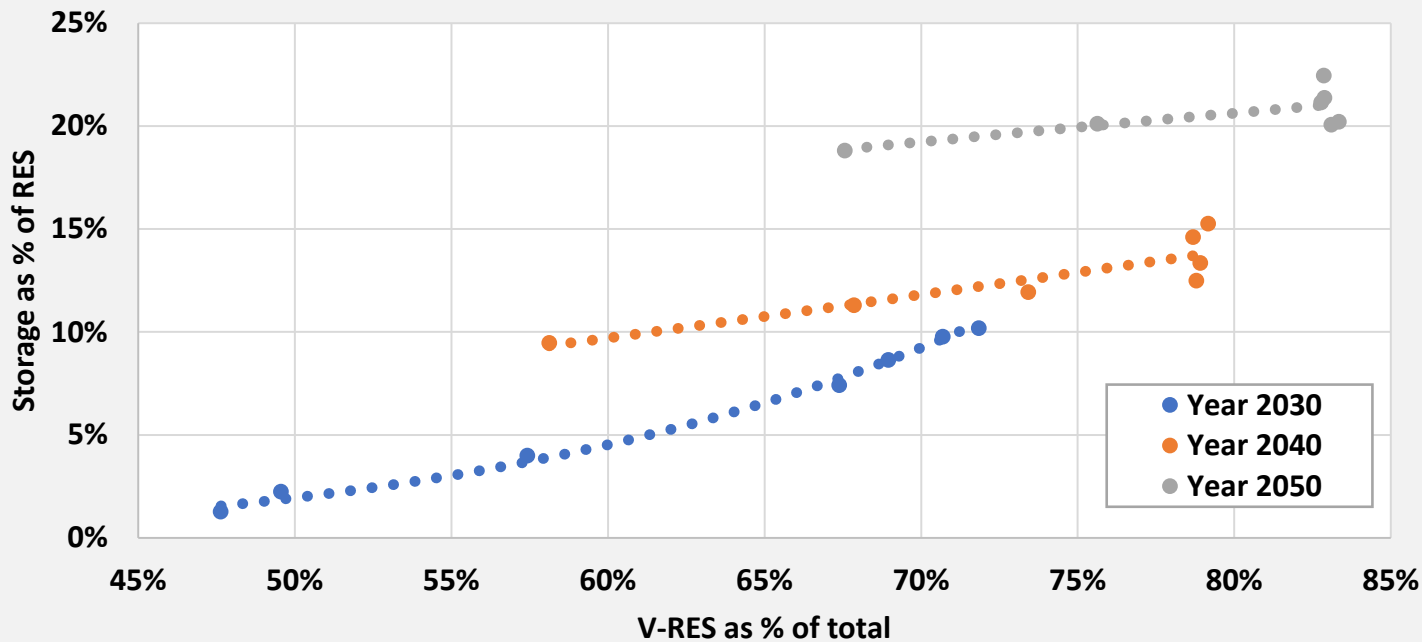
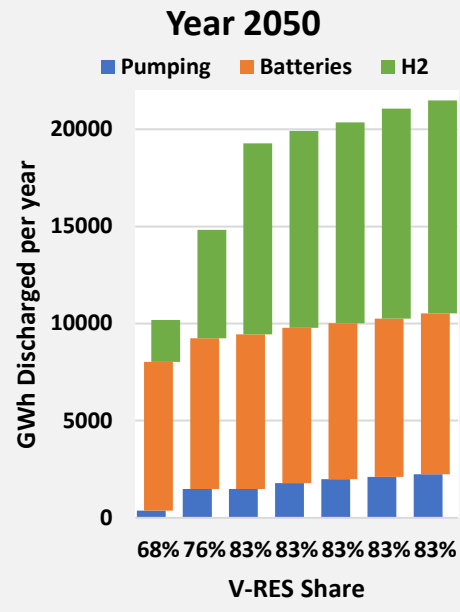
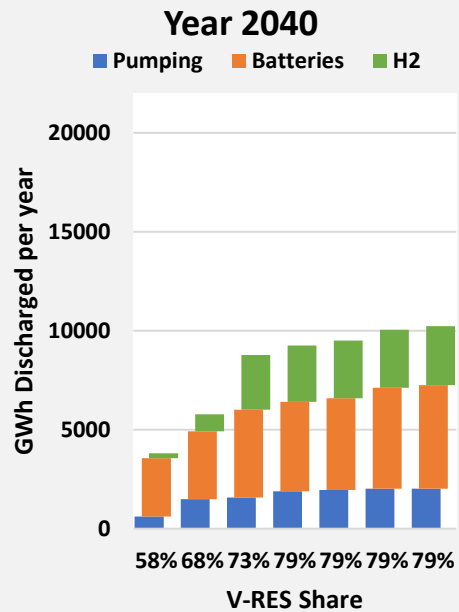
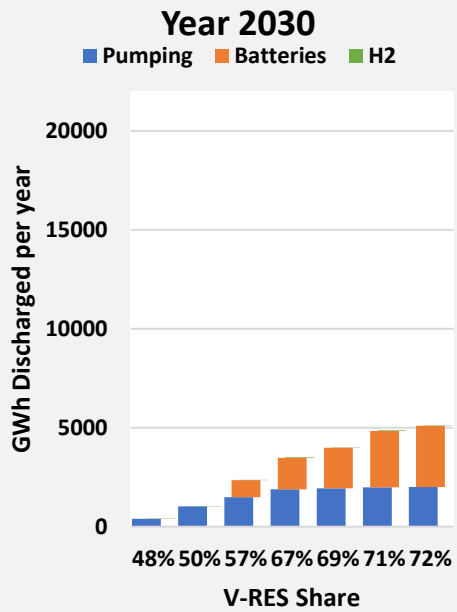


ENABLING THE RES AND STORAGE NEXUS IN THE POWER MARKET

*Prof. Pantelis CAPROS
April, 2021*





Greece: Source PRIMES model

EU: Upscaling to 55% GHG target for 2030 and carbon neutrality by 2050

Renewables above 65% of total electricity by 2030 and >85% by 2050

Natural gas plants are critical until 2030-35, but are not viable longer

First pumping, then batteries, along with decreasing technology costs

Hydrogen-based storage and e-fuels dominate in the long-term

Greece: Optimal Electricity Storage capacity
 2030: >3GW
 2040: >7 GW
 2050: >12GW

Rationale

Behind-the-meter storage is soon competitive.

System-scale batteries and pumping unlikely to be profitable based on market price arbitrage, unless covered by tariffs set after public procurement.

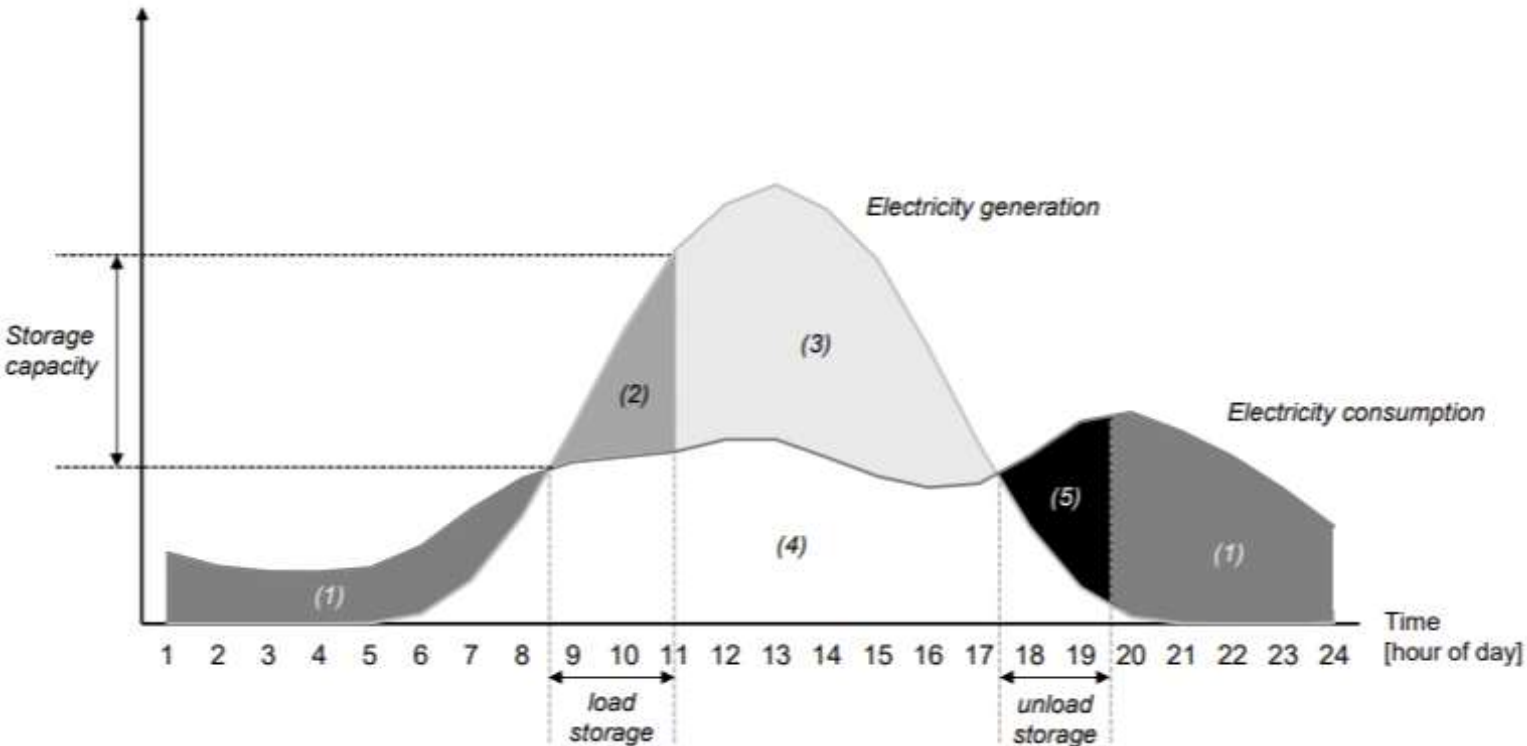
Storage-plus-Solar-PV levelized unit costs (LCOE) are already today or will soon be lower than LCOE from CCGTs. A Storage-plus-Solar-PV PPA uses LCOE as a strike price.

Storage-plus-RES PPA bundle solar PV, wind and front-of-the-meter storage – smoothing-out profiles

Storage costs can be recovered within PPAs.

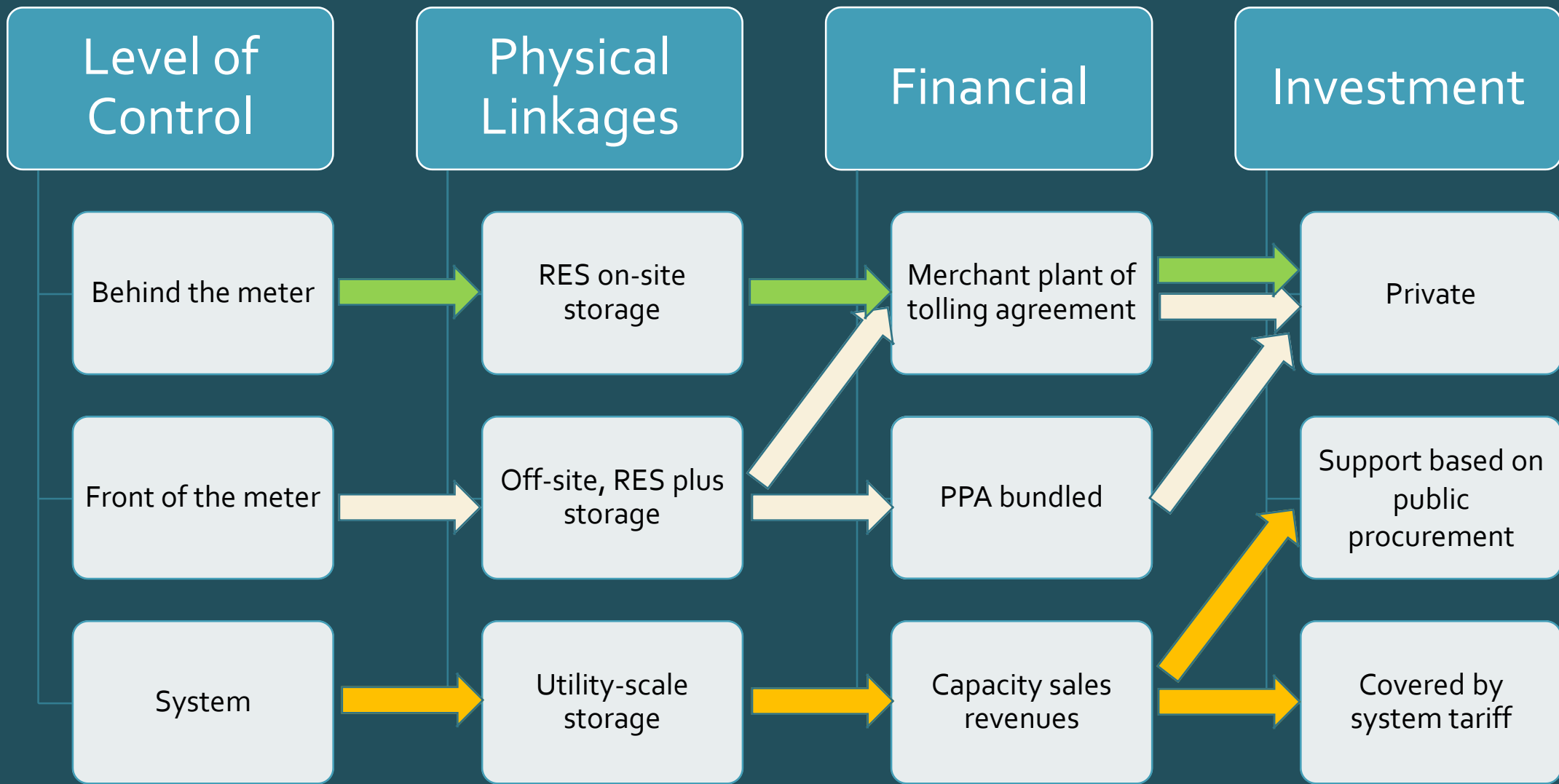
→ **Ultimate aim: define dispatchable portfolios with minimum exposure to balancing costs**

Electricity generation,
Consumption in Wh



- (1) From grid
- (2) To storage
- (3) To grid
- (4) Direct self-consumption
- (5) From storage (indirect self-consumption)

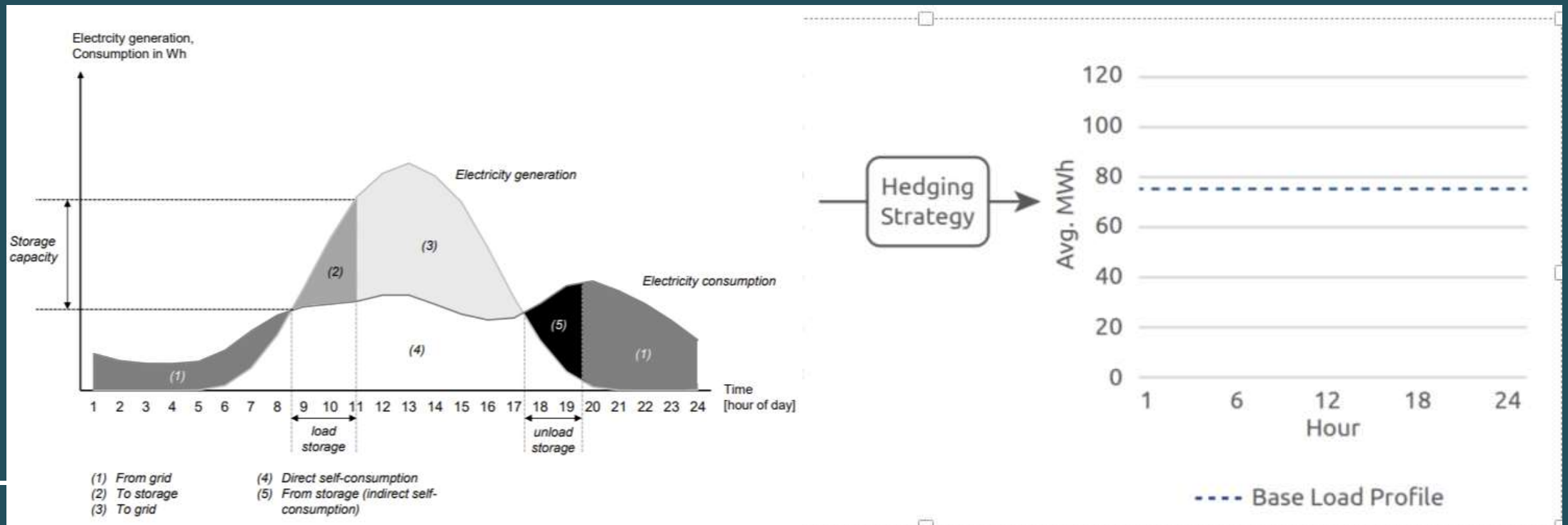
Classifications



Ultimate aim: form dispatchable portfolios – bilateral contracts with minimum exposure to balancing costs

Bilateral contract negotiation: Buyer: Competitive and non-volatile energy costs at an acceptable risk; Seller: Acceptable stream of revenues over a suitable long-term period

Bilateral contract execution: Pure financial - strike price and underlying market price, or "Physical" - nomination in the system operation, plus financial



Front-of-the-meter contracts

1. Merchant storage and capacity sales agreement

- Seller: builds, operates and sells storage products
- Buyer: optionally reserves capacity
- Fee: fixed charges

2. Tolling agreements

- Seller: builds and operates
- Buyer: off-takes and sells or uses the storage products
- Fee: Fixed and variable

3. Storage plus PPAs

- Bundled storage and RES plants
- As-available-take-or-pay contract
- Buyer: Load serving entity
- Fee: complex tariff

4. Utility service agreements

- Seller: storage owner or aggregator of storages
- Buyer: System operator
- Fees: fixed and variable

PPAs

1. On-site or physical

- Self-owned or leased
- Seller: builds and operate
- Buyer gets RES power and GOs

2. Off-site or virtual

- Physical: Bilateral contracts
- Single or multiple

3. Financial

- Hedging instrument
 - Single or multiple
 - Primary or secondary

Regulatory framework and policy

Define storage categories in the legal framework, attribute rights and obligations

Facilitate licensing and exempt storage from unjustified charges. Remove any unnecessary restriction especially for behind-the-meter and merchant storage

Provide direct support to investment in storage when bundled with RES, such as tax credits and funding facilitations

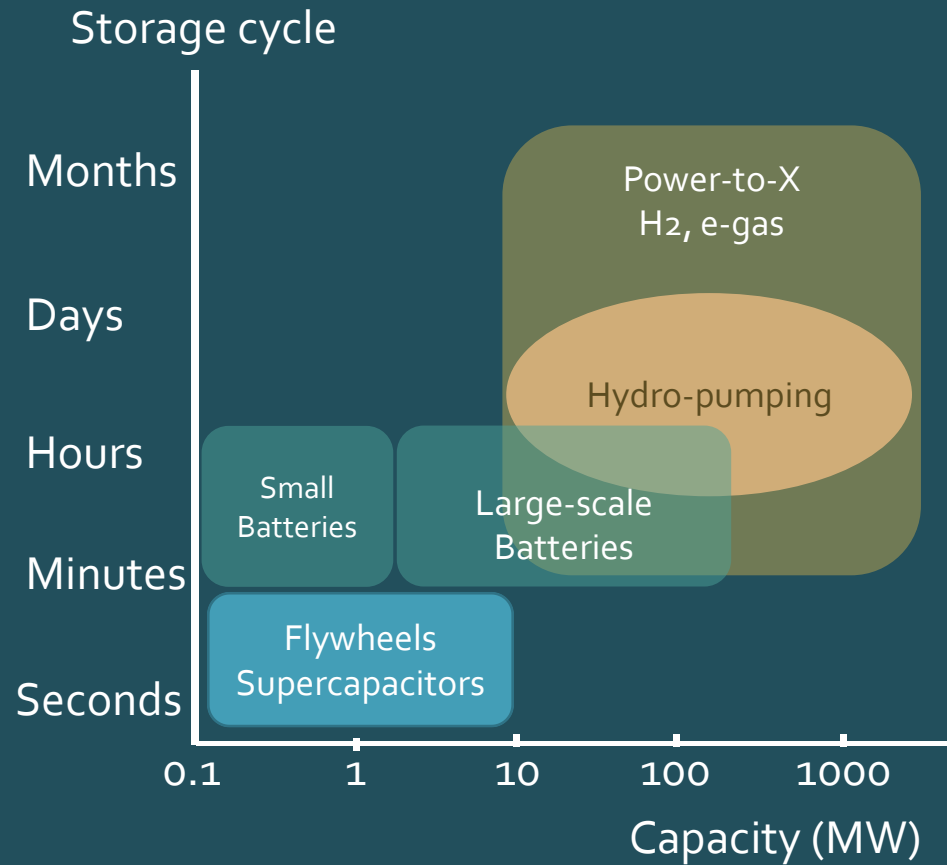
Allow system operators to invest in utility-level storage via joint ventures

Recognize and handle bundling of storage and RES plants off-site as potentially dispatchable units – virtual power plant

Extend the concept of bilateral contracts in the target model to include storage-plus-PPAs

Organize secondary trading of PPAs, storage tolling agreements and bundled storage-plus-PPAs

Electricity Storage Technologies



Indicative values	Efficiency (%)	Levelized total cost in EUR of a MWh stored			Storage cycle
		2020	2030-35	2040-50	
Compressed Air Energy Storage	80	225	192	172	Hours-Days
Flywheel	85	1127	905	511	Minutes
Large-scale batteries	95	150	10	80	Hours
Small-scale batteries	95	120	80	70	Hours
Hydro-Pumping	75-85	100	90	90	Hours
Electrolysis (cost of H ₂)	70-82	160	100	60	
Full storage cycle H ₂	52	200	110	85	All cycles
Nat. Gas balancing incl. ETS (from 25 up to 100 EUR/tCO ₂)	60	60	75	110	All cycles