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DIPARTIMENTO DI

INGEGNERIA INDUSTRIALE

Electrical Energy Storage

Renewable Energy Conversion Systems Course

Lecture 1

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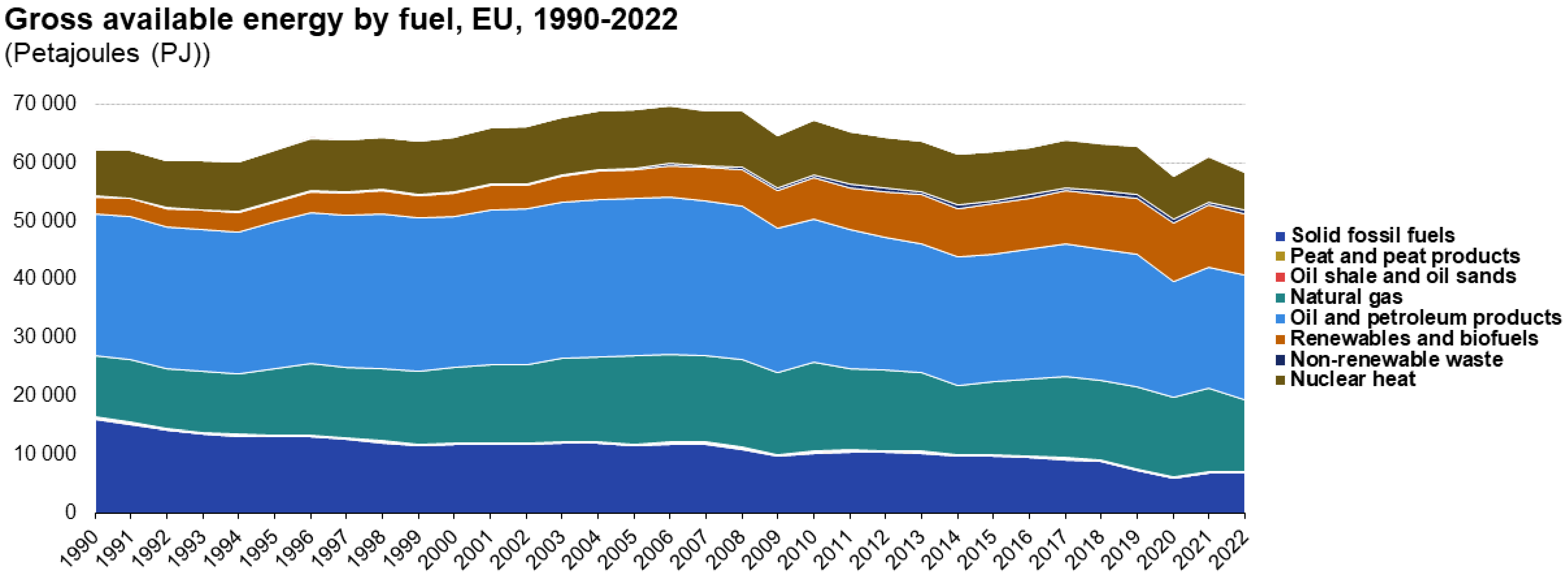
Academic Year 2024-2025

Electrical Energy Storage

Outline

- Introduction to Electrical Energy Storage
- Applications of Electrical Energy Storage
- Types of Electrical Energy Storage Systems
- Development of Energy Storage Systems

Introduction to Electrical Energy Storage



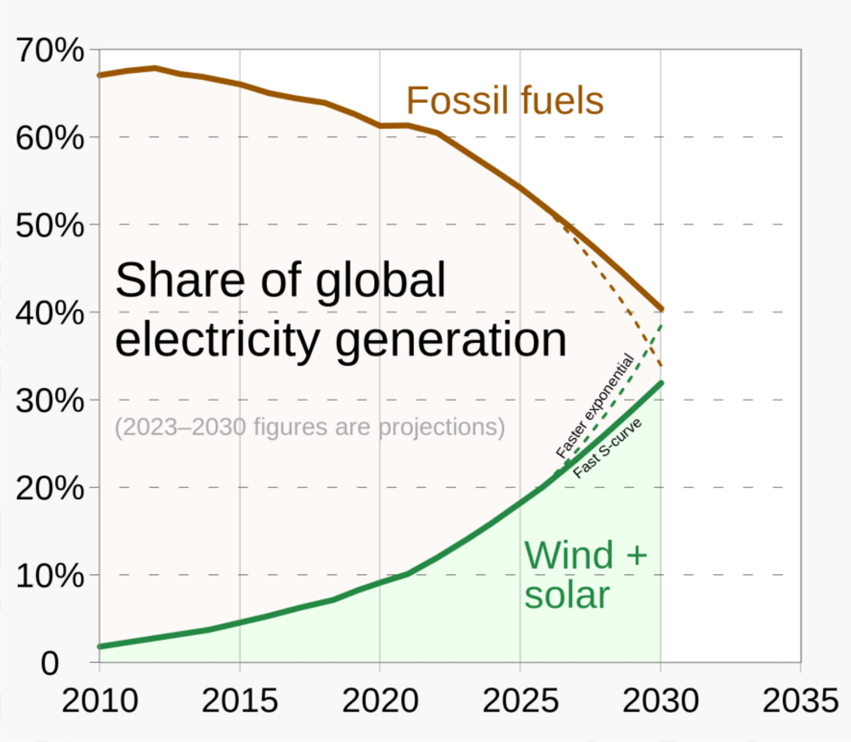
Decarbonization

How can we reach decarbonization?

EU targets by 2030:

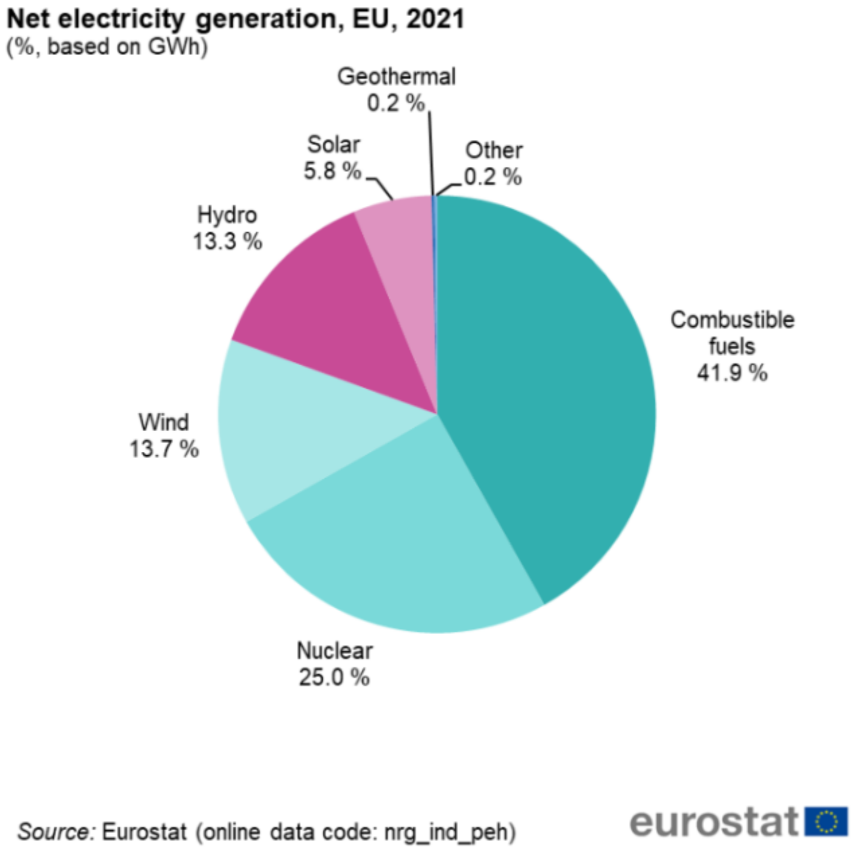
- Directive 2018/2001 → 32% of RES penetration
- Directive 2023/2413 → 42.5% of RES penetration

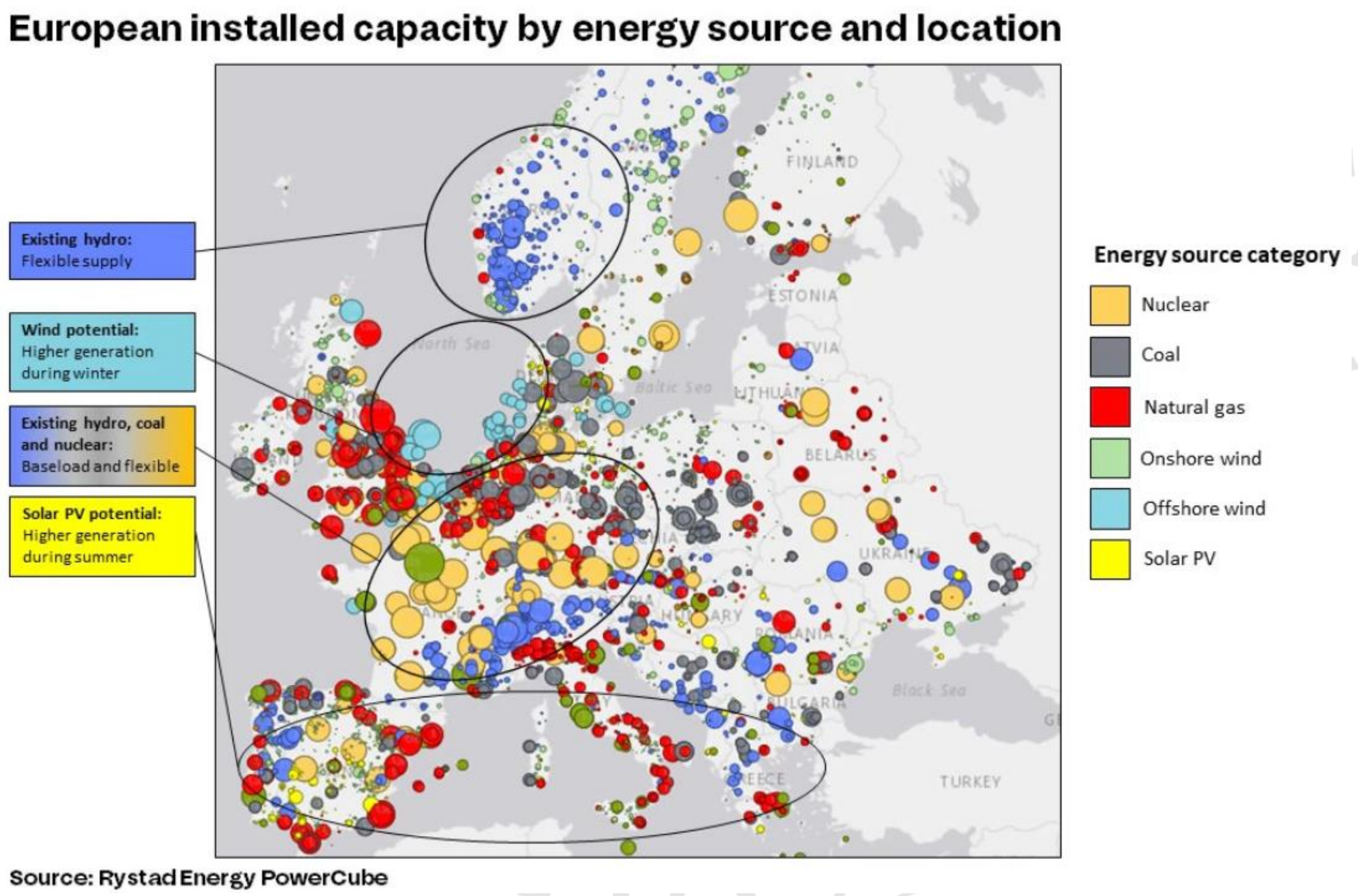
The second directive entered into force in all EU countries on 20 November 2023



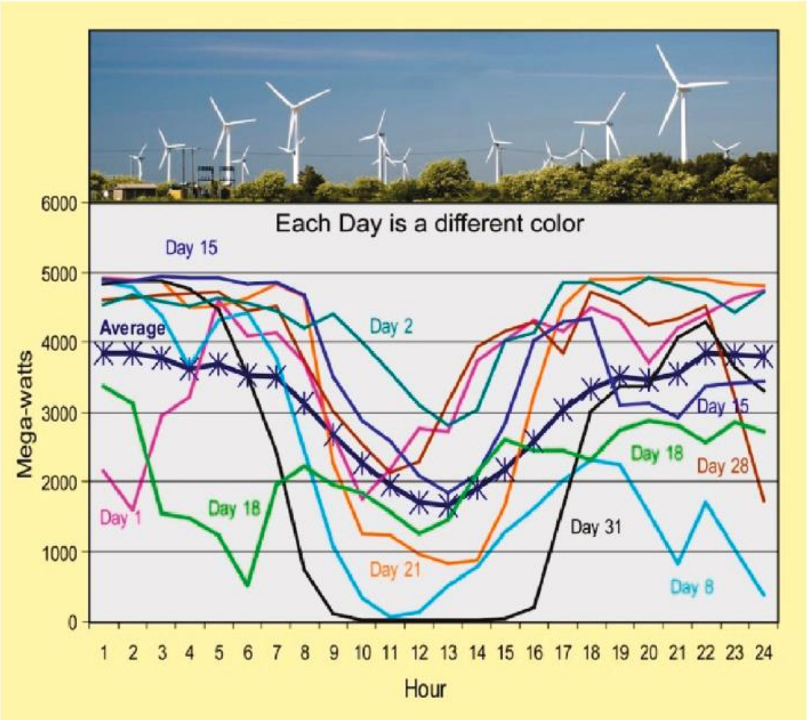
Source: *Energy Institute, RMI forward*.

Applications of Electrical Energy Storage





Introduction to Electrical Energy Storage



Daily profiles of wind power in Tehachapi, California (ISO California)

Variability of RES

Several Time Scales

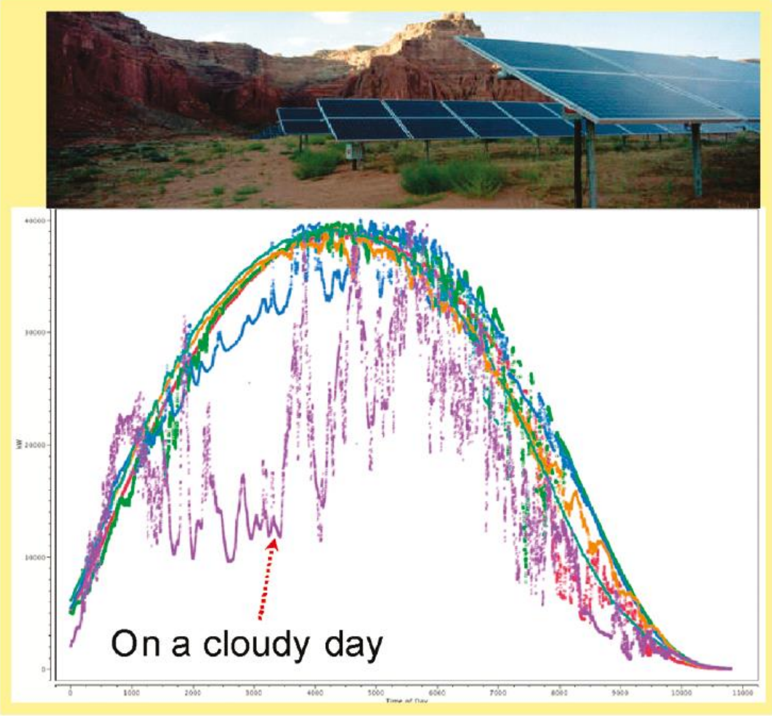
Years

Months

Days

Minutes

Seconds



5 MW PV power over a span of 6 days in Spain (AES)

Source: Yang, Zhenguo, et al. "Electrochemical energy storage for green grid." *Chemical reviews* 111.5 (2011): 3577-3613.

Introduction to Electrical Energy Storage

Decarbonization

Issues with “new” Renewable Energy Sources (wind, solar, marine):

- Variable output
- Not programmable!
- Only partially predictable

Electrical grids must always be balanced:
Energy Production = ***Energy Consumption***

WITH ENERGY STORAGE
WE CAN ~~NOT~~ USE RENEWABLES WHENEVER WE WANT !

We can use them when they are available only.

Fossil fuels-based plants must be controlled to supply the lacking energy and provide a fast response!

How can we reach decarbonization then? → ELECTRICAL ENERGY STORAGE !!!

Applications of Electrical Energy Storage

Decarbonization

Which are the sectors with higher need for decarbonization?

- *Mobility*
- *Residential*
- *Community*
- *Industry*
- *Utility*

Stationary Energy Storage Applications

Applications of Electrical Energy Storage

Mobility Applications

Average duration 1-4h

Mature

- Road transport
  - Passenger Vehicles
  - Buses
  - Trucks

- Off-road applications
  - Forklifts
  - Tractors
  - Earthmoving

- Railways
  - Substitution of fuel-based locomotives with battery-based locomotives

Research level

- Waterborne
  - Electric Ships
  - Hybridization with RES

- Airbourne
  - Electric Planes
  - Hybridization with RES

Applications of Electrical Energy Storage

Mobility Applications

Li-ion batteries are playing the major role in the decarbonization of transport. They are and will be the most dominant battery technology, at least in the medium term.

Given the expected increased demand of batteries for both transport and stationary storage, Europe is investing large resources in this sector (China and US even more). Although the major cell manufacturers are currently in Asia, several players are emerging in Europe also (e.g. SAFT, BASF, FIAMM, VARTA, Northvolt) and east-based companies are creating European branches (BYD, CATL).

These players are mainly investing in producing cells for the automotive sector, which is expected to show the largest growth, but the demand in niche sectors will also increase and these sectors will benefit from the large investments connected to automotive.

Europe has also several battery systems manufacturers that construct batteries for specific applications (e.g, light and heavy-duty vehicles, trains, defense, etc.) based on cells imported from Chinese or Korean companies (LG Chem, CATL, Panasonic).

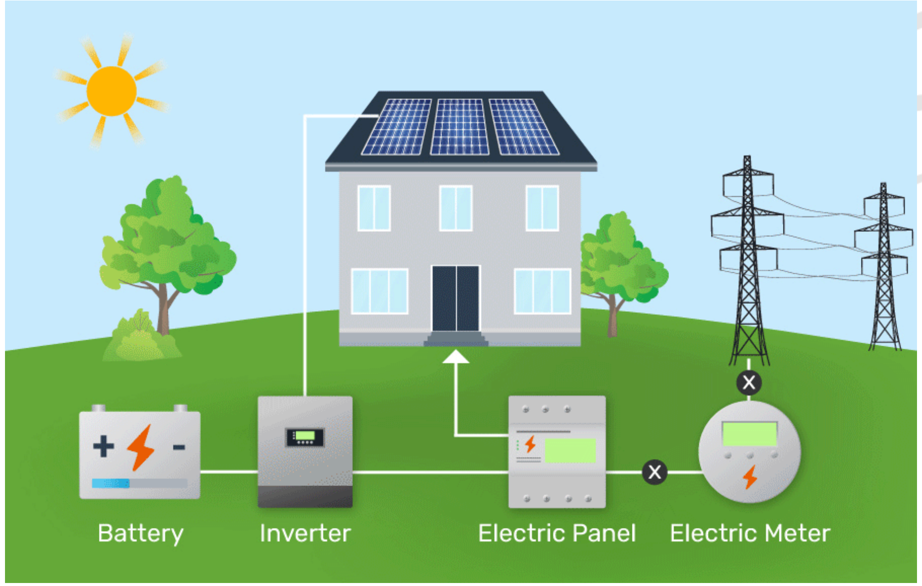
Applications of Electrical Energy Storage

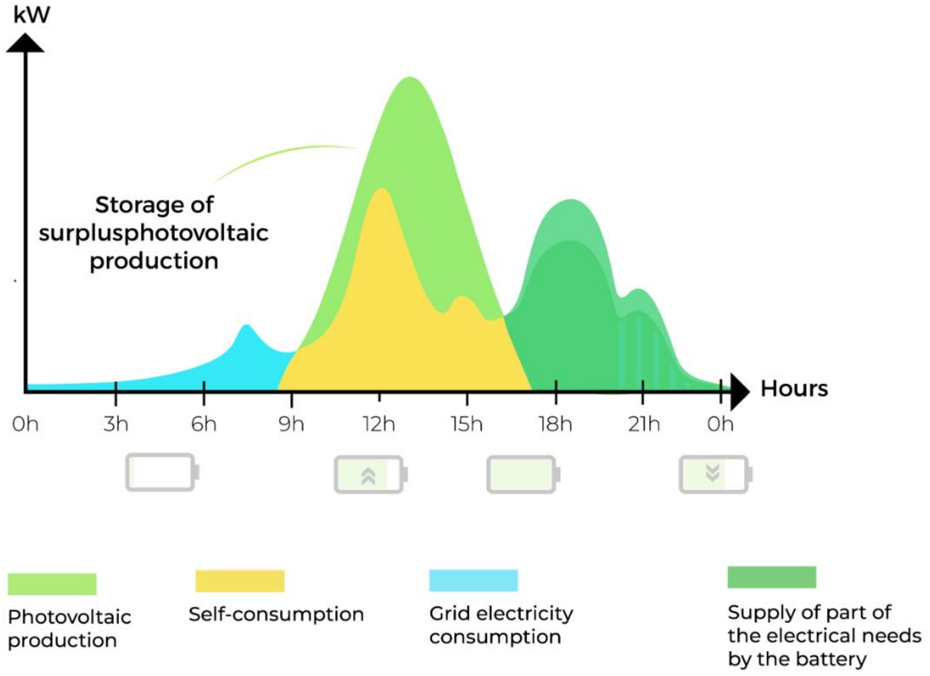
Stationary Applications – Residential 3-50 kW , 2-6 h

- Auto-consumption
- Backup

- EV Charging
- Islanded operation

Usually coupled with solar PV production



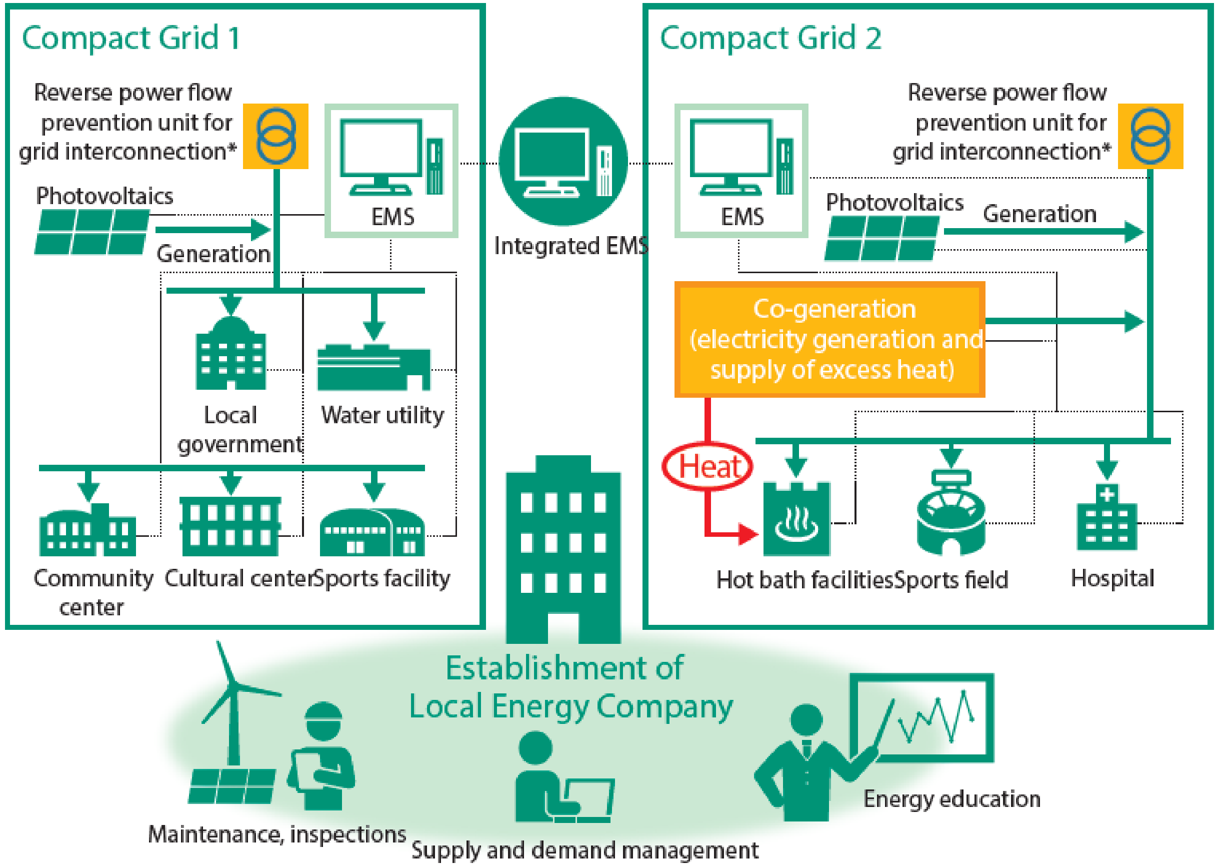


Applications of Electrical Energy Storage

Stationary Applications - Community

100 kW - 1 MW, 1-8h

- Consumption Facilities
  - Balancing internal loads
  - Backup
- Multigeneration and Consumption Facilities
  - Target auto-consumption
  - Avoid RES curtailment



Applications of Electrical Energy Storage

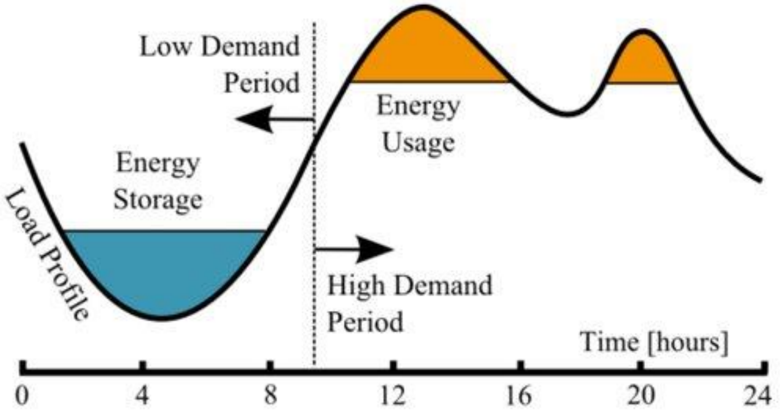
Stationary Applications - Industry

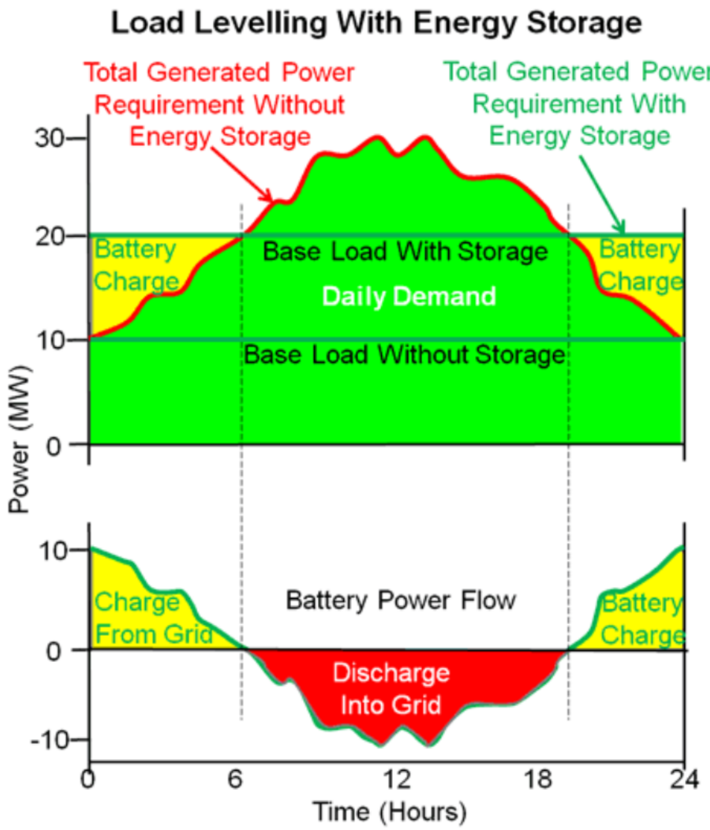
- Consumption Facilities
  - Load levelling
  - Peak shaving
  - Backup

- *Peak Shaving* or *Peak Shifting* → The energy storage system supplies power reducing the load on peak hours (high energy price) and recharges in low-load hours

- *Backup* → The energy storage system supplies power only in case of grid shortages and is recharged as soon as the grid is available again

- *Load Levelling* → Storing power during periods of light loading and delivering it during periods of high consumption, to get a uniform load profile





Applications of Electrical Energy Storage

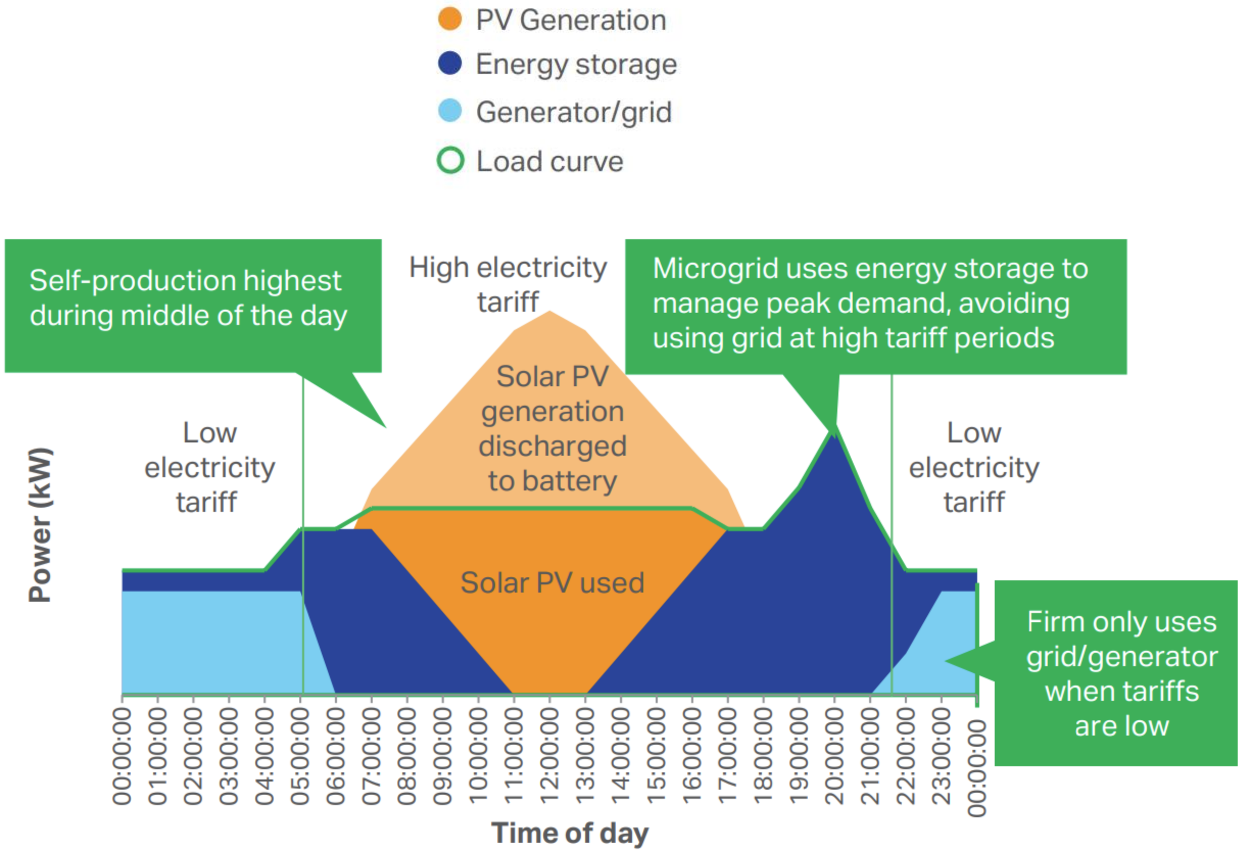
Stationary Applications - Industry

100 kW - 10 MW, 1-8h

- Generation and consumption facilities
  - Target auto-consumption
  - Avoid RES curtailment

Industrial, Residential and Community storages usually are ***Behind-of-the-Meter (BTM):***

The storage is installed in the facility, behind the meter that records the energy consumption (energy bill)



Applications of Electrical Energy Storage

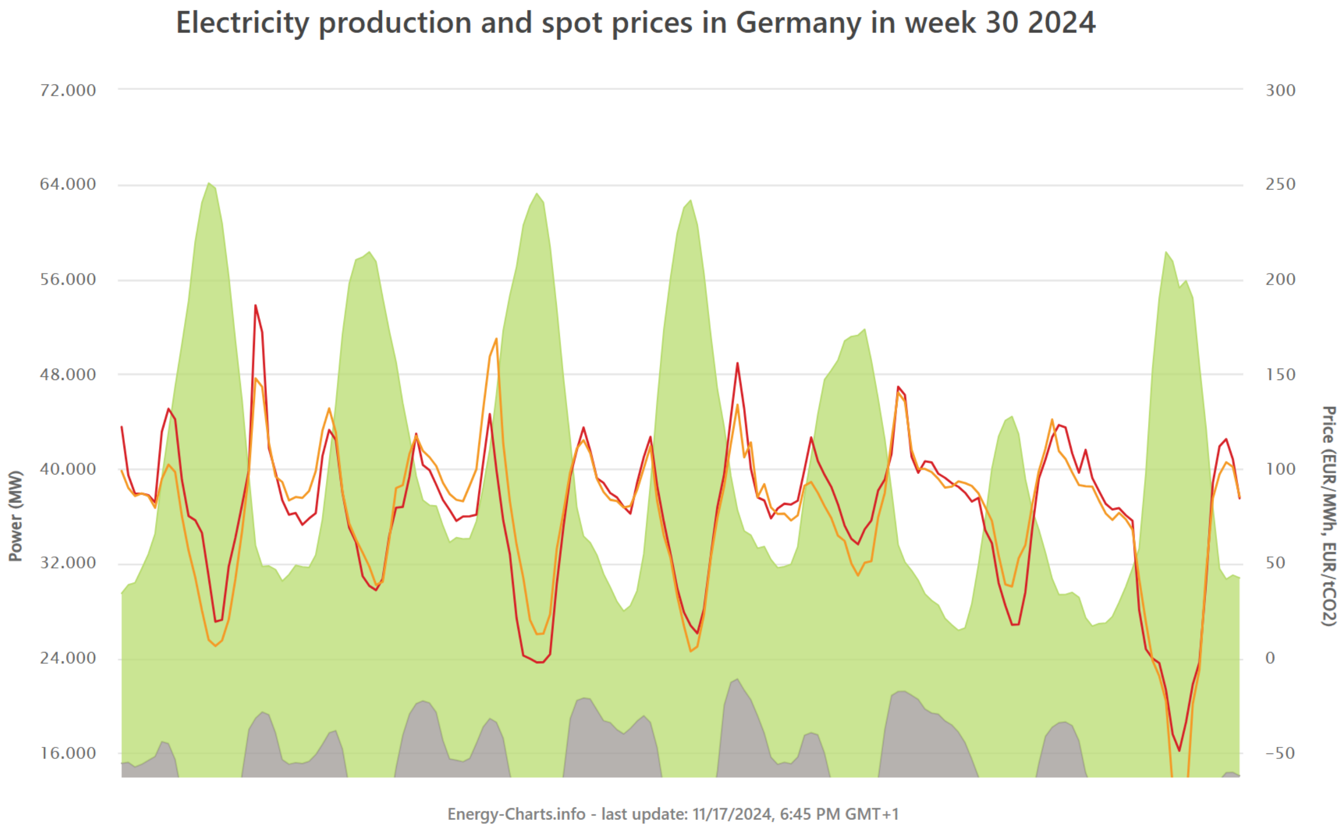
Stationary Applications - Utility 1MW - 10 GW, 1h-10h

- Arbitrage of Electrical Energy

↓

Energy Trading

Buying and selling energy toward the grid generating income due to the difference in price



Applications of Electrical Energy Storage

Stationary Applications - Utility

1MW - 10 GW, 10s-30m

- Ancillary or Flexibility Services → Provide services to support the electrical grid
  - Frequency regulation
  - Contingency reserve
  - Black-start

Utility applications are always

Front-of-the-Meter (FTM)

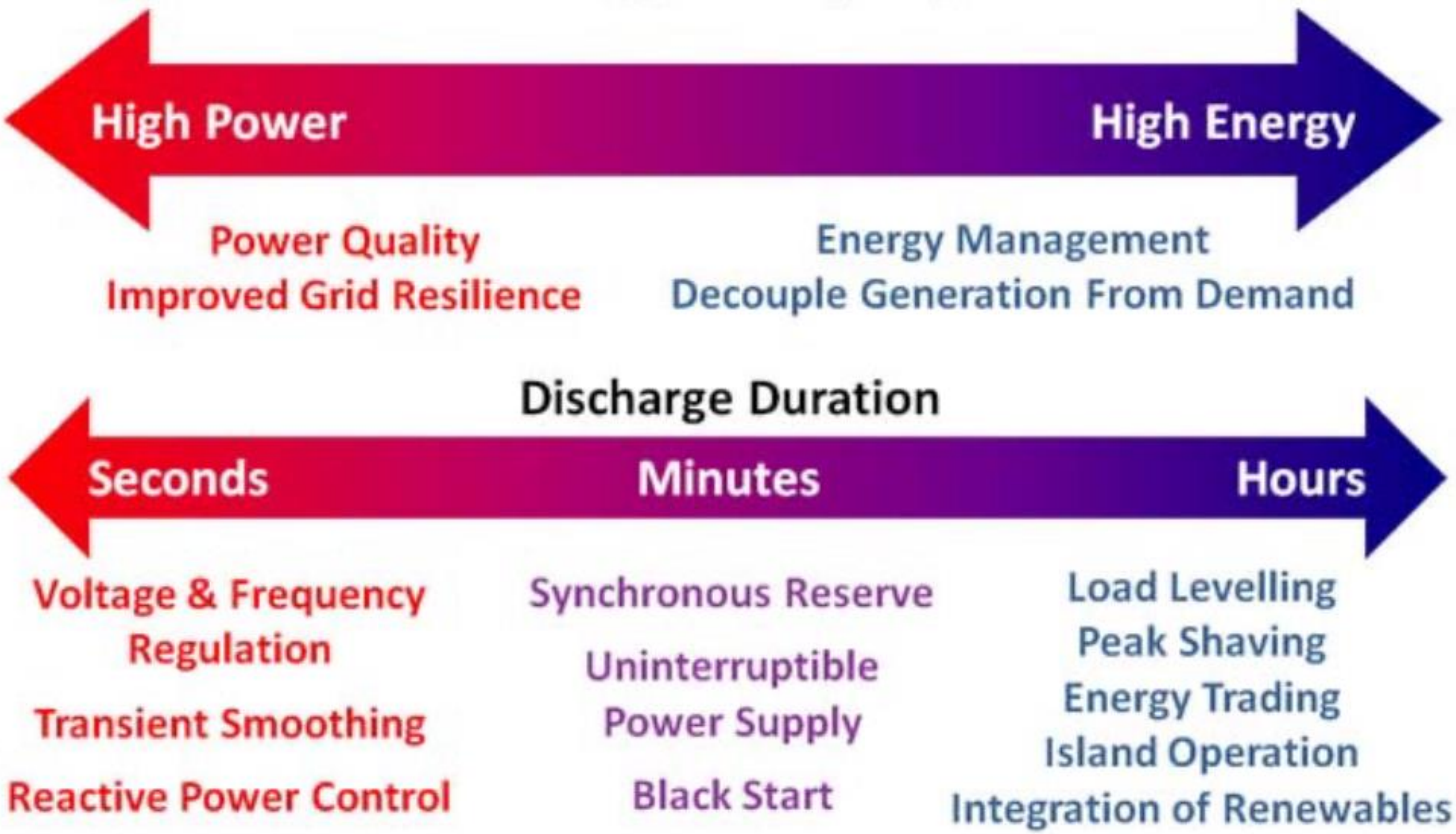
The facility is a storage or storage + generation system (no consumption), which is installed just in front of the meter recording energy flow

Applications of Electrical Energy Storage

Power = 1MW

Discharge time ≈< 1m

E=P*t ≈<16kWh



Power = 1MW

Discharge time ≈> 1h

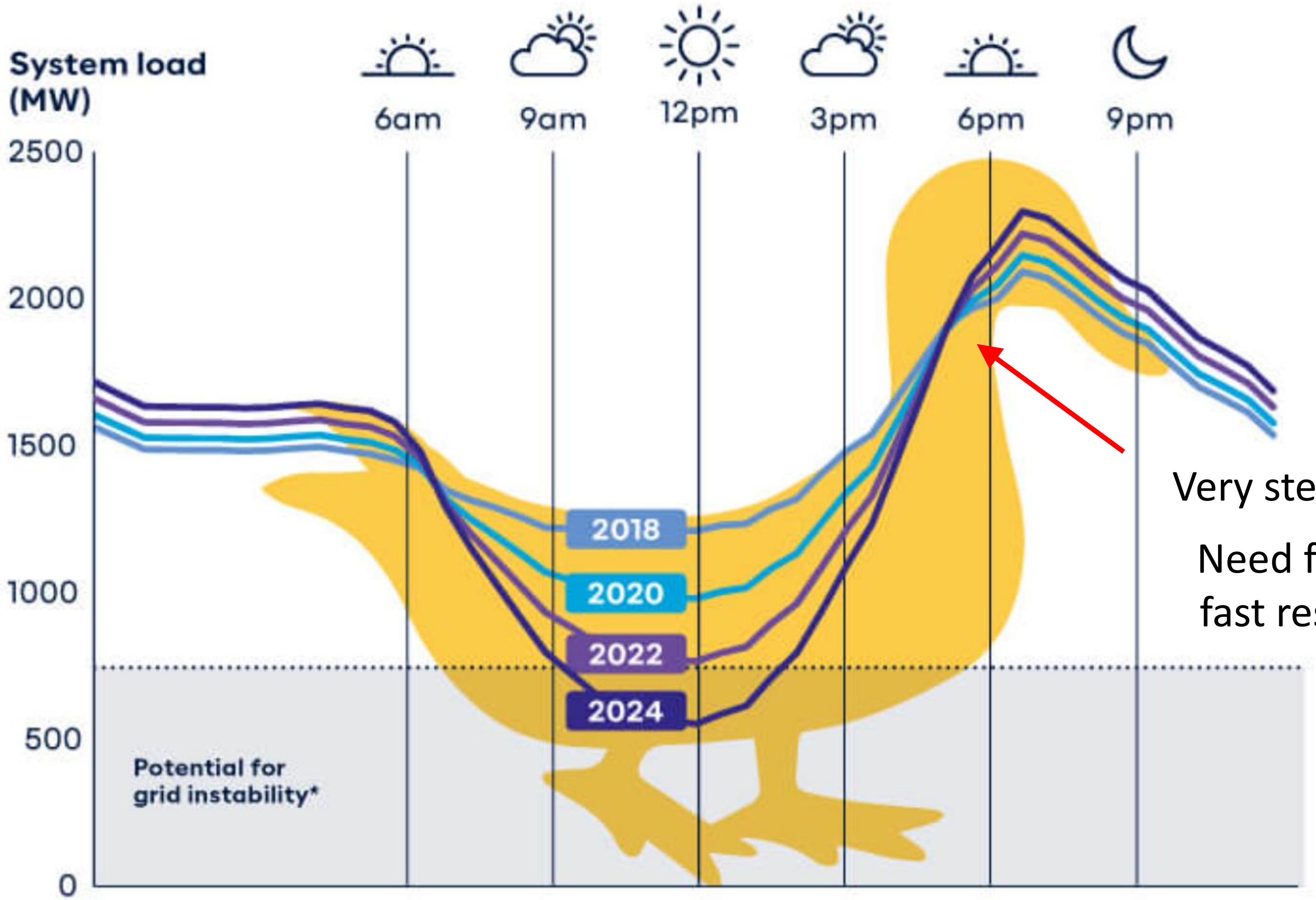
E=P*t ≈> 1MWh

Applications of Electrical Energy Storage

Daily Storage

Duck Curve

More and more
a Goose
than a Duck



Very steep ramp

Need for very
fast response

Applications of Electrical Energy Storage

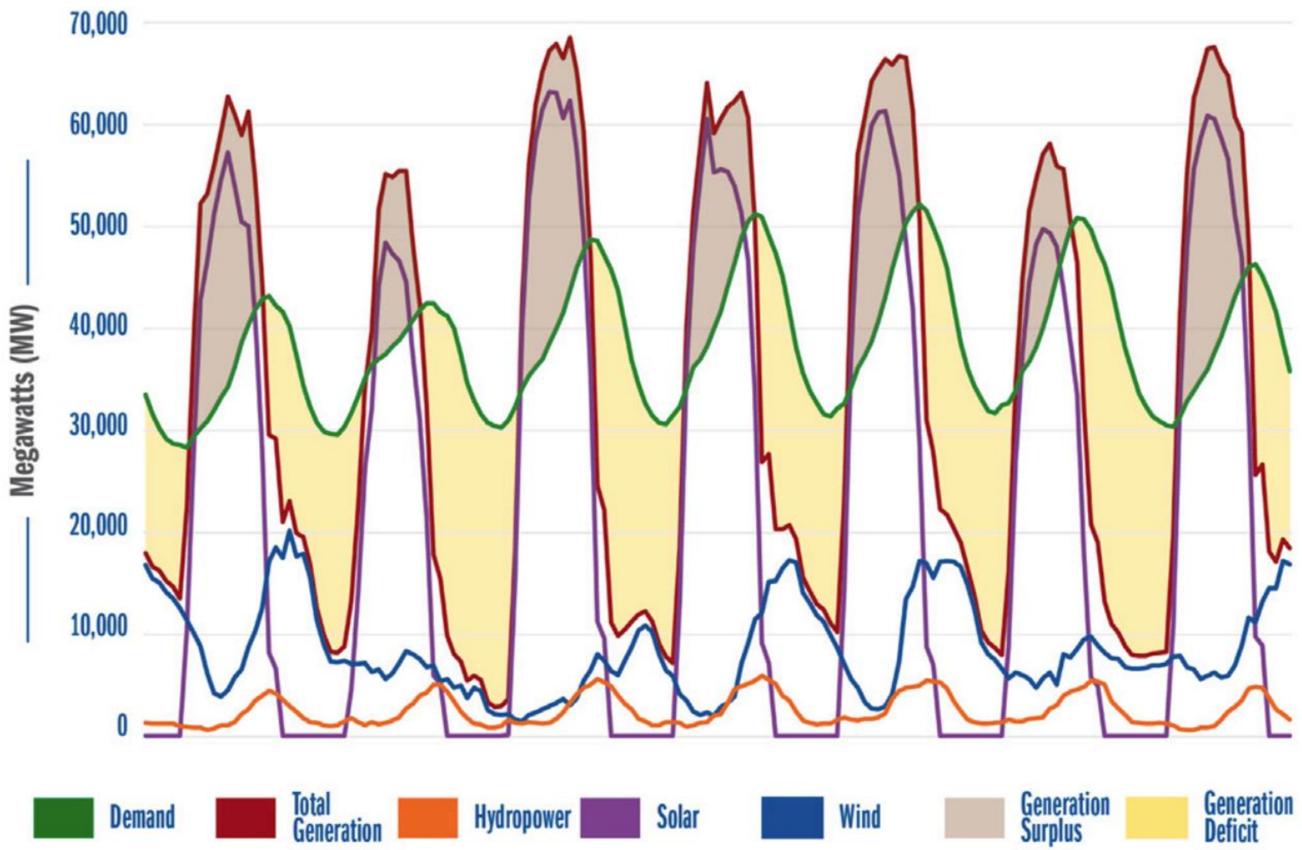


Fig. 6. Illustrative load and resource balance for California under full decarbonization, weekly resolution.

Source: Twitchell, Jeremy, Kyle De Somber, and Dhruv Bhatnagar. "Defining long duration energy storage." Journal of Energy Storage 60 (2023): 105787

Applications of Electrical Energy Storage

Seasonal storage

- Essential to reach complete decarbonization
- Up to now only pumped-hydroelectric storage have this capability

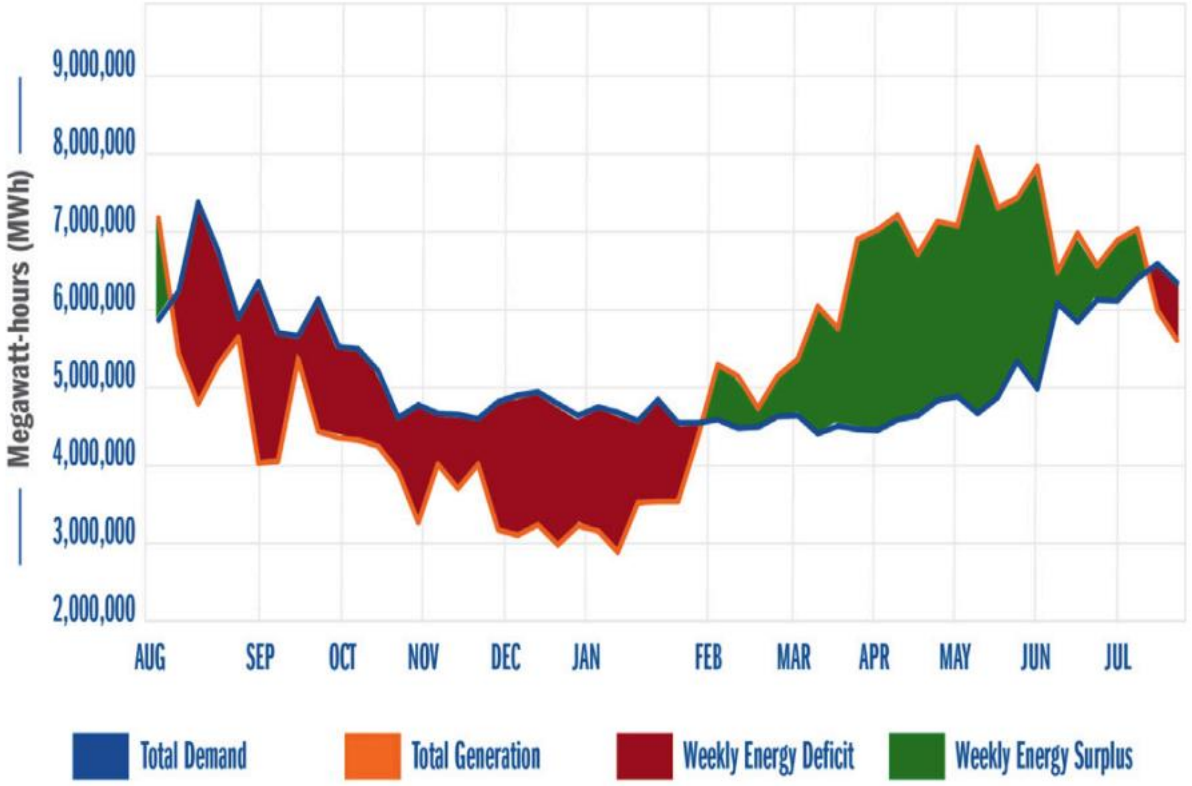


Fig. 7. Illustrative load and resource balance for California under full decarbonization, annual resolution.

Source: Twitchell, Jeremy, Kyle DeSomber, and Dhruv Bhatnagar. "Defining long duration energy storage." Journal of Energy Storage 60 (2023): 105787

Applications of Electrical Energy Storage

Curtailment of RES

Often renewable generating systems have to:

- Limit exporting to the grid
- Temporarily shut down
- Limit the output power

Due to different reasons:

- Overproduction vs load
- Power flow limitations
- Grid-connection constraints

This is called ***curtailment***

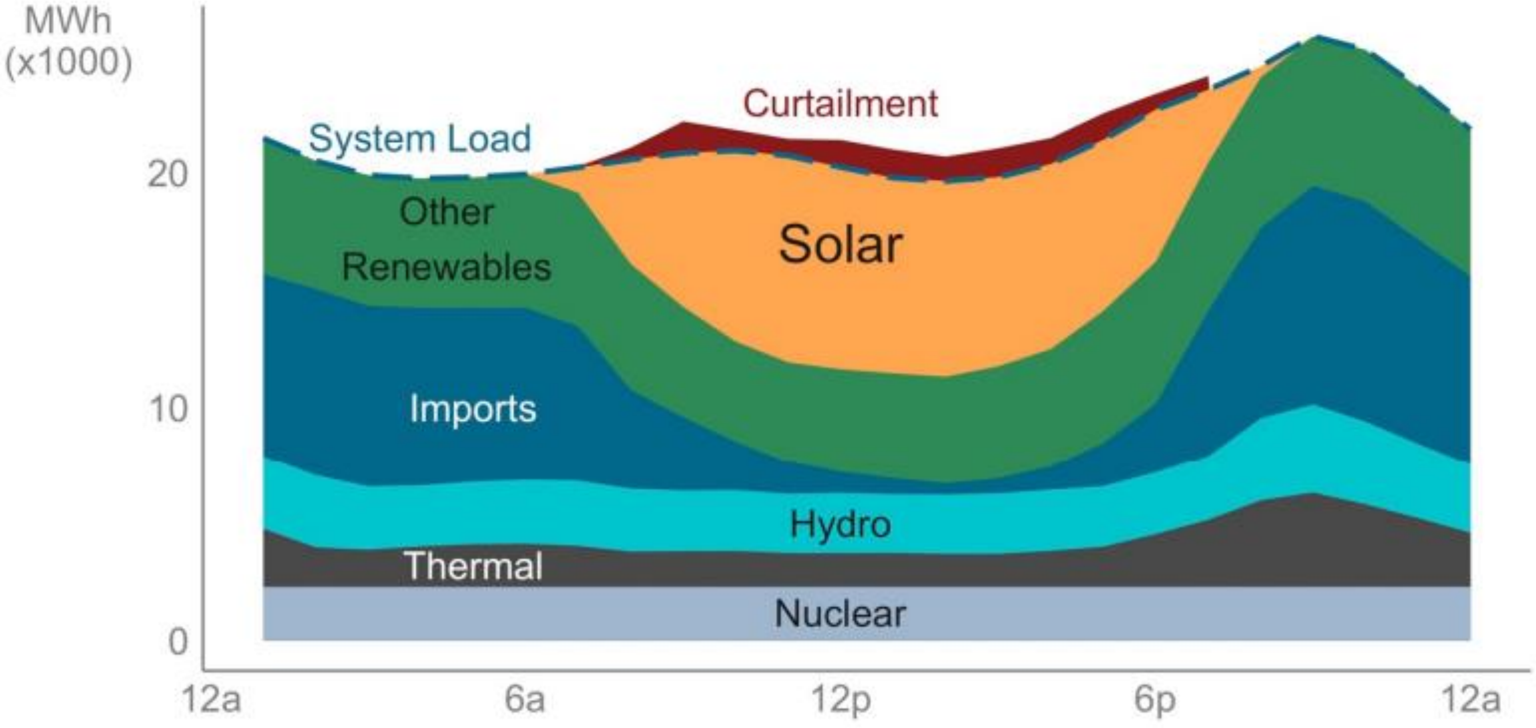
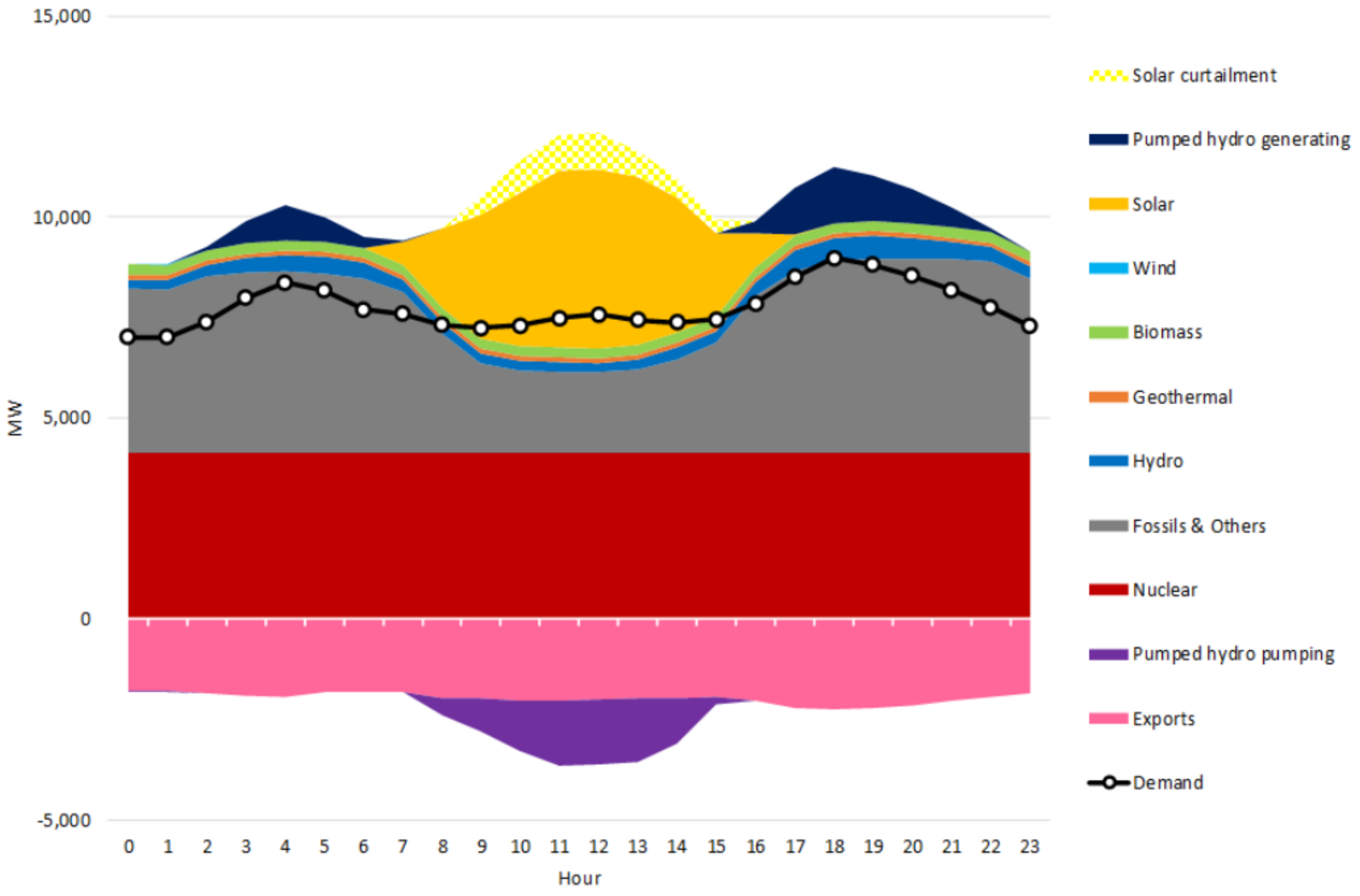


Figure 1. PV curtailment event on May 13, 2018 in California. Based on data from CAISO [16].

Applications of Electrical Energy Storage

Curtailment of Solar PV production

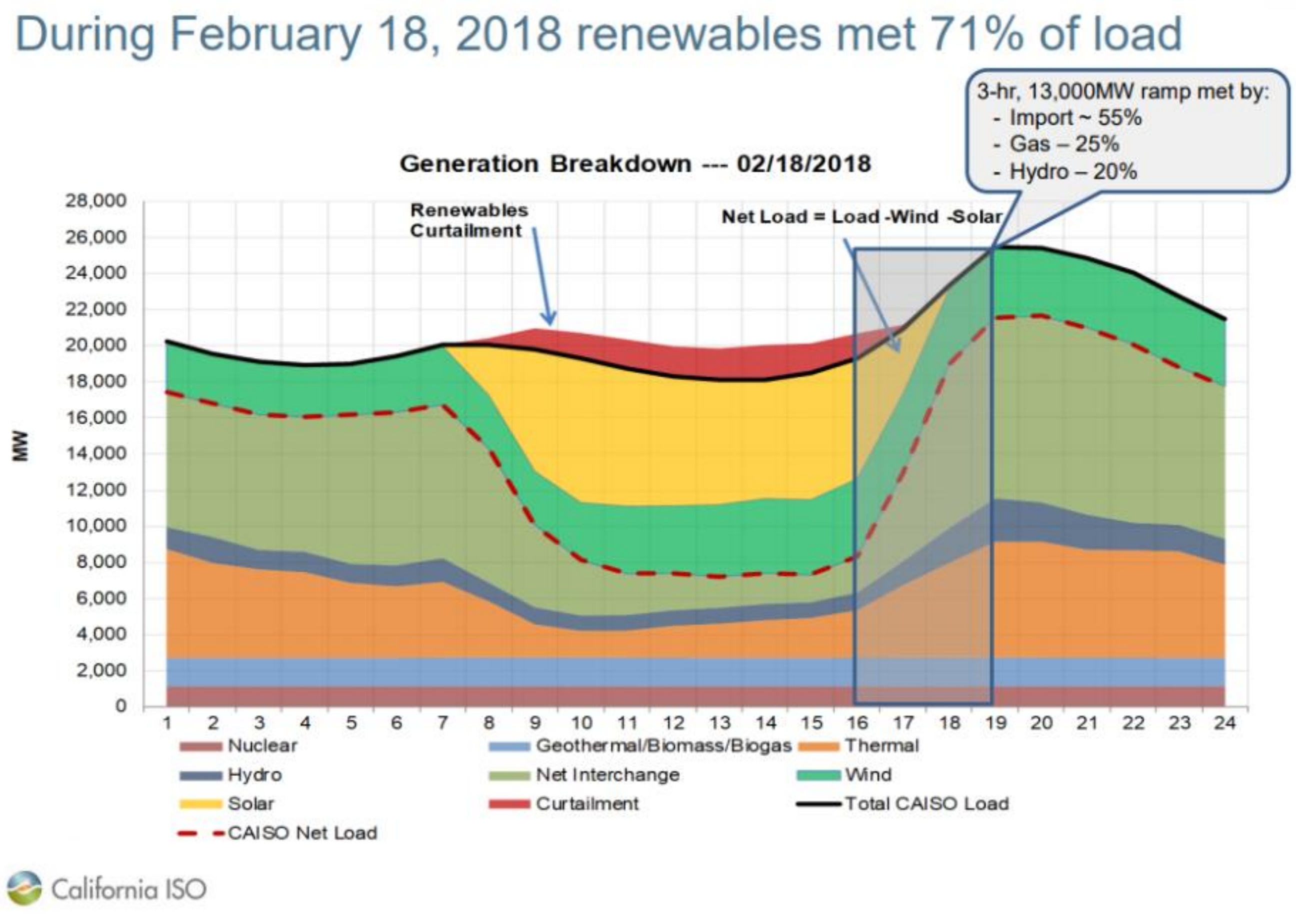
Kyushu Power System Operations
November 4, 2018



Applications of Electrical Energy Storage

Curtailment of Solar PV production

California overall grid balance
February 18, 2018



Source: CESA 2018 Market Development Forum

Applications of Electrical Energy Storage

Curtailment of Wind Power Production

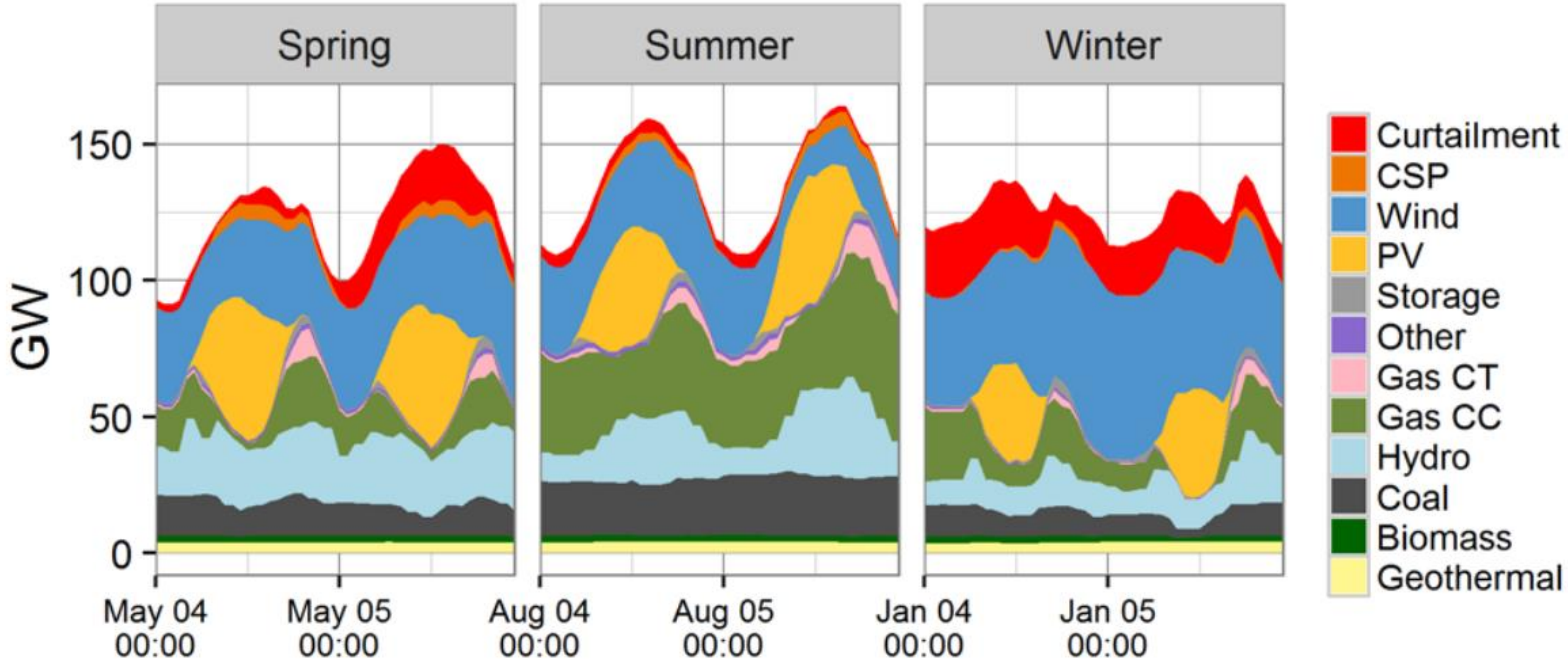


Figure 5. A dispatch stack showing how generation resources are being used in in three seasons

Applications of Electrical Energy Storage

Energy Storage for the Grid

- Energy storage is essential to achieve matching between electricity production and consumption at each instant
- Characteristics of renewable energy sources (variability, unpredictability, possible unavailability, localized production in certain geographical areas) lead to problems for the stability of grids electricity
- Storage plays a critical role in frequency regulation and is essential to maintain the stability and security of the power grid, otherwise provided by thermal power plants (baseload and transients) and gas turbines (fast reserve).
- It also enables the deferral of power production and consumption and works as a buffer in case of emergencies, all these functions ensure the resilience of the power grid
- Energy storage is critical to developing a low-emission energy system and enable massive integration of renewable energy sources;

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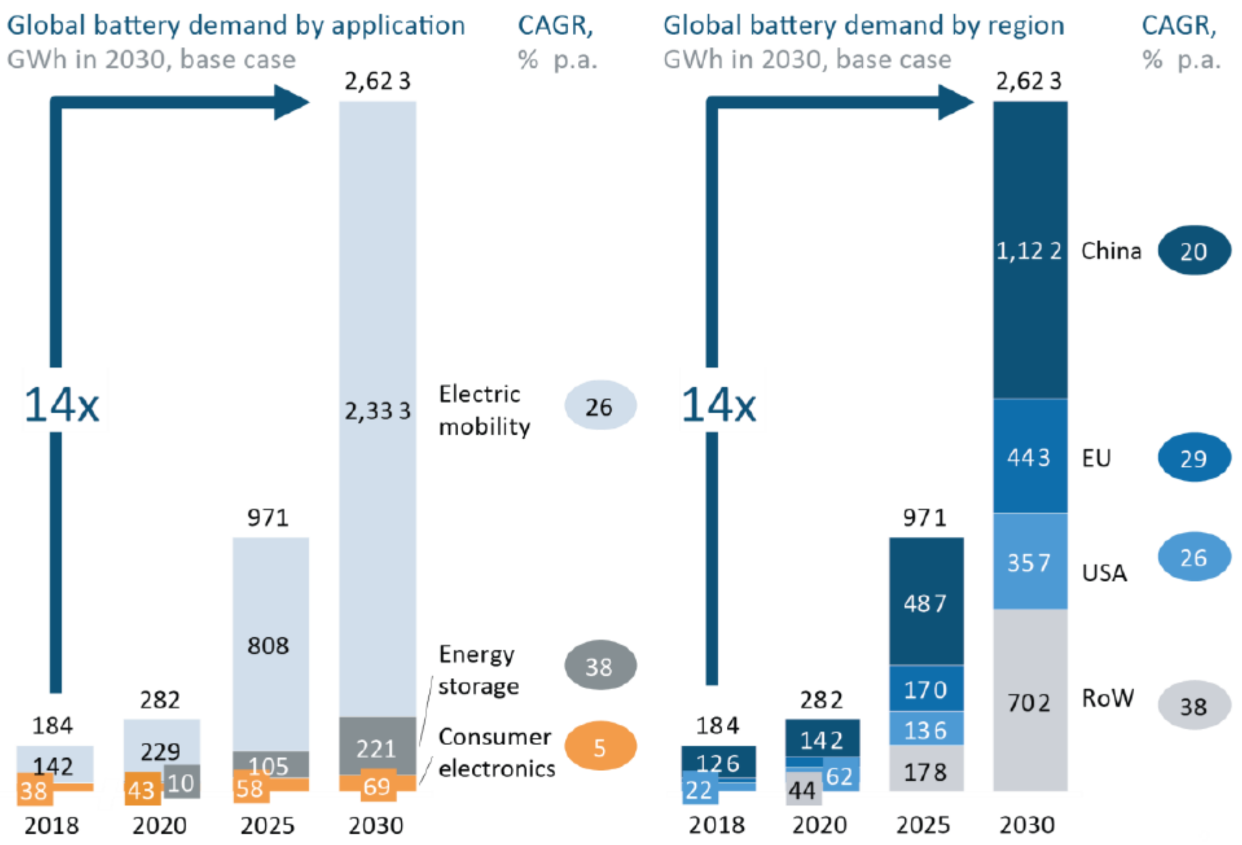
Applications of Energy Storage Systems



CURRENT AND PREDICTED GLOBAL BATTERY DEMAND.[3]

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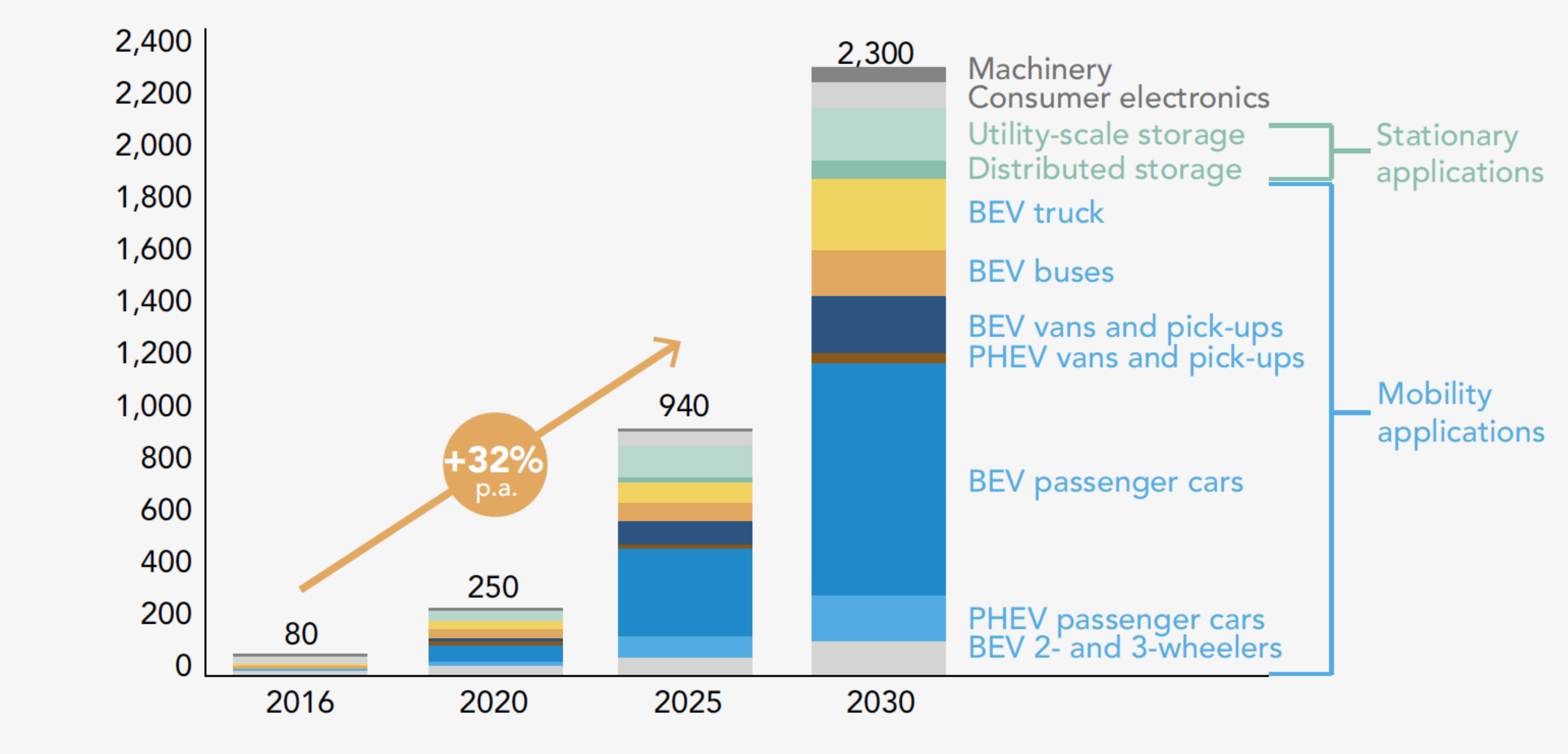
Applications of Energy Storage Systems

Figure 2 | Annual Battery Demand (GWh) - forecasted evolution of the electric mobility, stationary power storage, consumer electronics and machinery application areas from 2016 to 2030.



Source: BEPA SRIA Sept 2021

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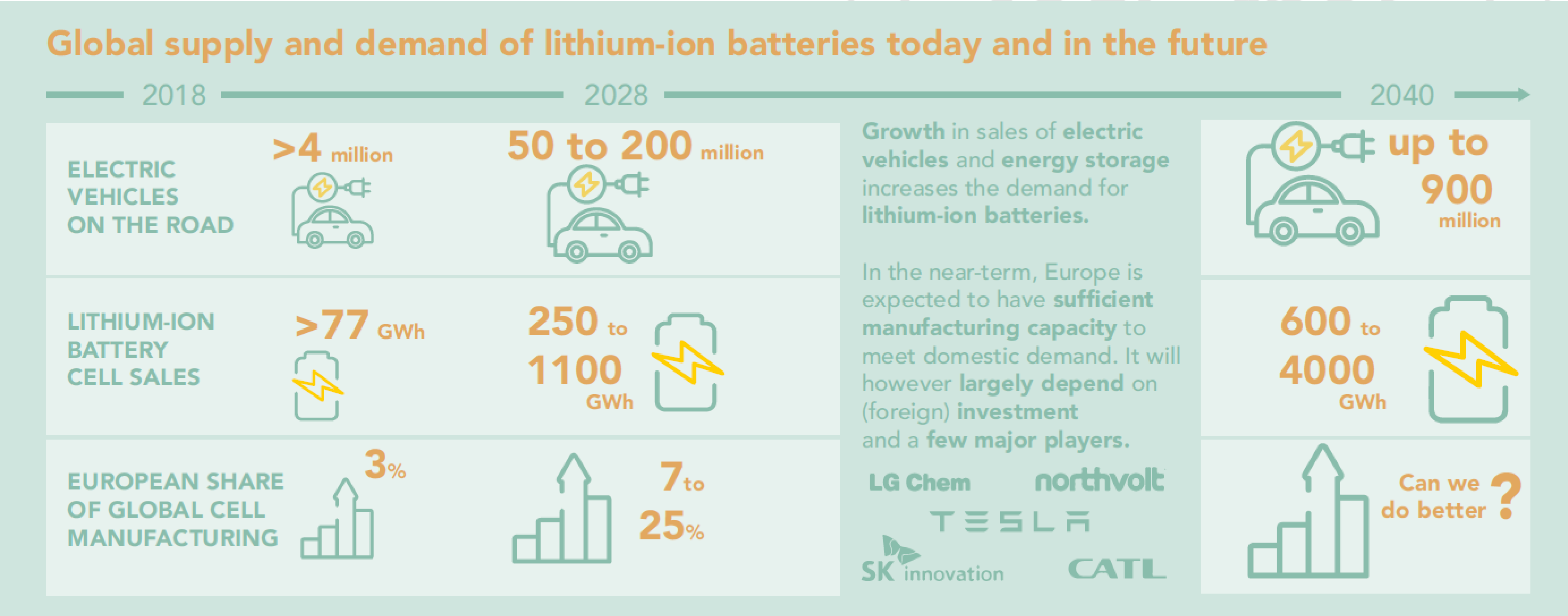
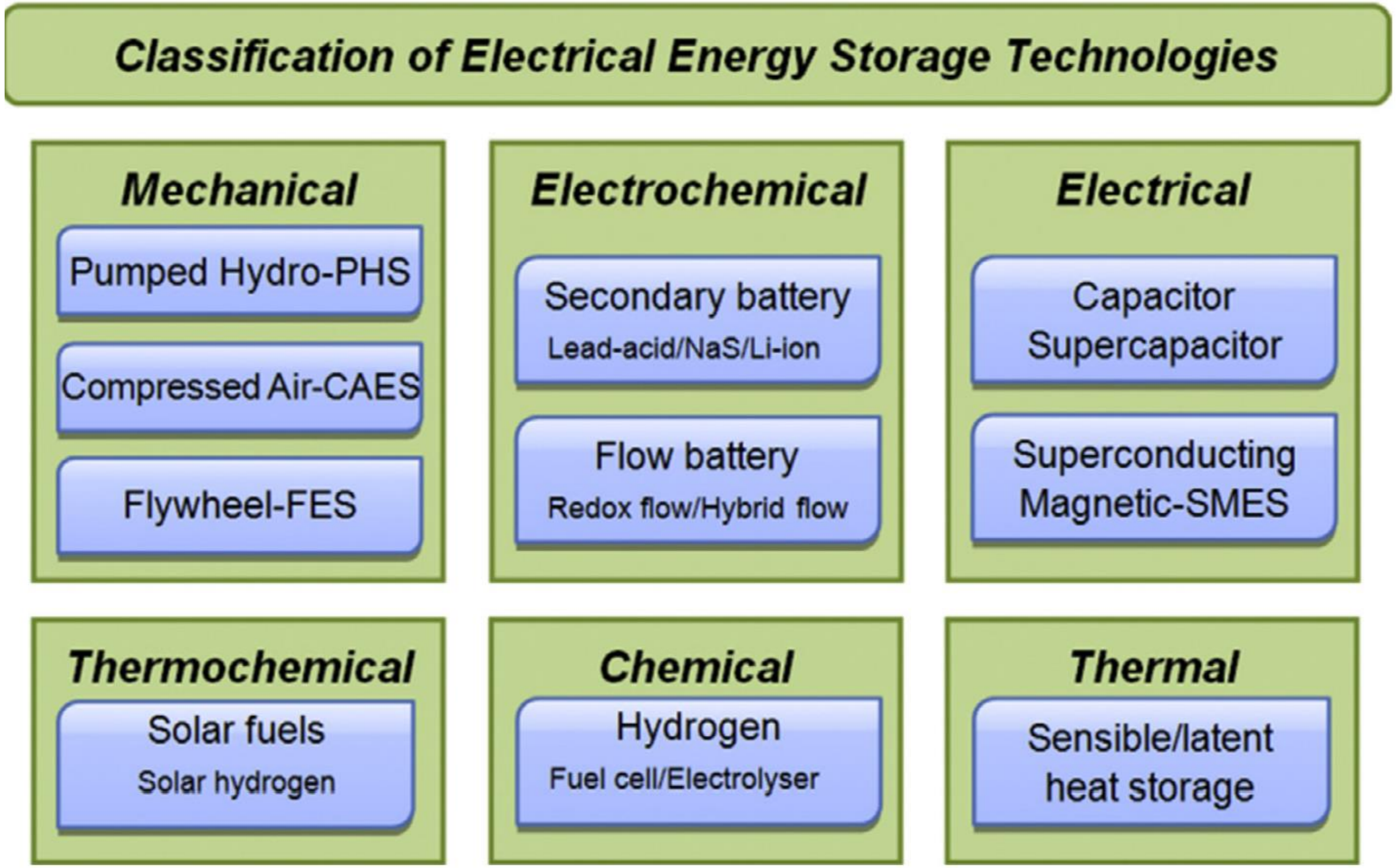
Development of Energy Storage Systems

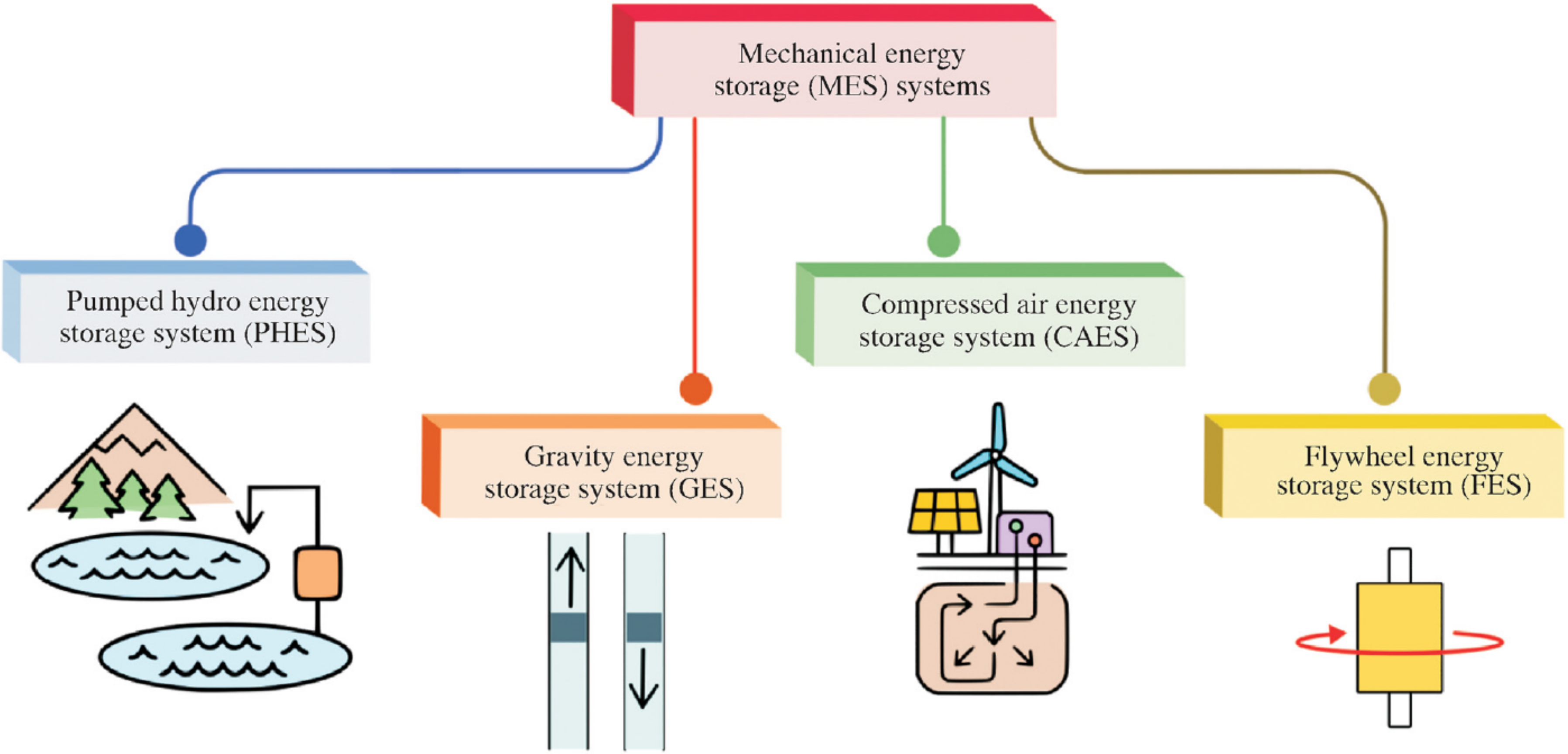


Source: BEPA SRIA Sept 2021

Types of Electrical Energy Storage



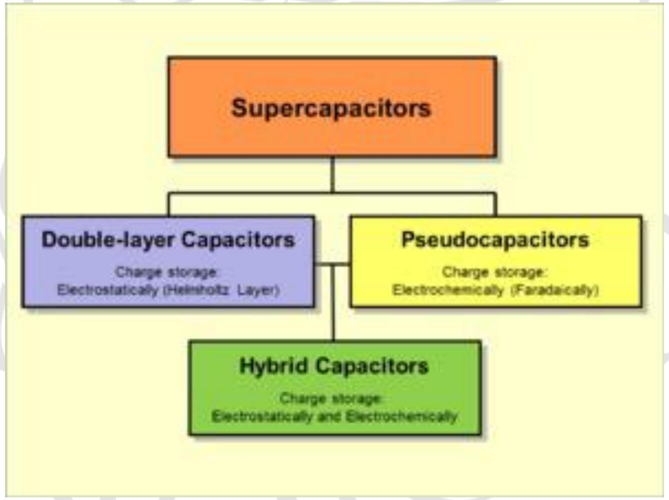
Types of Electrical Energy Storage



Types of Electrical Energy Storage

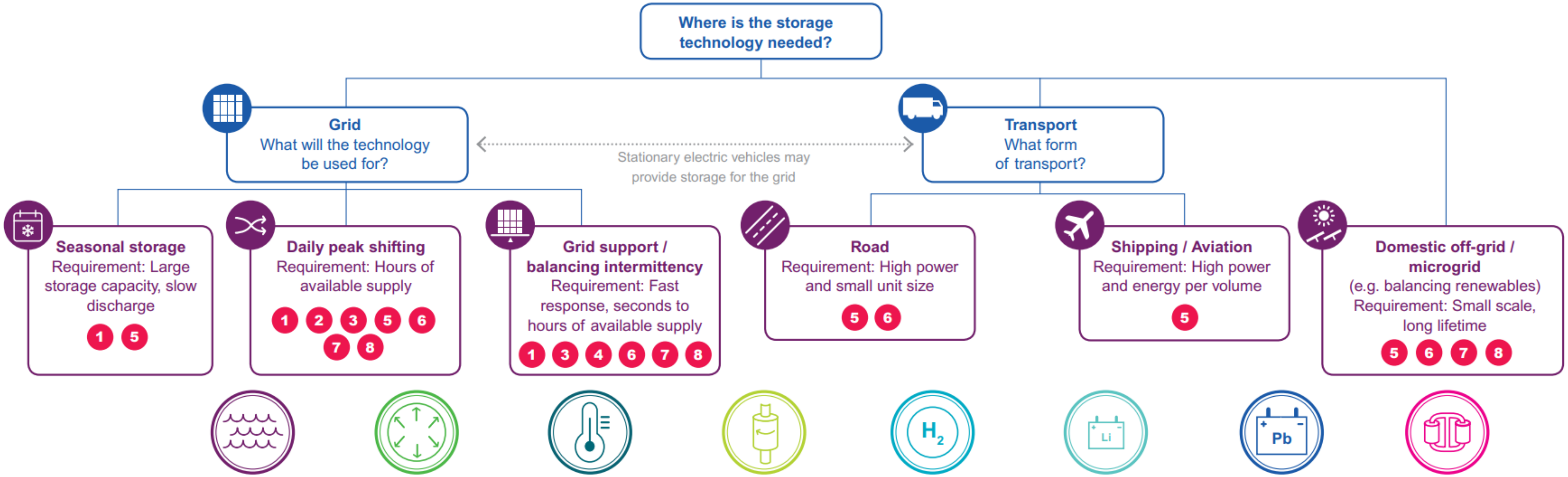
Electrochemical - Electrical – Chemical Energy Storage

- Batteries:
  - Lithium-ion batteries (NMC, LFP, LTO, etc.)
  - Aqueous batteries (lead acid, nickel/cadmium and nickel/metal hydride)
  - High-temperature batteries (sodium/sulfur, sodium/nickel chloride)
  - Redox flow batteries (vanadium, zinc/bromine, iron)
- Supercapacitors:
  - Double Layer Capacitors
  - Pseudocapacitors
  - Hybrid Capacitors
- Fuel cells and electrolyzers for hydrogen production



Types of Electrical Energy Storage

	Electrochemical Storage				Mechanical Storage		
	LEAD ACID	LITHIUM-ION	SODIUM-SULFUR	FLOW BATTERIES	FLYWHEELS	COMPRESSED AIR	PUMPED HYDRO
Round-trip efficiency	70-85%	85-95%	70-80%	60-75%	60-80%	50-65%	70-80%
Typical duration	2-6 hr	0.25-4 hr	6-8 hr	4-12 hr	0.25-4 hr	4-10 hr	6-20 hr
Time to build	6-12 mo	6-12 mo	6-18 mo	6-12 mo	1-2 yr	3-10 yr	5-15 yr
Operating cost	High	Low	Moderate	Moderate	Low	Moderate	Low
Space required	Large	Small	Moderate	Moderate	Small	Moderate	Large
Cycle life	500-2,000	2,000-6,000+	3,000-5,000	5,000-8,000+	100,000	10,000+	10,000+
Technology maturity	Mature	Commercial	Commercial	Early-moderate	Early-moderate	Moderate	Mature



	1 Pumped hydropower	2 Compressed air energy storage	3 Thermal cycle	4 Flywheels / supercapaci-tors / SMES†	5 Hydrogen electrolyser / fuel cell	6 Lithium-ion batteries	7 Lead-acid batteries	8 Redox flow batteries
Capital cost	\$ – \$\$	\$ – \$\$	\$ – \$\$	\$\$ – \$\$\$	\$\$\$	\$\$	\$ – \$\$	\$\$
Cost per cycle	–	–	–	–	–	–	–	
Response time	Seconds – Minutes	Minutes	Seconds	Milliseconds – Minutes	Minutes	Milliseconds	Milliseconds	Milliseconds
Total deployment	3	2	1	1 / 2 / 1	3	2	3	1
Efficiency (%)	70 – 85	50 – 75	55 – 80	85 – 98	<40 (mature) Up to 66 (developing)	80 – 90	65 – 85	65 – 85
Daily self-discharge	>0.5%	>10%	0.5 – 1%	(100% / 5 – 20% / 10 – 15%)	~0%	~0%	~0.2%	~0%
In a nutshell	Affordable, but large and site-specific	Affordable, but large and site-specific	Potentially affordable, non site-specific	Fast response, but rapid discharge	Potential for long-term storage, currently expensive	High energy density, rapidly developing	Mature, but bulky and toxic materials	High number of cycles in lifetime, but bulky

Capital cost: (\$/kWh for 1 – 8hr energy system): \$ = 10 – 100, \$\$ = 100 – 1000, \$\$\$ = 1000 – 10,000)

Cost per cycle: (including capital/cycle life, and operation, and maintenance. units \$/kWh/cycle):
= < 0.01, = 0.01 – 0.10, = 0.10 – 1, = 1 – 10

Response time: Time a storage system requires to ramp up supply

Total deployment:
1 = less than 100 MW / 100MWh deployed
2 = 100 MW / 100 MWh to 10 GW / 10 GWh deployed
3 = more than 10 GW / 10 GWh deployed

Efficiency: Energy out divided by energy in

Daily self-discharge: Percentage of charge lost in device each day

* Other measures, such as increased interconnectivity, demand side management, thermal storage and dispatchable generation, also play a part in regulating the supply of electricity

† Superconducting Magnetic Energy Storage

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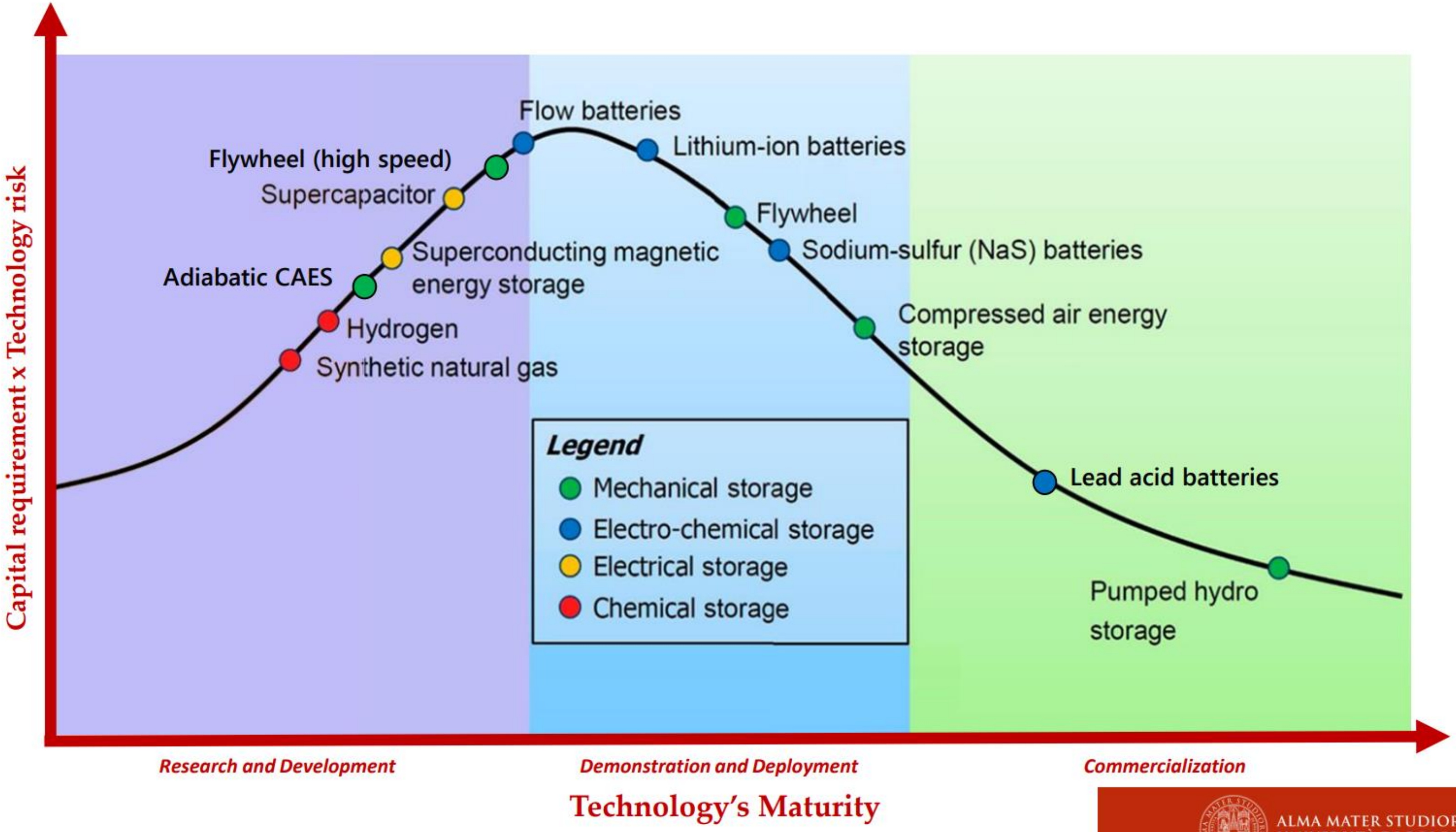
Types of Energy Storage Systems

Properties for different energy storage systems (ESS) [17,23,24,198].

ESS	Power range (MW)	Discharge time>	Power density (Wh/kg)	Energy density (Wh/kg)	Efficiency (%)	Lifetime (years)	Cycling capacity
SHS	250	–	–	–	50–90	10–30	>5,000
LHES	5	–	–	–	75–90	10–30	–
PHES	10–5,000	1–24 h	–	0.5–1.5	70–85	30–60	12×10^3–30×10^3
GES	40–1,600	1–4 h	–	–	75–80	–	–
CAES	3–300	1–24 h	–	30–60	40–80	20–50	0.5×10^3–13×10^3
FES	0.1–20	Sec–min	400–500	5–80	70–95	15–20	20×10^3–100×10^3
Hydrogen	0.1–50	Secs–24 h	5–800	600–1,200	20–66	10–20	20×10^3
Lead-acid	0–20	Secs–hours	75–300	30–75	70–90	5–15	200–2,000
Nickel-Cd	0–40	Secs–hours	150–300	40–90	60–90	10–20	3,000–4,000
Sodium sulphur	0.05–8	Secs–hours	90–230	150–240	75–90	10–15	2,000–4,000
Li-ion	0–0.1	Mins–hours	360	100–200	70–85	5–15	1,000–10^4
VRB	<3	<10 h	75–150	35–60	70–85	10	>16×10^3
PSB	<15	<20 h	–	15–30	60–75	–	15×10^3–20×10^3
Zn-Br	–	Secs–10 h	90–110	75–85	65–75	5–10	>12×10^3
Capacitor	0–0.05	Millisecs–1 h	10^5	0.05–5	60–90	5	>50×10^3
Supercapacitor	0–0.3	Millisecs–1 h	500–5,000	1.5–2.5	75–95	>20	>10^5
SMES	1–10	Millisecs–8 s	500–2,000	0.5–5	>95	>20	>10^5

Source: Mitali, J., S. Dhinakaran, and A. A. Mohamad. "Energy storage systems: A review." Energy Storage and Saving (2022).

Development of Energy Storage Systems



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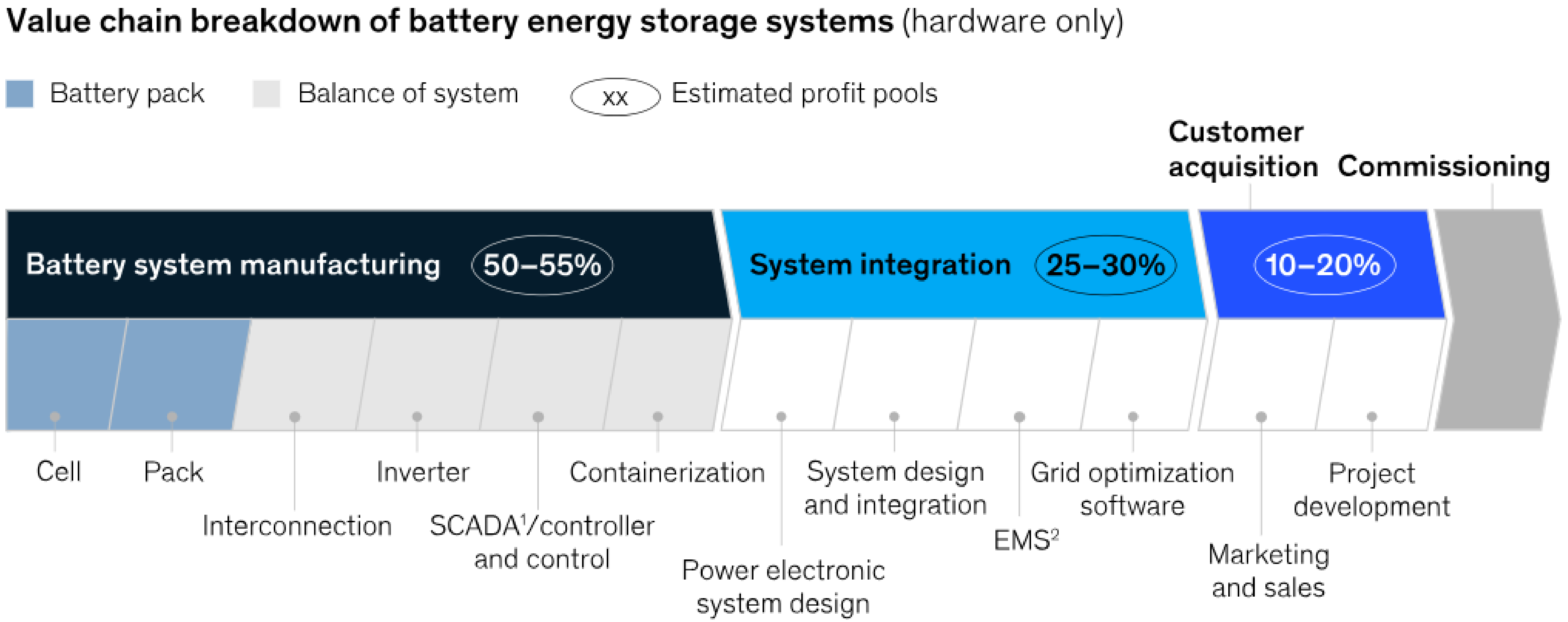
Graph referring to 2015

Development of Energy Storage Systems



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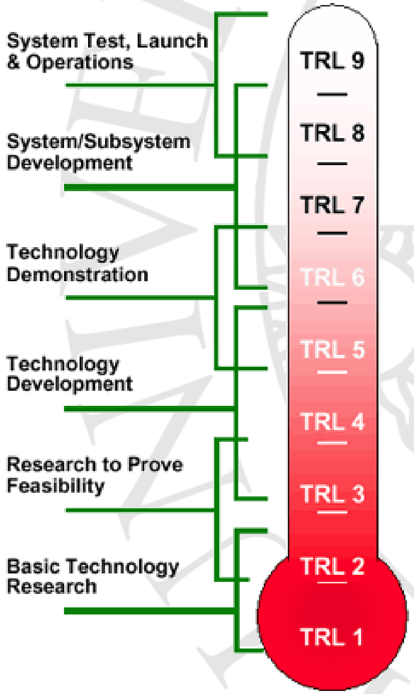
Development of Energy Storage Systems

Technology Readiness Level (TRL)

Scale to indicate the maturity of a technology with respect to the possibility of commercialization

Technology readiness level (TRL).

Stage	TRL	Description
Deployment	9	System deployed and operational in a real environment
	8	Complete validation and certification of system in real environment
	7	Prototype validated in real environment
Research	6	Technology demonstrated in relevant environment
	5	Technology validated in relevant environment
Development	4	Technology validated in lab
	3	Concept tested
	2	Concept/technology formulated
	1	Basic idea/concept



Current status of energy storage technologies [108,551,565,566].

Storage system	Current scenario	TRL
Lead-acid batteries	Mature technology, commercially available	9
Lithium-ion batteries	Commercial technology	9
Nickel-cadmium batteries	Mature technology	9
Sodium sulphur	Large-scale demonstration	8
Vanadium redox batteries	Mature technology	9
Polysulfide bromide batteries	–	4–5
Zinc bromine batteries	Demonstration	6
Electric double-layer capacitors	Early commercial technology	8–9
Hybrid energy storage system	–	7
Synthetic natural gas	Prototype testing to large scale demonstration	4–8
Pumped hydro energy storage system	Mature technology, commercially available	9
Compressed air energy storage system	–	7–8
Low speed flywheel energy storage system	–	9
High speed flywheel energy storage system	Prototype testing to small scale demonstration	5–7
Supercapacitors	–	6
Superconducting magnetic bnergy storage system	–	5–6

Source: Mitali, J., S. Dhinakaran, and A. A. Mohamad. "Energy storage systems: A review." Energy Storage and Saving (2022).

End of the Lesson