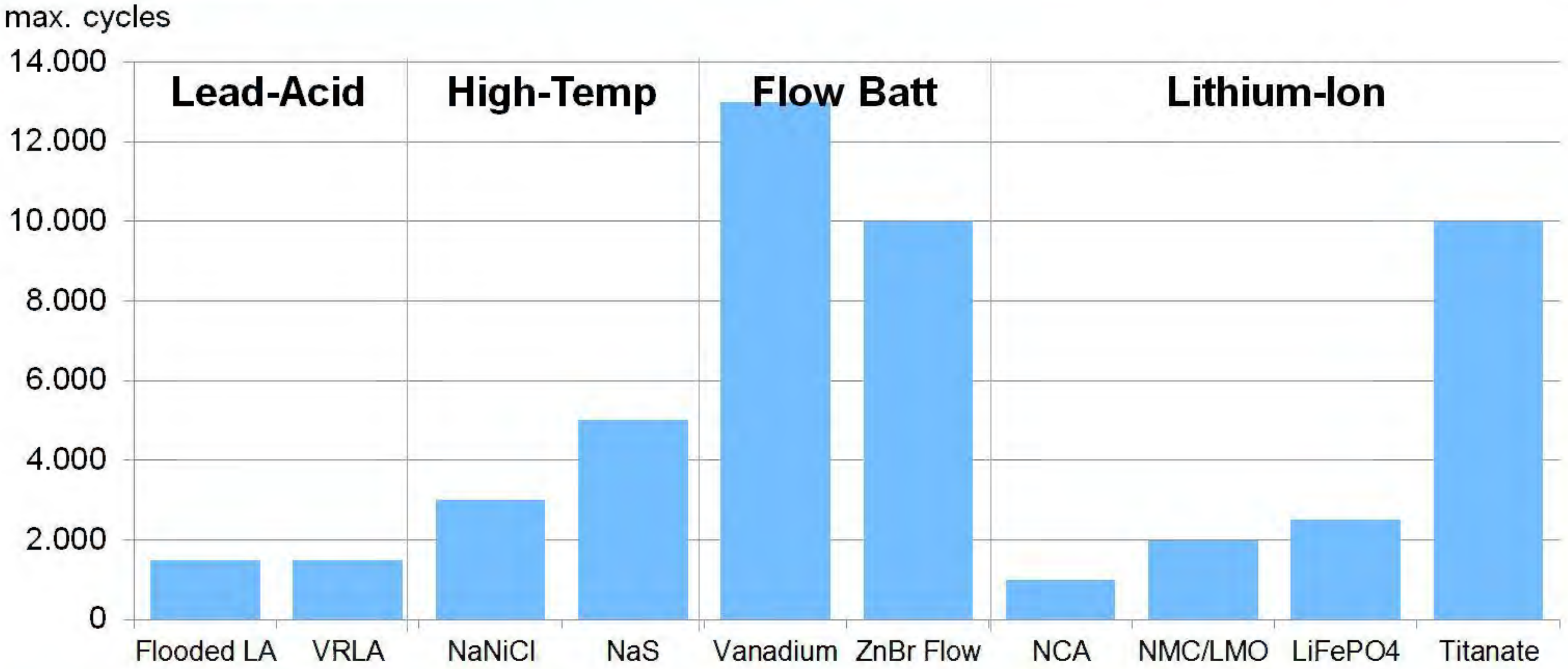
Cost development of different storage technologies



Potentials of multi-use of electric vehicles

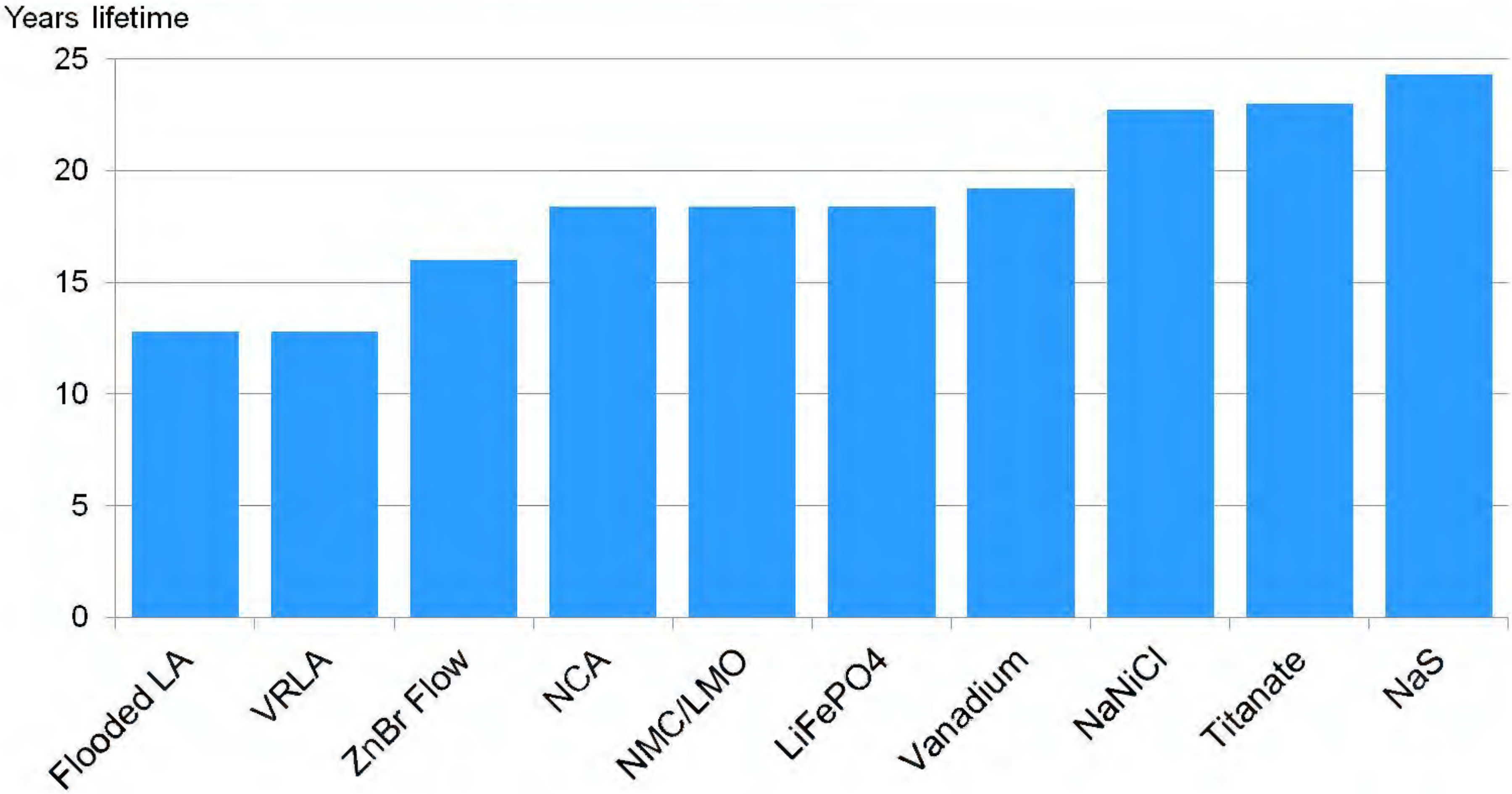
	Location			
Metric	China	Germany	California	UK
Assumed share of electric cars in 2030	30%	20%	20%	20%
Average battery capacity of electric cars [kwh]	20	20	20	20
Average charging power [kW]	22	22	22	22
Average percentage of cars connected to charger at all times	5%	5%	5%	5%
Inhabitants [Mio]	1,357	80	39	64
Number of automobiles [Mio]	175	45	29	32

Performance: Batteries are already offering excellent lifetimes (cyclic lifetime, 2016)

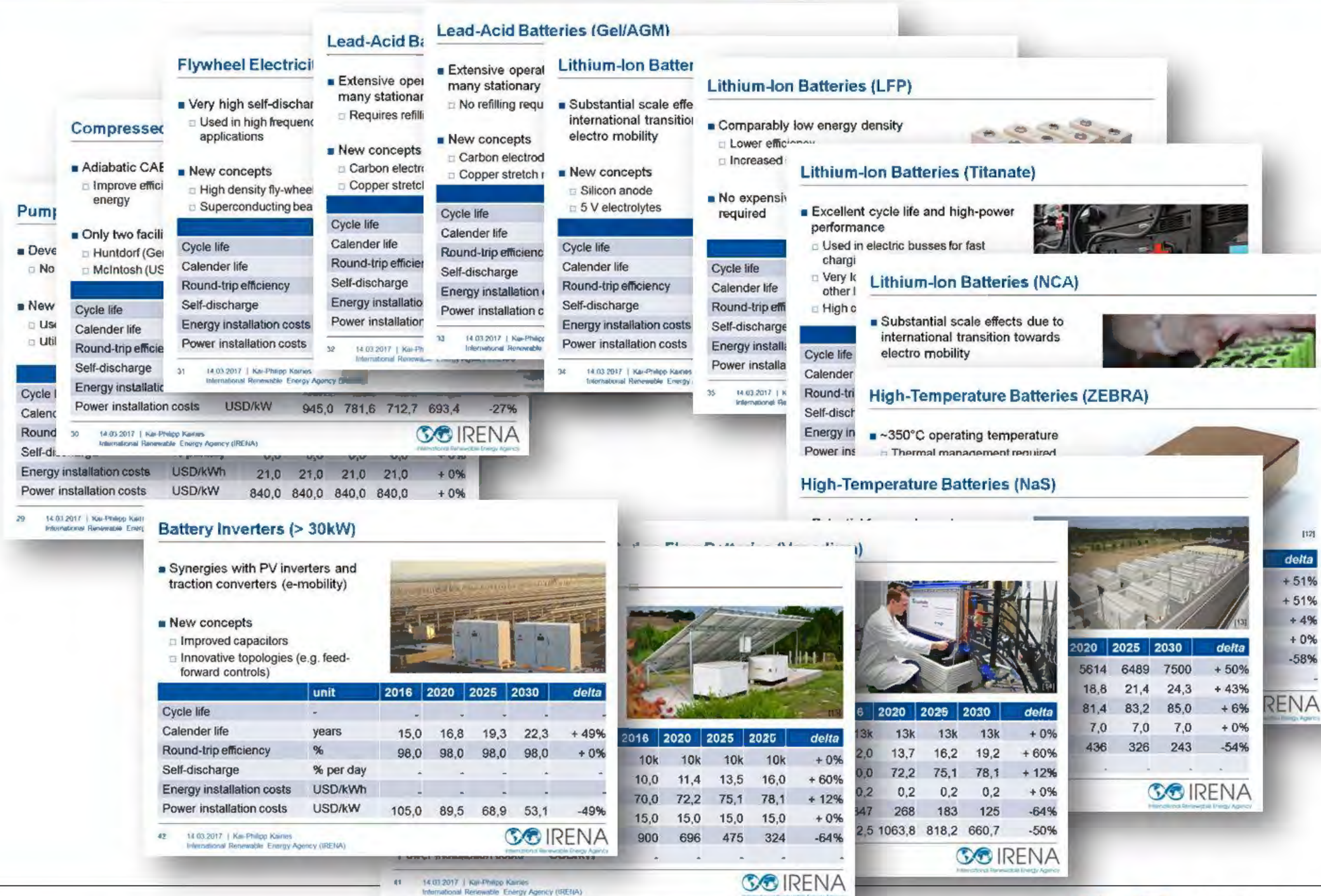


- Calendric aging most important factor
- Stationary applications: Storage systems often do not utilize their maximum cycles

Performance: Batteries are already offering excellent lifetimes (calender lifetime, 2030)



Detailed information for 15 storage technologies available



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Main Development Drivers
Lead-Acid Batteries (Flooded and VRLA)

- Production automation
  - Stationary lead-acid batteries are often produced in semi-automated plants
  - Scales and production automation can substantially decrease prices

- Further optimization of the cell design and additives promise to increases performance

- Largest risk: Competition of lithium-ion batteries in traditional lead-acid applications

- Innovative developments
  - Copper stretch metal
  - Carbon added electrodes
  - Hybridization (e.g. combining with lithium-ion or flywheels)

Main Development Drivers Lithium-Ion Batteries

- Differentiation between 4 different technologies
  - NMC/LMO, NCA, LFePO4 and Titanate
- International transition towards electro mobility leads to substantial scale effects (NCA NMC/LMO)
  - 70% price reduction since 2012
- > 170 GWh / year production capacities projected for 2020
  - Tesla Gigafactory / BYD / CALB /…
  - LG Chem / Foxconn / CATL / …


[11]

- Innovative developments
  - Mass production
  - Utilize silicon in anode
  - Durable LMO cathodes
  - 5 V electrolytes
  - Lithium-Sulphur
  - Lithium-Air

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International Renewable Energy Agency (IRENA)

Main Development Drivers
High-Temperature Batteries (NaS and ZEBRA)

- Sodium Sulfur (NaS)
  - Potential for very low cost active materials
  - Corrosion needs to be controlled

[13]

- "Low temperature" electrolytes (~150 °C) can
  - Reduce corrosion / Increase lifetime
  - Reduce thermal self-discharge
  - But low max. power, only stationary applications

- Innovative developments
  - Larger cell stacks promise cheaper production costs
  - Development of low cost corrosion resistant materials (e.g. coatings, joints, …)

Main Development Drivers
Flow Batteries (Vanadium and ZnBr)

- Flow batteries offer an independent design of storage- and power capacity
  - Optimal for high E/P ratio applications
- Production of larger cell packs promises higher outputs at lower costs
- In order to compete, electrolyte and active material costs need to fall below 100 USD/kWh

- Innovative developments
  - Improved membrane production
  - Improve calendric lifetime of electrolyte
  - Aqueous electrolytes (saltwater) flow batteries

Agenda

- Battery performance and cost
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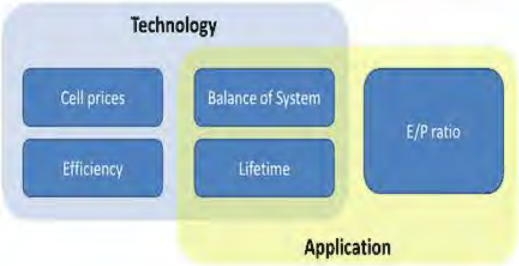

- **Calculating the cost of service of electricity storage**

- Example calculations
  - Load leveling
  - Rural electrification

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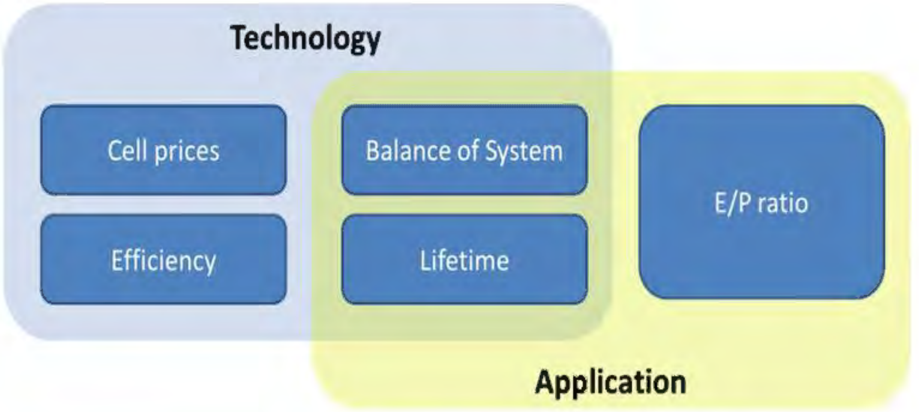
Calculating Cost of Service for ESS

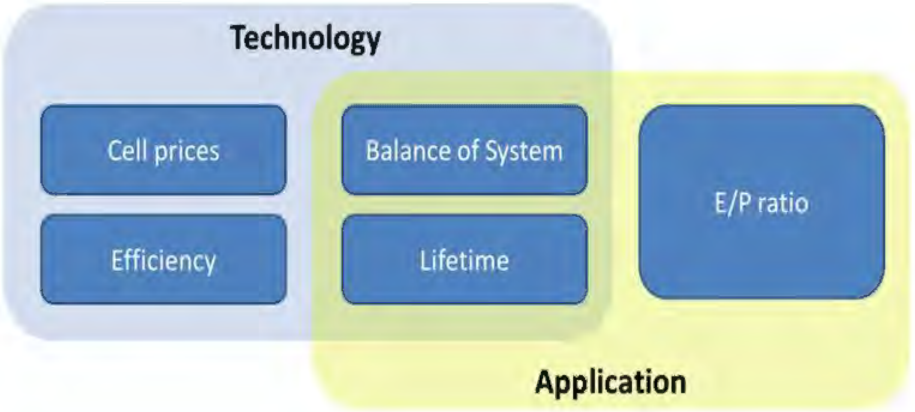
- Definition of „Cost of Service“
  - Different value of storage depending on application (energy vs. power)
  - Different battery lifetime depending on application



- Applications defined by four parameters
  - Power
  - E/P ratio
  - Cycles per day
  - Electricity price

Calculating Cost of Service for ESS

- Definition of „Cost of Service“
  - Different value of storage depending on application (energy vs. power)
  - Different battery lifetime depending on application



- Applications defined by four parameters

+ Invest (Energy Storage Unit)
+ Invest (Power Conversion Unit)
+ Invest (Other, i.e. planning, land)
+ Conversion losses
+ Self-discharge losses
+ Maintenance (Energy Storage Unit)
+ Maintenance (Power Conversion Unit)
+ Running costs (Other, i.e. rent)

Storage Application

- Grid Services
  - Enhanced Frequency Response
  - Frequency Containment Reserve
  - Frequency Restoration Reserve
  - Energy Shifting

- Behind-the-meter
  - Solar Self consumption
  - Community Storage
  - Increased Power Quality
  - Peak Shaving
  - Time-of-Ise

- Off-grid
  - Nano-grid
  - Village Electrification
  - Island Grid

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Effect of different locations / countries

- Local conditions can have a significant impact on the calculation of Cost of Service
  - Land costs
  - Interest rate
  - Grid connection point
  - Electricity price
  - Maintenance costs
    - Temperature / Humidity / Salt spray
    - Costs of labour

- Different storage system design for different parts of the world

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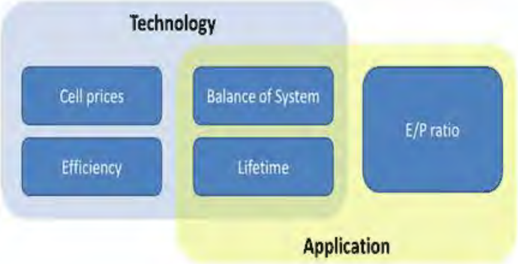
Agenda

- Battery performance and cost
  - The current and future cost and performance of battery electricity storage for electric power



- Calculating the cost of service of electricity storage

- **Example calculations**
  - Load leveling
  - Rural electrification

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Example 1: Peak shifting („power applications")

Application

- Industrial peak shaving
  - 200 kW rated power
  - 5 kWh nomical capacity
  - 0,6 cycles per day

Storage Technologies

- Li-Ion (LFP)
- Li-Ion (Titanate)
- Redox-Flow (ZbBr)

Results

- Cost of power per year [USD/kW]

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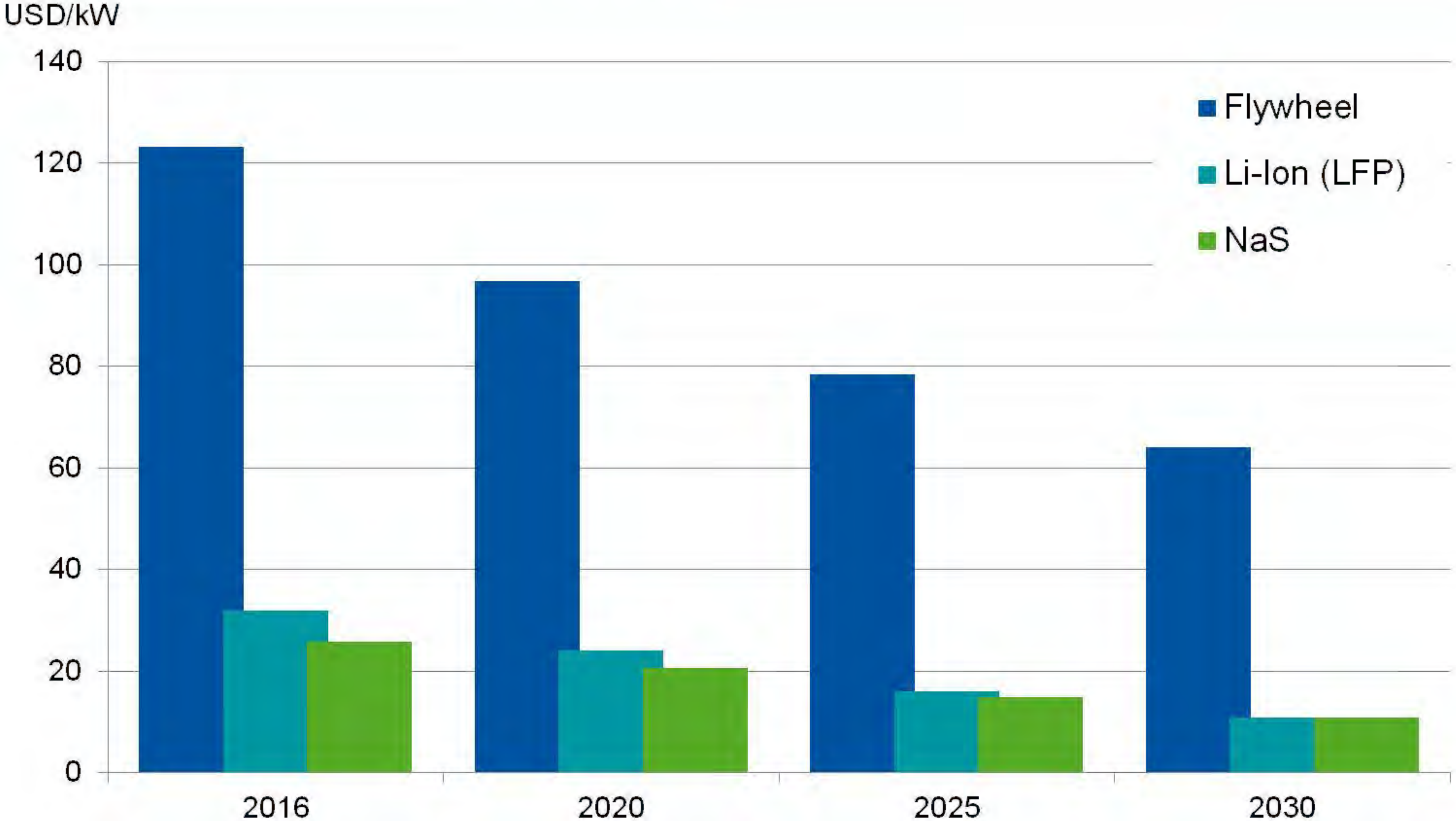
Cost of service: Peak shifting



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Example 2: Rural electrification

Application

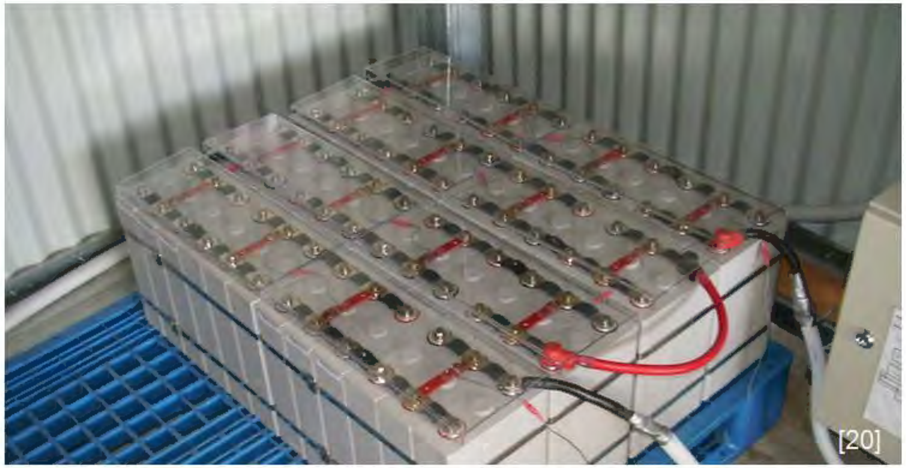
- Large Scale Energy storage:
  - 1060 GW rated power
  - 9 GWh nomical capacity
  - 0,8 cycles per day

Storage Technologies

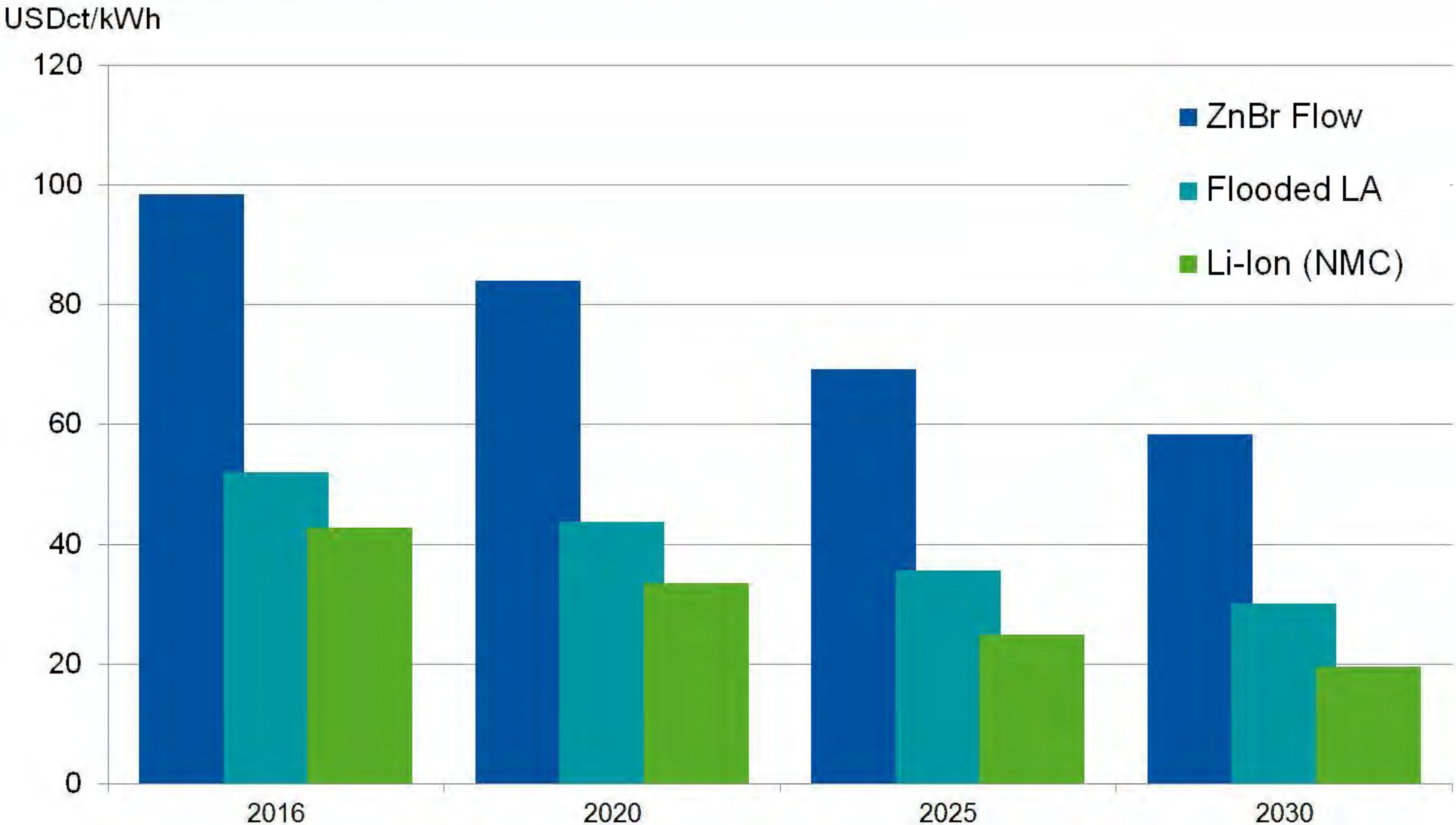
- Pumped Hydro Storage
- Redox-Flow (Vanadium)
- Lead Acid batteries (Flooded)

Results

- Cost of energy [USD/kWh]



Cost of service: Rural electrification



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Detailed information on storage technologies

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Pumped Hydro Electricity Storage (PHES):

- Developed technology
  - No major improvements expected
- New concepts
  - Use sea water as lower reservoir
  - Utilize mining shafts

	unit	2016	2020	2025	2030	*delta*
Cycle life	-	50k	50k	50k	50k	+ 0%
Calender life	years	60,0	60,0	60,0	60,0	+ 0%
Round-trip efficiency	%	80,0	80,0	80,0	80,0	+ 0%
Self-discharge	% per day	0,0	0,0	0,0	0,0	+ 0%
Energy installation costs	USD/kWh	21,0	21,0	21,0	21,0	+ 0%
Power installation costs	USD/kW	840,0	840,0	840,0	840,0	+ 0%

Compressed Air Electricity Storage (CAES):

- Adiabatic CAES
  - Improve efficiency by storing thermal energy
- Only two facilities worldwide
  - Huntdorf (Germany)
  - McIntosh (USA)

	unit	2016	2020	2025	2030	*delta*
Cycle life	-	50k	50k	50k	50k	+ 0%
Calender life	years	50,0	50,0	50,0	50,0	+ 0%
Round-trip efficiency	%	60,0	64,0	67,0	68,0	+ 13%
Self-discharge	% per day	0,5	0,5	0,5	0,5	+ 0%
Energy installation costs	USD/kWh	52,5	48,1	45,7	44,2	-16%
Power installation costs	USD/kW	945,0	781,6	712,7	693,4	-27%

Flywheel Electricity Storage

- Very high self-discharge
  - Used in high frequency / high power applications
- New concepts
  - High density fly-wheels
  - Superconducting bearings

	unit	2016	2020	2025	2030	*delta*
Cycle life	-	200k	225k	260k	303k	+ 51%
Calender life	years	20,0	22,5	26,1	30,3	+ 51%
Round-trip efficiency	%	84,0	85,0	86,0	87,0	+ 4%
Self-discharge	% per day	60,0	53,1	45,6	39,2	-35%
Energy installation costs	USD/kWh	3000,0	2655,9	2280,7	1958,5	-35%
Power installation costs	USD/kW	300,0	265,6	228,1	195,9	-35%

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Lead-Acid Batteries (Flooded)

- Extensive operating experience in many stationary applications
  - Requires refilling
- New concepts
  - Carbon electrodes
  - Copper stretch metal

[6]

	unit	2016	2020	2025	2030	*delta*
Cycle life	-	1500	1867	2454	3225	+ 115%
Calender life	years	9,0	9,9	11,3	12,8	+ 42%
Round-trip efficiency	%	82,0	83,0	84,2	85,5	+ 4%
Self-discharge	% per day	0,3	0,3	0,3	0,3	+ 0%
Energy installation costs	USD/kWh	147	127	99	77	-47%
Power installation costs	USD/kW	-	-	-	-	-

Lead-Acid Batteries (Gel/AGM)

- Extensive operating experience in many stationary applications
  - No refilling required
- New concepts
  - Carbon electrodes
  - Copper stretch metal

	unit	2016	2020	2025	2030	*delta*
Cycle life	-	1500	1867	2454	3225	+ 115%
Calender life	years	9,0	9,9	11,3	12,8	+ 42%
Round-trip efficiency	%	80,0	81,0	82,2	83,4	+ 4%
Self-discharge	% per day	0,3	0,3	0,3	0,3	+ 0%
Energy installation costs	USD/kWh	263	226	177	138	-47%
Power installation costs	USD/kW	-	-	-	-	-

Lithium-Ion Batteries (NMC/LMO)

- Substantial scale effects due to international transition towards electro mobility

- New concepts
  - Silicon anode
  - 5 V electrolytes

	unit	2016	2020	2025	2030	*delta*
Cycle life	-	2000	2406	3031	3819	+ 91%
Calender life	years	12,0	13,6	15,8	18,4	+ 53%
Round-trip efficiency	%	92,0	92,5	93,1	93,7	+ 2%
Self-discharge	% per day	0,1	0,1	0,1	0,1	+ 0%
Energy installation costs	USD/kWh	420	339	244	176	-58%
Power installation costs	USD/kW	-	-	-	-	-

Lithium-Ion Batteries (LFP)

- Comparably low energy density
  - Lower efficiency
  - Increased safety

- No expensive metals (Ni, Co, Al, ..) required

[9]

	unit	2016	2020	2025	2030	*delta*
Cycle life	-	2500	3008	3789	4774	+ 91%
Calender life	years	12,0	13,6	15,8	18,4	+ 53%
Round-trip efficiency	%	86,0	86,5	87,0	87,6	+ 2%
Self-discharge	% per day	0,1	0,1	0,1	0,1	+ 0%
Energy installation costs	USD/kWh	578	466	336	242	-58%
Power installation costs	USD/kW	-	-	-	-	-

Lithium-Ion Batteries (Titanate)

- Excellent cycle life and high-power performance
  - Used in electric busses for fast charging
  - Very low energy density compared to other lithium-ion batteries
  - High costs due to low scales

[10]

	unit	2016	2020	2025	2030	*delta*
Cycle life	-	10k	12k	15k	19k	+ 91%
Calender life	years	15,0	16,9	19,7	23,0	+ 53%
Round-trip efficiency	%	96,0	96,5	97,1	97,8	+ 2%
Self-discharge	% per day	0,1	0,1	0,1	0,1	+ 0%
Energy installation costs	USD/kWh	1050	880	665	502	-52%
Power installation costs	USD/kW	-	-	-	-	-

Lithium-Ion Batteries (NCA)

- Substantial scale effects due to international transition towards electro mobility
- High energy density
  - Low material costs per kWh

	unit	2016	2020	2025	2030	*delta*
Cycle life	-	1000	1203	1516	1910	+ 91%
Calender life	years	12,0	13,6	15,8	18,4	+ 53%
Round-trip efficiency	%	92,0	92,5	93,1	93,7	+ 2%
Self-discharge	% per day	0,2	0,2	0,2	0,2	+ 0%
Energy installation costs	USD/kWh	352	284	204	147	-58%
Power installation costs	USD/kW	-	-	-	-	-

High-Temperature Batteries (ZEBRA)

- ~350°C operating temperature
  - Thermal management required
  - Thermal self-discharge
- New concepts
  - Lower operating temperatures
  - Corrosion-resistant materials

	unit	2016	2020	2025	2030	*delta*
Cycle life	-	3000	3377	3914	4538	+ 51%
Calender life	years	15,0	16,9	19,6	22,7	+ 51%
Round-trip efficiency	%	84,0	85,0	86,0	87,0	+ 4%
Self-discharge	% per day	5,0	5,0	5,0	5,0	+ 0%
Energy installation costs	USD/kWh	399	323	234	169	-58%
Power installation costs	USD/kW	-	-	-	-	-

High-Temperature Batteries (NaS)

- Potential for very low prices
  - Sodium and sulfur abundantly available
  - High corrosion requires expensive components


[13]

	unit	2016	2020	2025	2030	*delta*
Cycle life	-	5000	5614	6489	7500	+ 50%
Calender life	years	17,0	18,8	21,4	24,3	+ 43%
Round-trip efficiency	%	80,0	81,4	83,2	85,0	+ 6%
Self-discharge	% per day	7,0	7,0	7,0	7,0	+ 0%
Energy installation costs	USD/kWh	525	436	326	243	-54%
Power installation costs	USD/kW	-	-	-	-	-

Redox-Flow Batteries (Vanadium)

- Only one active material (V)
  - No cross contamination
  - Very good cyclic lifetime
- New concepts
  - Improved membranes
  - Calendric lifetime critical

	unit	2016	2020	2025	2030	*delta*
Cycle life	-	13k	13k	13k	13k	+ 0%
Calender life	years	12,0	13,7	16,2	19,2	+ 60%
Round-trip efficiency	%	70,0	72,2	75,1	78,1	+ 12%
Self-discharge	% per day	0,2	0,2	0,2	0,2	+ 0%
Energy installation costs	USD/kWh	347	268	183	125	-64%
Power installation costs	USD/kW	1312,5	1063,8	818,2	660,7	-50%

Redox-Flow Batteries (ZnBr)

- Comparably high energy densities
  - Very high cyclic lifetime
  - Zn and Br abundantly available
- Complex BMS required
  - Dendrite growth requires regular full discharge

	unit	2016	2020	2025	2030	*delta*
Cycle life	-	10k	10k	10k	10k	+ 0%
Calender life	years	10,0	11,4	13,5	16,0	+ 60%
Round-trip efficiency	%	70,0	72,2	75,1	78,1	+ 12%
Self-discharge	% per day	15,0	15,0	15,0	15,0	+ 0%
Energy installation costs	USD/kWh	900	696	475	324	-64%
Power installation costs	USD/kW	-	-	-	-	-

Battery Inverters (> 30kW)

- Synergies with PV inverters and traction converters (e-mobility)
- New concepts
  - Improved capacitors
  - Innovative topologies (e.g. feed-forward controls)

	unit	2016	2020	2025	2030	*delta*
Cycle life	-	_	_	_	_	_
Calender life	years	15,0	16,8	19,3	22,3	+ 49%
Round-trip efficiency	%	98,0	98,0	98,0	98,0	+ 0%
Self-discharge	% per day	_	_	_	_	_
Energy installation costs	USD/kWh	_	_	_	_	_
Power installation costs	USD/kW	105,0	89,5	68,9	53,1	-49%