Peer to Peer activity
December 05.2020

Energy storage technologies for storing renewable energy: technical and economic overview

PROSPECT2030 | HSMD | Prof. P. Komarnicki, Dr. P. Lombardi

AGENDA

Motivation

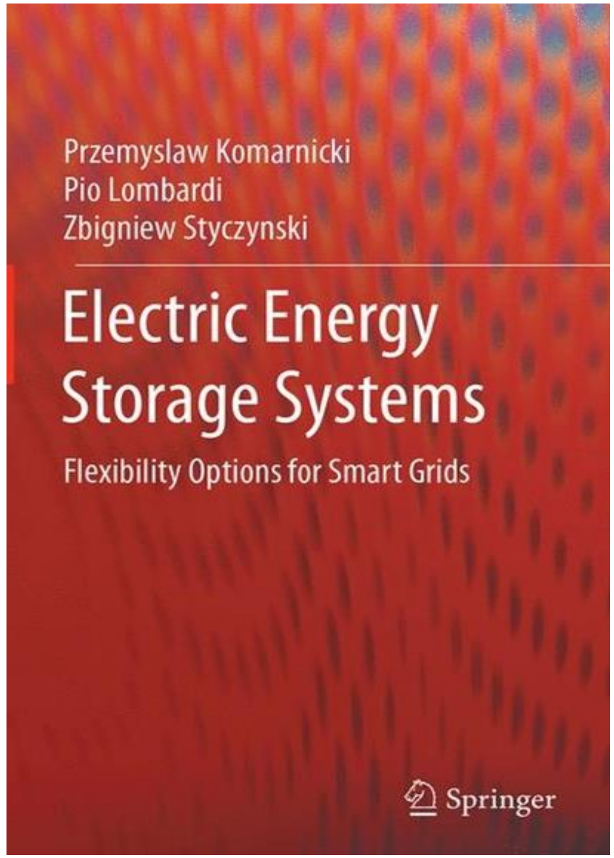
Why do we need energy storage systems?

Energy storage classification

Energy storage technologies

Economical aspects

SOURCE


Przemyslaw Komarnicki
Pio Lombardi
Zbigniew Styczynski
Electric Energy
Storage Systems
Flexibility Options for Smart Grids
Springer

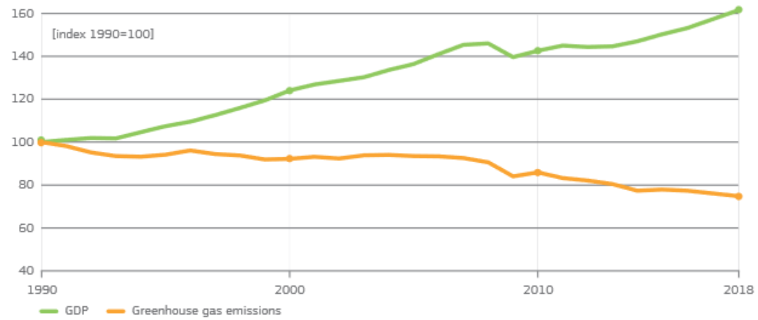
PHISICAL PROPERTY OF ENERGY STORAGE

Interreg CENTRAL EUROPE European Union European Regional Development Fund PROSPECT2030

Property	Unit	Comment
Power	W	Charging and discharging power
Power density	W7kg; W/m³	Usable power pro mass/volume
Energy capacity	Wh	Usable energy content of the storage
Energy density	Wh/kg; Wh/m³	Usable energy content pro mass/volume
Efficiency	%	Efficiency to convert and store energy from an form to another one
Self-discharge	%	Amount of energy lost during the time

EUROPEAN GREEN DEAL STRATEGY

Interreg CENTRAL EUROPE
European Union European Regional Development Fund
PROSPECT2030



CO_2: - 23%
(in 2018)

2020

RES: 20%
(in 2018: 18,9%)

CO_2: - 55%

2030

RES: 32%
***CO_2: - 40%**
EEff:+32,5%

RES: 100%

CO_2: climate neutrality

2050

* Through the EU ETS, Effort Sharing Regulation (Building, transport, agriculture and waste) and Land use, forestry regulation

BACKGROUND-SET PLAN CONSEQUENCES

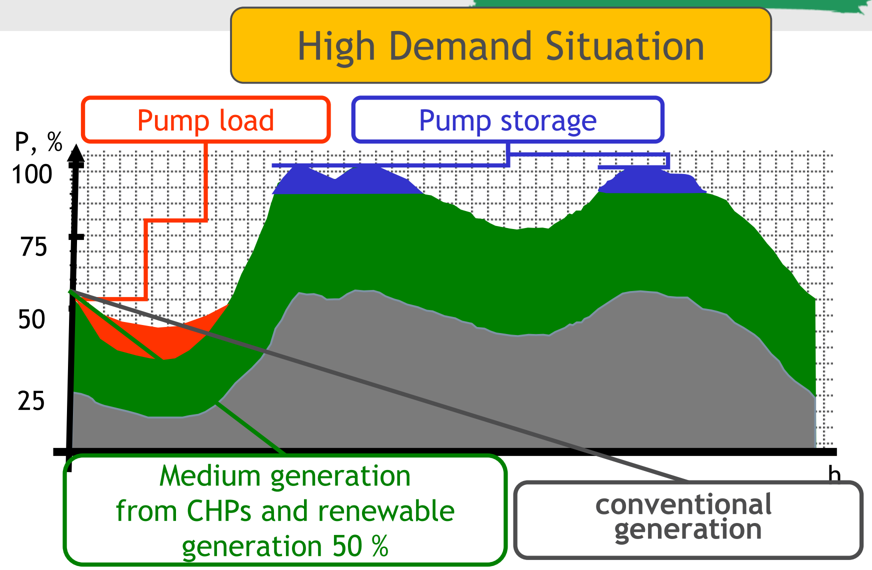
Interreg CENTRAL EUROPE
European Union European Regional Development Fund
PROSPECT2030

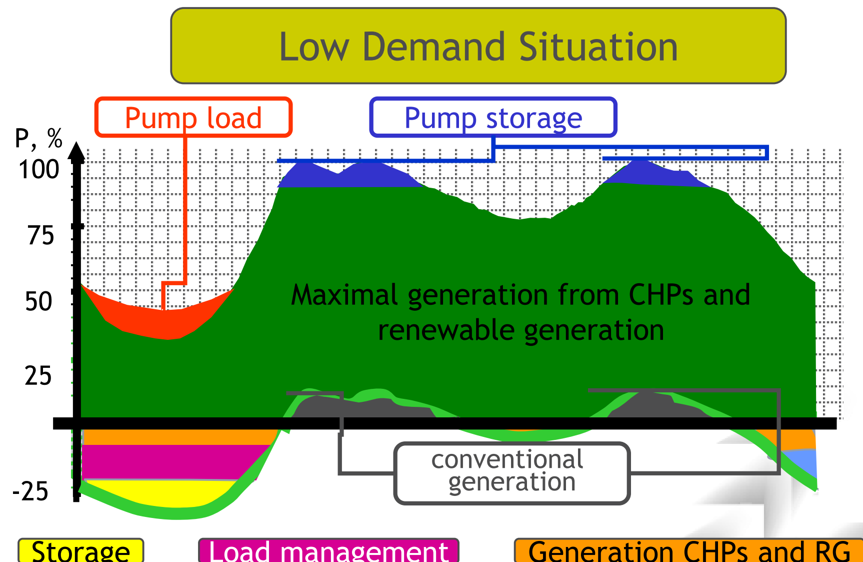
SET-Plan	2020		2030	
Plant	E, %	P, GW	E, %	P, GW

Wind 11 180 18 300 PV
3 125 14 665
Solar- 1,6* 1,8 5,5 4,6 H2O,
L.S. 8,7 108 8,3 112 H2O, S.S
1,6 18 1,6 19 Tidal 0,8
10 1,1 16 Biomass 4,7 30
5,3 190 Bio-CHP 18 185
21 235 **Sum** **49,4** **657,8**
75,8 **1542**

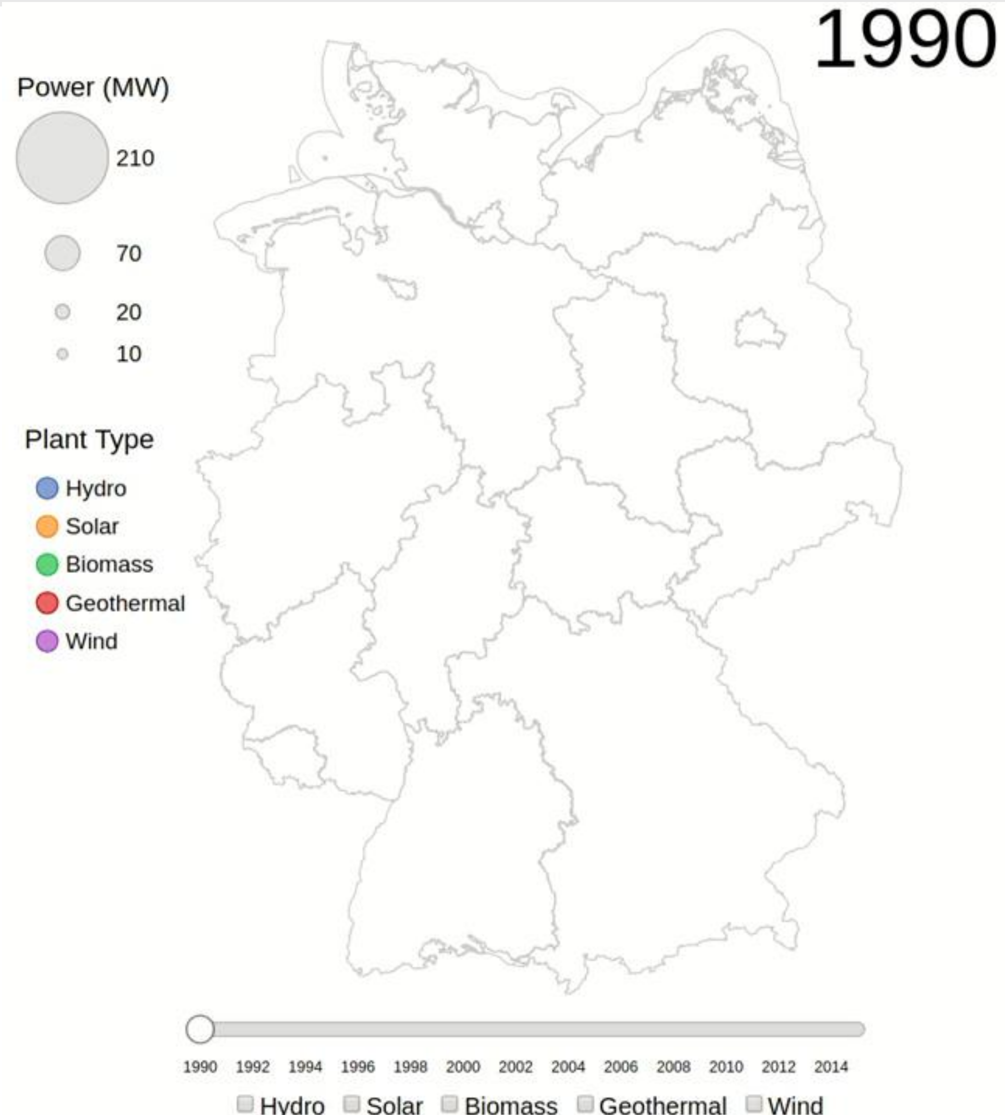
*) Import from Nord Africa

UCTE 2009:
610 GW





DEVELOPMENT OF RES IN GERMANY



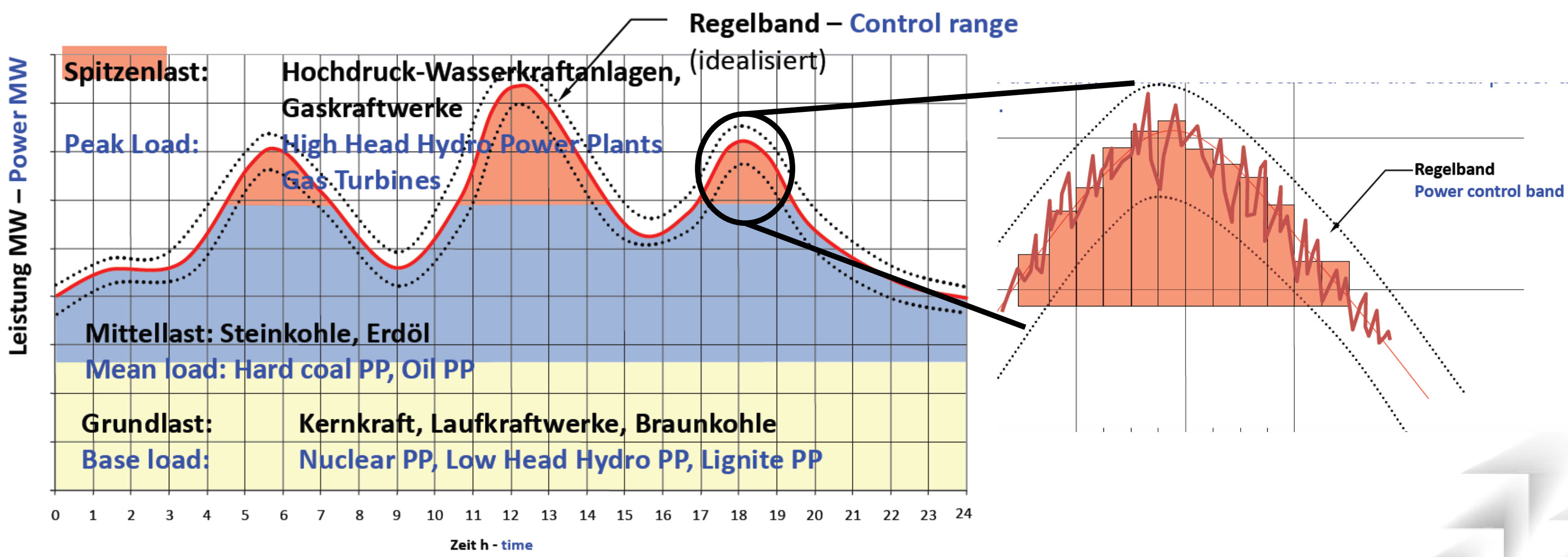
BACKGROUND BALANCING DEMAND AND SUPPLY

To maintain electricity quality, balancing the demand and supply is essential. Middle load, usually supplied by natural gas combined-cycle plants, can play an important role in balancing the demand and supply, and can also serve as backup capacity in case of a renewable power supply shortfall. A much higher share of renewable power with variable generation will raise a number of engineering issues in the future:

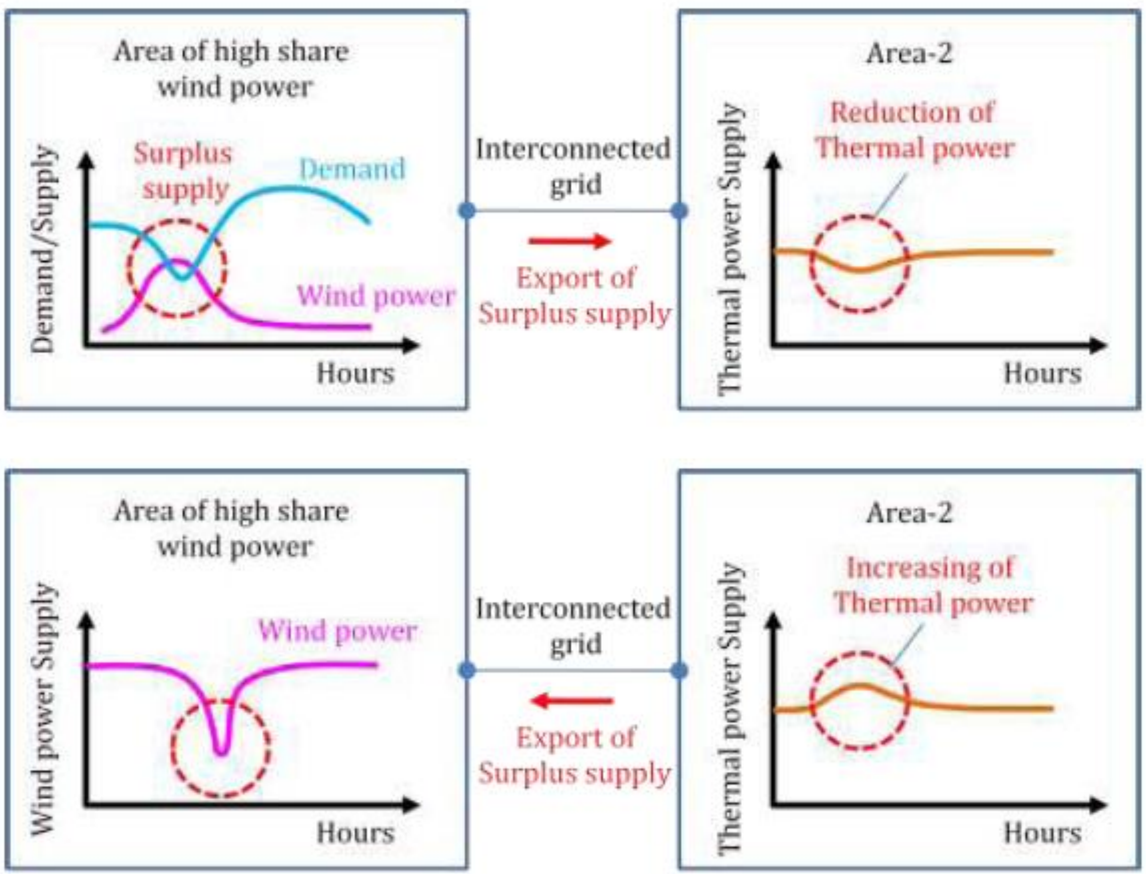
1) Short-term variation: variability on the scale of seconds or minutes will cause larger deviations of power system frequency.

2) Hourly variation: variability on the scale of hours will increase the difficulty of hourly generation dispatch and unit commitments, and influence the electricity trade between power systems.

3) Longer-term variation: variability on the scale of days or months, which influences the stable supply of wind power.



BACKGROUND BALANCING DEMAND AND SUPPLY FROM RES



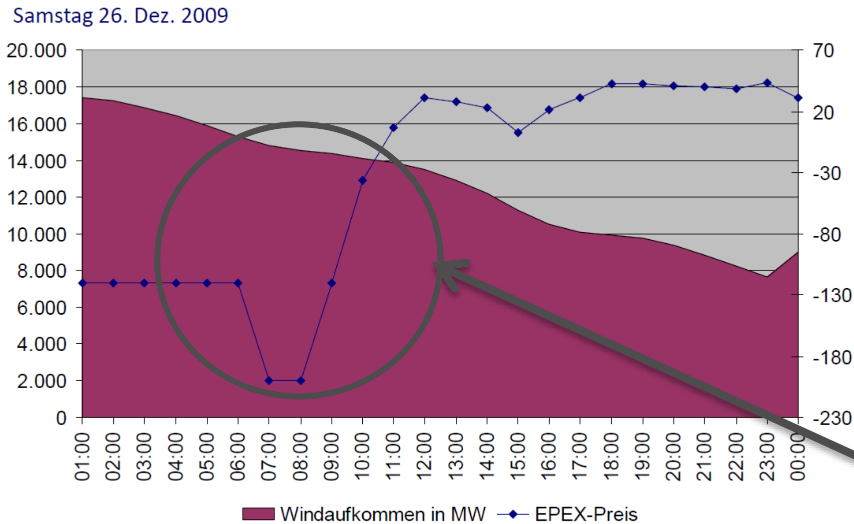
In case of surplus, the excess power is transferred to other areas where it is balanced by thermal power plant (NGCC or CHP).

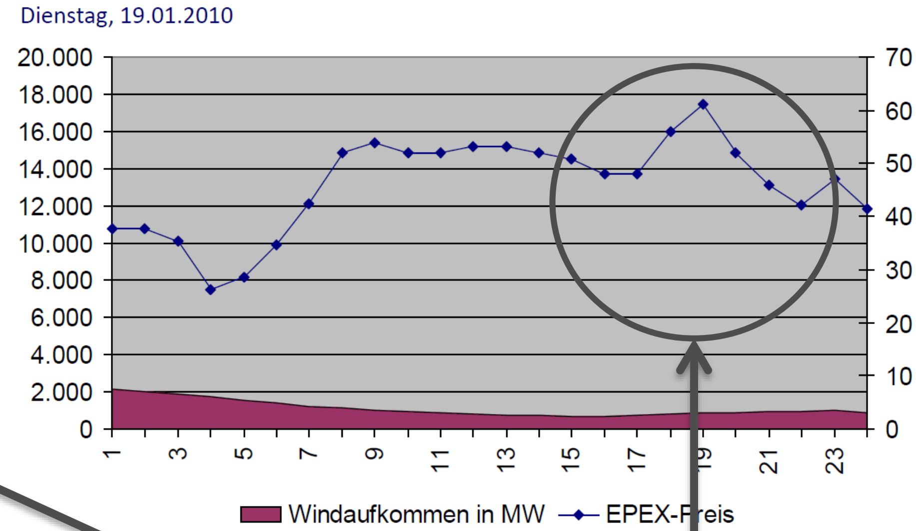
In case of deficit, thermal power plants increase their power capacity. The power is then transferred in the areas where deficit is.

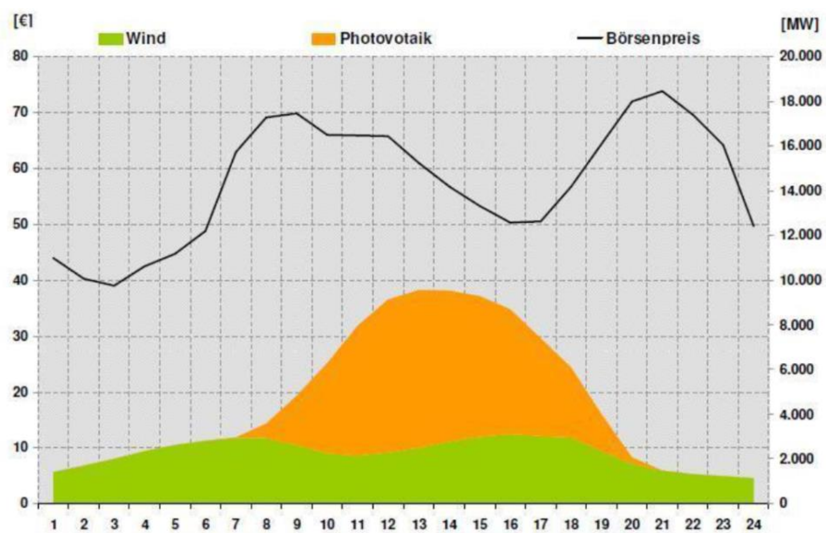
Source: International Energy Agency

BACKGROUND-EFFECT OF RES GENERATION ON THE ELECTRICITY PRICE

Interreg CENTRAL EUROPE
European Union European Regional Development Fund
PROSPECT2030



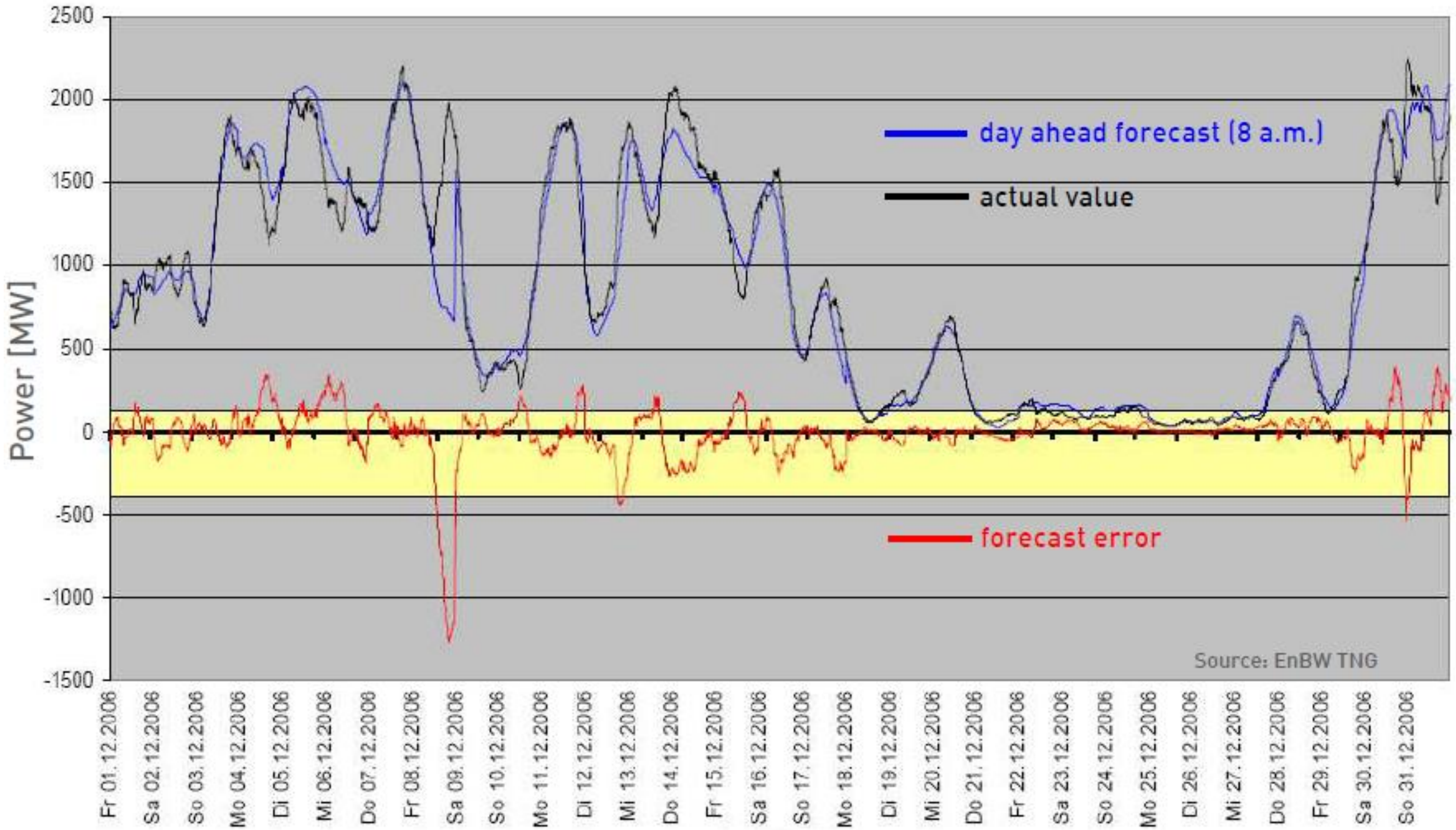




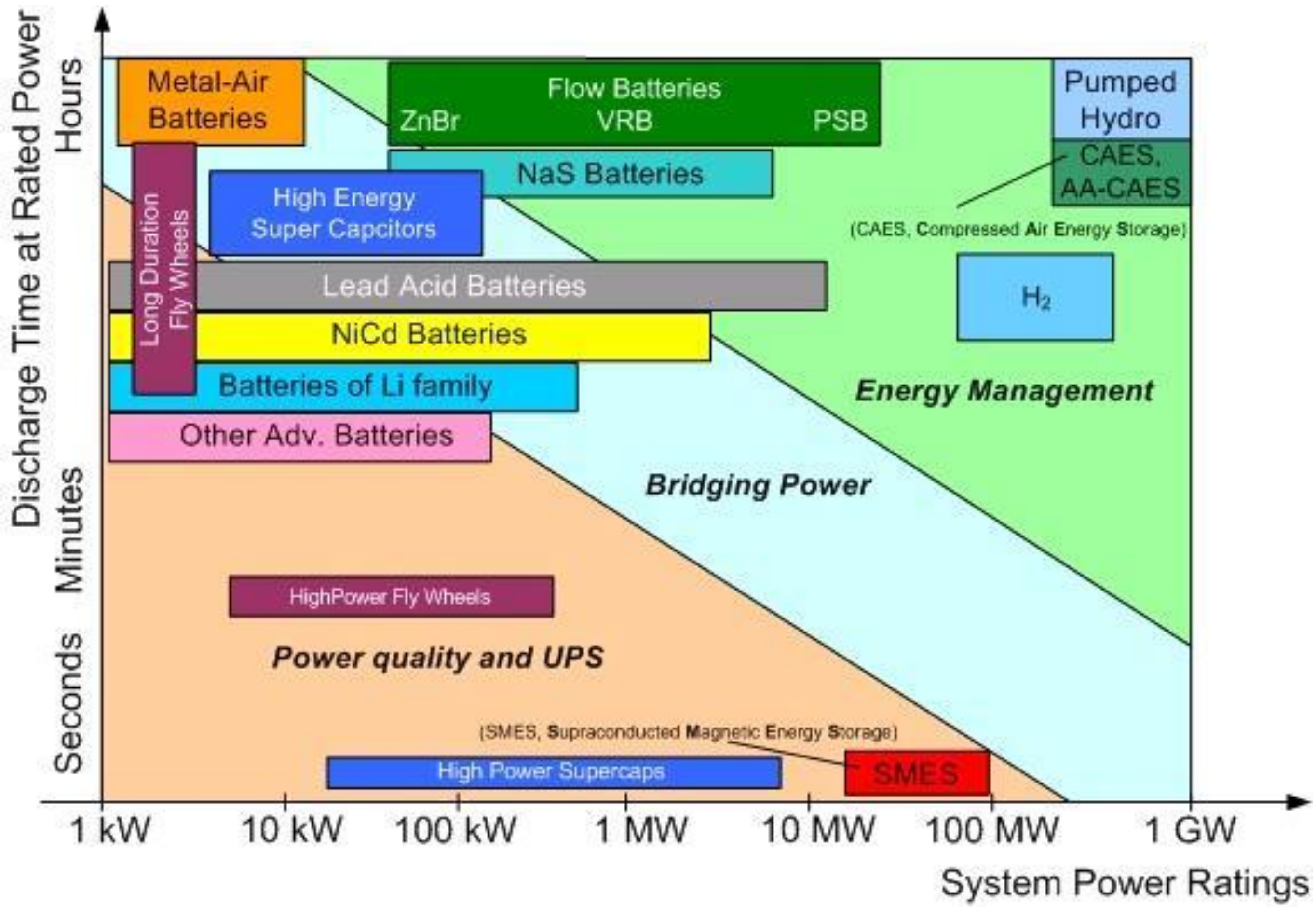
High RES generation and low demand → negative electricity price

Low wind generation and high demand → high electricity price

BACKGROUND-EFFECT OF RES GENERATION ON ELECTRICITY PRICE



ENERGY STORAGE SYSTEMS CLASSIFICATION

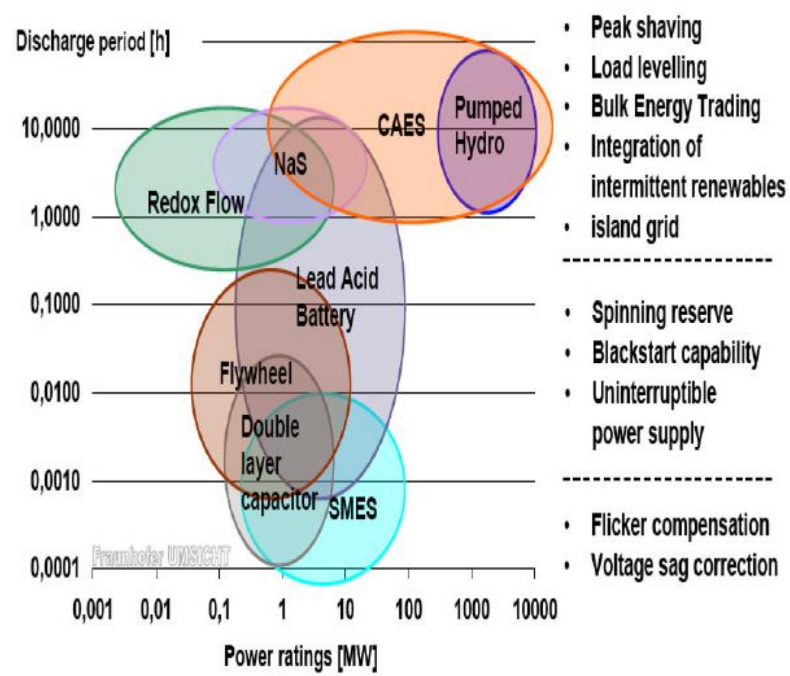


ENERGY STORAGE SYSTEMS, CLASSIFICATION

Storage Technologies	Main Advantages (relative)	Disadvantages (Relative)	Power Application	Energy Application
Pumped Storage	High Capacity, Low Cost	Special Site Requirement		●
CAES	High Capacity, Low Cost	Special Site Requirement, Need Gas Fuel		●
Flow Batteries: PSB VRB ZnBr	High Capacity, Independent Power and Energy Ratings	Low Energy Density	◐	●
Metal-Air	Very High Energy Density	Electric Charging is Difficult		●
NaS	High Power & Energy Densities, High Efficiency	Production Cost, Safety Concerns (addressed in design)	●	●
Li-ion	High Power & Energy Densities, High Efficiency	High Production Cost, Requires Special Charging Circuit	●	○
Ni-Cd	High Power & Energy Densities, Efficiency		●	◐
Other Advanced Batteries	High Power & Energy Densities, High Efficiency	High Production Cost	●	○
Lead-Acid	Low Capital Cost	Limited Cycle Life when Deeply Discharged	●	○
Flywheels	High Power	Low Energy density	●	○
SMES, DSMES	High Power	Low Energy Density, High Production Cost	●	
E.C. Capacitors	Long Cycle Life, High Efficiency	Low Energy Density	●	◐

● Fully capable and reasonable ○ Feasable but not quite practical or economical

◐ Reasonable for this application None Not feasable or economical



Source: Storage Technology Comparison: Application from: NRCAN - "State of Technologies", 2008

Source: Electricitystorage.org: "Technologies and applications". 2003

ENERGY STORAGE SYSTEMS, TECHNICAL PARAMETERS

Storage Type	Power	Duration of Discharge	Efficiency (%)	Lifetime	Total Capital Cost (USD/kW)
CAES (100-300 MW, Underground)	15-400 MW	2-24 hrs	54 (Eff_{NG}=1)* 76(Eff_{NG}=0.54)* 88(Eff_{NG}=0.39)*	35 years	600-750
Pumped Hydro	250 MW >1 GW	12 hrs	87	30 years	2700-3300 Upgrade:300**
Li Ion	5 MW	15 min to several hrs	90 (DC)	15 years	4000-5000
Lead Acid	3-20 MW	10 sec to several hrs	75-80 (DC) 70-75 (AC)	4- 8 years	1740-2580
NaS	35 MW	8 hrs	80–85 (DC)	15 years	1850-2150***
VRB Flow Cell	4 MW	4-8 hrs	75–80 (DC) 63–68 (AC)	10 years	7000-8200
ZnBr Flow Cell	40-100 kW, 2 MW	2-4 hrs	75–80 (DC) 60–70 (AC)	20 years	5100-5600
High Power Flywheel	750-1650 kW	15 sec to 15 min	93	20 years	3695-4313
ZEBRA	<10 MW	Up to 8 hrs	80-85 (DC)	Over 1500 cycles shown	1500-2000***
Fe/Cr Flow Battery	<10 MW	2-4 hrs	50-65	20 years	200-2500***
Zn/Air	20 kW-10 MW	3-4 hrs	40-60	a few hundred cycles	3000-5000***
SMES	1-3 MW	1-3 sec	90	>30,000 cycles	380-490
SMES****	100 MW-200 MW	100 sec (MWh) 0.5-1h (100MWh) 5-10 hr (GWh)	90	>30,000 cycles	700-2000
Ultra capacitors	10 MW	Up to 30 sec	90	>500,000 cycles	1500-2500

*For CAES, the following efficiency is usually used:

$$\bullet \eta = \frac{1.00\ kWh}{\left(\frac{4330}{3600}\right)Eff + 0.67}$$

Where Eff is
- 1.0 for natural gas
- 0.54 for NGCC
- 0,385 for simple GT

** Based on an interview for manufactures

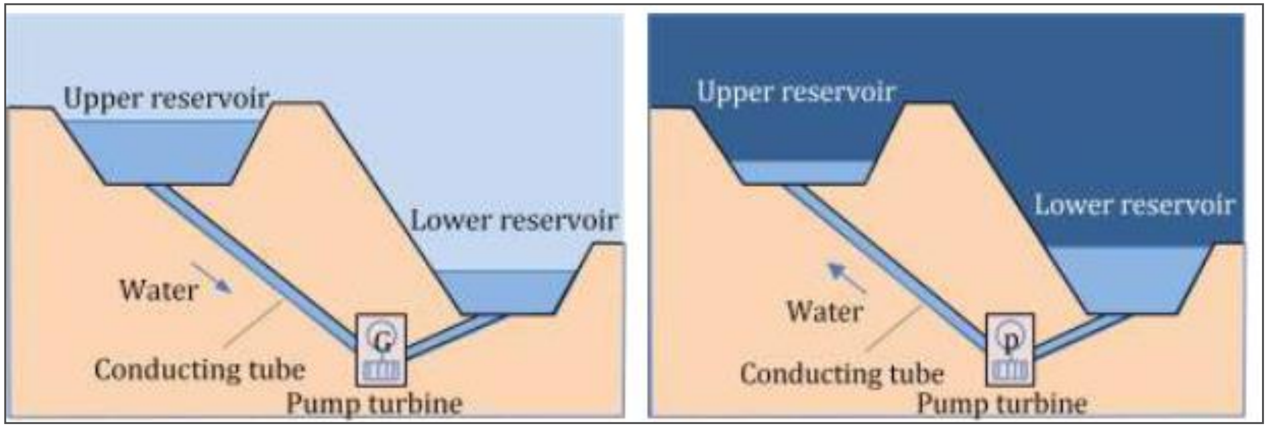
***Projected

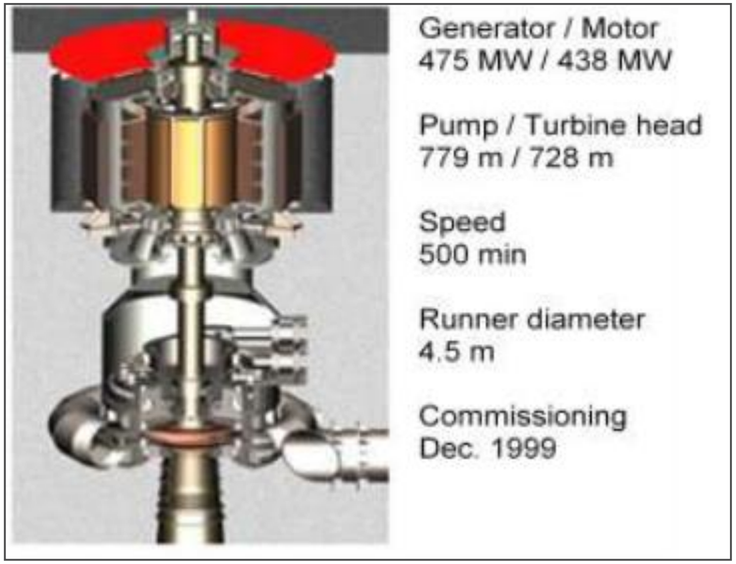
****Estimated by RASMES (Research Association of SMES, Japan)

Source: IEA

ENERGY STORAGE SYSTEMS, PUMPED HYDRO SYSTEMS

Interreg CENTRAL EUROPE
European Union European Regional Development Fund
PROSPECT2030

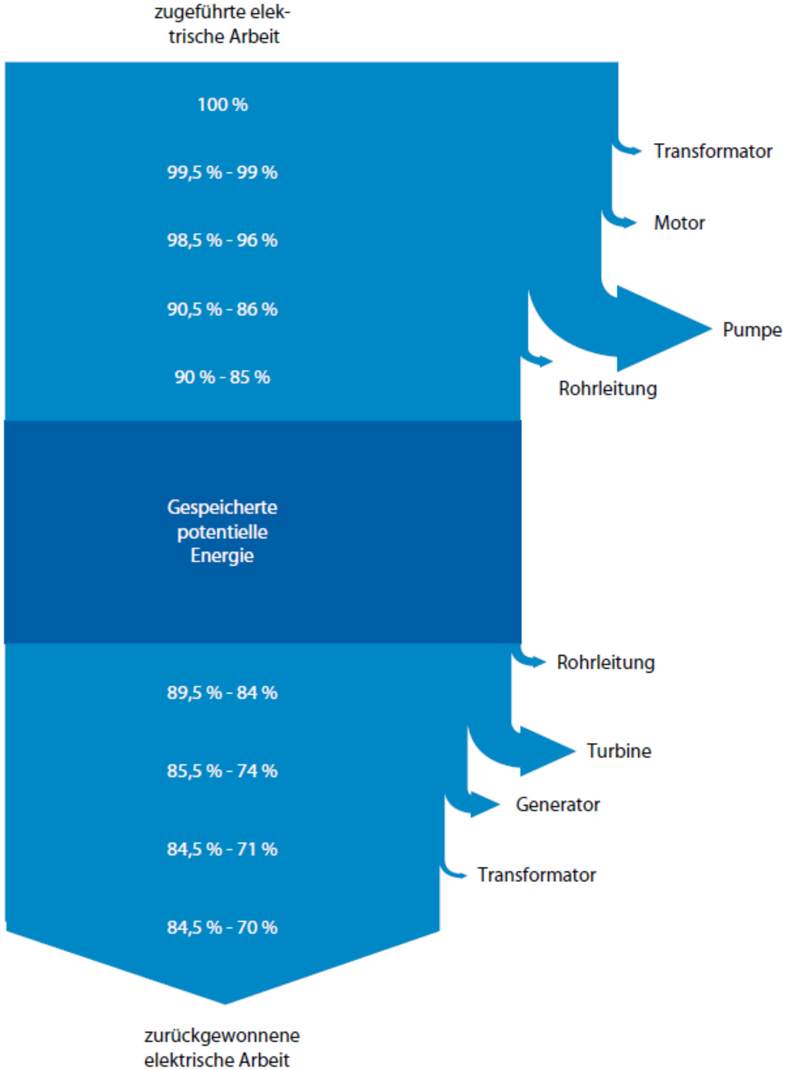




Source: Hitachi ltd, 2008

Pumped hydro systems are today the most widely applied energy storage technology, with about 110 GW installed worldwide. The pump-turbine is the key device. In periods of discharging (usually during daytime), the system generates power just like a conventional hydropower plant. In periods of charging (usually during night), water is pumped from a lower reservoir to an upper reservoir. In some designs, a single machine operates as a turbine and as a as pump; in other cases, two separate machines are installed.

ENERGY STORAGE SYSTEMS, PUMPED HYDRO SYSTEMS



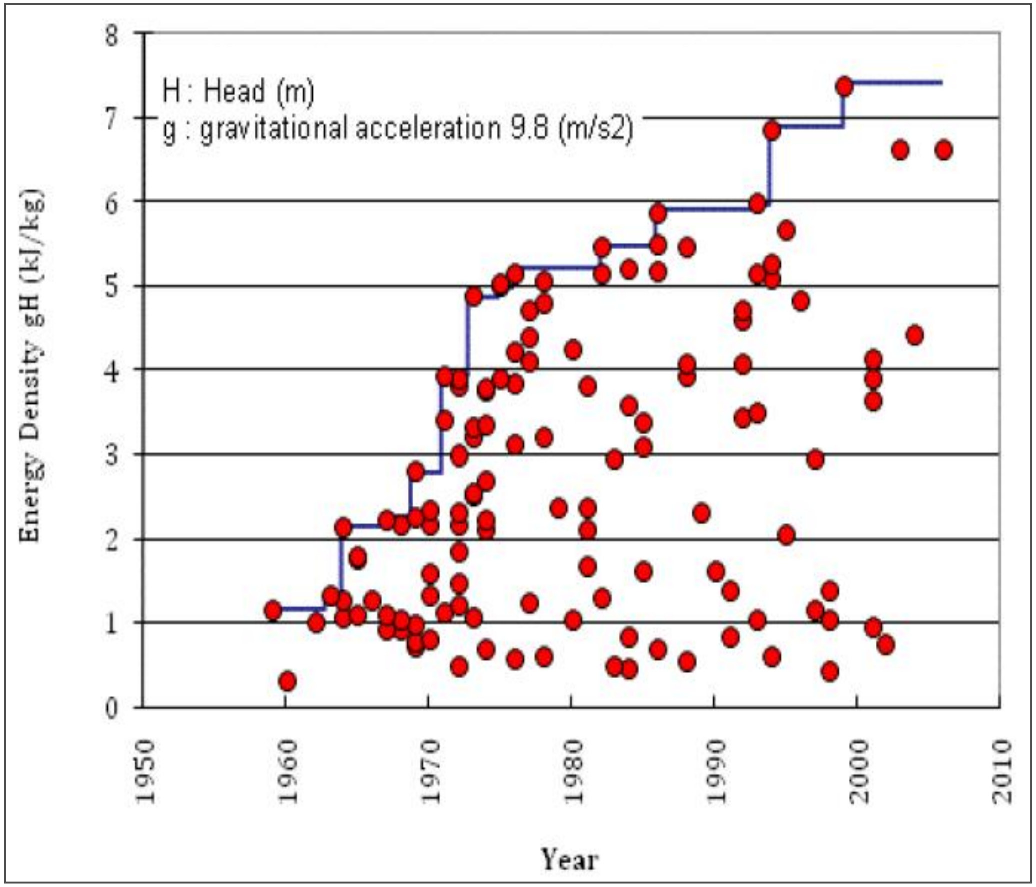
Pumped hydro systems are suitable for large capacity energy storage, as described above, and have long lifetimes of over 40 years. Their efficiency is approximately 70% as shown in the following equation.

$$\eta_{Tot} \cong [0.92 \times 0.98 \times 0.93][0.92 \times 0.92 \times 0.93] \cong 0.70$$

$$\eta_{Tot} = \eta_c \, \eta_d = \left[\eta_p \eta_M \left(\frac{H-\Delta H_p}{H}\right)\right]\left[\eta_t \eta_G \left(\frac{H-\Delta H_t}{H}\right)\right]$$

- η_c: charging efficiency,
- η_d: discharging efficiency,
- η_p: pumping efficiency,
- η_t: turbine efficiency,
- η_M: motor efficiency of generator/motor,
- η_G: generator efficiency of generator/motor,
- H: head, The difference in water elevation between the upper and lower reservoirs
- ΔH_p: loss head of water way in pumping operation,
- ΔH_t: loss head of water way in turbine operation

ENERGY STORAGE SYSTEMS, SEA WATER PUMPED HYDRO SYSTEMS



Sources IEA, based on data Mc COY, report 2008 (2008)

The energy density of the water in a pumped hydro plant increases as the pump turbine head increases, as shown in the following equation:

$$E = \frac{\int P dt}{\rho V} = gH$$

where

- E is specific energy or energy density of water (J/kg),
- P is power (W),
- ρ is water density (kg/m3),
- V is volume of water (m3),
- g is gravitational acceleration (m/s2),
- H is pump turbine head (m).

Consequently, relatively small-volume water reservoirs and relatively compact pump turbines are required for high-head pumped hydro units, which have a large amount of energy stored in the upper reservoir. This feature of high-head pumped hydro has led to the use of higher and larger pump turbines in order to make the storage system more cost-effective.

ENERGY STORAGE SYSTEMS, SEA WATER PUMPED HYDRO SYSTEMS

A seawater pumped hydro plant has the following advantages:
1) It is comparatively easy to find an appropriate location for the plant because the vast
ocean is utilized as the lower reservoir.
2) They can attain up to 80% efficiency because of the short waterway length, which reduces the hydraulic losses by 93% to 98%

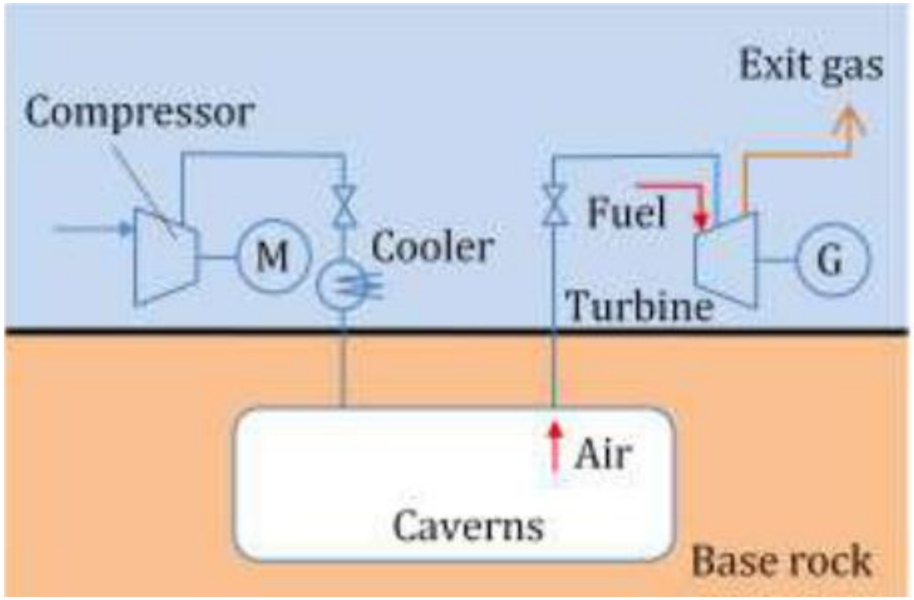
COSTS COMPARATION

Devices	Conventional pumped hydro	Seawater pumped hydro
Pump turbine	1.0	1.54
Generator motor	1.0	
Main transformer and BOP	1.62	
Total	3.62	4.16

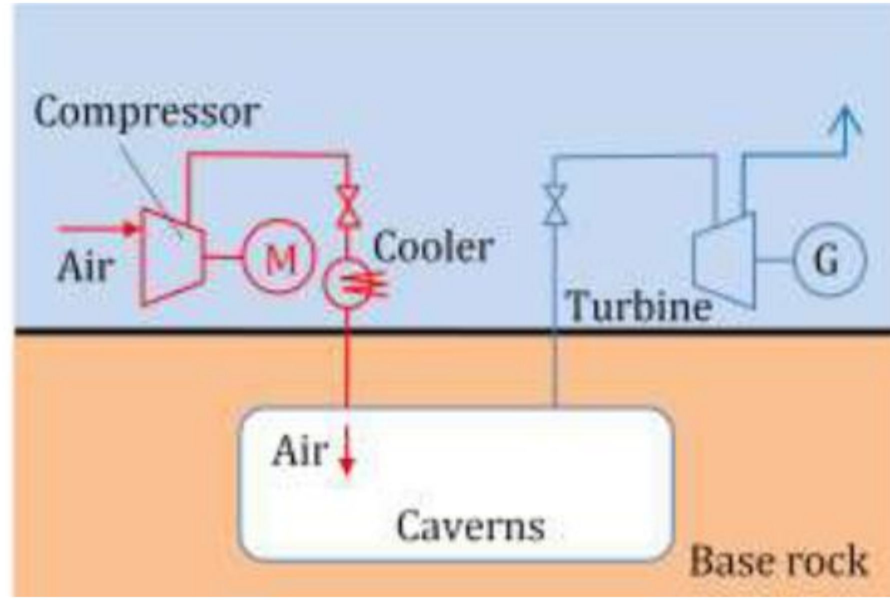
ENERGY STORAGE SYSTEMS COMPRESSED AIR STORAGE SYSTEMS (CAES)

Interreg CENTRAL EUROPE European Union European Regional Development Fund
PROSPECT2030

discharging

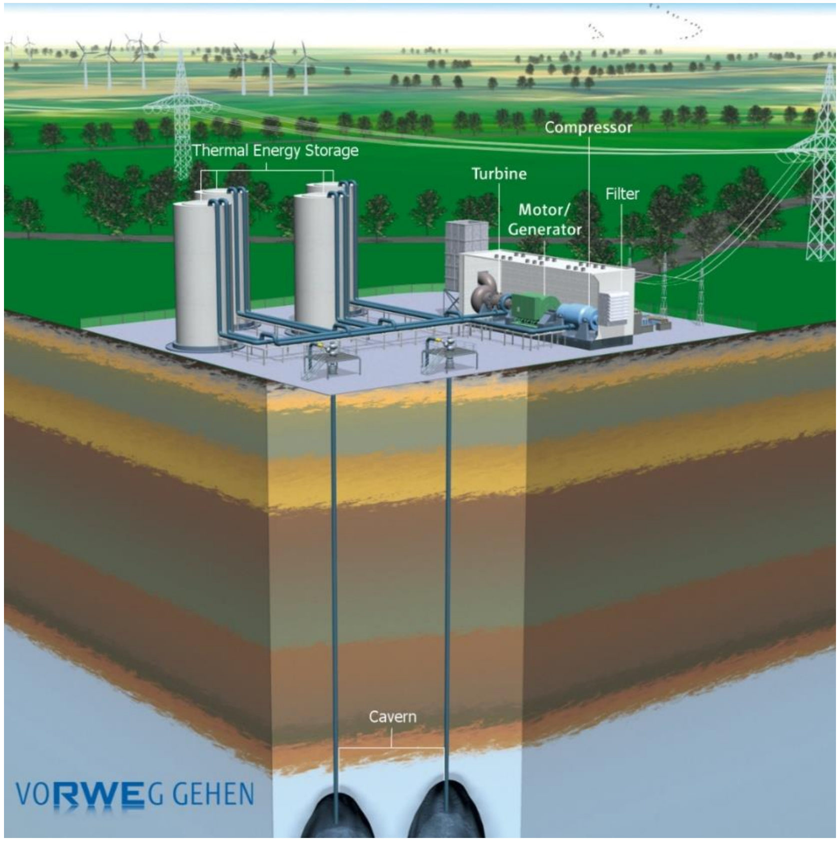


charging



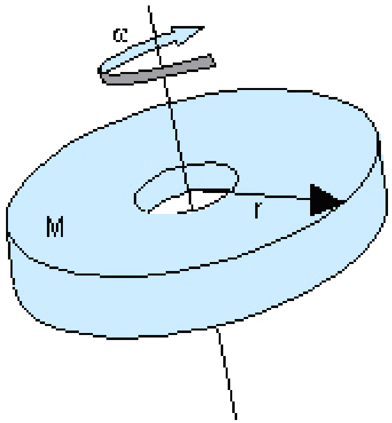
A CAES system consists of compressor unit with a motor unit, gas turbine, and underground compressed air storage in salt caverns. When charging, usually at night, the motor unit consumes power to compress and store air in the underground chamber. The compressed air is usually cooled via a cooler unit. When discharging, usually during daytime peak loads, the compressed air is supplied to a combustor in the gas turbine to burn fuel. The combusted gas is expanded through the turbine, which drives the generator and produces electric power.

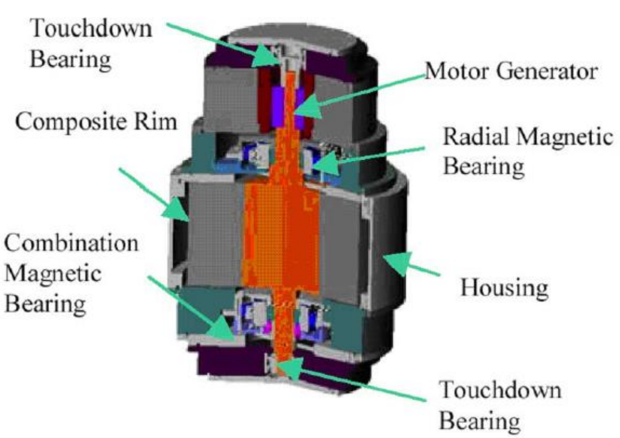
ENERGY STORAGE SYSTEMS COMPRESSED AIR STORAGE SYSTEMS (AA-CAES)



The storage efficiency of the CAES plants is reduced by cooling the air before it enters the cavern and reheating it prior to burning it with the fuel. In the advanced adiabatic cycle, heat energy is extracted and stored separately before the compressed air enters the cavern. When energy is required by the grid, the compressed air and heat energy are recombined, and expanded through an air turbine. This adiabatic CAES system benefits from higher storage efficiencies and, notably, zero CO2 emissions. It is being developed through the ―AA-CAES (Advanced Adiabatic - Compressed Air Energy Storage).
As for different approaches, a compressor with an internal cooler and water atomization cooling (WAC) might effectively reduce the power needed to drive the compressor. This power depends on the density of air, which is a function of air temperature. With an intermediate cooler, the air temperature is decreased. The WAC is a simple system that injects water mist of 10μm particle size at the compressor inlet. The water mist particles are vaporized through the compressor and the air temperature is decreased by the heat of vaporization.

FLYWHEEL STORAGE SYSTEMS





Flywheels store energy in the form of the angular momentum of a spinning mass, called a rotor. The work done to spin the mass is stored in the form of kinetic energy. The amount of kinetic energy stored in a spinning object is a function of its mass and rotational velocity:

$$E = \frac{1}{2} I \omega^2$$

Where
E is the kinetic energy
I is the moment of inertia (with units of mass-distance^2),
ω is the rotational velocity (with units of radians/time). The moment of inertia is dependent on the mass and geometry of the spinning object. It can be shown that for a solid disc rotating about its axis, stored kinetic energy is described by the equation:

$$E = \frac{1}{4} M r^2 \omega^2 \cong \frac{1}{4} M v^2$$

Where M is the mass of the disc, r is its radius, and v is the linear velocity of the outer rim of the cylinder (approximated by r). Increasing the rim speed is more effective than increasing the mass of the rotor in improving the energy capacity of a flywheel.

FLYWHEEL STORAGE SYSTEMS, ENERGY CONVERSION, FRICTION-LOSSES AND THERMAL EFFECTS

Increase the speed of the flywheel

Charge

Discharge

Decrease the speed of flywheel

Friction-losses
- Rotor-Surrounding environment
- Rotor bearing and its supports

Thermal effect
- Losses transformed into heat → increase temperature flywheel

Solution
- Heat is removed from the flywheel
- Vacuum containment and magnetic bear are used
- Cooling system may be used

FLYWHEEL STORAGE SYSTEMS, COMPONENTS: ROTOR90ß0

- Rotor
  - Low speed (up to ~10,000 rpm)
    - Horizontal shaft
    - Vertical shaft
  - High speed (up to ~100,000 rpm)
    - Horizontal shaft
    - Vertical shaft

Low speed horizontal shaft flywheel. Source: Satcom power system

High speed vertical shaft flywheel. Source: Satcom power system

ENERGY DENSITY

Interreg CENTRAL EUROPE European Union European Regional Development Fund PROSPECT2030

Energy storage technology	Energy density
Condensator	10 kWh/m^3
SMES	3 kWh/m^3
Li-ion Battery	300 kWh/m^3
Lead-acid battery	70 kWh/m^3
Hydrogen	400 kWh/m (@300 K,200 bar)
Gasoline	10.000 kWh/m^3
Flywheel	20 kWh/m^3 (@ 5000 rpm)
CAES	20 kWh/m^3 (@ 70 bar)

THANK YOU FOR YOUR ATTENTION