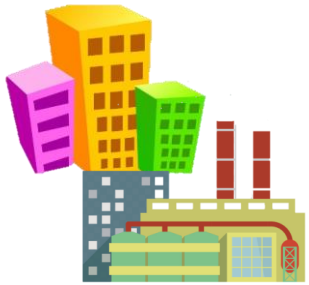
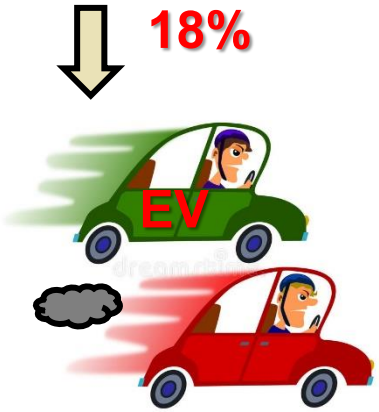
ENERGY STORAGE IN POWER SYSTEM: APPLICATION OVERVIEW, KEY PARAMETERS AND FUTURE TECHNOLOGICAL OUTLOOK

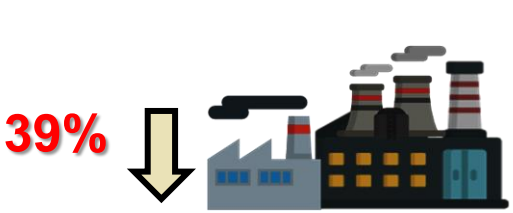
พิมพา ลิ้มทองกุล

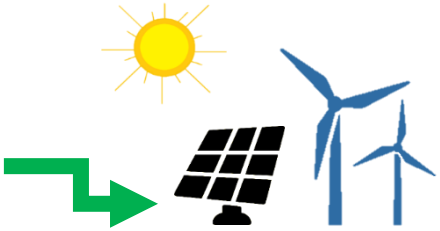
สมาคมเทคโนโลยีระบบกักเก็บพลังงานไทย

ESS Tech Driver









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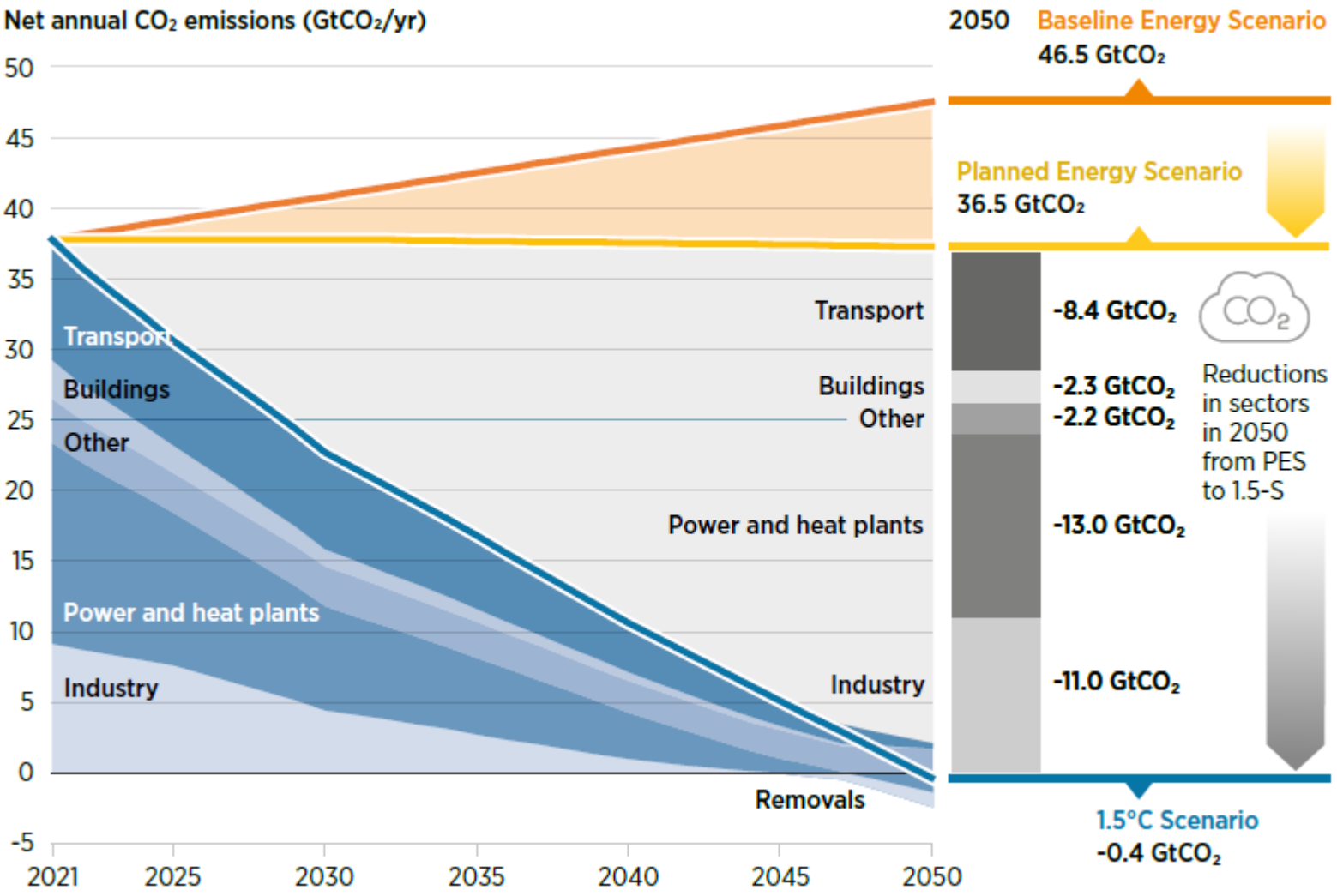
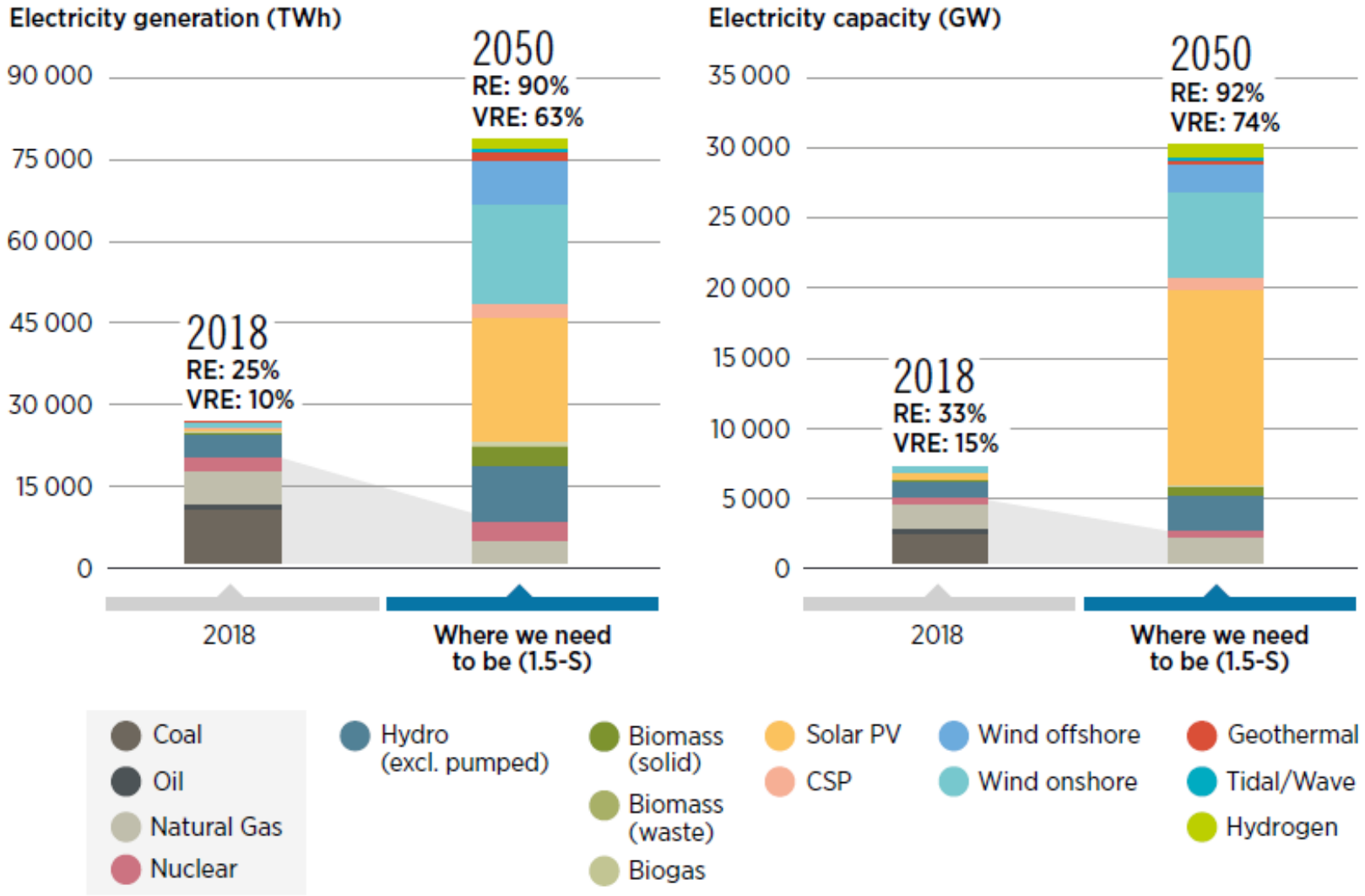


Source: IRENA_World_Energy_Transitions_Outlook_2021

ESS Tech Driver



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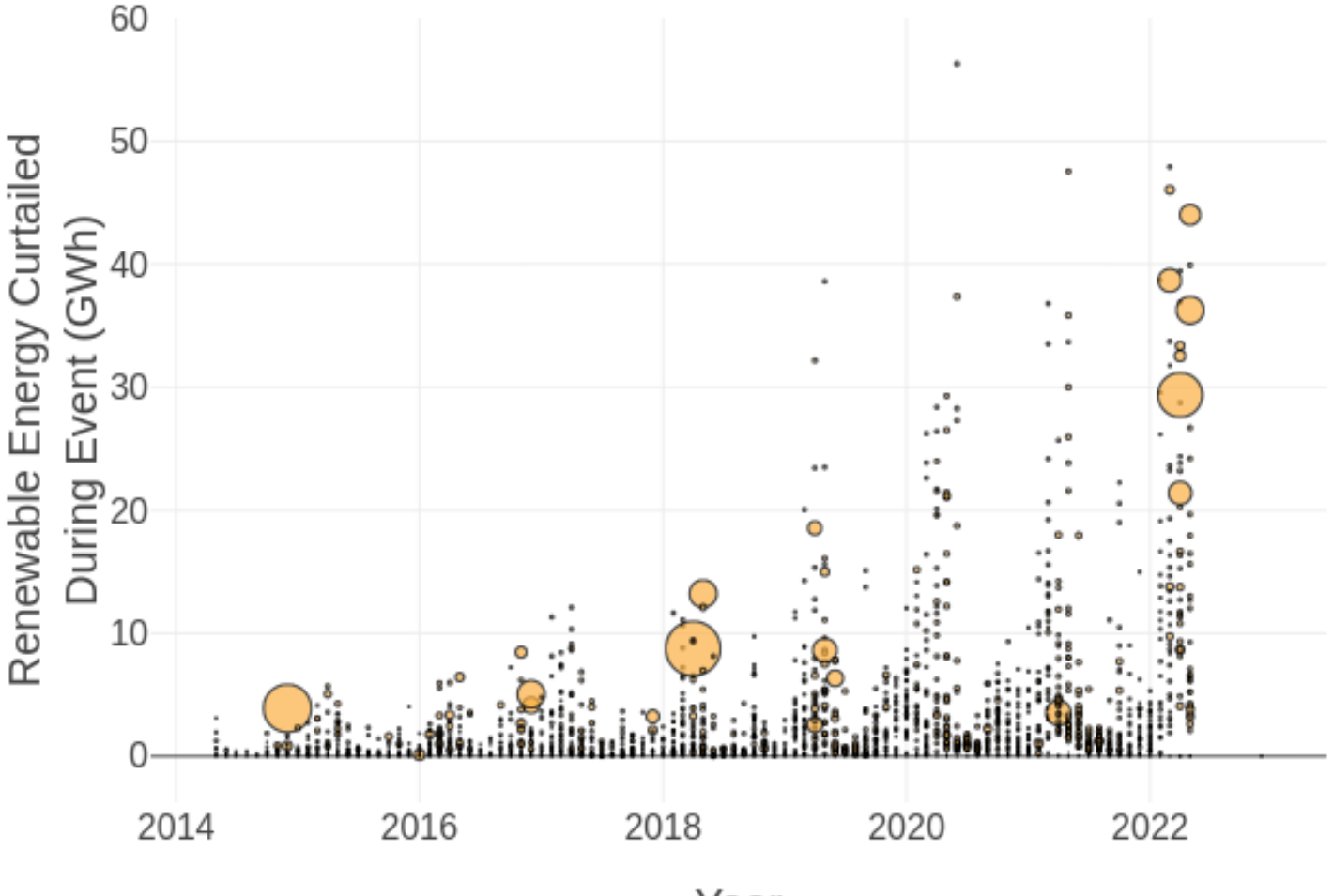
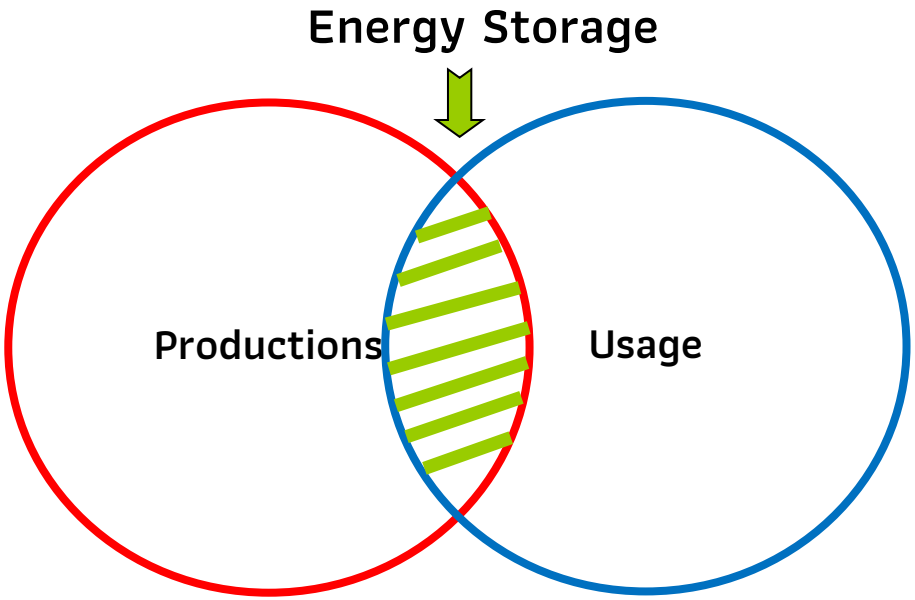


Source: https://www.energy-storage.news/long-duration-and-multi-day-storage-tech-allow-california-to-put-surplus-renewable-energy-to-good-use/

ESS Tech Driver

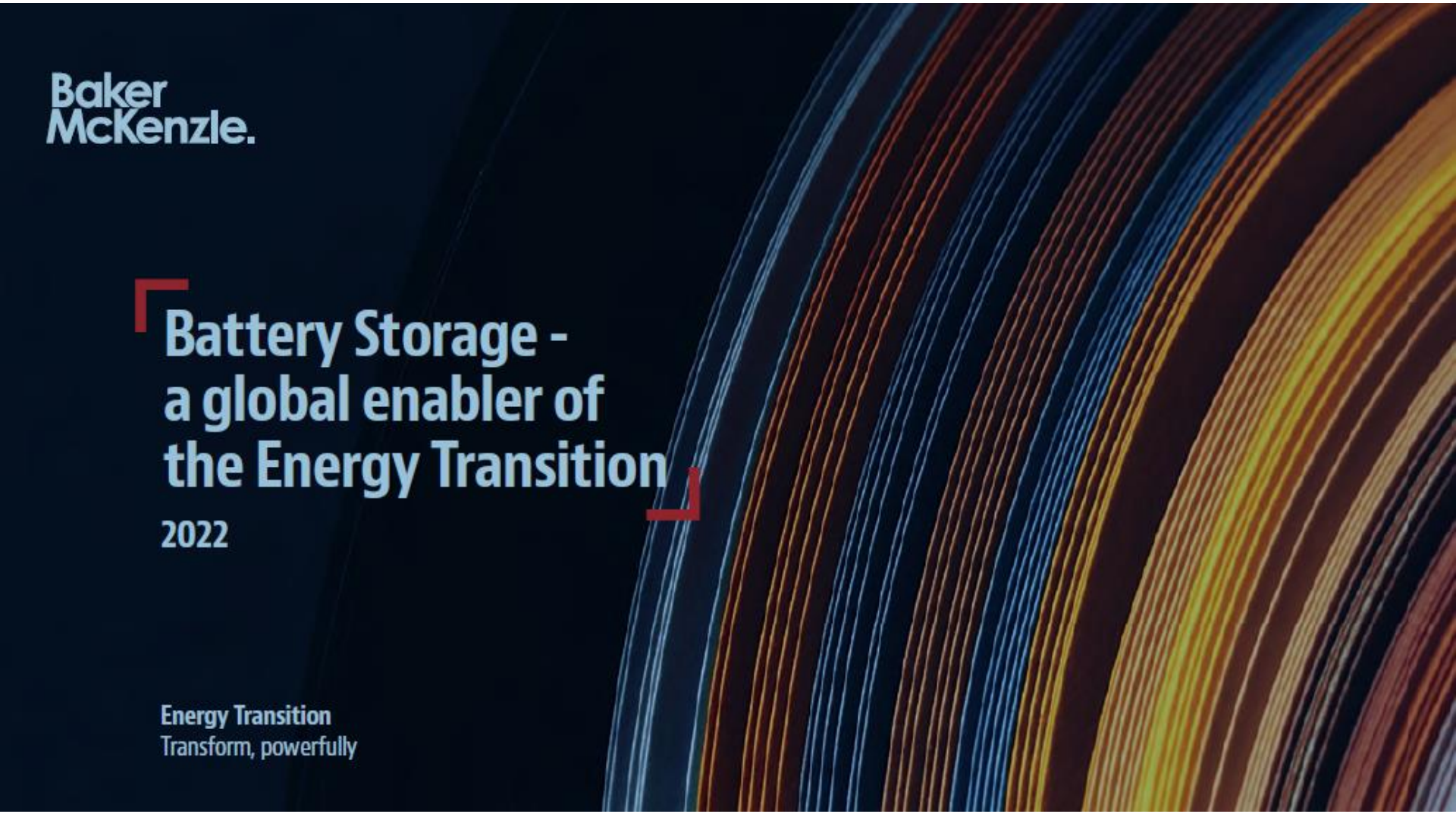


Role of Energy Storage

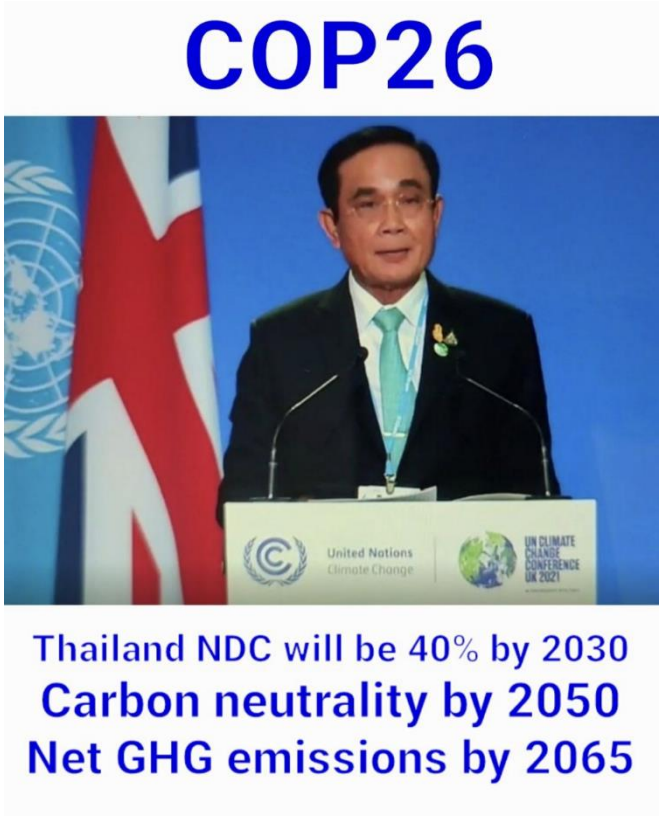
ENERGY STORAGE

ENABLE FOR RE, EV AND EE

ES: Enabler for Energy Transition



Energy Storage and National Plan



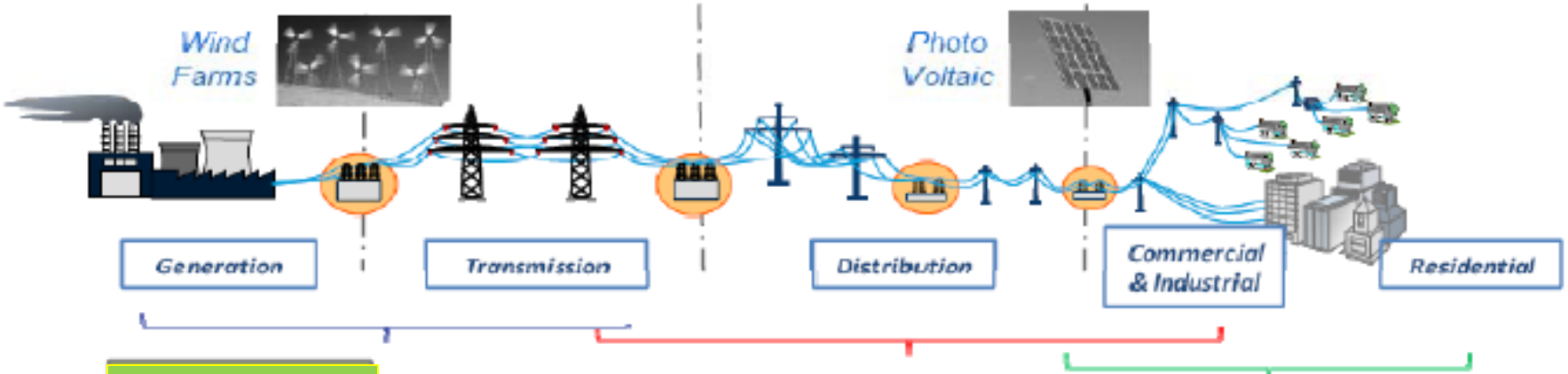
- National Plan of Thailand
- No. 16 in the country's ENERGY 4.0 Plan

National Electric Vehicle Policy committee set up (Dec 2019)

- No. 17 in the country's ENERGY 4.0 Plan

National Energy Storage Technology Promotion Committee (February 2021)

ESS in Power System



Bulk Storage

- Electric Energy Time-Shift (Arbitrage)
- Electric Supply Capacity
- Renewable Integration

Grid Operations

- Regulation
- Spinning & Non-Spinning reserve
- Voltage Support
- Black Start
- Load Following

Aggregated Utility Scale

- Transmission Upgrade Deferral
- Transmission Congestion Relief

Transmission Infrastructure

Utility Scale

- Distribution Upgrade Deferral
- Voltage Support

Distribution Infrastructure

Community Scale

- Power Quality
- Retail Electric Energy Time-Shift
- Power Reliability
- Demand Charge Management

End User

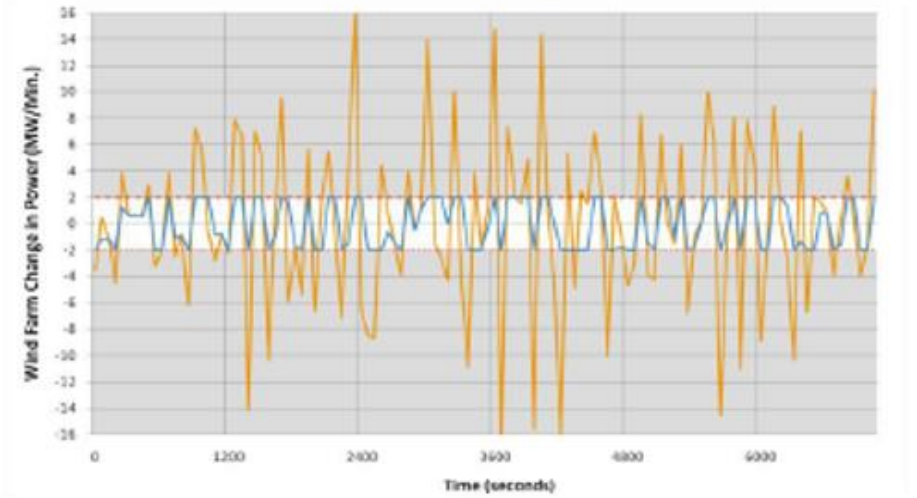
Adapted from DOE Grid Energy Storage December 2013

สรุปบทบาทของ ESS ในระบบ Power Sys.

1. ประหยัดและเพิ่มประสิทธิภาพด้านการผลิตและส่ง
   - ชะลอการสร้างโรงไฟฟ้าใหม่
   - ช่วยรองรับปริมาณของ Renewable power system ในระบบ ให้มากขึ้นและมีประสิทธิภาพยิ่งขึ้น
   - ชะลอการเพิ่มขนาดสายส่ง
2. สร้างเสถียรภาพทางการจ่ายไฟฟ้า ทั้งด้าน
   1. ปริมาณ (energy capacity – demand vs. supply)
   2. คุณภาพ (voltage support, frequency regulations)
3. เพิ่มประสิทธิภาพการใช้งาน/ประหยัดค่าไฟ
   - Peak shaving
   - Demand charge management

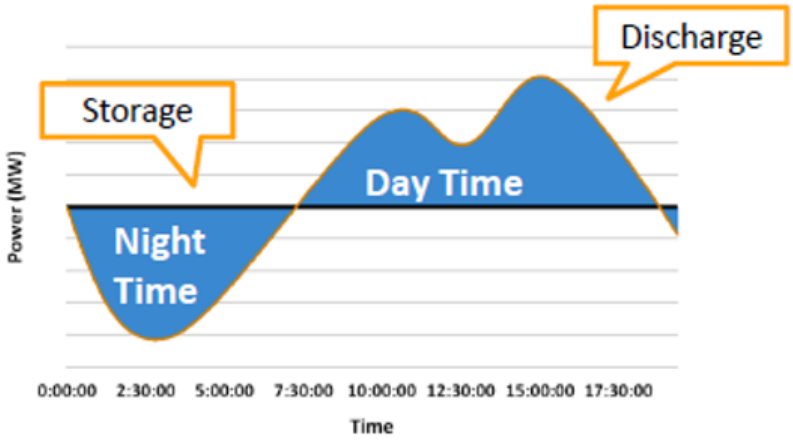
ESS in Power System: Power/Energy

Power



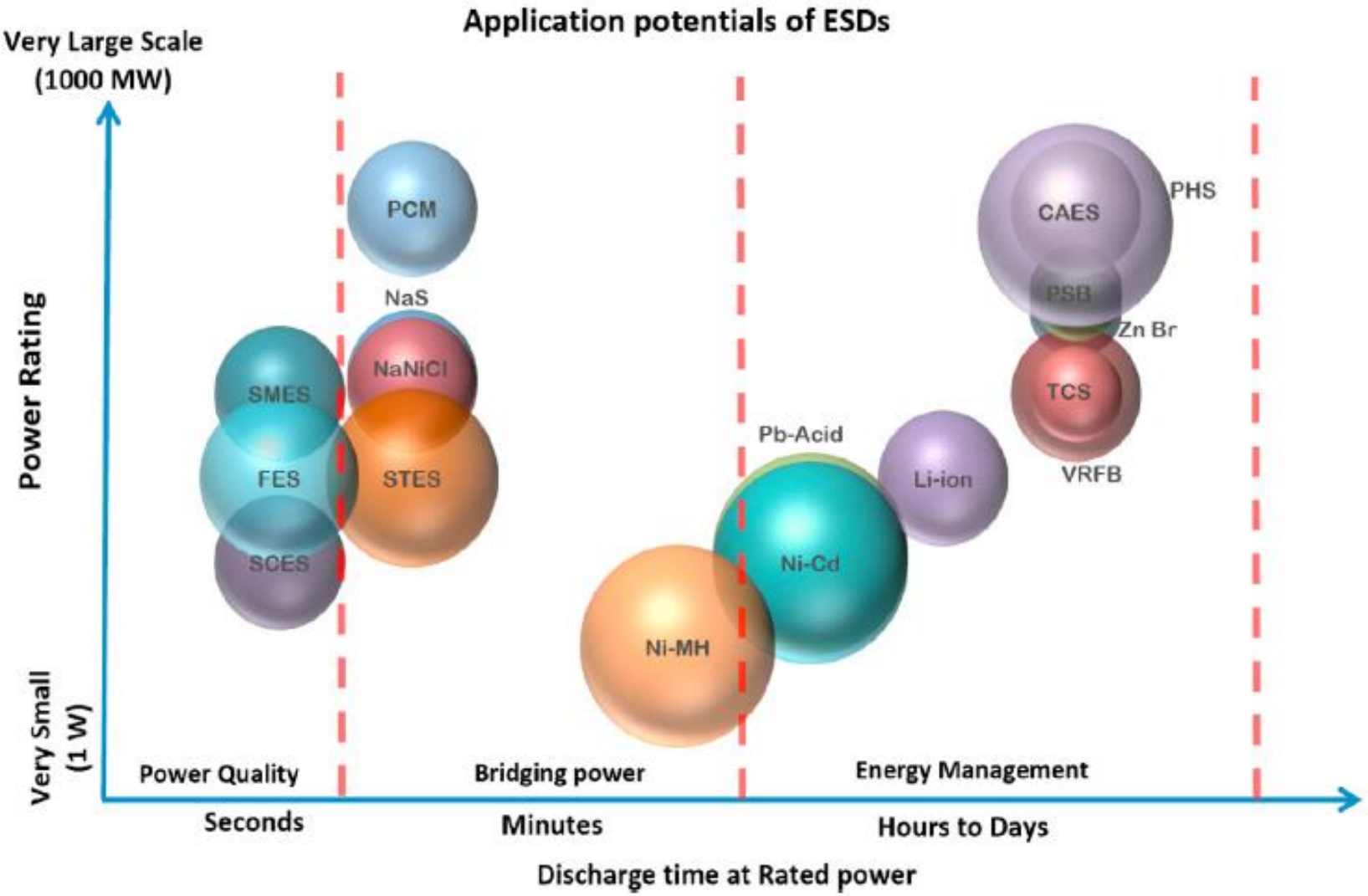
- Short duration (< 1 hr)
- Very high charge/discharge rate
- Many cycle (100/day)
- Continuous use

Energy



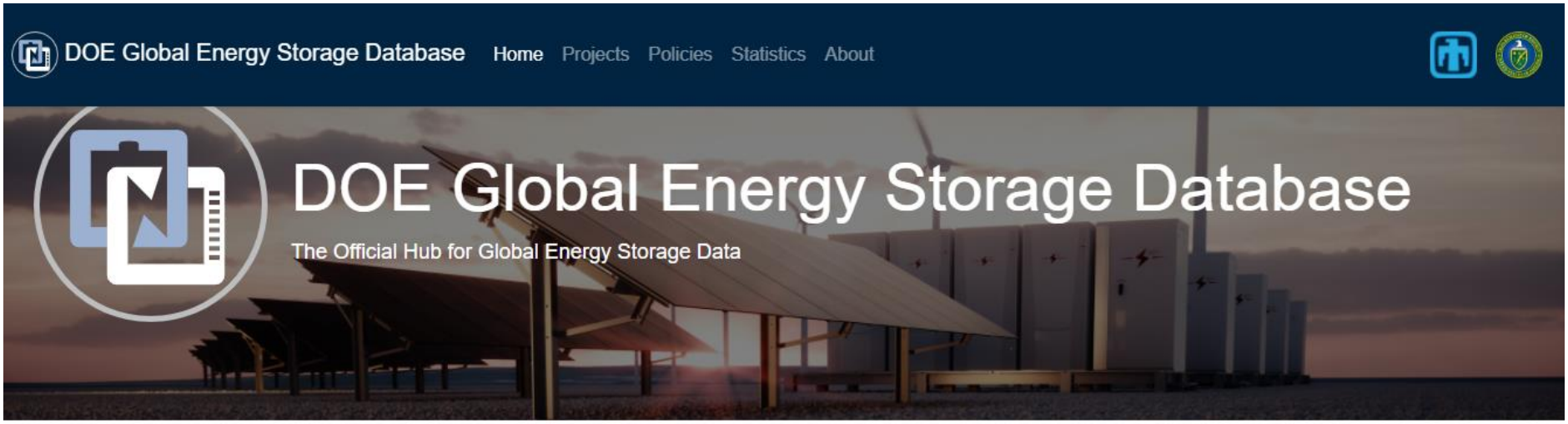
- Long duration (1+ hr)
- 1-2 cycle/day

ESS in Power System: Power/Energy



Source: A A. Kebede, et. Al. A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration, Renewable and Sustainable Energy Reviews 159 (2022) 112213

Global Status of ESS Installation

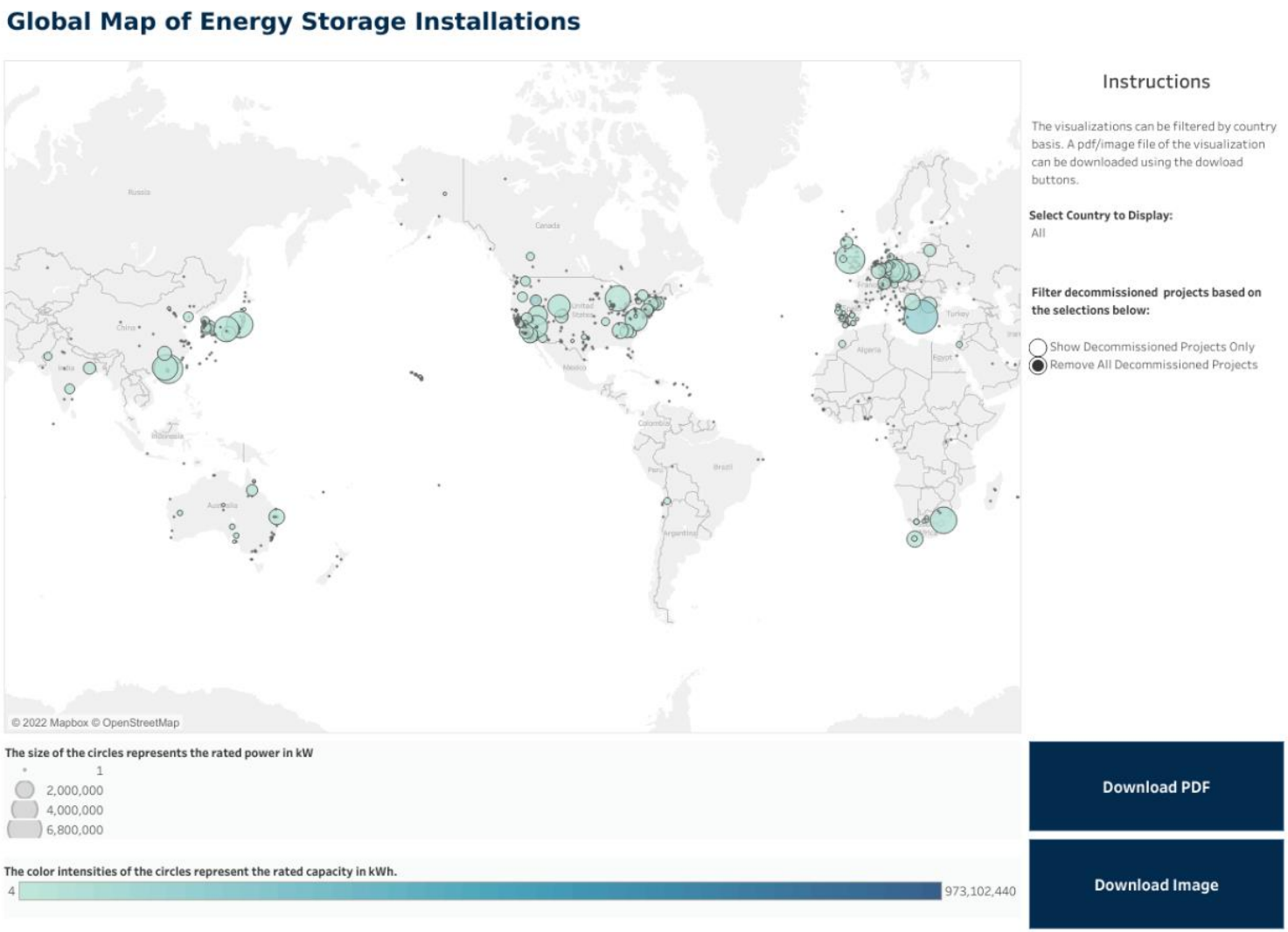


DOE Global Energy Storage Database

The DOE Global Energy Storage Database provides research-grade information on grid-connected energy storage projects and relevant state and federal policies. All data can be exported to Excel or JSON format. As of September 22, 2021, this page serves as the official hub for The Global Energy Storage Database.

US DOE Energy Storage Database https://sandia.gov/ess-ssl/gesdb/public/statistics.html

Global Status of ESS Installation



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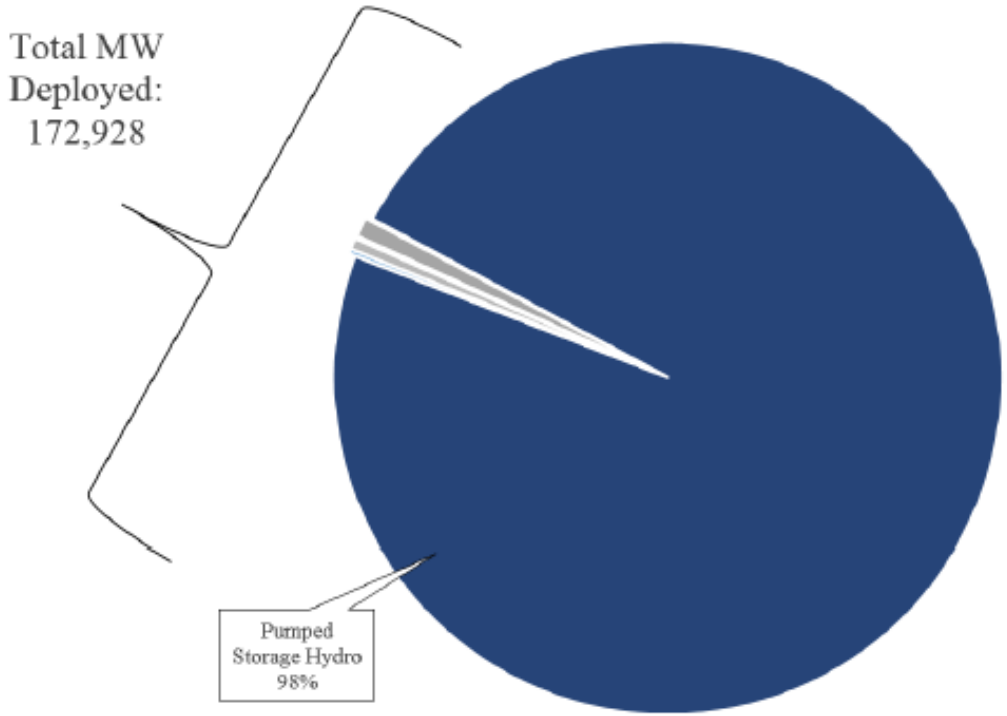

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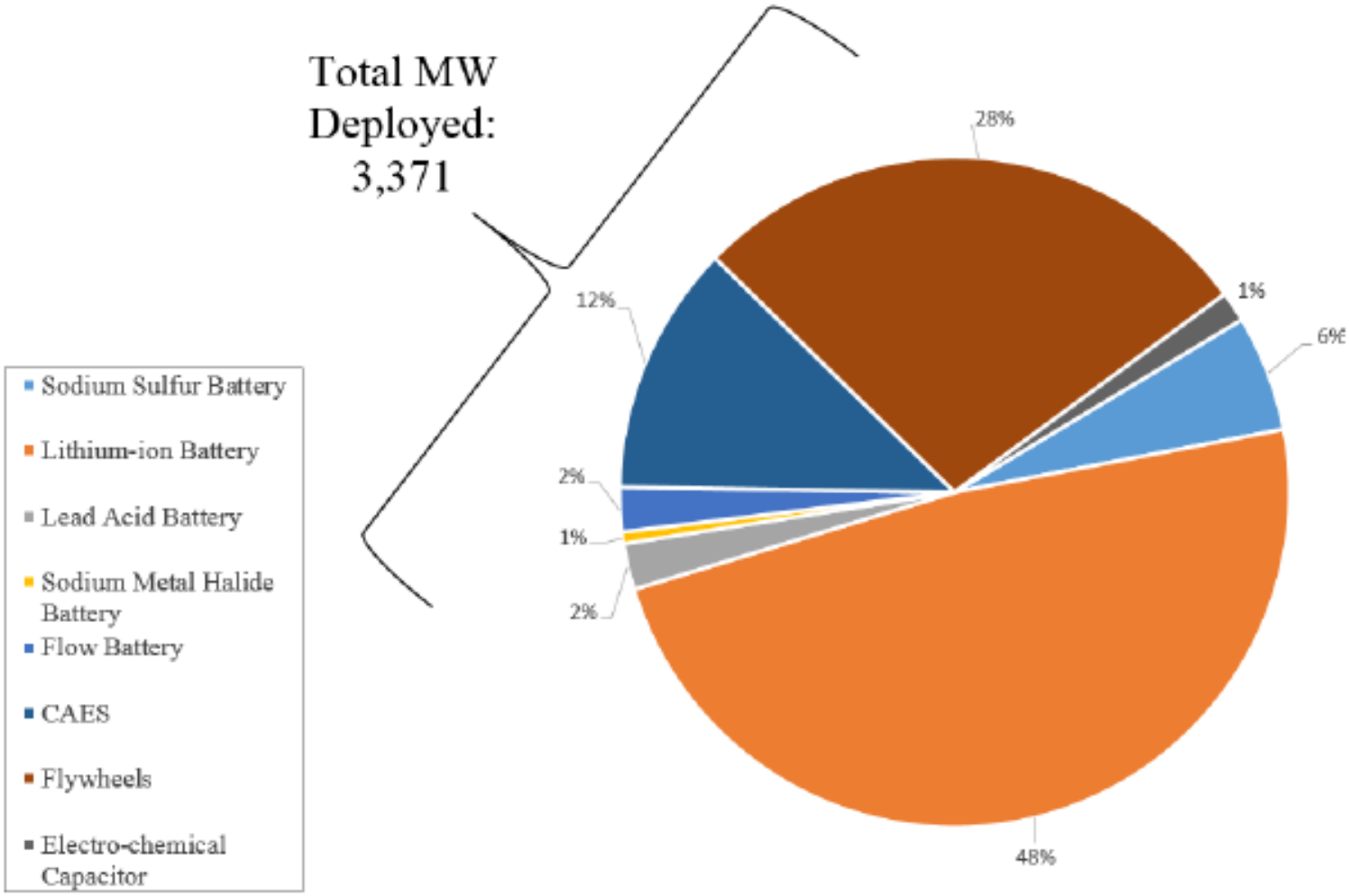
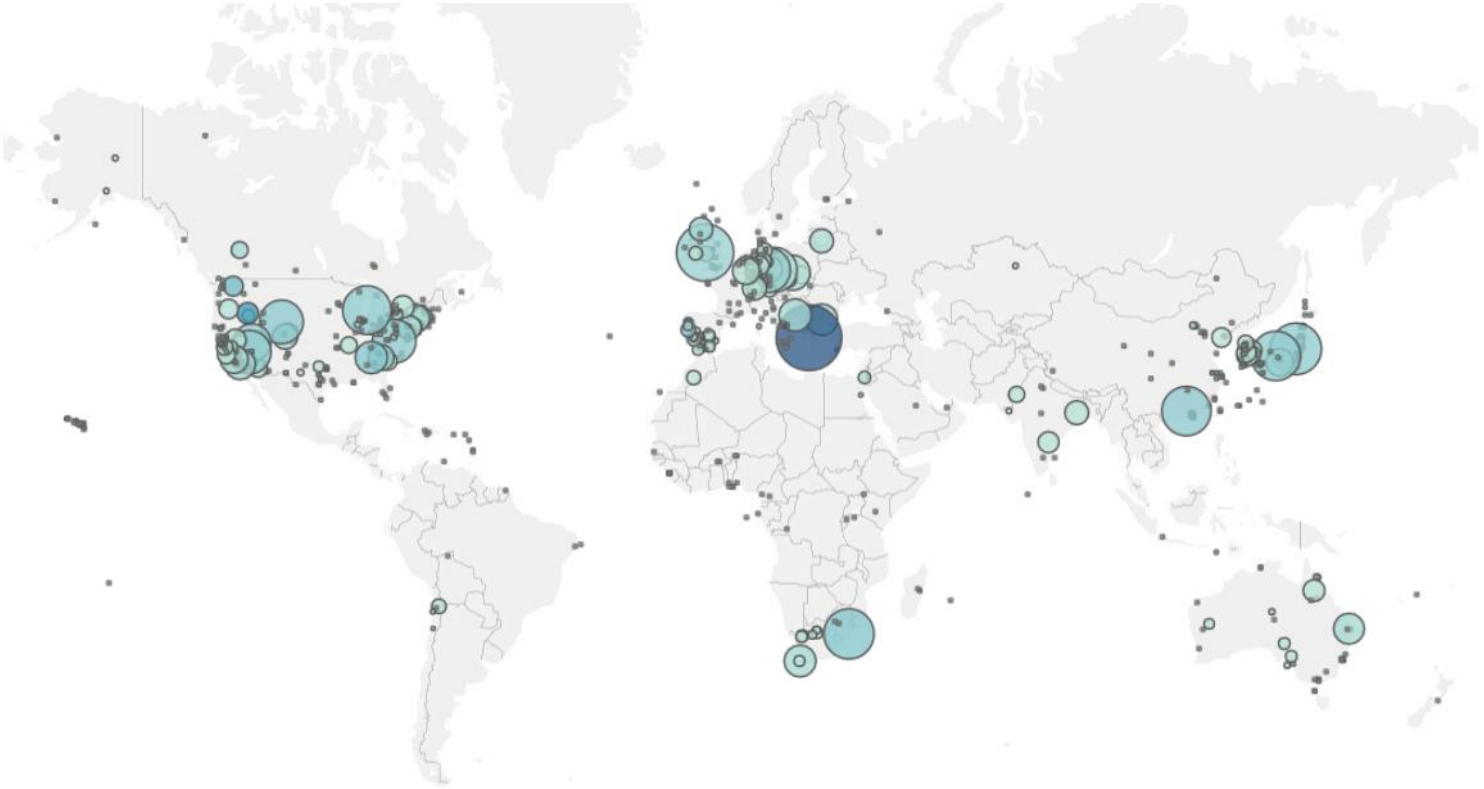


US DOE Energy Storage Database https://sandia.gov/ess-ssl/gesdb/public/statistics.html

Global Status of ESS Installation

>95 GW

>1,220 GWh



DOE Global Energy Storage (OCT 2021) https://sandia.gov/ess-ssl/gesdb/public/projects.html

Global Status of ESS Installation

Installed power by Technology until OCT, 2021

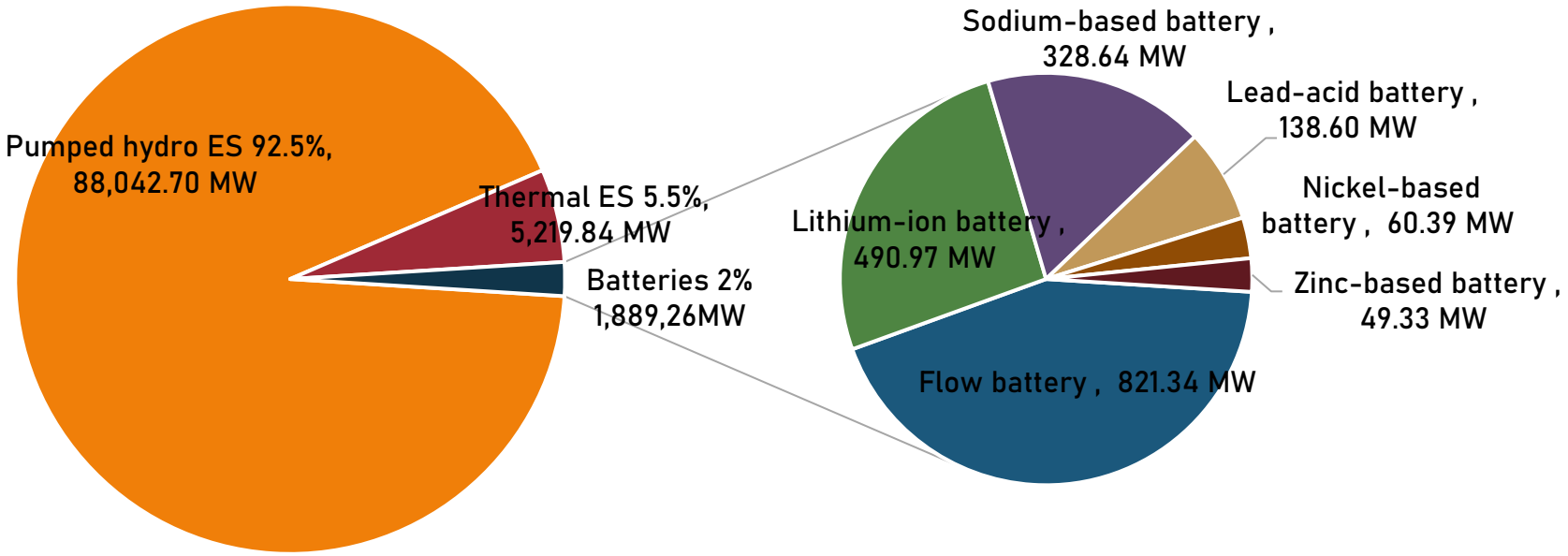


Chart made from DOE Global Energy Storage (OCT 2021) https://sandia.gov/ess-ssl/gesdb/public/projects.html

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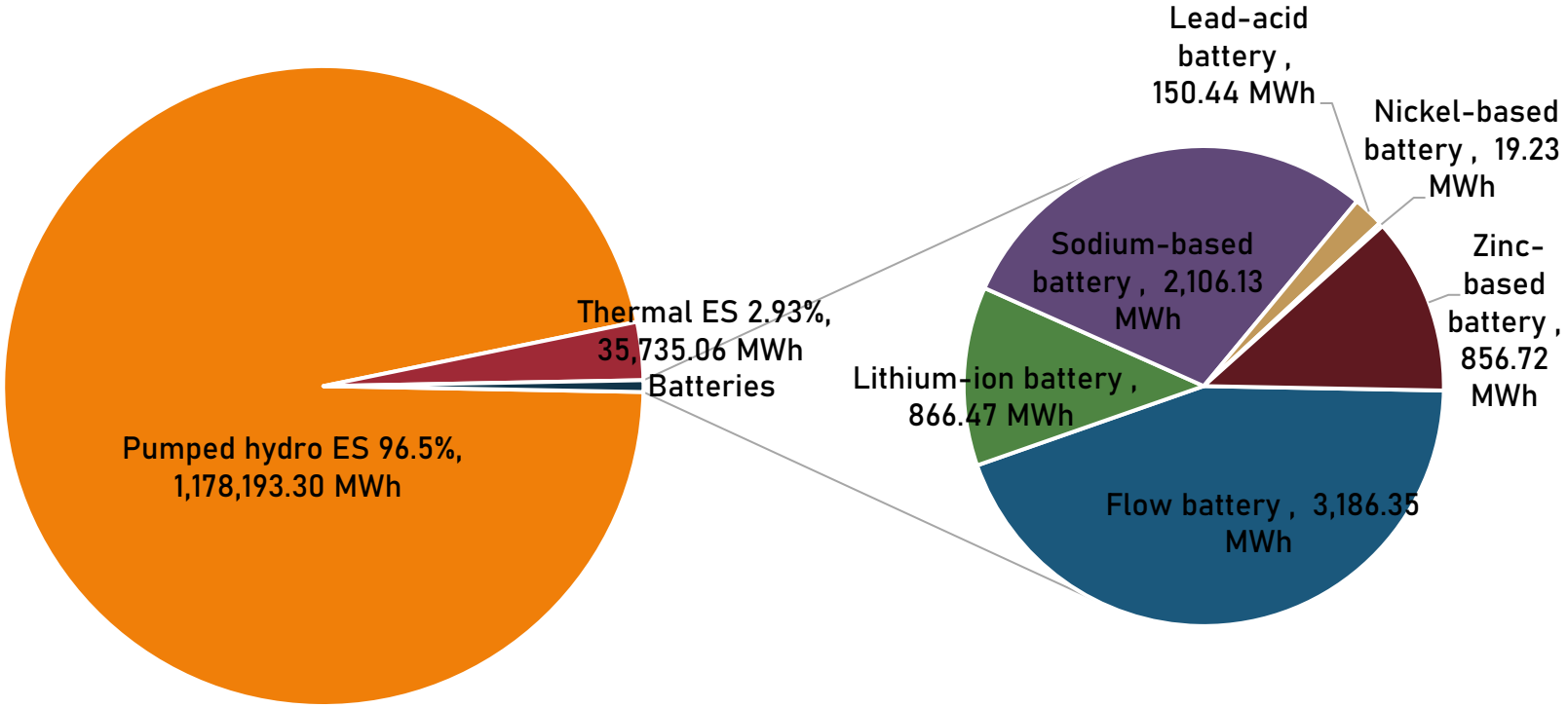

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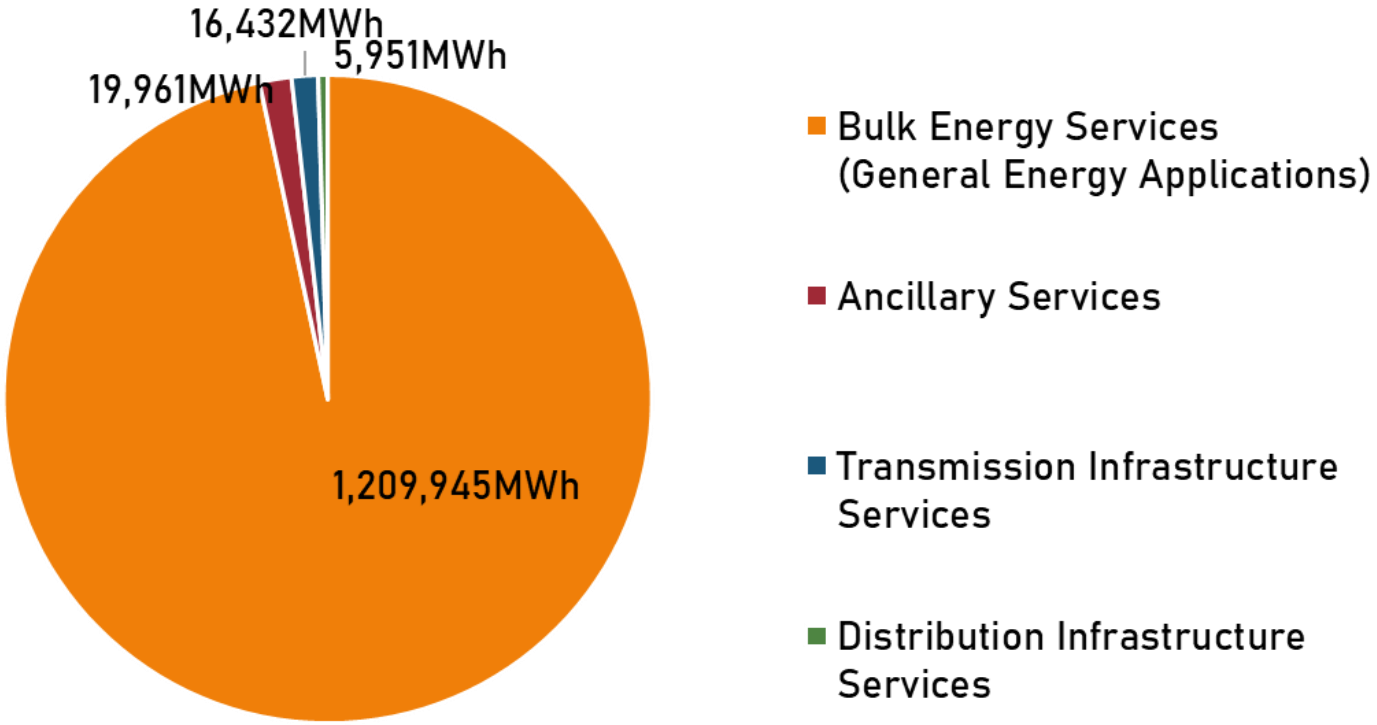
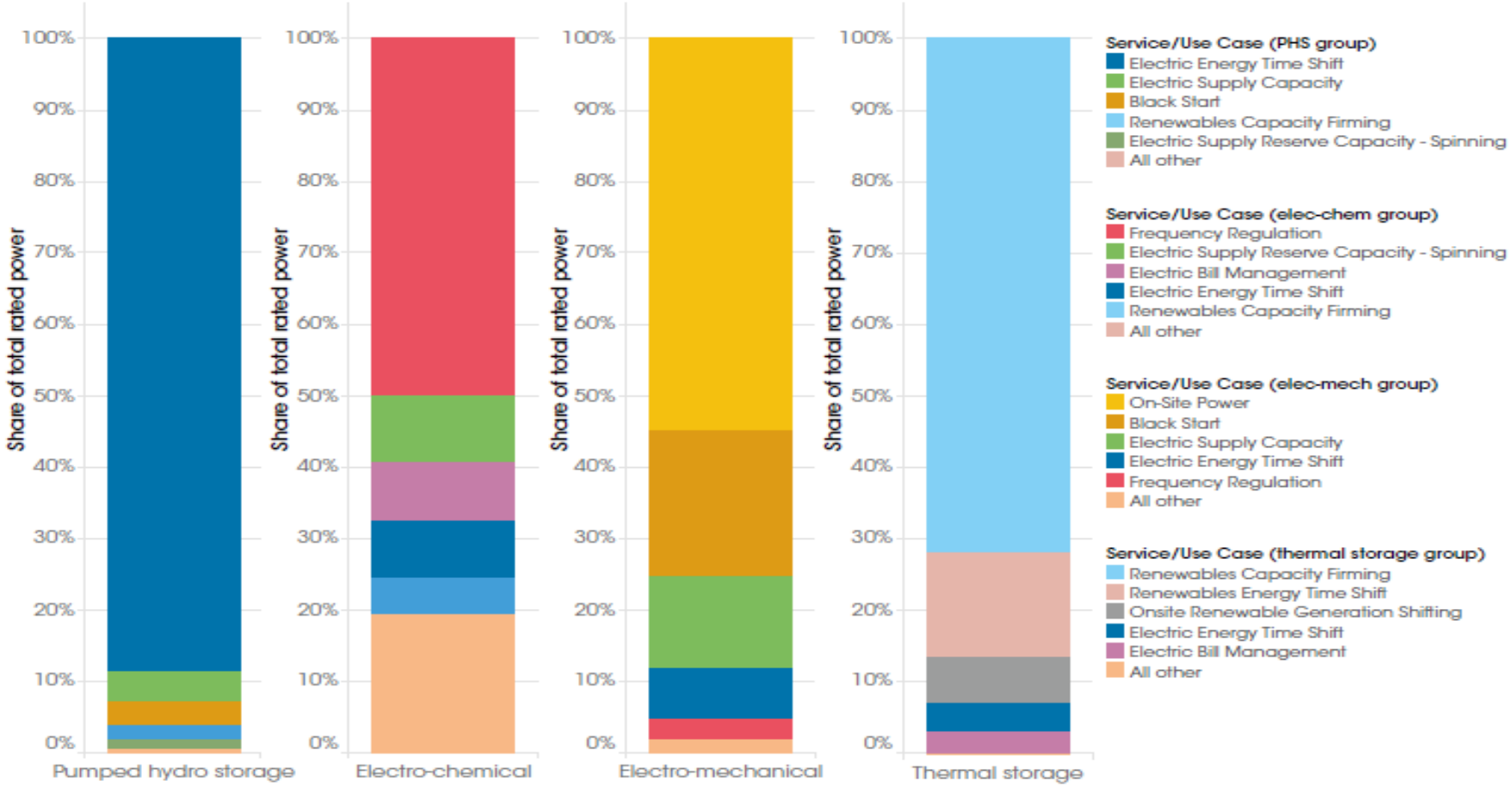


Chart made from DOE Global Energy Storage (OCT 2021) https://sandia.gov/ess-ssl/gesdb/public/projects.html

Global Status of ESS Installation

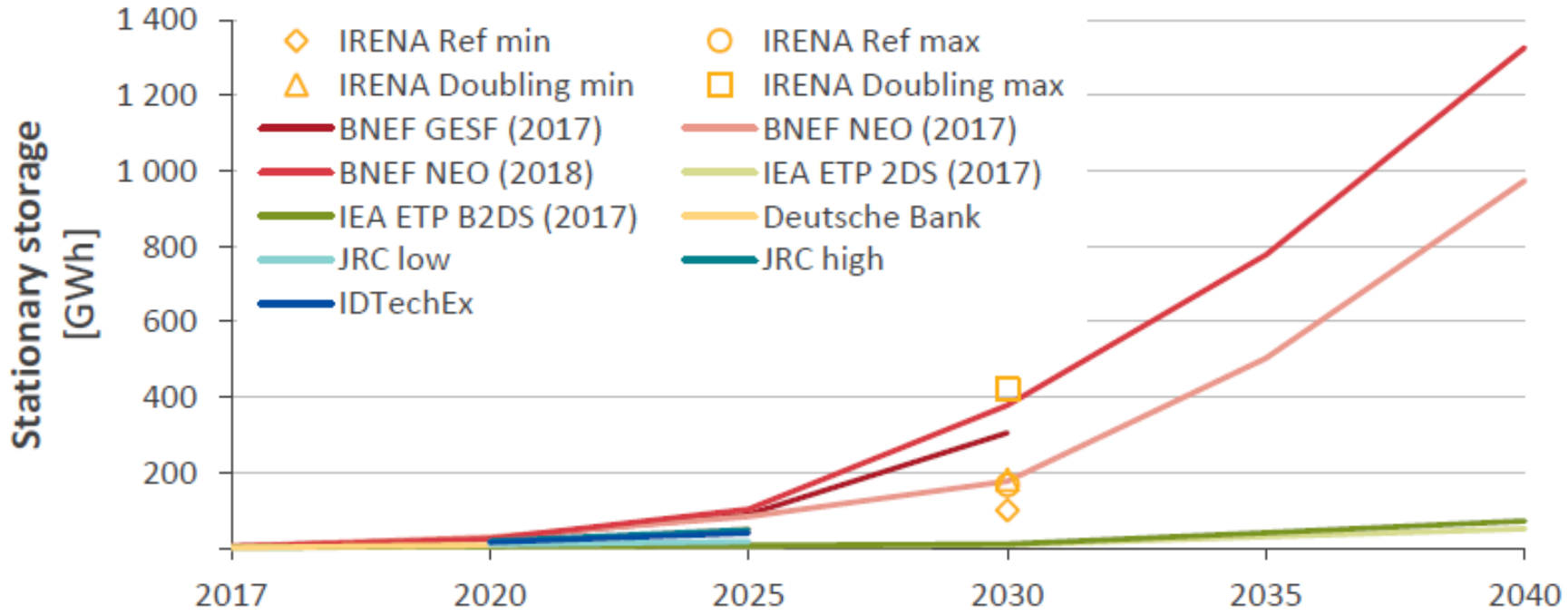
Technology and Application Matching (2017)



Global Status of ESS Installation

Forecasted Energy Storage Capacity

Figure 27 Projections of total stationary storage installed front- and behind-the-meter globally



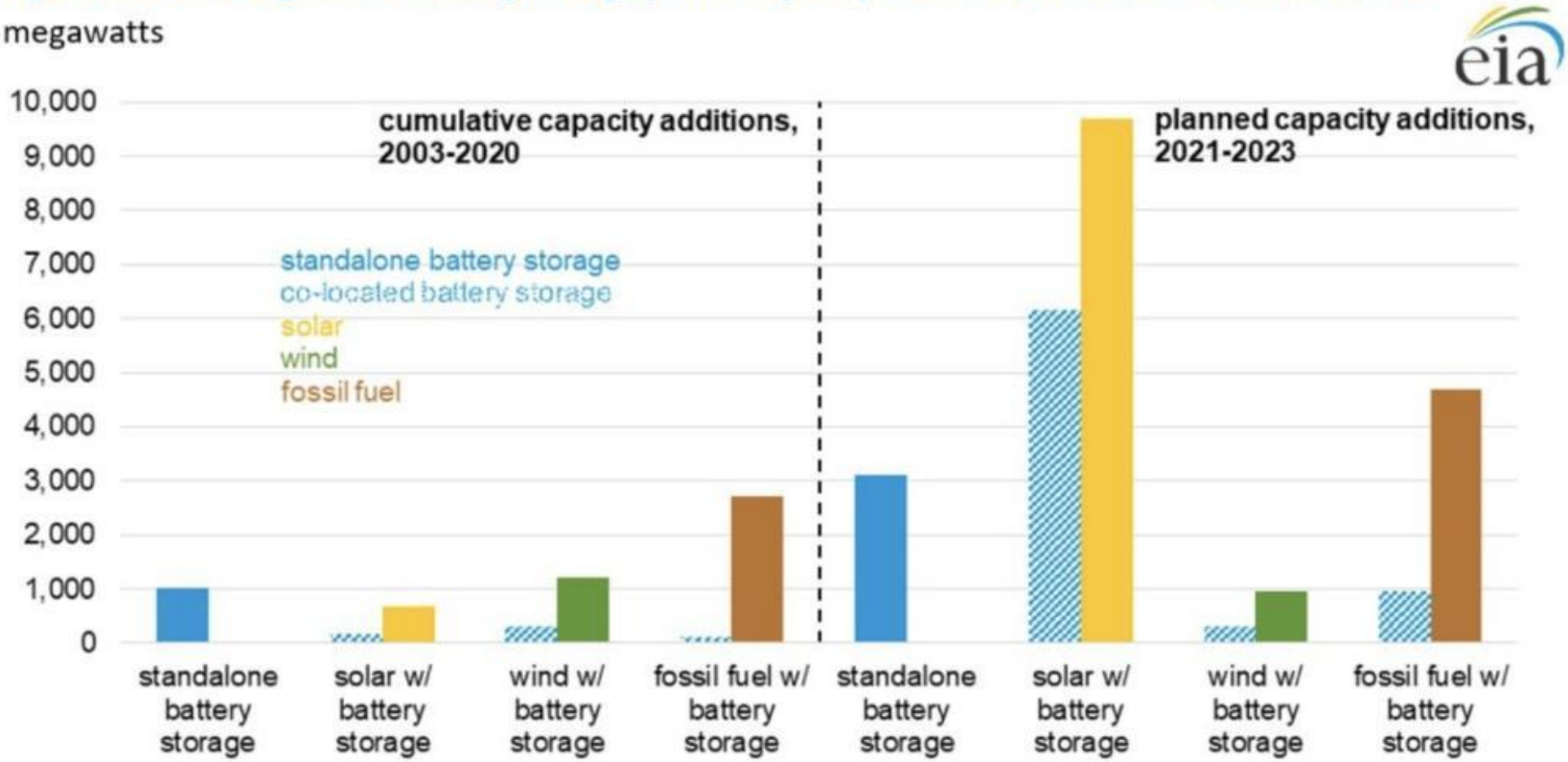
Source: JRC based on various literature sources [31,39,43,52,58,65,83,105]. Abbreviations of the studies can be found in the references. *Note*: IEA [103] is not clear as to whether they include behind-the-meter applications in their projections for storage.

Source: JRC Science and Policy Report "Li-ion Battery for Mobility and Stationary Storage Applications", 2018

Global Status of ESS Installation

Battery storage's energy capacity growth

Figure ES3. U.S. large-scale battery storage power capacity additions, standalone and co-located

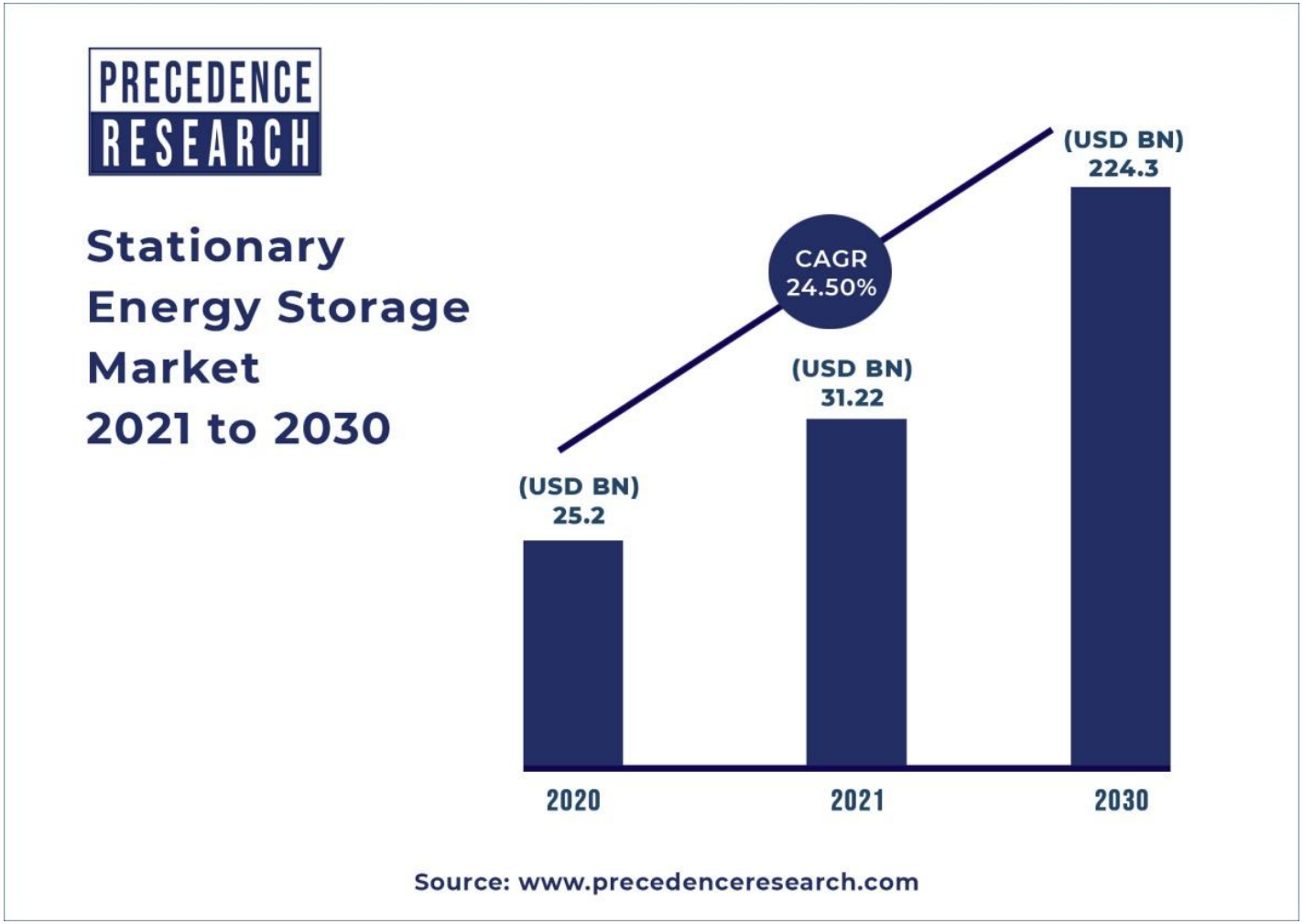


Source: U.S. Energy Information Administration, Dec 2020 Form EIA-860M, *Preliminary Monthly Electric Generator Inventory*

Note: Solid yellow, green, and brown bars indicate generating total capacity of solar, wind, and fossil fuels that have battery storage on-site.

Global Status of ESS Installatino

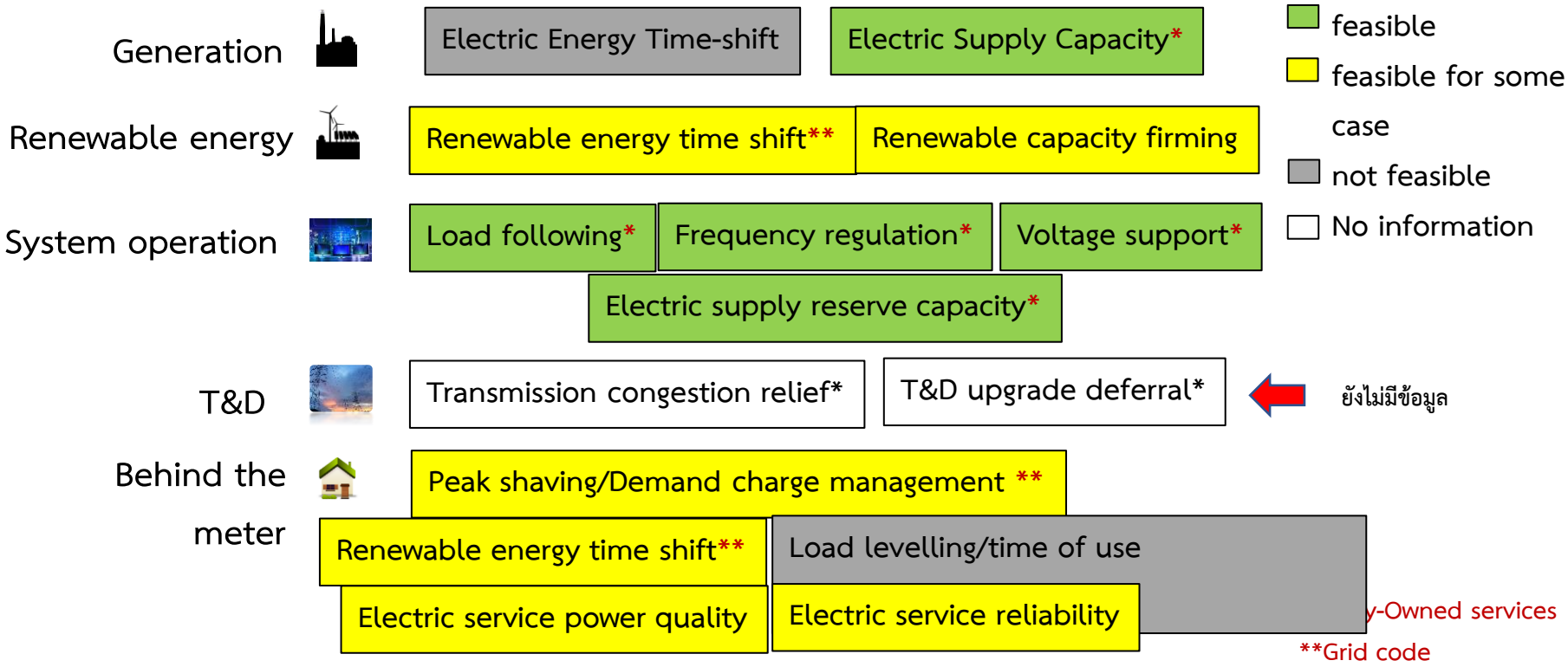
Forecasted Energy Storage Market



Source: https://www.globenewswire.com/en/news-release/2022/02/15/2385503/0/en/Stationary-Energy-Storage-Market-Size-to-Hit-US-224-3-Bn-by-2030.html

Thailand: ESS Current Status

Energy Storage Values in Current Thailand Grid



Source:
- Jiravan Mongkonthanatas, นำเสนอใน The Future Energy Show Thailand 2019, 27 Nov 2019 รวบรวมจาก:
  - สถาบันวิจัยเพื่อการพัฒนาประเทศไทย (TDRI), โครงการศึกษาความเหมาะสมและแนะแนวทางในการส่งเสริมอุตสาหกรรมสารองไฟฟ้าสาหรับโครงข่ายไฟฟ้าของประเทศ (Grid Energy Storage), 2019
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  - MTEC, รวบรวมข้อมูลในโครงการศึกษาภายใต้การสนับสนุนจาก กองทุนพัฒนาไฟฟ้า เพื่อการส่งเสริมการใช้พลังงานหมุนเวียน และเทคโนโลยีที่ใช้ในการประกอบกิจการไฟฟ้าที่มีผลกระทบต่อสิ่งแวดล้อมน้อย (มาตรา 97(4)) ประจำปีงบประมาณ พ.ศ. 2561

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ESS application	Value
Energy arbitrage	-0.5 to 2.5 Baht/kWh
Load following	0.07 to 0.09 Baht/kWh
Spinning reserve	0.023 to 0.028 Baht/kWh
SPP Hybrid firm (Renewable capacity firming)	2.212 to 4.062 Baht/kWh
Electric bill management (no demand charge)	Approx. 1.6 Baht/kWh
Peak Shaving	1,500 to 2,800 Baht/kW.year
Frequency regulation	3,000 to 5,500 Baht/kW.year

- BESS cost in energy application -> 400USD/kWh = 12,000Baht/kWh (for 3000 cycles) -> **4 Baht/kWh.cycle**
- BESS cost in power application -> 600USD/kWh = 18,000Baht/kW (for 10 years) -> **1,800 Baht/kW.year**

Source:

- Jiravan Mongkonthanatas, นำเสนอใน The Future Energy Show Thailand 2019, 27 Nov 2019 รวบรวมจาก:
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$100/kWh

- BESS cost in energy application -> 400USD/kWh = 12,000Baht/kWh (for 3000 cycles) -> **4 Baht/kWh.cycle**
- BESS cost in energy application -> 250USD/kWh = 7,500Baht/kWh (for 3000 cycles) -> **2.5 Baht/kWh.cycle**
- BESS cost in energy application -> 100USD/kWh = 3,000Baht/kWh (for 3000 cycles) -> **1 Baht/kWh.cycle**
- BESS cost in energy application -> 60USD/kWh = 1,800Baht/kWh (for 3000 cycles) -> **0.6 Baht/kWh.cycle**

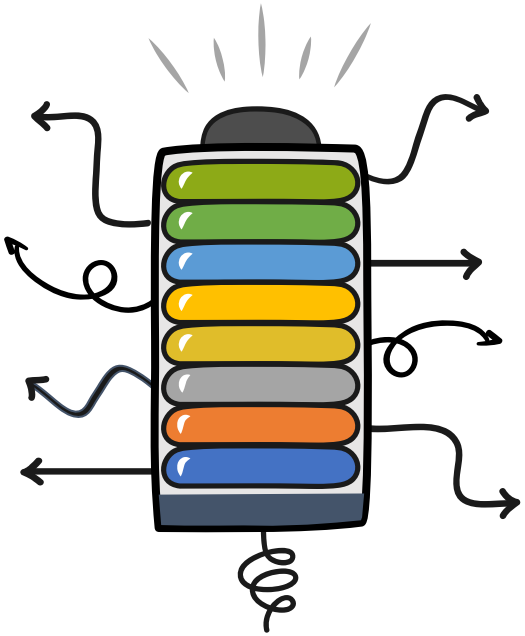
ESS – ในฝัน

1 ถูก

2 เล็ก

3 เบา

4 ปลอดภัย



แรง 5

ชาร์จเร็ว 6

ใช้ได้นาน 7

? 8, 9, 10...

Source: IRENA_World_Energy_Transitions_Outlook_2021

ESS Key Parameters

Figure of merit	*Unit*	*ความหมาย*
Specific energy density	Wh/kg	พลังงานไฟฟ้า ต่อ น้ำหนัก หรือ ต่อ ปริมาตร => ความจุพลังงาน
Volumetric energy density	Wh/liter	
Specific power density	W/kg	กำลังไฟฟ้า ต่อน้ำหนัก หรือ ต่อ ปริมาตร => จ่าย/ ชาร์จไฟได้เร็วเท่าไร
Volumetric power density	W/liter	

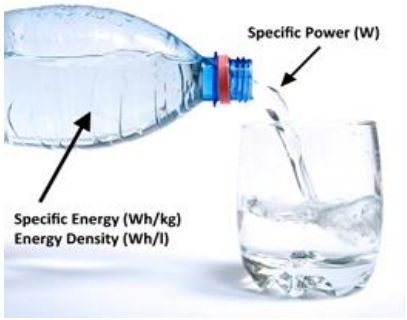


Image Source : http://batteryuniversity.com/learn/article/battery_definitions

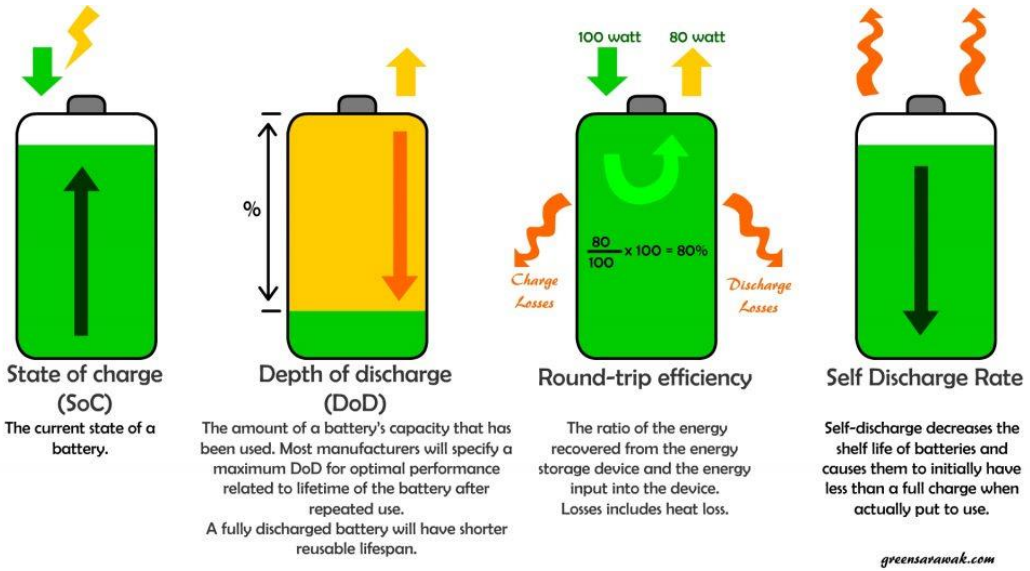
ESS Key Parameters

Figure of merit	*Unit*	*ความหมาย*
Capital cost per unit power	$/kW	ราคา
Capital cost per unit energy	$/kWh	
Cost per unit energy per cycle	$/kWh-cycle	
Cost per unit power per cycle	$/kW-cycle	
Life cycle	cycles	จำนวนครั้งที่แหล่งกักเก็บพลังงานสามารถจ่ายได้ต่อหนึ่งการ recharge => ใช้ได้กี่ครั้ง
Shelf life	years	จำนวนปีที่สามารถเก็บแหล่งกักเก็บพลังงานไว้บนชั้นวางโดยที่ยังมีคุณสมบัติตามกำหนด =>สามารถเก็บได้นานเท่าไร
Operating temperature range	°C	ช่วงอุณหภูมิที่ใช้งานได้

SourceImage Source : http://batteryuniversity.com/learn/article/battery_definitions

ESS Key Parameters

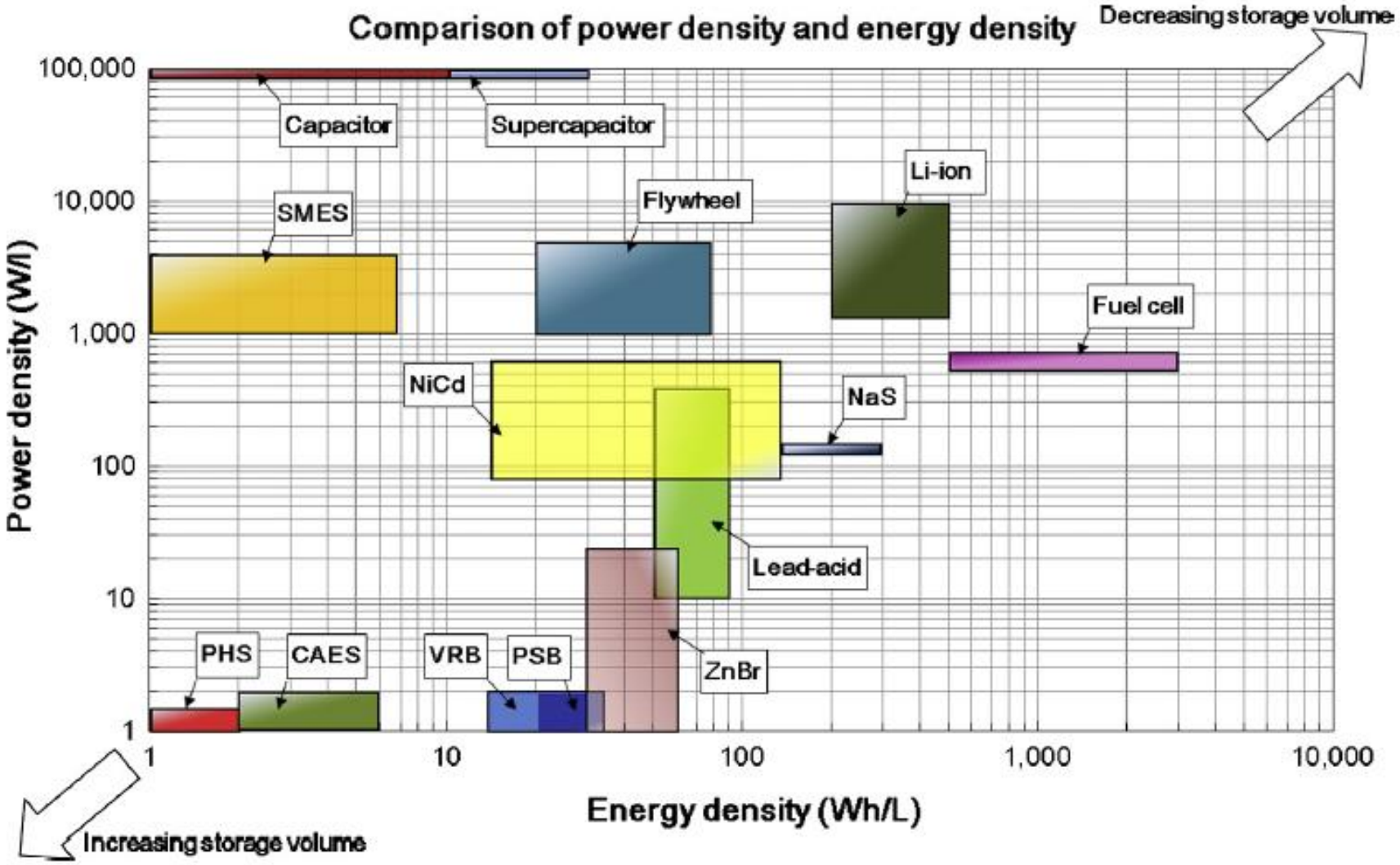
Figure of merit	*Unit*	*ความหมาย*
Efficiency	%	อัตราส่วนระหว่างพลังงานที่จ่ายได้ ต่อ พลังงานที่สะสมไว้ => ไฟที่ชาร์จไปเอามาใช้ได้กี่ %
Self- Discharge rate	%/year	อัตราส่วนของพลังงานที่สูญเสียไปเมื่อไม่ได้ใช้งานต่อพลังงานเริ่มต้น => เสียไฟไปเท่าไรเมื่อไม่ได้ใช้



Source : https://greensarawak.com/things-to-know-before-going-solar/going-solar-chapter-15-know-your-battery/

ESS Key Parameters

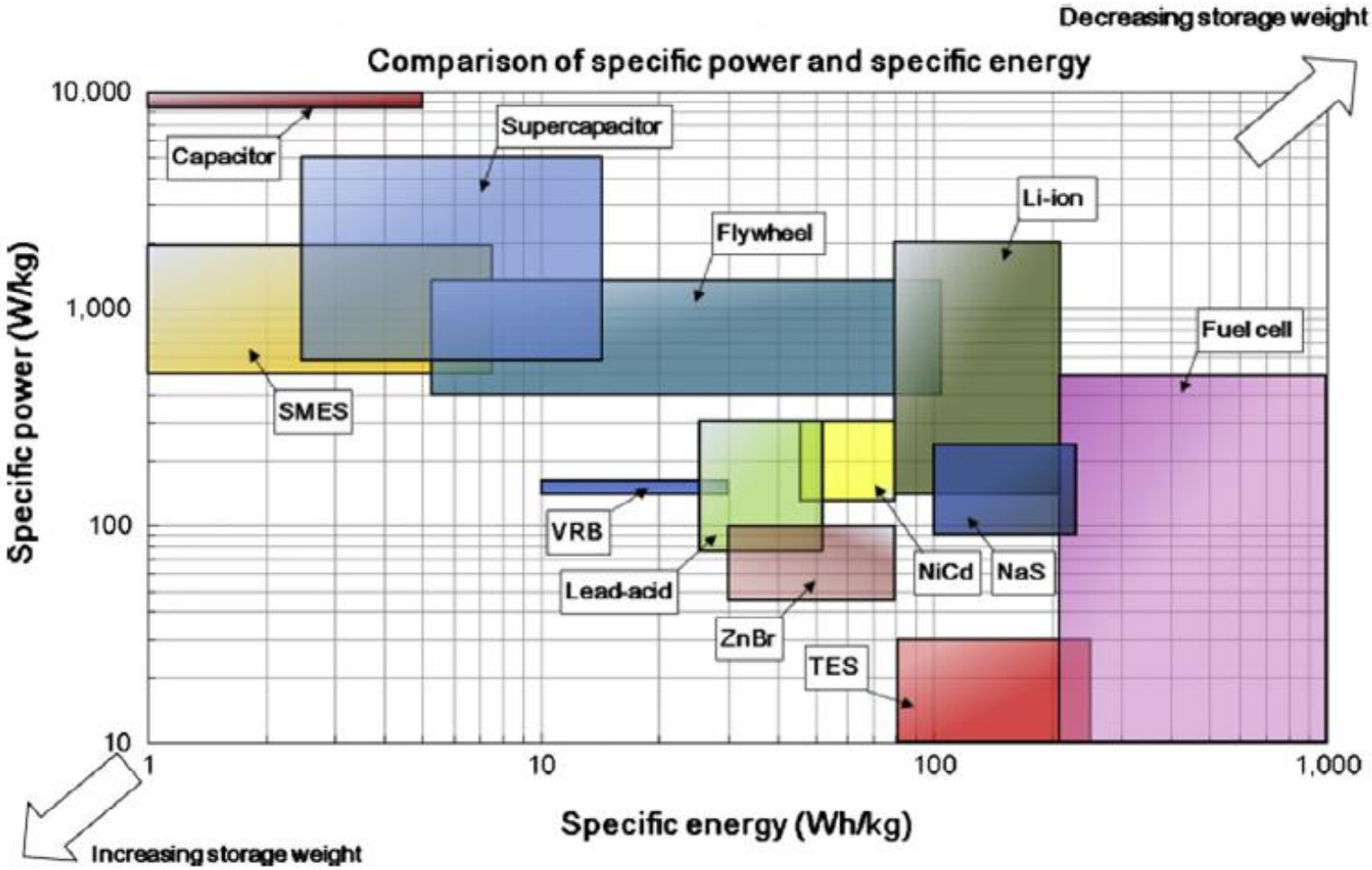
Power vs. Energy Density



Source: Lue_X_2015 Overview of current dev in ESS for power system

ESS Key Parameters

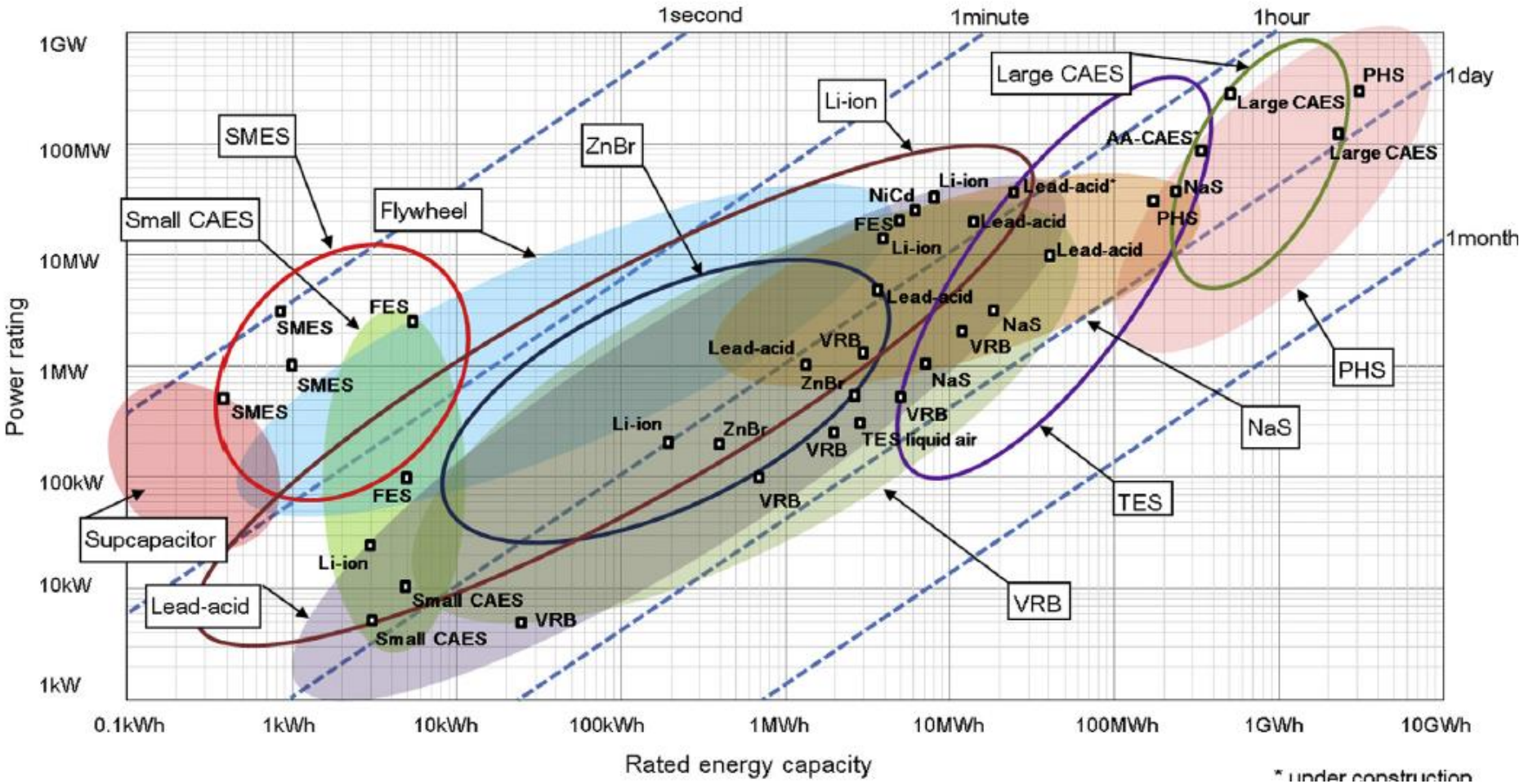
Power vs. Energy Density



Source: Lue_X_2015 Overview of current dev in ESS for power system

ESS Key Parameters

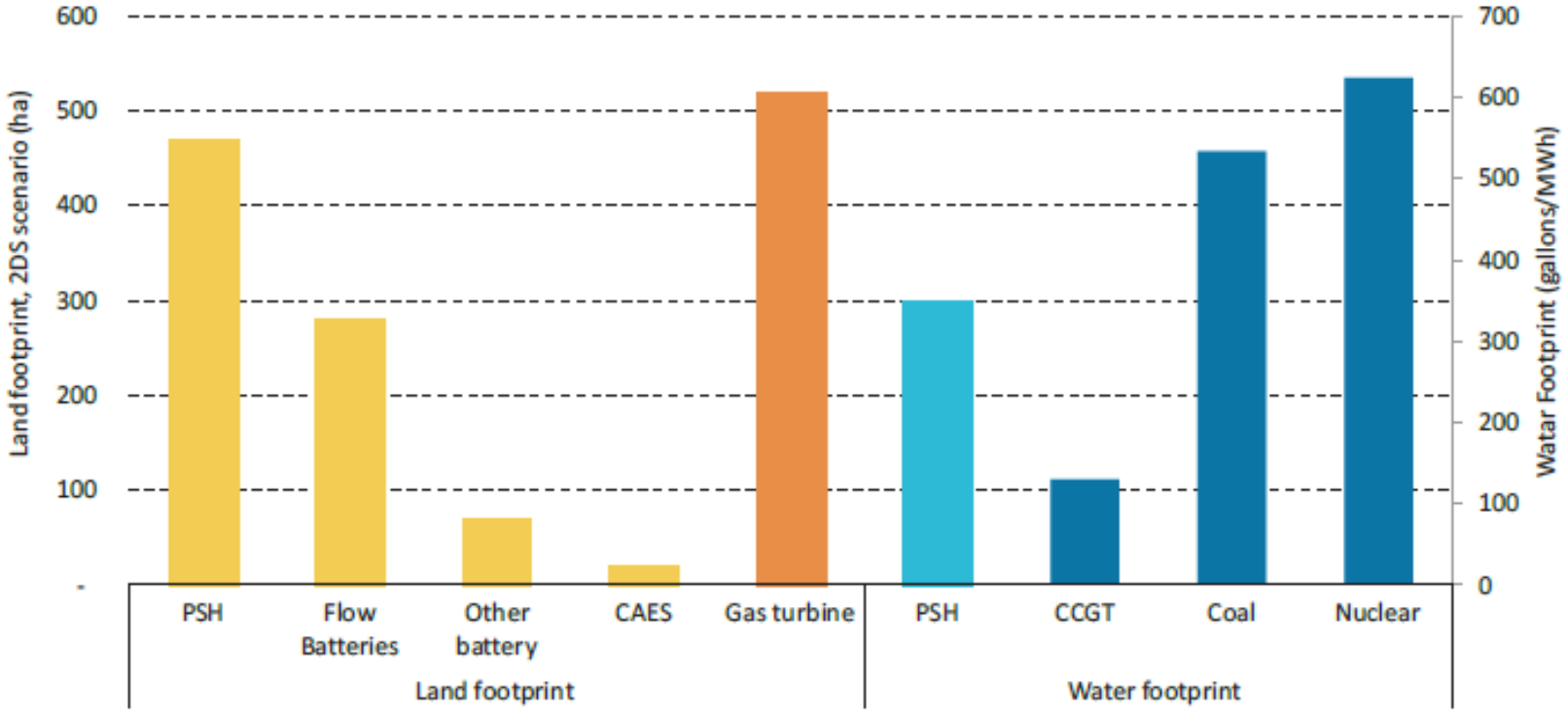
Rated Power, Energy



Source: Lue_X_2015 Overview of current dev in ESS for power system

ESS Key Parameters

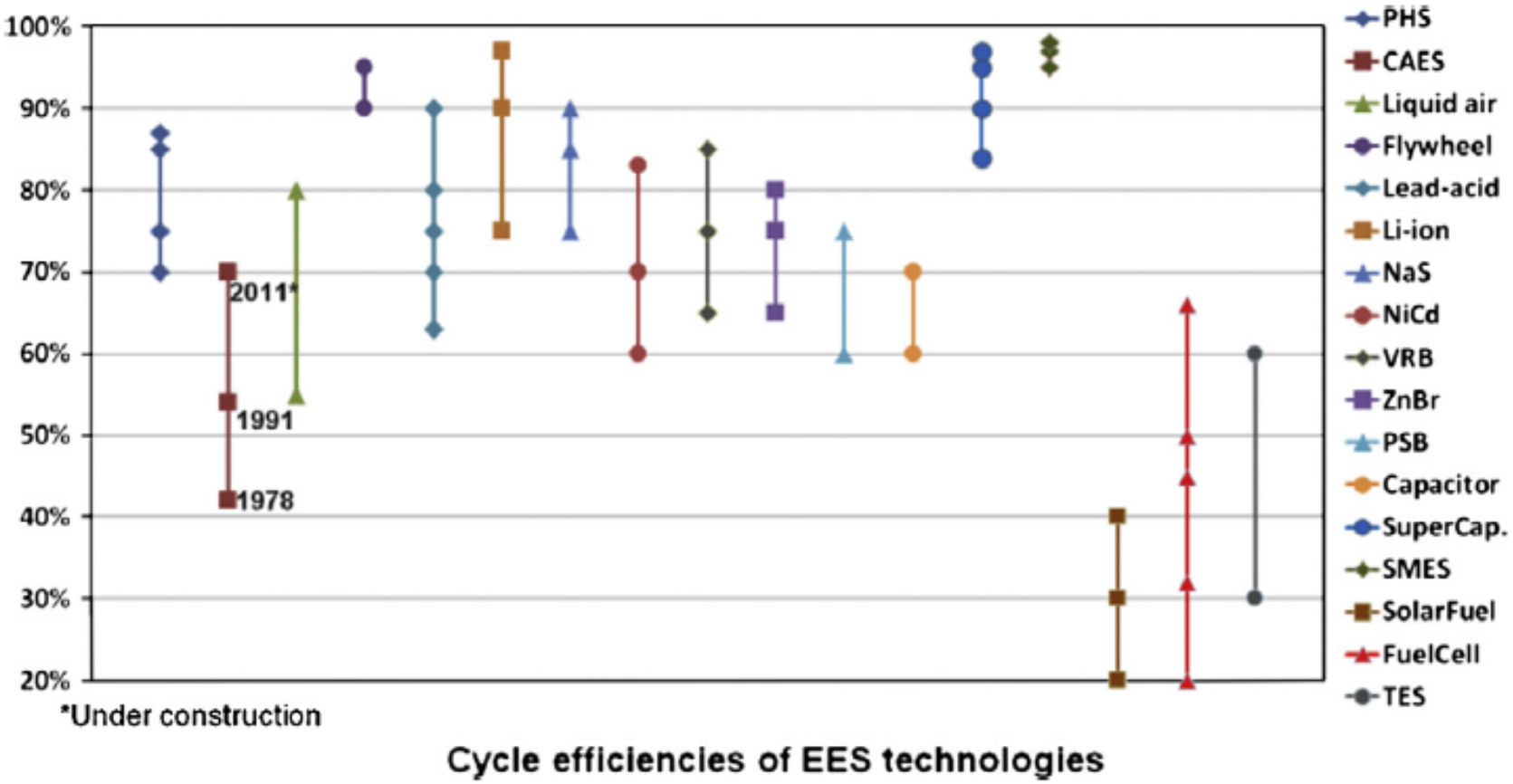
Land and Water Footprint



Source: Decourt, B. and R. Debarre (2013), "Electricity storage", *Factbook*, Schlumberger Business Consulting Energy Institute, Paris, France. National Energy Technology Laboratory (NETL) (2010), "Life cycle analysis: supercritical pulverized coal (SCPC) power plant, NETL, September, Pittsburgh. National Renewable Energy Laboratories (NREL) (2013), *Renewable Electricity Futures Study (RE Futures)* Golden, CO, United States, www.nrel.gov/analysis/re_futures/.

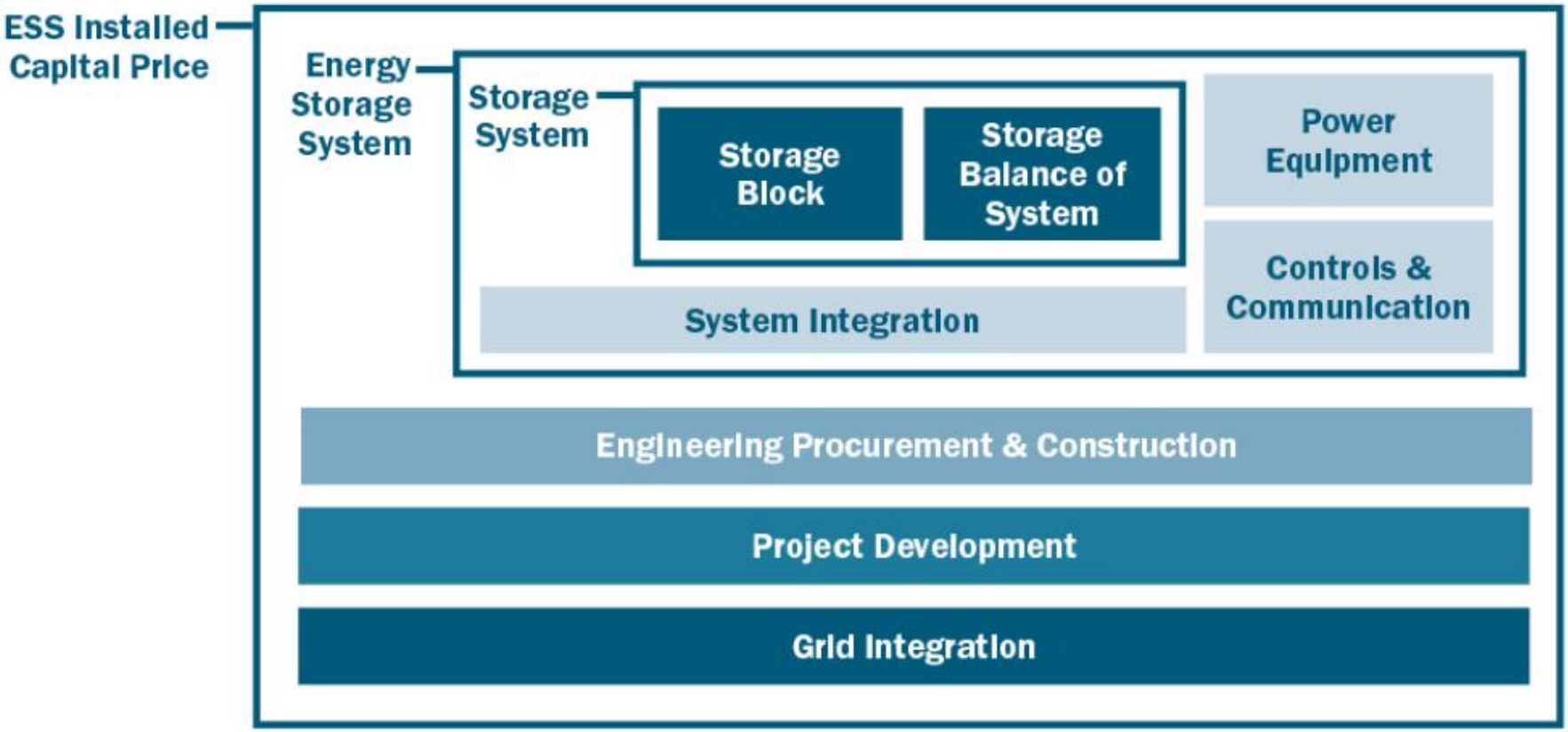
ESS Key Parameters

Efficiency



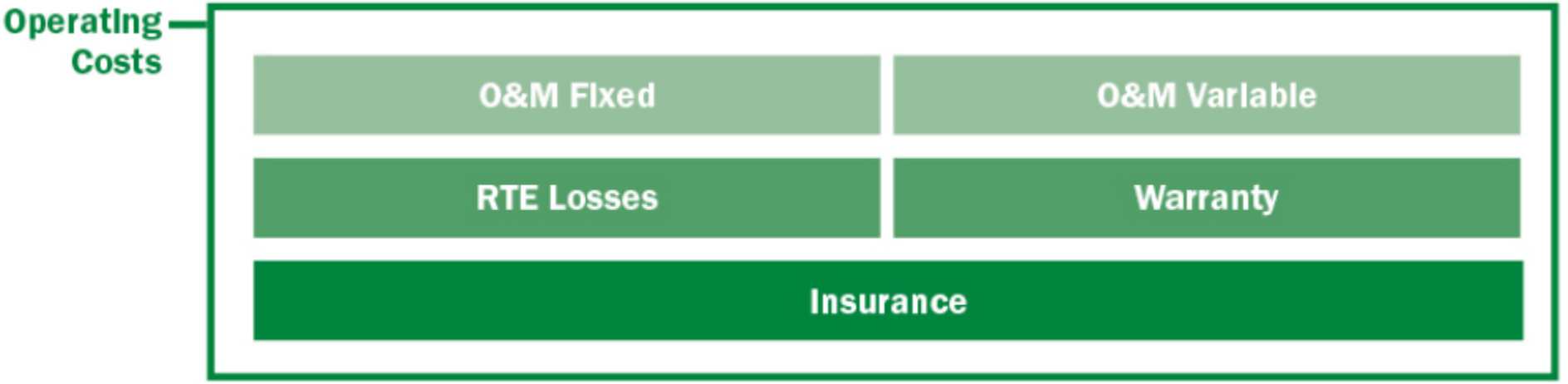
Cycle efficiencies of EES technologies

ESS Cost Structure



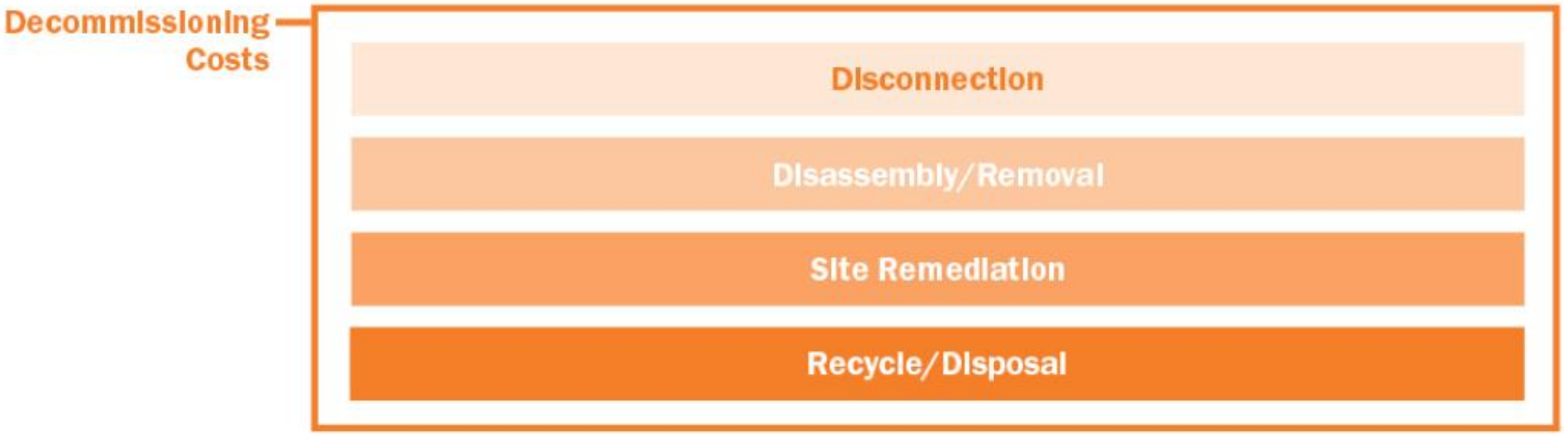
Source: US DOE Energy Storage Grand Challenge Roadmap December 2020. Web [20 May, 2022]

ESS Cost Structure



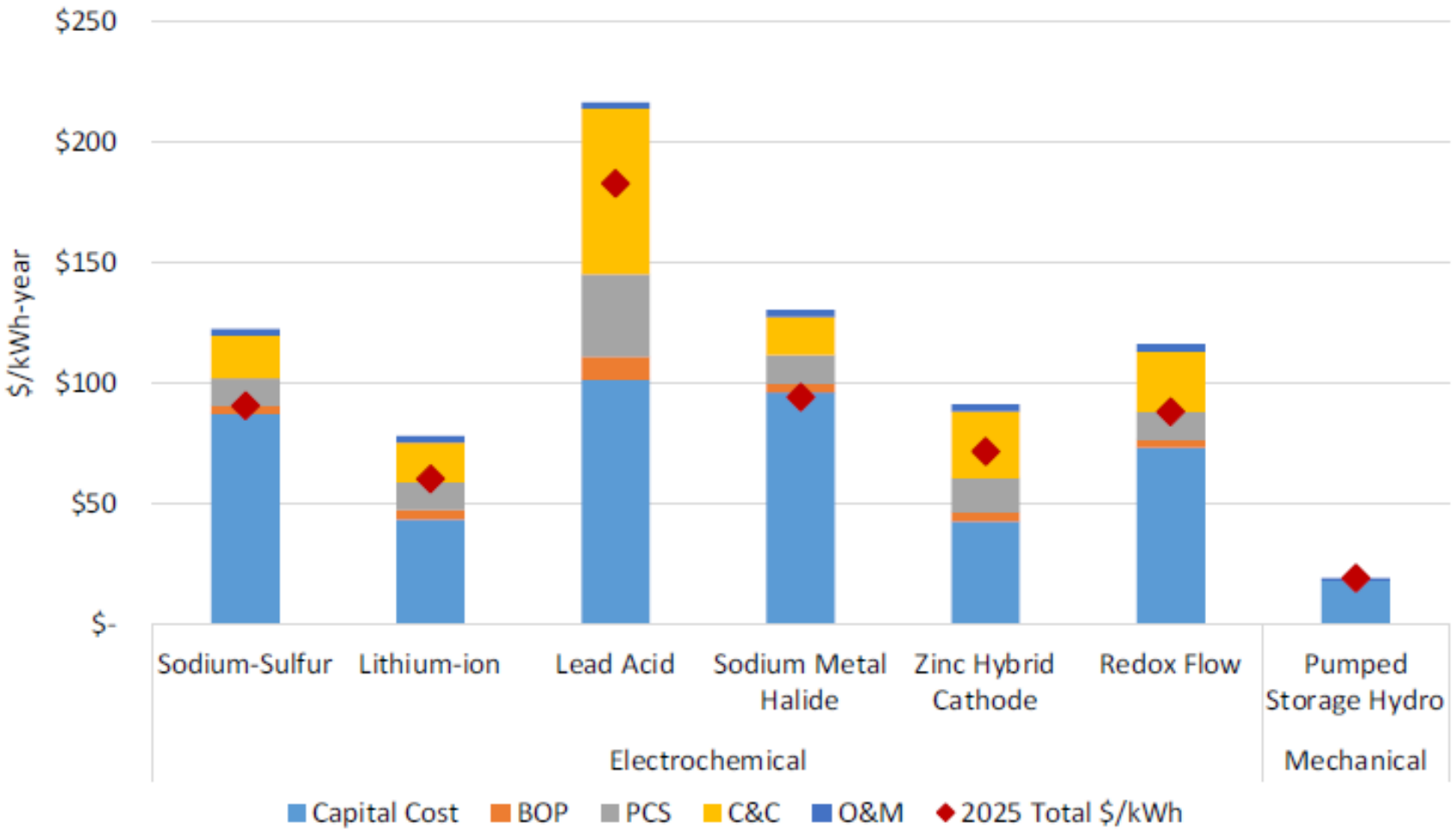
Source: US DOE Energy Storage Grand Challenge Roadmap December 2020. Web [20 May, 2022]

ESS Cost Structure



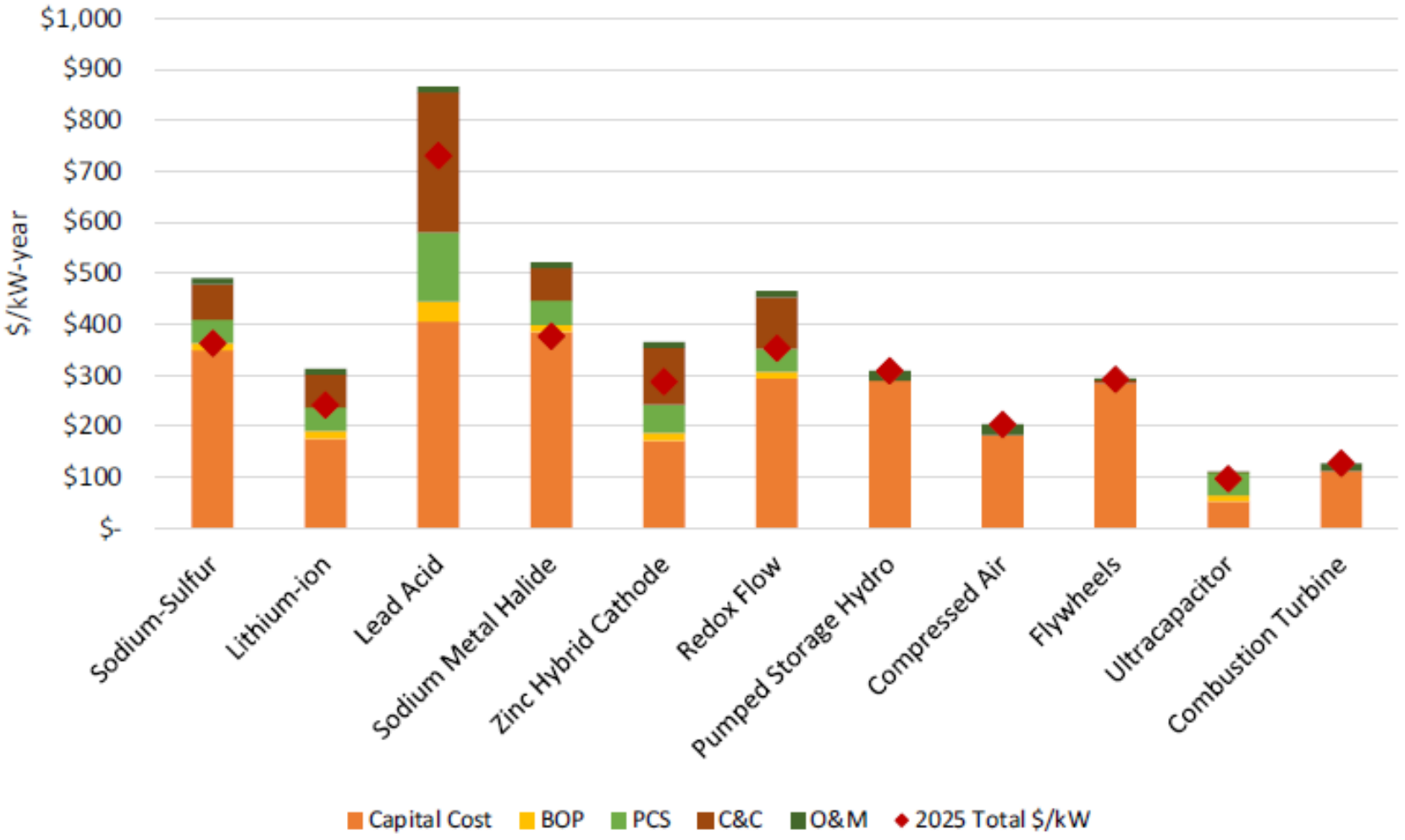
Source: US DOE Energy Storage Grand Challenge Roadmap December 2020. Web [20 May, 2022]

ESS Cost Structure



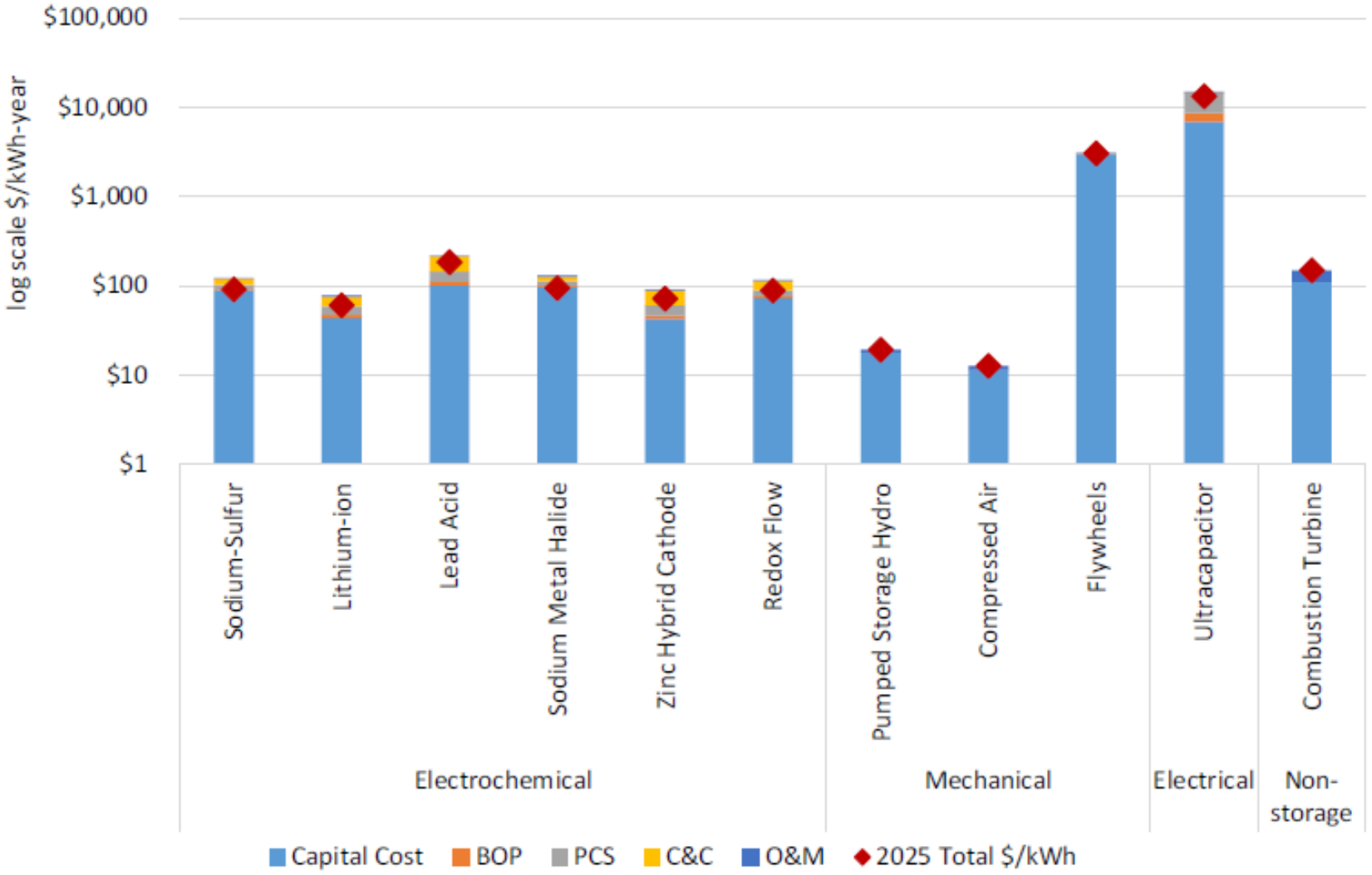
Source: US DOE Energy Storage Grand Challenge Roadmap December 2020. Web [20 May, 2022]

ESS Cost Structure



Source: US DOE Energy Storage Grand Challenge Roadmap December 2020. Web [20 May, 2022]

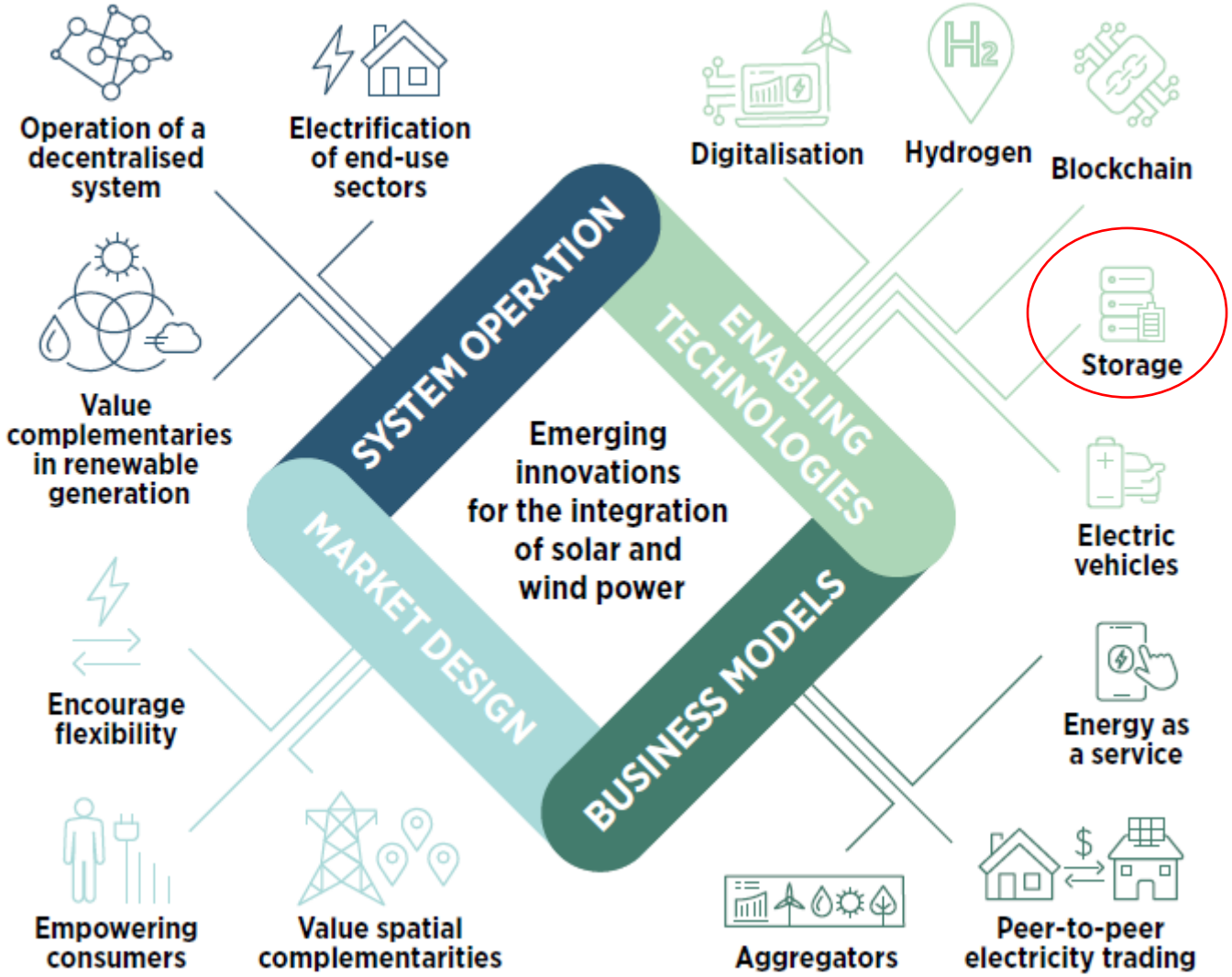
ESS Cost Structure



Source: US DOE Energy Storage Grand Challenge Roadmap December 2020. Web [20 May, 2022]

ESS – Key Emerging Innovation

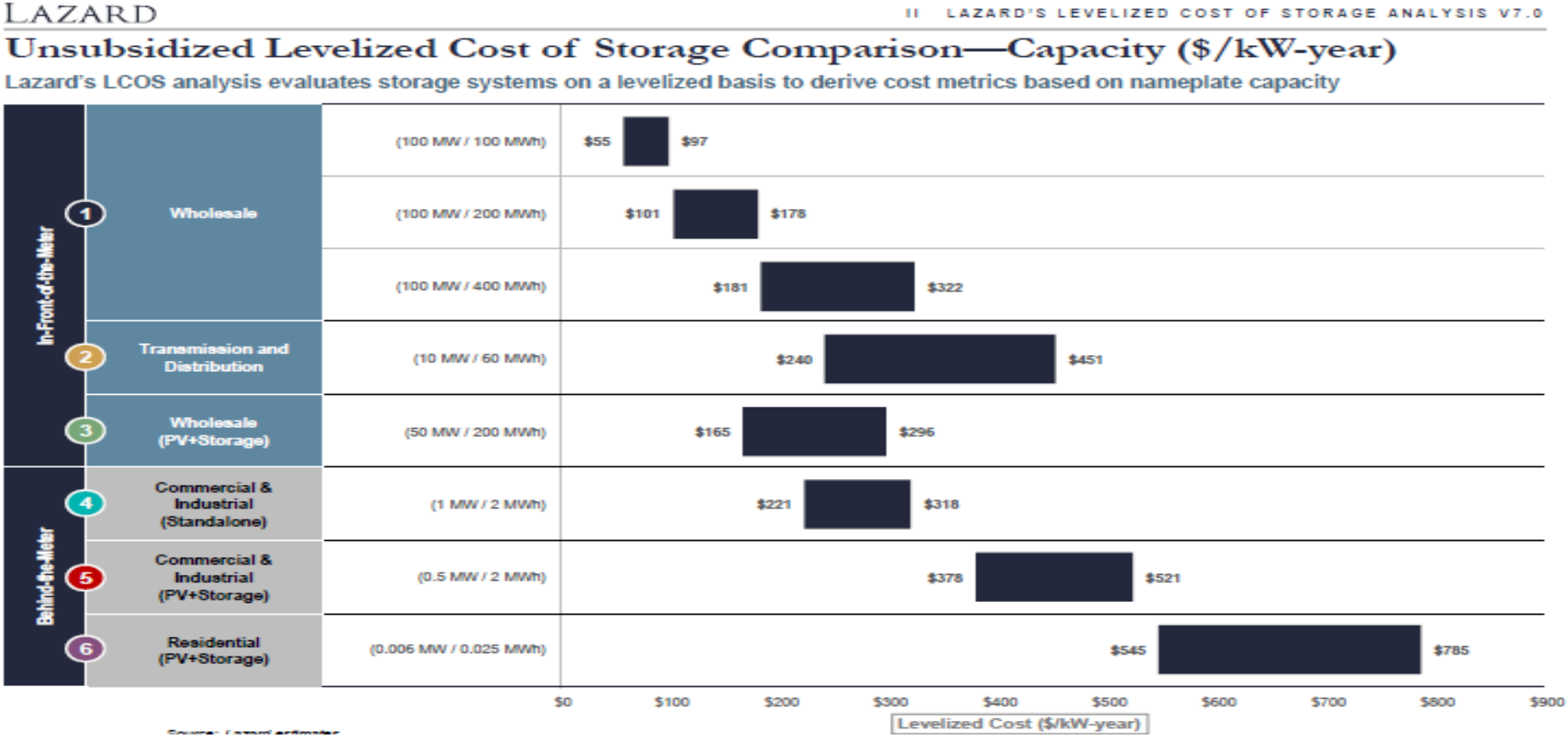
For Integration of variable RE



Source: IRENA_World_Energy_Transitions_Outlook_2021

Key Challenges: Cost

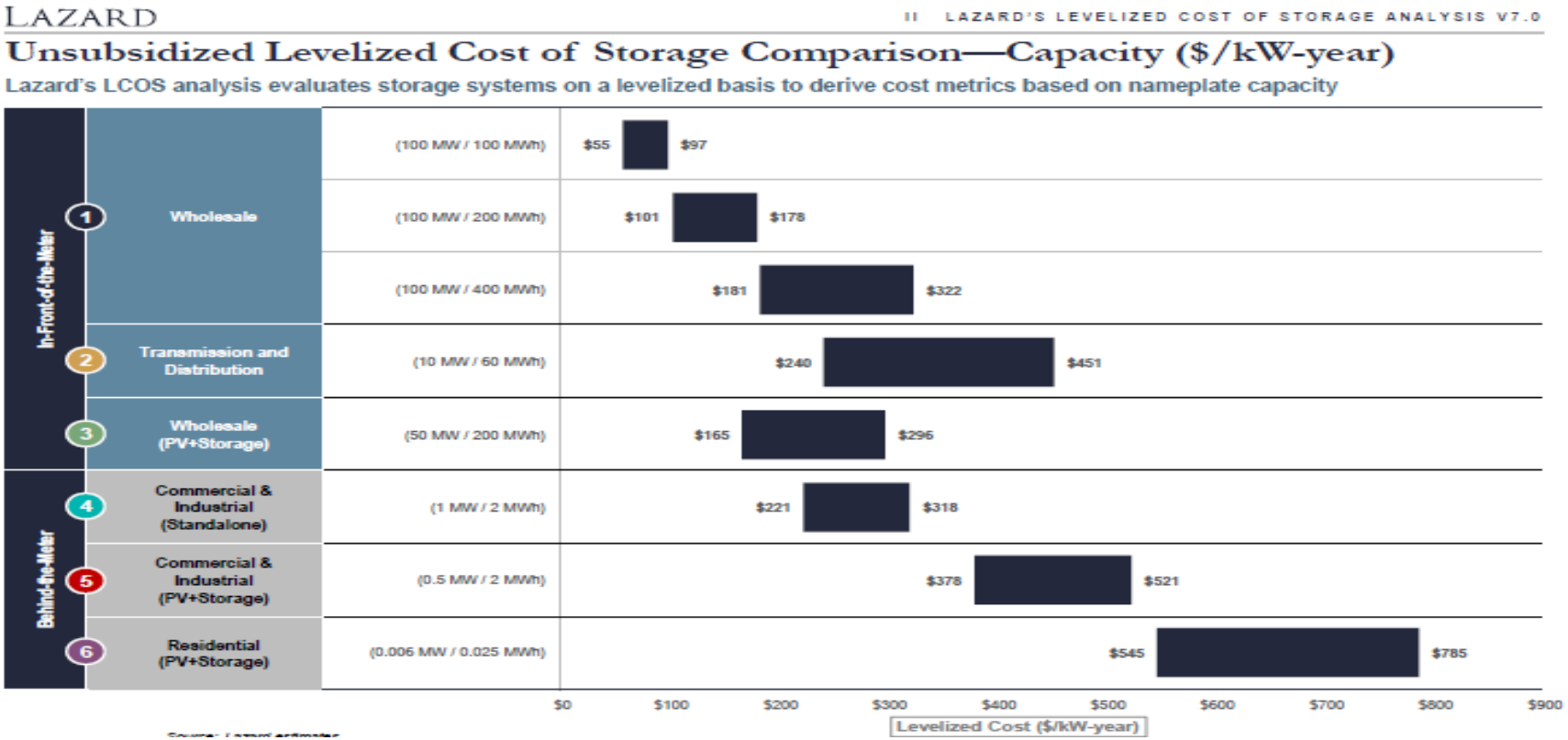
A Race to Drive Down Cost



Source:: Lazard's Levelized Cost of Storage 2021

Key Challenges: Cost

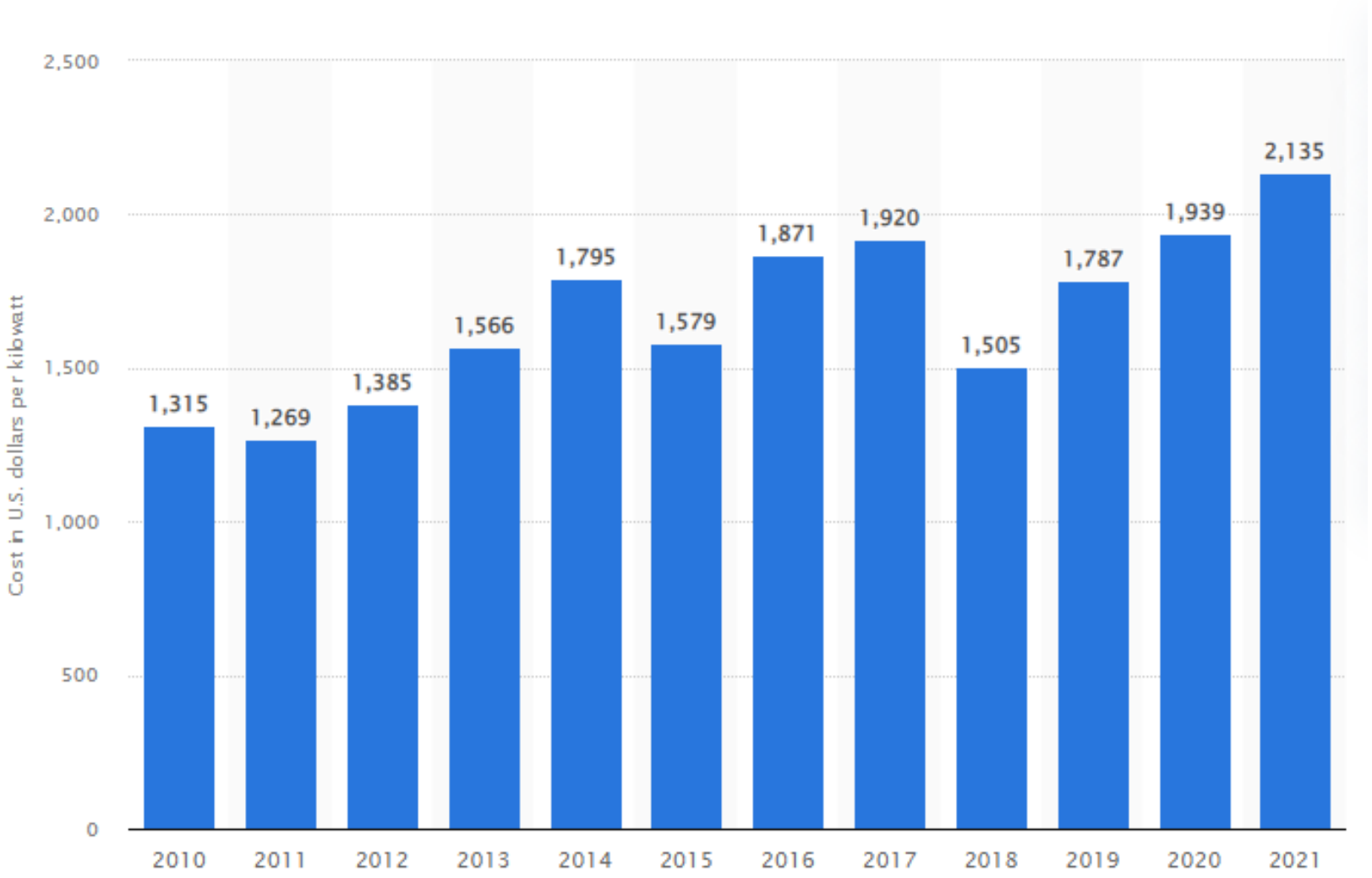
A Race to Drive Down Cost



Source:: Lazard's Levelized Cost of Storage 2021

ESS – Key Emerging Innovation

Benchmark – traditional storage → Pump Hydro Power

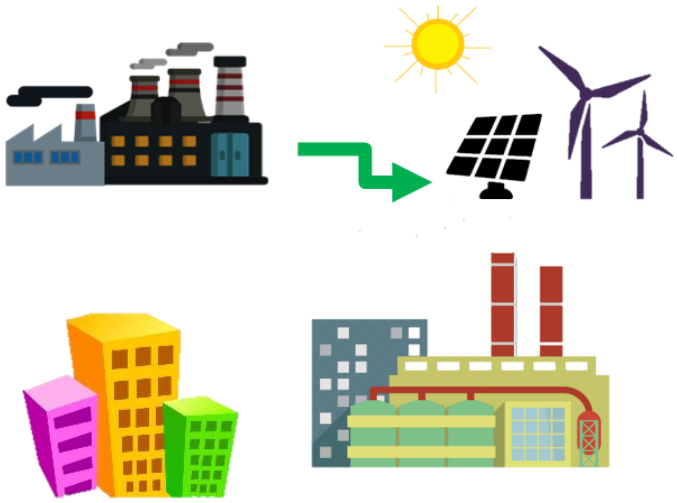


Source: https://www.statista.com/statistics/799341/global-hydropower-installation-cost/

Key Challenges

A Race to Drive Down Cost

90%



0.05$/kWh.cycle (~$60/kWh @ 3000 cycles)

(~1.5 baht/kWh.cycle)

ปัจจุบันอยู่ที่ ~ 4-6 baht/kWh.cycle (Li-ion batt)

44%

$80/kWh

(pack for 300 miles EV)

Source: US DOE Energy Storage Grand Challenge Roadmap December 2020. Web [20 May, 2022

Which Technology? - BESS

A Race to Drive Down Cost

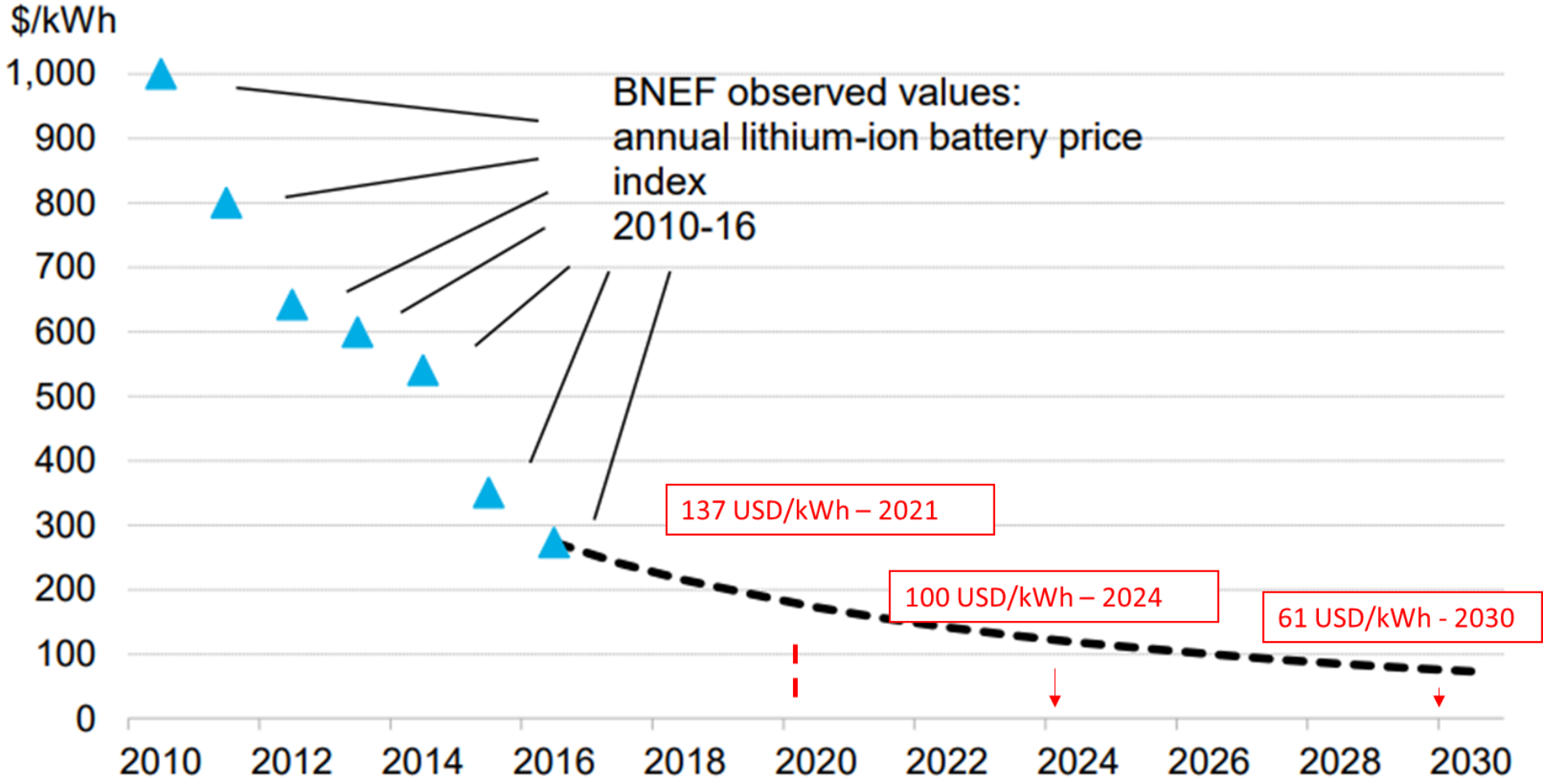
Table ES.1. Summary of compiled 2018 findings and 2025 predictions for cost and parameter ranges by technology type – BESS.[a]

Parameter	Sodium-Sulfur Battery		Li-Ion Battery		Lead Acid		Sodium Metal Halide		Zinc-Hybrid Cathode		Redox Flow Battery	
	2018	2025	2018	2025	2018	2025	2018	2025	2018	2025	2018	2025
Capital Cost – Energy Capacity ($/kWh)	400-1,000 **661**	(300-675) **(465)**	223-323 **271**	(156-203) **(189)**	120-291 **260**	(102-247) **(220)**	520-1,000 **700**	(364-630) **(482)**	265-265 **265**	(179-199) **(192)**	435-952 **555**	(326-643) **(393)**
Power Conversion System (PCS) ($/kW)	230-470 **350**	(184-329) **(211)**	230-470 **288**	(184-329) **(211)**	230-470 **350**	(184-329) **(211)**	230-470 **350**	(184-329) **(211)**	230-470 **350**	(184-329) **(211)**	230-470 **350**	(184-329) **(211)**
Balance of Plant (BOP) ($/kW)	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**	80-120 **100**	(75-115) **(95)**
Construction and Commissioning ($/kWh)	121-145 **133**	(115-138) **(127)**	92-110 **101**	(87-105) **(96)**	160-192 **176**	(152-182) **(167)**	105-126 **115**	(100-119) **(110)**	157-188 **173**	(149-179) **(164)**	173-207 **190**	(164-197) **(180)**
Total Project Cost ($/kW)	2,394-5,170 **3,626**	(1,919-3,696) **(2,674)**	1,570-2,322 **1,876**	(1,231-1,676) **(1,446)**	1,430-2,522 **2,194**	(1,275-2,160) **(1,854)**	2,810-5,094 **3,710**	(2,115-3,440) **(2,674)**	1,998-2,402 **2,202**	(1,571-1,956) **(1,730)**	2,742-5,226 **3,430**	(2,219-3,804) **(2,598)**
Total Project Cost ($/kWh)	599-1,293 **907**	(480-924) **(669)**	393-581 **469**	(308-419) **(362)**	358-631 **549**	(319-540) **(464)**	703-1,274 **928**	(529-860) **(669)**	500-601 **551**	(393-489) **(433)**	686-1,307 **858**	(555-951) **(650)**
O&M Fixed ($/kW-yr)	10	(8)	10	(8)	10	(8)	10	(8)	10	(8)	10	(8)
O&M Variable (cents/kWh)	0.03		0.03		0.03		0.03		0.03		0.03	
System Round-Trip Efficiency (RTE)	0.75		0.86		0.72		0.83		0.72		0.675	(0.7)
Annual RTE Degradation Factor	0.34%		0.50%		5.40%		0.35%		1.50%		0.40%	
Response Time (limited by PCS)	1 sec		1 sec		1 sec		1 sec		1 sec		1 sec	
Cycles at 80% Depth of Discharge	4,000		3,500		900		3,500		3,500		10,000	
Life (Years)	13.5		10		2.6	(3)	12.5		10		15	
MRL	9	(10)	9	(10)	9	(10)	7	(9)	6	(8)	8	(9)
TRL	8	(9)	8	(9)	8	(9)	6	(8)	5	(7)	7	(8)

(a) An E/P ratio of 4 hours was used for battery technologies when calculating total costs.
MRL = manufacturing readiness level; O&M = operations and maintenance; TRL = technology readiness level.

Source: K. Mongird Energy Storage Technology and Cost Characteriztaon Report

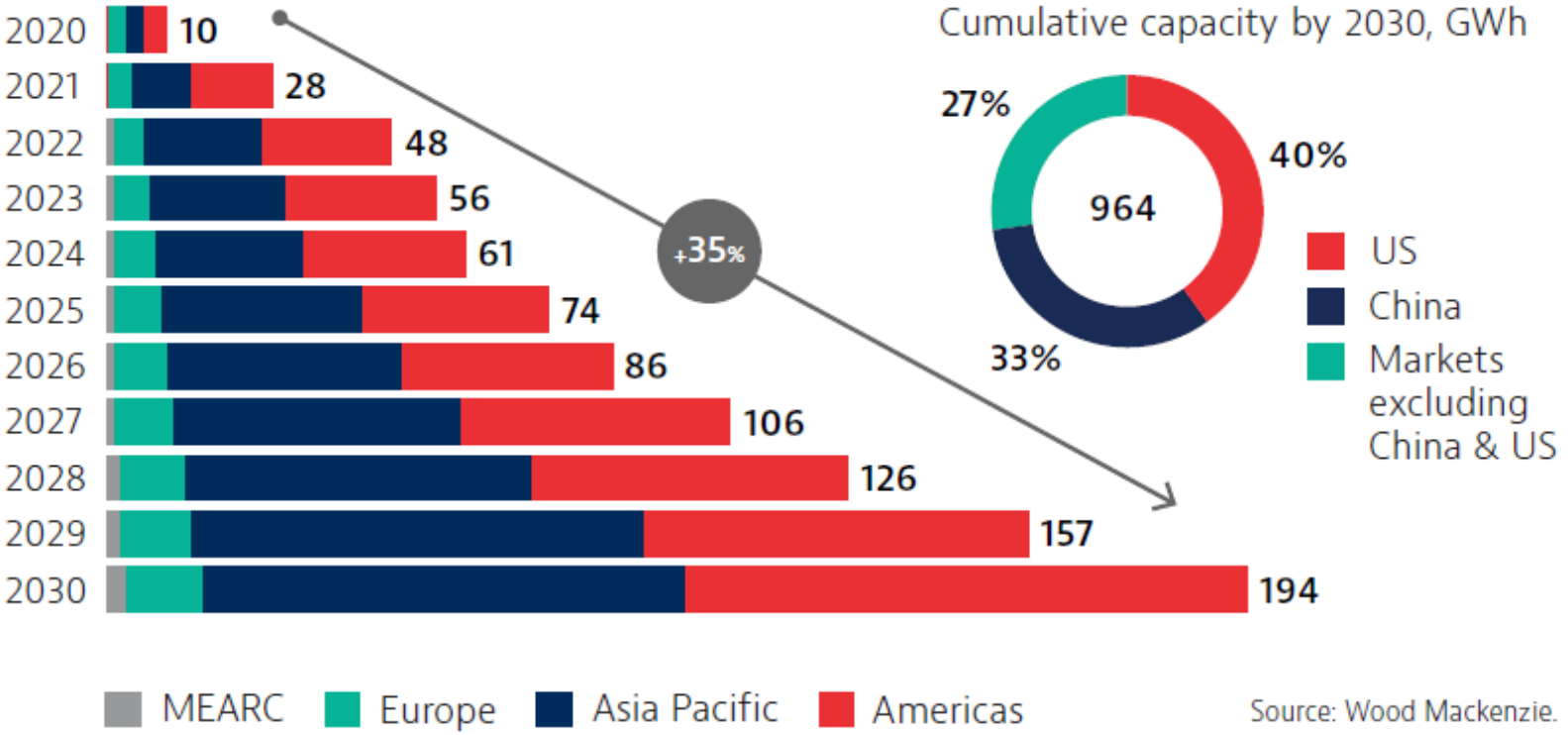
Which Technology? - BESS



Source: Source: Bloomberg New Energy Finance June 2017

Which Technology? - BESS

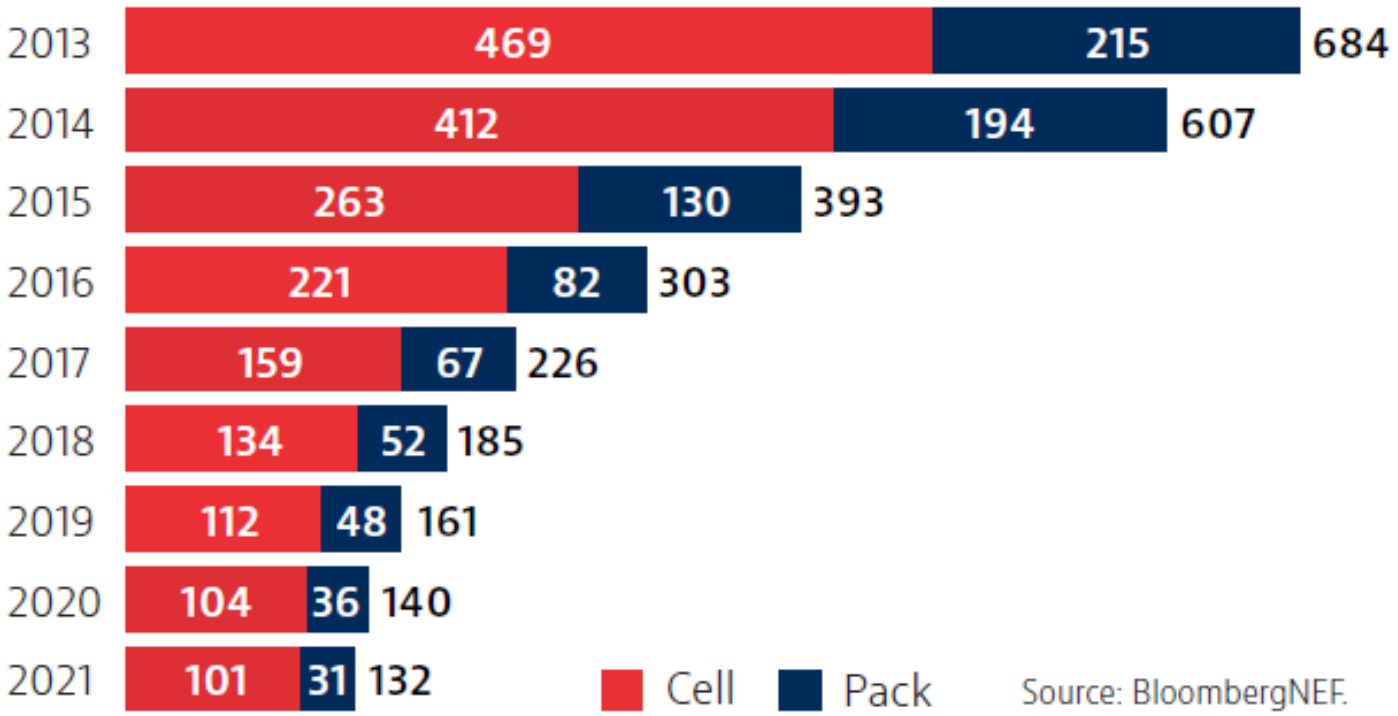
FIGURE 1 - GLOBAL ENERGY STORAGE ANNUAL CAPACITY GWH



Source: Baker and Mckinsey 2022, Battery Storage - a global enabler of the Energy Transition 2022

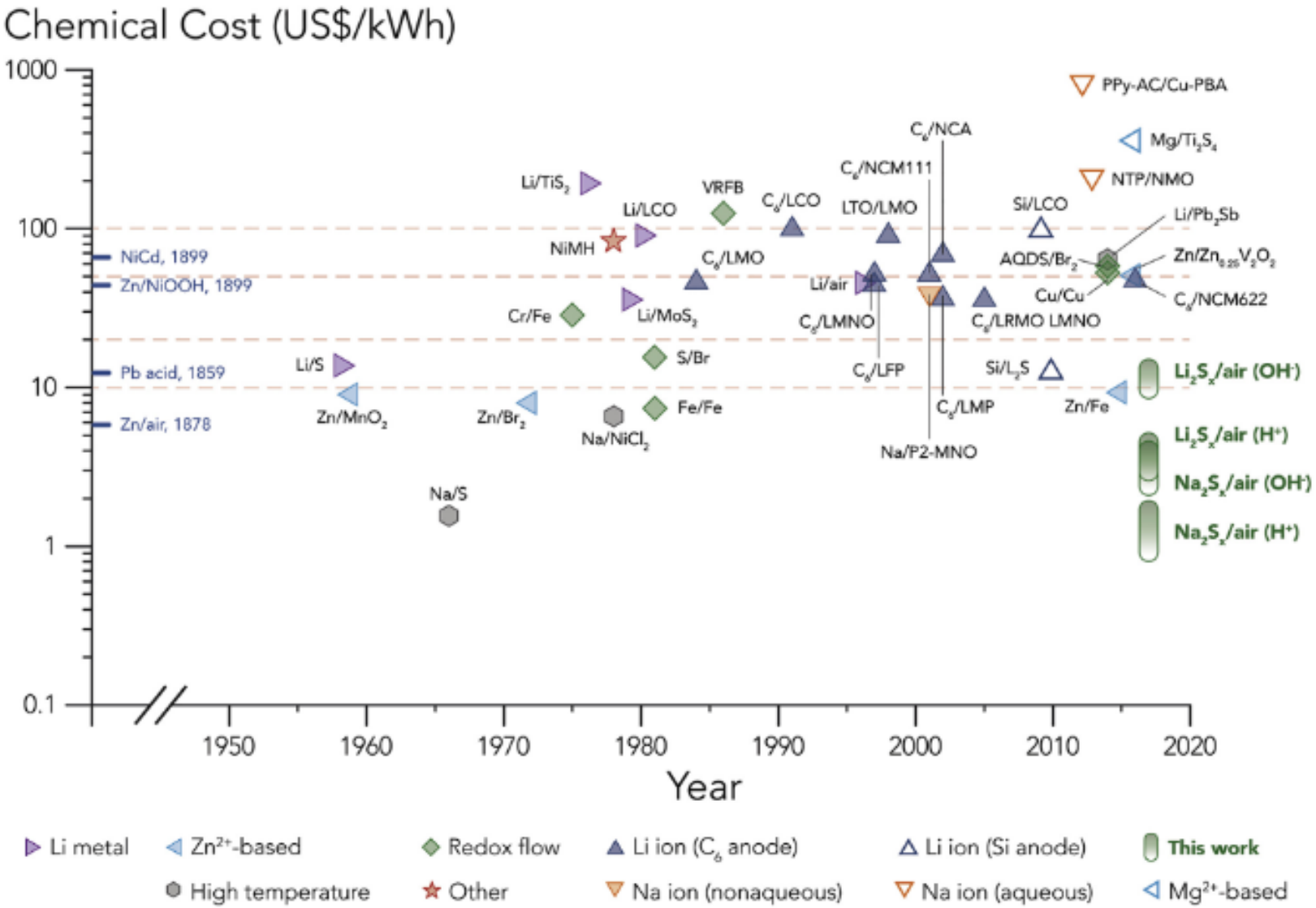
Which Technology? - BESS

FIGURE 2 - AVERAGE LITHIUM-ION BATTERY COST USD (2021)



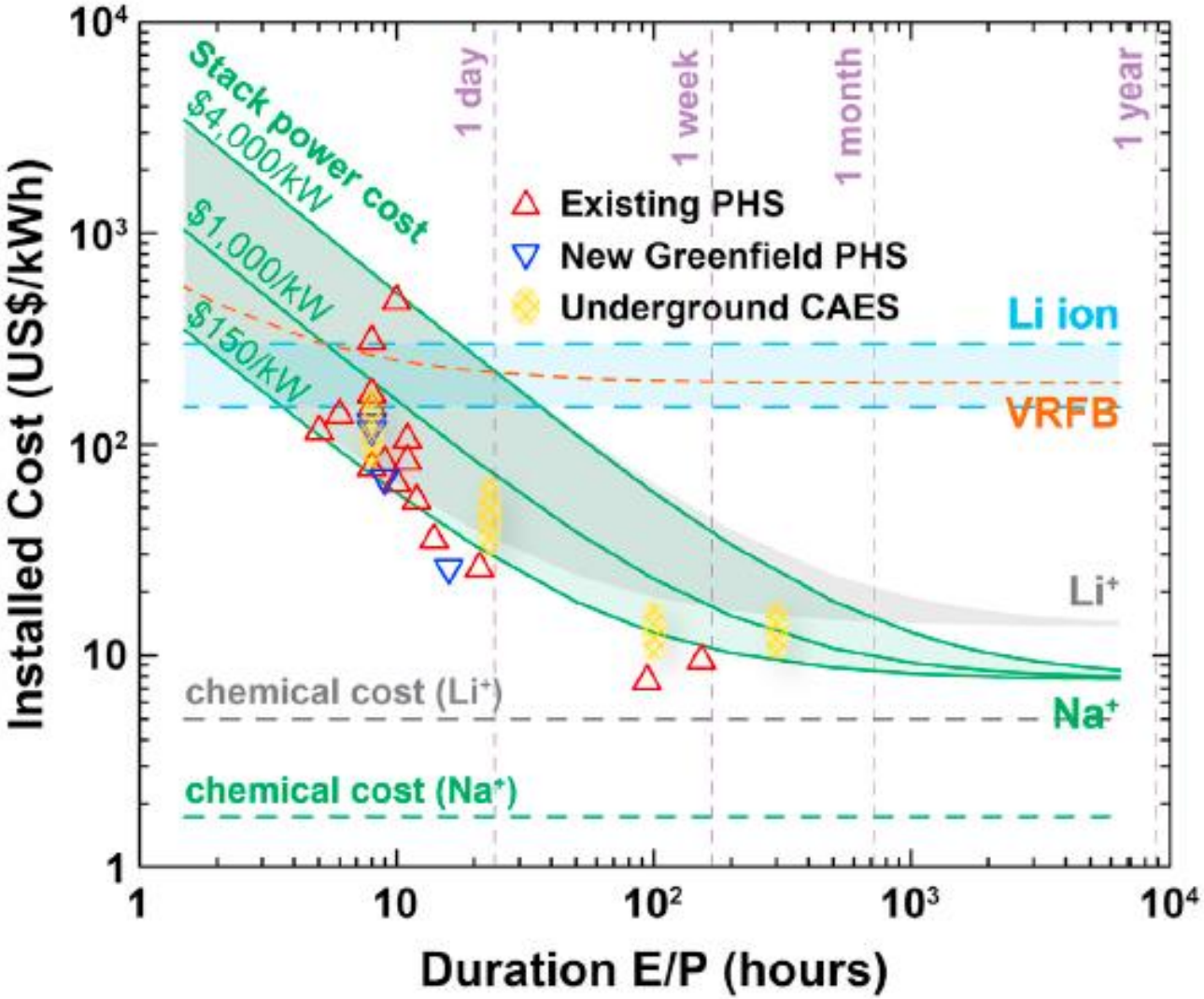
Source: Baker and Mckinsey 2022, Battery Storage - a global enabler of the Energy Transition 2022

Which Technology? - BESS



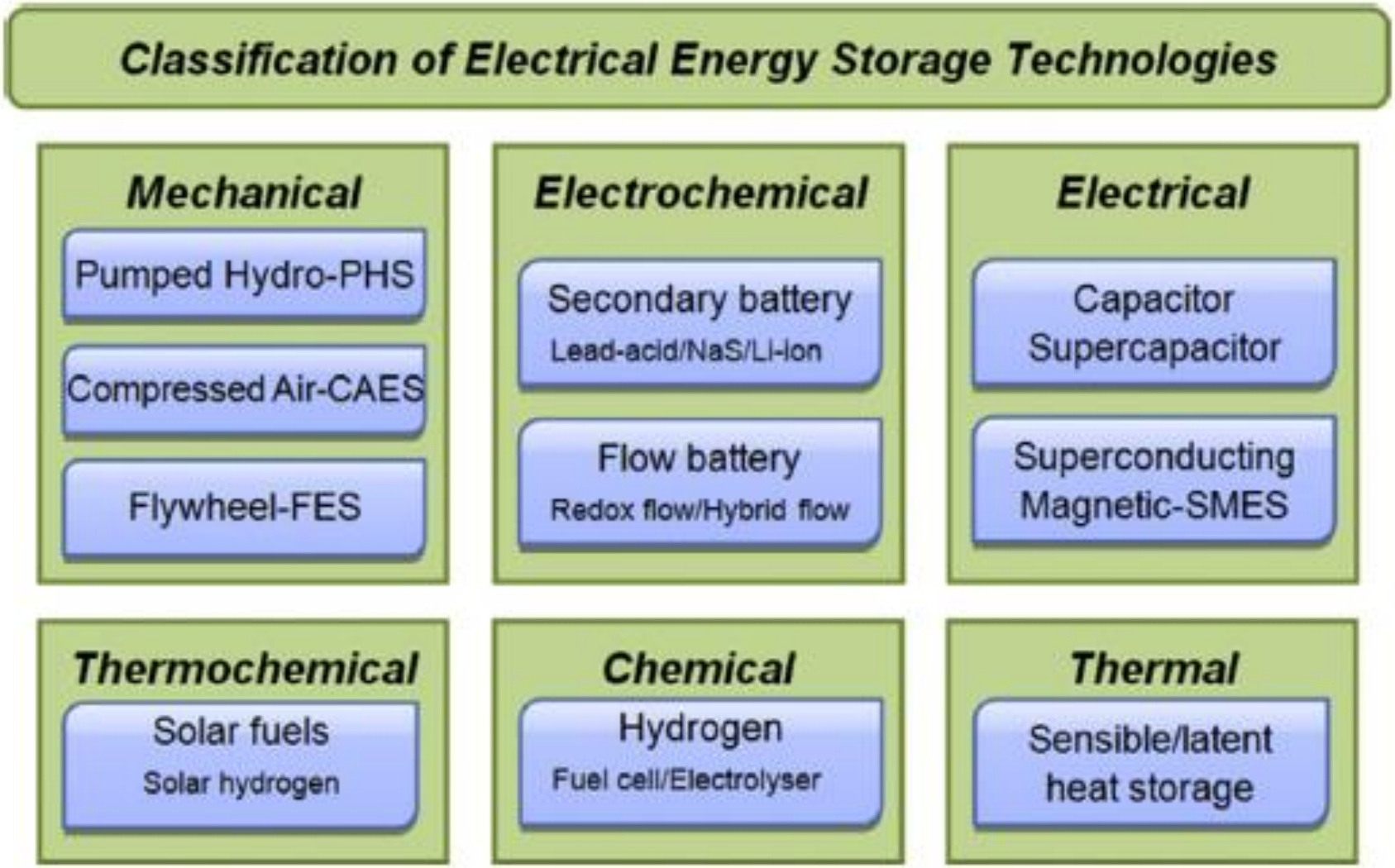
Source: Li et al. Air-Breathing Aqueous Sulfur Flow Battery for Ultralow-Cost Long-Duration Electrical Storage,

Which Technology? - BESS



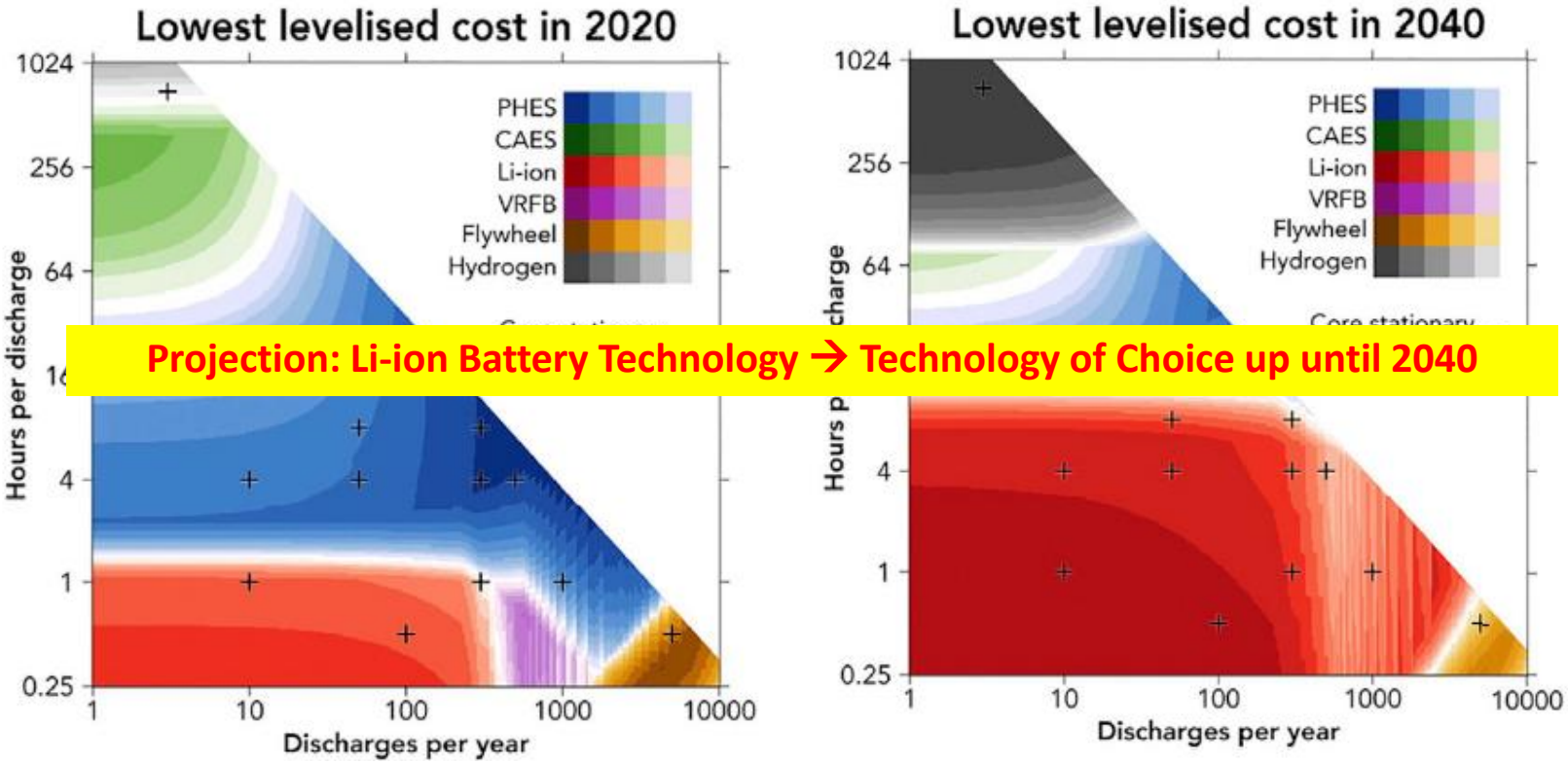
Source: Li et al. Air-Breathing Aqueous Sulfur Flow Battery for Ultralow-Cost Long-Duration Electrical Storage,

Which Technology? Any Other?



Source: Lue_X_2015 Overview of current dev in ESS for power system

Which Technology? Any Other?



Projection: Li-ion Battery Technology → Technology of Choice up until 2040

Source: K. R. Pullen, "The Status and Future of Flywheel Energy storage, Joule, 3, 1394-1403, June 19, 2019

ESS Innovation

The Battery Report 2021" Volta Foundation & Intercalation, 8 January 2022. Web [20 May, 2022]

ESS Innovation

Innovators | Stationary Storage

Company	Technology	Tot. Funding, Stage	Major Investors*
ZincFive	Rechargeable Ni-Zn battery for emergency backup power	$36M, Series C	Helios Capital Ventures, Qiming Venture Partners
ENERVENUE	Metal-hydrogen batteries over wide temperature range for 2-12 hrs of storage	$112M, Series A	Schlumberger, Peter Lee
Form energy	Long-duration (100-150 hrs) rechargeable iron-air batteries	$368M, Series D	ArcelorMittal, Energy Impact Partners, Breakthrough Energy Ventures
FREEWIRE	Li-ion fast DC charging for grid infrastructure and EV chargers	$105M, Series C	Riverstone Holdings, BP Ventures
Ambri	Molten-salt batteries for wind and solar power systems	$211M, Series C	Reliance Industries, Khosla Ventures
MALTA	Heat exchanger-based with superheated molten salt	$87M, Series B	Chevron Technology Ventures, Proman, Breakthrough Energy Ventures
RELECTRIFY	Cell-level battery management system and inverter	$4.5M, Series A	Energy Innovation Capital, Clean Energy Finance Corporation
ESS INC	Medium duration (4-12 hrs) iron flow battery	$308M, SPAC	Bill Gates, SoftBank

Industry

* Non exhaustive list of companies

Intercalation | Volta Foundation

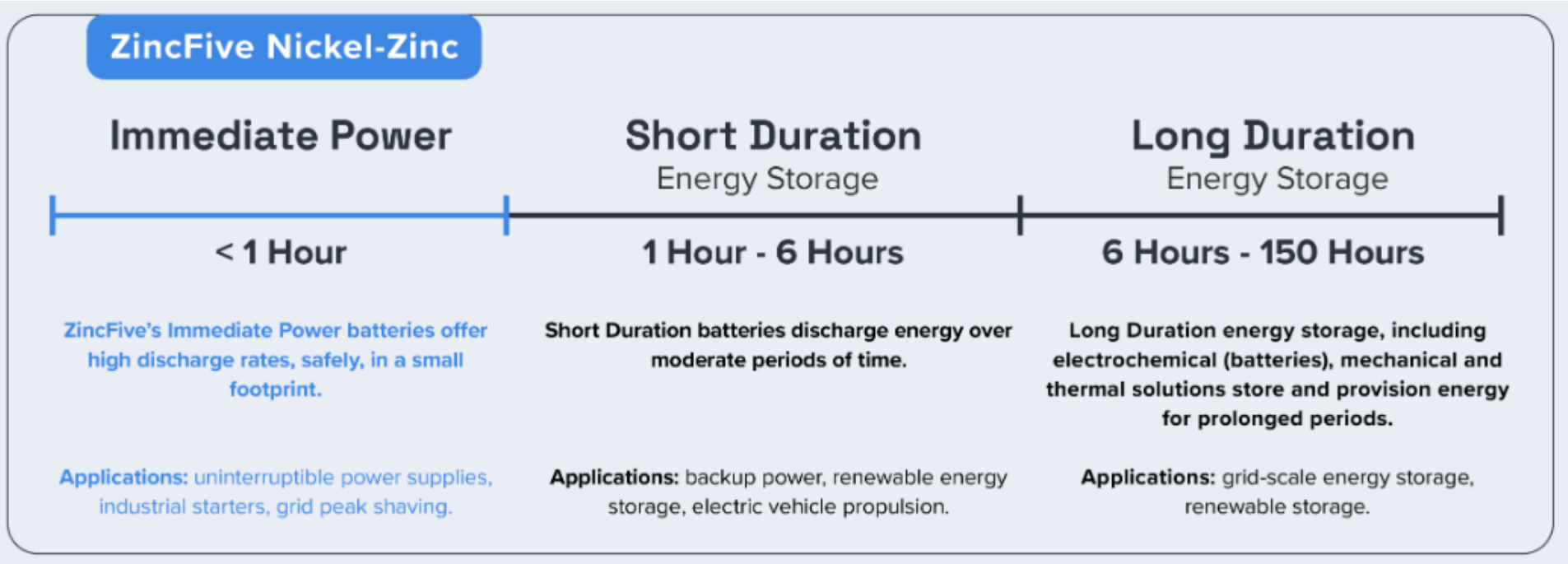
** Most stationary storage companies are venture-backed as opposed to strategic partnerships, partly due to the higher capex required, longer development time & longer time period for return

The Battery Report 2021" Volta Foundation & Intercalation, 8 January 2022. Web [20 May, 2022]

ESS Innovation

ZincFive

BATTERY



ESS Innovation

ENERVENUE

Ni-H2 BATTERY

EnerVenue secures 250 MWh order for nickel-hydrogen batteries

EnerVenue has agreed to supply batteries to Green Energy Renewable Solutions for use in customized building blocks for maritime applications, construction sites, and other heavy industry projects. The agreement marks EnerVenue's fourth major battery supply deal since it launched operations in 2020.

SEPTEMBER 23, 2022 BEATRIZ SANTOS

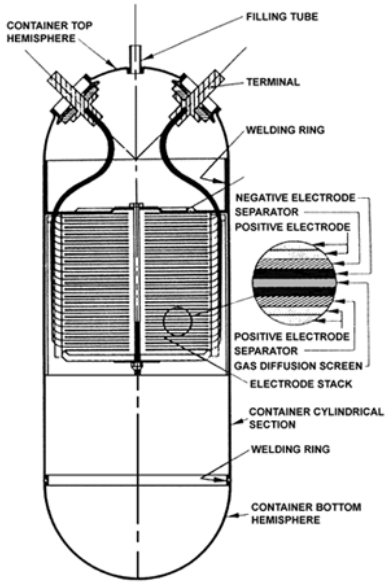
- **Found in 2020 w/ $12M**
- **Series A $100M**
- **"Reinventing technology that's been used for space exploration for nearly 30 years."**

Source: https://www.energy-storage.news/we-think-we-can-beat-lithium-ion-enervenue-bids-for-battery-storage-supremacy/

ESS Innovation

ENERVENUE

Ni-H2 BATTERY



- **Found in 2020 w/ $12M**
- **Series A $100M**
- **Wide range of operating T**
- **Long life time >30,000 cycle**
- **$20,000/kWh → $100/kWh**

Source: https://www.energy-storage.news/we-think-we-can-beat-lithium-ion-enervenue-bids-for-battery-storage-supremacy/

ESS Innovation

Eos Energy Storage

Zn-ion BATTERY

- **Found in 2008**
- **NASDAQ 2020**
- **3-12 duration for grid**
- **Current deal**

$325/kWh

(@MWh scale)

Eos customer takes zinc battery storage master supply agreement to 1GWh

By Andy Colthorpe

July 6, 2022

Americas, US & Canada Grid Scale Business, Products, Technology

LinkedIn Twitter Reddit Facebook Email

Source: https://eosenergystorage.com/

ESS Innovation

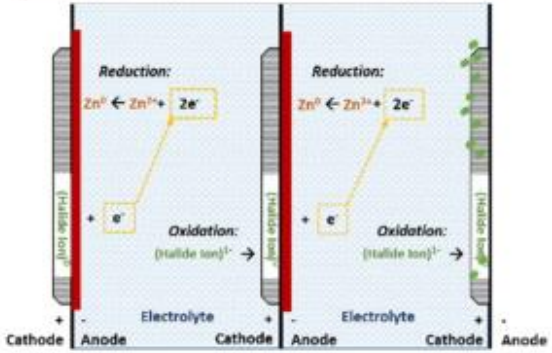
Eos Energy Storage

Zn-ion BATTERY

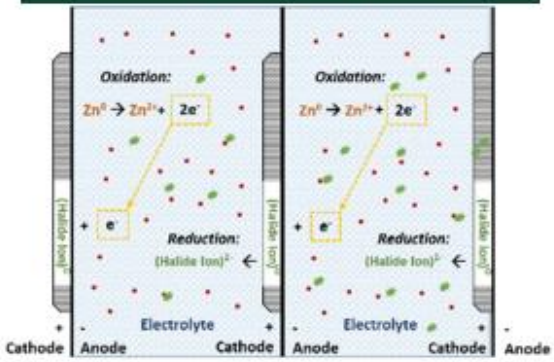
- **Found in 2008**
- **NASDAQ 2020**
- **3-12 duration for grid**
- **Current ~ $325/kWh -> Targeted $95/kWh**

Chemical Inspiration: Zinc Plating Baths

Top of Charge



End of Discharge and Rest



Source: https://eosenergystorage.com/

ESS Innovation

Ambri
Batteries for clean energy

Liquid Metal BATTERY

- **Found in 2010**
- **Sb based battery**
- **Backed by Bill Gates**
- **5 pilot projects planned in 2023**
- **4-12 hr duration**
- **20 years life**

DIVE BRIEF

Liquid battery startup Ambri ready to embark on first utility demonstration project with Xcel Energy

Published Sept. 6, 2022

By Emma Penrod

Petmal via Getty Images

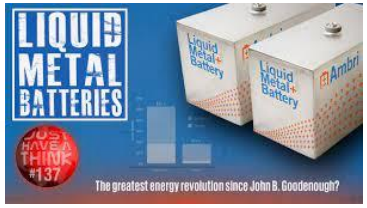
Source: https://www.energy-storage.news/we-think-we-can-beat-lithium-ion-enervenue-bids-for-battery-storage-supremacy/

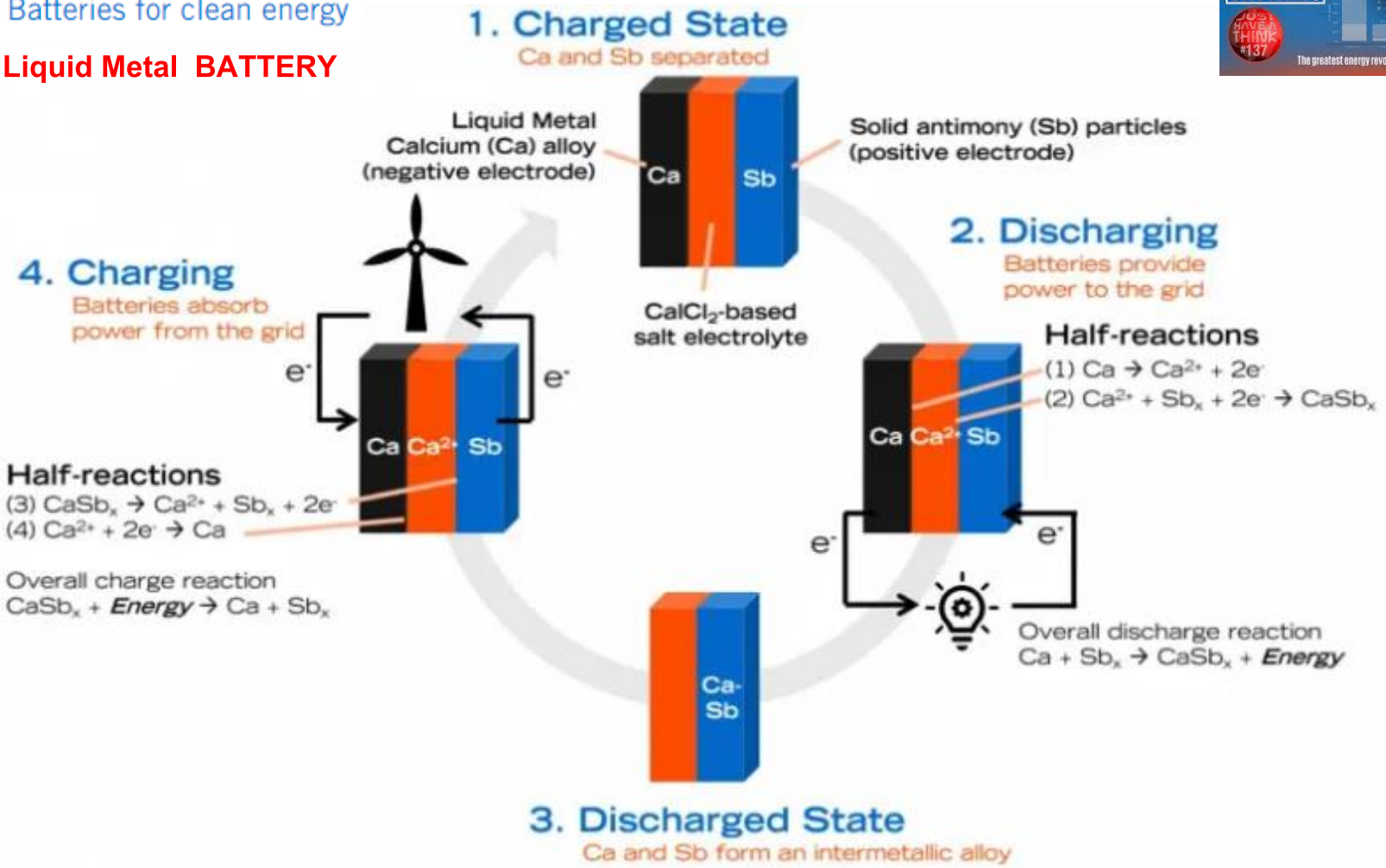
ESS Innovation

Ambri

Batteries for clean energy

Liquid Metal BATTERY





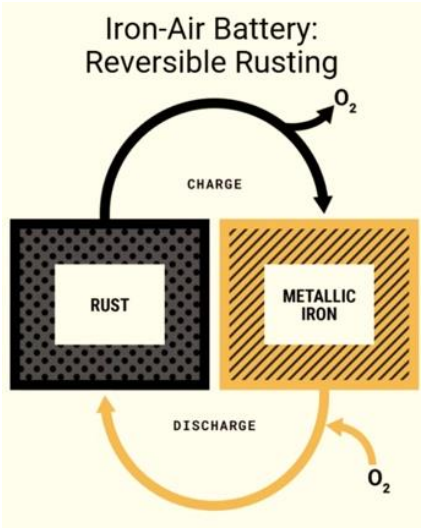
Source: https://www.energy-storage.news/we-think-we-can-beat-lithium-ion-enervenue-bids-for-battery-storage-supremacy/

Which Technology? Any Other?

Form energy

Fe-Air BATTERY

- **Found in 2017**
- **Backed by Bill Gates and Jeff Bezos**
- **Cheap → $20/kWh**
- **Long duration – multidays**
- **Hundreds of cycles**



Source: Y-M. Chiang, Presentation @ TESTA Symposium No. 2, September 16, 2022

Which Technology? Any Other?

Form energy

Leveraging the lowest-cost iron materials from the steelmaki supply chain

More oxidized
Higher impurities
Lower cost

→

More metallic
Lower impurities
Higher cost

Direct Reduced Iron (DRI) is the lowest cost form of metallic iron

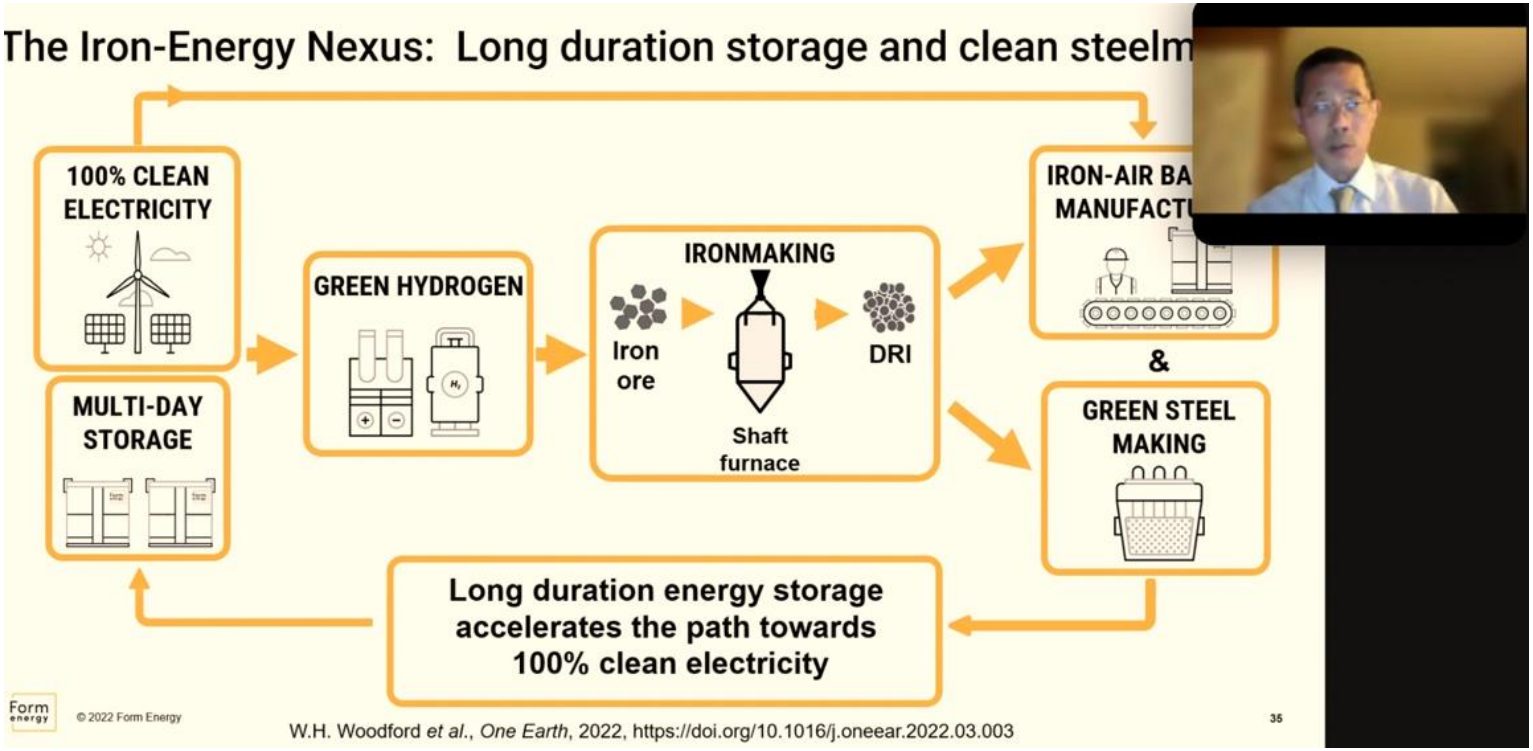
W.H. Woodford *et al.*, *One Earth*, 2022, https://doi.org/10.1016/j.oneear.2022.03.003

Source: Y-M. Chiang, Presentation @ TESTA Symposium No. 2, September 16, 2022

Which Technology? Any Other?

Form energy

Fe-Air BATTERY



Source: Y-M. Chiang, Presentation @ TESTA Symposium No. 2, September 16, 2022

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energiestro

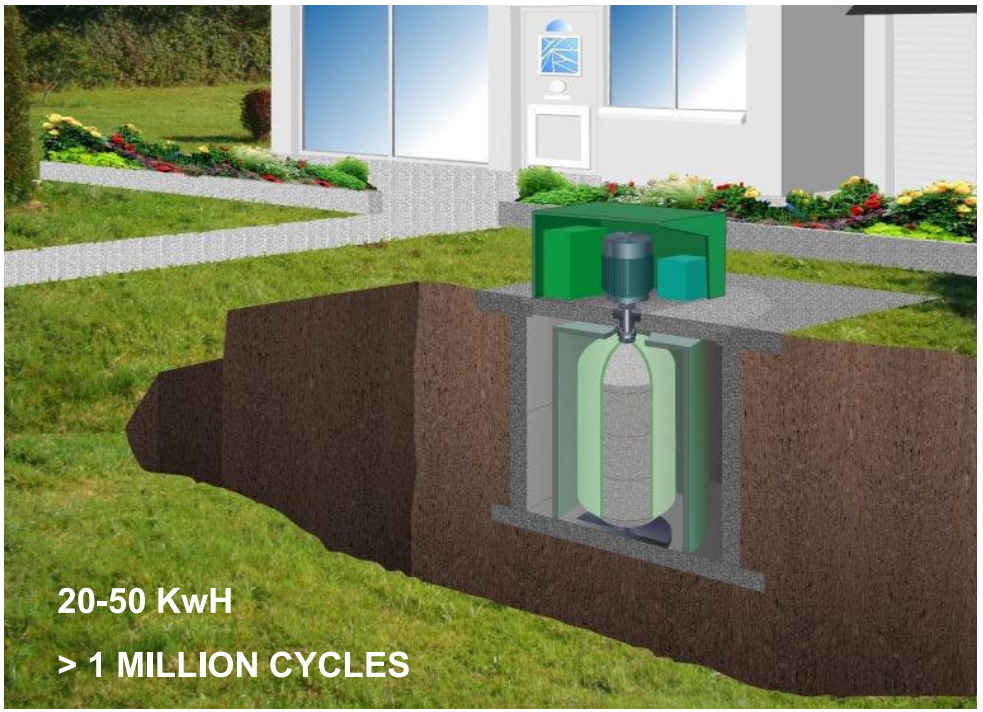
FLYWHEEL

- **Found in 2014 (France)**
- **10kWh – 1 MWh**
- **> 1M cycles**
- **Used pre-stressed concrete**

French flywheel storage system specialist secures €10 million investment

Madagascar-based Filatex has invested €10 million in French flywheel storage system manufacturer Energiestro. The two companies are planning to deploy Energiestro's flywheel storage solutions across Madagascar and Mauritius

FEBRUARY 24, 2022 GWÉNAËLLE DEBOUTTE



Source: https://energiestro.net/

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FLYWHEEL

ENERGIESTRO plans to produce a range of flywheels with storage capacity from 10 kWh to 1 MWh.

The table below gives the main features of the flywheels of the intended range:

Capacity	Diameter (m)	Height (m)	Mass (t)	Power (kW)
10 kWh	1,0	1,5	3,0	10
20 kWh	1,3	1,9	6,0	20
50 kWh	1,7	2,6	15	50
100 kWh	2,2	3,2	30	20
1 MWh	4,6	7,0	300	200

Source: https://energiestro.net/

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MALTA

THERMAL STORAGE

MOLTEN SALT

Pumped heat energy storage seeks to demonstrate commercial readiness

Southwest Research Institute (SwRI) has commissioned a first-of-its-kind pilot plant pumped heat energy storage demonstration facility with tech from US startup Malta. Its 10-150+ hour energy storage technology is said to be applicable in a range of grid-scale applications.

SEPTEMBER 5, 2022 MARIJA MAISCH

- 10-150 hr storage
- < $100/kWh
- 100MW/ 1000+ MWh
- Life 30 years

Source: https://www.maltainc.com/

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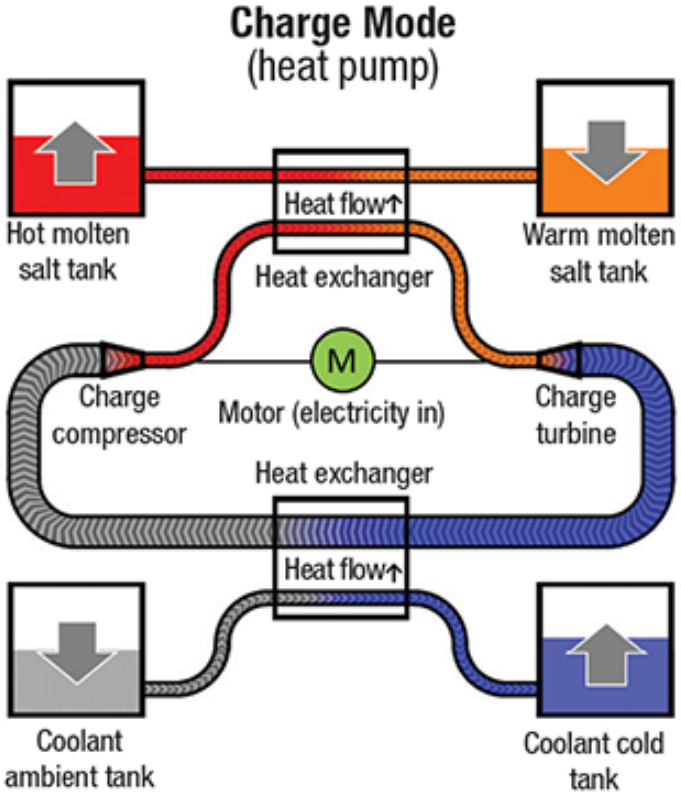
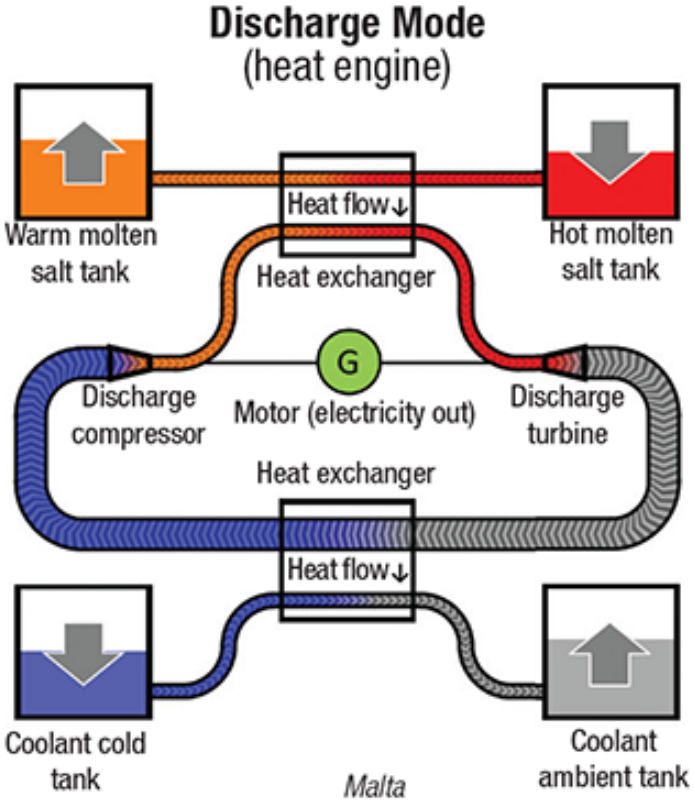
MALTA

THERMAL STORAGE

MOLTEN SALT

8 HR – 8 DAYS 1000MWH SYSTEM SIZE





Source: https://www.maltainc.com/

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ENERGY VAULT
Enabling a Renewable World

GRAVITATIONAL

- **Found in 2017 (Switzerland)**
- **Long duration**

Source: https://www.maltainc.com/

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COMPRESSED AIR

'Transformational': Goldman Sachs $250m backing for gigawatt-scale compressed-air energy storage

Source: https://www.maltainc.com/

Thank you ☺