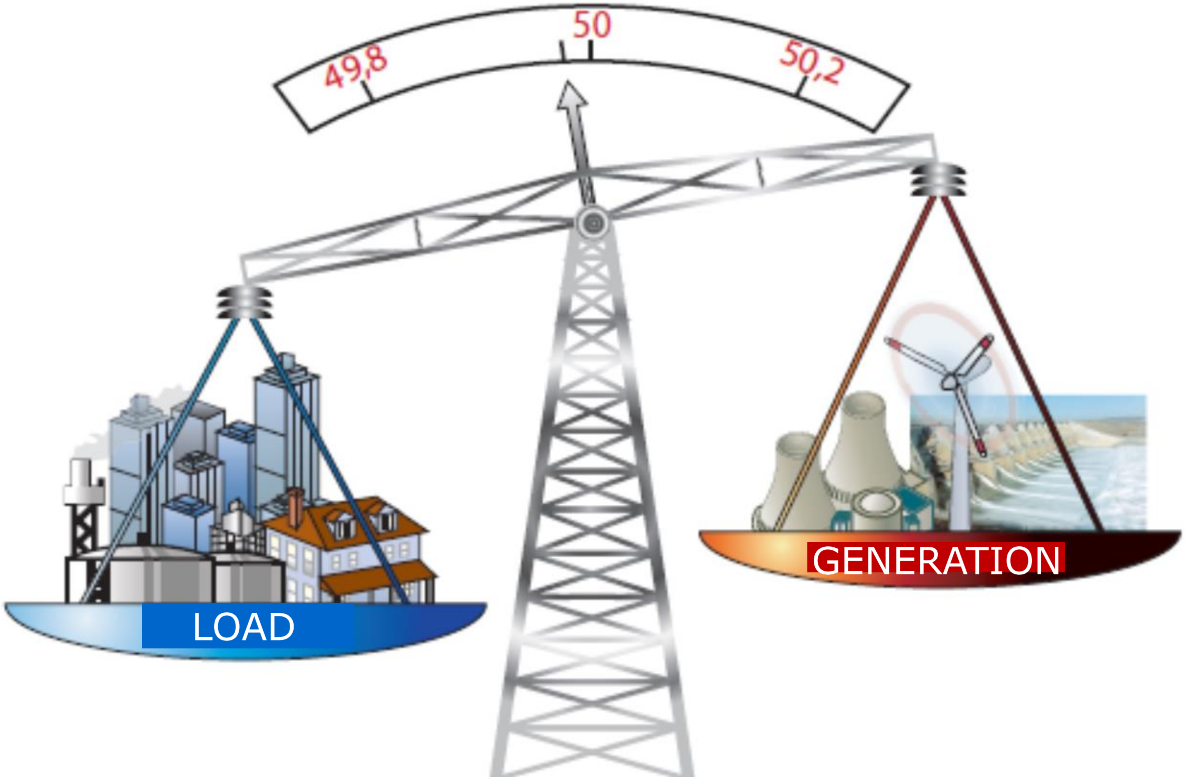
Energy Storage

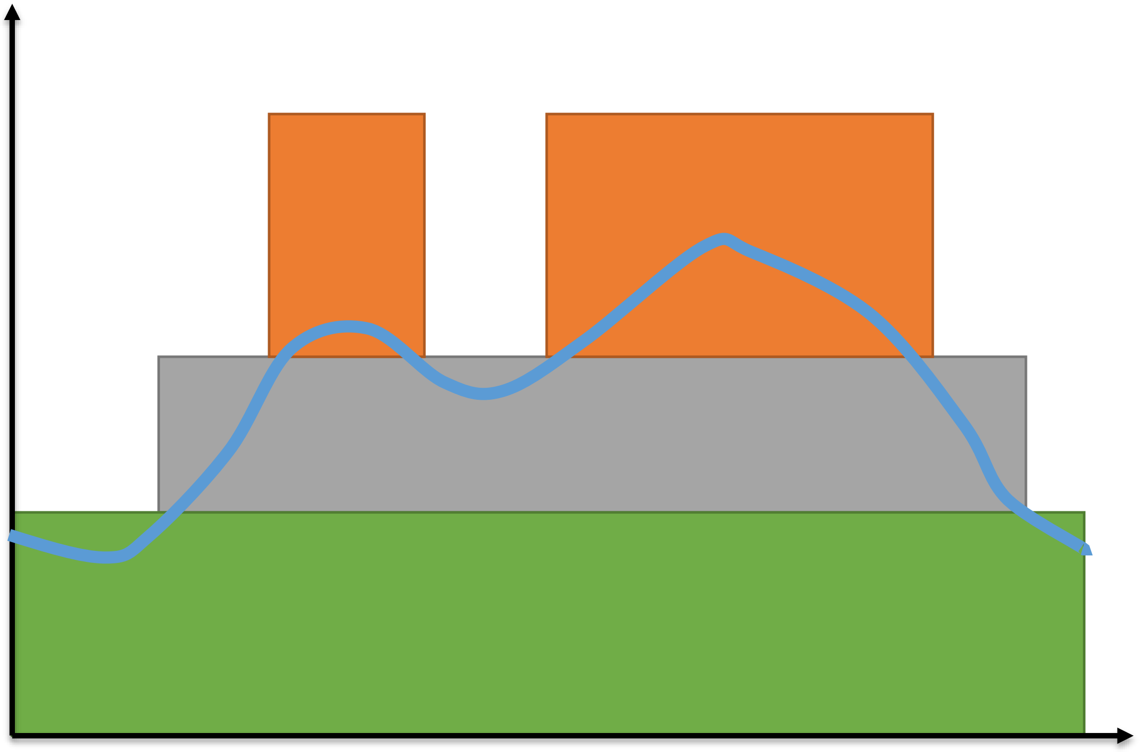
1. Energy Storage in Power Systems

Assoc. Prof. Hrvoje Pandžić

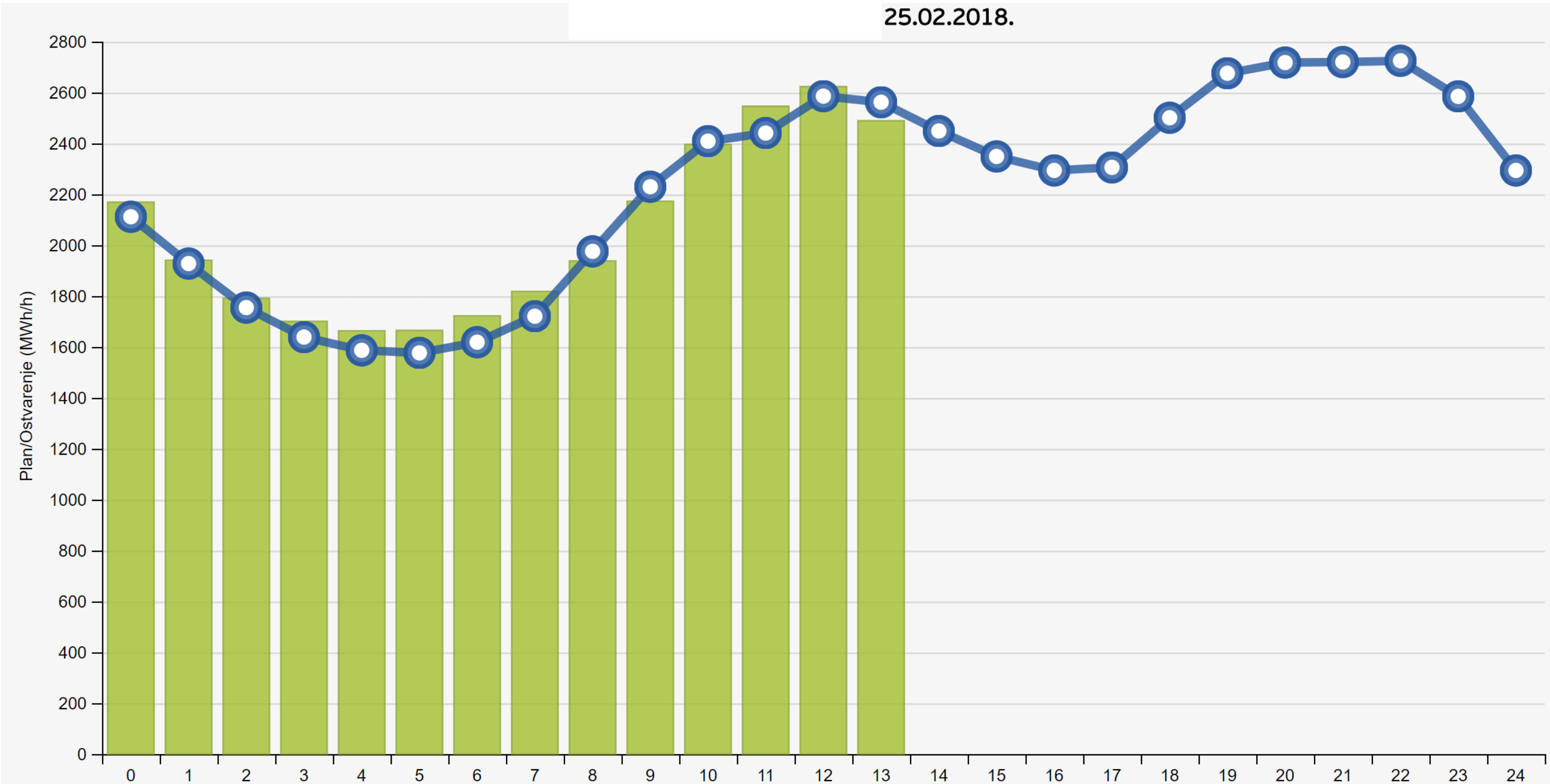
Power System



Daily Load Curve



Daily Load Curve

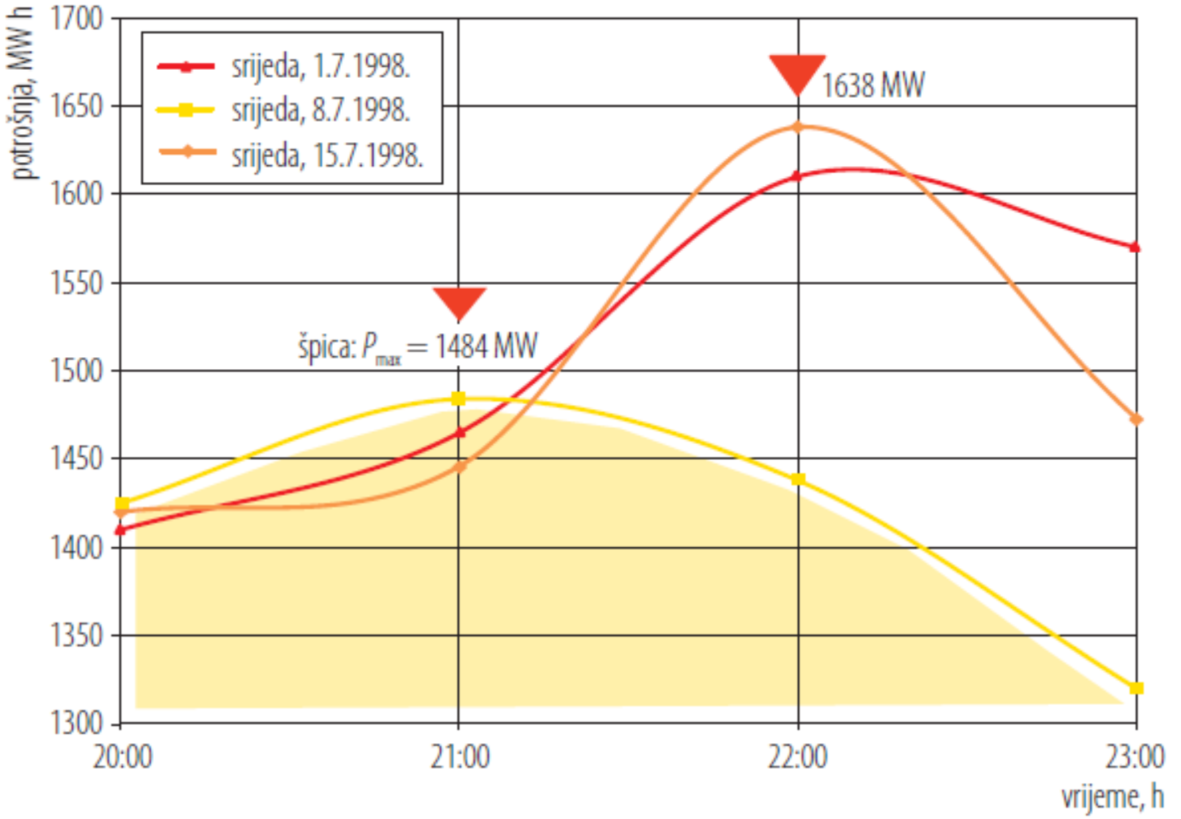


Load Forecasting

- Based on historical data
- Relatively simple task
- Error within 5%
- Temperature has the greatest influence (HVAC)
- Influence of certain specific events

Load Forecasting

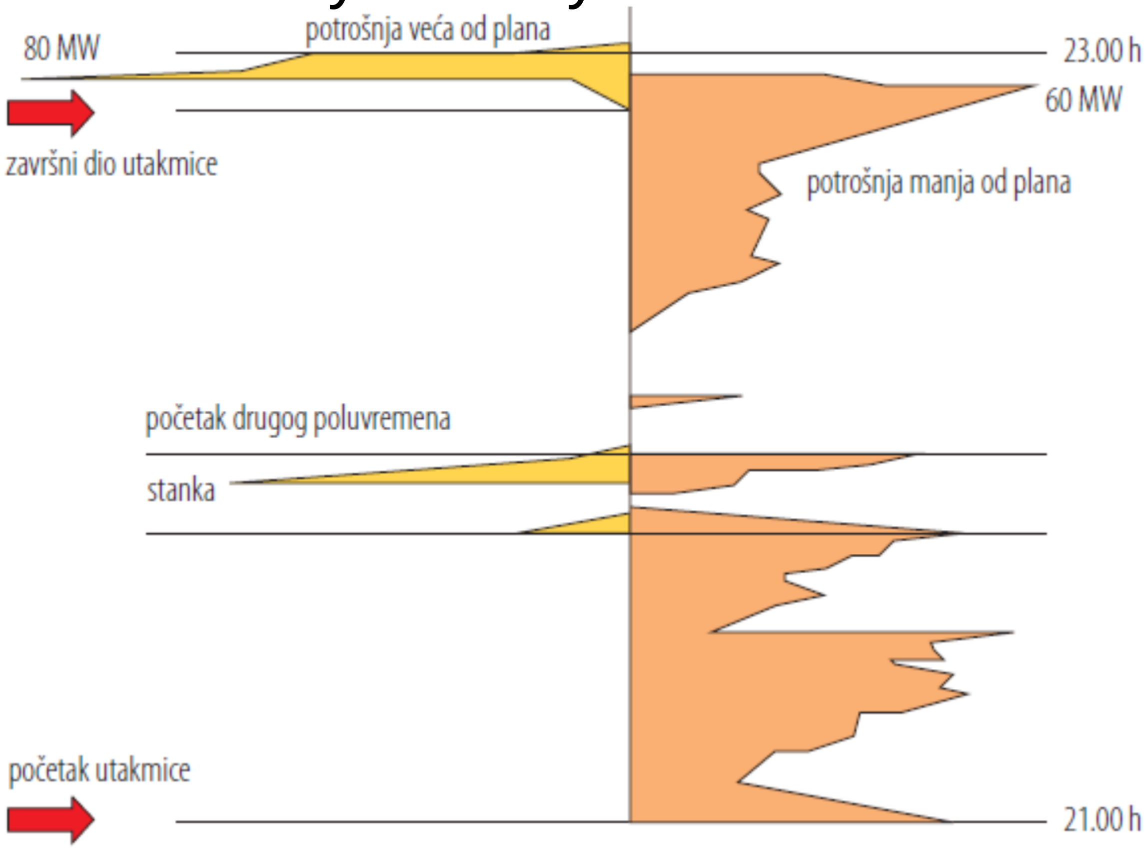
- 1998 FIFA World Cup Semi-Finals: France - Croatia, Wednesday 8th July 1998



Niko Mandić, „What connects football and power system?," EGE 3/2008, pp. 44-50

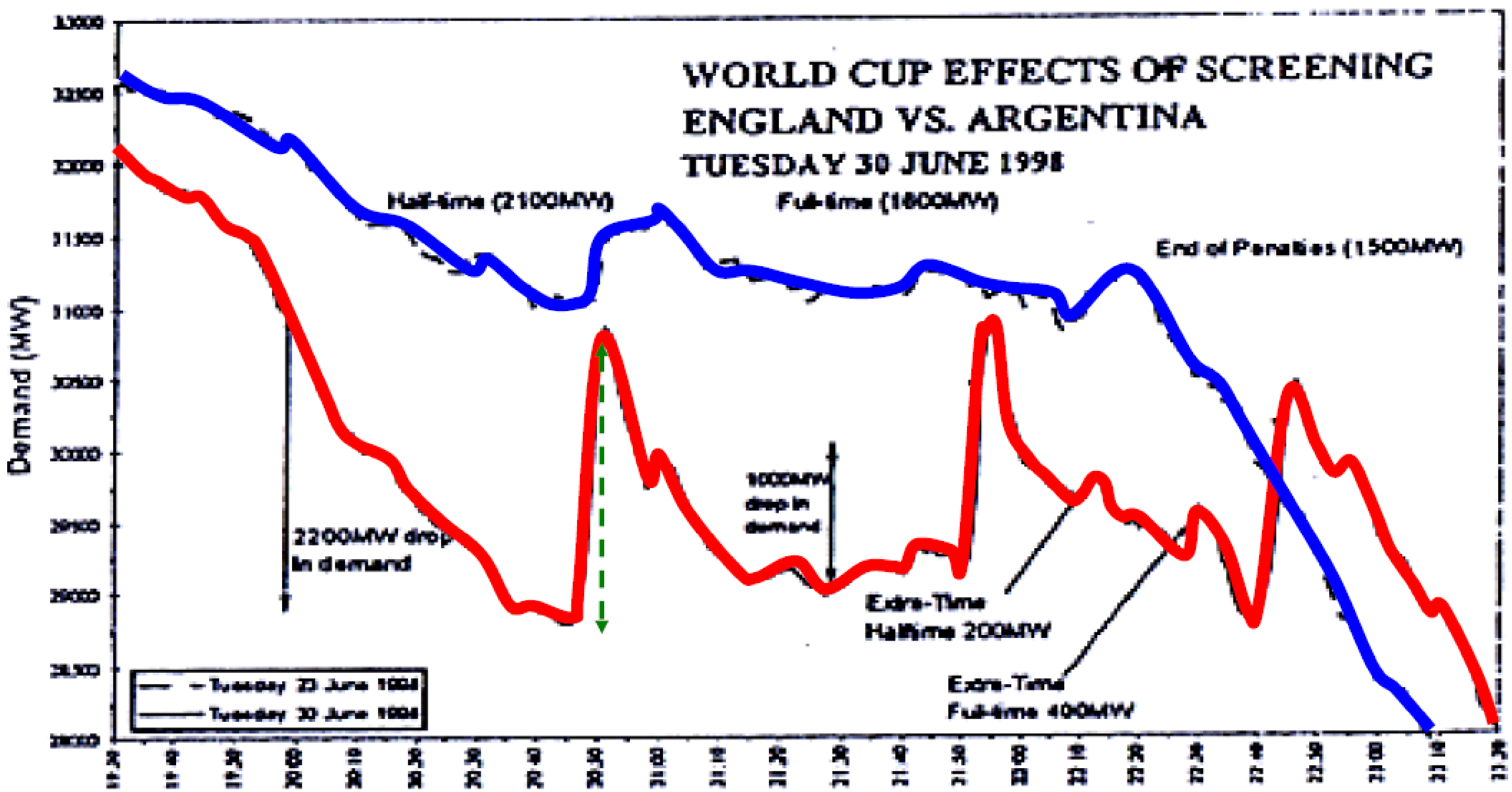
Load Forecasting

- 1998 FIFA World Cup Semi-Finals: France - Croatia, Wednesday 8th July 1998



Niko Mandić, „What connects football and power system?," EGE 3/2008, pp. 44-50

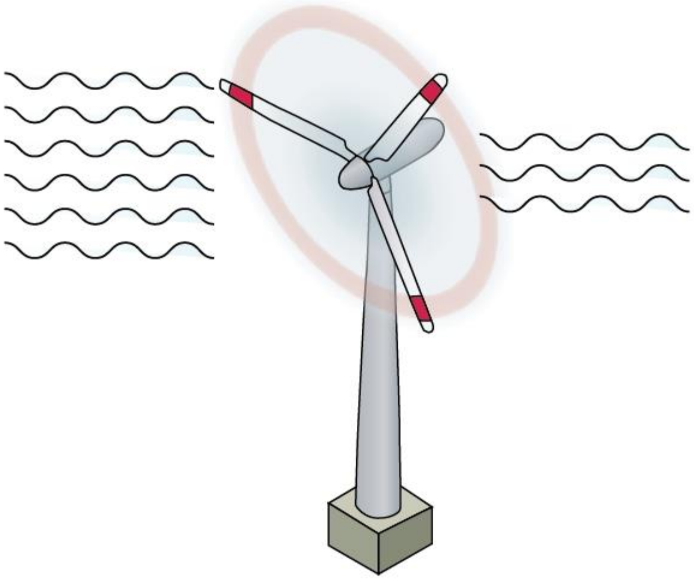
Load Forecasting



Ilustracija 5 : Detalj originalnog zapisa NG (Engleska) potrošnje električne energije za vrijeme nogometne utakmice Engleska-Argentina 30.06 1998. godine u vremenu 19:10 do 23:30. Rezolucija vremenske ose je 10 minuta. Plavi grafikon prikazuje potrošnju srijeda 23.06. 1998. godine crvenom bojom grafikon potrošnje srijeda 30.06. 1998.godine sedam dana kasnije.

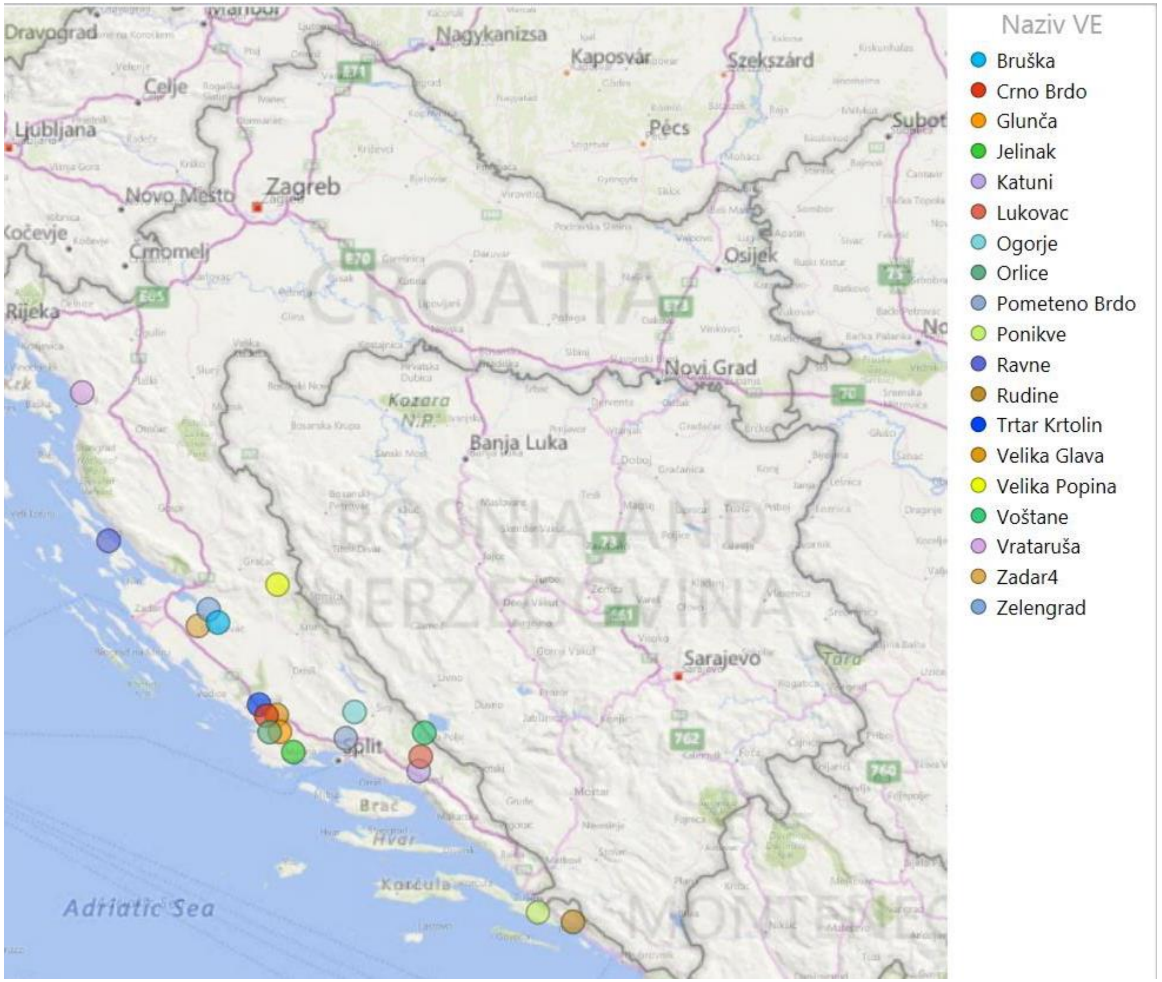
Renewable Energy Sources (RES)

- Wind energy is the most popular renewable energy source
- Wind power capacity of 744 MW is expected to be achieved within a few years
- Wind power capacity of 575 MW is already in operation
- Problematic location
- Production factor around 25%

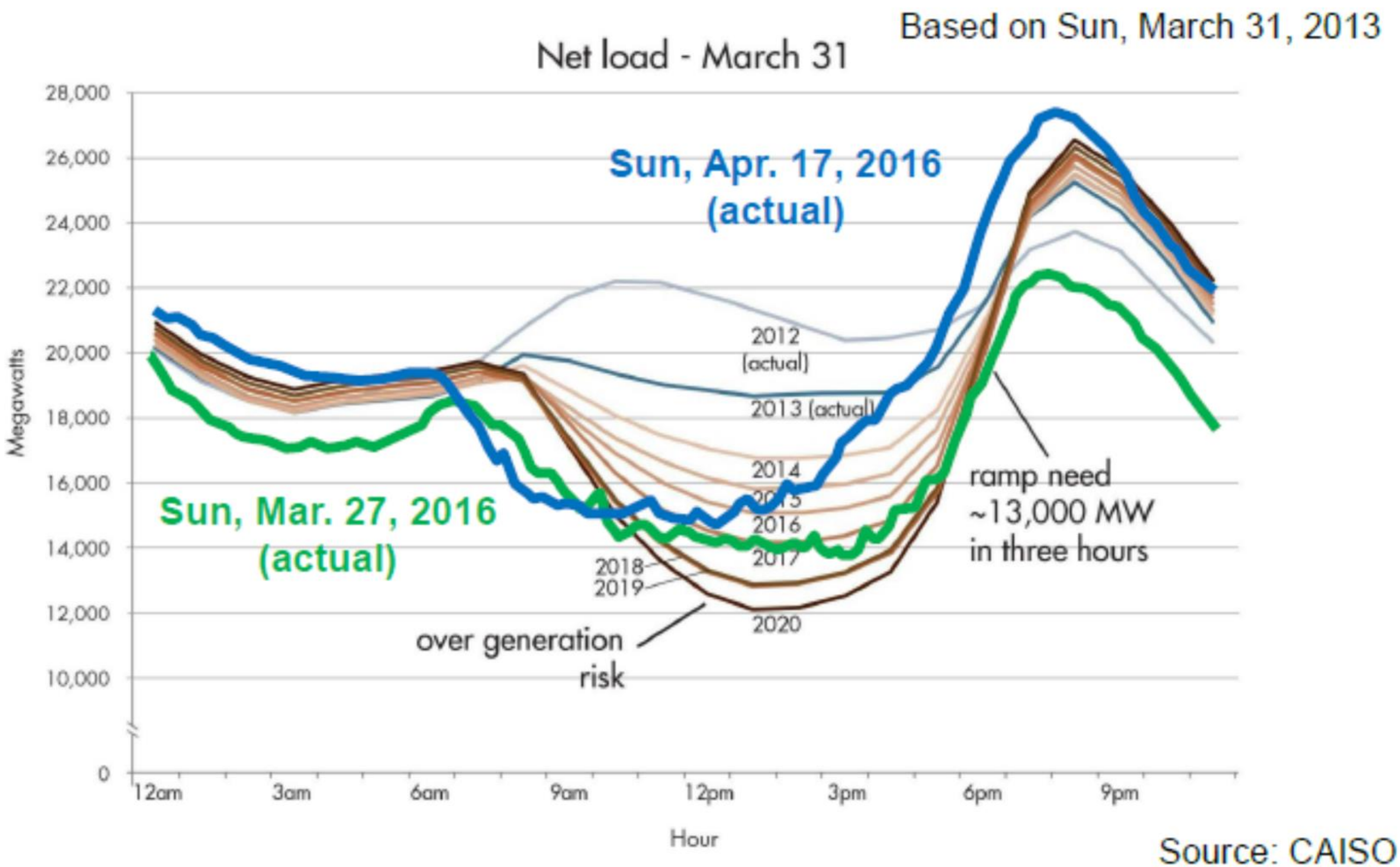


Renewable Energy Sources (RES)

- 16 out of 19 wind farms, whose installed capacity is 75% of the overall wind farm capacity in Croatia, is located in a square 110 x 70 km^2



Renewable Energy Sources



Why RES?

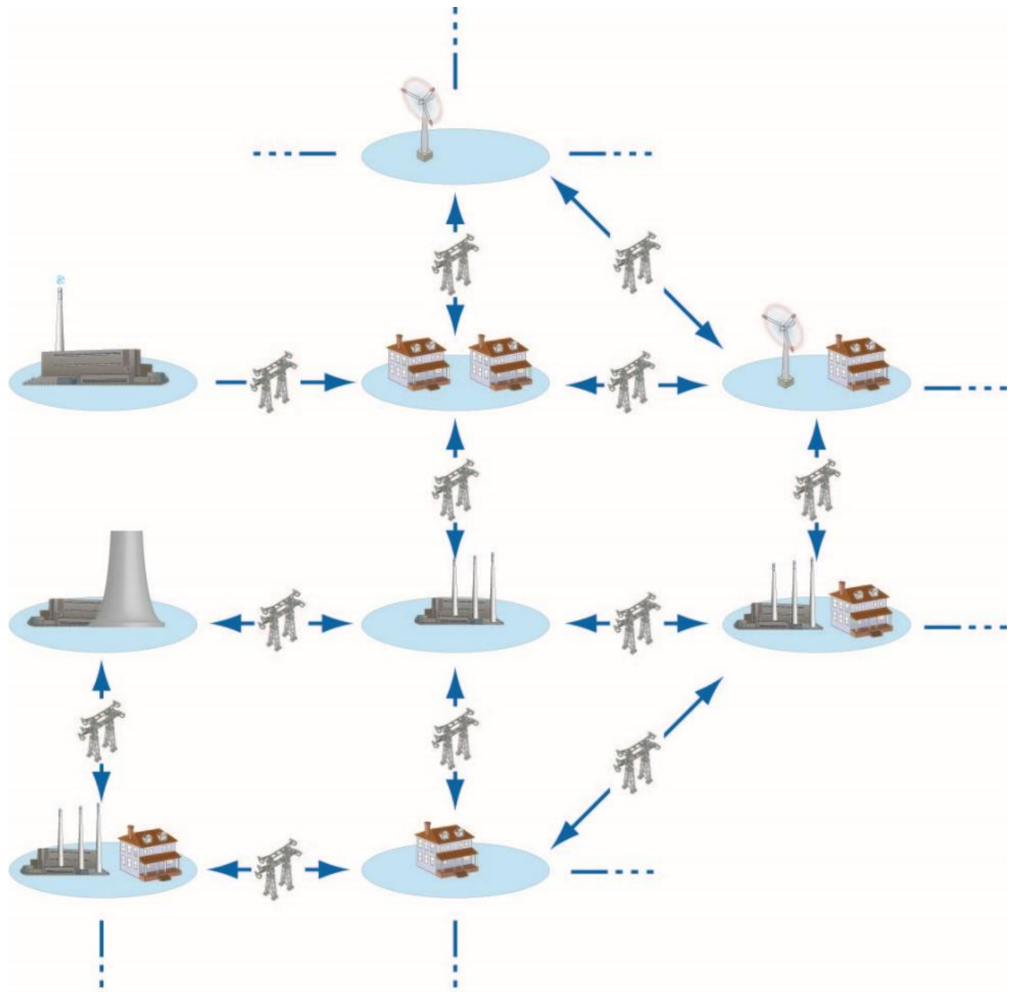
- Europe imports:
  - 90% oil
  - 66% gas
  - 42% coal
  - 40% uranium

Why RES?

- System flexibility:
  - Technical: system's ability to quickly and appropriately respond to sudden changes in production and consumption in the system.
  - Market: market's ability to enable trading of electricity at the appropriate time scale in order to avoid imbalance.
- Non-dispachable RES reduce the flexibility of the system :
  - Unpredictability: increased demand for reserve in the system.
  - Variability: increased need for flexible units.

Power System

- Frequency 50 Hz
- The production follows consumption
- Generators provide reserve
- Increased price of reserve due to uncertainty of electricity production from RES



Potential Solutions

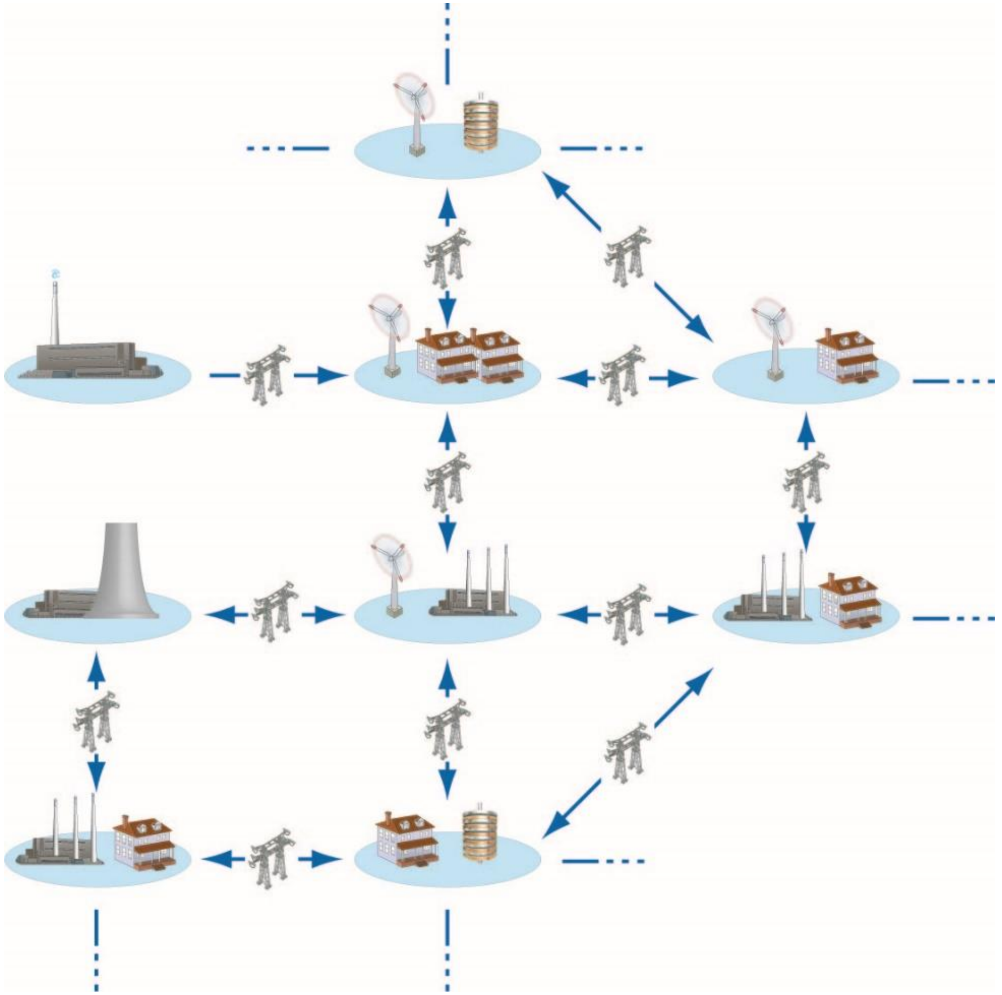
Technology	Congestion	Electricity production	Reserve provision	Impact on emissions
FACTS devices				
Gas power plants				
Grid reconfiguration				
Energy storage				

Potential Solutions

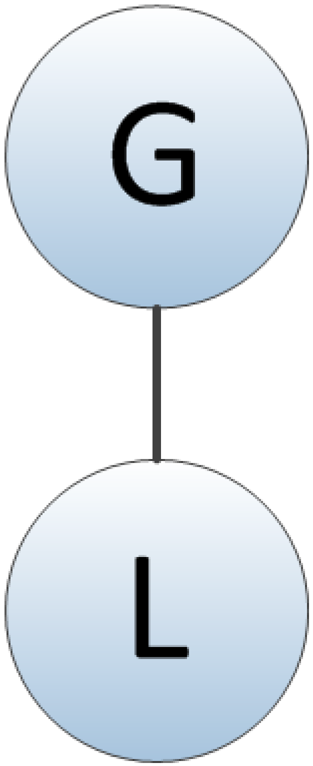
Technology	Congestion	Electricity production	Reserve provision	Positive impact on emissions
FACTS devices	+	-	-	-/+
Gas power plants	-	+	+	-
Grid reconfiguration	+	-	-	-/+
Energy storage	+	-/+	+	-/+

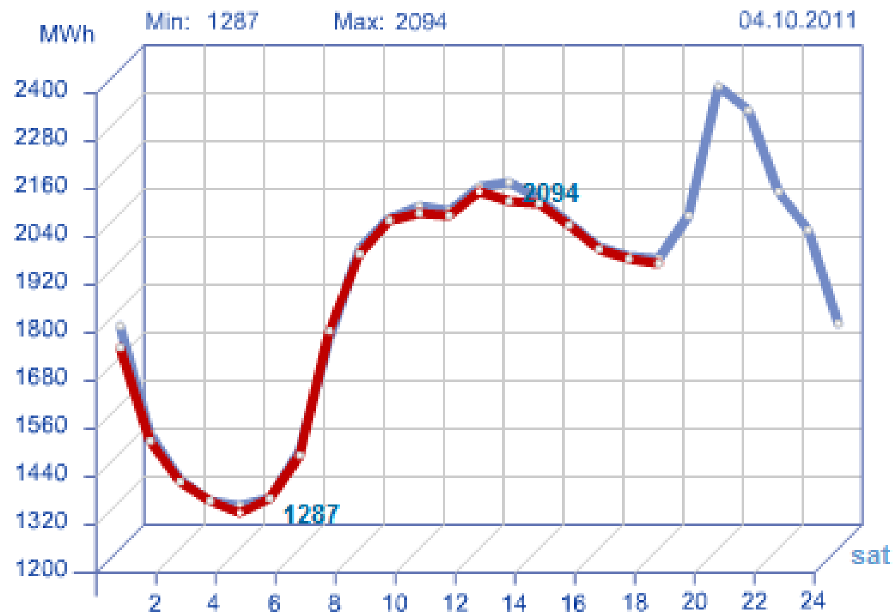
Energy Storage in Power Systems

- Balance between the production and consumption within a longer period of time
- Increased RES share
- Energy storage reduces control requirements on power plants
- Energy storage provides flexibility
- Energy storage is used for corrective N-1 security

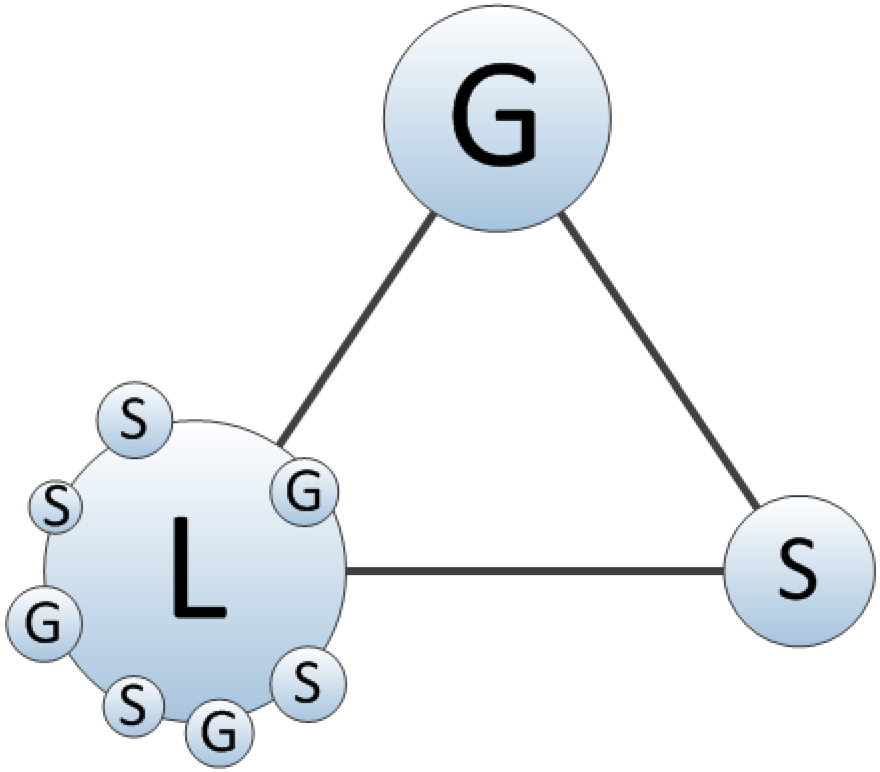


Relatively Recently …





… and Today



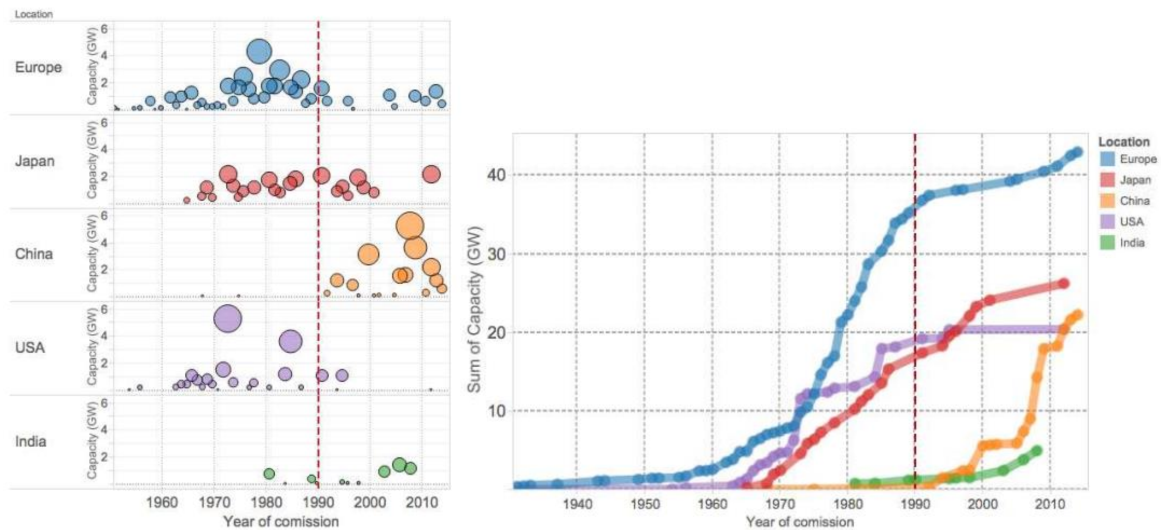
Energy Storage in Power Systems

- Benefits:
  - Levelling of the load curve
  - Ancillary services (frequency containment reserve – "primary reserve", frequency restoration reserve – "secondary reserve", replacement reserve – "tertiary reserve" and voltage stability)
  - Reduction of congestion
  - Greater utilization of wind and solar energy
  - More cost-effective operation of the system (less fuel, less power plant cycling, ...)
  - Transition from the preventive to the corrective N-1 security operation

Energy Storage in the World

- Stored / delivered electricity:
  - USA 2.5%
  - Europe 10%
  - Japan 15%

Pump storage trends



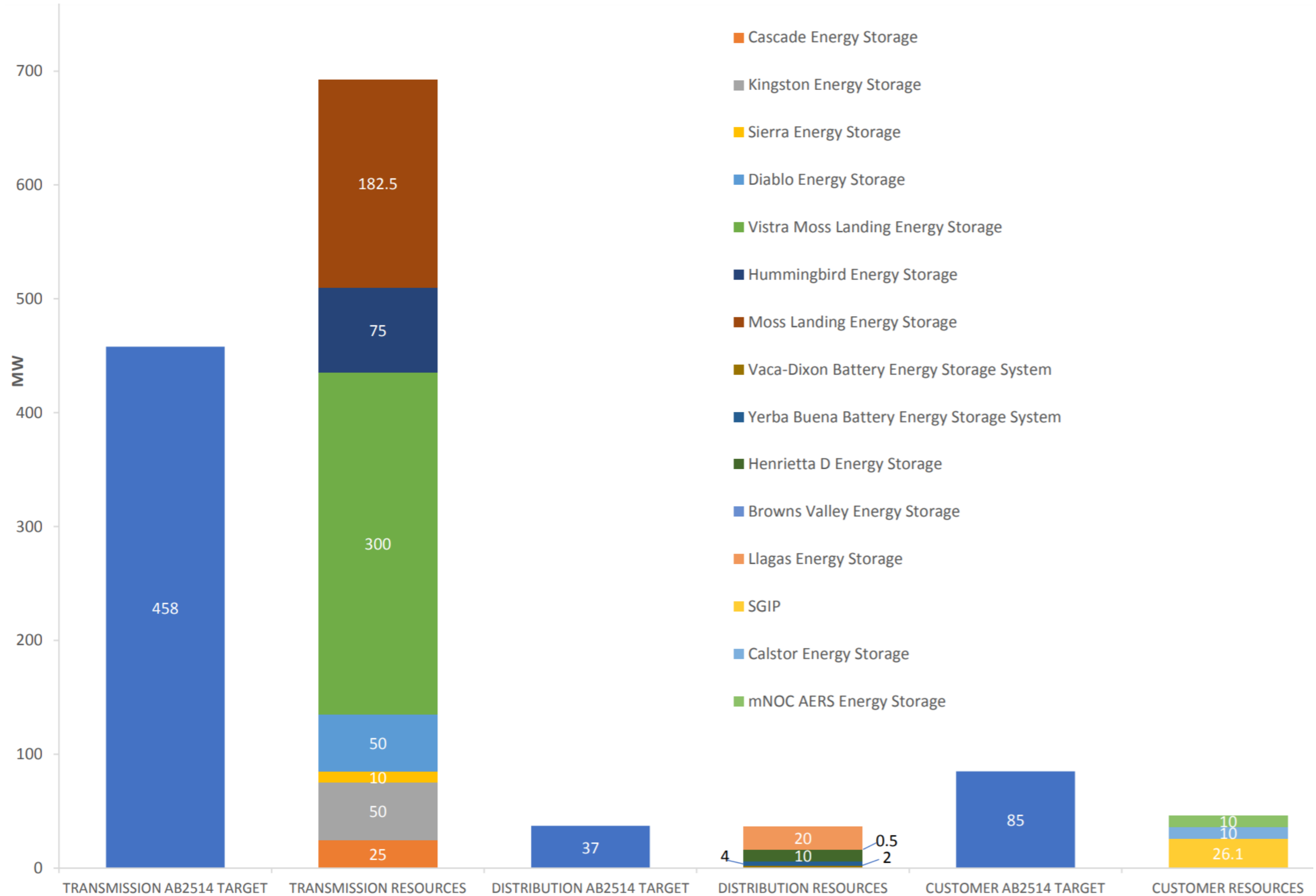
Energy Storage in California

- California
  - CPUC requires installed capacity of 1.325 MW in storage by 2020 (PG&E 580 MW, SCE 580 MW, SDG&E 165 MW)
  - Energy storage will be connected to the three levels:
    - Transmission network
    - Distribution network
    - End-users

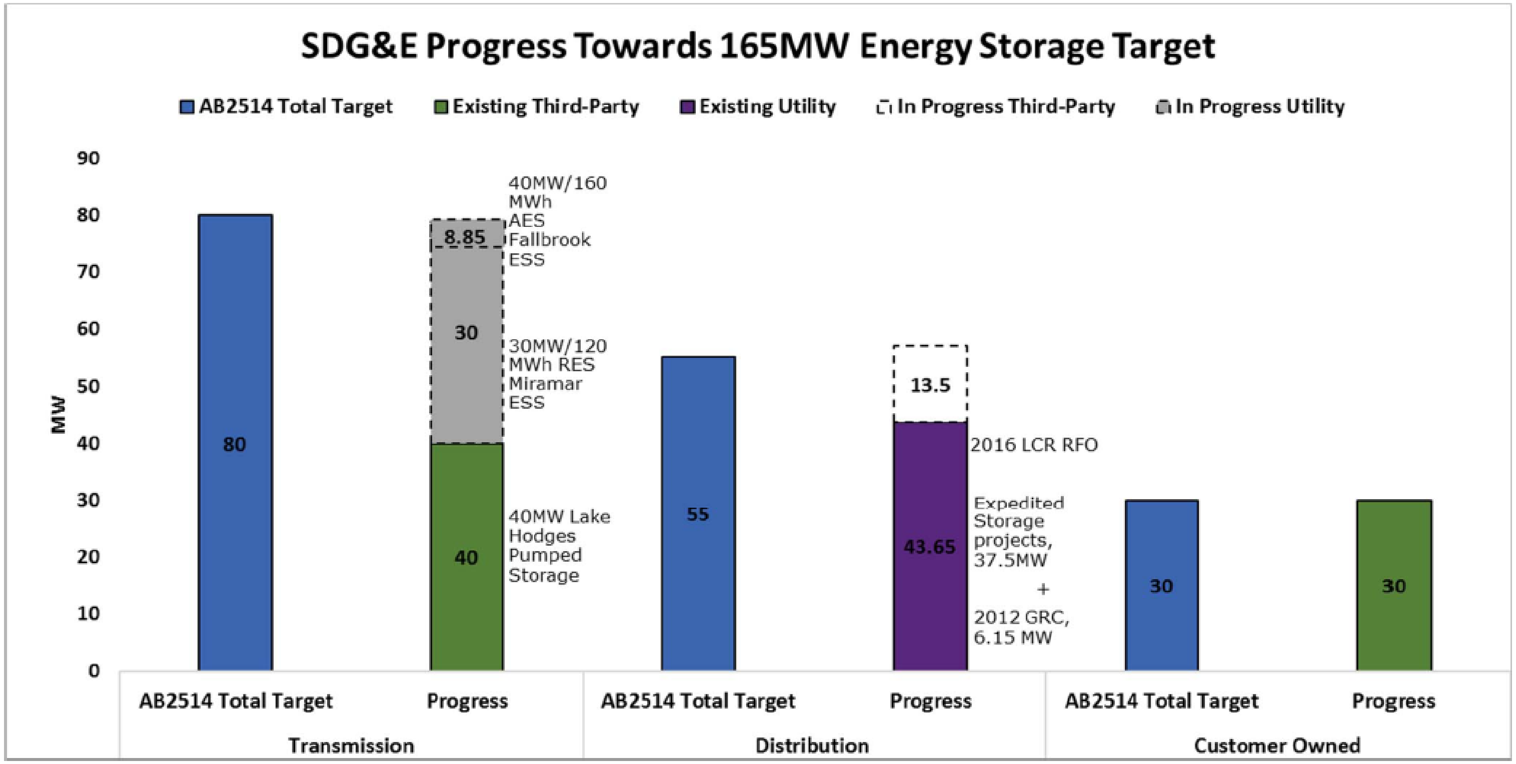
Energy Storage in California

		2014	2016	2018	2020	Total
SCE i PG&E	Transmission	50	65	85	110	310
	Distribution	30	40	50	65	185
	End-users	10	15	25	35	85
	Total	80	120	160	210	580
SDG&E	Transmission	10	15	22	33	80
	Distribution	7	10	15	23	55
	End-users	3	5	8	14	30
	Total	20	30	45	70	165
	MW	**200**	**270**	**365**	**490**	**1.325**

Energy Storage in California



Energy Storage in California



Energy Storage in the World

- 27 MW during 15 min NiCd – Fairbanks, AL (2003)
- 20 MW during 15 min flywheel – Stephentown, NY (2011)
- 32 MW during 15 min Li-Ion – Laurel Mountain, WV (2011)
- 36 MW during 40 min Lead Acid – Notrees, TX (2012)
- 8 MW during 4 h Li-Ion – Tehachapi, CA (2014)
- 25 MW during 3 h Flow bat. – Modesto, CA (2014)
- 5 MW during 1 h Li-Ion – Schwerin, Germany (2014)
- ….

- Interactive map available at http://www.energystorageexchange.org/projects

Energy Storage in Alaska

- 27 MW during 15 min NiCd – Fairbanks, AL (2003)
- Consumption on wide area
- Back-up, N-1 supply
- Rotating reserve
- Low winter temperatures
- 26 MW through 15 min or 40 MW through 7 min

Energy Storage in Germany

- Schwerin, Germany upgrade 2016
- WEMAG north Germany, 15 MW and 15 MWh
- Primary frequency regulation, black start
- 53.444 Samsung lithium mangan oxid cell

Energy Storage in Italy

Power Intensive

- **Mission:** increase safety of grid
- **Total Power:** ≈ 40 MW
- **Solutions:** Li-Ion, Zebra, Flow, Supercaps
- **Number of sites:** 2
- **Investment Size:** 93 €mln;

PHASE I: 16 MW Storage Lab

Site 1 Codrongianos
- Total Power: ≈ 9,15 MW
- Status: operational ≈ 5,4 MW
  in commissioning ≈ 2,1 MW
  under construction ≈ 0,4 MW
  procurement initiated ≈ 1,25 MW

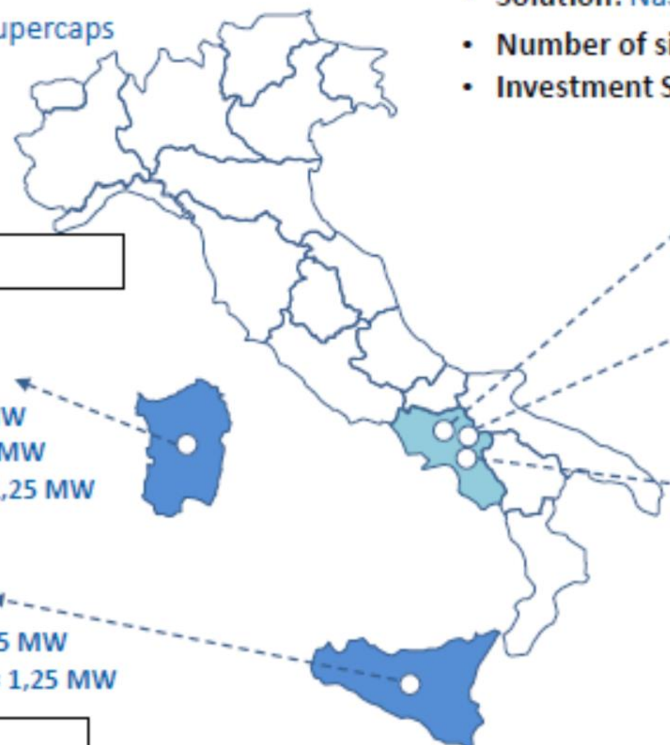
Site 2 Ciminna
- Total Power: ≈ 6,8 MW
- Status: operational ≈ 5,1 MW
  under construction ≈ 0,45 MW
  tender to be submitted ≈ 1,25 MW

PHASE II: 24 MW

Casuzze and Codrongianos: *to be initiated*

Energy Intensive

- **Mission :** reduce grid congestions
- **Total Power:** ≈35 MW
- **Solution:** NaS *Sodium Sulfur*
- **Number of sites:** 3
- **Investment Size:** 160 €mln;



Site 1: Ginestra
- Total Capacity: ≈ 12 MW
- Status: operational

Site 2 Flumeri
- Total Capacity: ≈ 12 MW
- Status: operational

Site 3 Scampitella
- Total Capacity: ≈ 10.8 MW
- Status: operational

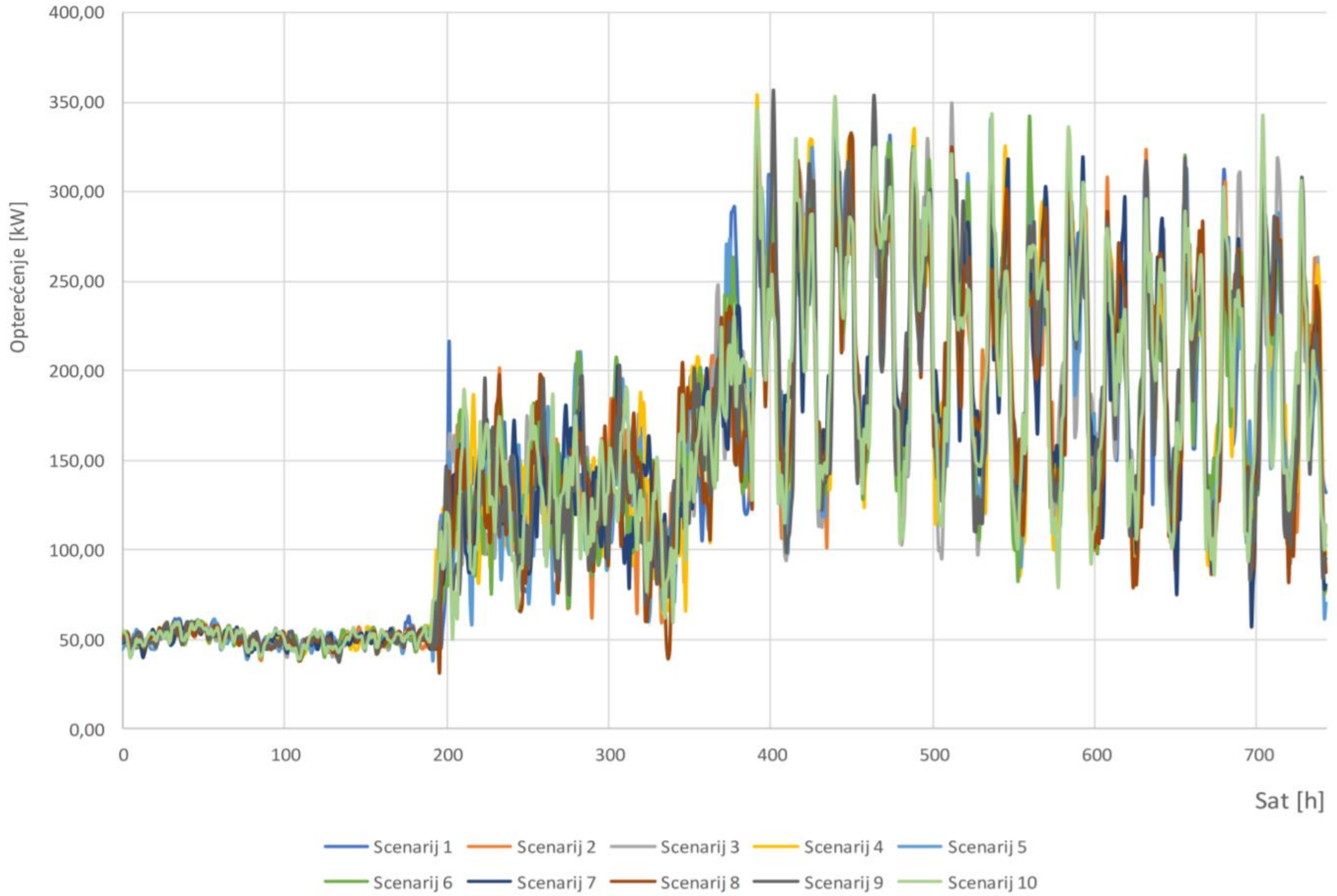
Electricity Bill Components

- Energy payment (high and low tariff)
- Distribution and transmission network charge
- Charge for meter-reading
- Charge for incentivizing RES

- Power factor charge
- Capacity charge

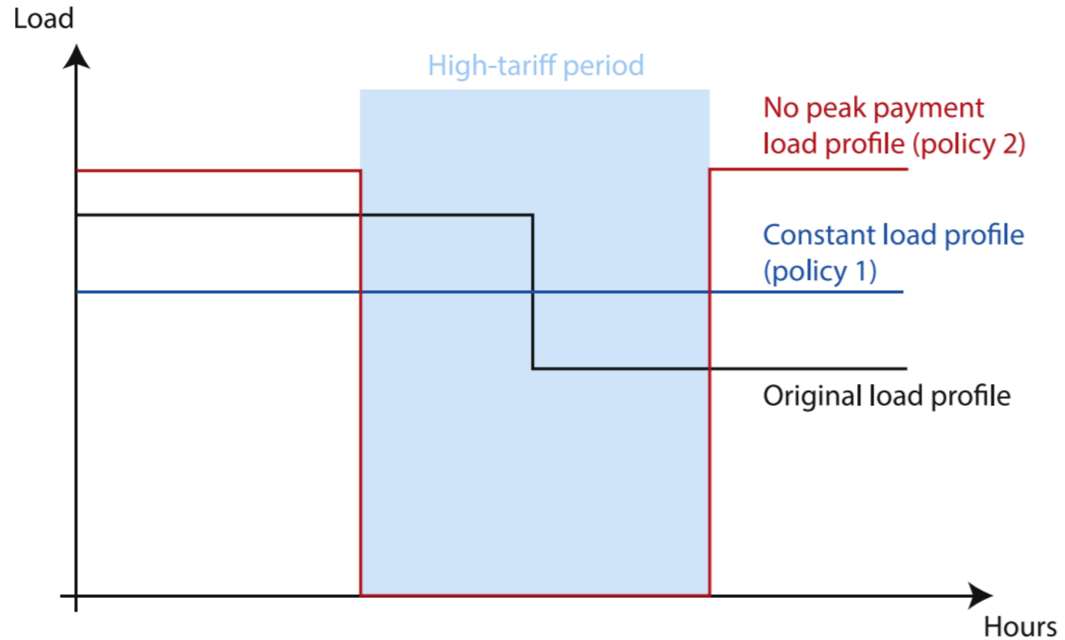
Load Diagram

- Energy storage can reduce the cost of electricity supply



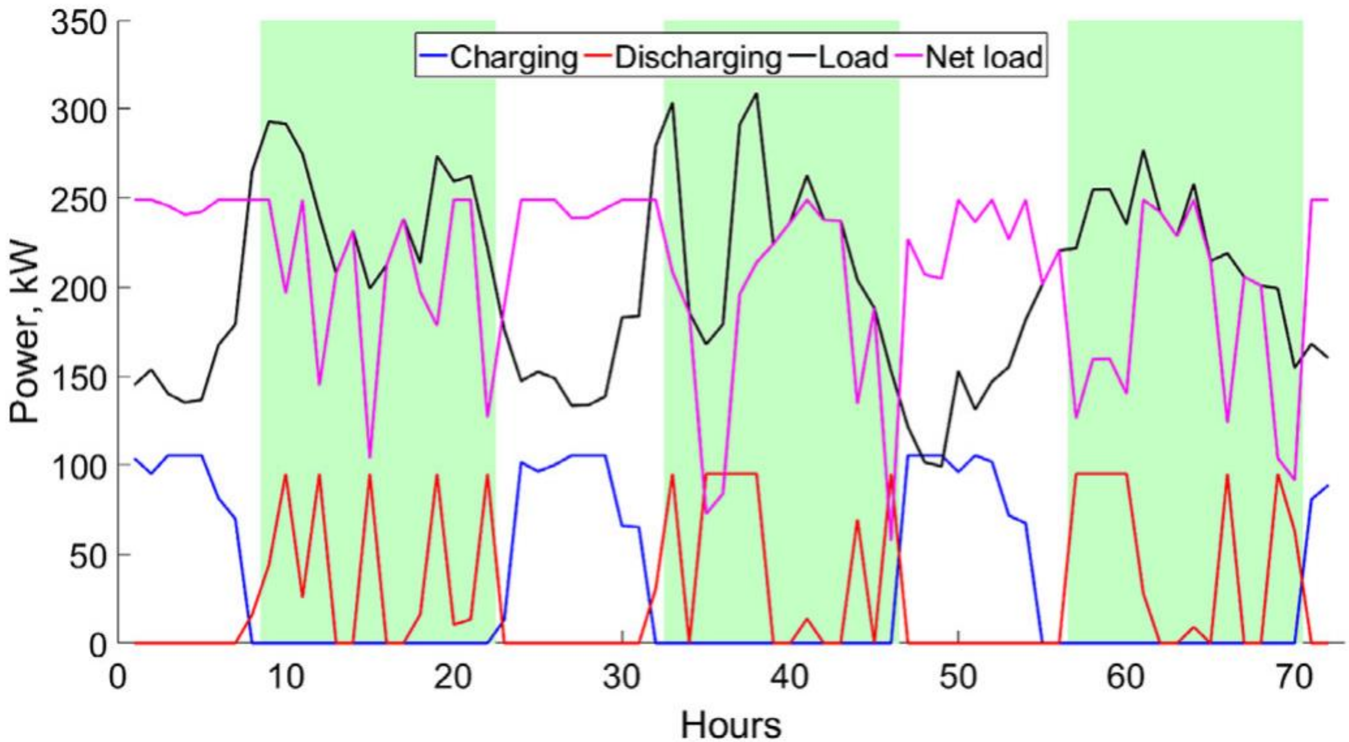
Optimal Load Profile

- Optimal load profile under different peak load policies when considering only peak load payments
- The original load profile is denoted with black line
- If peak load payments apply to all the hours of the day (policy 1), the optimal load profile is flat, since it incurs minimum peak load payments
- However, if peak load payments are applicable only to the high-tariff hours (policy 2), the optimal load profile is zero during the high-tariff period, since it avoids any peak load payments



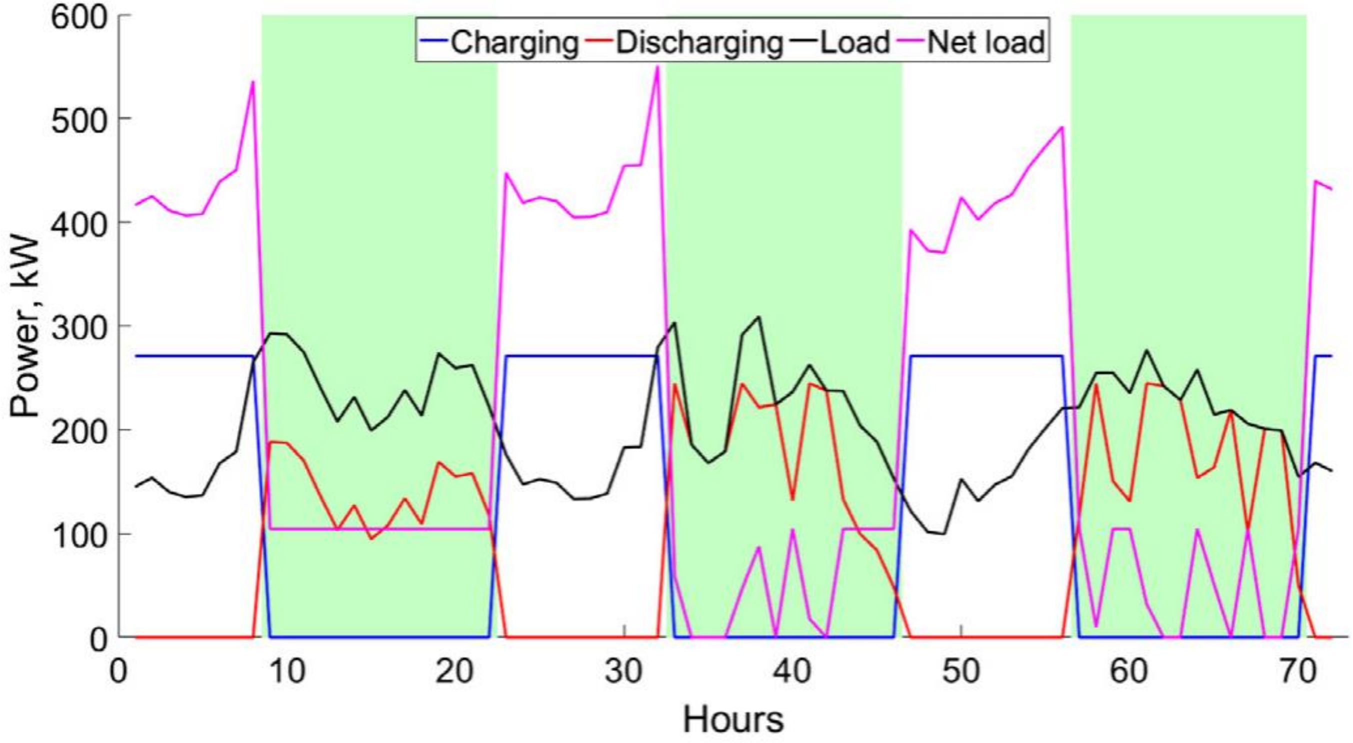
Optimal Battery Operation

- Load, battery storage charging and discharging quantities and net load when peak load payments are applicable to all hours
- Colored background denotes the high-tariff periods



Optimal Battery Operation

- Load, battery storage charging and discharging quantities and net load when peak load payments are applicable to only high-tariff hours



Optimal Investment in Energy Storage

- Optimization results as investment decision in the energy storage

Price $/kW	200	250	300
Price $/kWh	100	150	200
Installed capacity (kW)	95.38	5.76	0
Installed capacity (kWh)	836.81	7.58	0
Annual cost ($)	253,848	256.690	256.695
Savings (%)	1.12%	0%	0%

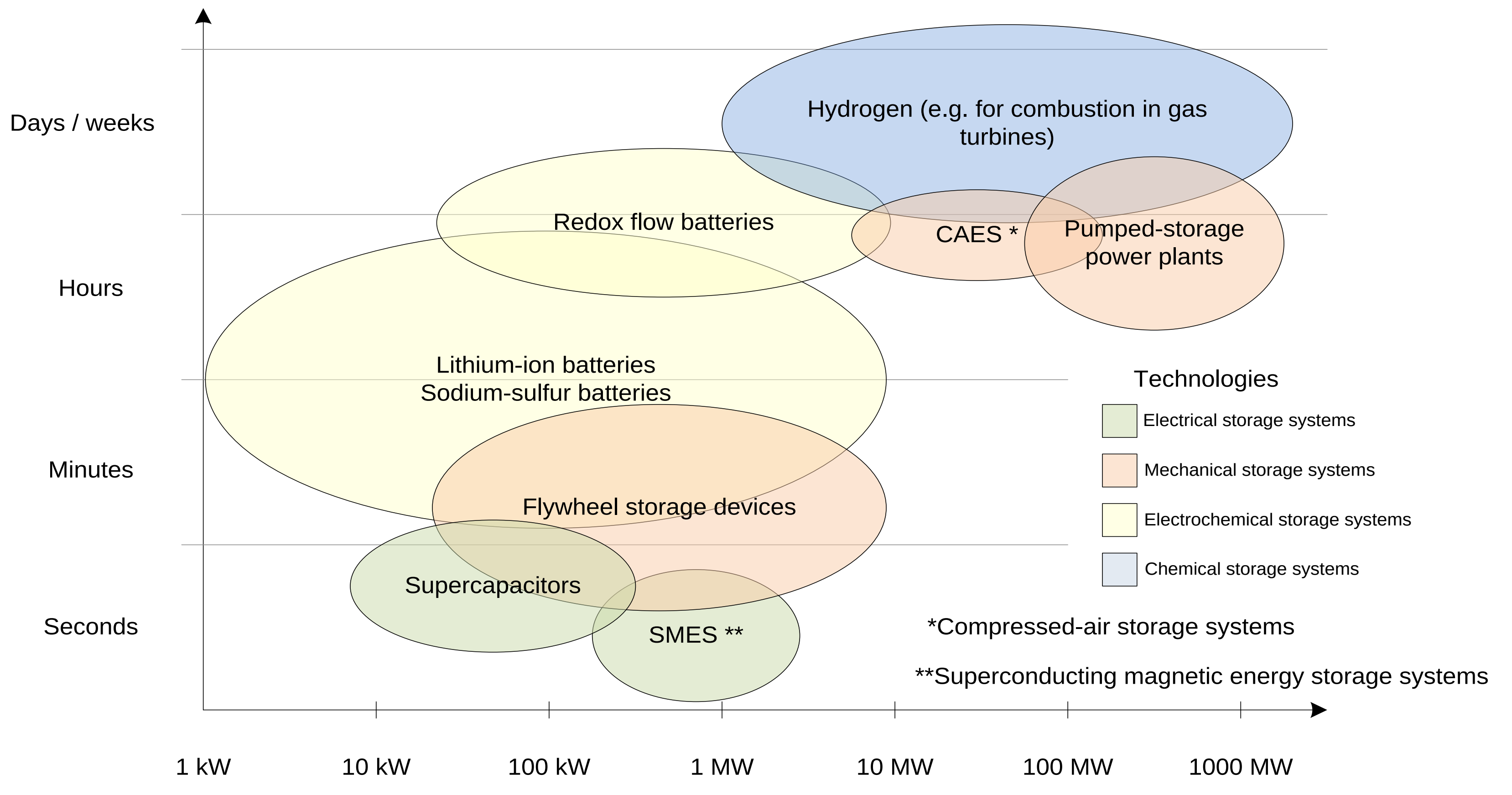
Electricity higher rate: 0.93 kn/kWh

Electricity lower rate: 0.43 kn/kWh

Active power: 29.50 kn/kW

Energy Storage Technologies

Energy Storage Systems by Duration and Power



Energy Storage Technologies

- Pumped hydropower plants
- Compressed air energy storage (CAES)
- Batteries
- Flywheels
- Ultracapacitors
- Fuel cells (hydrogen)
- Heat pump
- Demand response

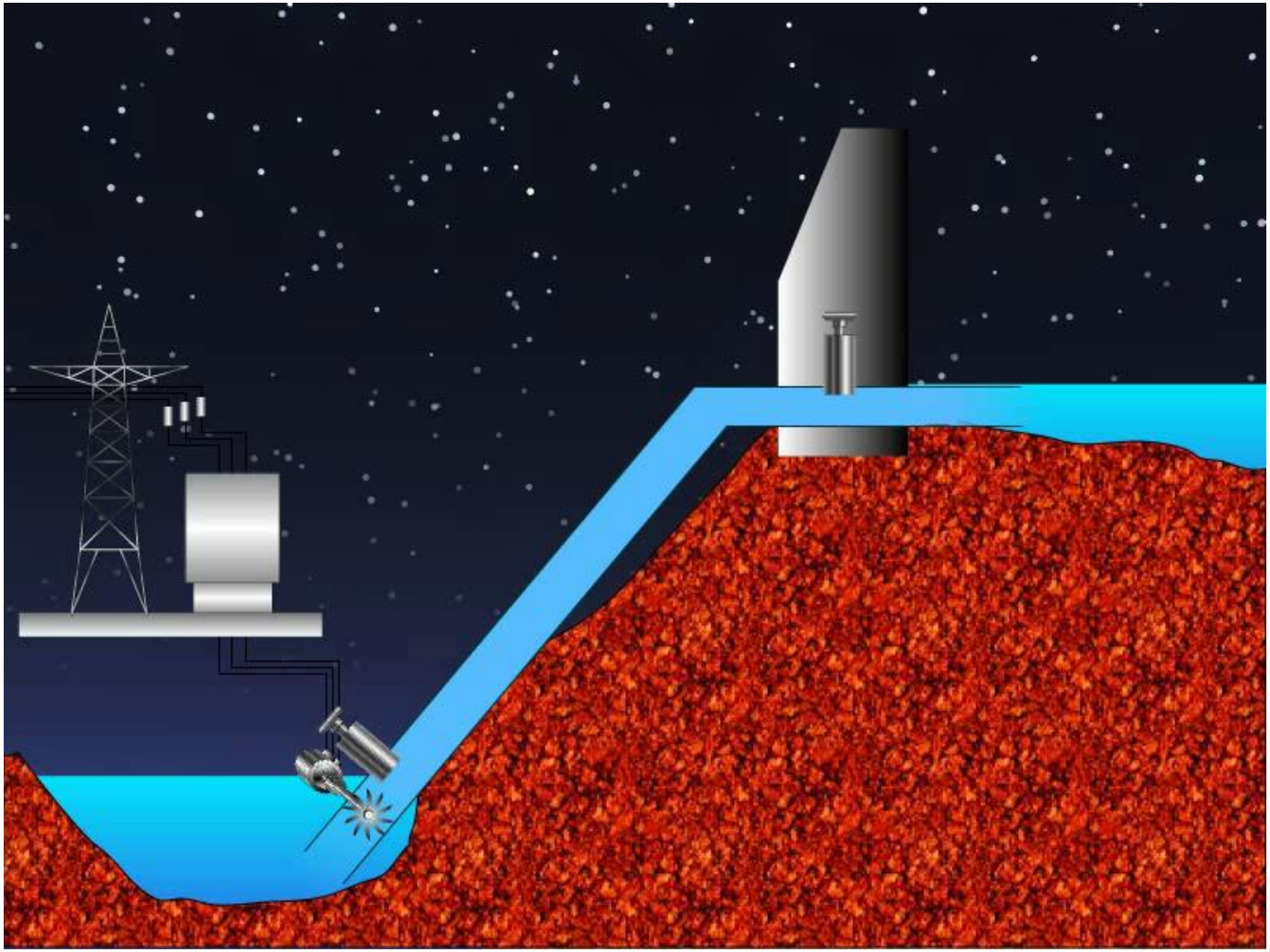
Pumped Hydropower Plants

- A hydraulic turbine converts kinetic energy of falling water into mechanical energy
- A generator converts the mechanical energy from the turbine into electrical energy
- Water is pumped into the upper reservoir during periods of low consumption and significant production of other plants

$$P = \rho \cdot g \cdot h \cdot Q \cdot \eta_T \cdot \eta_G \quad \text{(W)}$$

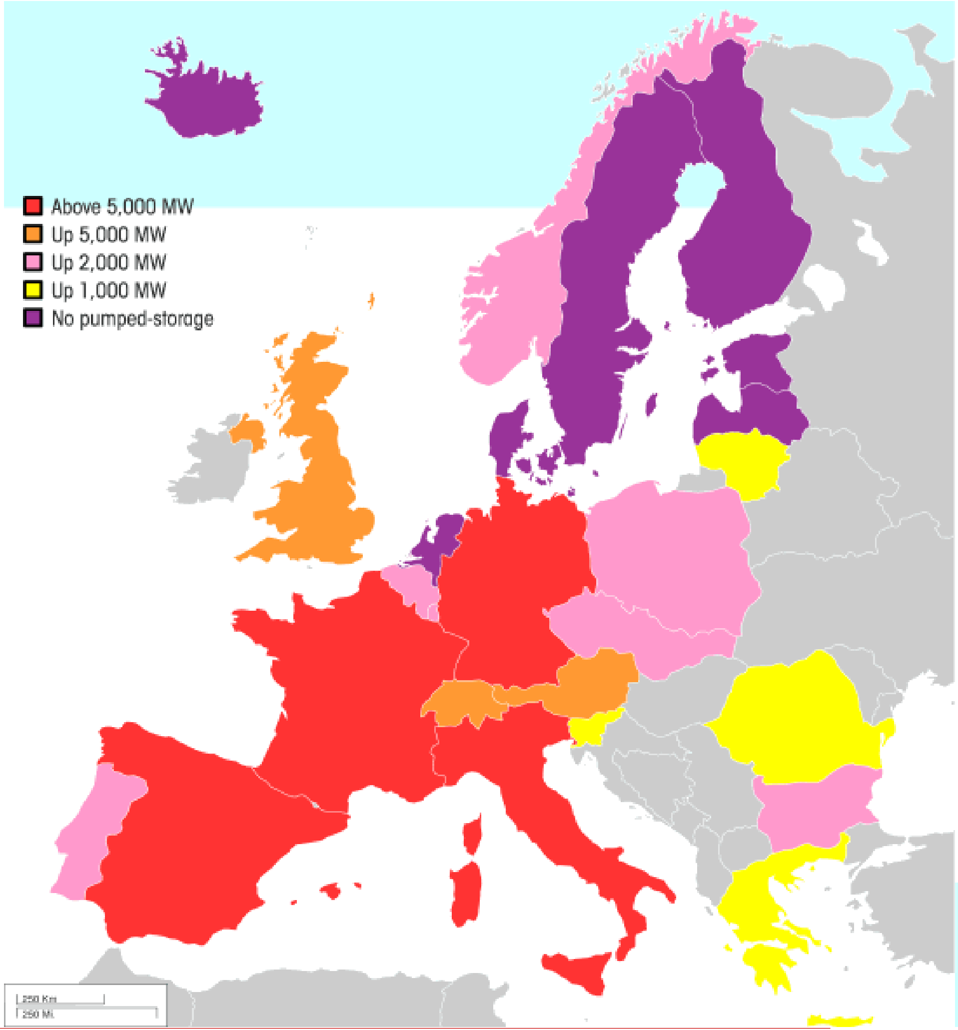
$$P \approx g \cdot h \cdot Q \cdot \eta_T \cdot \eta_G \quad \text{(kW)}$$

Pumped Hydropower Plants



Pumped Hydropower Plants in Europe

- Pumped HPP total installed capacity in the world is around 104 GW
- 44 GW in Europe:
  - Germany
  - Italy
  - France
  - Spain



Pumped Hydropower Plants in Europe

Europe	44 GW		
Austria	4.4 GW	Luxembourg	1.1 GW
Belgium	1.3 GW	Norway	1.4 GW
Bulgaria	0.9 GW	Poland	1.4 GW
Croatia	0.3 GW	Portugal	1.0 GW
Czech Rep.	1.1 GW	Serbia	0.6 GW
France	4.3 GW	Slovakia	0.9 GW
Germany	6.7 GW	Spain	5.3 GW
Greece	0.6 GW	Sweden	0.1 GW
Ireland	0.3 GW	Switzerland	1.8 GW
Italy	7.5 GW	UK	2.7 GW

Pumped Hydropower Plants in the World

North America	**22.4 GW**		
Canada	0.2 GW	SAD	22.2 GW
Central and South America	**1 GW**		
Argentina	1 GW		
Africa	**2 GW**		
Morocco	0.5 GW	South Africa	1 GW
Asia and Oceania	**33 GW**		
Australia	1 GW	South Korea	4 GW
Japan	25 GW	Taiwan	3 GW

CAES

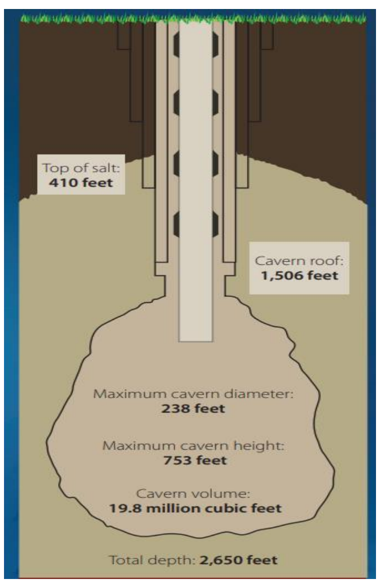
- The air is stored in underground tanks, caves and caverns
- The stored energy is released during periods of high load
- The operation of the CAES is based on some of the following thermodynamic processes:
  - diabatic (system exchanges energy with the environment)
  - adiabatic (system does not exchange energy with the environment)
  - isothermal (constant temparature)

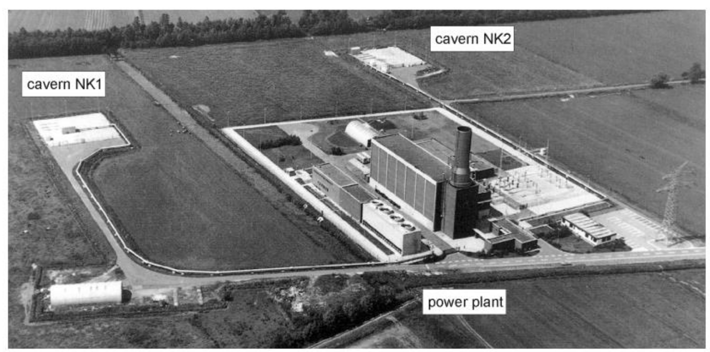
CAES

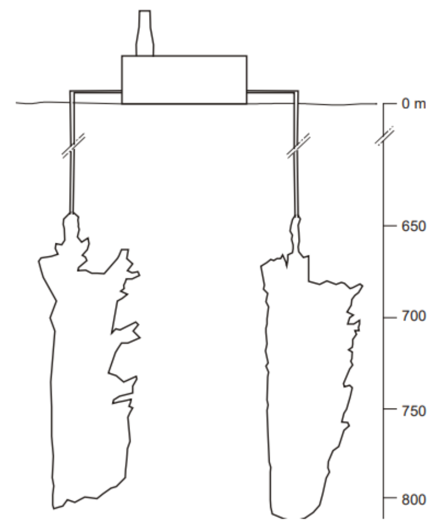
- Standard gas turbines are used with exception that the compression of the combustion air is independent of the standard process of the gas power plant
- Compression phase uses about half the power of the gas turbine and therefore CAES enables the production of twice more electricity with the same amount of gas
- Due to the reduced gas consumption, CO_2 emissions have been reduced by 30-6%
- The process efficiency is around 42% without the use of waste heat and around 55% with the use of waste heat

CAES

- McIntosh, Alabama 110 MW 1991.
- Huntorf, Germany 290 MW 1978.







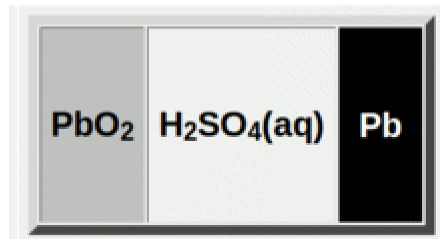
Batteries

- Battery is a device that coverts chemical energy of its active materials directly into electrical energy through an electrochemical redox reaction
- In case of rechargeable batteries, the process is reversible
- Batteries have an efficient energy conversion since they use electrochemical process to convert chemical energy into electricity
- Although the term battery is often used, the basic unit in which the reaction occurs is known as battery cell
- Battery consists of multiple cells connected in series and parallel, depending on the desired voltage and capacity

Batteries

- Battery types:
  - Lead-acid
  - Nickel-cadmium
  - Nickel-metal hybrid
  - Lithium-ion
  - Zinc-oxide
  - Vanadium-redox (flow battery)

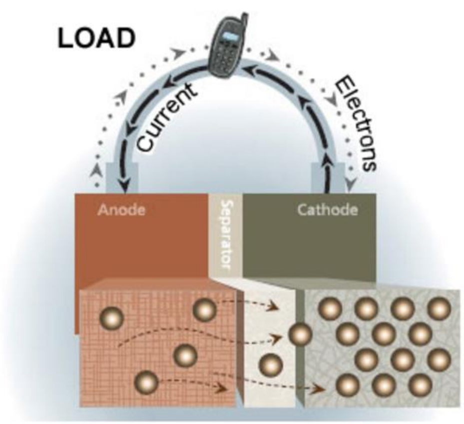
Full



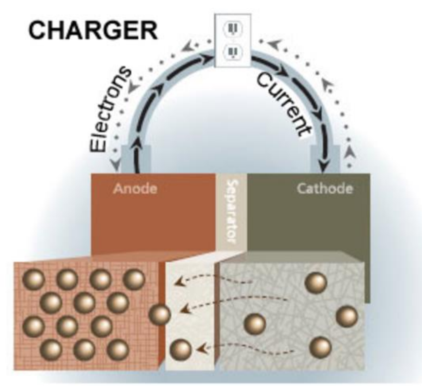
$$PbO_2 + Pb + 2H_2SO_4 \Rightarrow 2PbSO_4 + 2H_2O$$

Empty

$$2PbSO_4 + 2H_2O \Rightarrow PbO_2 + Pb + 2H_2SO_4$$



Lithium-ion Rechargeable Battery
Discharge Mechanism

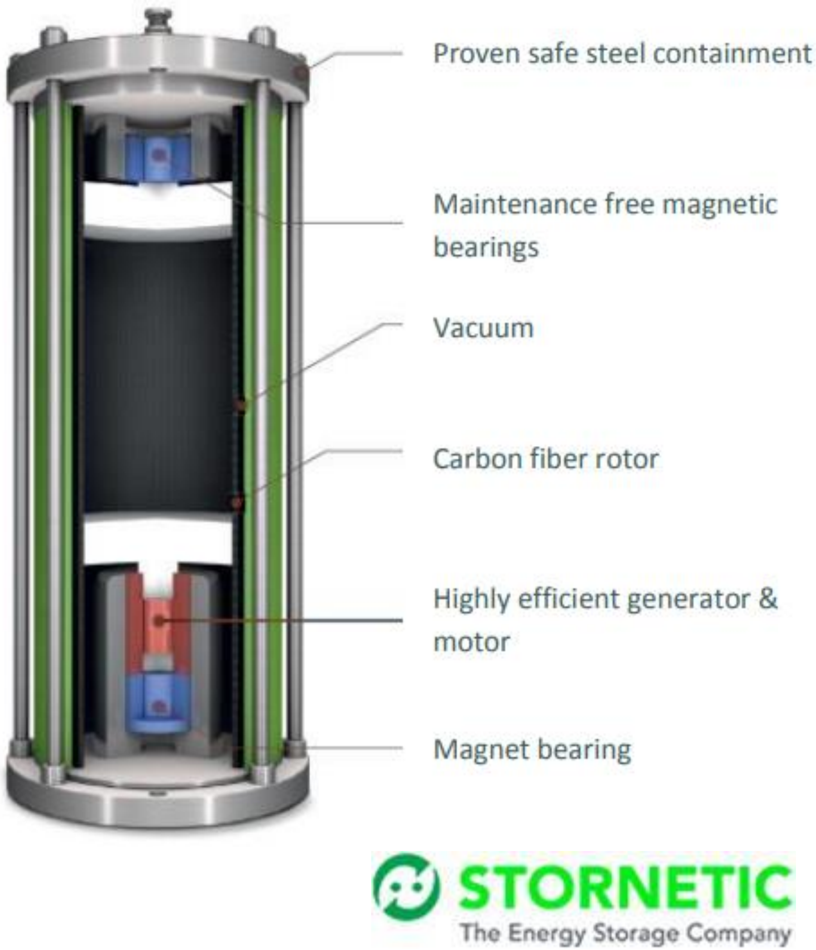


Lithium-ion Rechargeable Battery
Charge Mechanism

Flywheels

- Flywheel is a rotating mechanical device used to store mechanical (rotational) energy
  - $E_k = \frac{1}{2} I \omega^2$
- Flywheel resists changes in rotational speed by its moment of inertia
- The amount of energy stored in flywheel is proportional to the square of its rotational speed
- External torque is used to deliver energy to flywheel and in that case the flywheel acts as a load
- When flywheel provides energy, it acts as a generator and provides the necessary torque for the load while at the same time its rotational speed is decreasing

Flywheels



Design Concept	
Single flywheel machine EnWheel® 60 with DC Drive	

Lifespan	
Mechanics	20 years + (expected)
Charge cycles	100,000 +
Power Electronics	±10 years replacement time

Operational Capacity	
Name plate power	60 kW
Effective energy	3.4 kWh
Bi-directional capacity @ 60kW	65 sec
One-directional capacity	120 sec

Electrical Data	
Input/output voltage	700 to 750 V DC
Maximum voltage	800V DC
Maximum effective power	83 kW peak
Round trip efficiency (typical)	90 %
Response time	10 ms

Capacitors

- A capacitor consists of two metal plates, i.e. conductors (typically aluminium), separated by a dielectric medium (air, plastics or ceramics)
- During charging, the electrons pile up on one conductor and go away from the second
- Charge Q is proportional to voltage V and capacitance C, whereas energy is proportional to capacitance and the square of voltage

$$Q = C \times V \qquad E = \frac{1}{2}CV^2 \qquad C = \varepsilon\frac{A}{d}$$

- Electrons want to reach the positive side, but they can not pass through the insulator – energy is stored in electric field

Ultracapacitors

$$C = \varepsilon \frac{A}{d} \qquad E = \frac{1}{2} C V^2$$

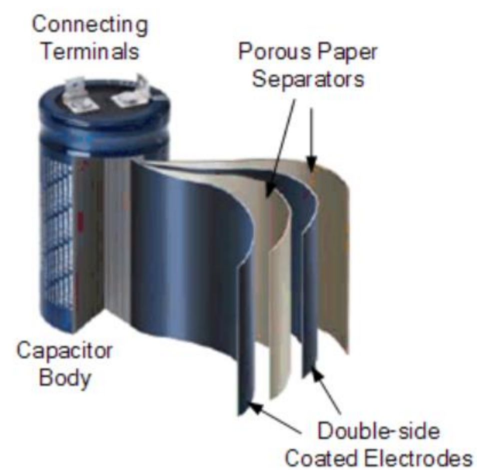
- Ultracapacitors are another type of capacitor which is constructed to have a large conductive plate, called an electrode, surface area (A) as well as a very small distance (d) between them.
- The ultracapacitor uses a liquid or wet electrolyte between its electrodes making it more of an electrochemical device
- Still, no chemical reactions are involved in the storing of its electrical energy.
- It remains an electrostatic device storing its electrical energy in the form of an electric field between its two conducting electrodes

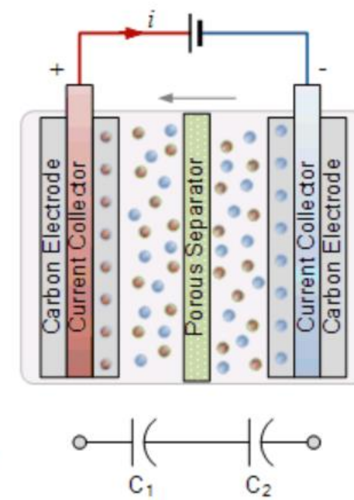
Ultracapacitors

- Electrodes → carbon; porous membrane → separator keeps electrodes apart, blocks electrons, leaks ions,
- Electrodes and separator are impregnated with electrolyte
- Voltage 1-3 V
- Capacitance

hundreds of farads

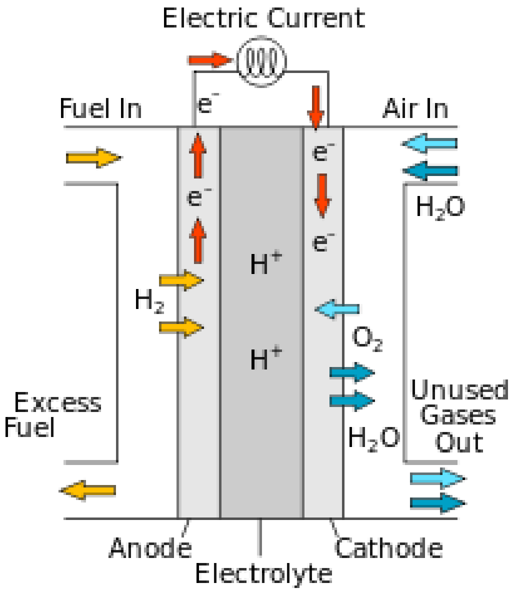


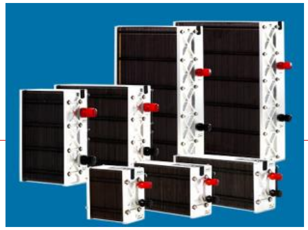


Fuel Cells

- A device that produces electricity through a chemical reaction, requires a continuous source of fuel and oxygen
- The reactions that produce electrical energy takes place on the electrodes
- Fuel cells also contains an electrolyte carrying ions from one electrode to the other, and a catalyst which accelerates the reaction at the electrodes
- Electricity <-> hydrogen as a fuel

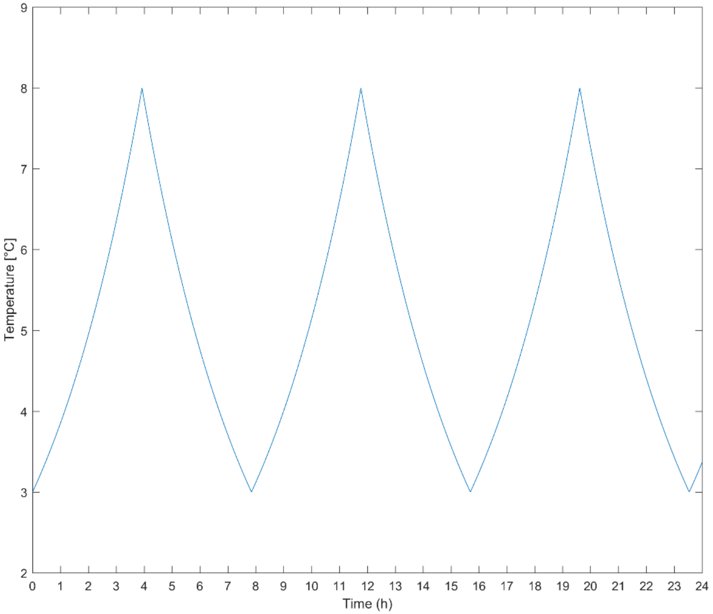


1 MW



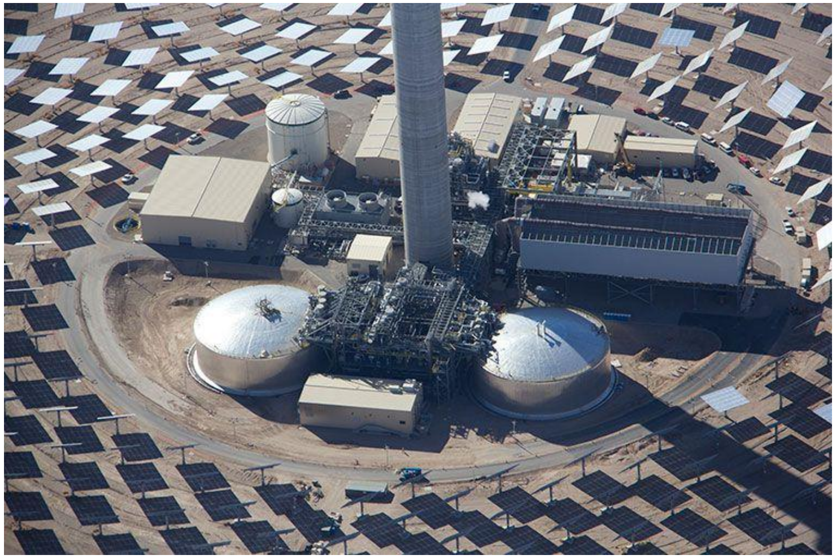
Storing Thermal Energy

- Boiler
- Refrigerator
- Building (HVAC)
- In district heating
- Molten-salt technology



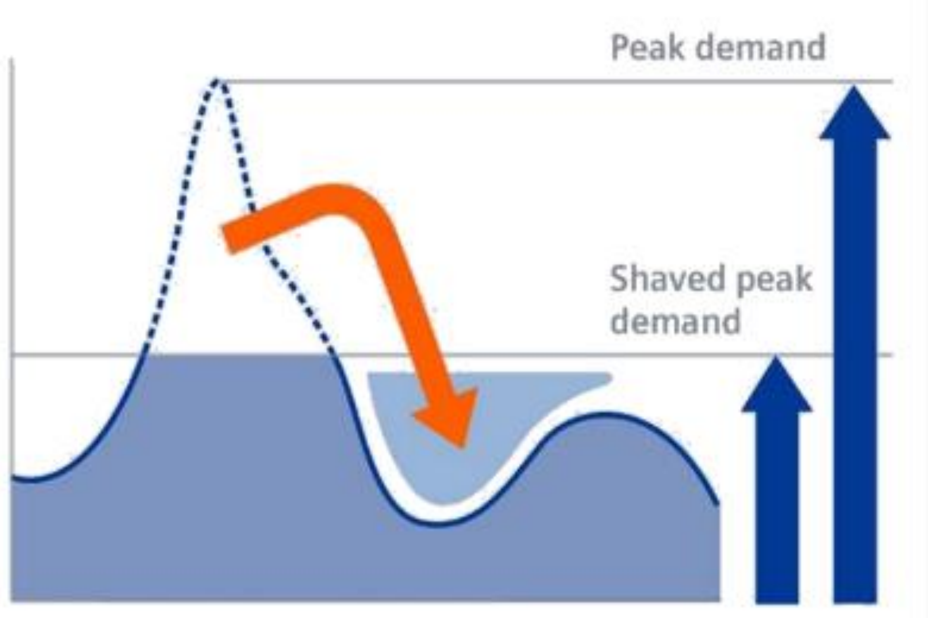
Storing Thermal Energy

- Molten-salt technology
- Molten salt is stored at 566ºC until electricity is needed



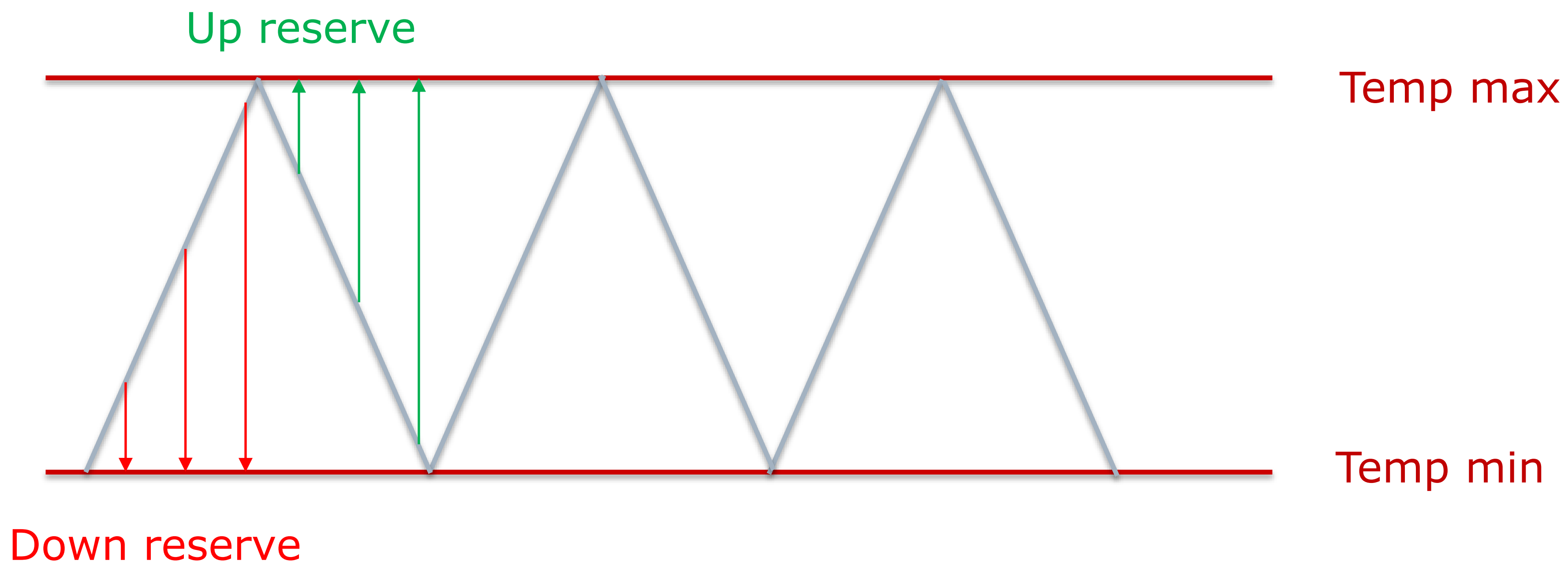
Demand Response

- Load shifting
- Stored thermal/cold energy, pressure (water supply), etc.
- Again, it stores energy through different energy vectors
- Multi-energy arbitrage, energy vector switching



Demand Response

- Load shifting
- Mainly based on the stored thermal energy, pressure (water supply), etc.



The length of the arrow corresponds to the possible duration of the service

How Can Energy Storage Earn Money (or Save)?

- Large-scale energy storage is connected to the transmission network
- Medium-scale energy storage is connected to distribution network
- Small-scale energy storage is connected by the end-user behind the meter

Energy Storage in the Day-Ahead Market

- Prices at CROPEX-u on Monday, February 26th 2018 (Eur/MWh)

Hour	Price	Hour	Price	Hour	Price
1	40,12	9	71,77	17	64,23
2	42,40	10	72,03	18	70,49
3	42,32	11	64,39	19	81,21
4	40,03	12	59,28	20	76,01
5	39,97	13	53,08	21	59,95
6	43,05	14	54,51	22	57,63
7	56,45	15	53,07	23	45,00
8	77,53	16	59,00	24	45,63

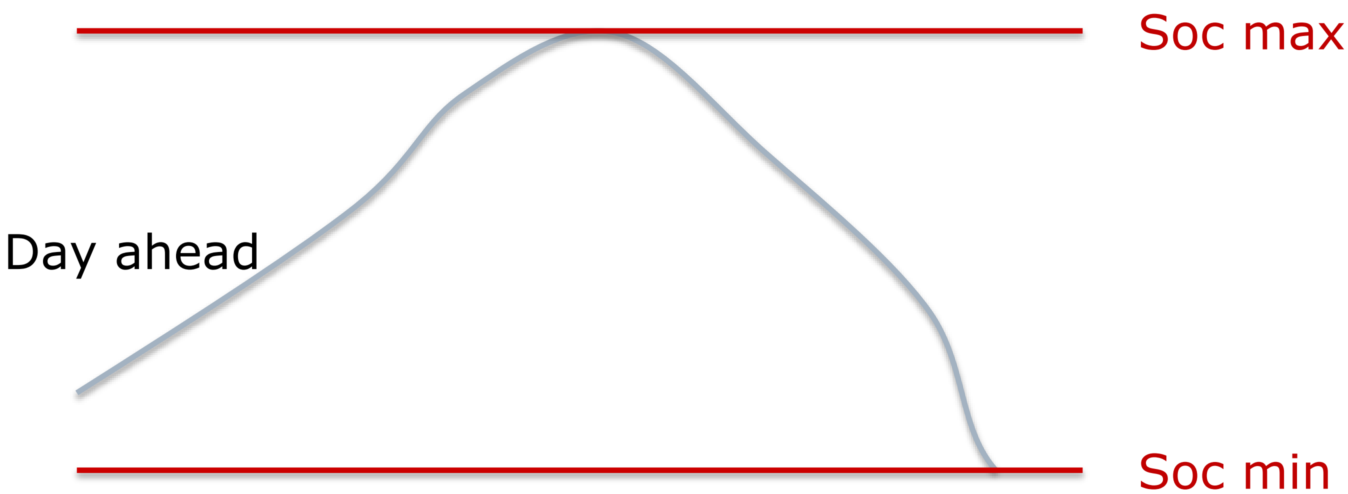
Energy Storage in the Day-Ahead Market

- In what way the storage should be charged and discharged in order to maximize profit? The rated power of the storage is 1 MW, energy capacity is 1 MWh, and efficiency is 0.9.

Hour	Price	Hour	Price	Hour	Price
1	40,12	9	71,77	17	64,23
2	42,40	10	72,03	18	70,49
3	42,32	11	64,39	19	81,21
4	40,03	12	59,28	20	76,01
5	39,97	13	53,08	21	59,95
6	43,05	14	54,51	22	57,63
7	56,45	15	53,07	23	45,00
8	77,53	16	59,00	24	45,63

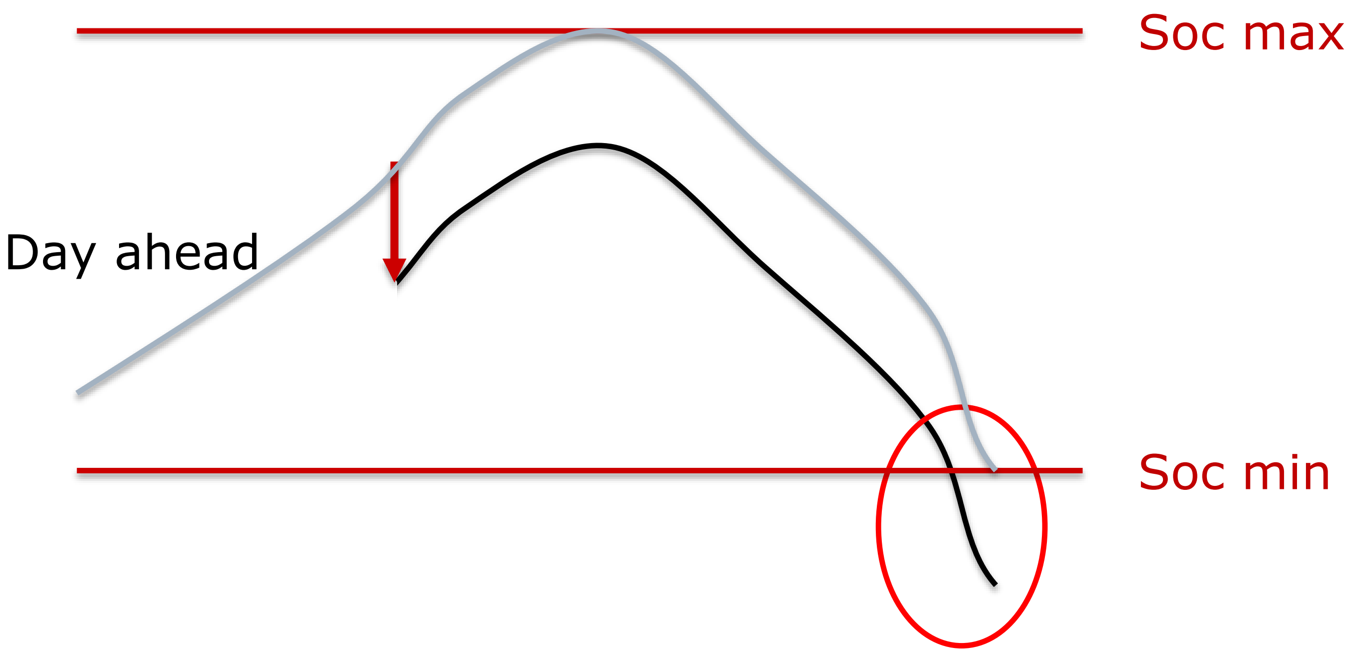
Energy Storage in the Reserve Market

- Batteries provide secondary/tertiary reserve:
  - It is possible to provide capacity, but what happens when this capacity is activated?

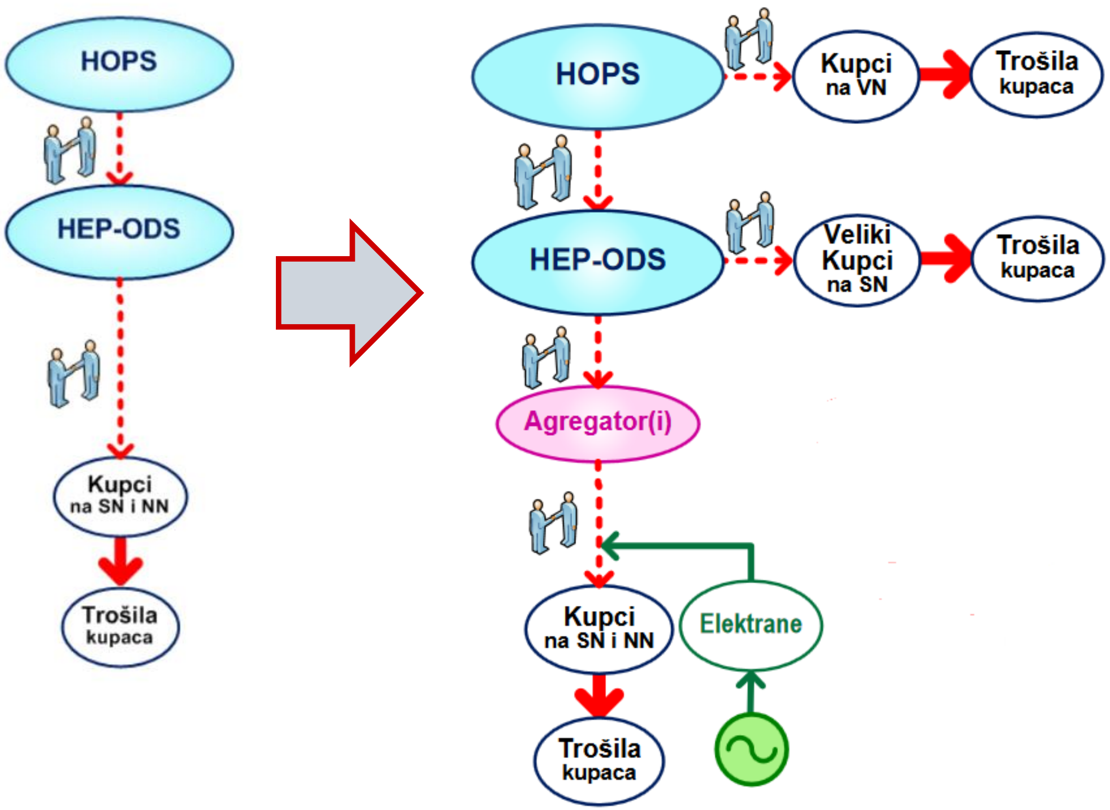


Energy Storage in the Reserve Market

- Batteries provide secondary/tertiary reserve:
  - It is possible to provide capacity, but what happens when this capacity is activated?



Energy Storage in the Distribution Network



Energy Storage in the Distribution Network

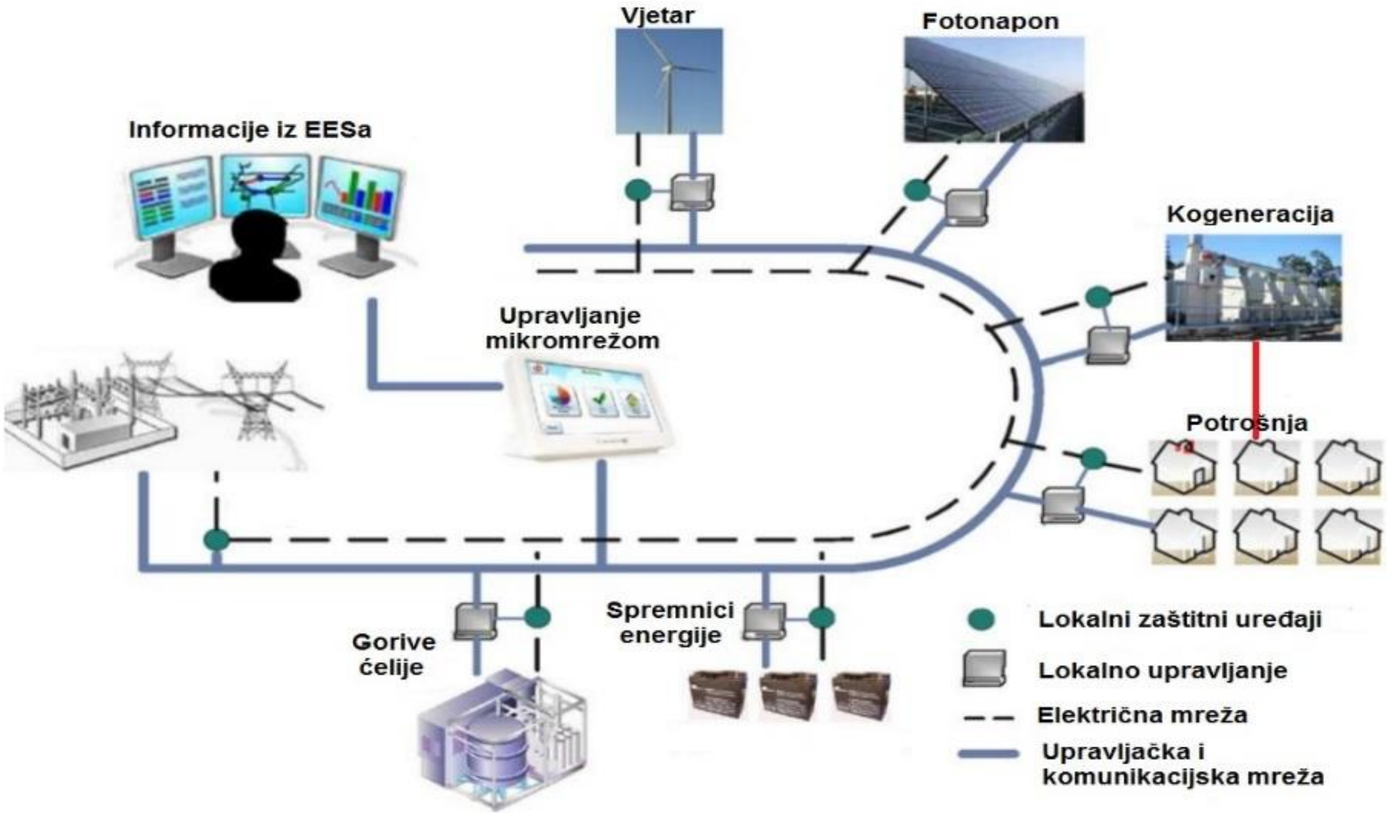
- Energy storage in the distribution network is able to participate in all the markets the same as storage in the transmission network, but it must be done by means of aggregators/virtual power plants/balancing group
- Virtual power plant (VPP) represents a dislocated flexible power plants/loads who act as a larger “central unit”/ conventional power plant

Behind-the-Meter Energy Storage

- Savings on energy consumption (shifting the consumption from high tariff to low tariff)
- Savings on the monthly peak load charge
- The ability to provide ancillary services through aggregators
- Microgrid concept

Microgrid

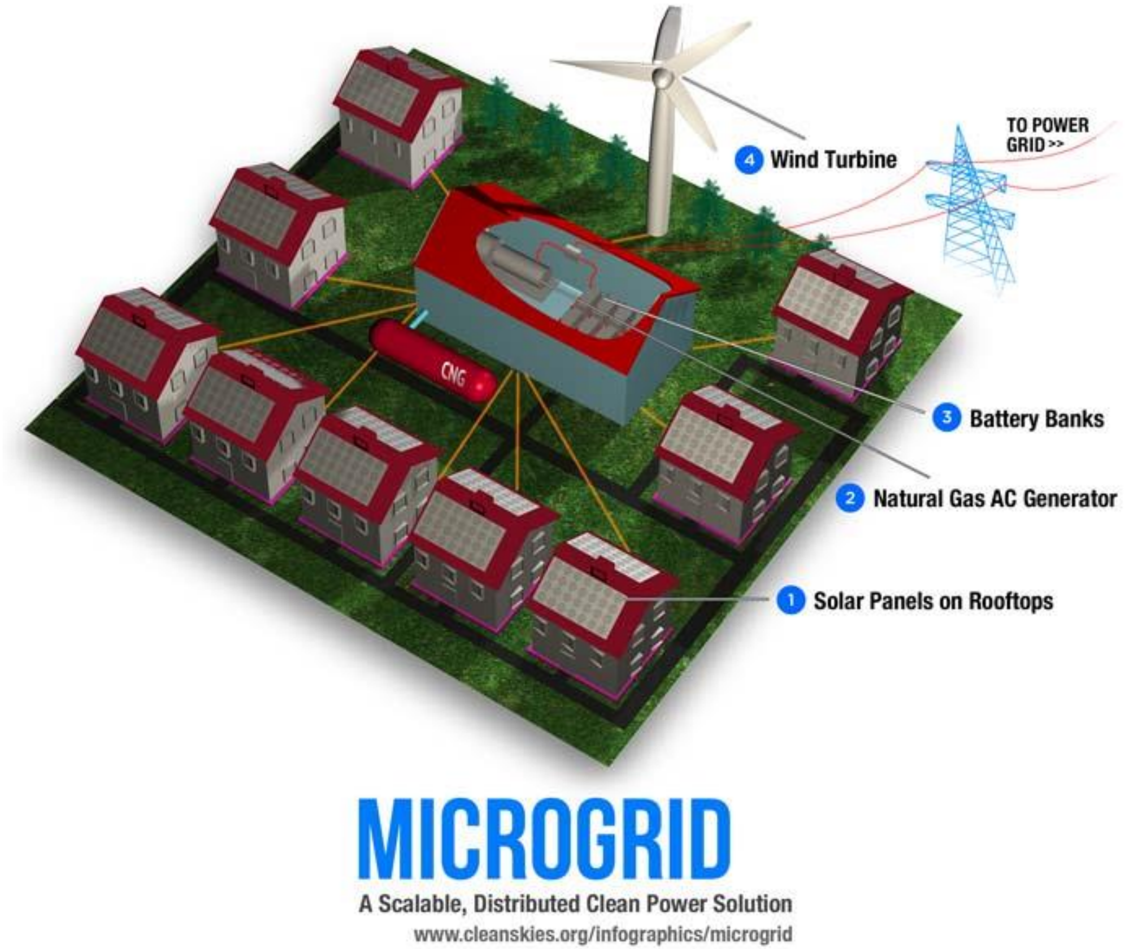
- Unlike virtual power plant, the microgrid has only one metering point



Microgrid

- Microgrids are subsystems of the distribution grid, which comprise generation capacities, storage devices, and controllable loads, operating as a single controllable system either connected or isolated from the utility grid.
- The control system of the microgrid automates and optimizes the operation of energy sources (conventional generators and RES), storage devices and controllable loads
- Optimal operation of a microgrid involves coordination of all the microgrid elements (minimization of the overall microgrid operating costs or emissions)

Microgrid Example



Optimal Microgrid Operation

- The central microgrid controller makes a decision based on the optimization model
- The model looks for optimal solution by taking into account technical limitations, current conditions in the microgrid and microgrid parameters
- The microgrid controller must take decisions about:
  - How much electricity each dispatchable units should generate
  - When should storage device be charged or discharged
  - Curtailment schedule
- Decisions are being implemented using the control and measurement system
- Optimization is performed periodically

Microgrid’s Dispatchable Components

- Conventional generators:
  - Maximum production (kW)
  - Minimum production (kW)
  - Ramp rate (kW/min)
  - Minimum up time (min)
  - Minimum down time (min)
  - Operating costs (Eur/kW)
  - Start-up costs (Eur)

Microgrid’s Dispatchable Components

- Energy storage:
  - Maximum charging/discharging power (kW)
  - Storage energy capacity (kWh)
  - Minimum energy level of the storage (kWh)
  - Cycle efficiency
  - Degradation
- Controllable loads
  - Efficiency level?
    - Lightning: 100% -> 0%
    - Air conditioners (home): 100% -> 100 – 130%
    - HVAC: 100% -> 50 – 130%
    - Industry: 100% -> 100 – 120%

Optimal Microgrid Operation

- The expected non-dispatchable loading during 6 hour period is given in the table. The microgrid also comprises of two dispatchable units and a controllable load. The first dispatchable unit has rated power 150 kW and operating costs 0,040 €/kWh, while the second unit has rated power 150 kW and operating costs 0,060 €/kWh. Controllable load has rated power 25 kW. Determine the operation costs in the following cases:
  1. Controllable load cannot be controlled.
  2. Controllable load is lightning (0% retrieveal factor) and it is possible to shift 20% of consumption in each hour, a total of 12.5 kWh during 6 hours.
  3. Controllable load is HVAC (120% retrieval factor) and it is possible to shift 20% of consumption in each hour, a total of 12.5 kWh during 6 hours.
  4. Controllable load cannot be controlled, but a battery is included in the microgrid; roundtrip efficiency is 0.9 and battery is empty at the beginning.
  5. Combination of 3 and 4.

Hour	Load
1	80 kW
2	160 kW
3	220 kW
4	90 kW
5	200 kW
6	180 kW