Fundamentals of Energy Storage

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National Renewable Energy Laboratory

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Background

This slide deck was developed for and presented at an Energy Fundamentals Course hosted by the Bangladesh University of Engineering and Technology (BUET) in October 2022. The National Renewable Energy Laboratory (NREL) helped organize this course in partnership with the United States Agency for International Development (USAID). The students in this four-day course were postgraduates and working professionals in the energy sector or related industries in Bangladesh. While some of the content in the slide deck is tailored to Bangladesh specifically, this presentation is intended to be a general primer on energy storage that can be utilized for similar purposes by other universities or organizations throughout the world. The content of this slide deck is not intended to be fully comprehensive of all energy storage concepts.

Outline

1. Storage Trends

a. Global trends
b. Regional trends

2. Storage Technology

a. Electrochemical
b. Mechanical
c. Thermal

3. Battery Storage

a. Attributes
b. Utility-scale & Distributed
c. Resilience

4. Grid Services

a. Energy & capacity
b. Ancillary services
c. Transmission

Image: Werner Slocum (NREL)

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Image: Werner Slocum (NREL)

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Global Trends

Market

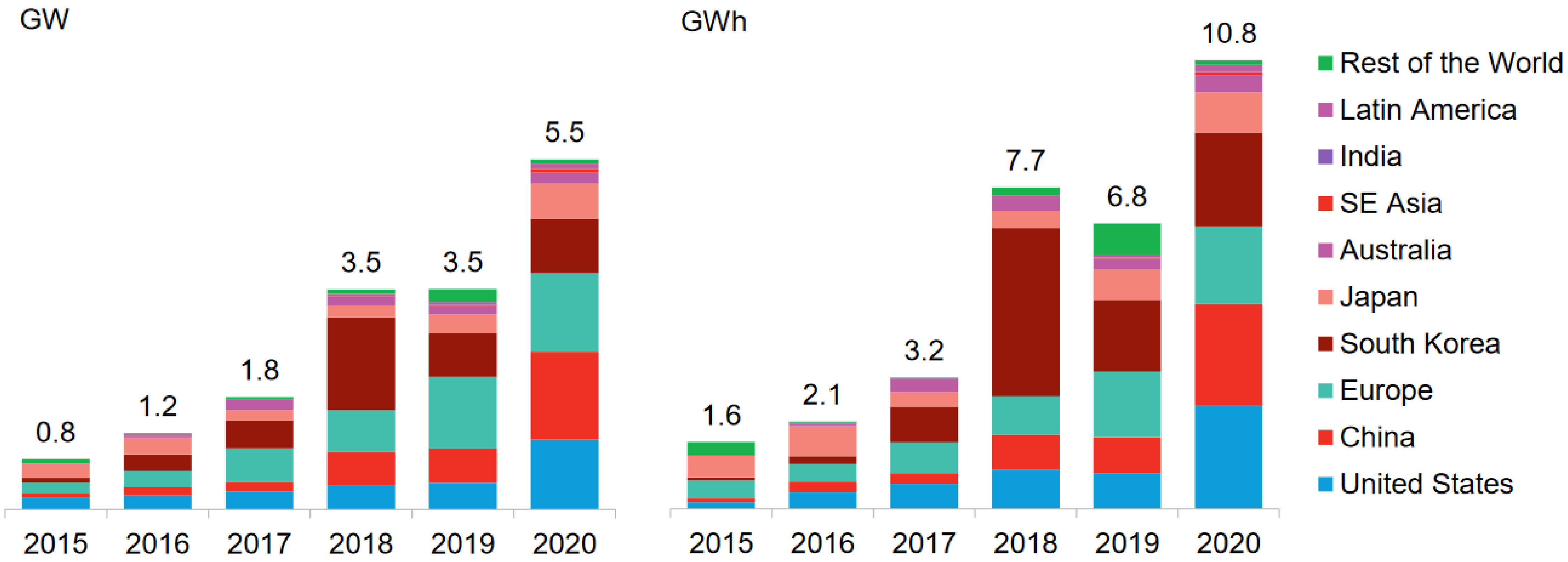

Figure. Global energy storage build by market, 2015-2020

Source: Bloomberg New Energy Finance (2022)

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Global Trends

Market

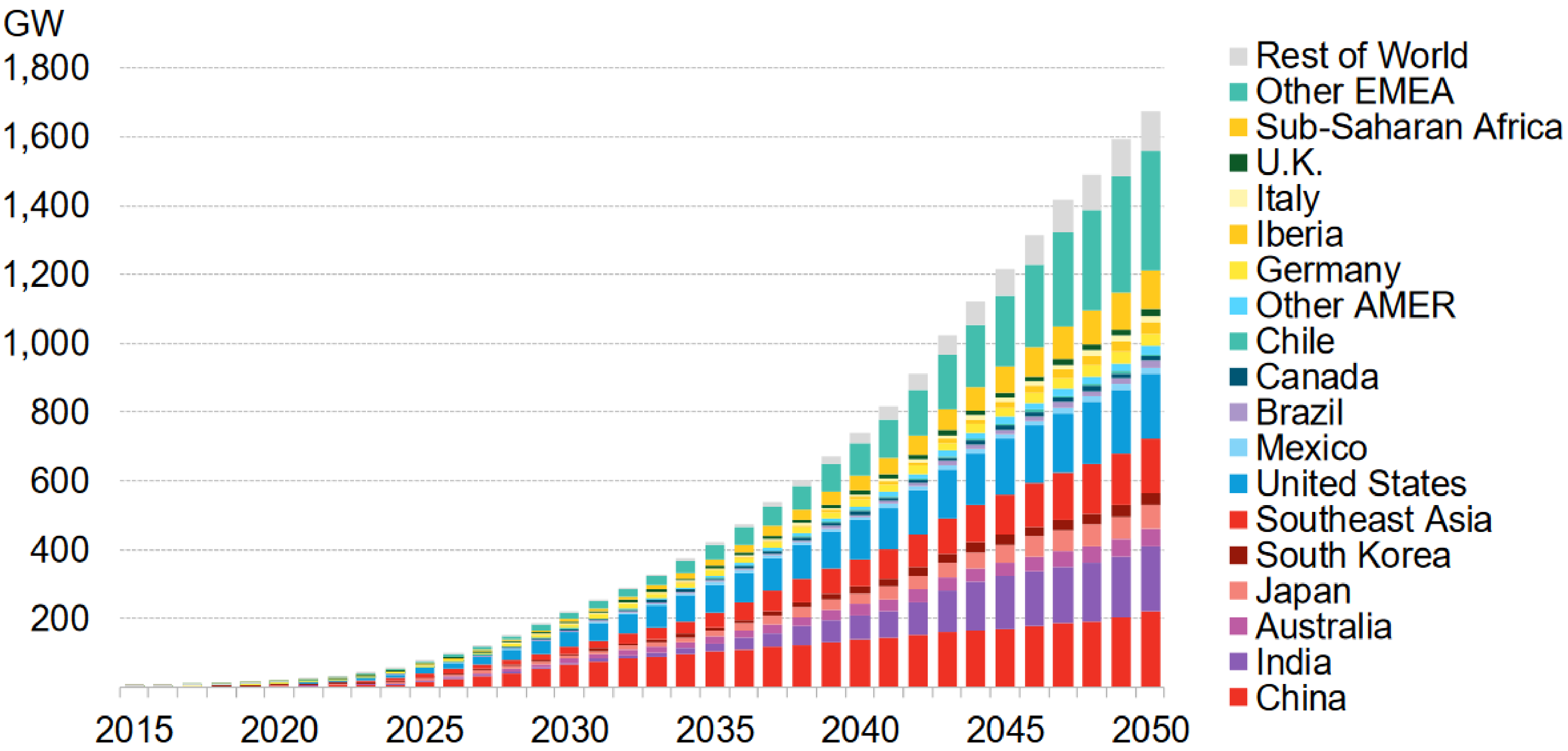

Figure. Global energy storage projection by market, 2015-2020

Source: Bloomberg New Energy Finance (2022)

Global Trends

Cost

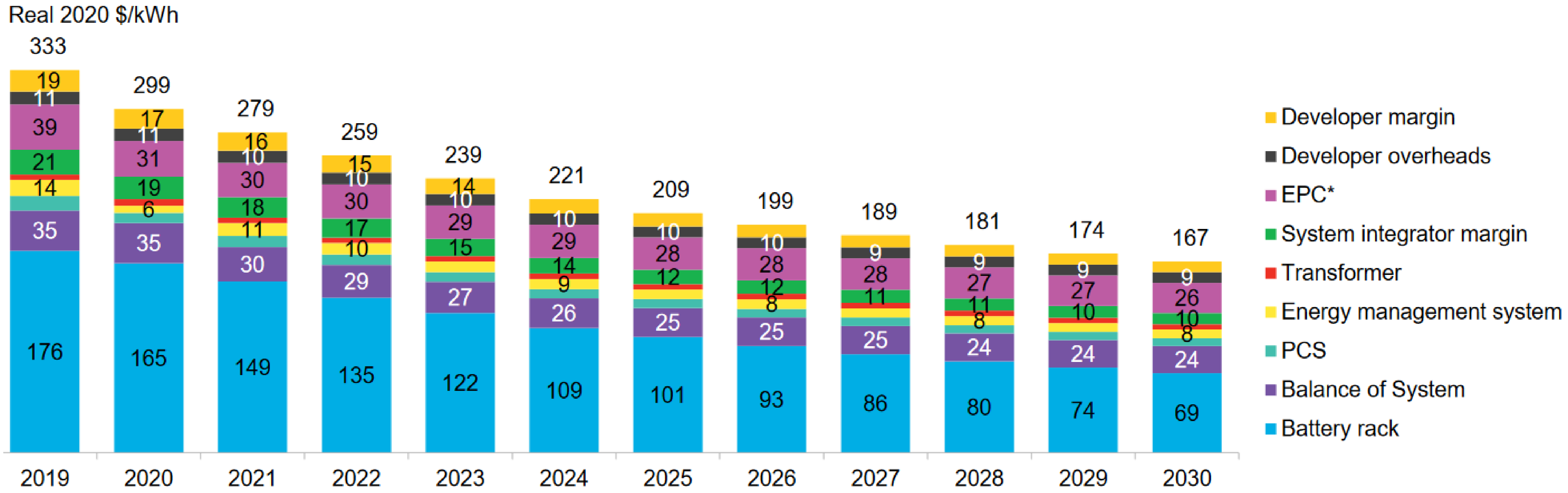

Figure. Stationary storage system (4-hour AC battery energy storage system) cost trend and projection, 2019-2030

Source: Bloomberg New Energy Finance (2022)

Regional Trends

Scenarios for modeled energy storage deployment varied based on:

- Regulations
- Fossil fuel policies
- Battery costs
- Solar PV costs
- Pumped storage hydropower costs

Storage capacity in Nepal, Bangladesh, and Bhutan

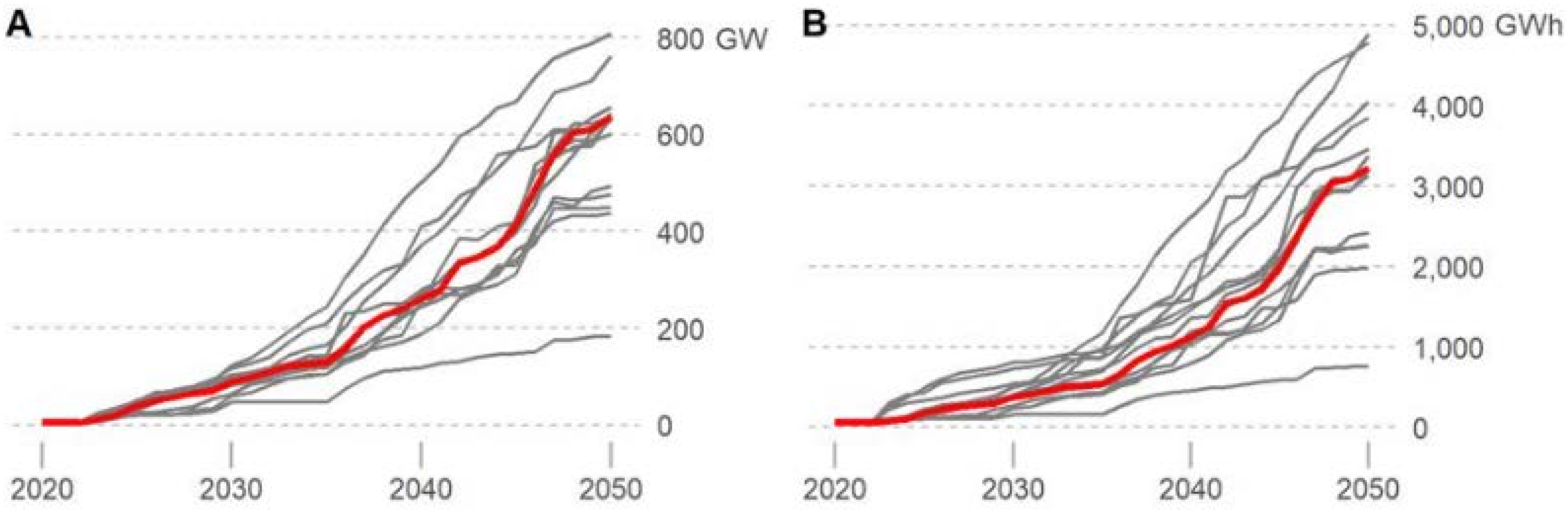

Figure. Energy storage power (A) and energy (B) modeled capacity deployment in India, 2020-2050

Note: Each line represents one modeled scenario. The Reference Case is highlighted in red.

Source: Chernyakhovskiy et al. (2021)

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Storage Technology Overview

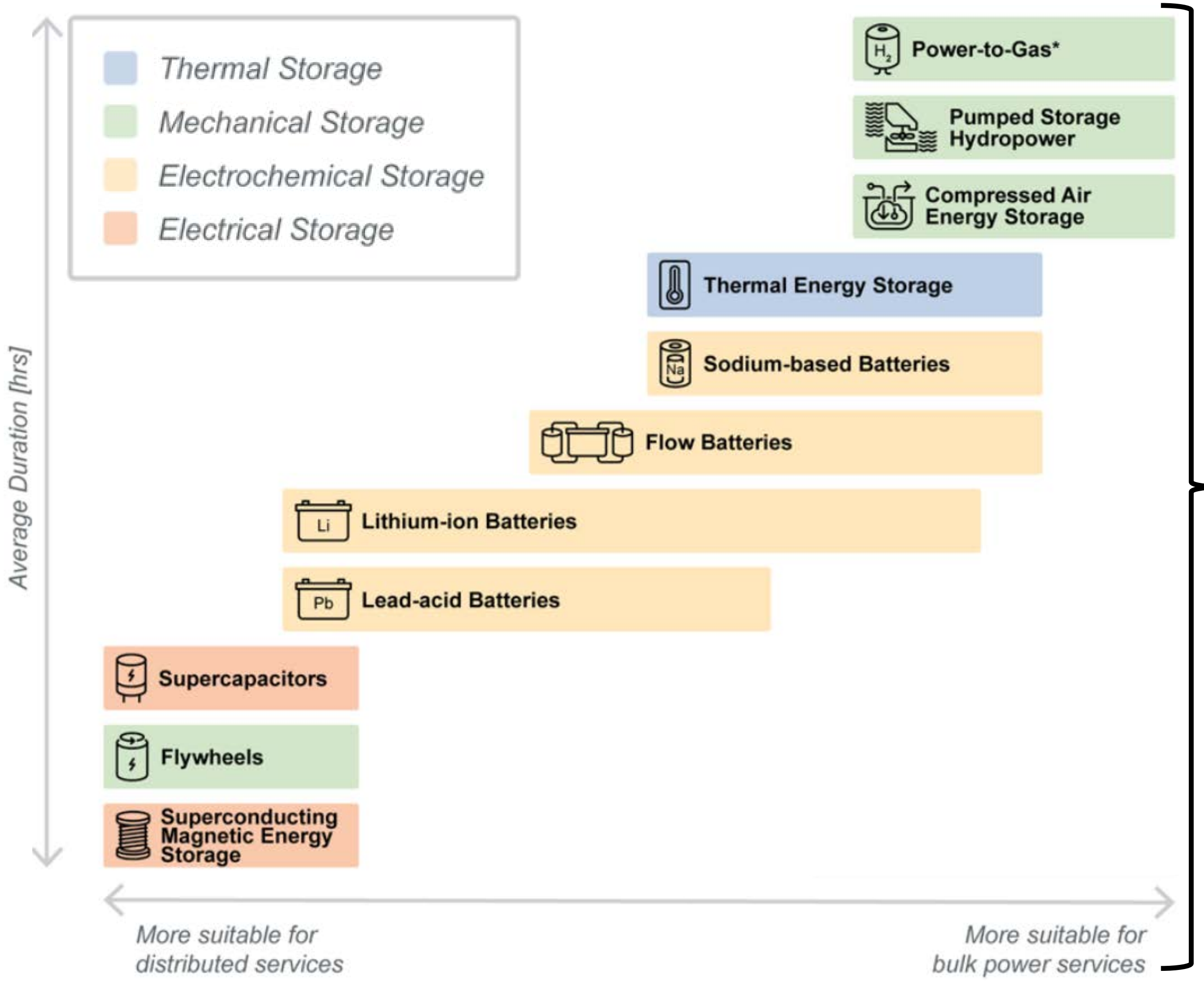

Figure. Ecosystem of energy storage technologies and services

Source: Bowen et al. (2021)

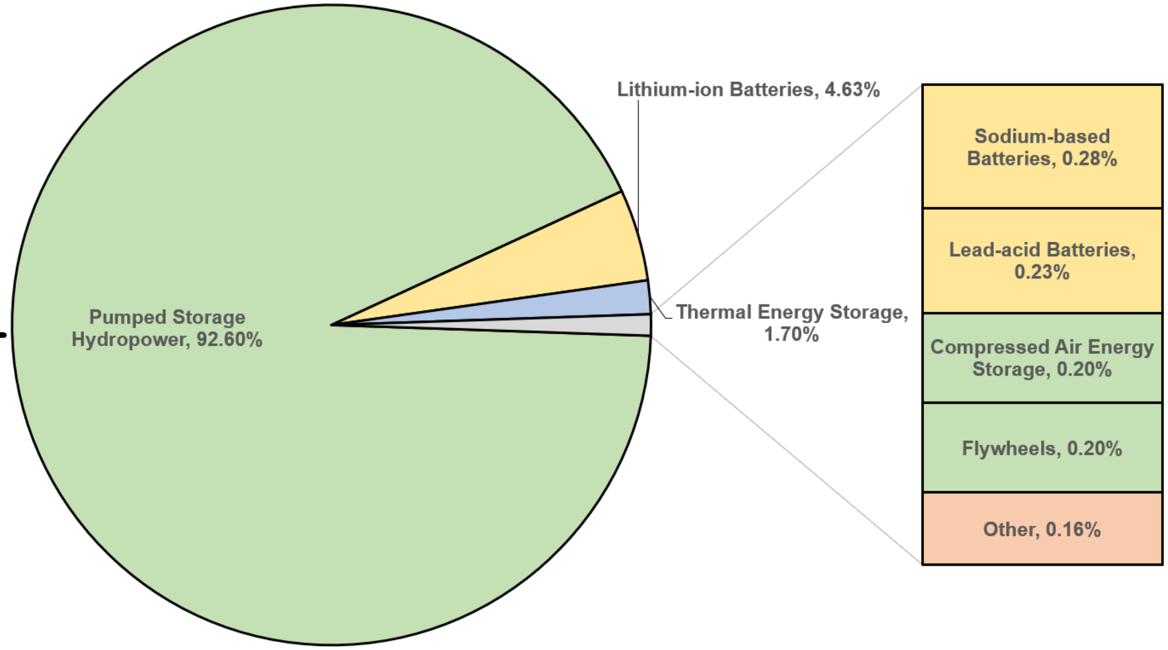

Figure. Global total operational energy storage project capacity, 2020

Data: China Energy Storage Alliance (2020)

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Pumped Storage Hydropower (PSH)

Technology	Duration	Reaction Time	Round-Trip Efficiency	Unique Geographic Requirements
PSH	Several hours to days	Several seconds to minutes (depends on technology choice)	80+%	Separate reservoirs with adequate differences in elevation

Open-Loop PSH
Projects are continuously connected to a naturally flowing water feature.

Closed-Loop PSH
Projects are not continuously connected to a naturally flowing water feature.

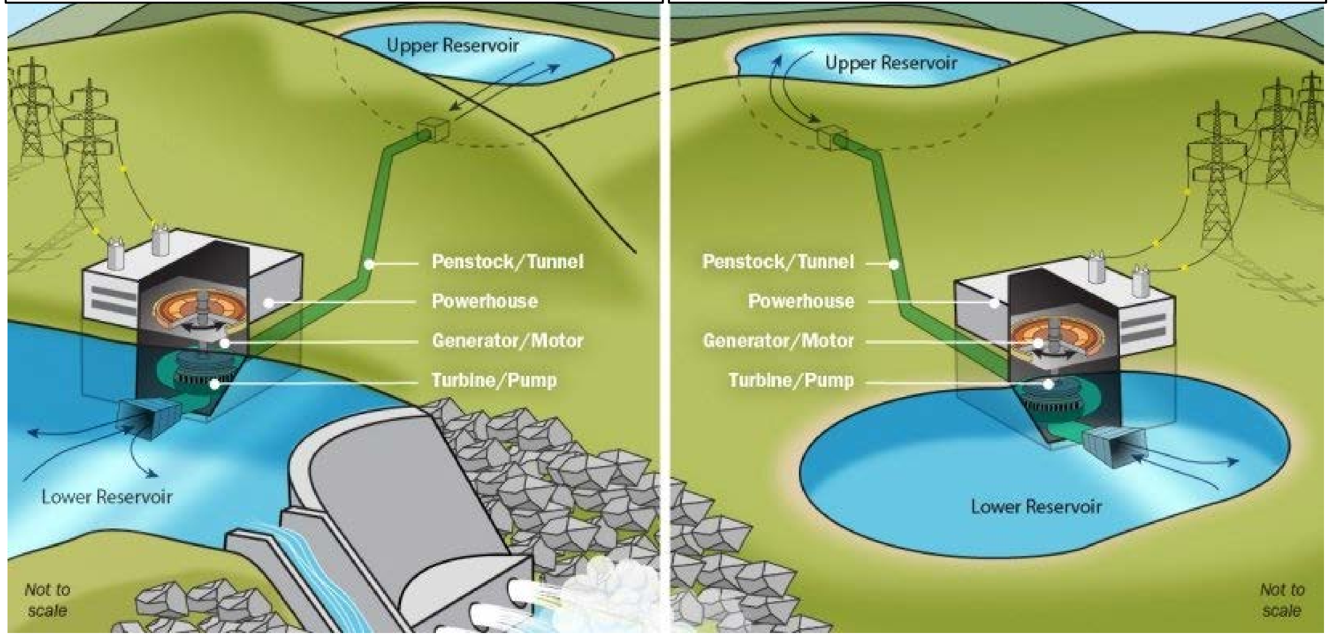

Image: U.S. Department of Energy

Advantages

- Most developed and widely commercialized energy storage technology in power sector
- Large capacities and long durations make it well suited to provide a variety of grid services

Challenges

- Limited by geographic requirements
- High capital costs

Source: Bowen et al. (2021)

Power-To-Gas: Hydrogen

Method	Status	Feedstock
Gasification	Mature	Coal or biomass
Steam (Methane) Reforming	Mature	Natural gas or biogas
Electrolysis		
Proton-Exchange Membrane	Pilot for at-scale production	Electricity plus water
Alkaline	Mature at scale	
Solid Oxide	R&D	

Figure. Select methods for producing hydrogen

Source and Image: Bowen et al. (2021); Denholm et al. (2021)

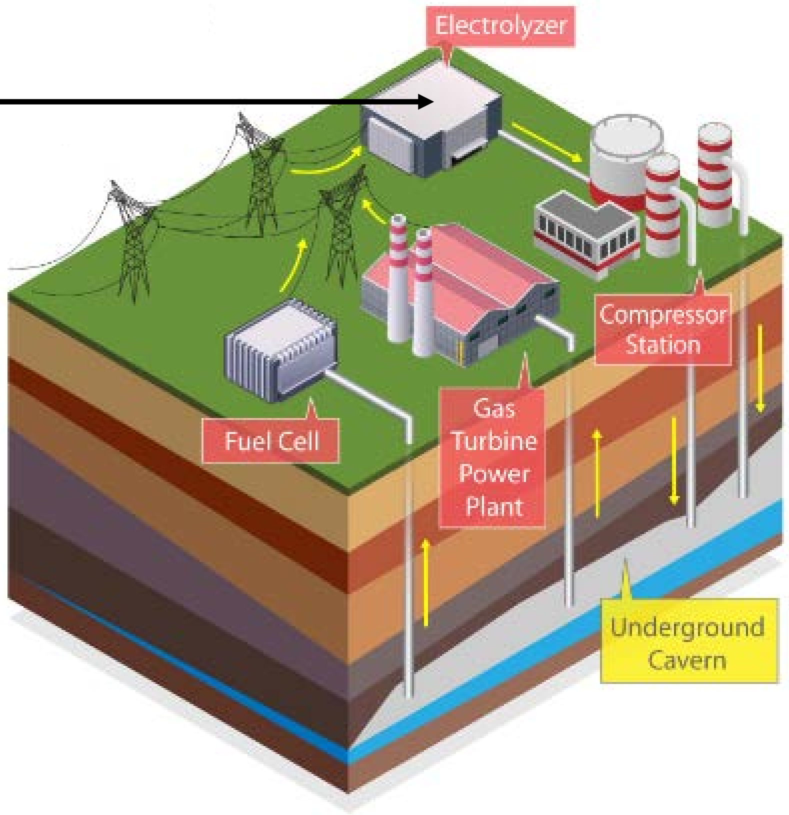

Figure. Schematic of hydrogen production via electrolysis, storage, and use in fuel cells or turbines

Advantages

- Potential to provide seasonal long-duration storage
- Applications for hydrogen in transportation and industry

Challenges

- Costs of electrolysis and subsequent power generation are currently high
- Significant support infrastructure required

Thermal Energy Storage (TES)

Sensible heat storage

- Uses temperature changes within a solid or liquid medium to store thermal energy.

Latent heat storage

- Phase change materials that absorb and release thermal energy through melting and freezing.

Thermochemical storage

- Releases or stores thermal energy as a byproduct of chemical reactions.

Source: Bowen et al. (2021)

Images: Engie; Dennis Schroeder (NREL)

Applications of TES

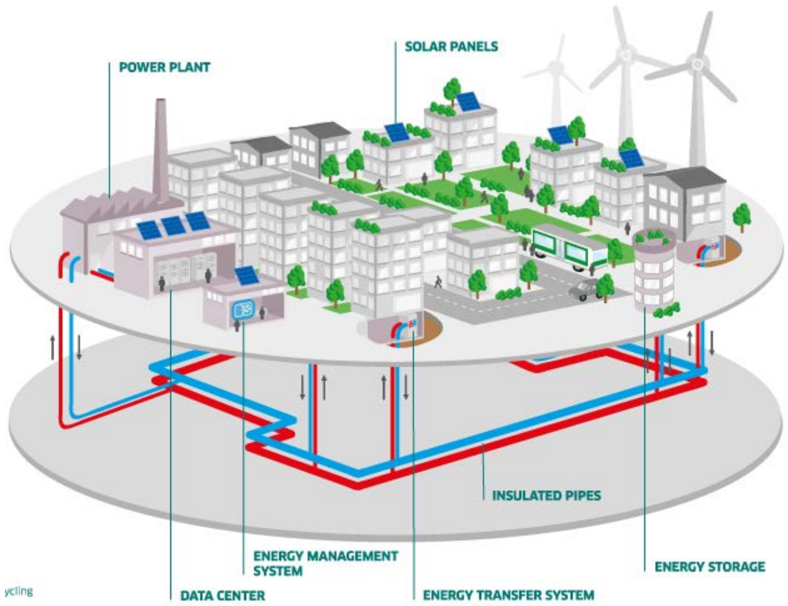

Figure. District heating schematic

- TES decouples electricity supply from heat supply in district heating systems, enabling flexibility.

Figure. Concentrated solar power plant

- TES allows electricity production from concentrated solar power plants even when sunlight is not available.

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Electrochemical Battery Storage

	Advantages	Disadvantages
Lithium-Ion	• Relatively high energy and power density • Lower maintenance costs • Rapid charge capability • Many chemistries offer design flexibility • Established technology with strong potential for project bankability.	• High upfront cost ($/kWh) relative to lead-acid (potentially offset by longer lifetimes) • Poor high-temperature performance • Safety considerations, which can increase costs to mitigate • Currently complex to recycle • Reliance on scarce materials.
Flow (Vanadium-Redox)	• Long cycle life • High intrinsic safety • Capable of deep discharges.	• Relatively low energy and power density.
Lead-Acid	• Low cost • Many different available sizes and designs • High recyclability.	• Limited energy density • Relatively short cycle life • Cannot be kept in a discharged state for long without permanent impact on performance • Deep cycling can impact cycle life • Poor performance in high temperature environments. • Toxicity of components
Sodium-Sulfur	• Relatively high energy density • Relatively long cycle life • Low self-discharge.	• High operating temperature necessary • High costs.

Source: Bowen et al. (2021)

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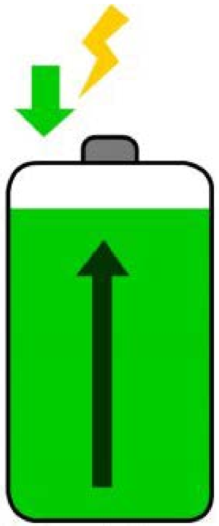
Image: Werner Slocum (NREL)

Attributes

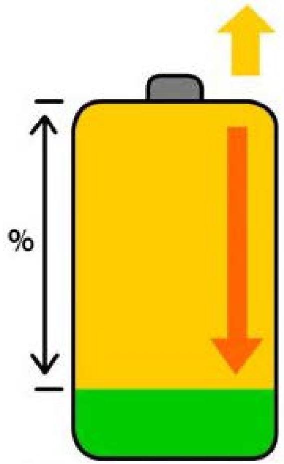
Energy storage projects are rated based on **power** (MW/kW) and **energy** (MWh/kWh).

Figure. Other attributes of battery storage systems



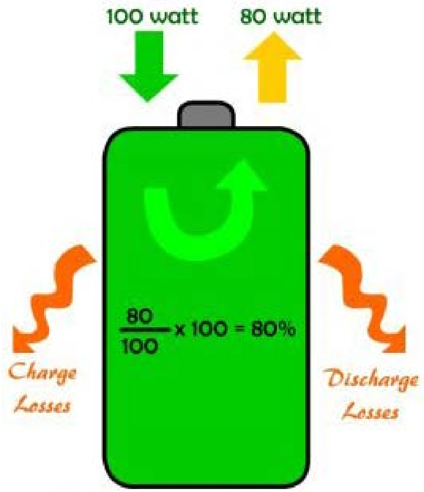
State of Charge

The percentage of battery energy capacity still available in the battery.



Depth of Discharge

The percentage of the battery that has been discharged relative to the total battery energy capacity.



Round-Trip Efficiency

The ratio of the energy recovered from the battery to the energy input into the battery. Losses include heat loss.

Images: Future Green Technology (2018)

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Utility-Scale and Distributed Storage

Sector

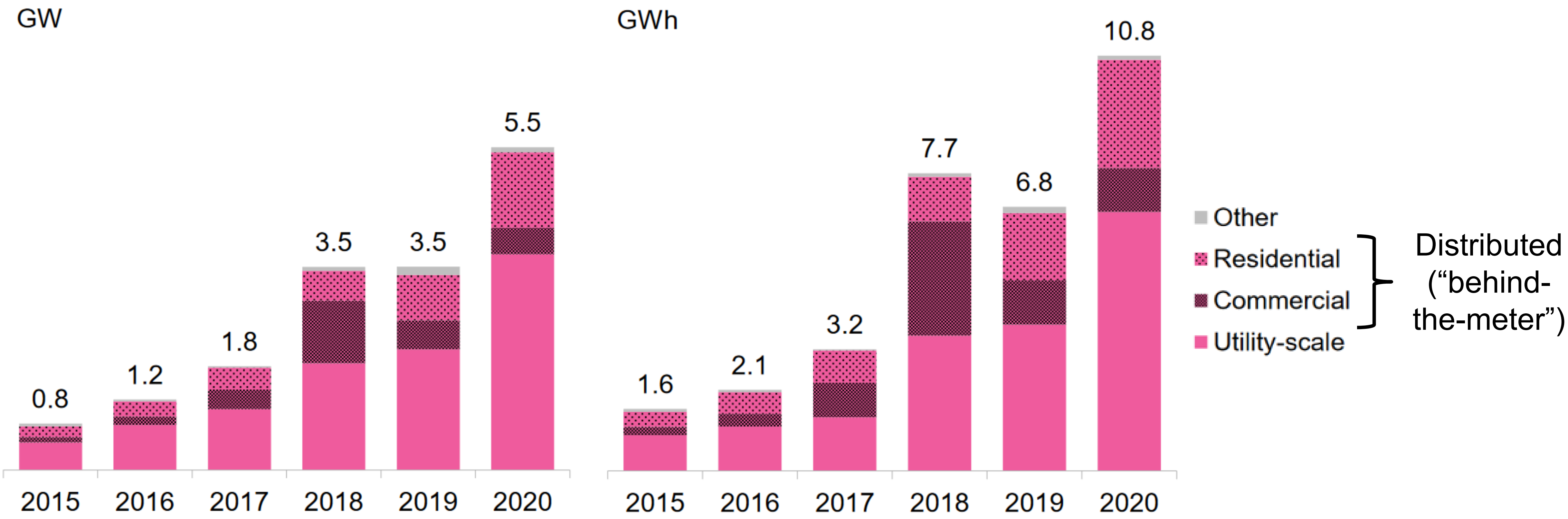

Figure. Global energy storage build by sector, 2015-2020

Source: Bloomberg New Energy Finance (2022)

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Distributed Battery Storage for Resilience

When coupled with a renewable distributed energy generation source (e.g., solar PV), battery storage can provide backup generation for extended periods of time (days to weeks):

- Decreases the size of other backup generation (e.g., diesel generators) and extends limited fuel supply
- Is a fully renewable backup power source (when coupled with renewables) that does not need refueling
- Can provide revenue streams while grid connected (e.g., demand charge reduction, demand response programs, energy arbitrage, etc.)

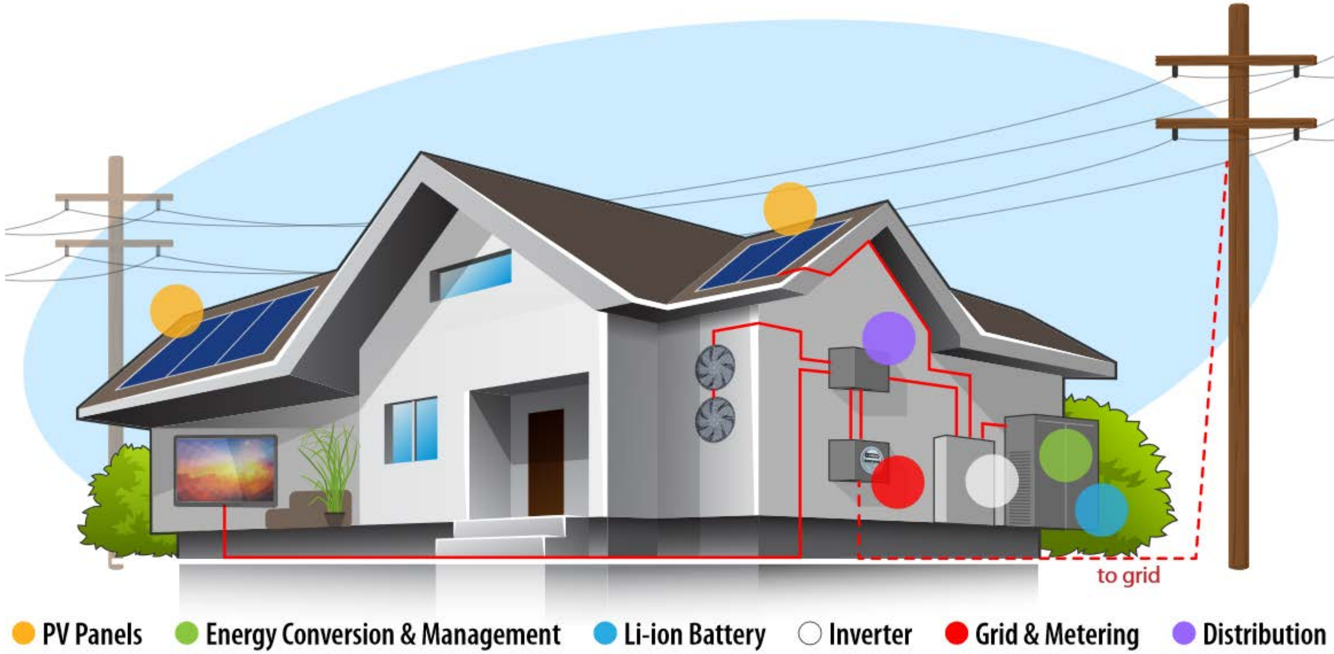

Figure. Illustration of residential solar PV and distributed battery storage system

Image: Alfred Hicks (NREL)

Source: Elgqvist (2020)

Considerations for Distributed Storage as Backup Power

CRITICAL LOADS

OUTAGE DURATION

VALUE OF RESILIENCE

COST OF ISLANDING PV + STORAGE

- There are considerations for using renewable energy and storage to provide backup power in the event of a grid outage (in addition to the ones for grid-connected-only systems).

- Different technology solutions have different costs and can provide different levels of resilience.

Source: Elgqvist (2020)

Image: David Shankbone (Wikimedia Commons)

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Image: Werner Slocum (NREL)

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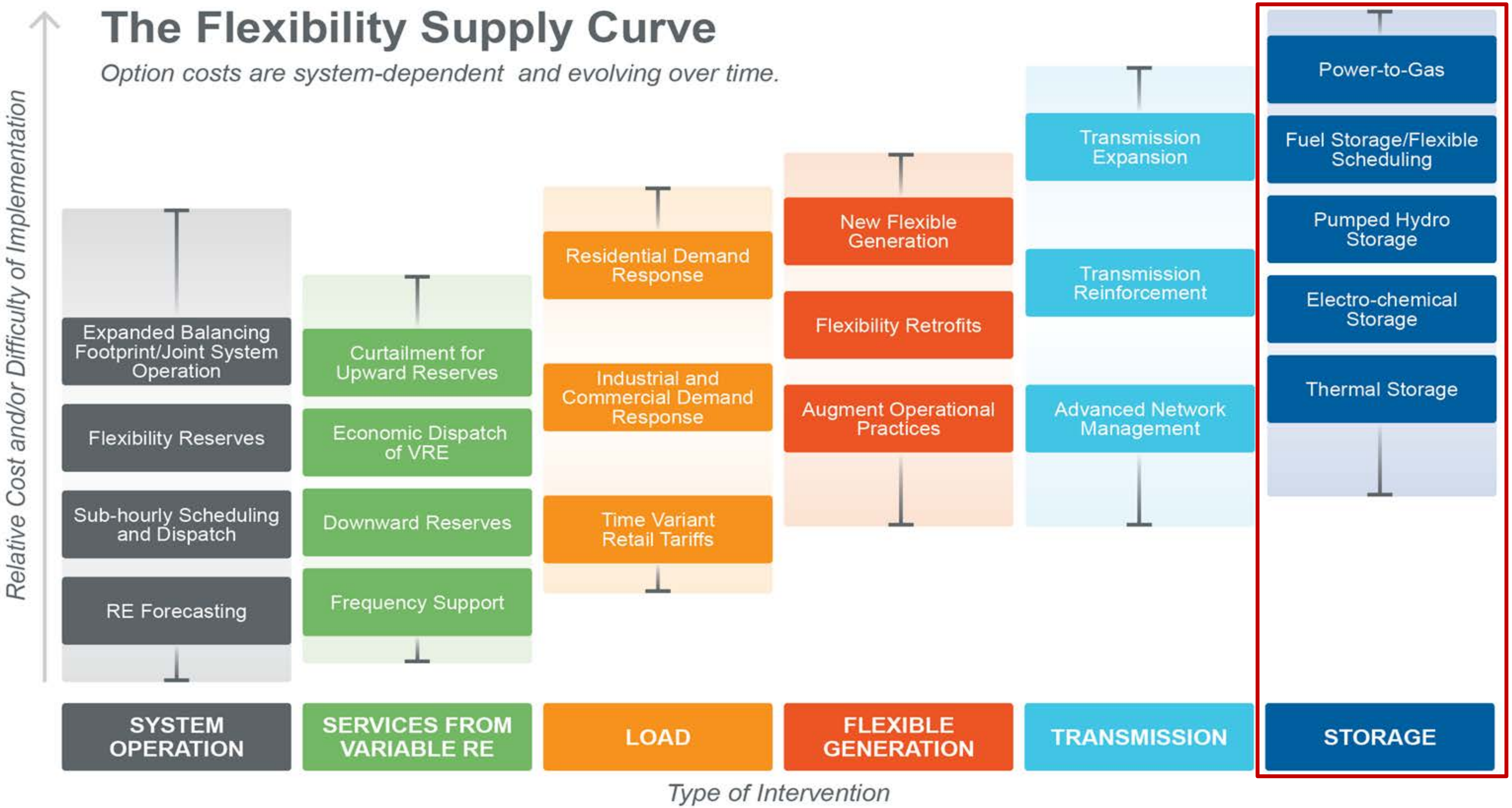
Storage Can Provide Flexibility and Help Integrate Renewables



Source: Chernyakhovskiy et al. (2021)

Storage Can Provide Services Throughout the Grid

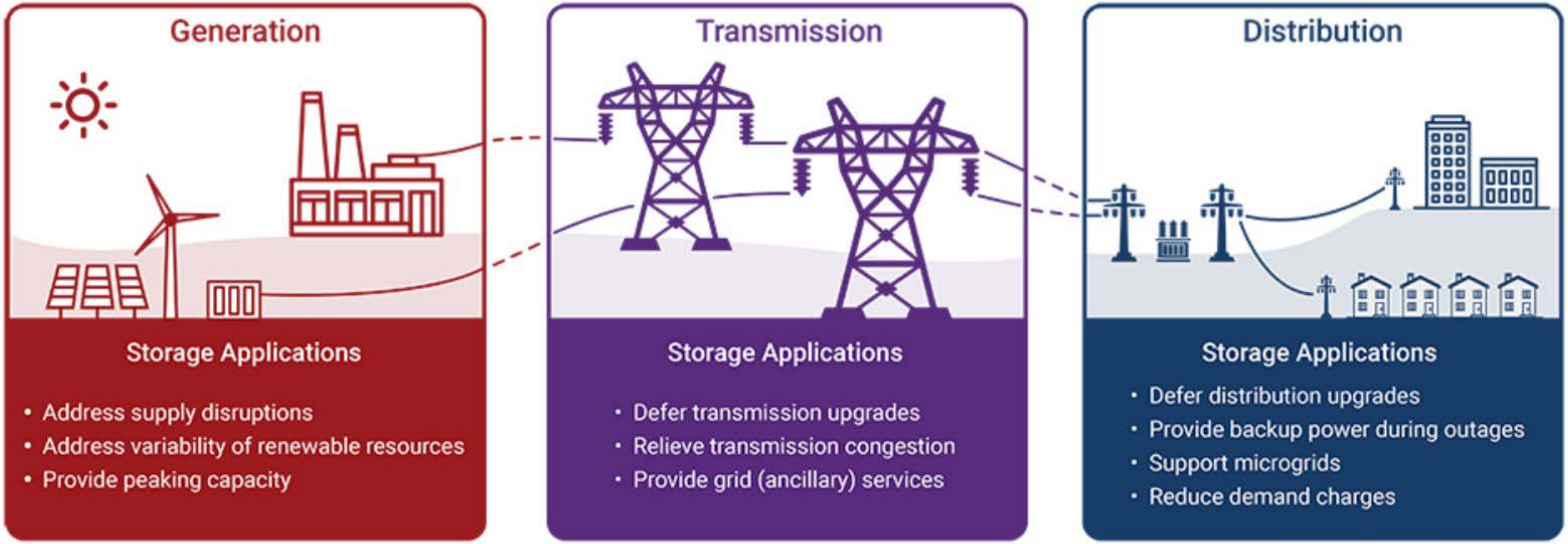
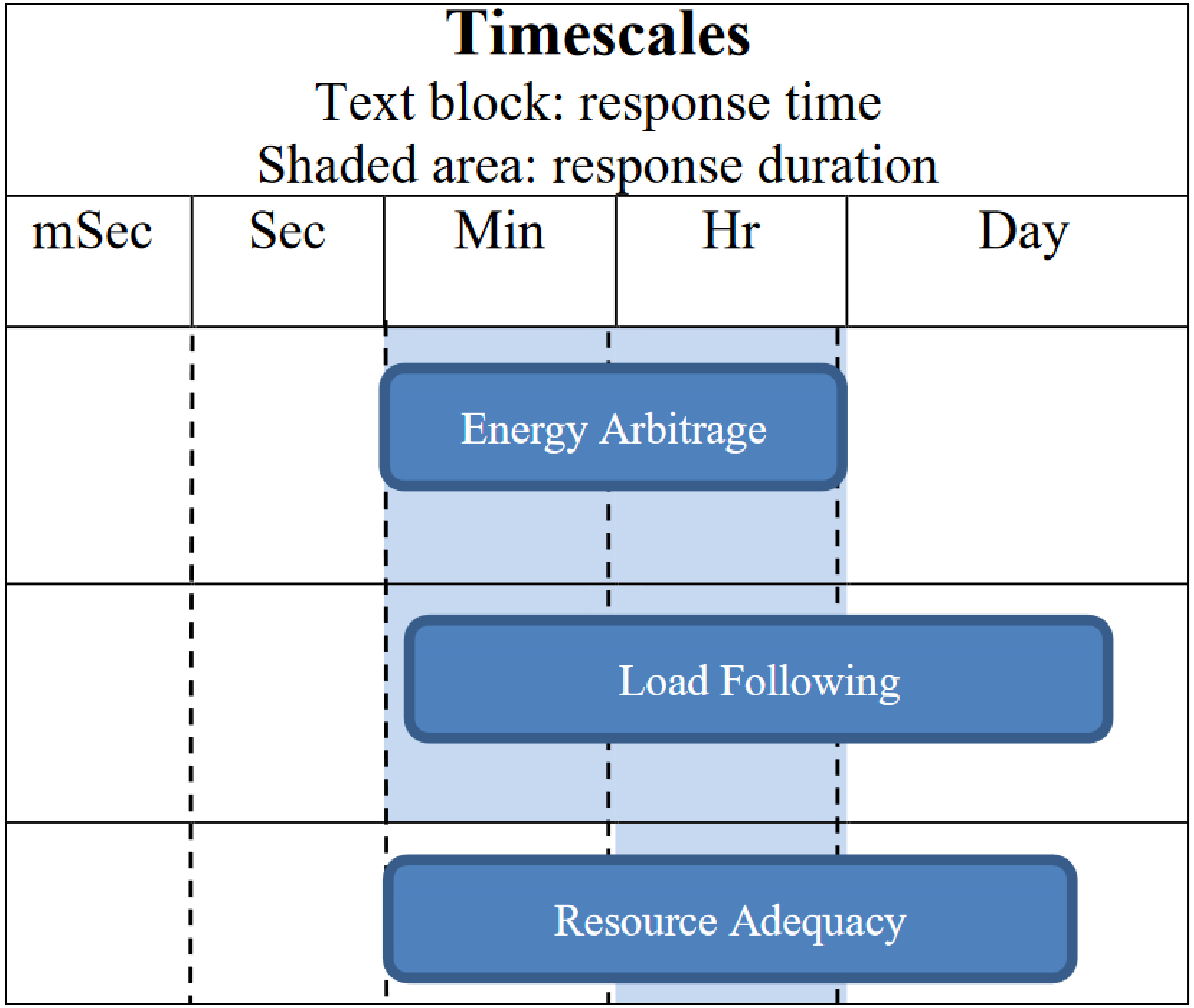


Image: Clear Path (2018)

Energy and Capacity Services



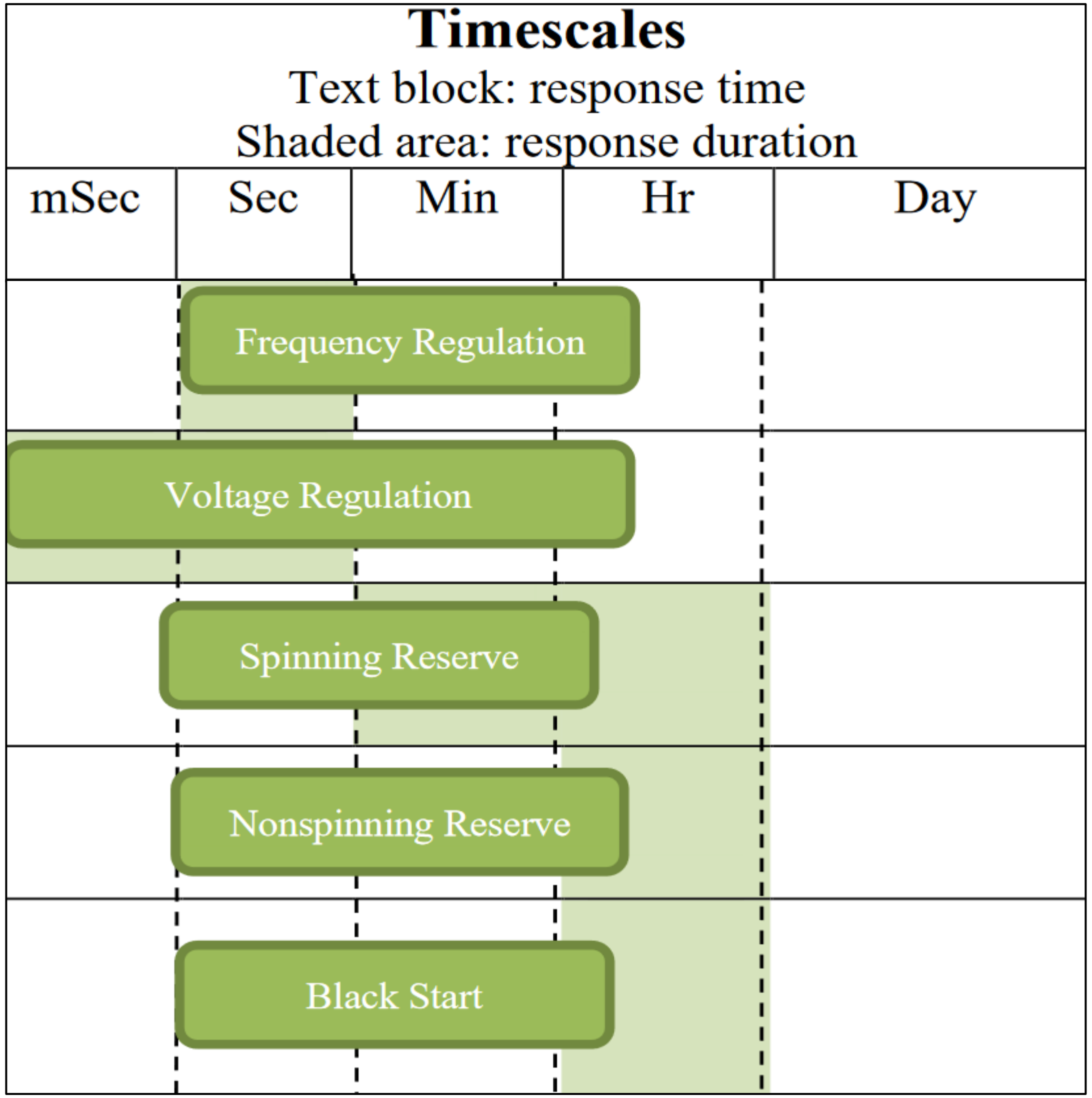
"Effectively increase available load during periods with excess generation for peak demand management and reduction of renewable energy curtailment."

"Stabilize net electricity demand to minimize thermal unit ramping and cycling and minimize errors in renewable energy and demand forecasts."

"Provide capacity to meet generation requirements during peak loading periods and contingency events."

Source: Rose and Joshi (2021)

Ancillary Services



Source: Rose and Joshi (2021)

"Provide power to maintain generation-load balance and prevent frequency fluctuations."

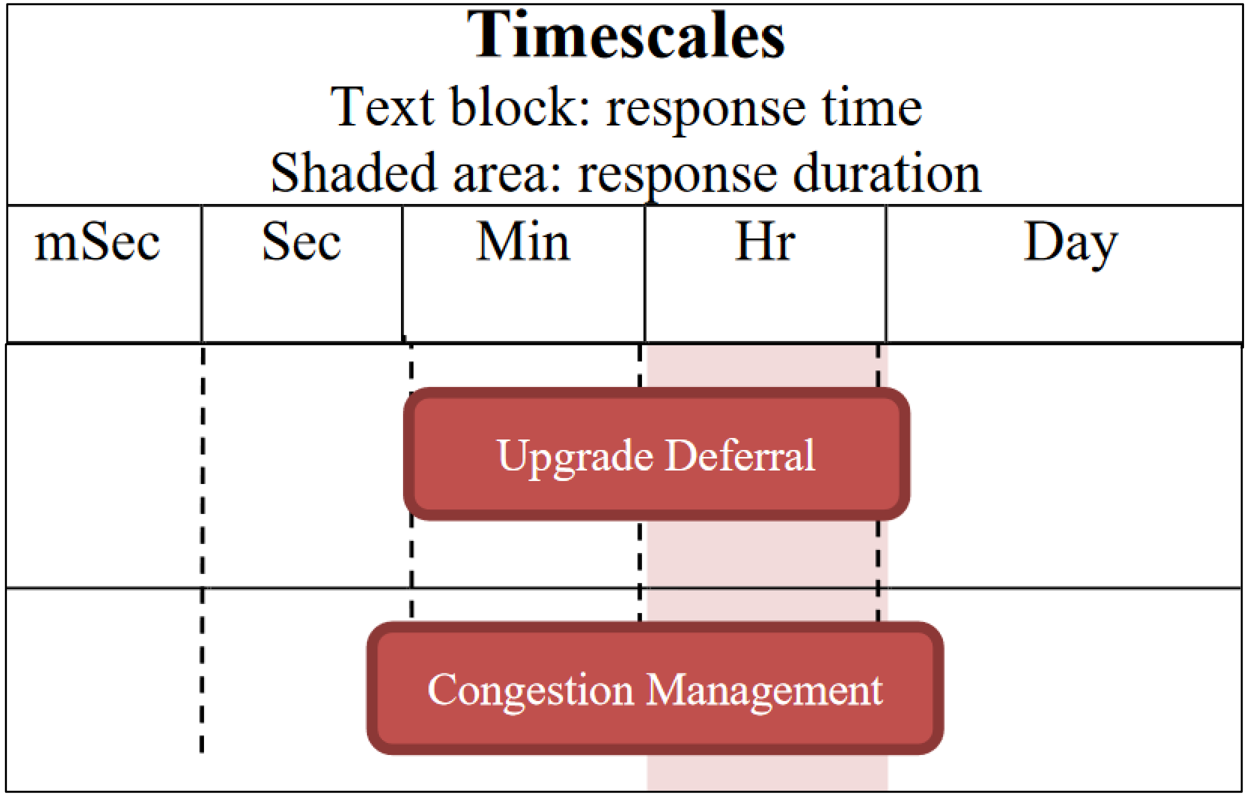
"Inject or absorb incremental voltage to maintain voltage stability on the transmission system."

"Provide immediate response to maintain electricity output during a contingency event."

"Maintain electricity output during contingency events within a short time period."

"Start main turbine of grid-connected generator, or feed power into the grid so other plants can start up and restore power."

Transmission Services



"Provide extra capacity to meet anticipated load growth for the purpose of delaying, reducing, or avoiding transmission system investments."

"Absorb power to reduce network congestion."

Source: Rose and Joshi (2021)

Thank you!

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https://www.nrel.gov/usaid-partnership/reinforcing-advanced-energy-systems-bangladesh.html

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