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ENERGY STORAGE APPLICATIONS IN SMART GRIDS

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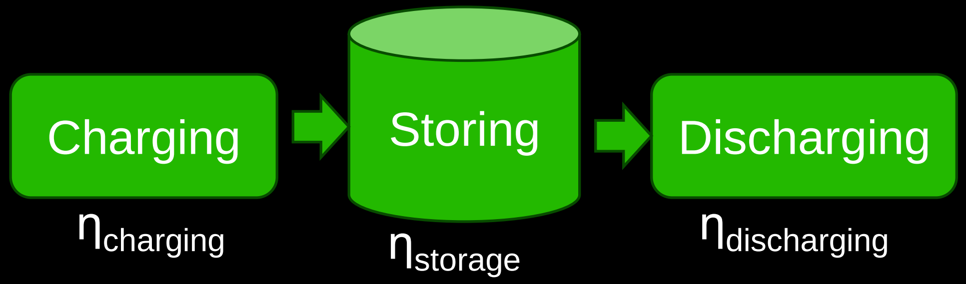
CONTENT

1. Storages — Why they are needed
2. Overview of different storage technologies
3. Services from storages
4. Applications in smart grids
5. Challenges and future

ENERGY STORAGES

ENERGY STORAGES



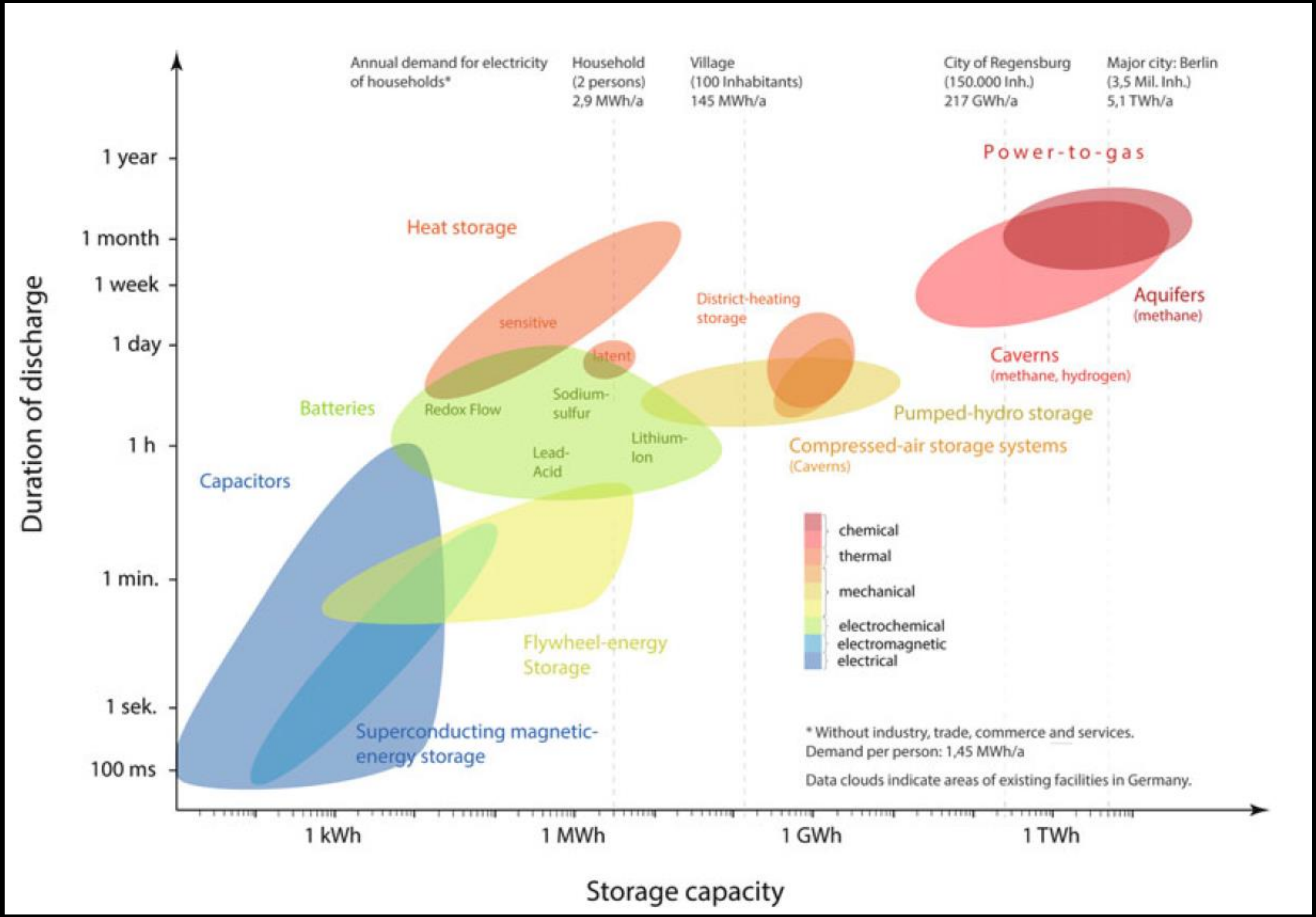
- Store energy from one moment to another.
- Different types
  - Mechanical, electrochemical, thermal, electric, P2X
  - Different storage type for different needs
  - From very small home battery installations (kWh) to very large utility scale storage (GWh), like pumped hydro
  - No single solution to all the challenges
- **Sector coupling** in smart grids allows to efficiently utilize different forms of storage for storing renewable electricity.

ENERGY STORAGES

- Mechanical
  - Pumped hydro storage (PHS)
  - Gravity storage
  - Compressed air (CAES)
  - Liquid air (LAES)
  - Flywheels
- Electrochemical (Batteries)
  - Lead acid
  - Lithium ion
  - Flow
  - High temperature
  - Nickel
- Thermal
  - Sensible
  - Latent (phase change materials, PCM)
  - Thermo-chemical
- Electrical
  - Super-capacitors
  - Coils (SMES)
- P2X
  - Hydrogen
  - Power-to-Fuel

Some of the storage types divided into different categories.

ENERGY STORAGES

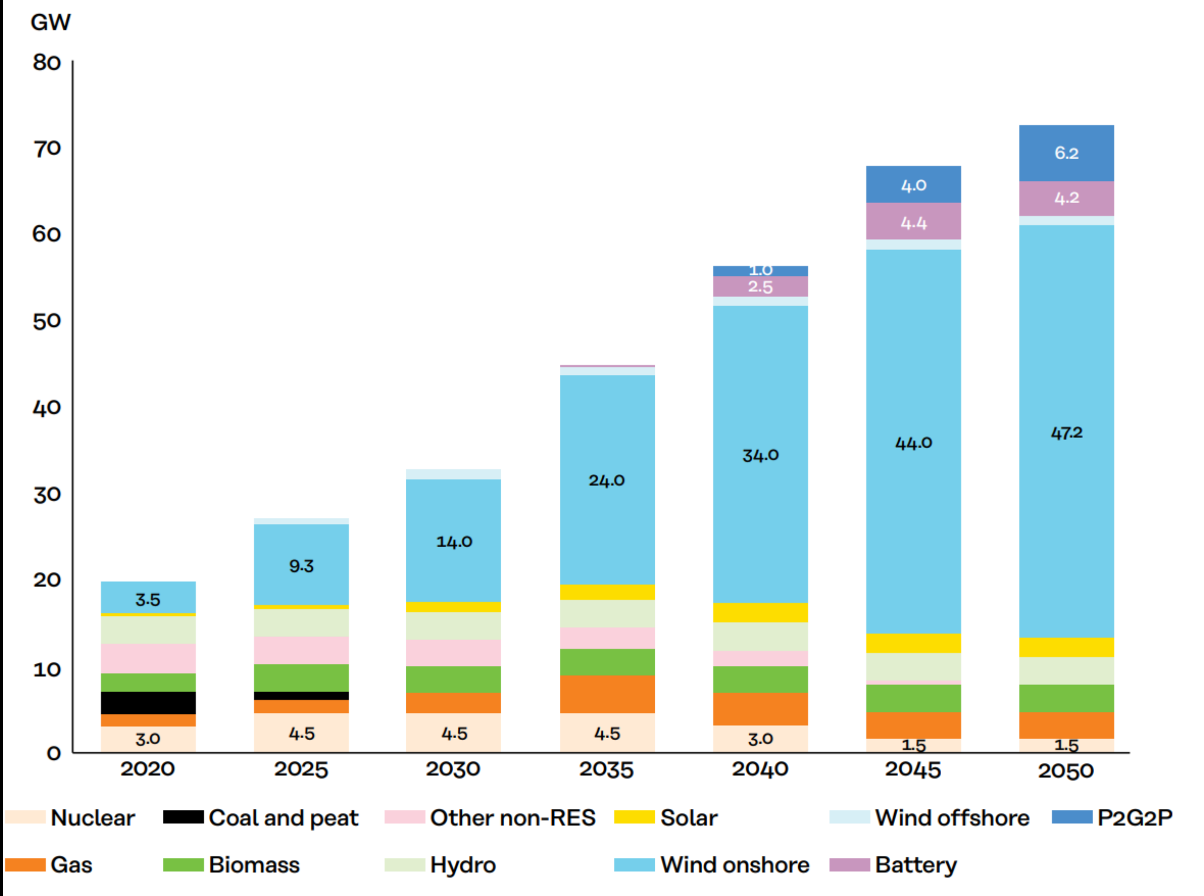


Storages come in different sizes for different use purposes.

Sterner, M., Stadler I. (Eds.). (2019). *Handbook of Energy Storage*. Springer.

WHY ENERGY STORAGES?

- Increasing share of intermittent renewable energy resources that cannot be dispatched to same extent.
- Dispatchable generation (e.g., coal, peat, natural gas) is being phased out due to climate targets and increasing cost.
- Significant demand for balancing the power system.
  - Very fast, less than one second balancing **power**
  - Fast responding daily balancing **power and energy**
  - Long term balancing **energy**



One modelling result for future electricity generation capacity in Finland in a decarbonized energy system.

Roques, F., et al. (2021). *Enabling cost-efficient electrification in Finland*. Sitra.

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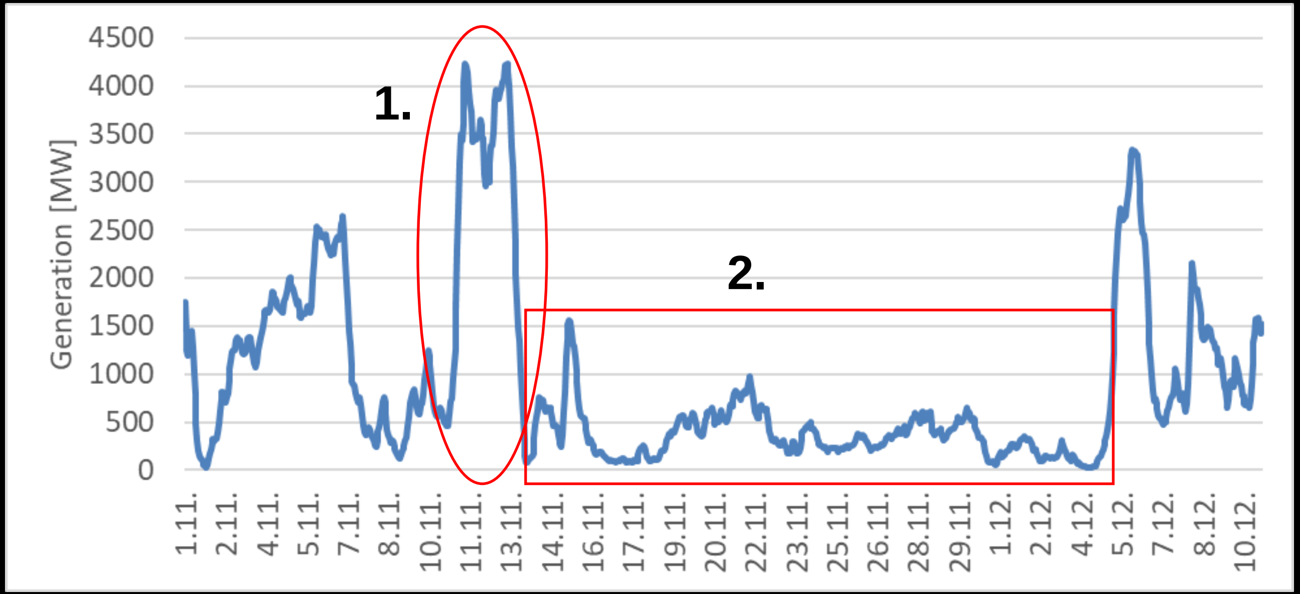
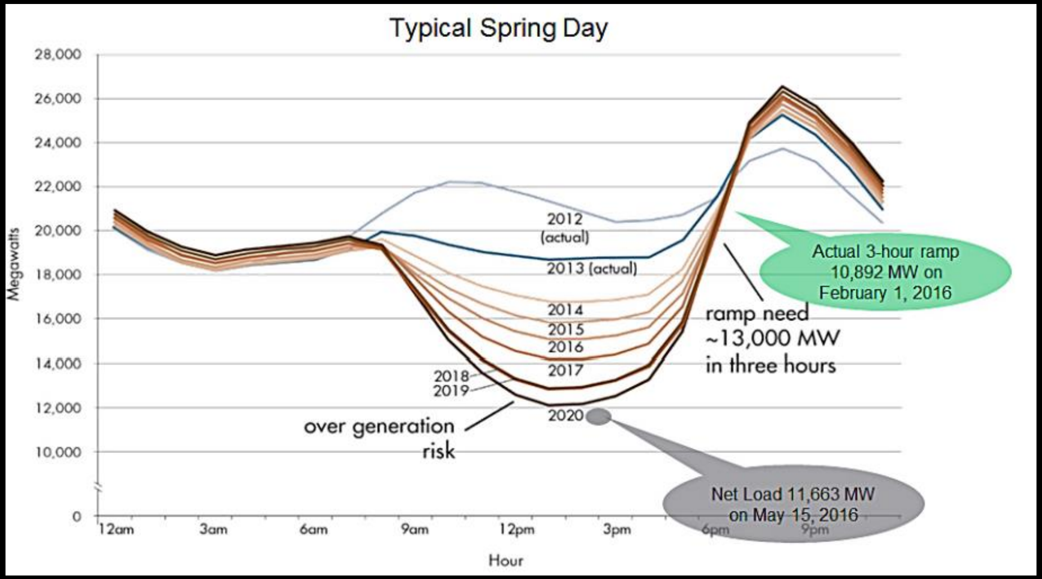
ENERGY STORAGE APPLICATIONS IN SMART GRIDS

NON-DISPATCHABLE VARIABLE RENEWABLE GENERATION





- Wind power profile in Finland, 2022
- Large power shifts in short period
- Nearly three weeks with very little generation
  - Demand for longer duration storage or alternative generation

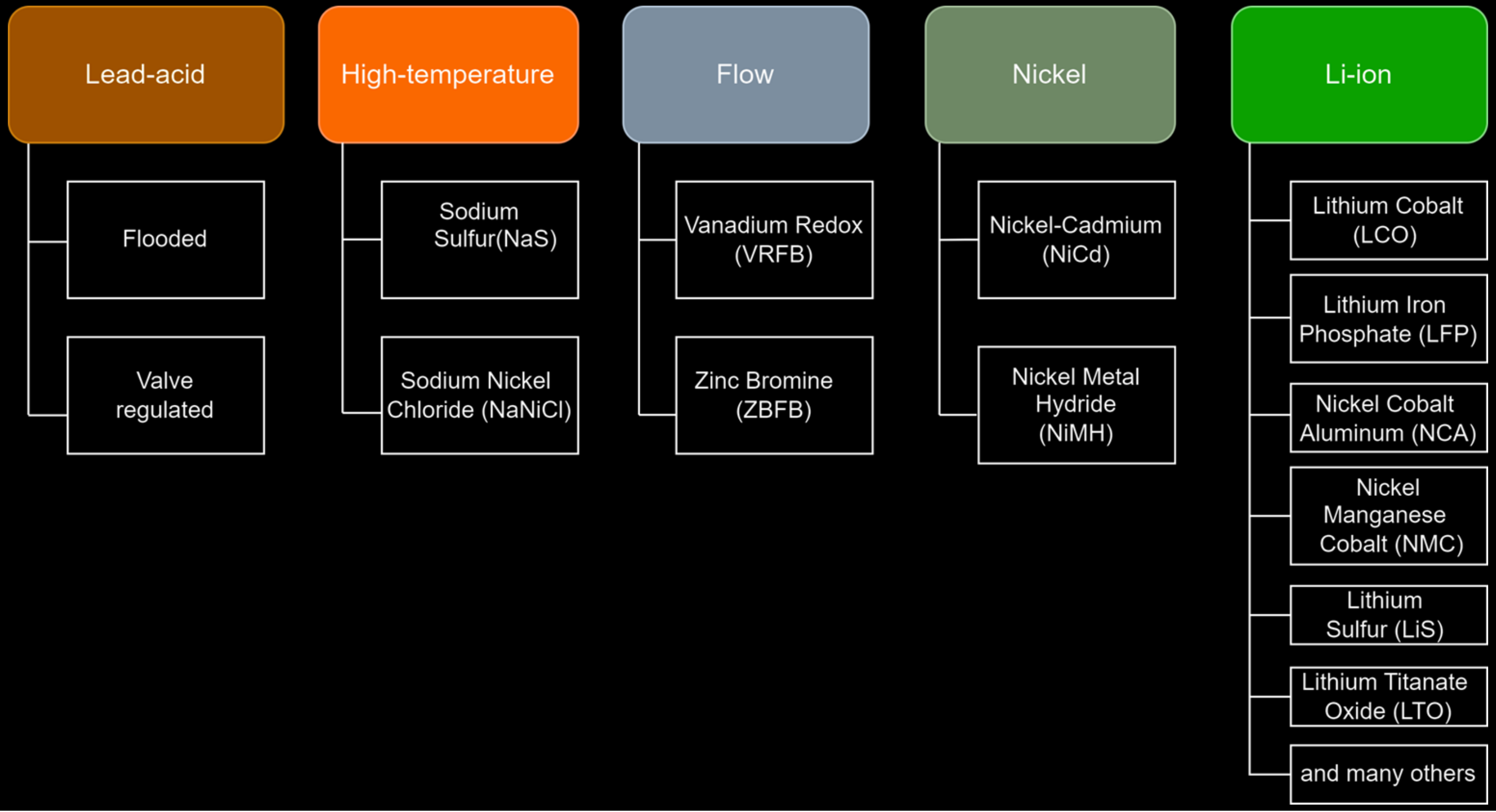
Source: Finnish Energy. (2022). Hourly Values of Electricity Production.

- PV generation during the day reduces the need for (fossil) power plants but causes significant demand for ramping the generation in short period after the sunset.

Source: California ISO. (2016). What the duck curve tells us about managing a green grid.

ELECTROCHEMICAL STORAGE

BATTERIES (ELECTROCHEMICAL)



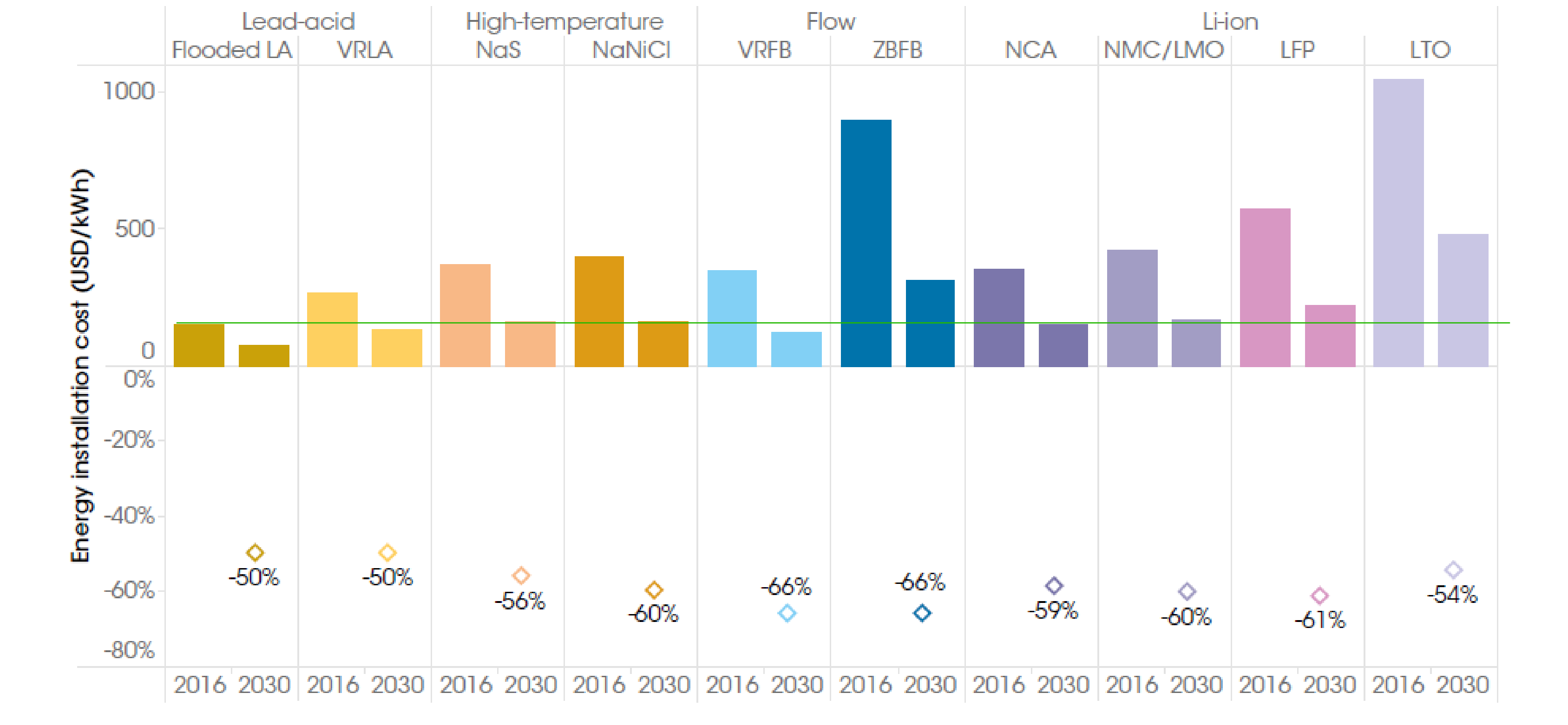
- Different technologies, with multiple different chemistries.

BATTERIES

- Short term storage (hours) – Prominent storage technology for the daily balancing.
- Each technology has its advantages and disadvantages
  - Cost
  - Energy and power density (kWh/m3, kW/m3, kWh/kg, kW/kg)
  - Cell voltage
  - Cycle and calendar life
  - Response time
  - Safety
  - Self-discharge
  - Efficiency
  - Environmental impact

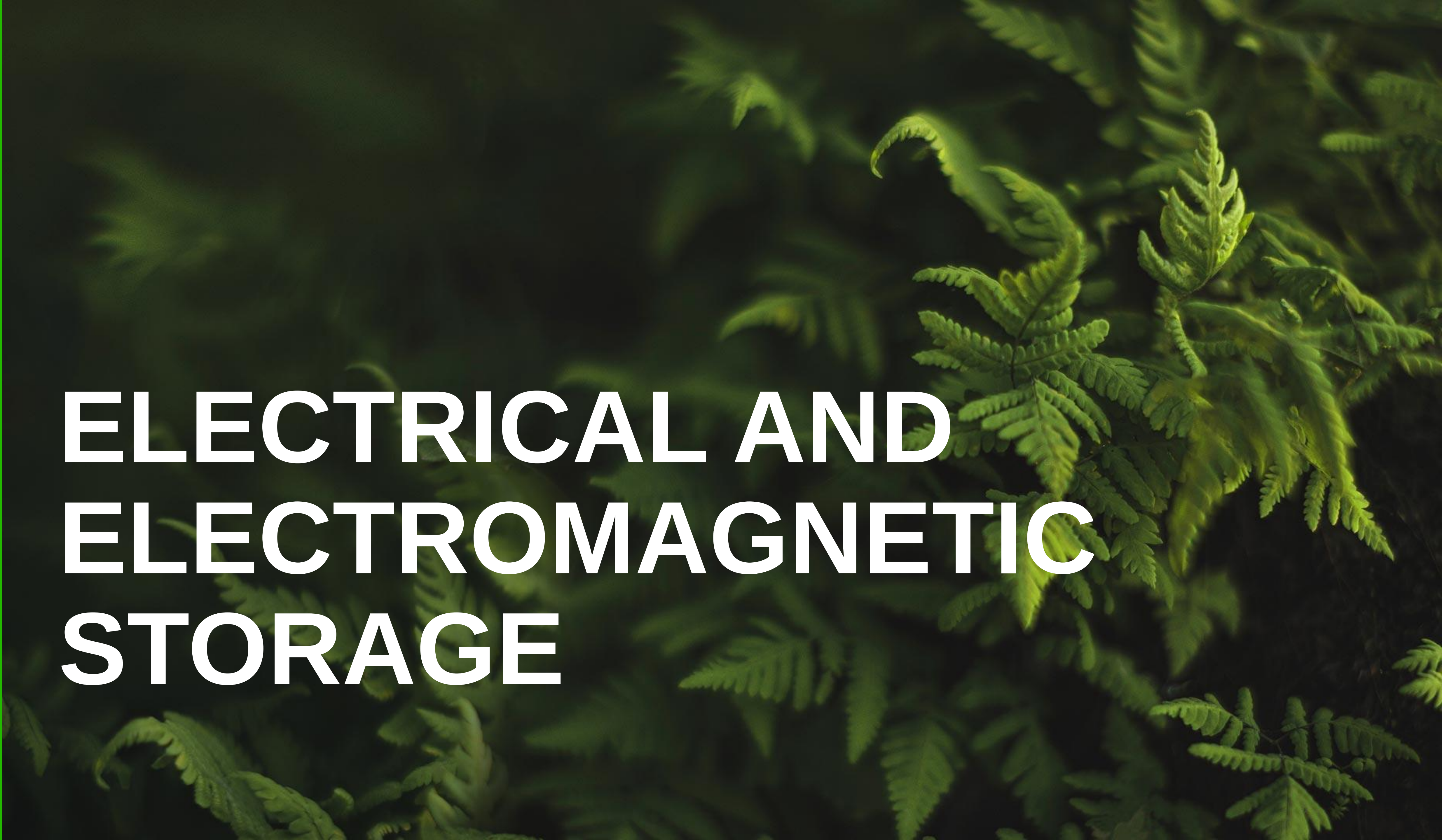
BATTERIES

- Cost trend for battery technologies.
- The 2030 values are already outdated, as the industry is moving forward with extreme pace.
- The trend is still similar, and the constant reduction in the battery cost is expected to continue to the near future.



Energy installation cost estimates for battery technologies.

Source: IRENA. (2017). Electricity storage and renewables: costs and markets to 2030.



ELECTRICAL AND ELECTROMAGNETIC STORAGE

ELECTRICAL AND ELECTROMAGNETIC

- Supercapacitors
- Coils (SMES, superconducting magnetic energy storage)
- As a grid connected storage
  - Very low energy capacity
  - Very high power output
  - Very fast charge and discharge
- More of a ”power storage” than an energy storage

MECHANICAL STORAGE

PUMPED HYDRO STORAGE (PHS)

- PHS is currently the most used electricity storage technology in the world.
- Benefits
  - Very large energy and power capacities
  - Has grid connected generators – Inertia for the power system
- Drawbacks
  - Limited by geography
  - Relatively slow to react (tens of seconds to minutes, compared e.g., to most batteries)
  - Costs are completely dependent on the specific project
  - Has some environmental challenges (reservoirs and dams)
- Research into possibilities of utilizing old mines, wells in farms or creating artificial reservoirs.

OTHER MECHANICAL STORAGES

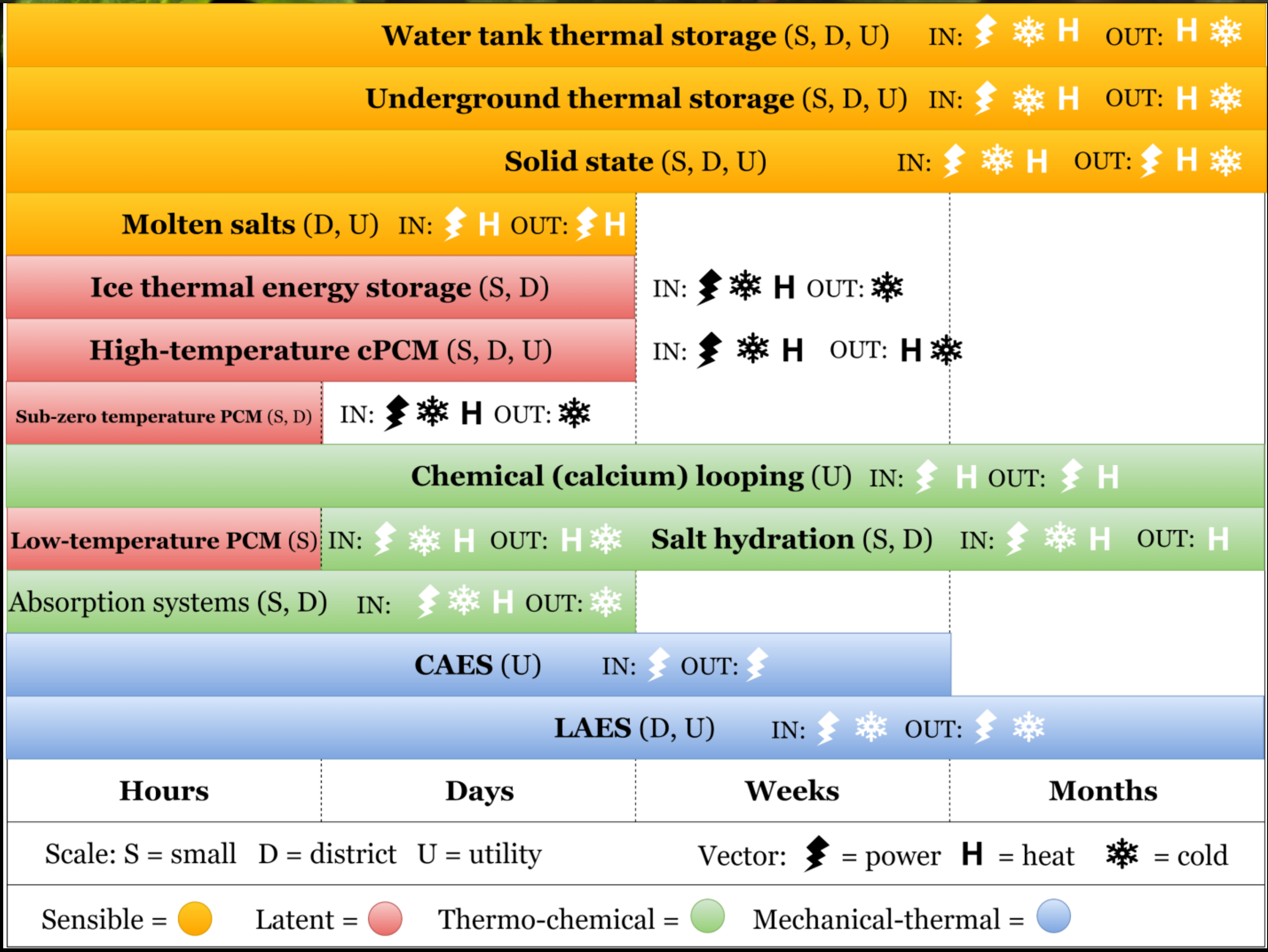
- Compressed Air Energy Storage (CAES)
  - Potentially very large energy and power capacities
  - Seasonal storage
  - Costs very dependent on the storage method (tank or natural cavern)
- Liquid Air Energy Storage (LAES)
  - Similar to CAES
- Flywheel
  - High power output very fast
- Gravity Energy Storages
  - Experimental technology, offering potential for long term storage

THERMAL ENERGY STORAGE

ENERGY STORAGE APPLICATIONS IN SMART GRIDS

THERMAL ENERGY STORAGE

- Both short- and long-term storage
- Sensible
  - Buildings
  - Hot water tanks
  - Sand, rocks, other granule material
- Latent
  - Phase change material (PCM)
- Thermo-chemical
  - Chemical looping
- Mechanical-thermal
  - Adiabatic compressed air energy storage (ACAES)
- Like batteries, each technology has its advantages and disadvantages (energy density etc.)



Different thermal storage solutions, storage duration, inputs, and outputs.
Source: Jaanto J., et al. (2023). *Thermal storage deployment in the framework of current electricity market design*. 19th International conference on the European energy market.

ENERGY STORAGE APPLICATIONS IN SMART GRIDS

THERMAL ENERGY STORAGE

- Thermal energy storages (TES) have often been identified as one of the least-cost solutions for storing energy.
- **Sector coupling** between power, heat, and cooling sectors to efficiently integrate renewable energy.
- Key enabler in decarbonizing heat demand.
- Heat sources
  - Power and heat plants
  - Direct electrical heating
  - Solar thermal
  - Heat pumps
    - Waste process heat
    - Data centers
- Thermal energy released to
  - District heating network
  - Directly to building
  - Hot use water
  - Industrial processes
  - Cold storages
- Possibility to also generate electricity (e.g., organic Rankine cycle (ORC))

CHEMICAL STORAGE

POWER-TO-X (PtX/P2X)

- Power-to-Hydrogen (electrolyzers)
- Power-to-gas, Power-to-electrofuels (Hydrogen combined to CO2)
  - Methane
  - Ammonia
  - Methanol
  - Kerosene, Naphtha
  - Nearly any hydrocarbon
- Can be stored in liquid or gaseous form into tanks and caverns.
- Mainly utilized on larger scale for seasonal energy storage, as well as for creating fuels for maritime transport and aviation.
- Very low overall efficiency when compared to direct electricity use (e.g., EVs, heat pumps).

SERVICES FROM STORAGE

ENERGY STORAGE APPLICATIONS IN SMART GRIDS

SERVICES FROM ELECTRICITY STORAGES

Bulk energy services	Ancillary services	Transmission infrastructure services	Distribution infrastructure services	Customer energy management services	Off-grid	Transport sector
Electric energy time shift (arbitrage)	Regulation	Transmission upgrade deferral	Distribution upgrade deferral	Power quality	Solar home systems	Electric 2/3 wheelers, buses, cars and commercial vehicles
Electric supply capacity	Spinning, non-spinning and supplemental reserves	Transmission congestion relief	Voltage support	Power rellability	Mini-grids: System stability services	
	Voltage support			Retail electric energy time shift	Mini-grids: Facilitating high share of VRE	
	Black start			Demand charge management		
				Increased self-consumption of solar PV		

Boxes in red: Energy storage services directly supporting the integration of variable renewable energy

Source: IRENA. (2017). Electricity storage and renewables: costs and markets to 2030.

SERVICES FROM THERMAL STORAGES

- Strong potential for **sector coupling** by utilizing electricity for the heating (power-to-heat, PtH)

Seasonal storage

Application: Storing energy for longer periods

Value: Help to address seasonal variability (e.g., summer-winter) in demand and supply

Variable supply integration

Application: Power balancing services in a timescale from minutes to hours, thermal demand shifting across hours, capacity firming, reduce VRE curtailment

Value: Reduce balancing costs, increase flexibility, reduced need for ramp-up in fossil fuel-based peaking plants, improved utilization of RES

Sector integration

Application: Power generation linked to other sectors' demand, e.g., excess power converted to heat, optimal dimensioning of the heating system

Value: Increase flexibility, reduce curtailment, improve renewable energy utilization, increased system efficiency, reduce need for fossil fuel and biomass

Network management

Application: Heating and cooling load shifting, frequency management

Value: Avoid grid reinforcement, increase flexibility, grid stability

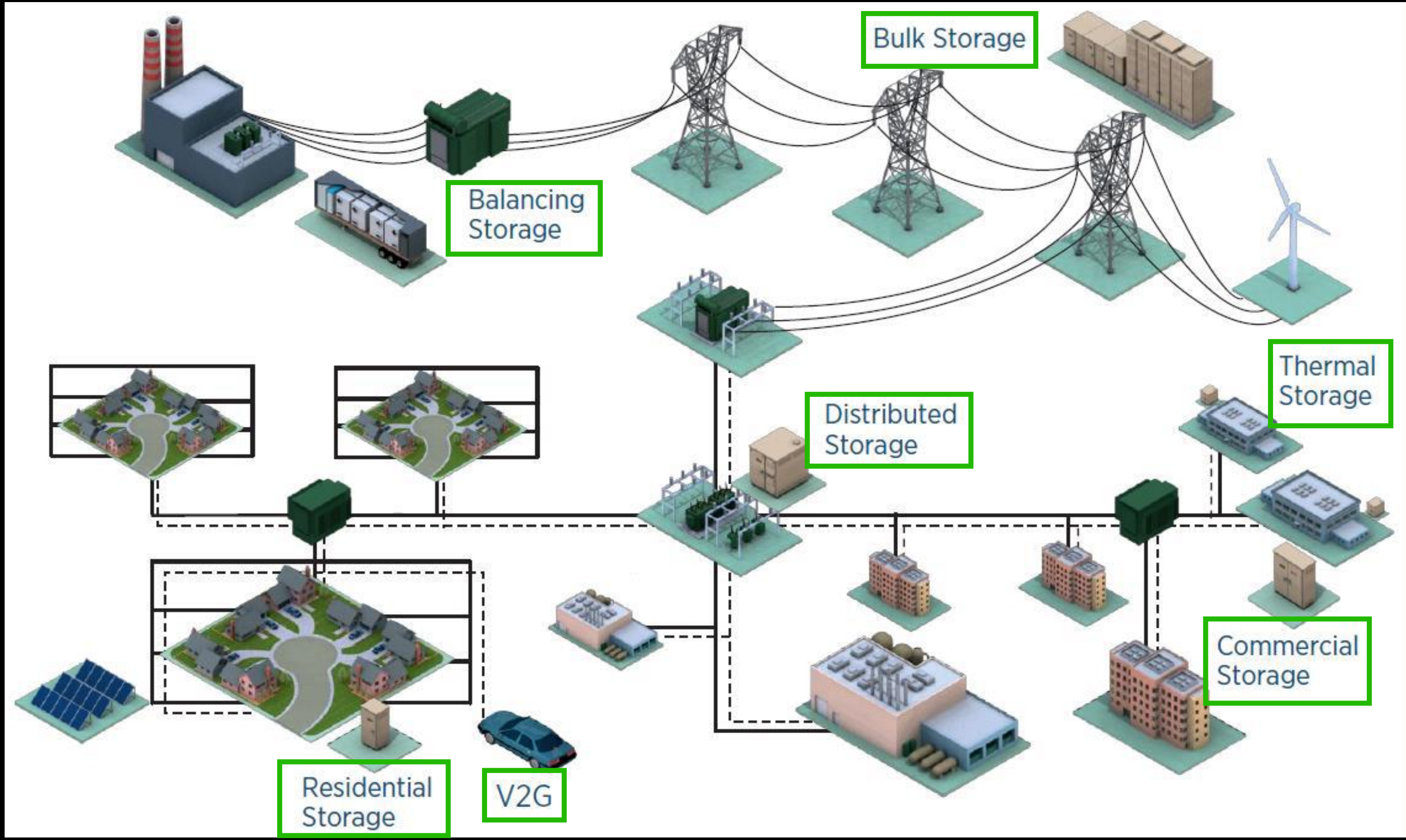
Demand shifting

Application: Peak shaving, demand response, increase of self-production and consumption rates, end-consumer arbitrage

Source: Jaanto, J., et al. (2023). *Thermal storage deployment in the framework of current electricity market design*. 19th International conference on the European energy market.

SMART GRID APPLICATIONS

STORAGES IN SMART GRID



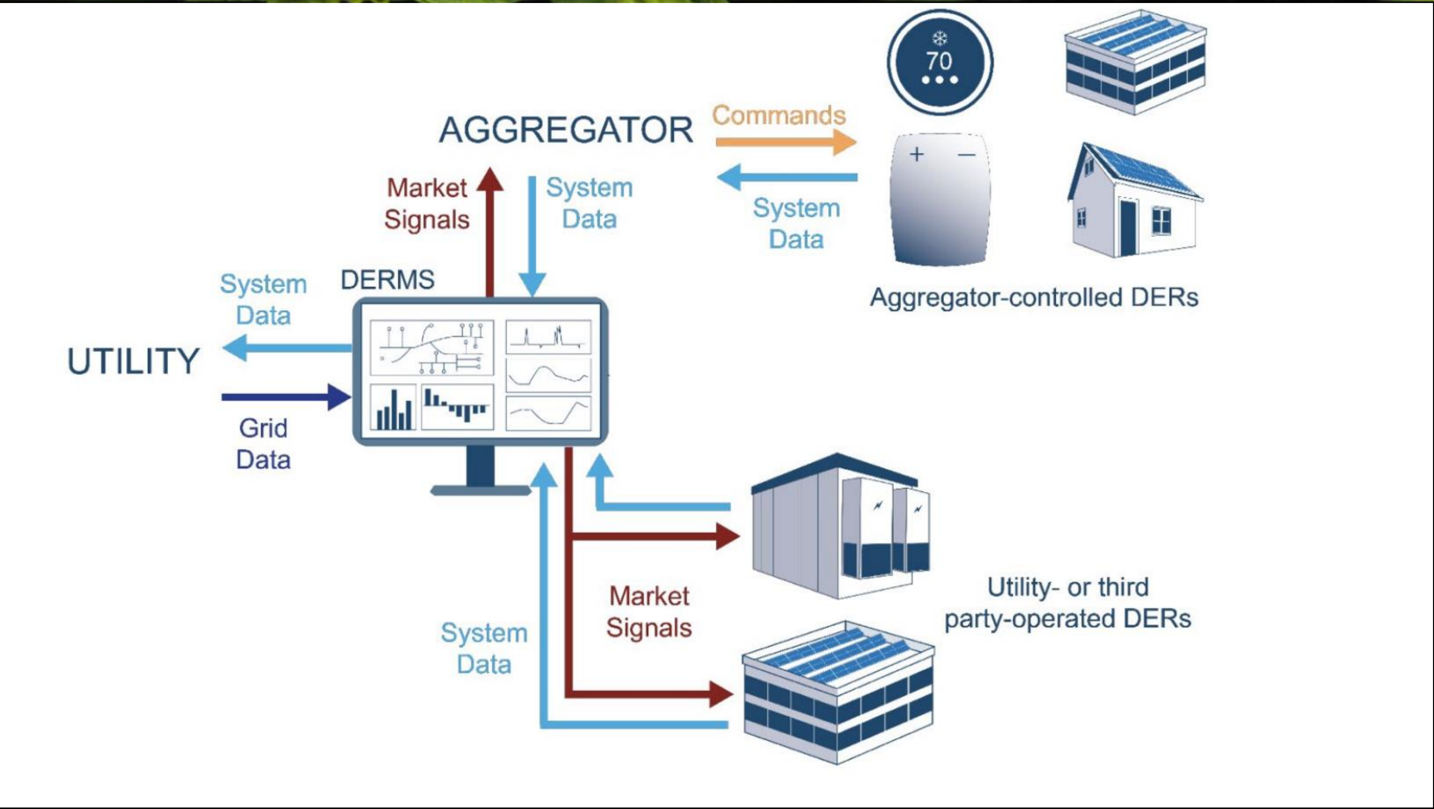
Source: IRENA. (2017). *Electricity storage and renewables: costs and markets to 2030*.

USE CASES – SMART GRIDS

- Wide range applications in different parts of the smart grid.
- Enables efficient, secure, and reliable (smart) grid with greater integration of renewable generation.
  - Balancing the entire power system
  - Support transmission and distribution networks
  - Energy efficiency and economic benefits for customers

COMMUNICATION

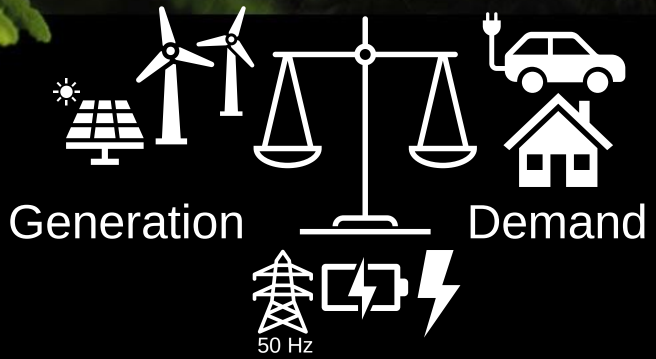
- Key part of smart grid is being able to control the resources.
- Need for accurate and fast measurement and communication.
- Making the storages also smarter, enabling
  - Remote monitoring
  - Management of the storage
  - Trading of energy and the storage as a resource
  - Aggregation of the storage



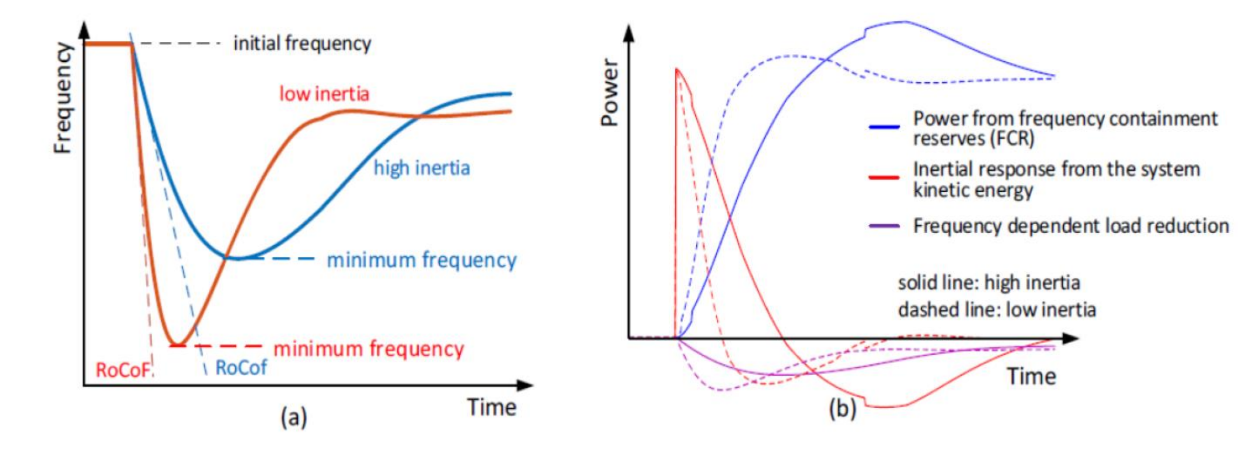
Measurement, communication, and data as part of the smart grid.
Source: U.S. Department of Energy (DOE). (2022). *2020 Smart Grid System Report.*

- For instance, separate controller systems or part of the home automation.

POWER SYSTEM



- Power system must be constantly in **balance**.
- Storages offer crucial support for the power system stability.
- Need for measurements, such as rate of change of **frequency** (RoCoF).
- Electricity market in a key position for acquiring needed balancing capacity.
- New reserve market products appearing. Fast frequency response (FFR) market already launched, especially for low inertia situations.



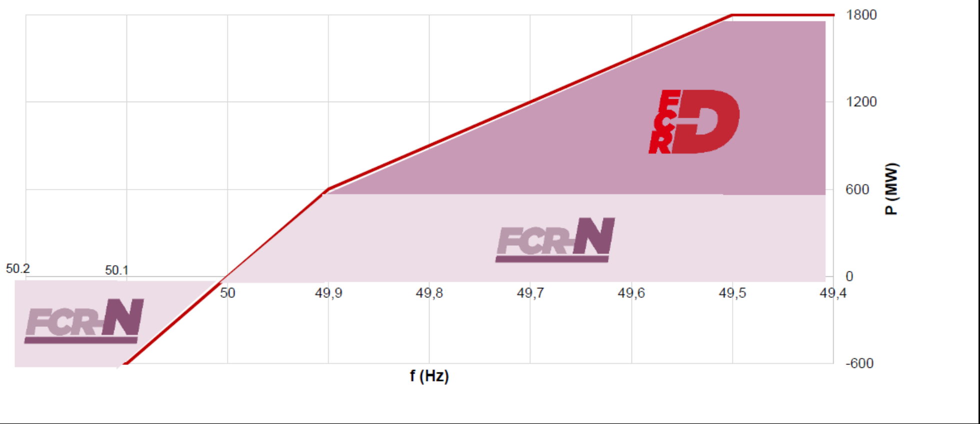
How level of inertia affects change on frequency during a larger fault (a) and timescale of different frequency response methods during frequency disturbance (b).

Source: ENTSO-E. (2019), Fast Frequency Reserve–Solution to the Nordic inertia challenge.

ENERGY STORAGE APPLICATIONS IN SMART GRIDS

RESERVE MARKET PRODUCTS IN FINLAND
(AS A REMINDER)

	FFR	FCR-D	FCR-N	aFRR	mFRR
	Fast Frequency reserve, Finland 20 %, In Nordics, total 0-300 MW (estimate)	**Frequency Containment Reserve for Disturbances,** Finland 290 MW, Nordics total 1450 MW	**Frequency Containment Reserve for Normal Operation,** Finland 120 MW, Nordics total 600 MW	**Automatic Frequency Restoration Reserve,** Finland 60-80 MW, Nordics total 300-400 MW	**Manual Frequency Restoration Reserve** Reference incident + imbalances of balance responsible parties
Activated	In big frequency deviations, In low inertia situations	In big frequency deviations	Used all the time	Used in certain hours	Activated if necessary
Activation speed	In a second	In seconds	In a couple of minutes	In five minutes	In fifteen minutes

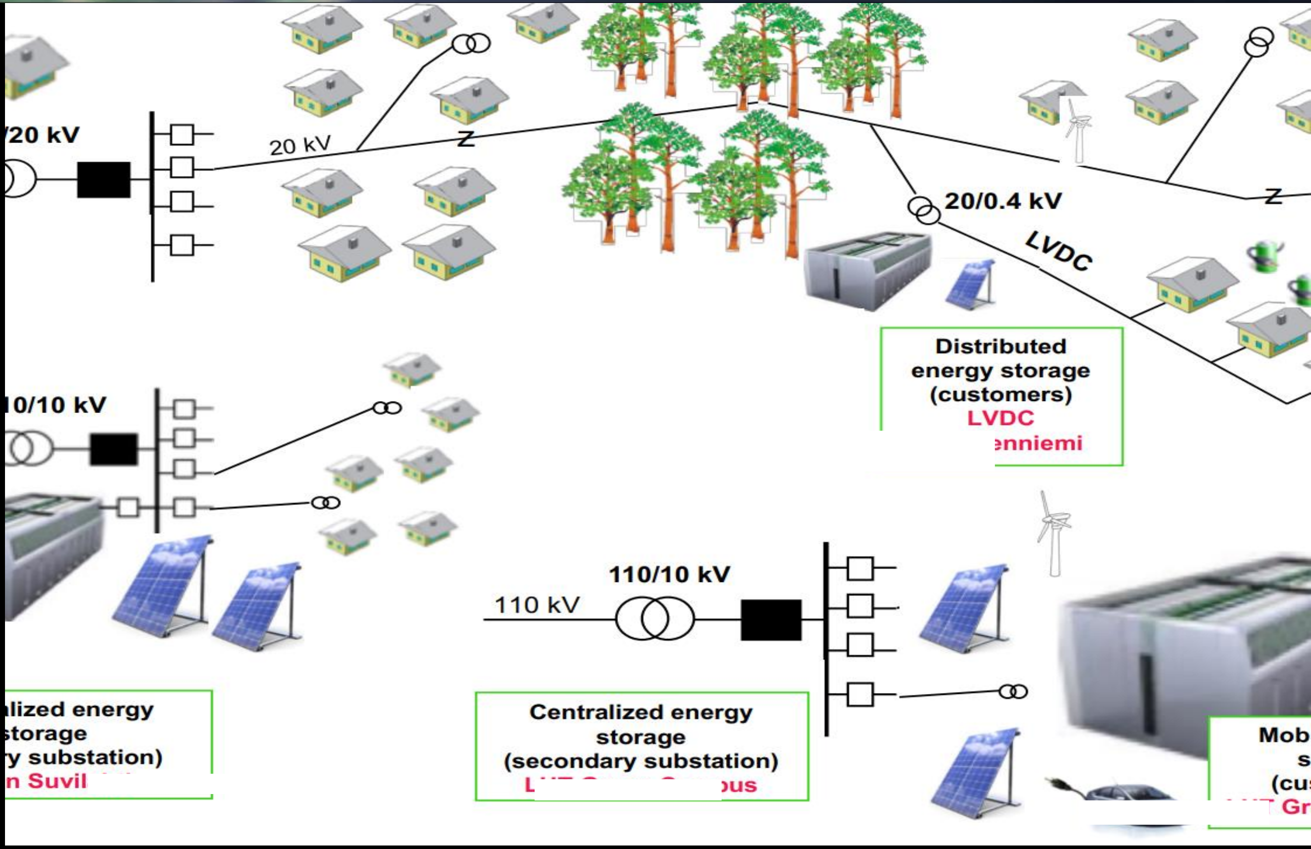


Source: Fingrid

ENERGY STORAGE APPLICATIONS IN SMART GRIDS

DISTRIBUTION SYSTEM

- Can be located by the substation (centralized) or near the customer (decentralized, distributed).
- Storages offer
  - Peak load management, reduces capacity constraints, and deferral for grid upgrades
  - Reduce the peak load of PV on distribution network
  - Reliability of the network – Protect customers from disturbances
  - Voltage control – Important because of new loads (EV) and generation (PV) in the customer’s end



Source: Tikka, V., et al. (2018). *Final report: Multi-objective role of battery energy storages in an energy system*. LUTPub.

TRANSMISSION SYSTEM

- Large storages by the substation or aggregated from distributed storages.
- Load management of the transmission lines
  - For both demand (e.g., large PtX-industry) and generation (large concentrations of wind power)
  - Relieve transmission capacity constraints, potentially reducing need for new lines
- Voltage control
  - For the transmission lines in specific areas
  - For the large customers to manage their reactive power (industry or wind park)
- Overall improve stability of the transmission system.

GENERATION (POWER AND HEAT)

- Energy balancing of electricity producers – When producer has not managed to match their forecasted production.
- Thermal and electricity storages can enable more flexible operation of combined heat and power (CHP) plants by decoupling heat and power demands.
- Thermal storages with PtH can enable better utilization of low-cost hours of electricity for (district) heating.

HOME STORAGE

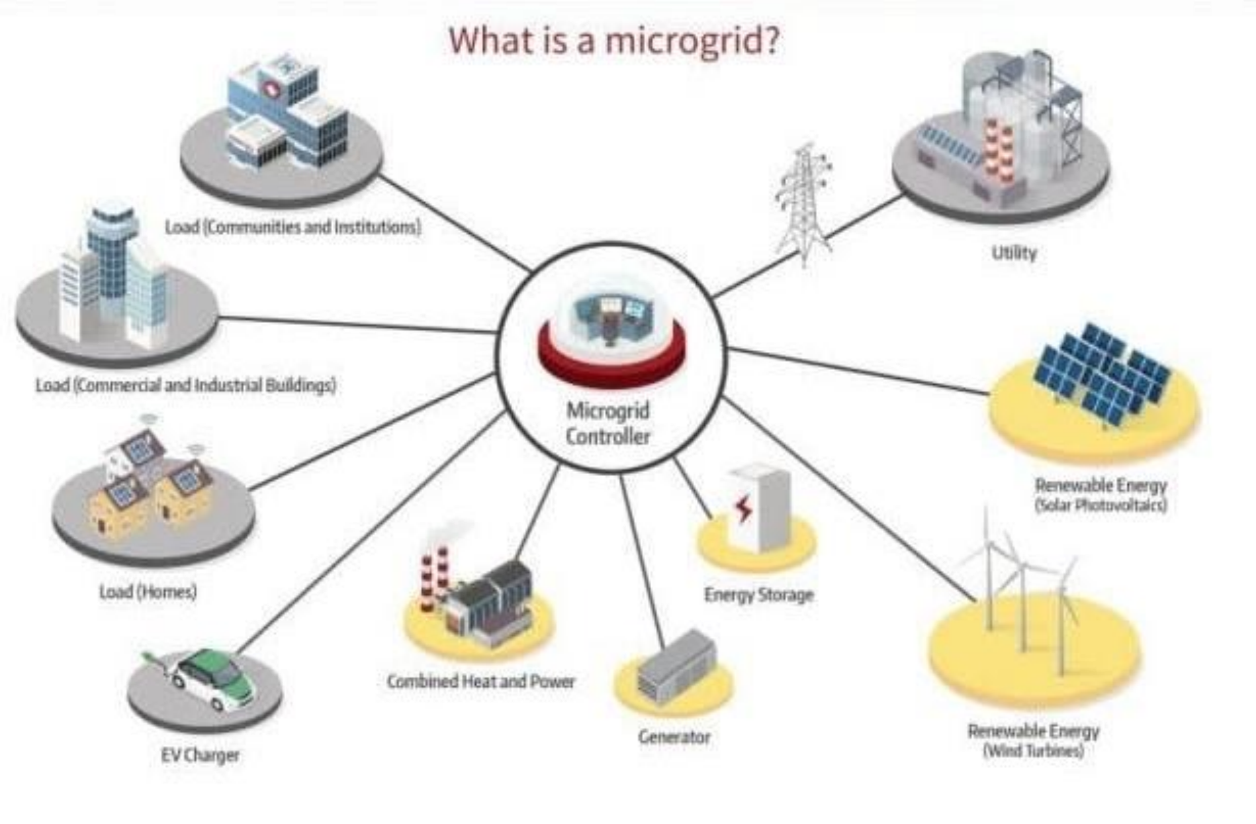
”Prosumager”, a consumer who has own generation and storage – Sioshansi (2020)

- Typically “behind the meter” (BTM) batteries and thermal storages (e.g., hot water tank, building).
- For instance, as part of home energy management system (HEMS).
- Battery electric vehicles (BEVs) have significant potential to contribute to the overall storage capacity (vehicle-to-grid (V2G), vehicle-to-building (V2B), vehicle-to-load (V2L)).
- Provides
  - Improved PV self-consumption
  - Reliability of delivery (uninterrupted power)
  - Energy arbitrage (save on energy cost)
  - Peak load management (tariff structures)
  - Reserve markets for extra income (aggregation)

ENERGY STORAGE APPLICATIONS IN SMART GRIDS

MICROGRIDS

- Combining generation, storage, measurements, and communications of assets in the same area.
- From one building to an **energy community** of multiple buildings.
- Capability to island operation in on-grid or off-grid setting. Typically, energy storage has to be in microgrid, to promote islanding capability.
- Low-voltage direct current (LVDC) network possible.



Source: Wood, E. (2023). *What is a microgrid?* Microgrid knowledge.

- Difference to the smart grid concept being, that the assets are not necessarily connected to the public network, but only to each other, and are in a close distance from each other.

CHALLENGES, ENABLERS, FUTURE SOLUTIONS

CHALLENGES

- Investment – Who and why?
  - Power-to-gas (or other e-fuel) will more than likely be required to offer seasonal, long-term storage, but related costs are still very high
  - Cost of batteries has decreased already, but still unprofitable in most cases
  - Profitable business models necessary for wider adaptation (average consumers, utilities, and industry)
  - Need for new markets to compensate for the offered flexibility services, e.g., inertia undervalued
- Changing and partly unstable regulation can prevent larger investments, especially to piloting plants.
- Different stakeholders might have conflicting interests (e.g., storage owner or network operator).
- Environmental and sustainability challenges with different technologies, as well as general raw material sufficiency.

ENABLERS

- Cost of storages, mainly batteries, is forecasted to decrease even further to the future.
- Properly valuating the flexibility offered by the storages.
- Offering multiple services from same storage (e.g., energy arbitrage and FCR, “value stacking”) to improve profitability.
- Making the storages more approachable for average customer, e.g., automation.
- Regulation must be predictable and stable (not to change every 4 years).
  - Regulation is evolving — For instance, Finland removed double taxation of batteries in 2018

NOVEL APPLICATIONS

- Virtual power plant (VPP)
  - A way to aggregate distributed energy resources (DER) together for bigger flexibility capacity and for larger markets
  - Digitally connected and operated like a regular power plant on the electricity market
  - Very dependent on data management and communication
- Peer-to-Peer (P2P) trading
  - Enabling trading of self-generated and/or stored energy between other consumers/prosumers/prosumagers
  - Transactions via distributed ledgers (blockchains)
  - Own regulatory and technical challenges (e.g., impact on network)

Project partners:

ENERGY STORAGE APPLICATIONS IN SMART GRIDS

RESEARCH AT LUT — NEWSETS

- NewSETS — New Energy Storages Promoting Sustainable Energy Transition in Societies
- In the project we study…
  - impacts of the storages on the energy system
  - different business models for the storages
  - scalability and replicability
  - impacts of increased energy system storability form viewpoint of different stakeholders
- Target is to provide
  - Market and regulatory suggestions to enhance energy storage integration
- Based on feasibility studies, demonstration, and replicability analyses
- Åland acts as a case study area for the research project

RESEARCH AT LUT — NEWSETS

- Studied technologies
  - Pumped hydro storage in an old mine
    - Helps alleviate the geographical limitations
    - Improves use of existing infrastructure
  - High Temperature Thermal Energy Storage (HTTES, combines PtH and TES)
    - Allows flexibility for both power and heat sectors
    - Decouples the heating from electricity price variations to a certain degree
      - Enables to utilize low-cost hours for heating, further promoting renewable energy integration by reducing wind curtailment
      - Allows to avoid high peak prices
    - Reduces need for biomass
- In future energy systems, there is need for multiple different storage solutions

RESEARCH AT LUT — NEWSETS

- Future tasks in the project
  - Replicability study on role of energy storages in an energy transition pathway for India, focusing on pumped hydro storage
  - Scientific publications on topics of
    - Combined utilization of electricity and thermal storages in a highly renewable energy system within an island society
    - Comparison of energy system modelling tools for a highly renewable energy systems and energy storages
    - Thermal storage deployment in the framework of current electricity market design
    - Role of power-to-heat and thermal storage in decarbonizing the Nordic district heating
    - Potential of pumped hydro storage in India (studying also business cases and possible regulatory challenges)
    - Study on thermal storages in reserve markets

- This project has received funding in the framework of the joint programming initiative ERA-Net Smart Energy Systems' focus initiatives Smart Grids Plus and Integrated, Regional Energy Systems, with support from the European Union's Horizon 2020 research and innovation programme under grant agreements No 646039 and 775970

SUMMARY

- Energy storages together with sector coupling offer the most cost-effective way to integrate renewable energy, and to decarbonize the entire energy system[1].
- Right type of storage for the need
  - Different time scales (daily or monthly balancing)
  - Power and energy capacities
  - Right energy carrier (**efficiency**!)
  - Examples
    - Homes: Store PV as hot use water in a water tank or as electricity for the EV
    - Industry: Store electricity for the electrolyzers or store the created hydrogen
- Profitability in a key role for investment decision.
  - Other factors can be e.g., environmental values or increasing self-sufficiency
- Flexibility offered by the storages is crucial for the energy system and should be properly valued.

[1] Sterner & Stadler. (2019). Handbook of Energy Storage.

GOOD SOURCES ON THE TOPIC

- US Department of Energy (DOE)
- National Renewable Energy Laboratory (NREL)
- International Renewable Energy Agency (IRENA)
- International Energy Agency (IEA)
- European Association for Storage of Energy (EASE)
- Sterner, M. & Stadler, I. (Eds.). (2019). *Handbook of Energy Storage*. Springer.
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QUESTIONS?


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