SESSION 1:

ENERGY STORAGE SYSTEM – INTRODUCTIONS AND TRENDS

Master: Renewable Energy Systems

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Wroclaw, 08.03.2024

Wrocław University of Science and Technology

Fraunhofer IFF

Hochschule Magdeburg • Stendal

Organisation

Lecture: Energy Storage Systems: WUST Wroclaw, 2024

Master: Renewable Energy Systems

Lecturer: Prof. Dr.-Ing. Przemyslaw Komarnicki,
M. Sc. Marcel Hallmann

Place: Building D20, Room 314

Time: Friday from 09:15 am to 2:00 pm.

Modules: **I 9.15-10.45; II 10.50-12.20; III 12.30-14.00; (5*45 Minutes)**

Contact: Justyna Herlender - Building D20, Room 212 - e-mail: justyna.herlender@pwr.edu.pl

Organisation

Date	Topic	Lecturer
Session 1: 08.03.24	Energy Storage System – introductions and trends	M. Hallmann
Session 2: 22.03.24	Physical properties, models and technologies	Dr. S. Balischewski
Session 3; 19.04.24	Applications and systems	M. Hallmann
Session 4: 17.05.24 (11.00 – 12.00)	EXAM Preparation (optional)	Prof. P. Komarnicki
Session 5: 07.06.24	FINAL EXAM	Prof. P. Komarnicki/ M. Hallmann

Overview and sources

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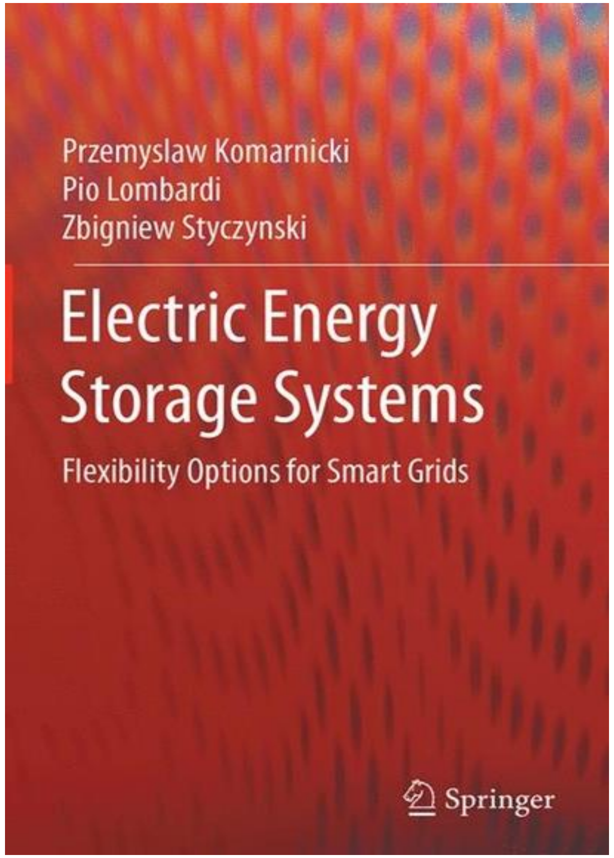

https://www.springer.com/de/book/9783662532744

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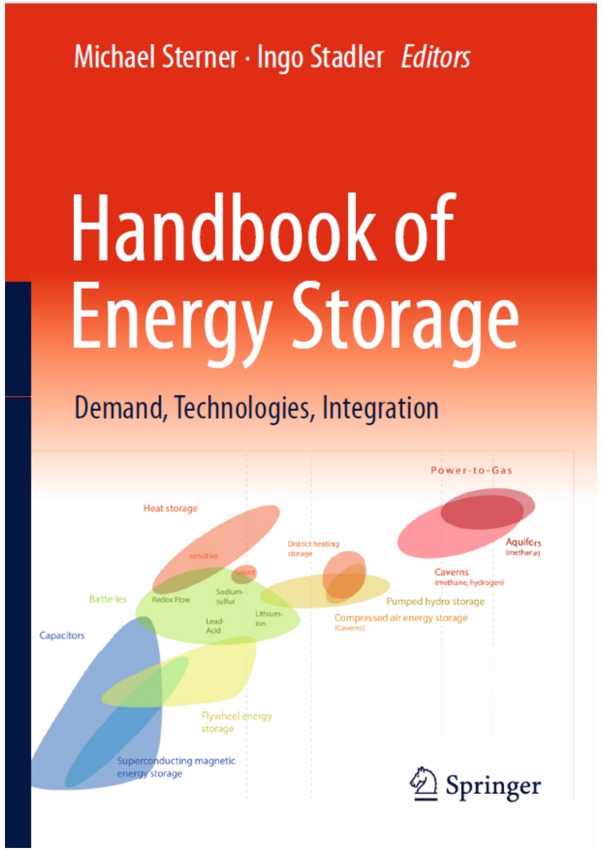

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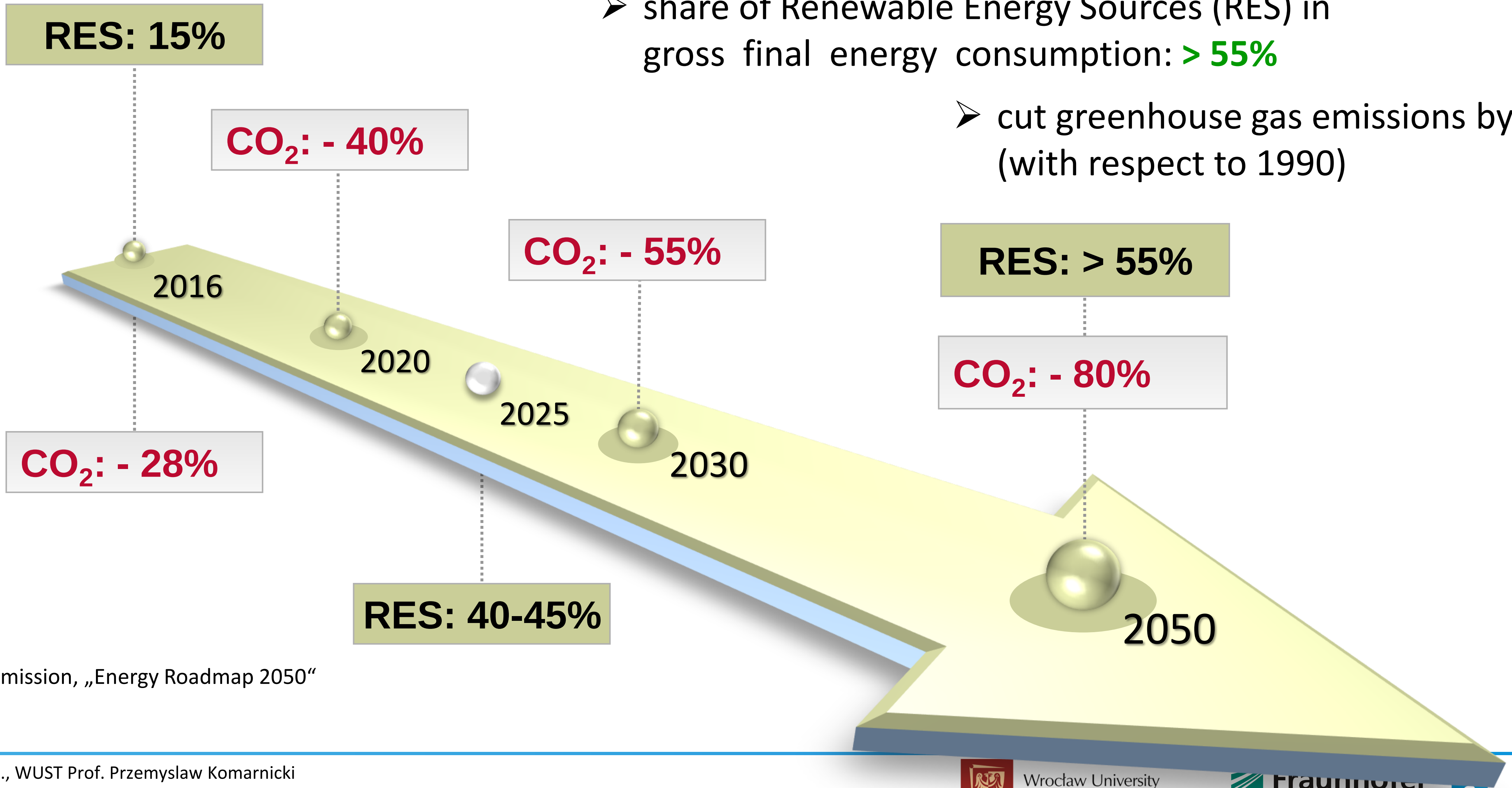
Storage requirements in the energy industry

Regulatory framework - EU and Germany - goals by 2050

- share of Renewable Energy Sources (RES) in gross final energy consumption: > 55%
- cut greenhouse gas emissions by: >80% (with respect to 1990)

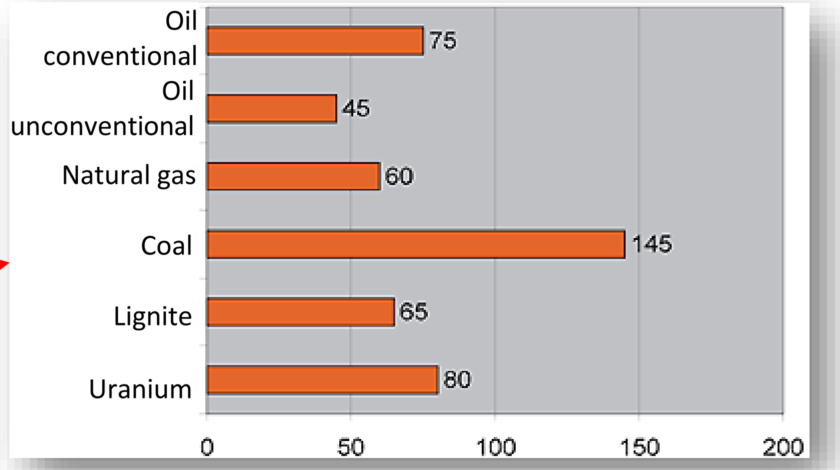


EU Commission, „Energy Roadmap 2050“

Storage requirements in the energy industry

Regulatory framework - Expansion of RES

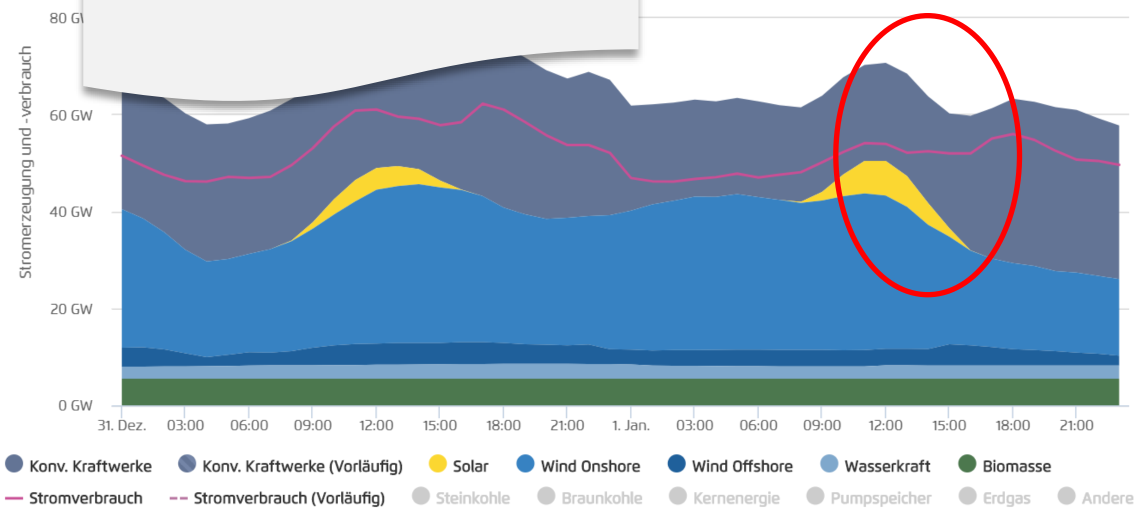
- RES are becoming more and more important around the world
  - increasing global energy demand
  - decreasing availability of fossil fuels
  - reduction of greenhouse gases (Stop global warming)



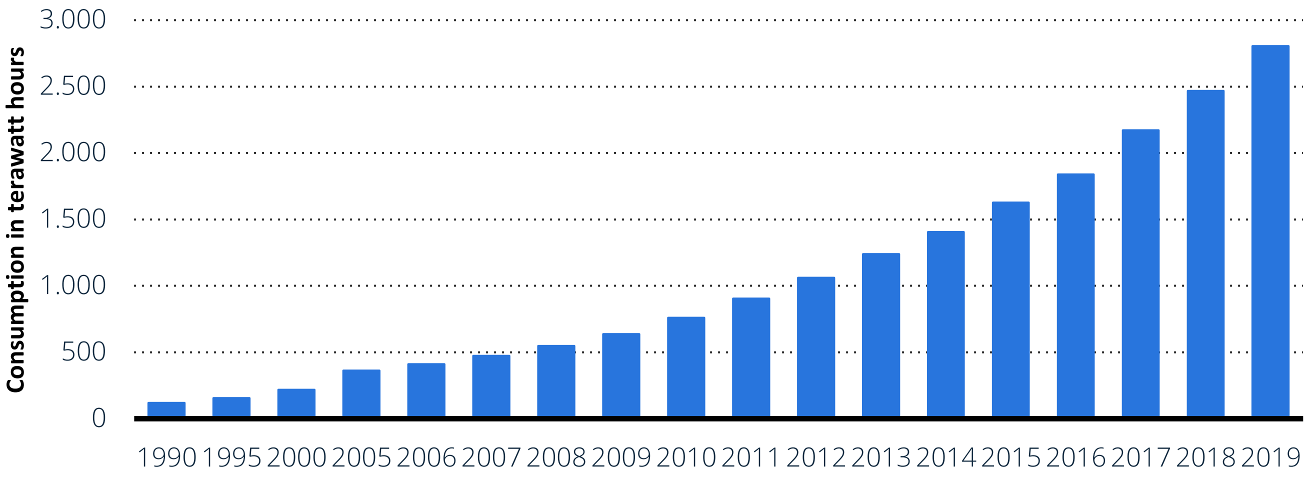
Volume of fossil fuel resources in years
source: IGS Braunschweig

NEW RECORD 2018

GERMANY RECEIVES 95PERCENT OF ITS ELECTRICITY FROM RENEWABLE ENERGIES



Worldwide consumption of renewable energies from 1990 to 2019 (in terawatt hours)



Source: statista.de

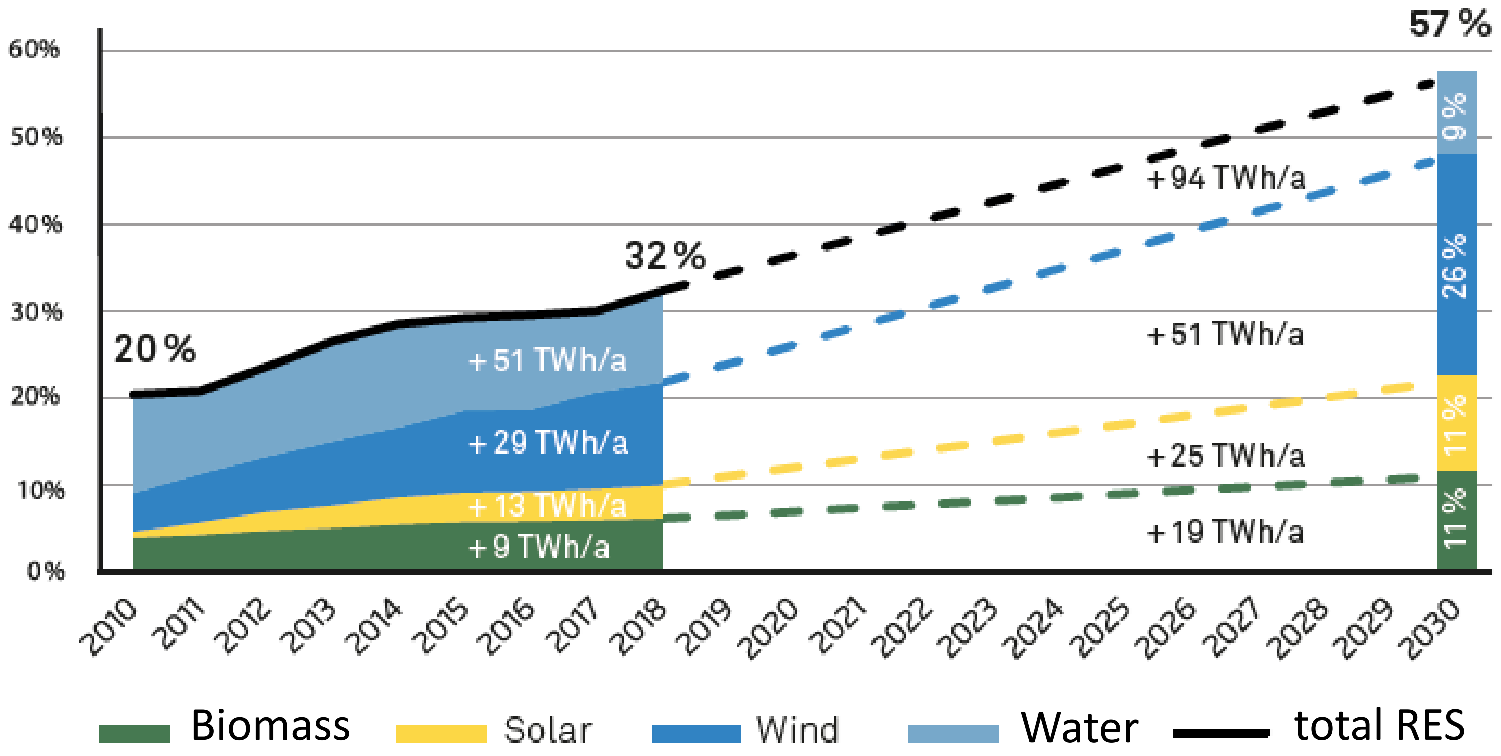
Storage requirements in the energy industry

Motivation - Characteristic of regenerative generation

- 2/3 of the RES from PV and wind
- Volatile feed-in especially with wind and PV
- Renewable energy supply profiles are not consumption-oriented
- The highest potential lies in wind energy
- Fluctuations EE feed must be compensated
- Increased need for balancing energy
- supply of power plant reserves increases

Long-term strategy of the European Union:
Projection of electricity from renewable energies until 2030

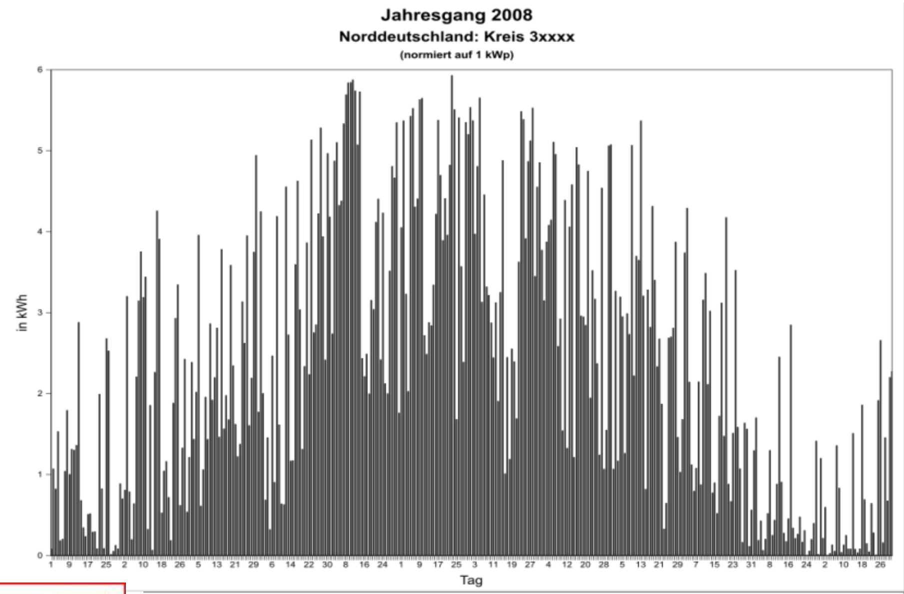
Quelle/Grafik: Agora Energiewende & Sandbag, The European Power Sector in 2018.

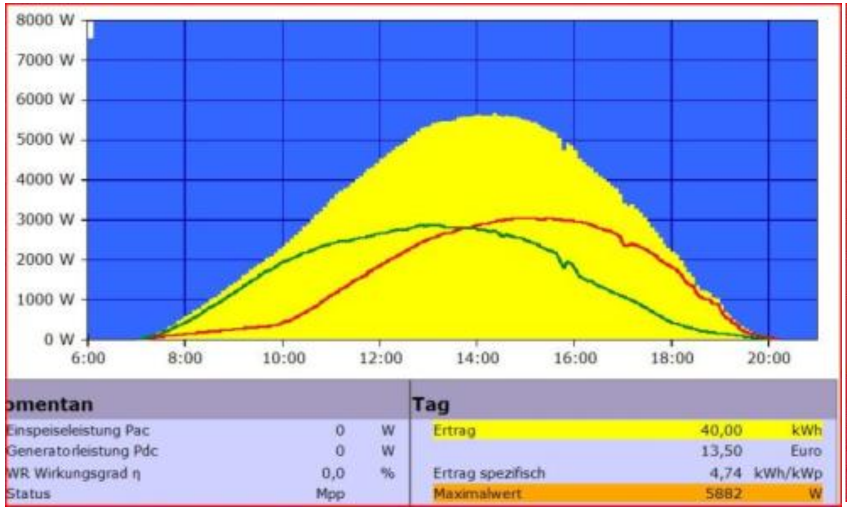


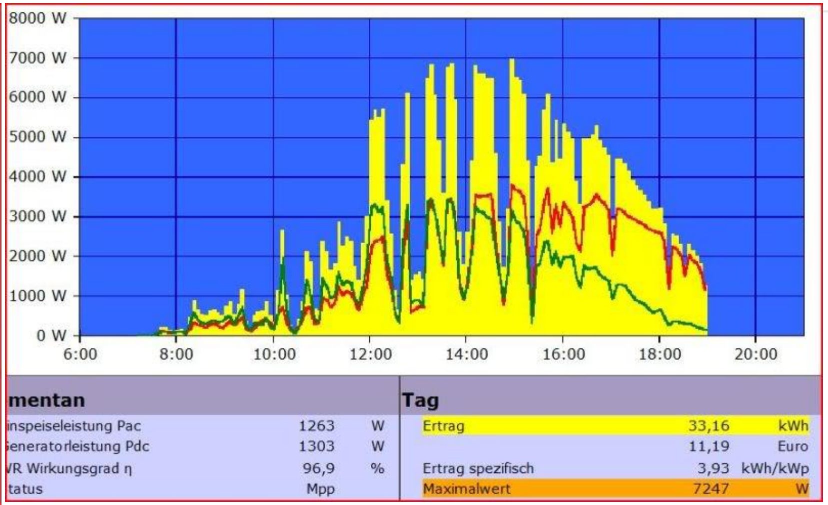
Storage requirements in the energy industry

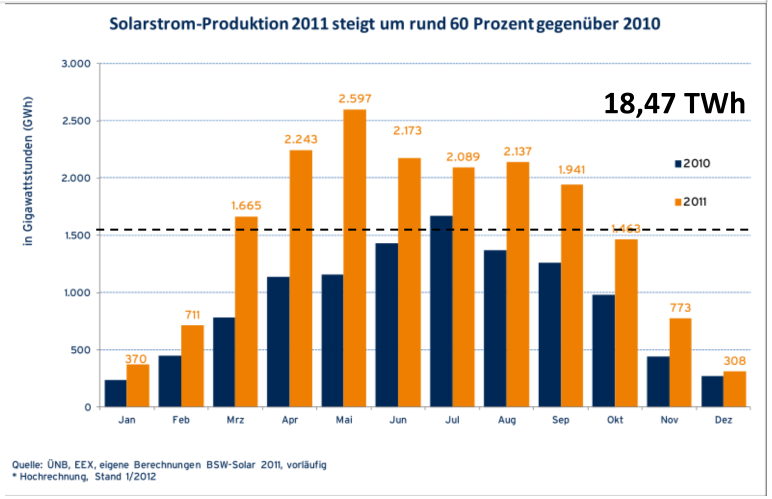
Motivation - Characteristic of regenerative generation

- **Strong dependence on :**
  - Daytime-dependent
  - Meteorological influence
  - Seasonal influence
- ➢ Main part of the annual yield in spring and summer
- ➢ **No supply security possible without storage!**





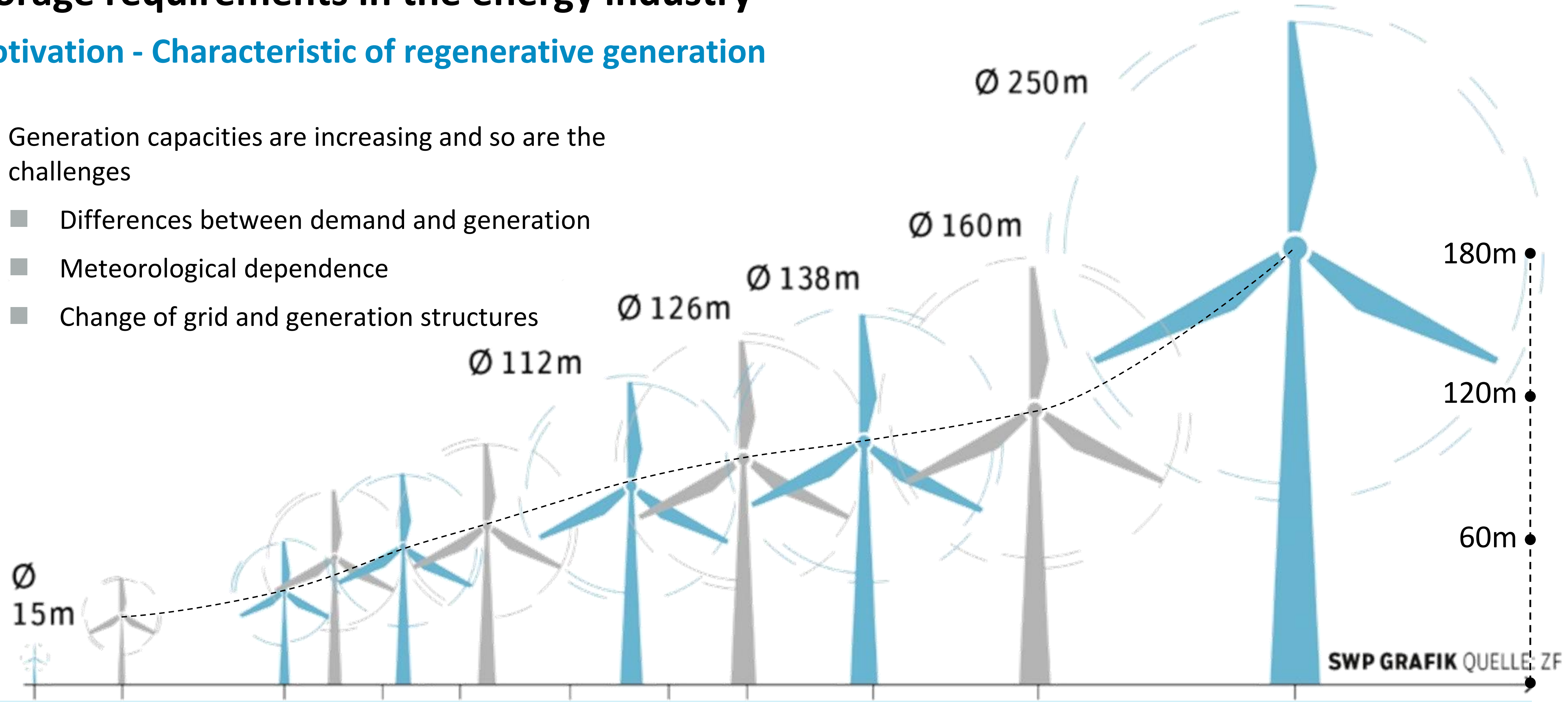




Storage requirements in the energy industry

Motivation - Characteristic of regenerative generation

- Generation capacities are increasing and so are the challenges
  - Differences between demand and generation
  - Meteorological dependence
  - Change of grid and generation structures



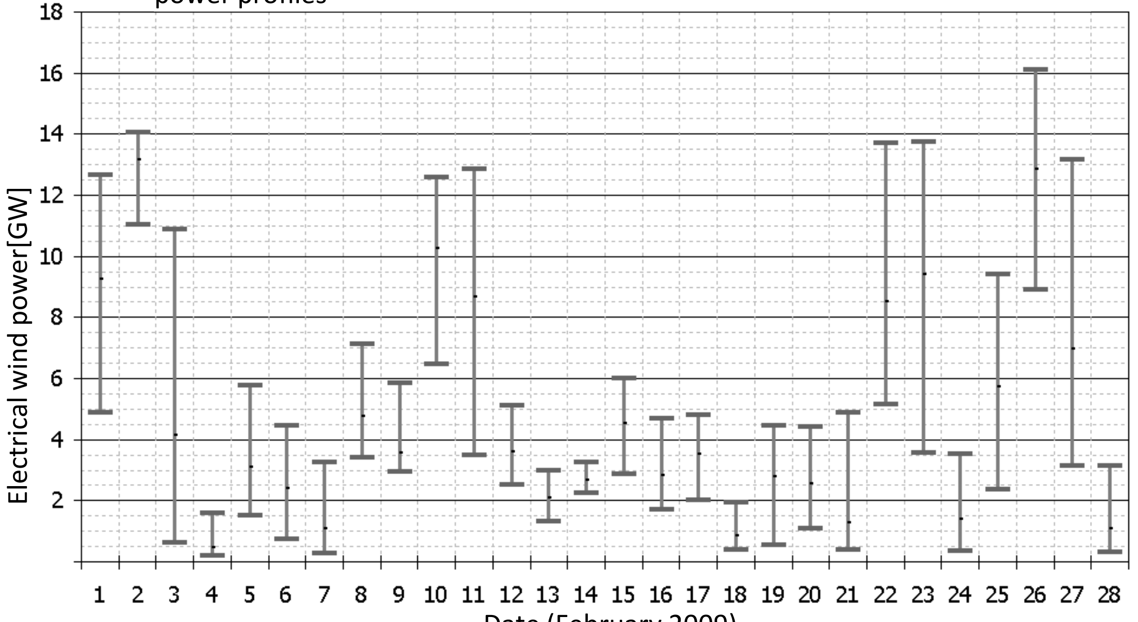
'85	'89	'93	'95	'97	2000	'03	'05	'10	'16	>'20 Jahre
0,05	0,3	0,5	1,3	1,6	2,0	4,5	5,0	7,5	8,0	10-20 MW
	0,4	1,2		3,7		10	11,4	17	18	22-45 GWh/a

Storage requirements in the energy industry

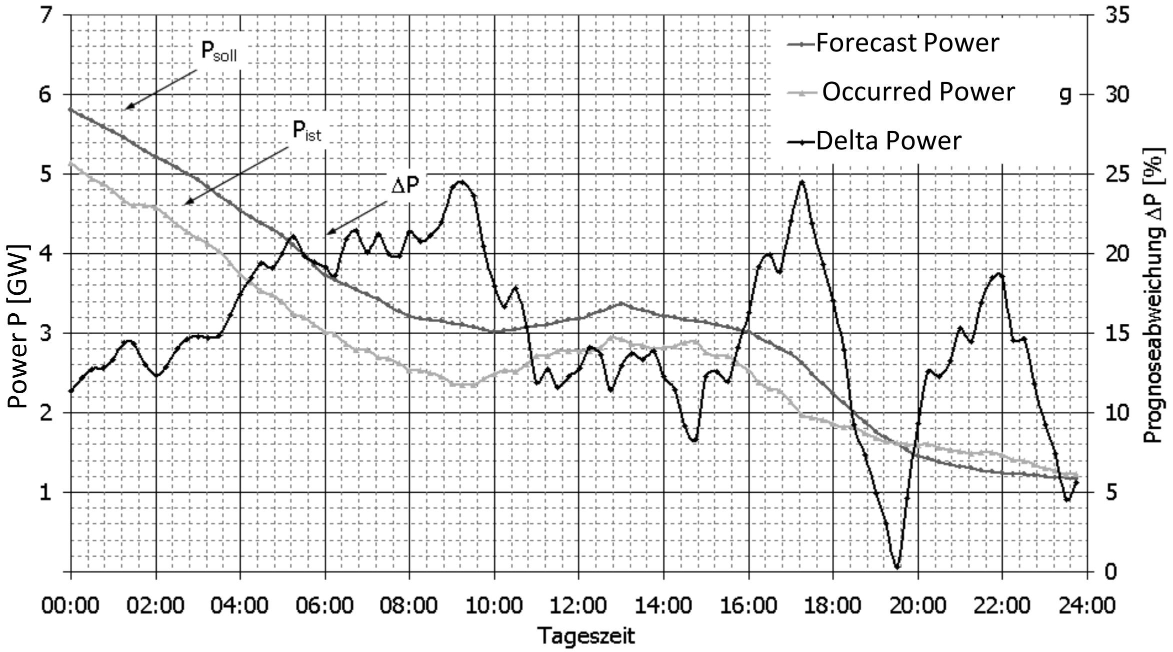
Motivation - Characteristic of regenerative generation

- Problem volatile feed-in and location of the plants
- Example Saxony-Anhalt, 2% land use over 15 TWh (>100%)*
- Example Germany, 2% (8% pot.) land use 390 TWh (65%)*
- ➢ Storage required

RES - Wind energy feed-in in Germany, daily minimum and maximum 1/4 hour power profiles



Wind energy feed-in Vattenfall control zone at 27.02.2009



Day hour [hh:mm]

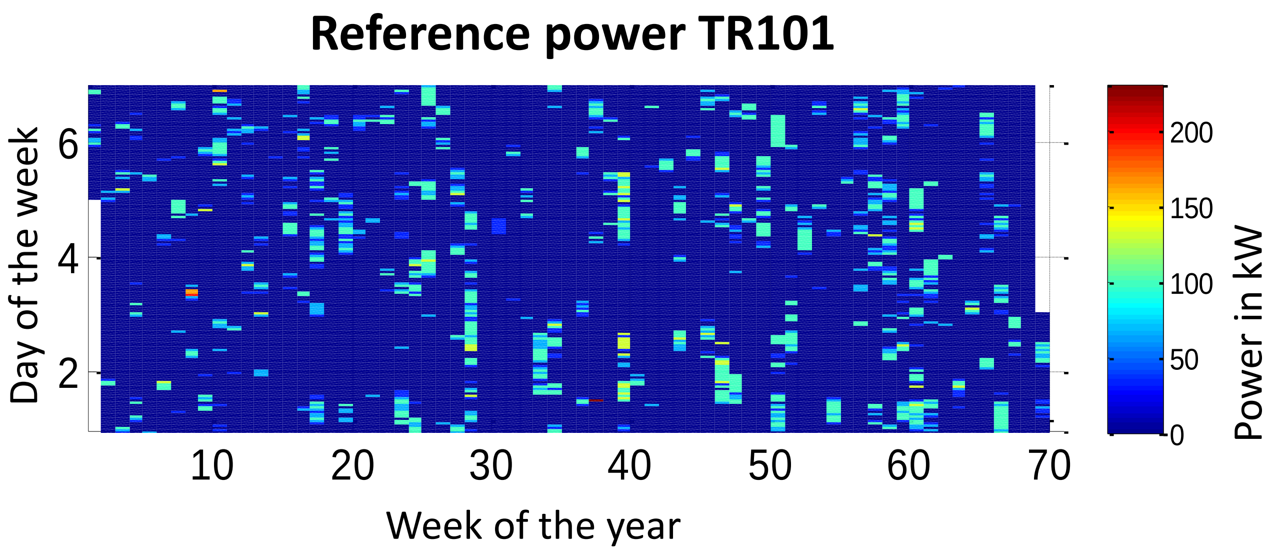
*[source: Bundesverband WindEnergie e.V.; „Windenergiepotential Sachsen Anhalt"]

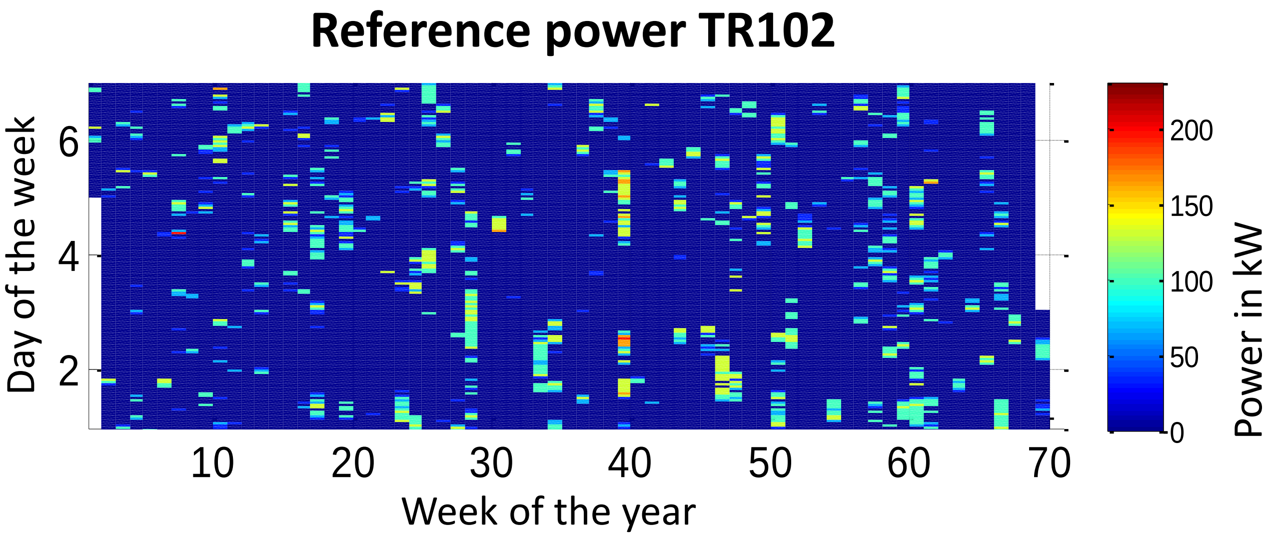
Storage requirements in the energy industry

Motivation - Characteristic of regenerative generation

- Example 80 MW wind farm in Central Germany
- Display of the reference power (no wind)
  - Observation period 70 weeks
  - No week with continuous supply
  - Sometimes several hours up to days

- Basic supply from wind power not possible
- Provision of reserve power plants or storage facilities



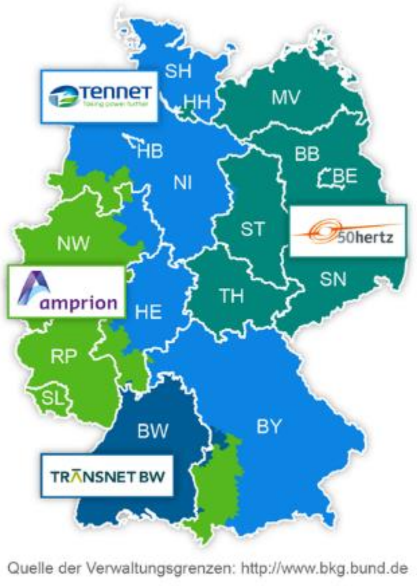


Basic knowledge of electrical energy supply

Terminology

- **RES - Renewable Energy Sources:** : denotes the energy sources which are ‘infinitely‘ available or can grow again in a shorter time (hydropower, solar and wind energy, biomass and geothermal energy)
- **Dispatch „ Power plant deployment planning**“: refers to the deployment planning of power plants by the power plant operator
- **Redispatch**: refers to the short-term change in the power plant operation at the behest of the transmission system operator to avoid network bottlenecks.
- When falling below the **49.5 Hertz problem**: many decentralized power generation systems (DEA) shut down at the same time due to technical safety installations in the systems themselves, these collective shutdowns endanger the power supply (blackout). The **System Stability Ordinance** has been in force since 2015, which defines a targeted, step-by-step shutdown for RES and prevents a rapid drop in grid frequency.
- **(n-1) criterion (N-minus-one criterion), (n-1) security:** refers to the redundancies (present several times) of components / subsystems in an overall system whereby failure safety is achieved. The (n-1) criterion means that if a component fails, this can be compensated for by another (e.g. duplication of equipment). Partly in critical infrastructures (n-2) execution.

Germany



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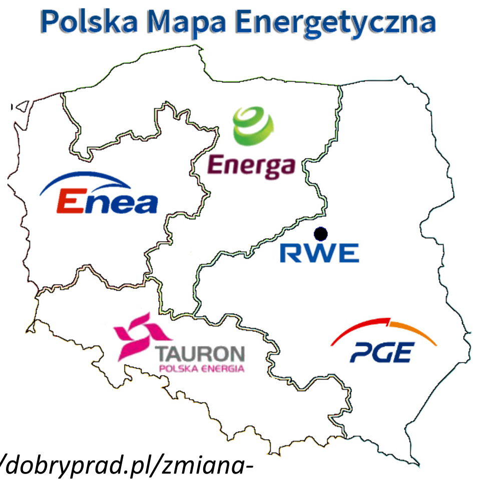
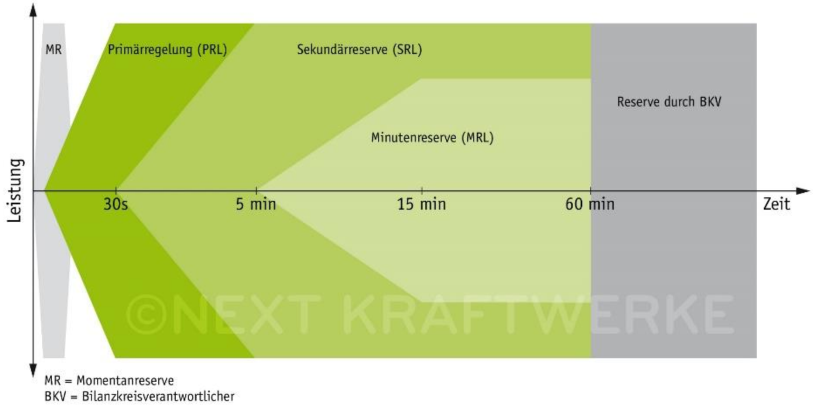


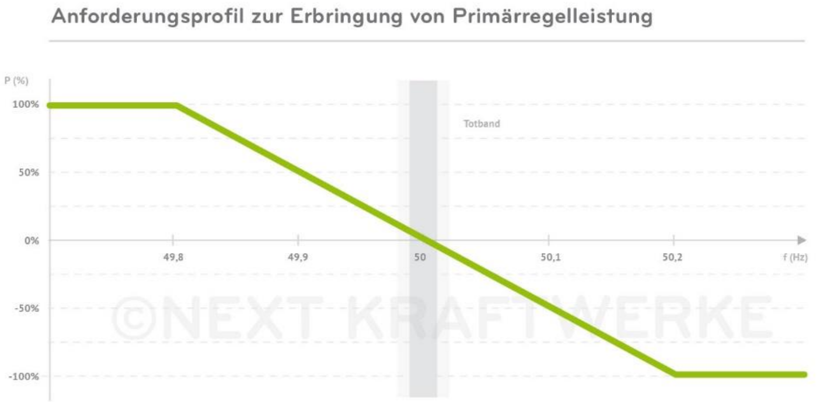
[Source: https://dobryprad.pl/zmiana-sprzedawcy/katowice/attachment-polska-mapa-energetyczna/

Basic knowledge of electrical energy supply

Terminology

- **Transmission System Operator (TSO):** are energy supply companies that operate the national power grids (in Poland PSE)
- **Distribution System Operator (DSO):** operate the electricity network between the transport level and almost all consumers and the medium and small power plants. (over 880 municipal utilities, national and regional network operators)
- **Balancing power/ energy:** compensates for fluctuations in the power grid. Increase in feed-in, positive control energy is provided at low grid frequency. The feed-in is throttled, negative control energy, is carried out to reduce the grid frequency.
- **Primary control power:** must be available within 30 seconds to prevent a power failure. The primary reserve is the first type of control energy to be activated and the immediate measure for a deviation in the network frequency.
- **Secondary control power**: serves as a reserve that can be activated at short notice to ensure the grid frequency stability. The secondary reserve is the second type of control energy to be activated.
- **Tertiary control power**: takes effect after a lead time of 15 minutes. The minute reserve is the third type of control energy to be activated.





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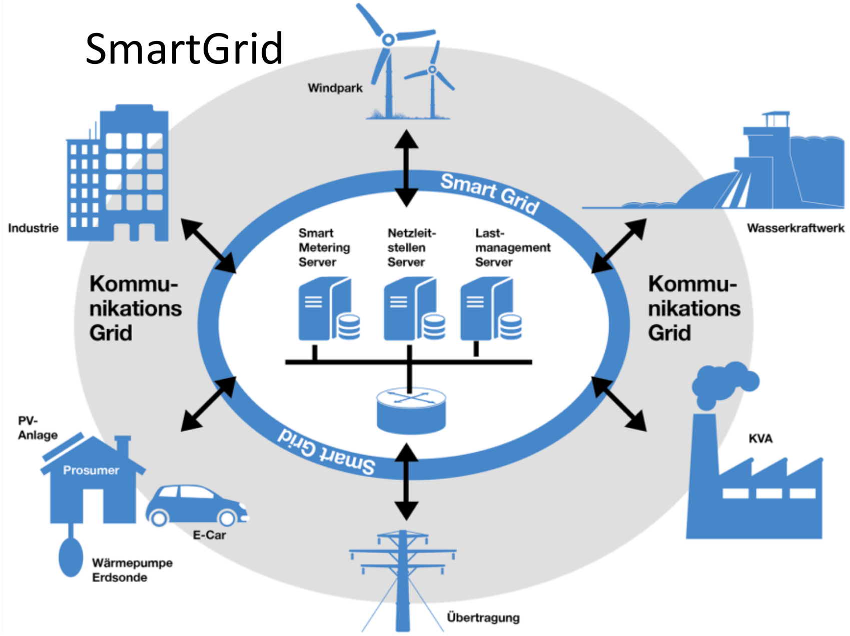
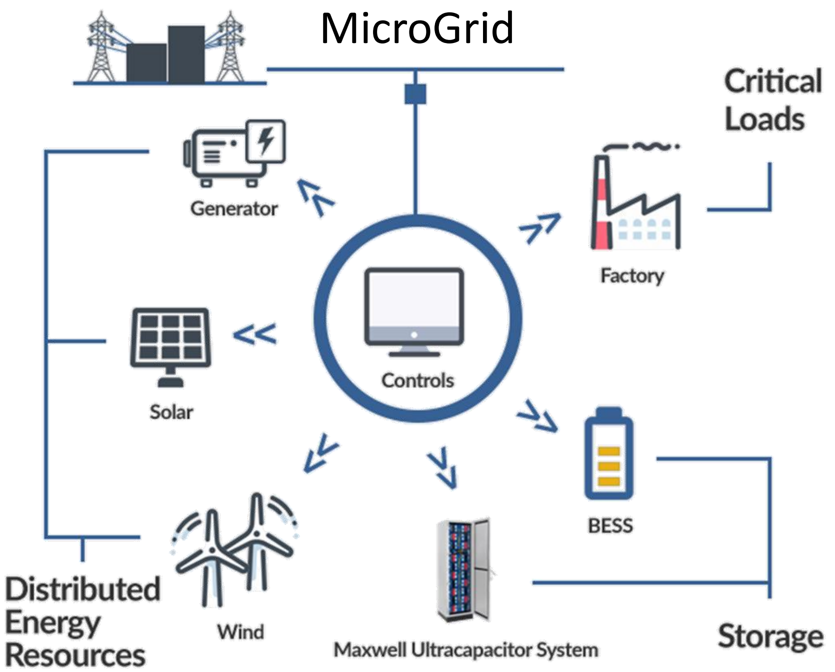
→ empfehlenswert zum Nachlesen

Basic knowledge of electrical energy supply

Terminology

- **Virtual power plant** is an amalgamation of decentralized units, e.g. biogas, wind power, photovoltaic, CHP or hydropower plants, electricity consumers, electricity storage and power-to-X systems (power-to-gas, power-to-heat), in the power grid, which are coordinated via a common control system.
- **Smart Grid** is an intelligent power grid in which information is exchanged, with the help of which power generation, consumption and storage can be controlled dynamically.
- **Micro Grid:** include low-voltage distribution systems with distributed energy resources (microturbines, fuel cells, PV, etc.) as well as storage devices (flywheels, capacitors and batteries) and flexible loads. Such systems can be operated in parallel with the grid (on the public grid) or as an island grid (self-sufficient).
- **Power-to-X** describes the conversion of electricity as primary energy into an energy carrier, heat, cold, product, fuel or raw material. It is a collective term for power-to-gas, power-to-liquid, power-to-fuel, power-to-chemicals, power-to-product and also power-to-heat.
- **Net Zero Energy:** The state that exists when the amount of energy that is provided by renewable energy sources on site is equal to or equivalent to the amount of energy consumed.

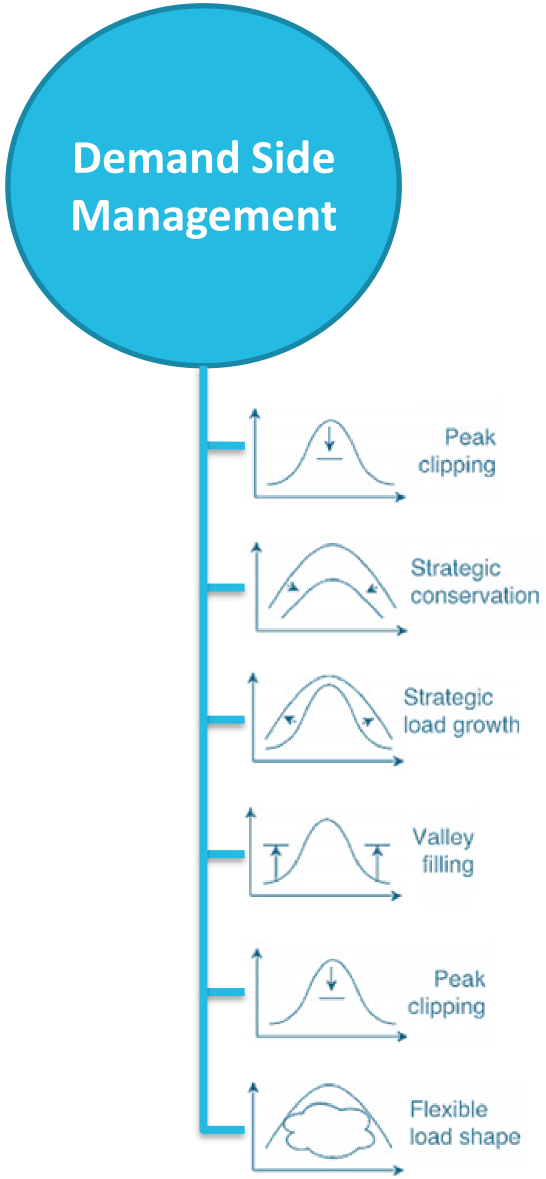




Basic knowledge of electrical energy supply

Terminology

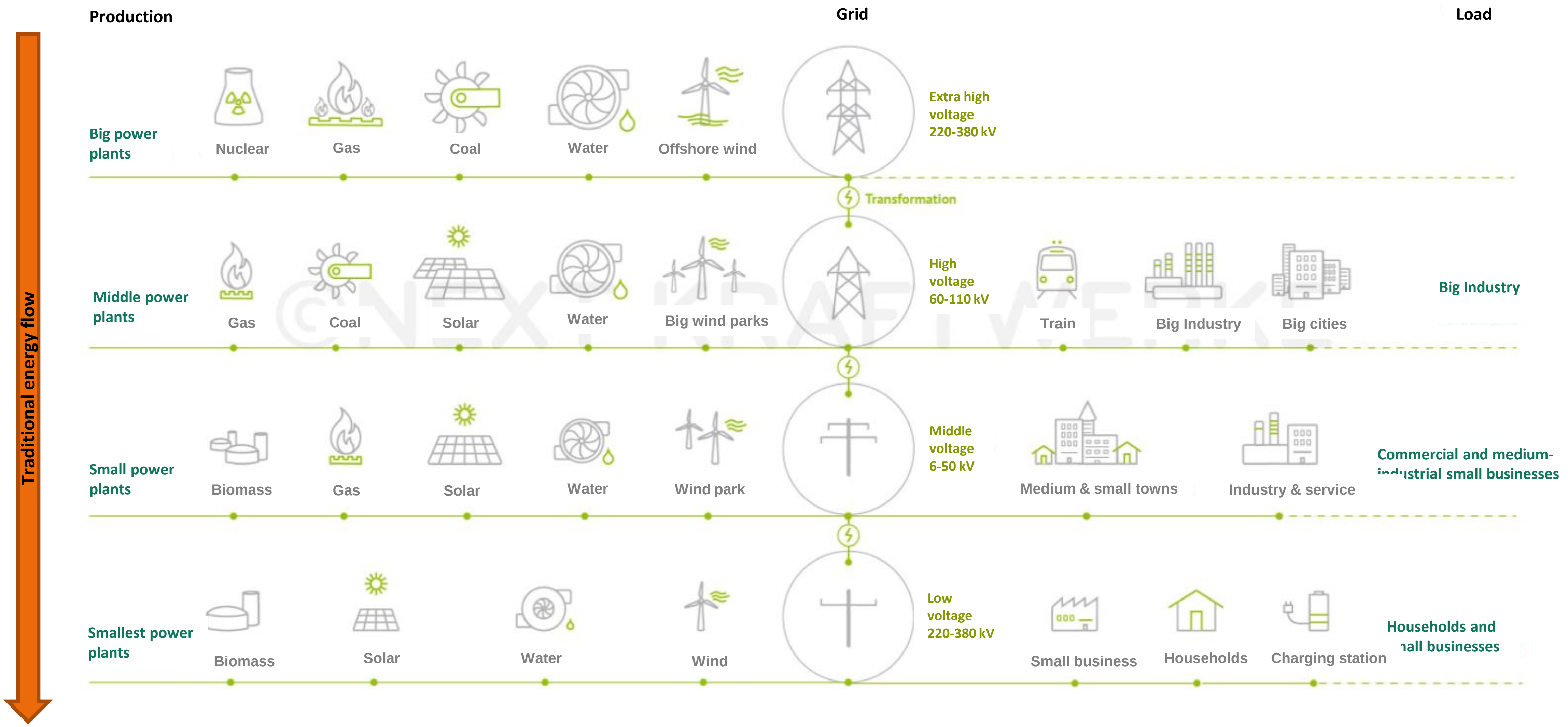
- **Feed-in management** is the curtailment of the feed-in of renewable energies as well as CHP and mine gas systems into the power grid carried out by the network operator. This mandatory limitation of the feed-in becomes (as a last measure) necessary if individual sections of a distribution or transmission network are overloaded and such a bottleneck threatens the security of supply. The energy that is regulated in this way is referred to as downtime and must be compensated.
- **Critical** infrastructures are organizations and facilities of major importance for the state community, the failure or impairment of which would result in lasting supply bottlenecks, significant disruptions to public safety or other dramatic consequences. Defined by the Federal Office for Information Security.
- **Demand-Side Management (DSM)** includes the direct influence on energy consumption on the consumer side. The energy consumption can be increased or reduced at a certain point in time.
- **Demand-Side Response (DSR)** comprises the consumer's reaction to an incentive signal, which is mostly of a monetary nature, i.e. a time-dependent tariff.
- **Demand-Side Integration (DSI)** denotes the overall term and is composed of DSM and DSR.



[Source: SCHRIFTENREIHE ENERGIESYSTEME DER ZUKUNFT: Demand-Side-Management im Strommarkt Technologiesteckbrief zur Analyse „Flexibilitätskonzepte für die Stromversorgung 2050“, Zbigniew A. Styczynski, Dirk Uwe Sauer (Hrsg.)]

Basic knowledge of electrical energy supply

Grid operation



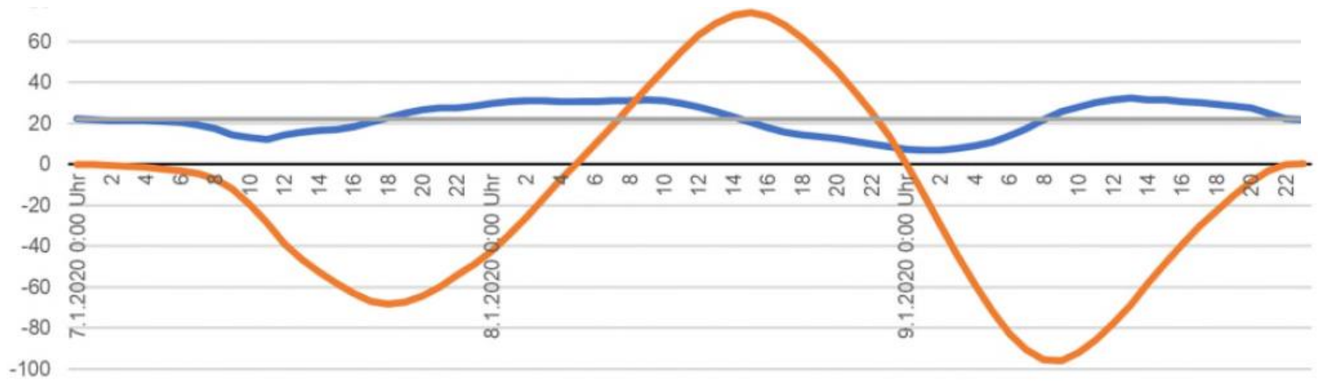
[Sourcehttps://www.next-kraftwerke.de/wissen/netzbetrieb

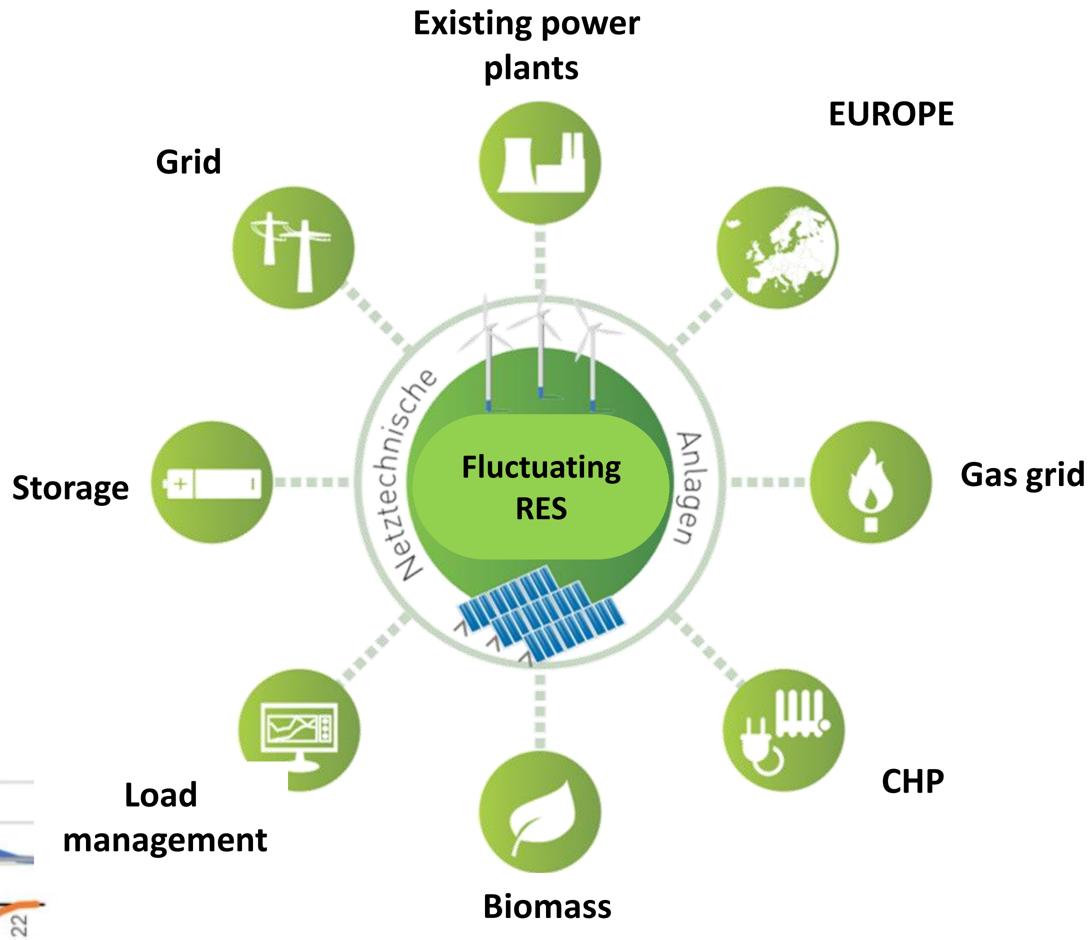
Basic knowledge of electrical energy supply

Necessity of storage technologies in energy supply

Change in energy production and demand

- Switching to renewable energy sources
- increasingly volatile feed-in from RES
- Big gap between generation and demand
- Decentralization in production
- Shutdown of conventional producers
- High power peaks in the power grid (electrification in mobility)





Source: Agentur für Erneuerbare Energien e.V.

Classification of the storage technologies

Technology overview and area of application

Electrical storage system

short- medium- long-
term storage

Electrical

- Double layer capacitor (super capacitor)
- Superconducting magnetic energy storage

Mechanical

- Pumped hydropower plant
- Compressed air storage
- Flywheels

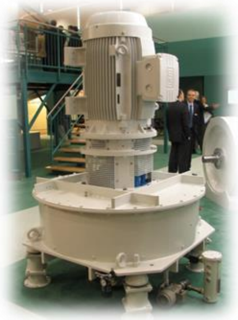
Thermal

Thermo-electric storage

Chemical

Lithium-ion battery
Lead-acid battery
High-temperature battery
Redox-Flow battery
Hydrogen storage
Natural gas storage system

source: http://www.itwissen.info/bilder/doppelschicht-kondensatoren-foto-academic-dotru.png



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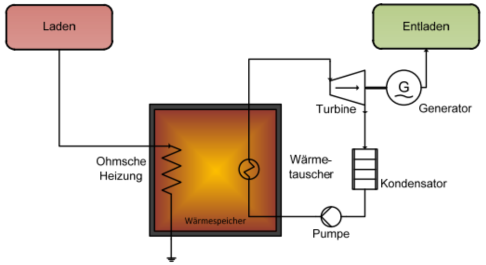


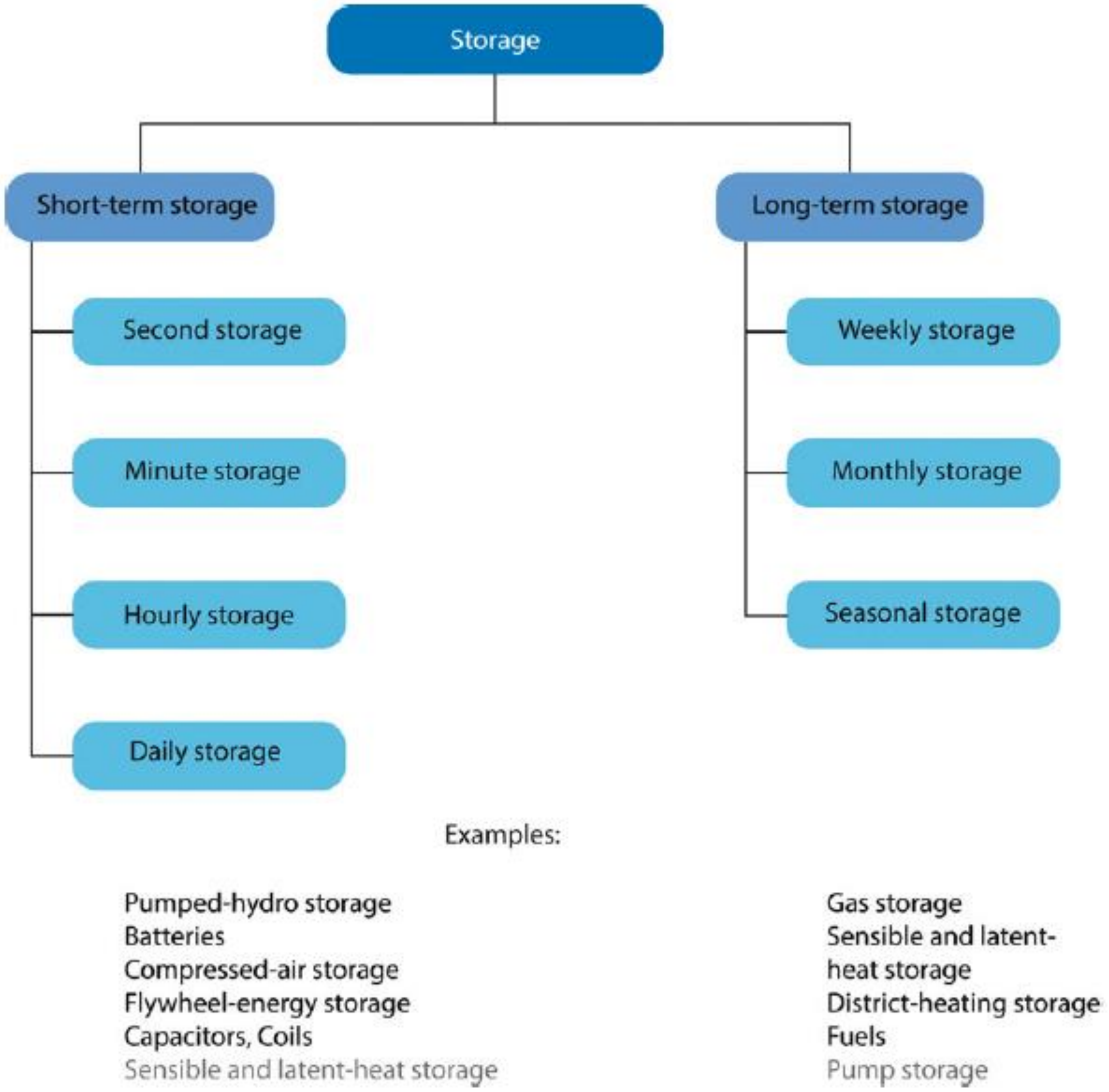
source: Technologischer Überblick zur Speicherung von Elektrizität, Smart Energy for Europe Platform GmbH, IAEW Aachen, September 2012

Quelle: Technologischer Überblick zur Speicherung von Elektrizität, Smart Energy for Europe Platform GmbH, IAEW Aachen, September 2012

Classification of the storage technologies

Storage time

- **Short-term storage** systems store energy for periods, ranging from a few nanoseconds to an entire day (t_{dischg} 24 h), but most short-term storage systems are designed for hourly or daily storage.
- **Long-term storage** systems hold energy for periods ranging from many days or weeks to several months or years (t_{dischg} 24 h). They are used to balance seasonal fluctuations in energy supply due to, for example, lengthy periods without wind, low water levels for hydropower, or long dark periods.
- ➢ Energetic and economic potential in a combination of different systems as well as use of the storage for different applications.



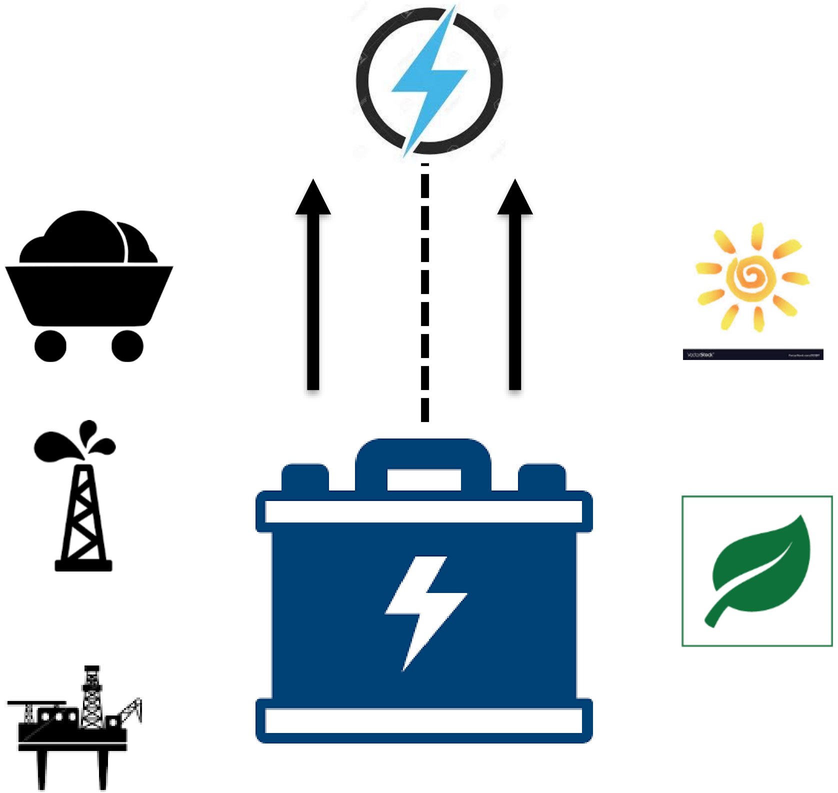
Source: Handbook of Energy Storage, ISBN 978-3-662-55503-3

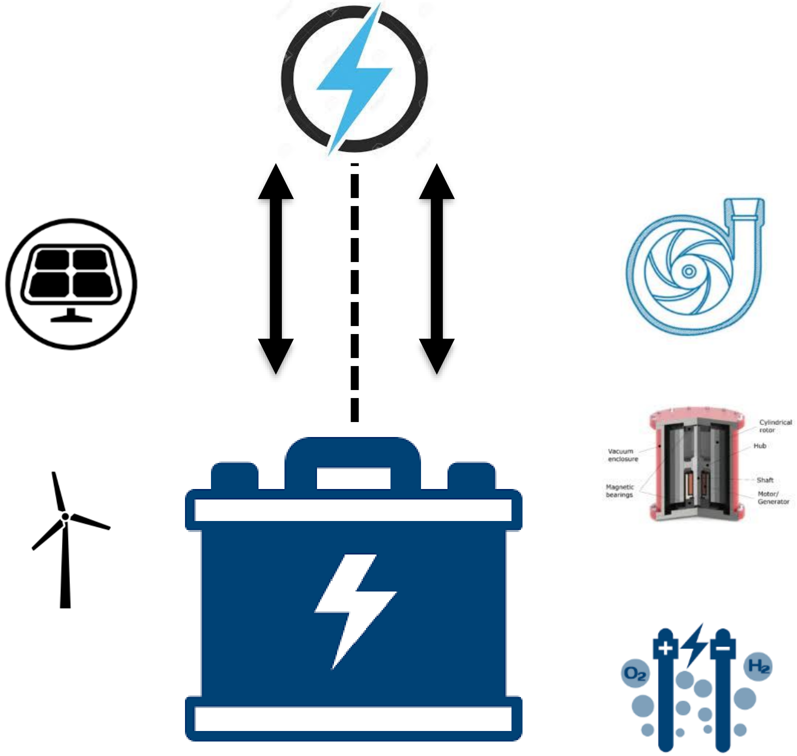
Classification of the storage technologies

Energy storage primary and secondary energy storage

Primary energy storages:
Energy storages that can only be charged and discharged once

Secondary energy storages:
Energy storages that can be charged and discharged several times

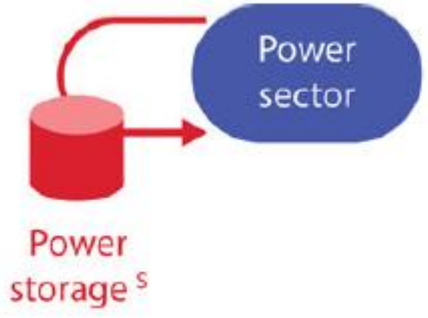




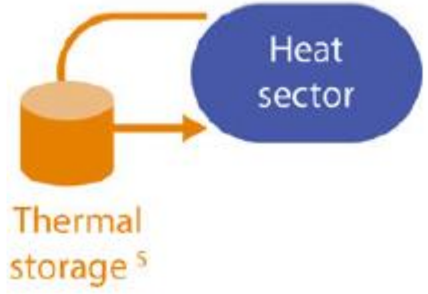
Classification of the storage technologies

Sectoral energy storage

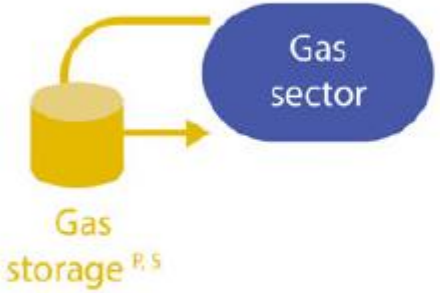
Sectoral energy storage:
Are energy stores that are used purely in one energy sector. Storage and retrieval are bidirectional in the same sector



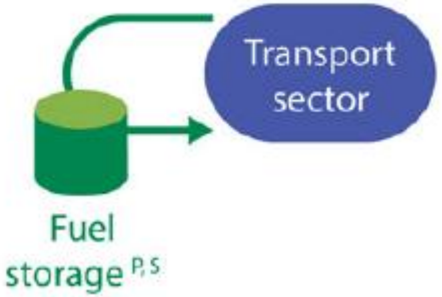
e.g., pumped hydro
batteries
supercaps



e.g., solar thermal hot water storage, PCM, zeolites



Charge:	power-to-X
Store:	X
Discharge:	X-to-power



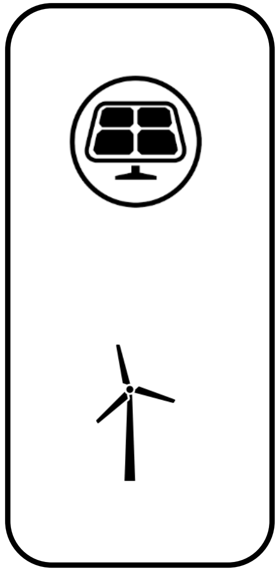
e.g., oil tank, fuel tank

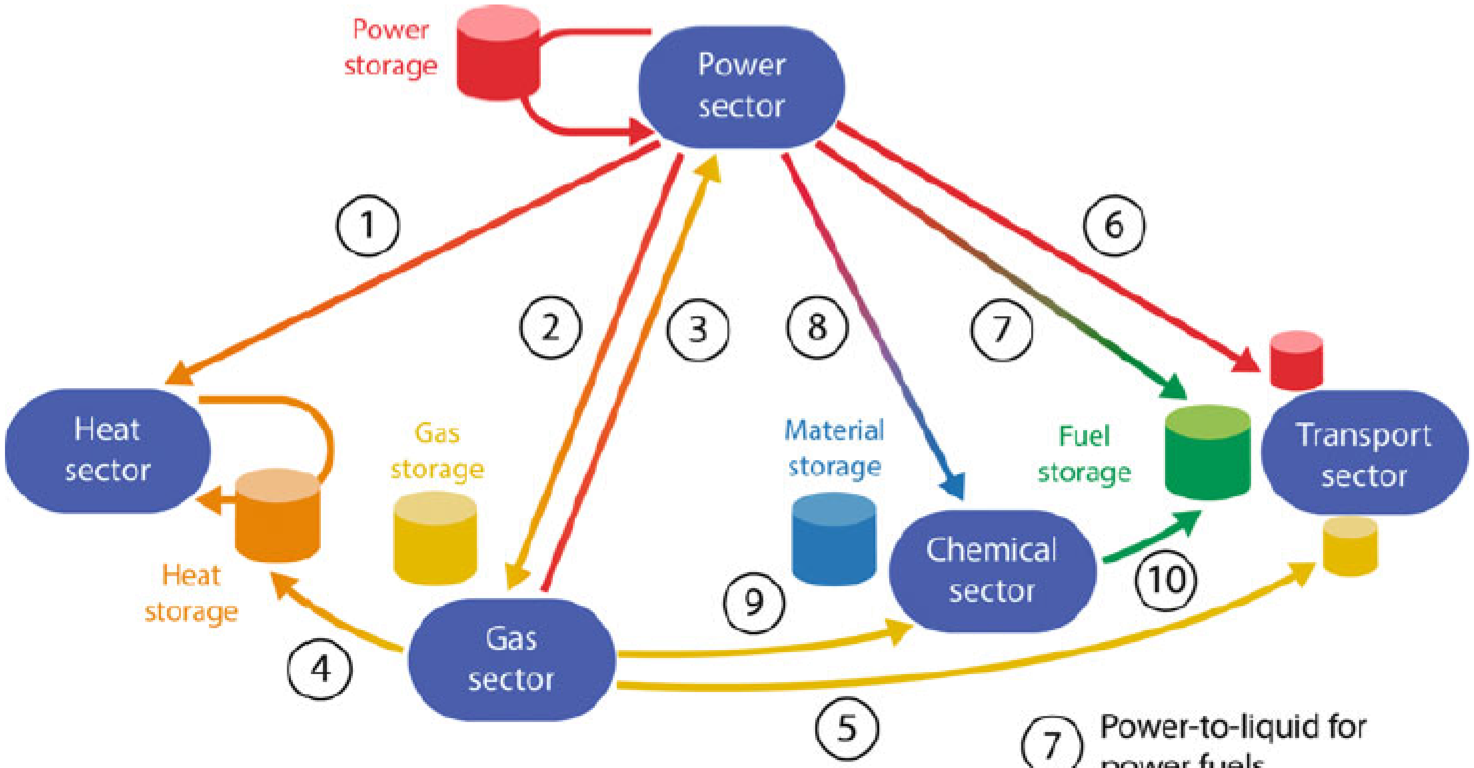
Charge:	Crude oil/Biomass-to-X
Store:	Tank, X
Discharge:	X-to-shaft power

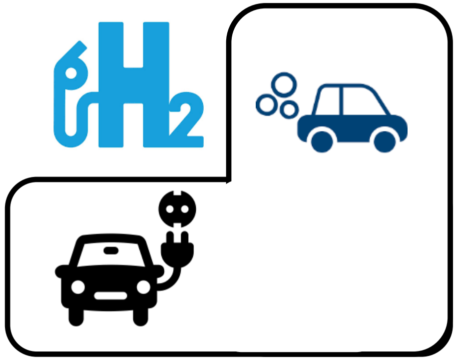
Source: Handbook of Energy Storage, ISBN 978-3-662-55503-3

Classification of the storage technologies

Sectoral energy storage







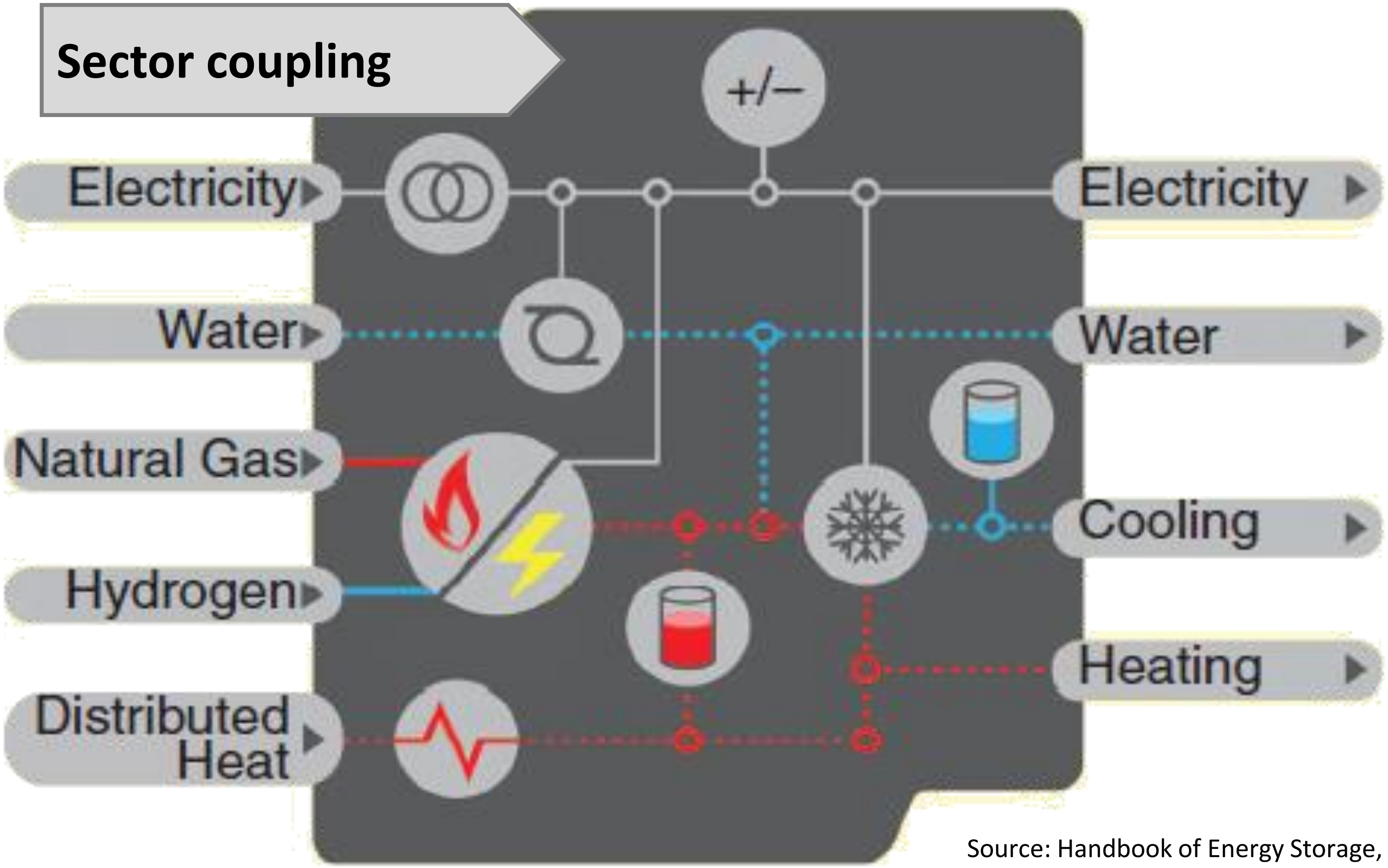
1. Power-to-heat, heat pump, flexible CHP
2. Charge technology power-to-gas
3. Power-to-gas for power storage
4. Power-to-gas for heat storage
5. power-to-Gas for power fuels
6. Electromobility
7. Power-to-liquid for power fuels
8. Charge technology power-to-Chemicals
9. Power-to-Gas for material storage
10. Power-to-chemicals for fuel storage

Source: Handbook of Energy Storage, ISBN 978-3-662-55503-3

Classification of the storage technologies

Sectoral energy storage

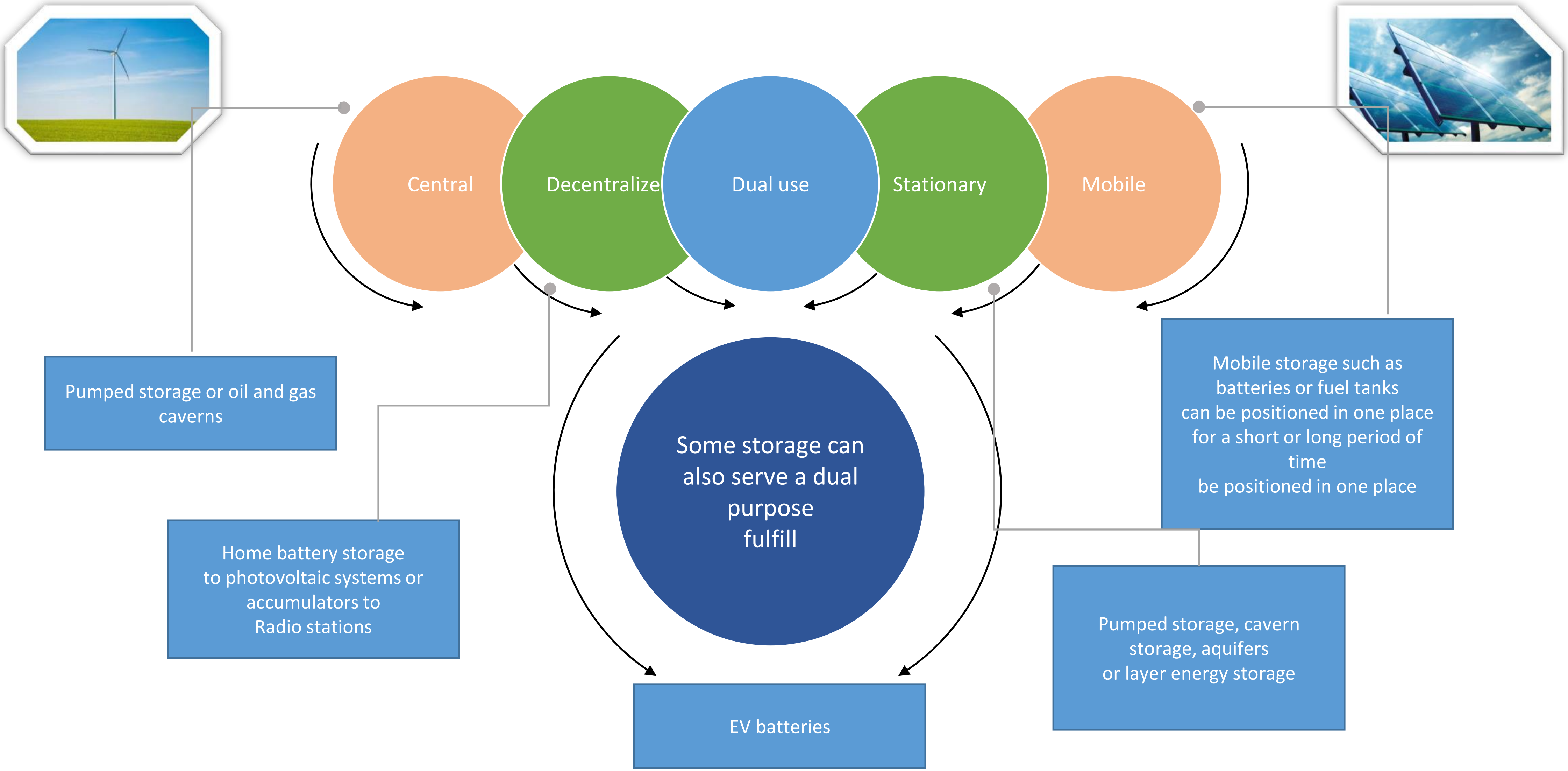
Cross-sector energy storage:
Are energy stores that are used in one or more energy sectors and work unidirectional and / or bidirectional. The storage and retrieval does not necessarily take place in the same sector.



Source: Handbook of Energy Storage, ISBN 978-3-662-55503-3

Classification of the storage technologies

Spatial classification



Development phases of RES and storage technologies

Development phases from fossil to regenerative energy supply using RES and storage

1 – basic technologies

RES development
RES expansion
Efficiency technologies

2030

2050

4 phases of transformation

2 – system integration

Flexibilisation, digitalisation, direct use of electricity, storage, development of new electricity market

3 – synthetic fuels

High negative residual loads
Large-scale electrolysis
Synthetic fuels for industry and traffic

4 – Final defossilization

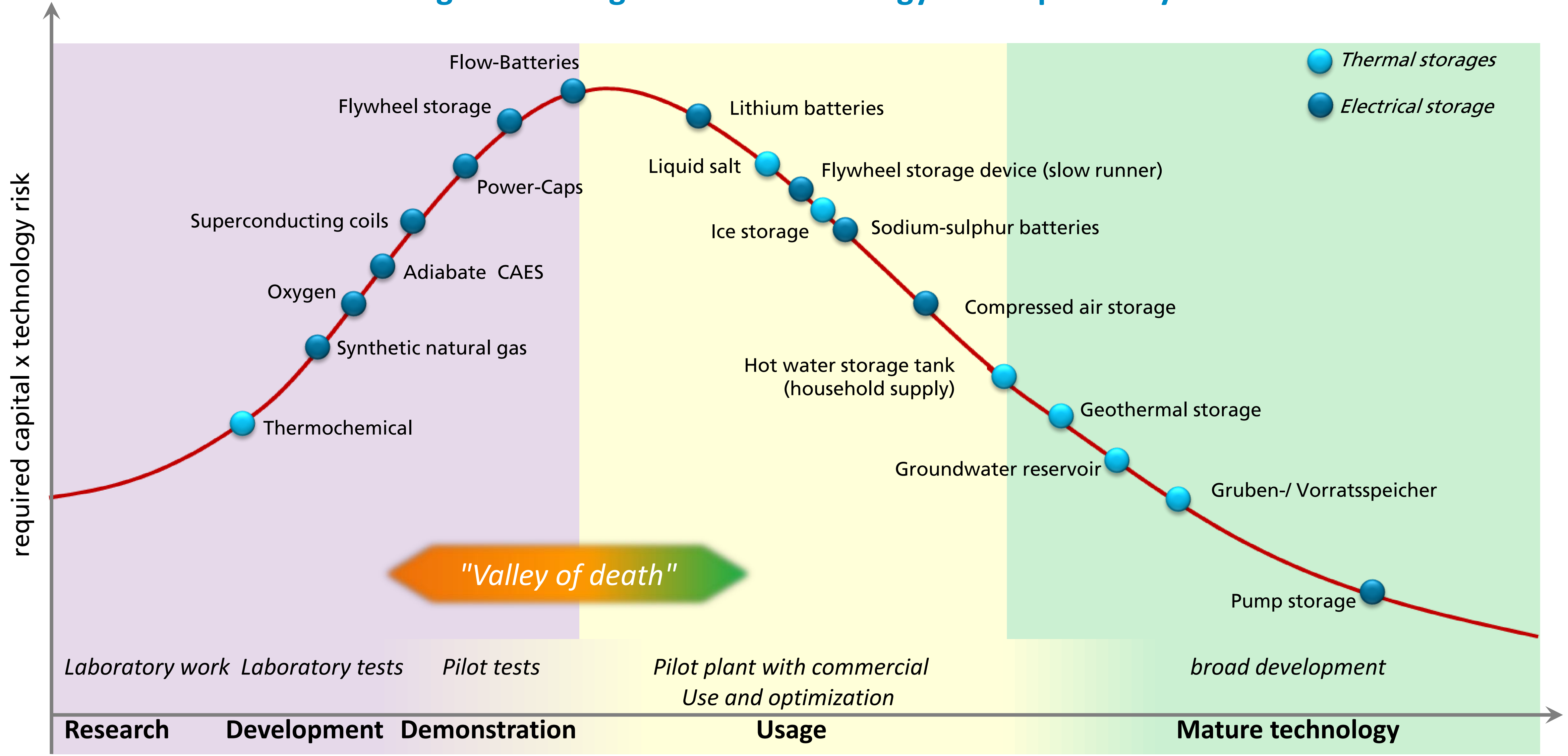
Renewable energy imports, Displacement of fossil fuels, Completion of energy supply restructuring

- continuous technology development
- efficiency improvement
- sector coupling

Fully integrated energy system

Development phases of RES and storage technologies

Current state of the art of storage technologies in the technology development cycle



Selection and evaluation of suitable storage technologies

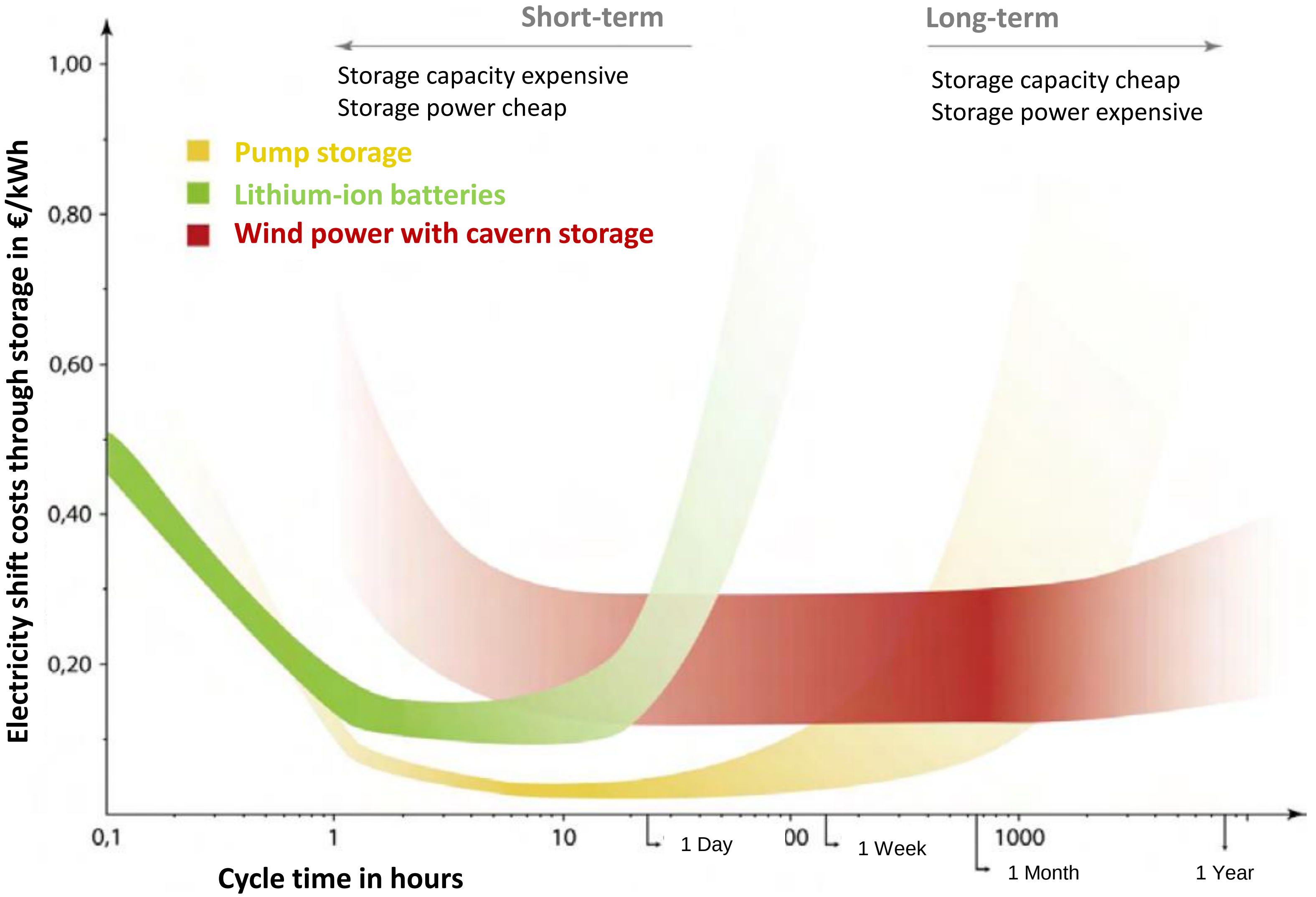
Technical and economic storage selection

- spec. Characteristics determine the area of application and use

Technology selection / decision criteria:

spec. technological feasibility (meeting the system requirements)

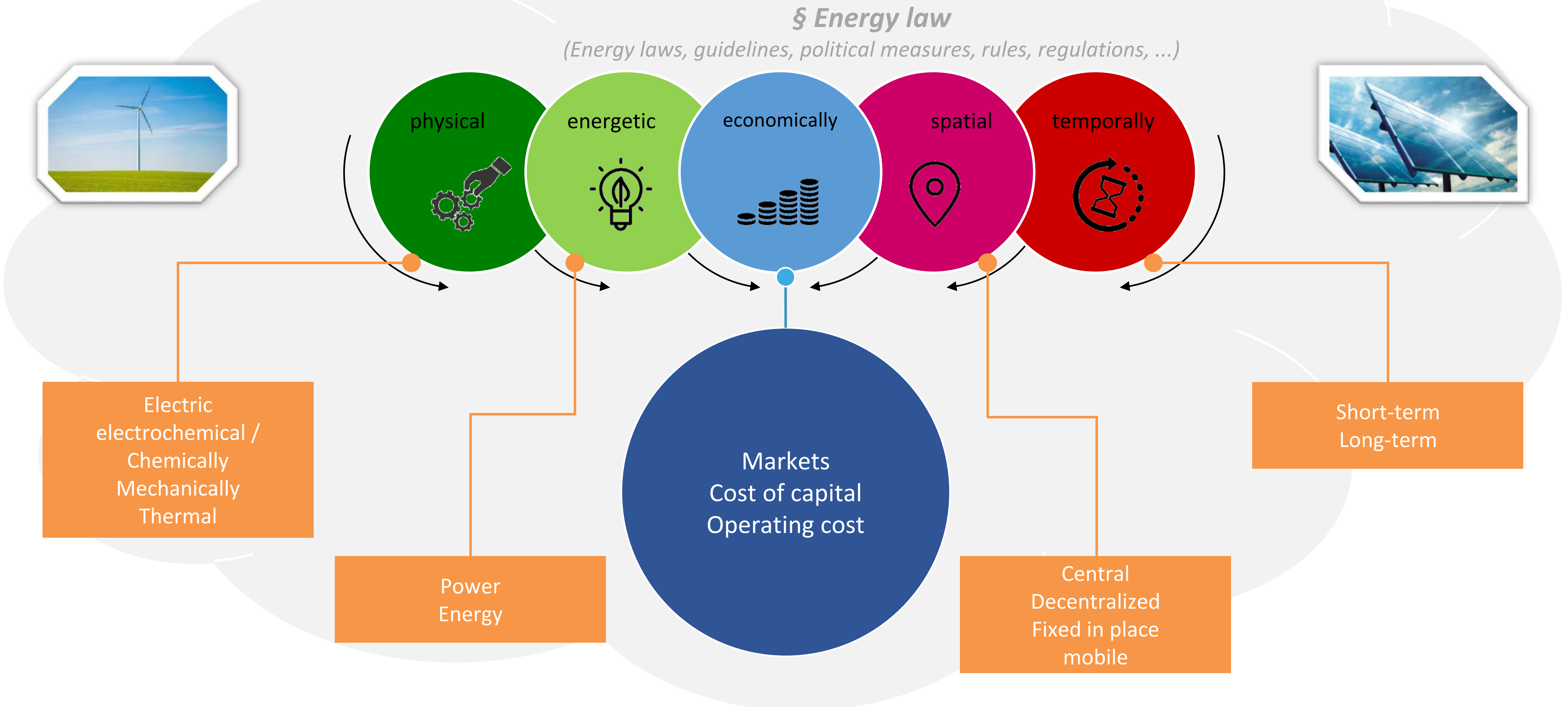
- spec. Boundary conditions for the purpose (synergies, infrastructure requirements, environmental requirements, location, etc.)
- Usage concept, flexibility options, reliability, technology experience, etc.
- Selection and design require a complex planning and optimization process for efficient use and economical operation



[Source: fenes.net, Sterner/Stadler et al.: Energiespeicher]

Selection and evaluation of suitable storage technologies

Influences on the planning and implementation of energy storage systems



Selection and evaluation of suitable storage technologies

Store energy, couple sectors

- Conservation of energy through thermal and electrical storage technologies
- Synergies through several energy media → Multi-energy system / sector coupling
- Provision and sale of flexibilities

+ **Compensation of fluctuations from RE**

+ **Use of existing resources possible (e.g. 2nd life batteries)**

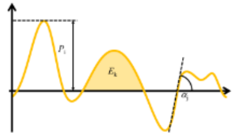
+ **Flexible and independent energy system**

Opportunities & risks

Missing experience

Falling investment costs

Unclear Framework conditions



Diverse Usage strategies

Selection and evaluation of suitable storage technologies

Applications of storage

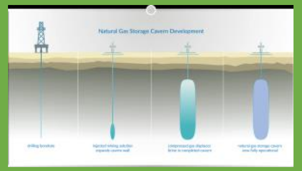
Use of storage

Surplus from RE

Electric grid support

Support of conventional power plants

Guarantee of security of supply



Selection and evaluation of suitable storage technologies

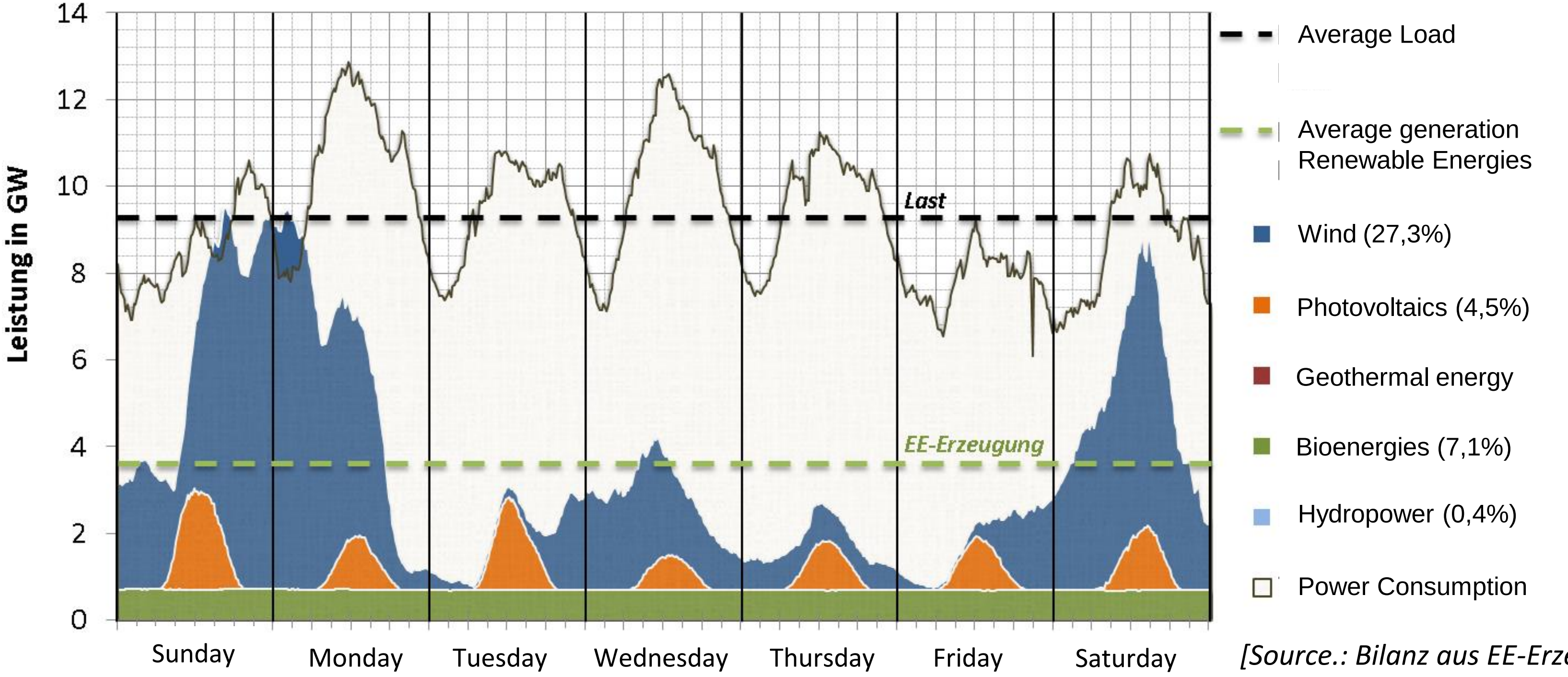
Example of technical requirements for storage systems according to the application

Economic management

- Reference variable according to the timetable
  - Price, power / electricity, reactive power (¼ hour value)
  - Reference variable Limitation of peak performance

Network-supporting operational management

- Dynamic reference variable in real time
  - Frequency, voltage
  - Power balance at the feed-in point, EE feed-in, reactive power



[Source.: Bilanz aus EE-Erzeugung und Lastgang im 50-Hertz-Stromnetz]

- ➢ The defined controlled variable defines the system requirements
  - Power gradient
  - System performance
  - Energy storage capacity
  - Storage time
  - Cycle stability
  - …

Selection and evaluation of suitable storage technologies

Motivation for grid services using storage systems

standard System Operation

future services

POWER GRID USEFUL

I. Control reserve (PRL, SRL, MR)
II. Voltage maintenance
III. Restoration of supply
IV. Optimazation of load flow (Component relief)

V. UPS-Function
VI. Provision of reactive power
VII. Network quality increase
VIII. Island network capability
IX. Short-circuit power supply

Stationary Storage

mobile Storage

MARKET USEFUL

Producer

Trader

Consumer

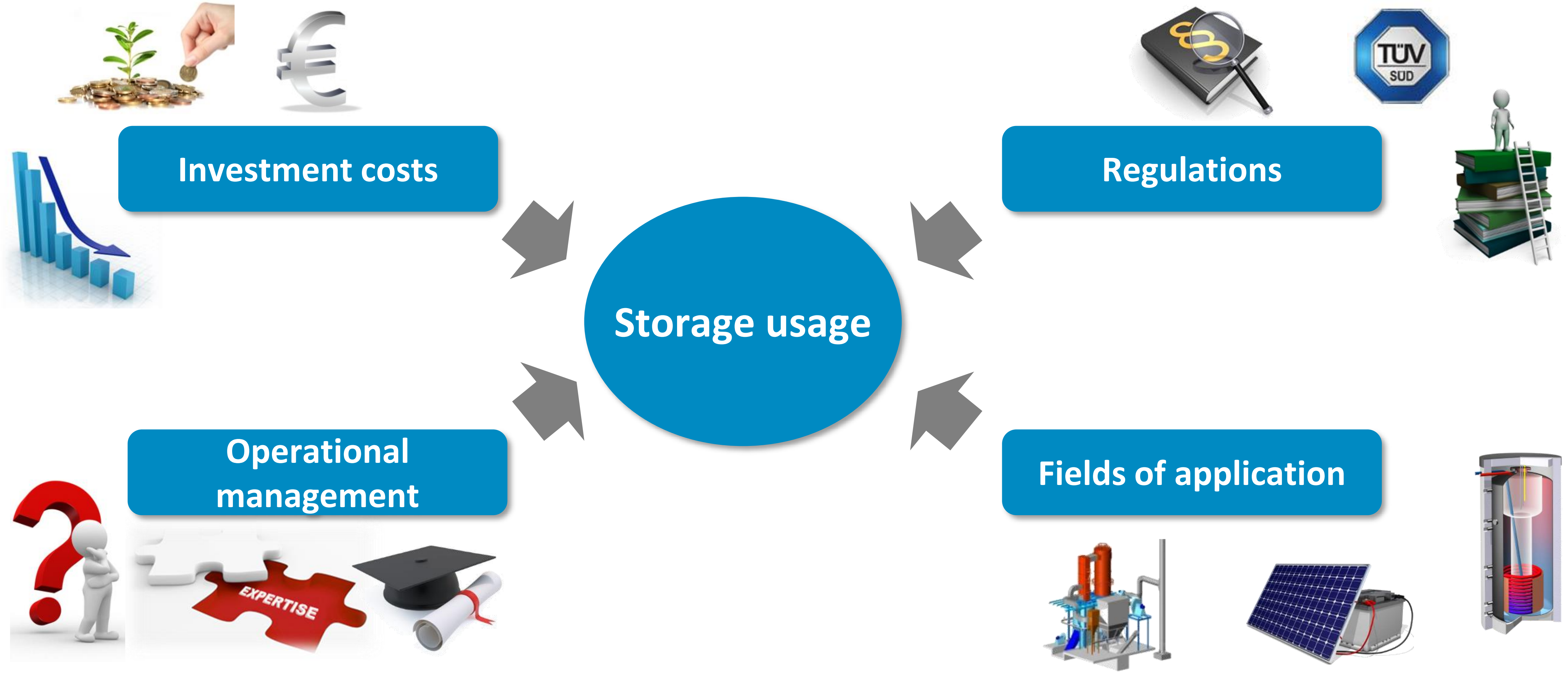
I. Use of regulated energy
II. Spot-Market
III. 1h- und 15min-Product of the Intraday-Market

IV. Arbitrage use
V. Compliance with Forecast
VI. Marketing: renewable energies (Market premium model)

VII. Aviodance of load peak
VIII. Increase in self-consumption

Selection and evaluation of suitable storage technologies

Challenges and Barriers



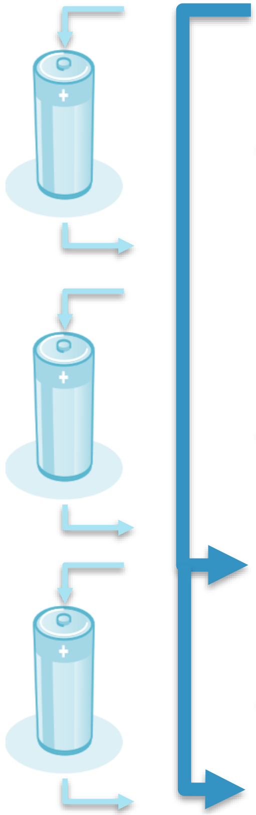
Storage requirements

Conclusion

- increased storage requirements due to the abandonment of fossil fuels
- Challenge of decentralization in energy supply (spatial distance between generation and demand)
- Challenge of lack of infrastructure for media and energy transfer and storage
- Established storage capacities are still too small
- Lack of standards and established technologies for making generation and loads more flexible
- New storage technologies are still too expensive and no testing
- Coupling of sectors and cross-sector storage systems necessary

Technical and physical basics

Storage in the energy chain



- **Primary energy** (fossil, nuclear or renewable)
  - resides in a naturally occurring source of energy
  - Oil, coal, uranium, natural gas, firewood, sun, wind, water, ...
- **Secondary energy**
  - is primary energy that has been converted into another form of energy and can be partially equated with end or useful energy
  - Coke, briquettes, gasoline, biodiesel, heating oil, logs, electricity, district heating, ...
- **End energy**
  - energy available at the end user
  - Briquettes, petrol, heating oil, natural gas, electricity, wood chips, district heating ...
- **Use energy**
  - Energy used for the purpose by the end consumer
  - Heath, power, light ...

Technical and physical basics

Calculation of the power quantities

Power	P	W	**Injectability / Dejectability (charging/discharging power),** **P_N - nominal power of system, P_L – power loss**	$P_{elec.} = U \cdot I = I^2 \cdot R$ $P_{mech.} = \vec{F} \cdot \vec{v} = \vec{M} \cdot \vec{\omega}$

- Injectability P_{in} (charging power) of a storage system in Watt (W) is calculated from the supplied, stored Energy; or Work W_{in} per time unit t_{in}.

$$P_{In} = \frac{dW_{in}}{dt} = \frac{W_{in}}{t_{in}}$$

- In analogy to the charging power the discharging power is calculated from the consumed, exportet Energy; or Work per time unit

$$P_{out} = \frac{dW_{out}}{dt} = \frac{W_{out}}{t_{out}}$$

Heating flow/ Heating power	$\dot{Q}$	W	**Heat transmitted per time unit**	$\dot{Q}_{Wl.,1\to 2} = kA(T_1 - T_2)$ $\dot{Q}_{Str.} = \varepsilon\sigma A T^4$

- In thermical storage systems the heating power or heating flow $\dot{Q}$ is specified in W (Watt). The thermal power has also to be mentioned with a view to the power loss.

Technical and physical basics

Calculation of the power quantities

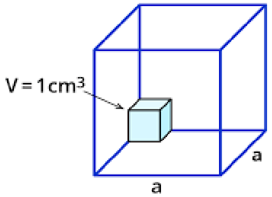
Power density	$\rho_{P,V}$	W/m^3	**volumetric power density of the system volume/capacity (or just power density)**	$\rho_{P,V} = P/V$
	$\rho_{P,m}$	W/kg	**gravimetric power density of the system mass (also called specific power)**	$\rho_{P,m} = P/m$

The volumetric power density of the system volume (or just power density) $\rho_{P,V}$ and the gravimetric power density of the system mass (also called specific power) $\rho_{P,m}$ are just relative power quantities, which related the charging power and the discharging power to its capacity or the mass of a energy storage systems. The volumetric power density is specified as W/m^3 and the gravimetric power density as W/kg.

They are for example used for the part electronic power in battery storage systems.

Heat flux density	$\dot{q}_V$	W/m^3	**Volumetric heat flux density of the system capacity**	$\dot{q}_V = \dot{Q}/V$
	$\dot{q}_m$	W/kg	**gravimetric heat flux density of the system mass**	$\dot{q}_m = \dot{Q}/m$

In respect of thermal storage systems we are talking about the volumetric heat flux density of the system capacity $\dot{q}_V$ in W/m^3 and the gravimetric heat flux density of the system mass $\dot{q}_m$ in W/kg.



Technical and physical basics

Calculation of the power quantities

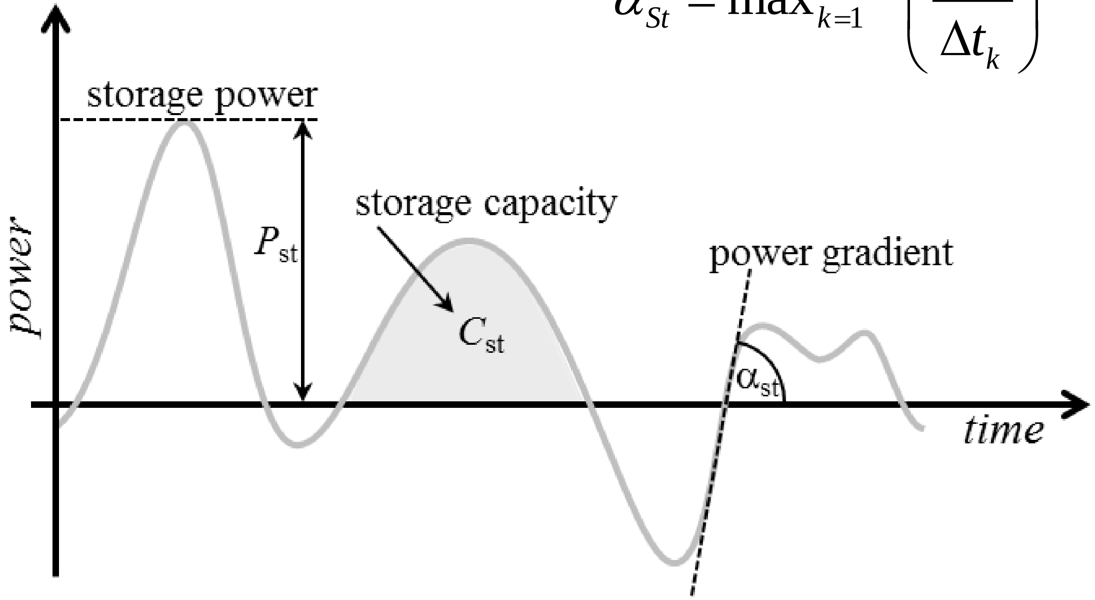
Power gradient	α	W/s	**Variation in power output per time unit**	$\alpha = \Delta P/\Delta t$

- The power gradient α in W/s (sometimes also standardised as $\%/min$) is a measure of the performance-related charge and discharge speed of a storage system and quite important for its dynamic use, for example to compensate the variations in energy supply and energy demand.

$$\alpha_{st} = \frac{dP}{dt} = mit\ P_{in}\ oder\ P_{out}$$

$$\alpha_{St} = \max_{k=1}^{k,\max}\left(\frac{\Delta P_k}{\Delta t_k}\right)$$

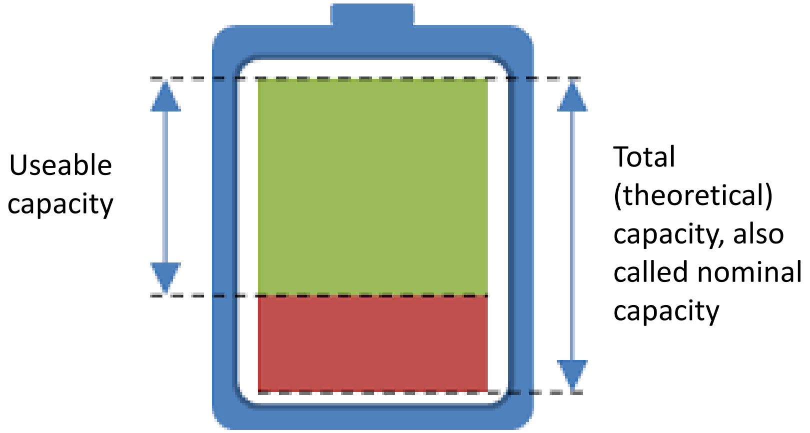
- As you can see in the diagram, the power gradient α_{st} equals the rise of the power development, and therefore it can be calculated from the variation in power ΔP_k per time unit Δt_k.

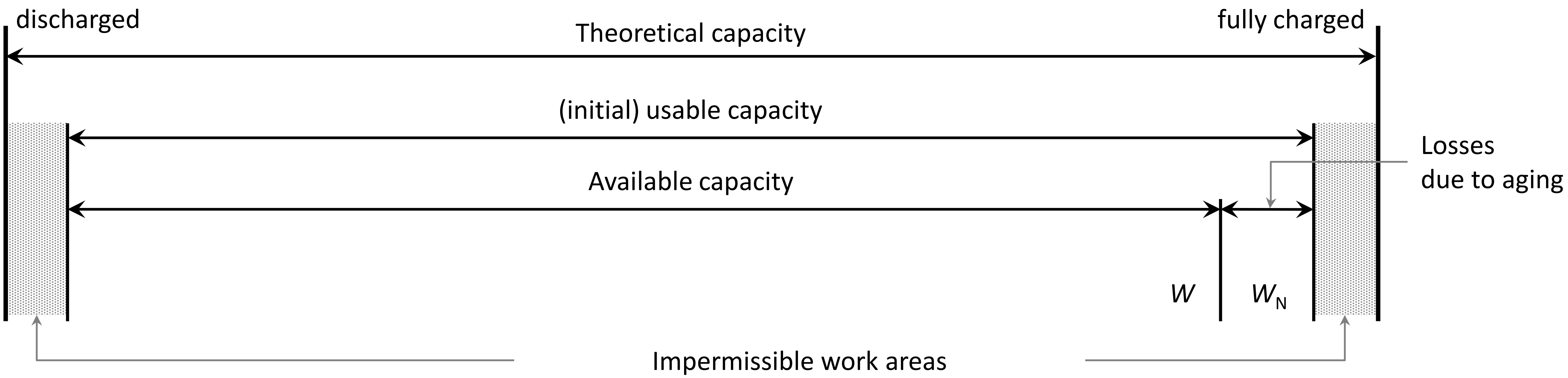


Technical and physical basics

Calculation of the power quantities

- *Excursus: Capacity terms*
- Capacity changes over time
- Different view depending on the viewer:
  - Producer → theoretical capacity
  - Customer → useable capacity
- Differences up to 20% (question of cost)





Technical and physical basics

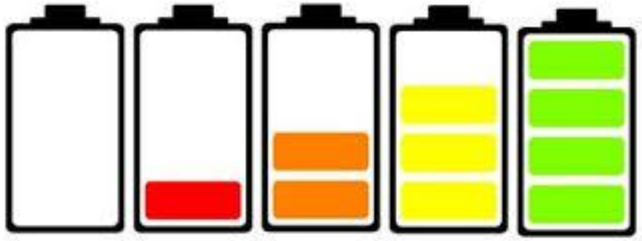
Calculation of the power quantities

Energy **Work**	E W	Wh	**Power over time, energy storage capacity of the system (Sys.) Or the battery** $(E_{\mathbf{Cap.}})$	$E_{elec.} = U \cdot I \cdot \Delta t$ $E_{\mathbf{Cap.}} = U_{Sys} \cdot C_{Sys}$ $E_{mech.} = \vec{F} \cdot \vec{s} = P \cdot \Delta t$

- The energy storage capacity $E_{Cap.}$ in watt-hours (Wh) describes the amount of energy that a storage device can hold, release, or hold in total. The total capacity $E_{Cap.,\mathrm{sys}}$ describes the design size and capacity of an energy storage device. During a storage or retrieval operation, usually only a partial capacity E_{in} and E_{out} is needed.
- The storage level changes accordingly. The partial capacities are obtained as the integral of the charging or discharging power or storage and retrieval power (P_{in} or P_{out}) over the charging or discharging time or storage and retrieval time (t_{in} oder t_{out}). For constant powers, the integrals are omitted, and the product of power and time remains.

$$E_{in} = W_{in} = \int_{t_1}^{t_2} P_{in}(t) \cdot dt$$

$$E_{\mathrm{out}} = W_{\mathrm{out}} = \int_{t_1}^{t_2} P_{out}(t) \cdot dt$$

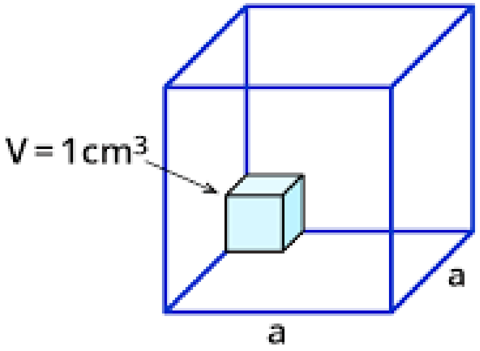


Technical and physical basics

Calculation of the power quantities

Energy density	$\rho_{E,V}$	Wh/m^3	**volumetric Energy density of the system volume/capacity (or just Energy destiny)**	$\rho_{E,V} = E/V$
	$\rho_{E,m}$	Wh/kg	**gravimetric Energy density of the system mass (also called specific Energy)**	$\rho_{E,m} = E/m$

- The volumetric energy density of the system volume (or just Energy density) $\rho_{E,V}$ is a relative energy quantity that relates the storage capacity of the energy storage device to its volume. It is expressed as volumetric energy density $\rho_{E,V}$ in Wh/m^3 .



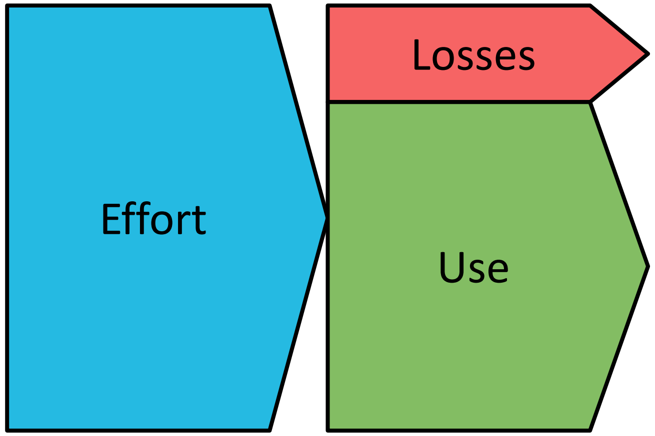
- The gravimetric energy density of the system mass (also called specific energy) is a relative energy quantity that relates the storage capacity of the energy storage device to its mass. It is expressed as gravimetric energy density $\rho_{E,m}$ in Wh/kg.
  Energy density is a key measure in the evaluation of energy storage devices.

Technical and physical basics

Calculation of the power quantities

Efficiency	$\boldsymbol{\eta}$	-	**The efficiency is calculated from the delivered energy/power to the supplied energy/power**	$\boldsymbol{\eta = \frac{E_{out}}{E_{in}} = \frac{P_{out}}{P_{in}}}$
Ampere-hour efficiency	$\boldsymbol{\eta_{Ah}}$	-	**Ampere-hour efficiency is defined as the delivered current to the supplied current**	$\boldsymbol{\eta_{Ah} = \frac{I_{out}}{I_{in}}}$

- Accordingly, energy efficiency η (or storage efficiency) is defined in unitless or percentage terms as the ratio of supplied/stored energy E_{in} to delivered/withdrawn energy E_{out}.
- The storage process can consist of several subprocesses whose individual efficiencies multiply to form the storage efficiency.
- In battery systems, the ampere-hour efficiency is clearly distinguishable from this. In this, only the charging (I_{in}) and discharging (I_{out}) current is considered. Therefore, the consideration of the stroke / drop of the voltage during charging and discharging is omitted and the η_{Ah} turns out to be higher than the energetic consideration η.



$$\eta_E = \frac{\int P_{out} \cdot dt}{\int P_{in} \cdot dt} = \frac{\int (U_{out} \cdot I_{out}) \cdot dt}{\int (U_{in} \cdot I_{in}) \cdot dt}$$

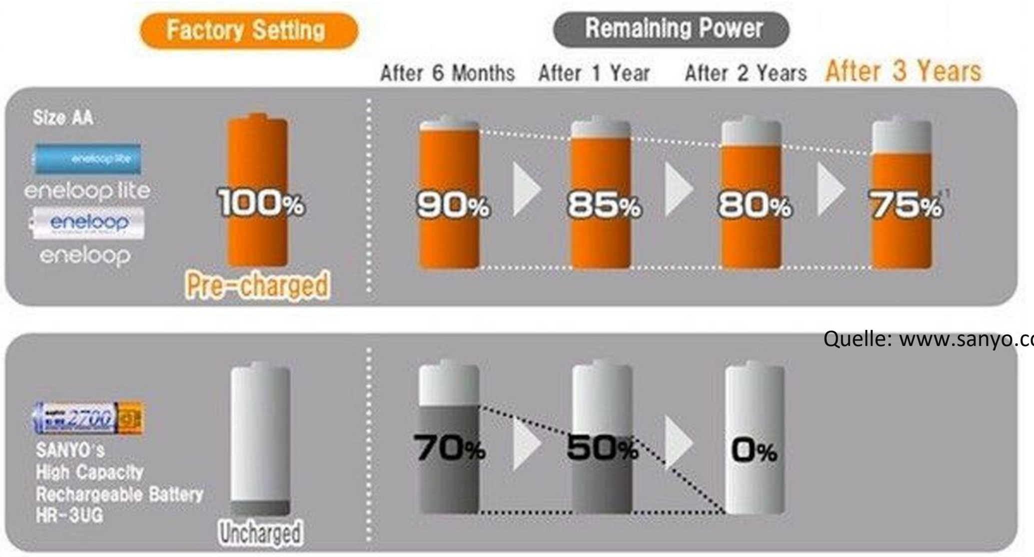
Technical and physical basics

Calculation of the power quantities

Self-discharge rate	n_{sd} SR	$\%/a$	Is the self-discharge (lowering of SOC) over time. Is expressed as a percentage per unit of time (= depending on the technology: per second up to year)	$n_{sd} = \Delta SOC/\Delta t$

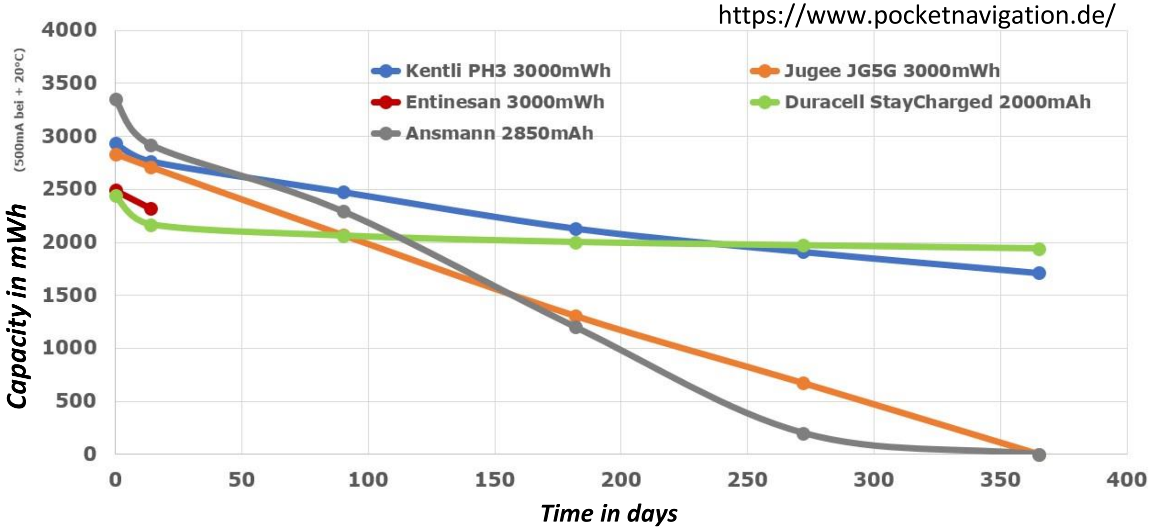
Almost all storage devices do not keep the stored energy constant and lose some of it over time. The self-discharge rate n_{sd} or SR indicates what percentage of the stored energy E_{st} as power loss P_L is released unused to the environment over a period of time dt due to self-discharge.

$$n_{sd} \approx SR = \frac{\int P_L \cdot dt}{E_{st}} = \frac{E_L}{E_{st}}$$



Quelle: www.sanyo.com

Self-discharge 1,5 Volt Lithium-Ion Battery AA/LR6 at +20 °C



https://www.pocketnavigation.de/

Quelle: www.sanyo.com

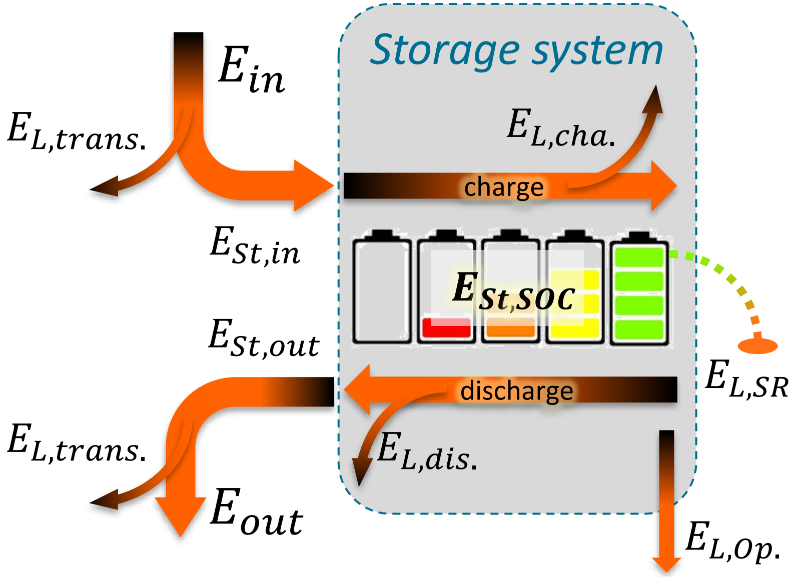
Technical and physical basics

Calculation of the power quantities

The charging and discharging process in storage systems includes different lossy subprocesses.

When the Energy E_{zu} is converting, transformation losses ($E_{L,trans.}$) occur before the energy added to the storage ($E_{St,in}$) is stored.

- Depending on the storage type, there are different high charging losses ($E_{V,cha.}$).
- In many storage technologies, the energy stored in the energy storage $E_{St,SOC}$ is subject to losses over time $E_{L,SR}$, self-discharge.
- Depending on the storage type, there are different high discharge losses ($E_{L,dis.}$).
- When the Energy $E_{St,out}$ is converting transformation losses ($E_{L,trans.}$) occur before the energy taken from the storage system (E_{out}) can be used in the downstream energy systems.
- For the operation of the storage system, self-consumption must be taken into account. ($E_{L,operation.} = \int P_{L,operation.} \cdot dt$) .
- The losses of a system are the sum of all partial losses.
  From this, the efficiency η_{tot} for the operating point / process can be derived.



$$Bsp. \rightarrow E_L = E_{L,dis.} + E_{L,SR} + E_{L,cha.} + E_{L,trans.out} + E_{L,trans.in} + E_{L,Op.}$$

$$E_{L,SR} = \int P_{L,SR} \cdot dt,$$

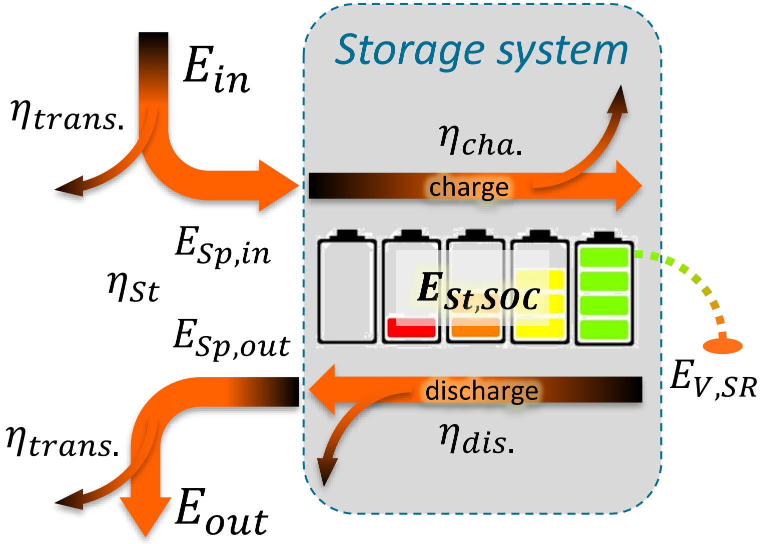
$$mit\ P_{L,SR} = f(SOC, \vartheta, SOH, \dots)$$

$$E_{out} = E_{in} - \sum E_{L,n}$$

$$\boldsymbol{E_{out} = \eta_{tot} \cdot E_{in}}$$

Technical and physical basics

Calculation of the power quantities



The charging and discharging process in storage systems includes different lossy sub processes

- The supplied form of energy E_{in} must be partially converted this energy conversion is subject to a transformation efficiency (η_{trans})
- When charging as well as discharging accumulators, the charging (η_{cha}) and discharging (η_{dis}) efficiencies must be considered.
- The self-discharge $P_{V,SR}\,(t)$ has a time dependence and can have a significant impact on the storage efficiency.
- Usually, all losses of the storage system are summarized in a storage efficiency (η_{St}). This value is always linked to certain boundary conditions (charging power, storage time, ambient temperatures, etc.). For a more precise consideration, the specific consideration of the individual losses is recommended.
- The overall efficiency n_{Sys} of a storage system is the product of all the efficiencies $\eta_{Sys,n}$ present in the system, i.e., taking into account all losses.

$$\eta_{SOC}(t) = \frac{E_{SOC} - \int P_{L,SR} \cdot dt}{E_{SOC}}$$

$$\eta_{Sys} = {E_{out}}/{E_{in}}$$

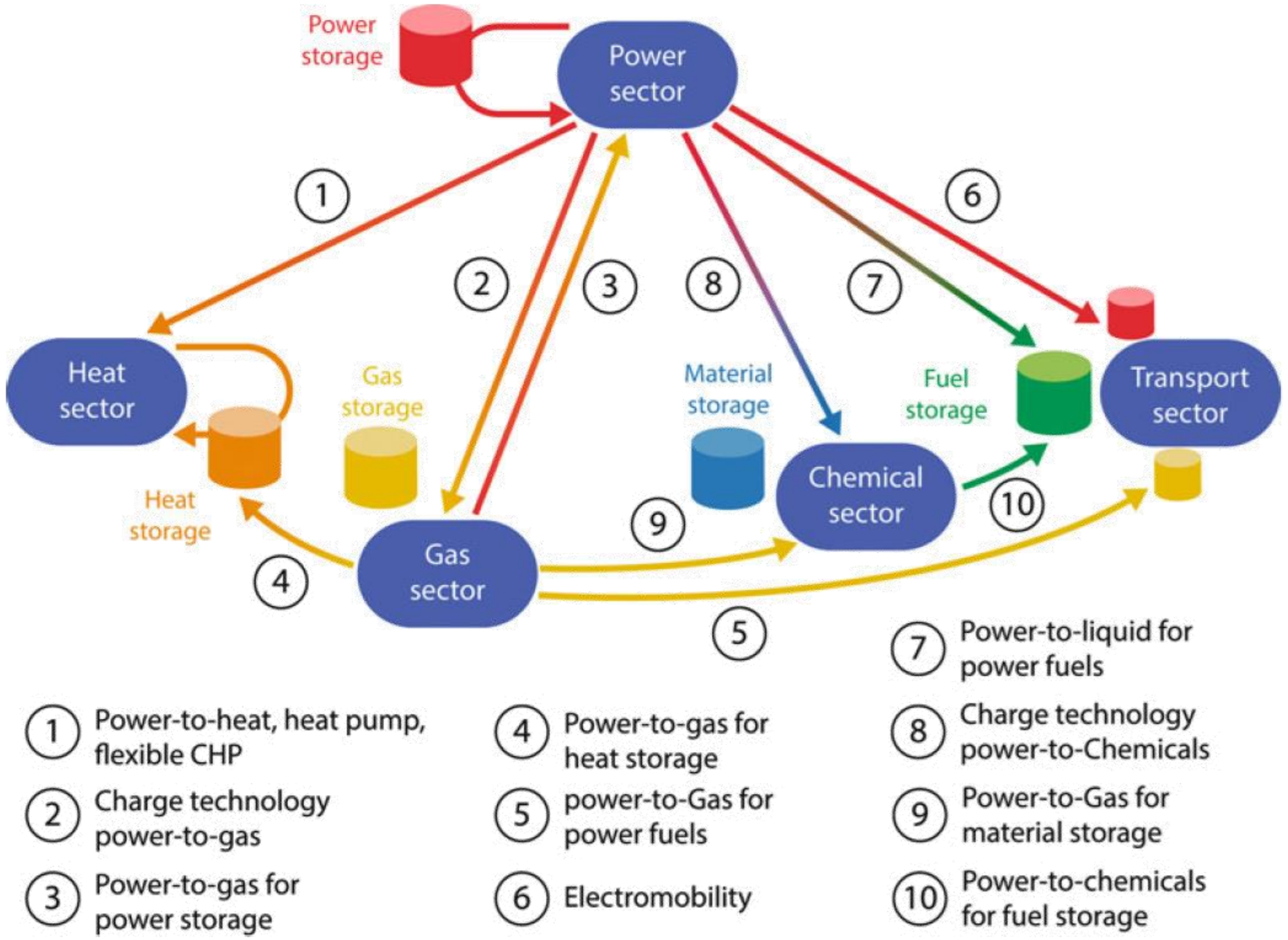
$$\eta_{Sys} = \prod \eta_{Sys,n}$$

Power-to-X

Definition

- The sector coupling is the connection the electricity, heating, transport and chemical sectors using electricity as primary energy to decarbonise the other sectors. It is also known as **Power-to-X** and is not possible without energy storage or largely corresponds to the definition or largely corresponds to the definition of sector-coupling energy storage systems.
- Definition: “Power-to-X describes the conversion of Electricity as primary energy and raw material in one Energy carrier, i.e. in heat, cold, product, Fuel or raw material. It is a collective term for power-to-gas, power-to-liquid, power-to-Fuel, power-to-chemicals, power-to-product and also power-to-heat.

Video

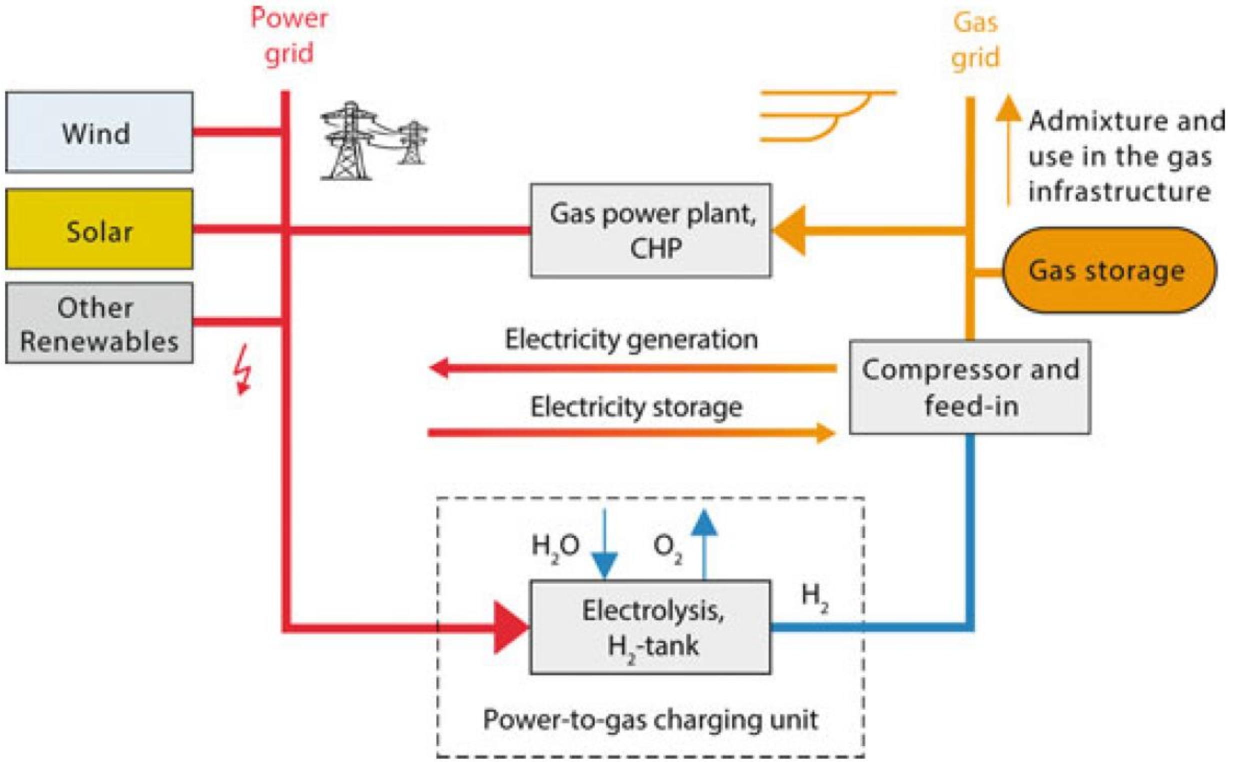


Source: Handbook of Energy Storage, ISBN 978-3-662-55503-3

Power-to-X

Power-to-Gas (PtG)

- Power-to-gas is an energy management concept according to which a fuel gas is produced by means of water electrolysis and electrical power. This fuel gas (usually hydrogen, possibly ammonia, methane) can be stored for later use.
- Water is first split into hydrogen and oxygen using electrolysers, then methanised with the addition of carbon dioxide and finally fed into the natural gas network.
- The stored gas can be exchanged for electricity or heat via combined heat and power plants.
- In addition to reconversion in gas-fired power plants or combined heat and power plants, it can also be used in the transport sector and for generating heat.



Source: Handbook of Energy Storage, ISBN 978-3-662-55503-3

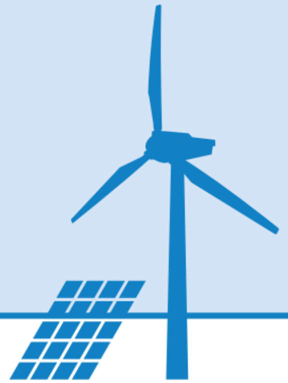
Power-to-X

Power-to-Gas (PtG) – Example of transformation chain

Agentur für Erneuerbare Energien e. V.

HIGH ELECTRICITY SUPPLY

The increasing expansion of wind energy and photovoltaics ensures a high electricity supply on sunny and windy days, which can also be used to generate synthetic gases.



CURRENT

ELECTROLYSIS

With the help of electric current, **water is split into hydrogen and oxygen** during electrolysis. In this way, part of the electrical energy is stored chemically in the form of hydrogen.

HYDROGEN

METHANATION

In methaniation, the electrically produced hydrogen is further processed into methane with the **addition of carbon dioxide (CO_2)**.
The synthetic methane produced in this way corresponds to chemical fossil natural gas and is easier to store, transport and use than hydrogen.

HYDROGEN

METHAN

CURRENT

POWER-TO-GAS

Power-to-X

Power-to-Gas (PtG) – Example of transformation chain

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HYDROGEN

METHAN

STORAGE

HYDROGEN STORAGE

Gaseous hydrogen is stored under high pressure, liquid hydrogen at very low temperature. This means a high material and energy input.

GAS NETWORK

Hydrogen can be fed into the existing natural gas grid up to a proportion of approx. 5 percent. Practically the entire storage capacity of the natural gas grid is available for synthetic methane. In Germany, this is about 200 billion kilowatt hours and corresponds to the nationwide electricity consumption in four months.

HYDROGEN / METHAN

Power-to-Gas (PtG) – Example of transformation chain

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HYDROGEN / METHAN

CURRENT AND HEAT

Hydrogen and methane can be reused in combined heat and power (CHP) plants or other gas (CHP) plants as well as fuel cells to generate electricity and heat as needed. However, the entire chain of action is associated with considerable energy losses.

FUEL

Hydrogen and methane can be used as fuel in technically appropriately equipped filling stations and vehicles.

GAS USAGE

CURRENT

HEAT

MOBILITY

Overview of battery storage systems

Power-to-Gas (PtG) – Example of transformation chain

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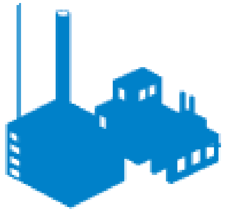
CURRENT HEAT MOBILITY

INDUSTRY

Industrial processes account for around 7 percent of total greenhouse gas emissions in Germany. Around 50 million tons of CO2 are emitted in the production of crude steel alone: The EU-funded Green Industrial Hydrogen project, in which eight partners from Germany, Italy, Spain, Finland and the Czech Republic are involved, aims to make industrial processes more climate-friendly. The key to this: a high-temperature electrolysis process. On the one hand, industrial companies can use this process to increase their efficiency through heat recovery. On the other hand, the raw material "hydrogen", which is important for industrial processes, can be provided with renewable energies in a climate-friendly way, for example for the:

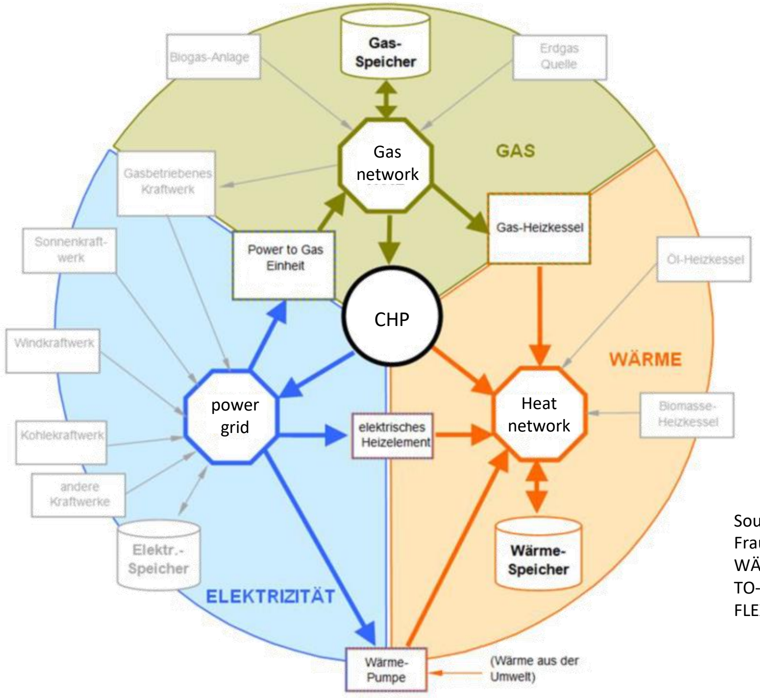
- **Chemical sector:** Hydrogen is the most important molecule in the production of ammonia, methanol and petroleum-based products
- **Steel sector:** Hydrogen creates a safe atmosphere in the process, excludes oxygen and thus prevents oxidation of the steel during the annealing process
- **Electricity sector:** Hydrogen is used to cool large generators



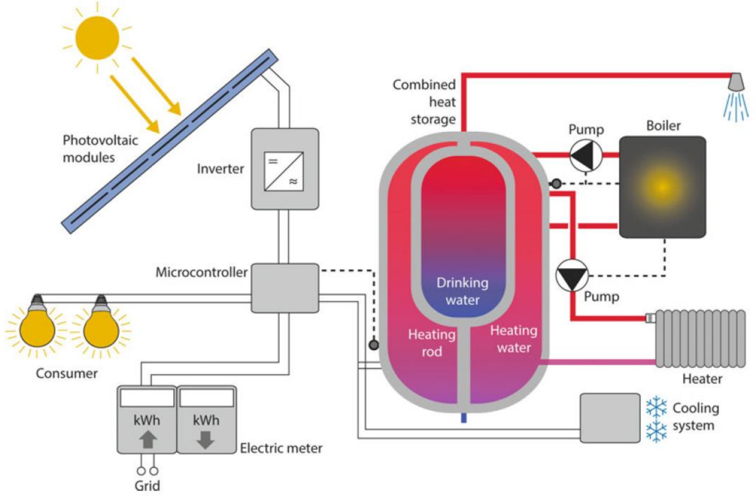
Power-to-X

Power-to-Heat (PtH)

- Power-to-heat is the generation of heat using electrical energy (optimally excess energy from renewable energies). This can be done using both electric boilers and heat pumps, which can save fossil fuels and emissions in the heating sector. To increase flexibility, power-to-heat systems are often coupled with heat storage systems.
- The feed mostly takes place in local or district heating networks, but power-to-heat systems can also supply individual buildings or large industrial plants with heat.
- In addition to electrical energy, the heat can also be obtained as a waste product from biogas plants (via CHP).
- Big advantage: Low investment costs (if CHP system and heat storage are available)



Source:
Fraunhofer IFAM: ENERGIESPEICHERUNG MITTELS WÄRMESPEICHERN; POWER-TO-HEAT UND POWER-TO-GAS – VERGLEICH VERSCHIEDENER FLEXIBILISIERUNGSOPTIONEN

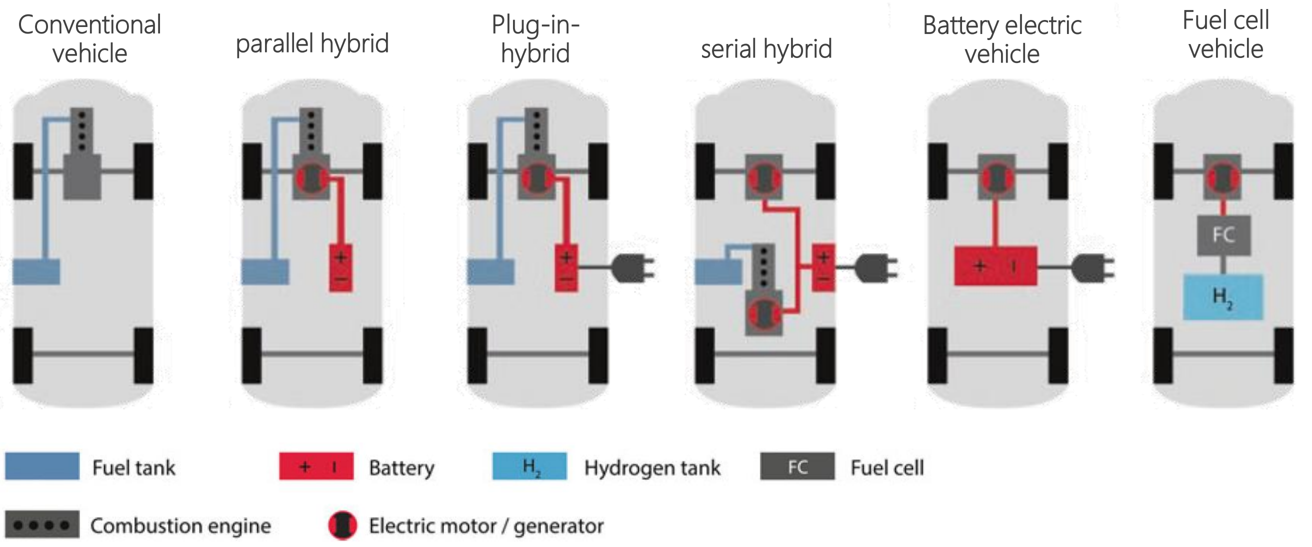


Source: Handbook of Energy Storage, ISBN 978-3-662-55503-3

Power-to-X

Power-to-Mobility (PtM)

- Power to Mobility enables the connection of the renewable electricity industry with sustainable mobility.
- Electromobility offers a direct link between electricity and the transport sector.
  - Only pure electric vehicles (battery-operated or via overhead lines) can use the electrical energy from renewable energies directly.
- According to forecasts, by 2050 50% of mobility requirements can be covered by renewable energies.



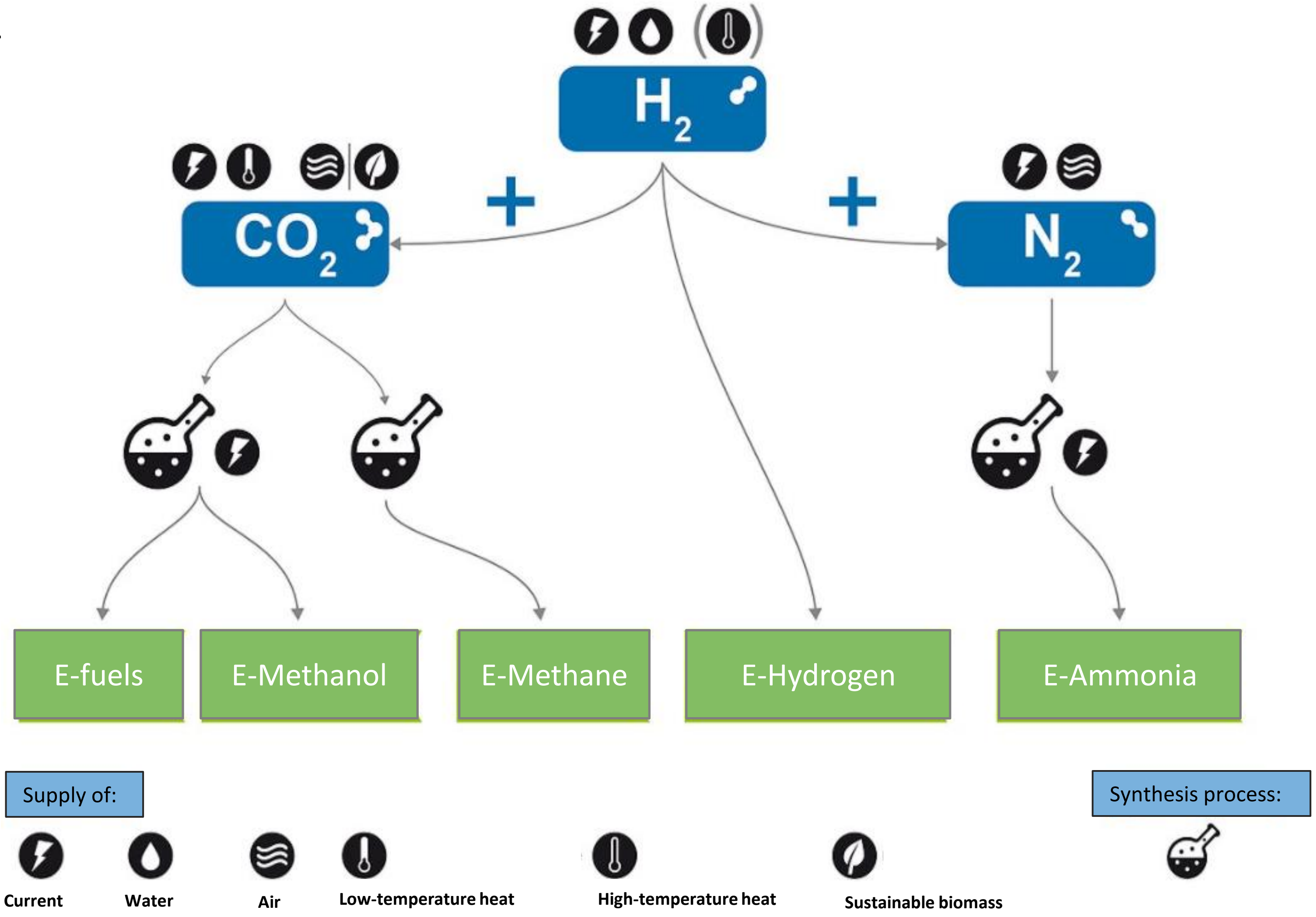
	2010		2050	
	Final energy in TW h/a	Shares	Final energy in TW h/a	Shares
Fossil fuels (gasoline, diesel, kerosene, gases)	685	93%	212	50%
Biofuels (bio-ethanol, biodiesel, and BTL)	36	4.9%	83	20%
Synthetic fuels (hydrogen, windgas, wind diesel)	0	0%	67	16%
Electricity (e-mobility)	16	1.6% conventional, 0.5% renewable	60	14% (purely renewable)

Source: Handbook of Energy Storage, ISBN 978-3-662-55503-3

Power-to-X

Power-to-Fuel (P2F)

- generally refers to the production of electricity-based synthetic fuels for the transport sector
- Power-to-fuel refers to the production chains of hydrogen, ammonia, methane and syngas (a mixture of hydrogen and carbon monoxide) via power-to-gas. This also includes the production of methanol using power-to-liquid technology. The starting point is always the generation of hydrogen through water electrolysis.
- The negative aspect, however, is the low overall efficiency, which is far lower than direct electrification via electric cars.



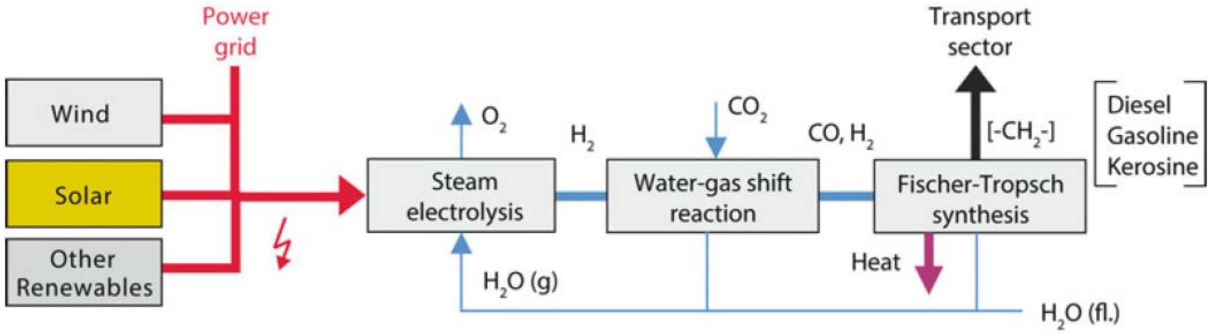
Source: Öko-Institut 2019, CC BY-SA 2.0

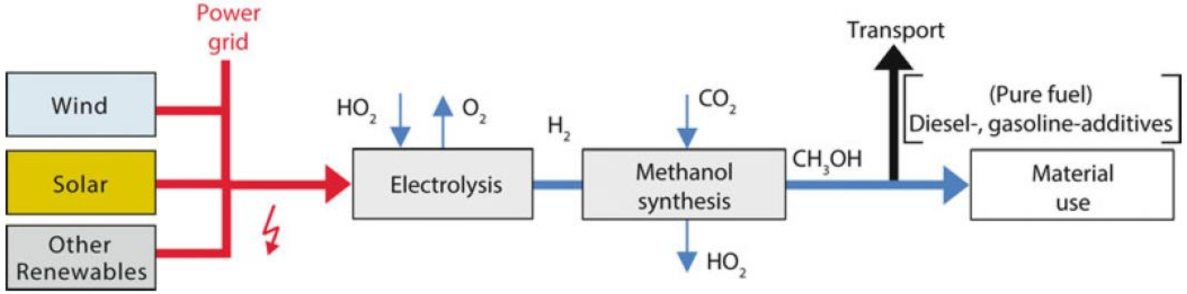
Power-to-X

Power-to-Liquid (PtL)

- The power fuels methanol, gasoline, diesel, kerosene and wax are suitable as target products from Power-to-Liquid.
- 4 steps are necessary to produce
  - 1. Electrolysis
  - 2. Hydrogen and CO2 to synthesis gas
  - 3. Synthesis gas to hydrocarbons (**Fischer-Tropsch synthesis**)
  - 4. Separation with a separator

Transformation	Efficiency	Process step	Cost per liter (10kWh)
Current to H2	90 %	1	1 Euro
Current to Methane	70 %	2	1,5 Euro
Current to Methanol	40 %	4	2 Euro
Current to Diesel	30 %	4	3 Euro



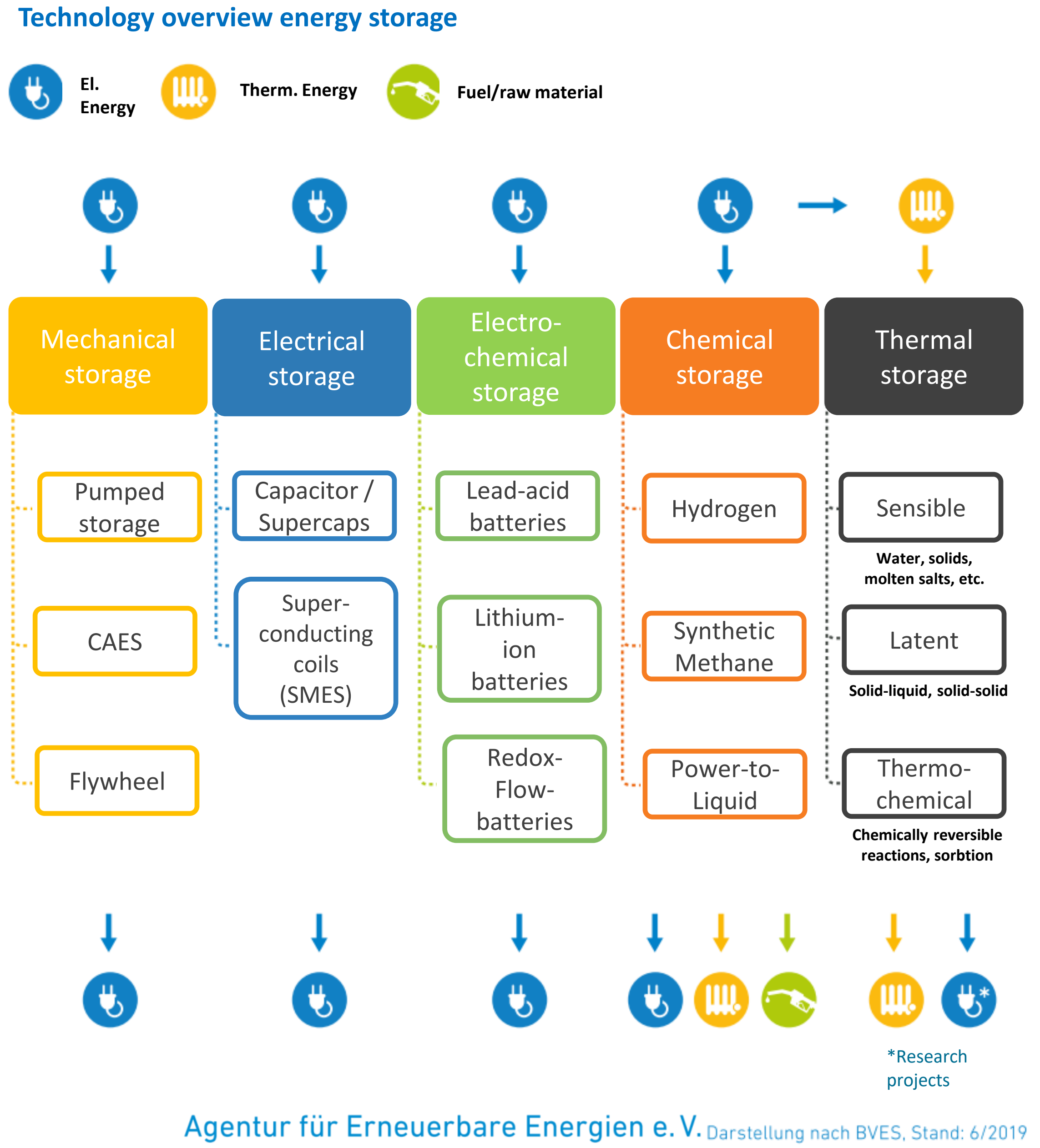


Source: Handbook of Energy Storage, ISBN 978-3-662-55503-3

Overview of battery storage systems

Storage properties and technologies

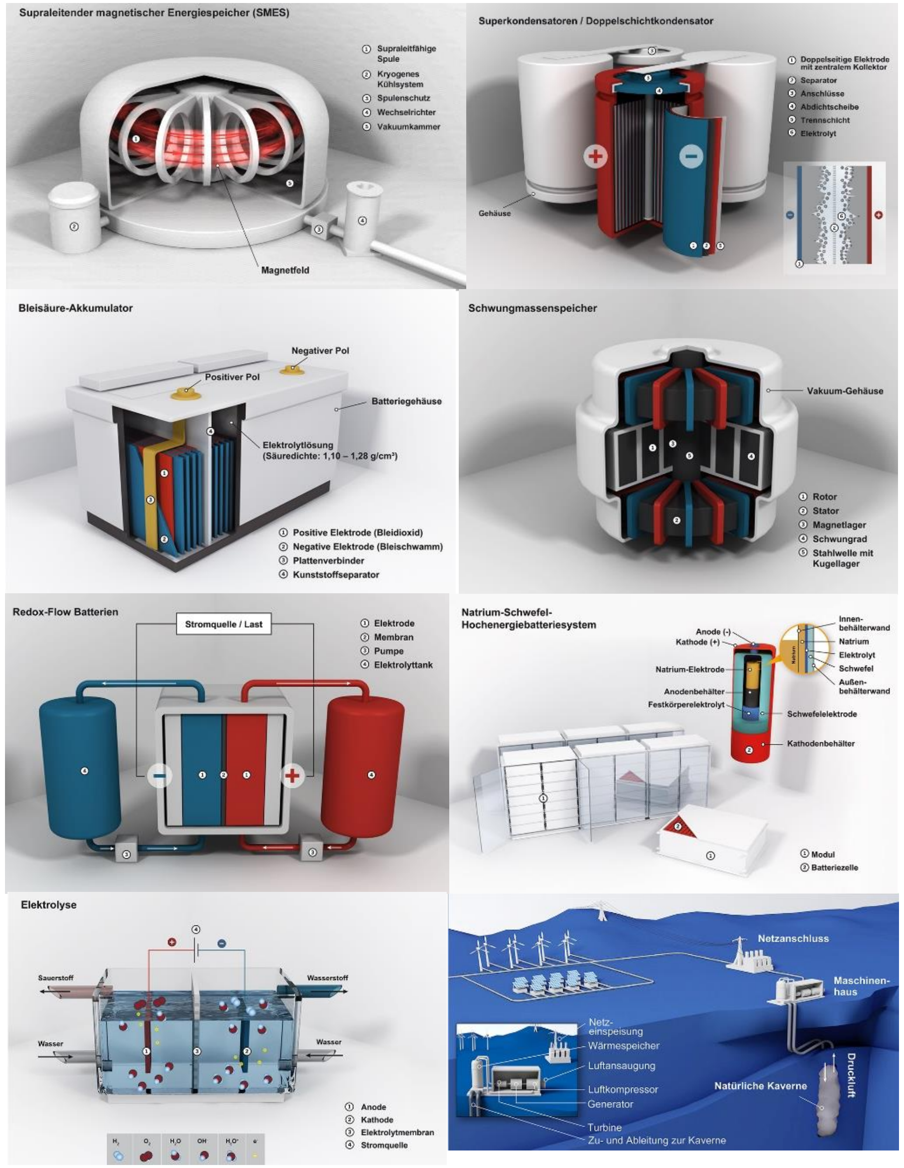
- Differentiation according to stored primary energy: Electricity, heat, biogas or other fuels
- Differentiation in stored energy form: electrical, electro-chemical, mechanical, thermal or chemical
- Differentiation according to subsequent recovery: Electricity, heat, fuel, raw materials
- Differentiation according to the amount of energy: Storage capacity (output energy form)
- Differentiation according to energy losses:
- Injection and withdrawal losses (efficiency), operating losses, self-discharge, etc.
- Differentiation according to performance values: Performance, performance change and response times (dynamics),
- Differentiation according to storage time: Short-term or long-term storage



Overview of battery storage systems

Classification of storage systems according to energy density

Energy storage technology	Energy density
Double layer capacitor	10 kWh/m^3
Superconducting magnetic coil	3 kWh/m^3
Lithium Ion Battery	300 kWh/m^3
Lead acid battery	70 kWh/m^3
Hydrogen	400 kWh/m^3 (at 300 K and 200 bar)
Methane	1200 kWh/m^3 (at 300 K and 200 bar)
Petrol	10.000 kWh/m^3
Potential energy (e.g. pump storage)	1,5 kWh/m^3 (at 540 m hight)
Kinetic energy (e.g. flywheel)	20 kWh/m^3 (Steel wheel at 5000 U/min)
"Pressure energy" (e.g. CAES Huntorf power plant)	20 kWh/m^3 (at 70 bar)
sensible heat storage (e.g. water)	175 kWh/m^3 (at ΔT = 150 K)
Latent heat storage (e.g. water - steam)	627 kWh/m^3 (at 1 bar and 273 K)
Thermo-chemical storage	200–500 kWh/m^3



Source: http://www.energieregion.nrw.de/

Overview of battery storage systems

Area of application of storage in energy supply

Repetition

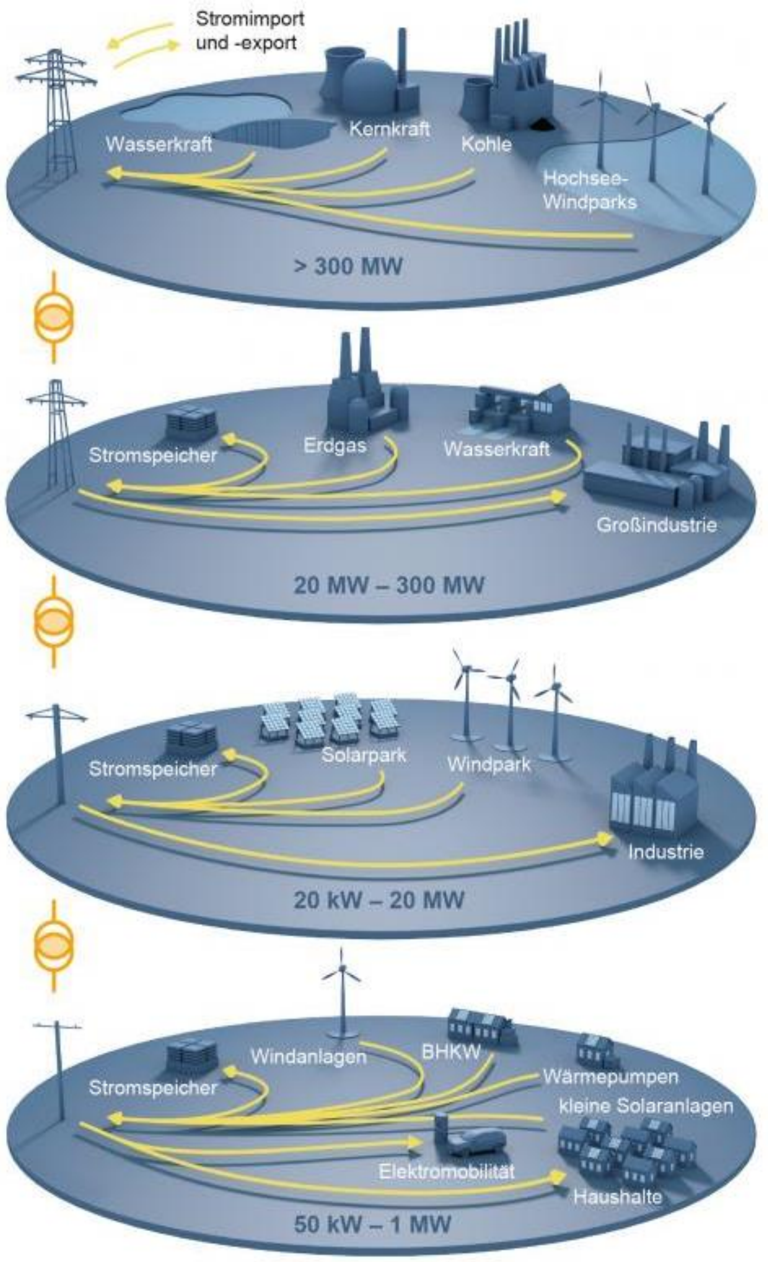
- *There are 4 network levels in the electrical energy supply (see graphic)The network was set up and planned for a central (generation in network level 1) energy supply*
- *The addition of renewable, decentralized generators brings generators to all network levels challenges for control, protection concepts, etc. Relocation of generation to the distribution grids, as currently 90% of the regenerative producers in the distribution network*
- *Another problem is the responsibilities for the individual network levels and the obligations associated with them*
  - *TSO transmission system operator*
  - *DSO distribution network operator*
- *With DSM, DSR, load / process flexibilization, local energy balancing (e.g. optimization of own electricity utilization), efficiency improvement measures, storage technologies are also in industry, trade and in the private sector*
- *The need for storage technologies for the various challenges is increasing Requirements for storage depend on the suitability of storage technologies*

Grid Level 1
Extra high voltage
220 – 380 kV

Grid Level 2
High voltage
60 - 110 kV

Grid Level 3
Middle voltage
3 – 30 kV

Grid Level 4
Low voltage
230 – 400 V

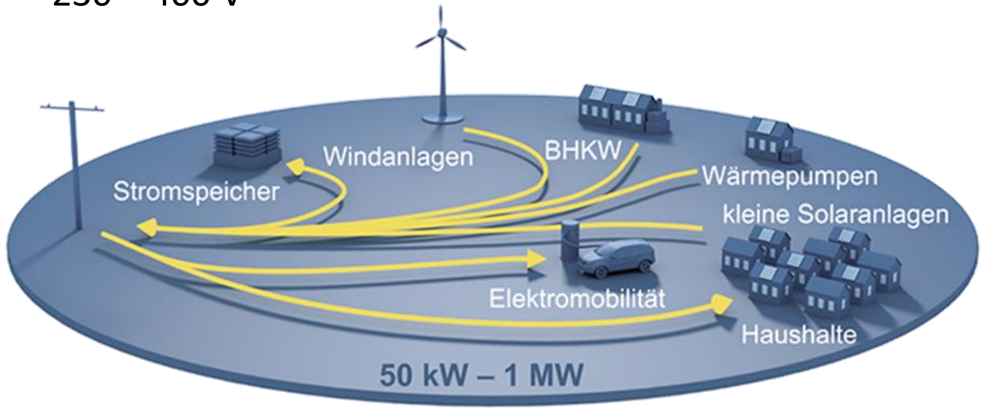


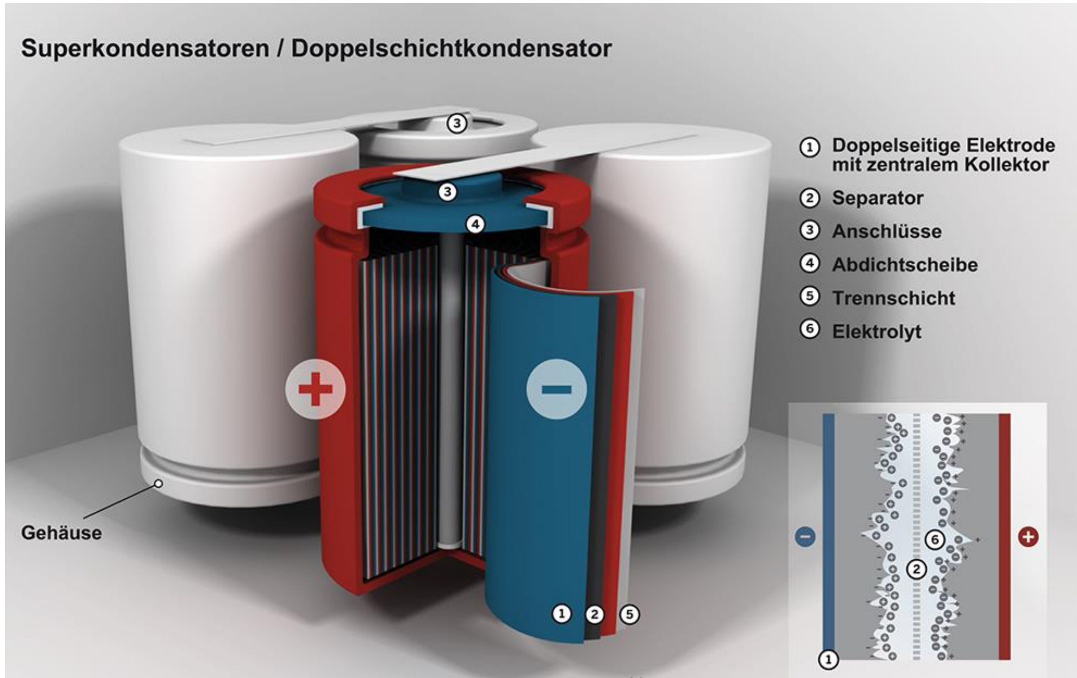
Overview of battery storage systems

direct electrical energy storage - capacitors

- established technology
- direct energy storage without conversion - (electric field)very high efficiency 98 - 100% and cycle stability
- significantly higher power density and slightly lower energy density compared to batteries
- Very high self-discharge 10 - 15% per day, therefore unsuitable as long-term storage
- Areas of application as short-term storage in mobility, elec. Network compensation systems, network filters, voltage stabilization, etc.
- Often used in combination with other storage systems to map dynamic loading and unloading processes

Grid Level 4
Low voltage
230 – 400 V





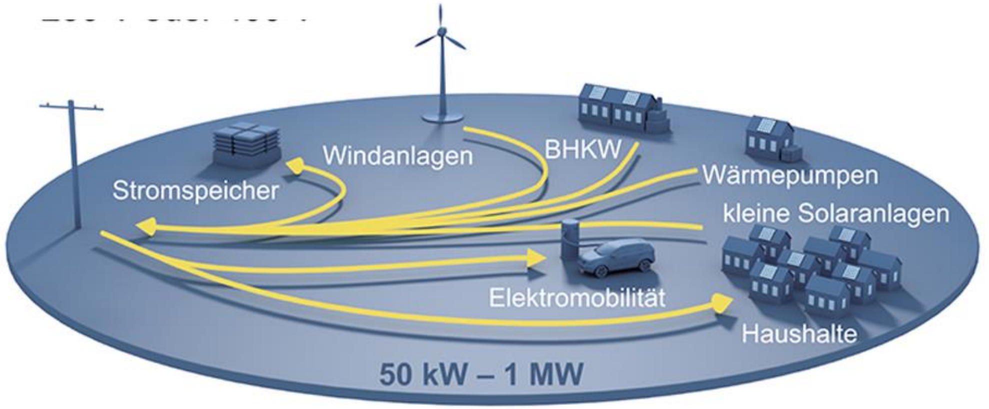
Quelle: EnergieAgentur.NRW

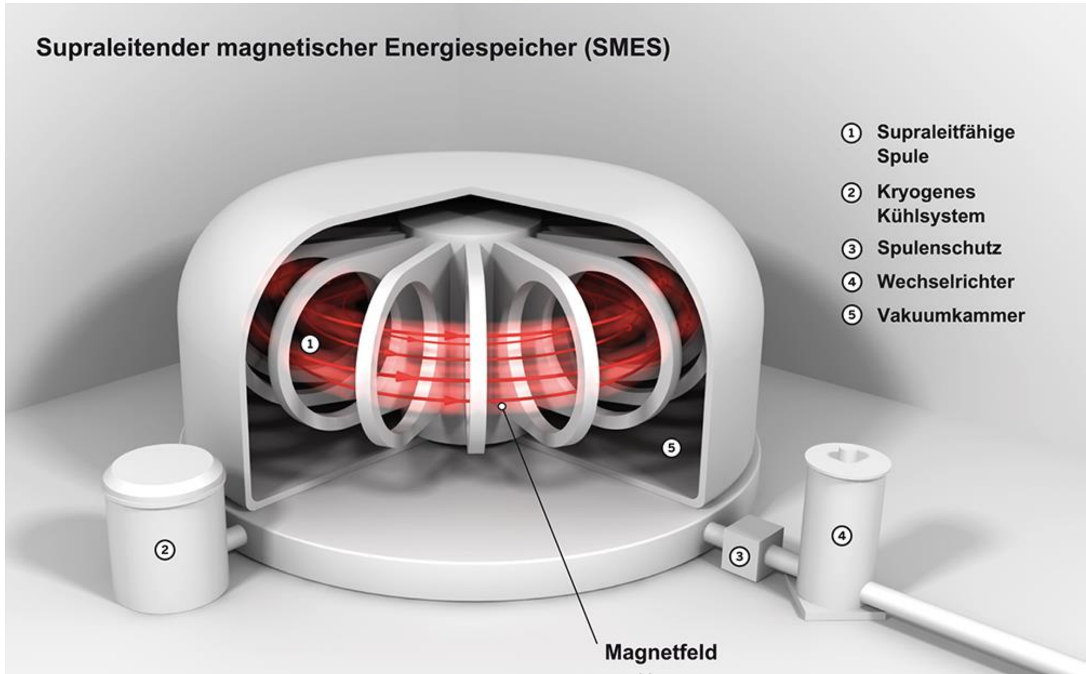
Overview of battery storage systems

direct electrical energy storage - SMES

- SMES - superconducting magnetic energy storage devices are not very common, use in special applications e.g. research
- direct energy storage without conversion - (magnetic field)high efficiency 90 - 95% and cycle stability, but quite high technological effort for the cooling system (-200 ° C) in order to achieve high conductance
- Resistance of the coil determines the energy expenditure for the storage of electricity, if the resistance approaches zero, then loss-free storage - therefore extreme cooling of the conductor
- Use as short-term storage e.g. network stabilization and to maintain the voltage quality as well as power modulation and load compensation
- Response times in the range of milliseconds, as well as very high power densities
- Currently up to 10 MW tested but not yet an option for broad use

Grid Level 4
Low voltage
230 – 400 V





Quelle: EnergieAgentur.NRW

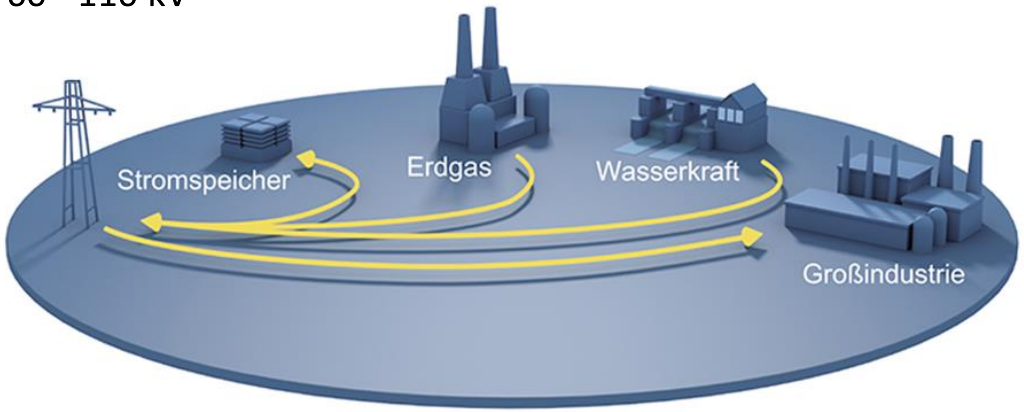
Overview of battery storage systems

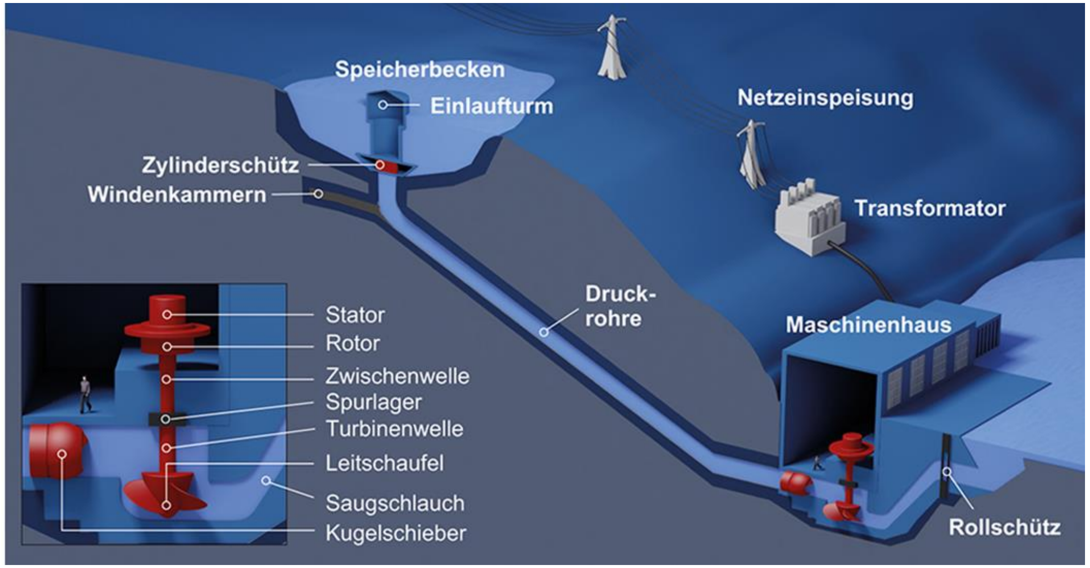
Mechanical storage - pumped storage power plants

- Worldwide> 99 percent of the energy storage type supply network
- Storage of potential energy through water in the reservoir, energy conversion through pump / turbine and motor / generator
- Site potential limited (difference in altitude, size of storage reservoirs, short headwaters, natural tributaries)
- Overall efficiencies from 70 to 80 percent
- Excellent long-term storage (no self-discharge)
- Balance between peak and base load (night power storage)
- New tasks in the volatile feeder arise with:
  - Peak load current and to stabilize the network
  - reinforced control energy black start capability (1-2 minutes up to nominal power)
- Alternative locations for hydropower plants
  - Salt water in pumped storage power plants on cliffs
  - Pumped storage power plants in disused mining sites

Grid Level 2
High voltage
60 - 110 kV

Quelle: EnergieAgentur.NRW





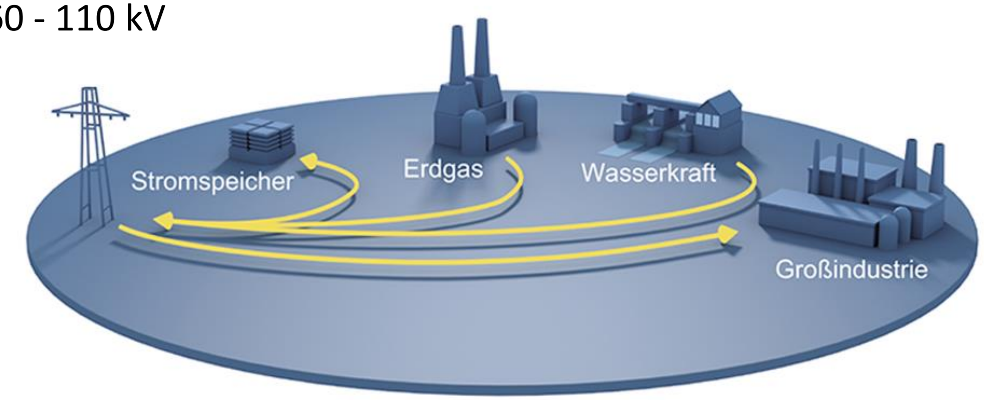
Overview of battery storage systems

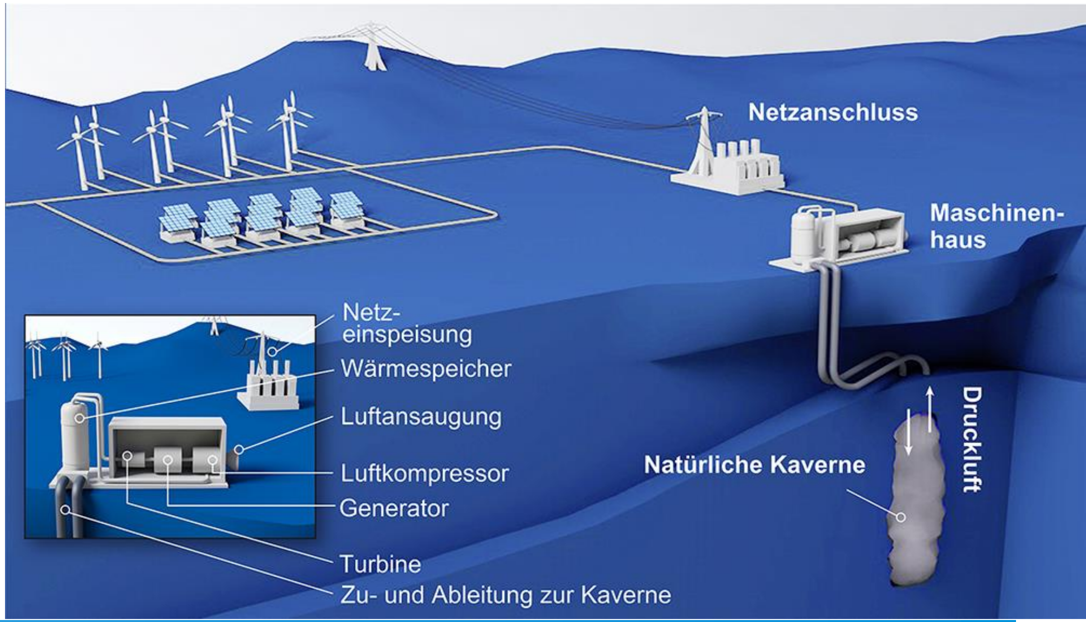
Mechanical storage – CAES (compressed air energy storage)

- Energy conversion into potential energy (internal energy gas)
- Air is pressed into underground cavities under high pressure (compressors) and when expanding, the energy is converted back into electrical energy by means of turbines and generators
- CAES power plants are underground compressed air storage facilities in salt caverns (Huntorf Germany 1978; McIntosch USA 1991)
- Due to the complex cooling and the subsequent heating, the efficiency is only 40% (Huntdorf) or 54% with waste heat recovery (McIntosh)
- With process integration of heat storage / use, an efficiency of up to 70% is theoretically possible
- Potential locations near the coast were identified. These are very well suited to compensate for the volatile wind feed-inApplication area as load balancing, control energy power plant, etc.
- Storage sizes currently several 100MW. In the future, several GW of power and GWh of storage capacity

Grid Level 2
High voltage
60 - 110 kV

Quelle: EnergieAgentur.NRW





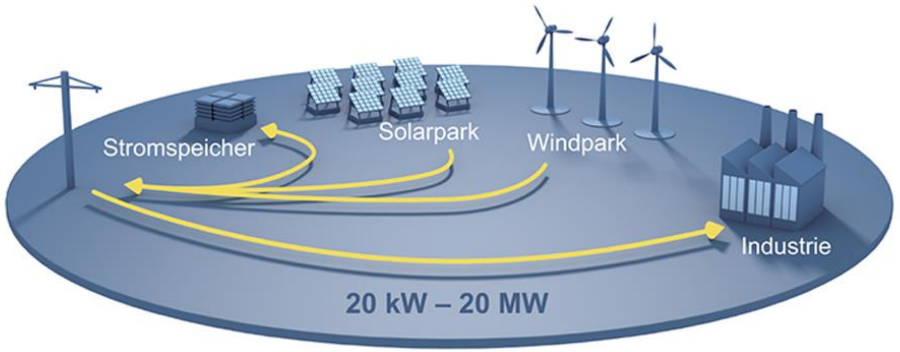
Overview of battery storage systems

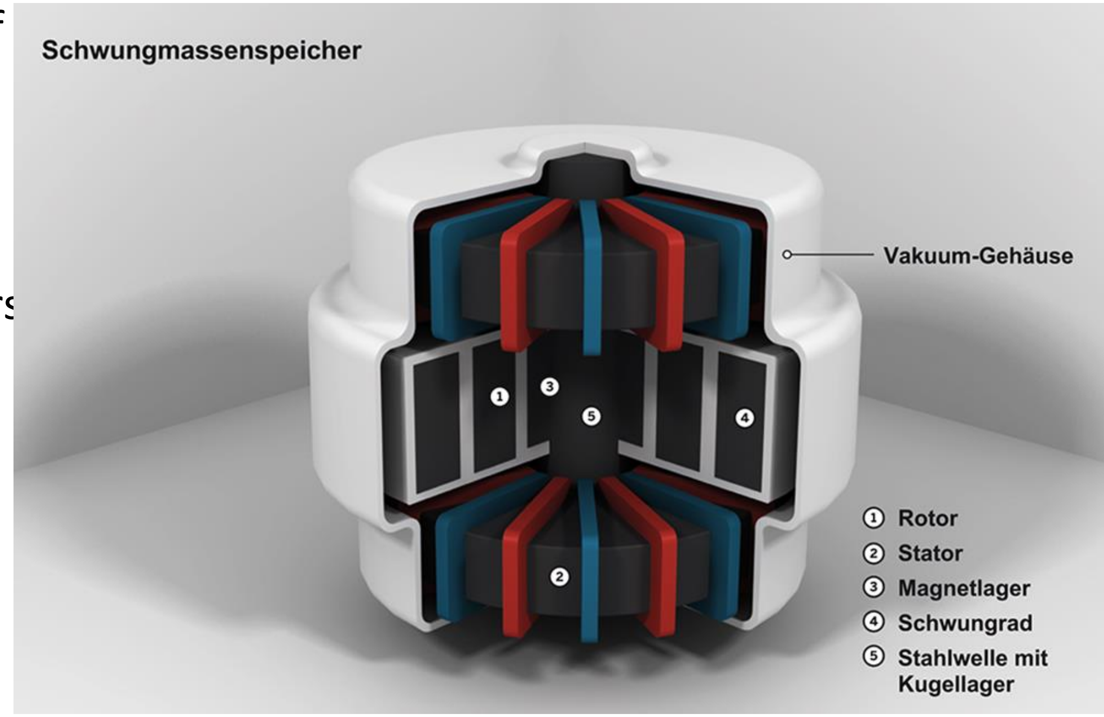
Mechanical storage - flywheel storage

Grid Level 3
Middle voltage
3 – 30 kV

Quelle: EnergieAgentur.NRW

- Energy conversion into kinetic energy (rotational energy)
- Large masses are accelerated to high rotational speeds.
- With superconducting magnetic bearings, maintenance-free and friction-free bearings can be realized, but this is associated with a very large installation space, great technological effort and costs.
- Very high power gradients and power density but small amounts of energy storage
- System efficiencies of 80% to 90% are possible and virtually unlimited storage cycles are possible
- Flywheel accumulators are only suitable as short-term accumulators due to their high self-discharge
- Storage sizes up to 3MW with up to 15min availability
- Applications: frequency control in the network, UPS, mobility, load flexibility, etc.





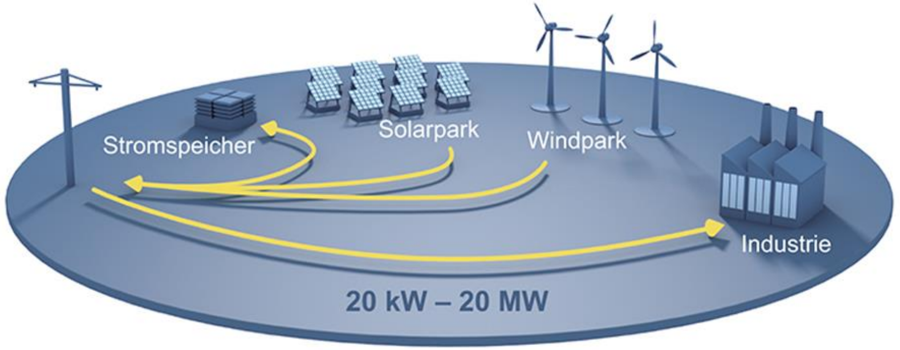
Overview of battery storage systems

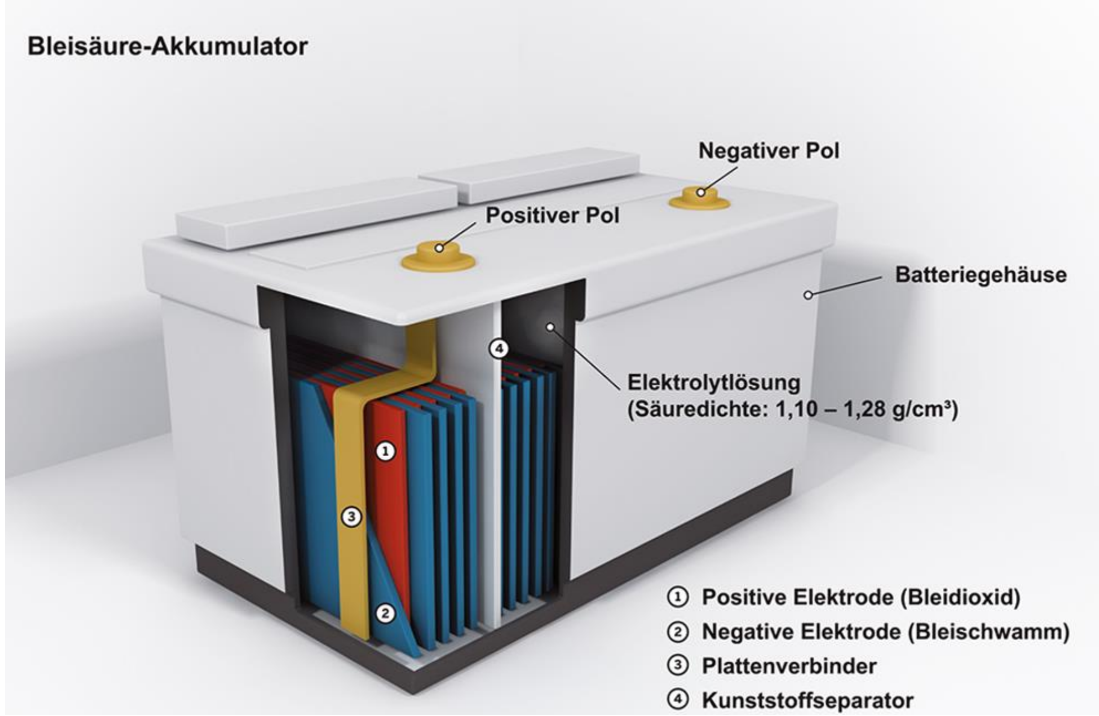
Electrochemical storage - lead-acid accumulator

Grid Level 3
Middle voltage
3 – 30 kV

Quelle: EnergieAgentur.NRW

- Energy conversion into electrochemical energy
- low battery and system costs
- Lead batteries have an efficiency of 80 to 90 percent
- Energy and power density compared to batteries is very low Cycle stability with 500 - 1000 cycles and a service life of 5 - 10 years is low (varies greatly depending on the operating mode and environmental conditions.)
- batteries have a high self-discharge and are therefore suitable as short to medium-term storage from milliseconds to weeks
- Storage sizes from a few Wh to a few MWh can be implemented
- Applications: mobility (on-board batteries, traction batteries, etc.), UPS, voltage stabilization, island networks, energy balancing (PV storage, etc.), load flexibility, etc.





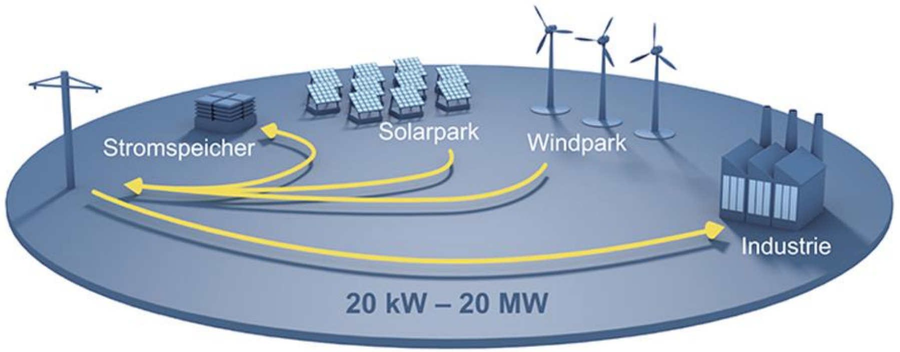
Overview of battery storage systems

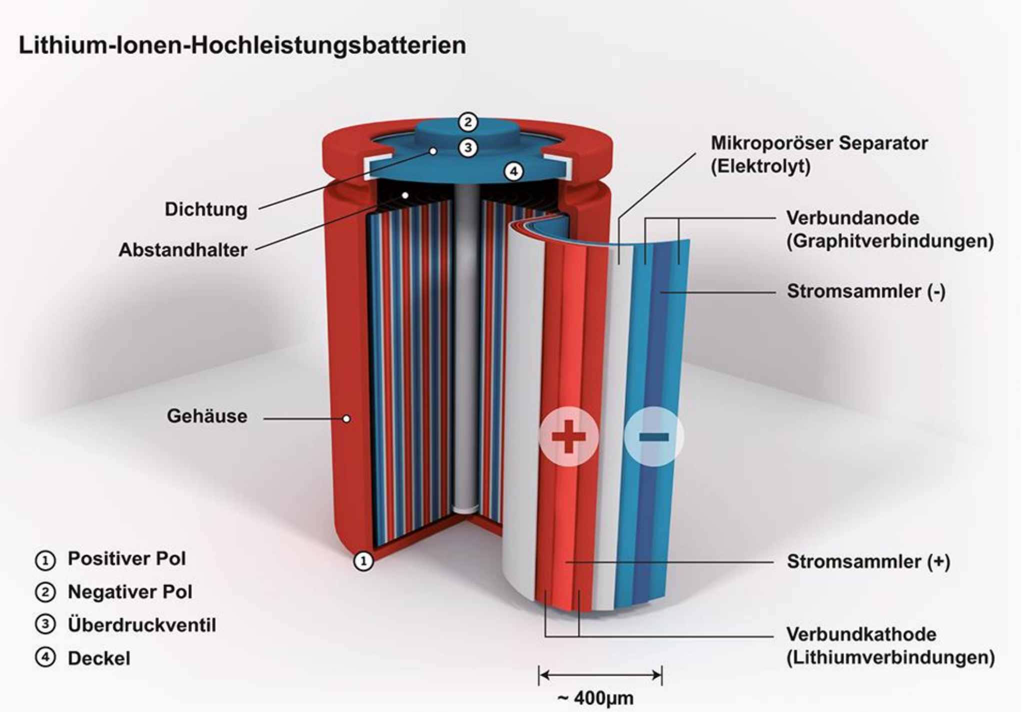
Electrochemical storage - lithium-ion accumulator

Grid Level 3
Middle voltage
3 – 30 kV

Quelle: EnergieAgentur.NRW

- Energy conversion into electrochemical energy
- high costs for batteries and technically complex peripherals in the battery system (battery management necessary, not intrinsically safe)
- Energy and power density very high compared to batteries
- High cycle stability with 5,000 - 15,000 cycles and a service life of 10 - 15 years (varies greatly depending on the operating mode and environmental conditions.)
- Li Ion batteries have a low self-discharge (approx. 3% per month) and are suitable as short to medium-term storage devices lasting from milliseconds to months
- Storage sizes from a few Wh to several MWh can be implemented and in use
- Applications: mobility (on-board batteries, traction batteries, etc.), UPS, voltage stabilization, island networks, energy balancing (PV storage, etc.), load flexibility, primary control power, etc.



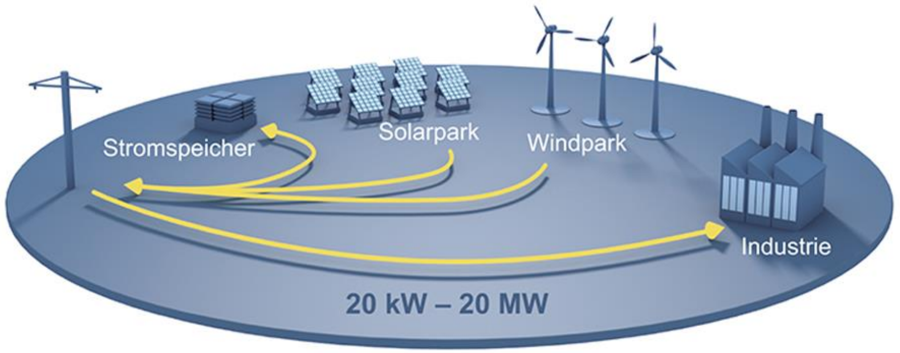


Overview of battery storage systems

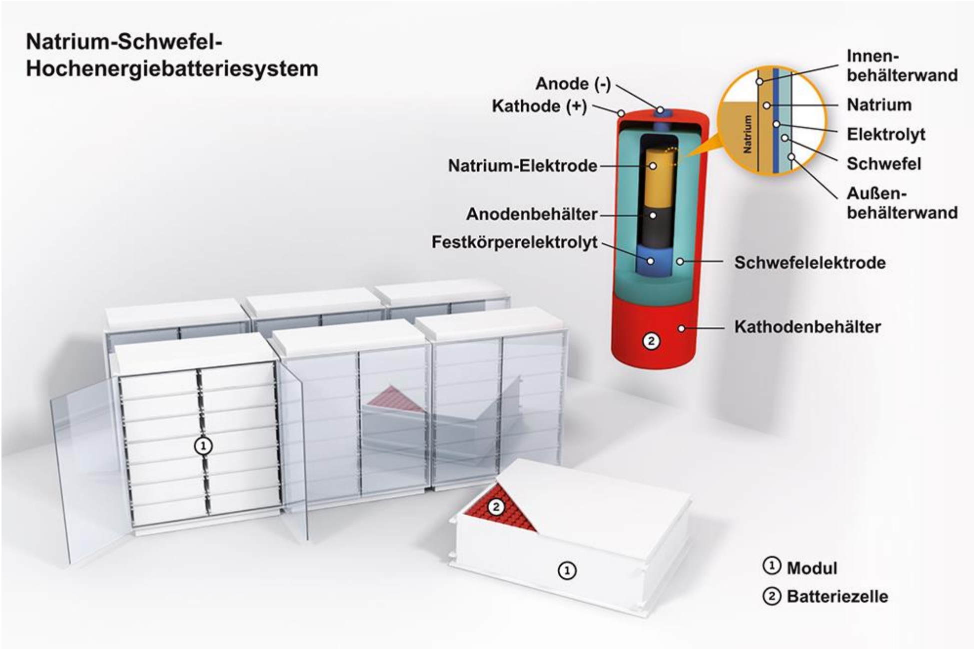
Electrochemical storage - sodium-sulfur accumulator

Grid Level 3
Middle voltage
3 – 30 kV

Quelle: EnergieAgentur.NRW



- Energy conversion into electrochemical energy
- Sodium-sulfur batteries are high-temperature batteries based on molten sodium with a temperature of 300 ° C
- have a one hundred percent Ah efficiency (losses due to voltage difference during charging, discharging and heating)
- Energy efficiency is around 80% (depending on storage duration due to high internal requirements)
- Very good ecological balance thanks to environmentally friendly materials and high availability
- High costs due to low production numbers
- Advantages with a high number of full load hours, as the operating temperature must be maintained at approx. 300 ° C.
- Use in the military, telecommunications, grid power storage, and occasionally in electromobility
- Still in the development stage



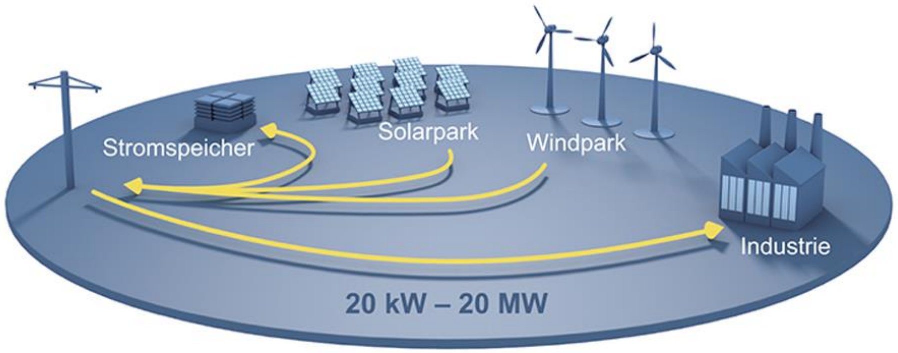
Overview of battery storage systems

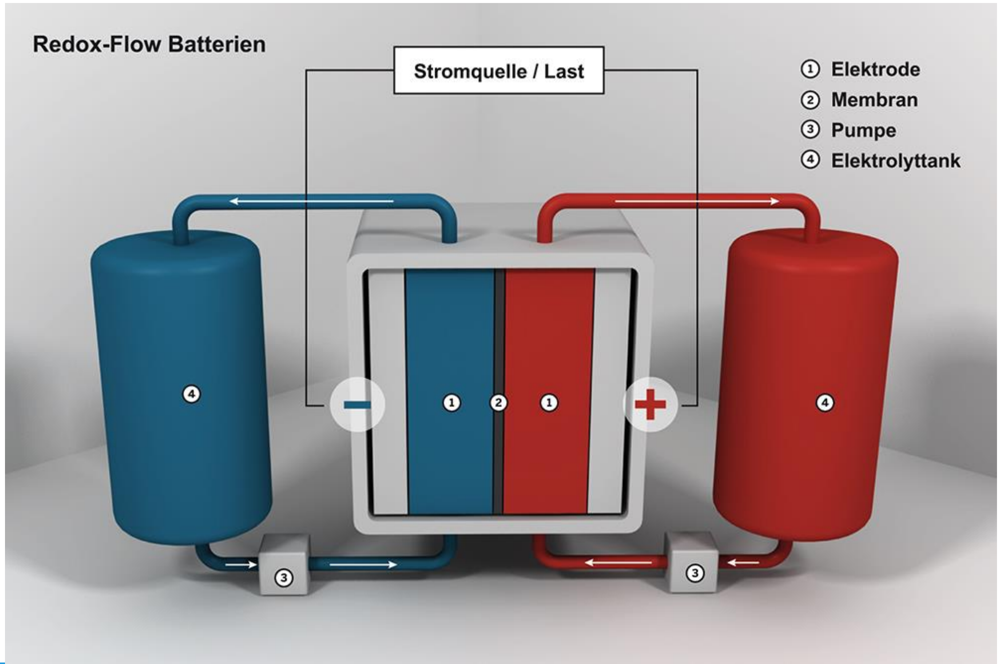
Electrochemical storage - redox flow battery

- Energy conversion into electrochemical energy
- Liquid vanadium (V) oxide (in the vanadium redox accumulator) or sodium bromide (in the sodium bromide redox accumulator) serve as storage
- The electrolyte is pumped through a membrane and the ion exchange takes place
- There is no self-discharge, only the self-consumption of the system
- The efficiency is 70-80%
- The system is not subject to aging, except for system components (pumps, membrane, etc.)
- Very high spec. Performance costs through the membranes
- Practically unlimited energy storage capacity, easy to expand by increasing the amount of electrolyte
- Still in the development stage, used as grid power storage

Grid Level 3
Middle voltage
3 – 30 kV

Quelle: EnergieAgentur.NRW





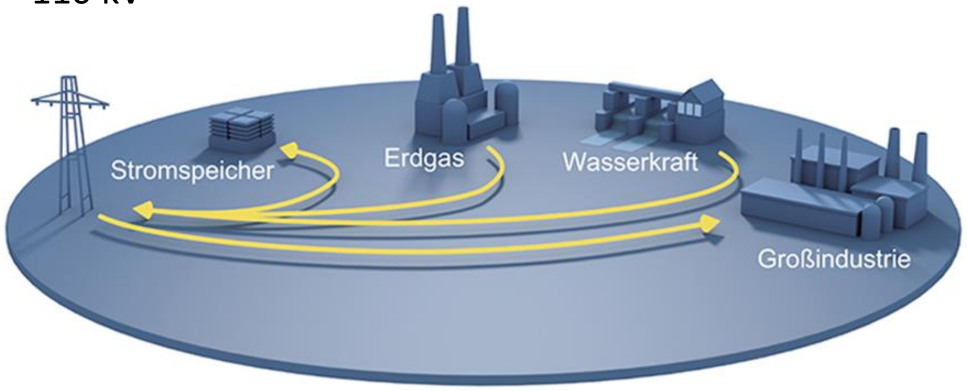
Overview of battery storage systems

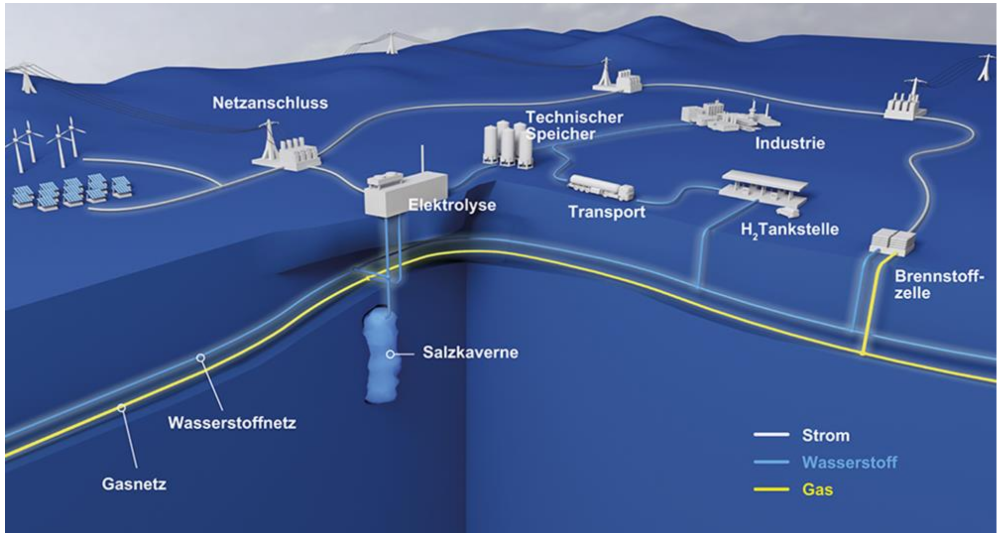
Quelle: EnergieAgentur.NRW

Chemical storage - Power-to-Gas (PtG)

- Energy conversion into electrochemical energy,
- H2 production by means of electrolysis or co-electrolysis (simultaneous electrolytic splitting of carbon dioxide and water vapor into hydrogen and carbon monoxide)
- Storage without time limit
- Possible recycling through reconversion in fuel cell systems, admixture in the gas network (5%) or for the production of fuel gases (methanation CH4) or power-to-liquids
- Power-to-gas efficiency 60% -85% then recycling
- Utilization through reconversion of fuel cells up to 60%
- Large storage potential through feeding into the gas network, use of existing gas storage facilities
- Use of excess capacities RES for H2 production and subsequent energetic utilization in electrical energy, thermal energy, mobility, chemical processes, power-to-liquids, etc.
- Still in the development stage, very high system and operating costs

Grid Level 2
High voltage
60 - 110 kV





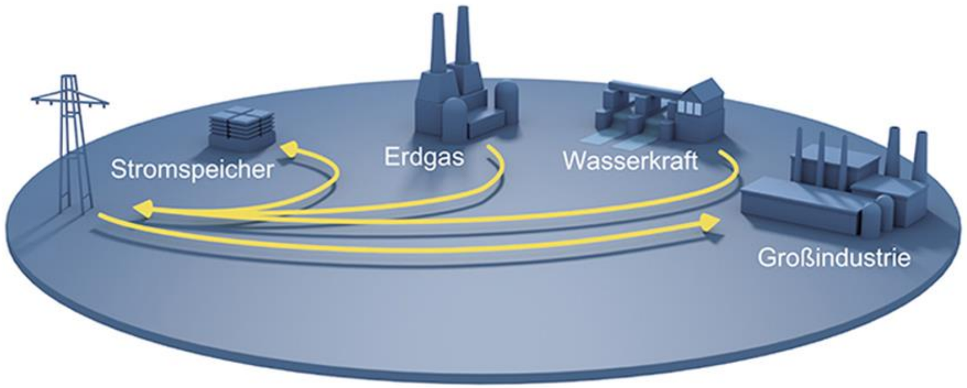
Overview of battery storage systems

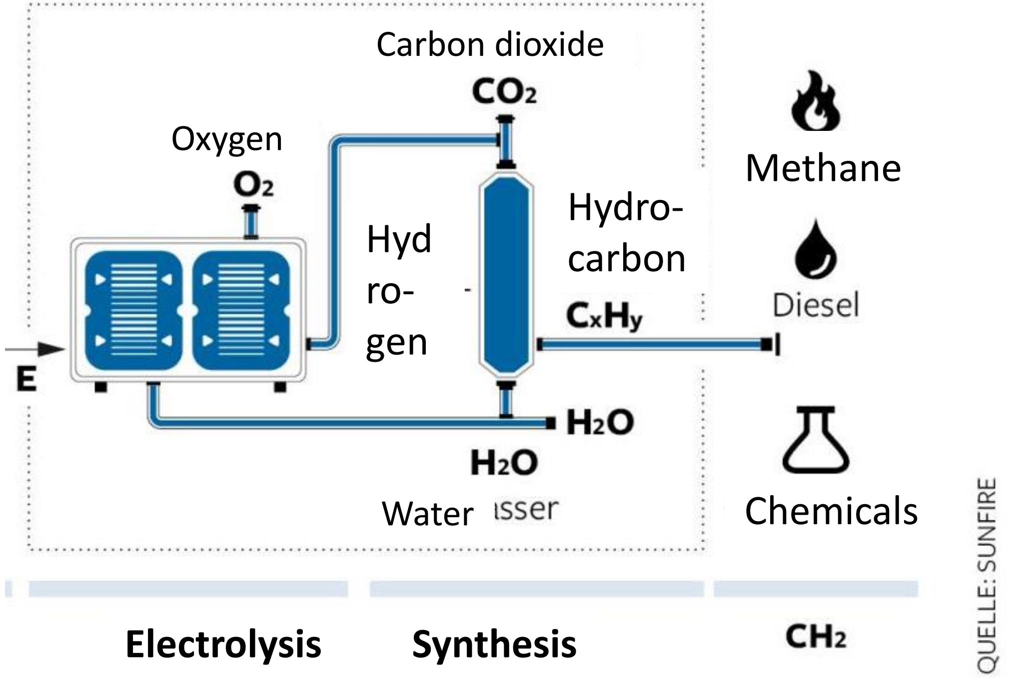
Chemical storage - Power-to-Liquids (PtL)

- Power-to-Liquids (PtL) is the second stage after Power-to-Gas (H2 from electrolysis), the chemical post-processing into synthetic liquid fuels
- H2 wir mittels CO oder CO_2 zu flüssigen Kohlenwasserstoffen synthetisiert
- Processes are methanol synthesis and a subsequent multi-stage conversion or the Fischer-Tropsch synthesis (FTS) using carbon monoxide
- Production of synthetic e-diesel fuel, e-gasoline or e-kerosene
- However, fuels are significantly more expensive (3.50 and 5 euros - without taxes)
- Theoretical efficiencies in coupled operation with internal process heat utilization of up to 60% possible
- Still in the development stage, very high system and operating costs

Grid Level 2
High voltage
60 - 110 kV

Quelle: EnergieAgentur.NRW





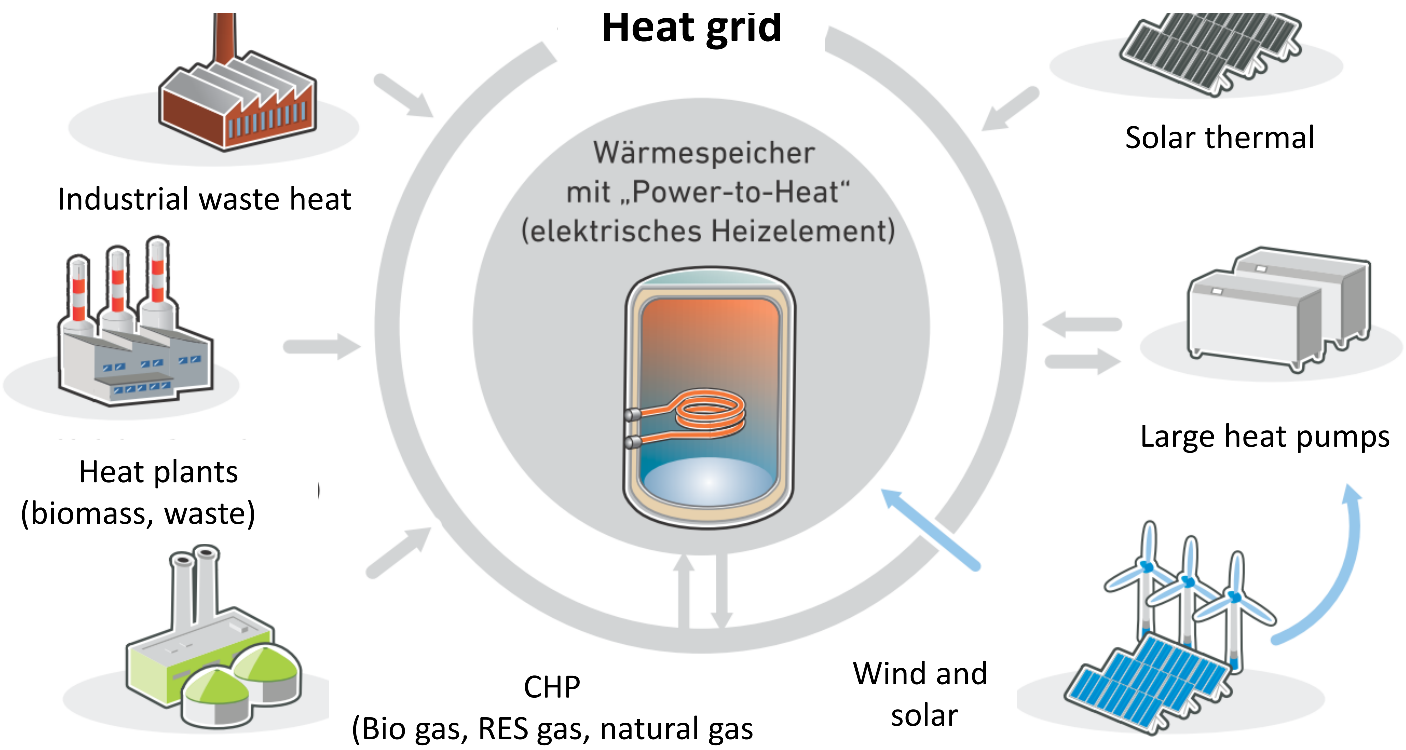
Overview of battery storage systems

Heat storage and heat grid

- Infrastructure for the supply of consumers or feed-in of accruing thermal energy
- Differentiation of grid types according to operating temperature (low-energy grid < 50°C < local heating grid < 100°C) and extent (local heating < 1km < district heating).
- Waste heat generated during production or in power plants can meet local demand for thermal energy (challenges are infrastructure, operating resources, costs, etc.).
- Increased efficiency in energy conversion and production (increased system efficiency)
- Design of energetically optimized process chains
- Challenges: Technology vs. cost

Heat storage: Single central component of a flexible electricity and heat supply

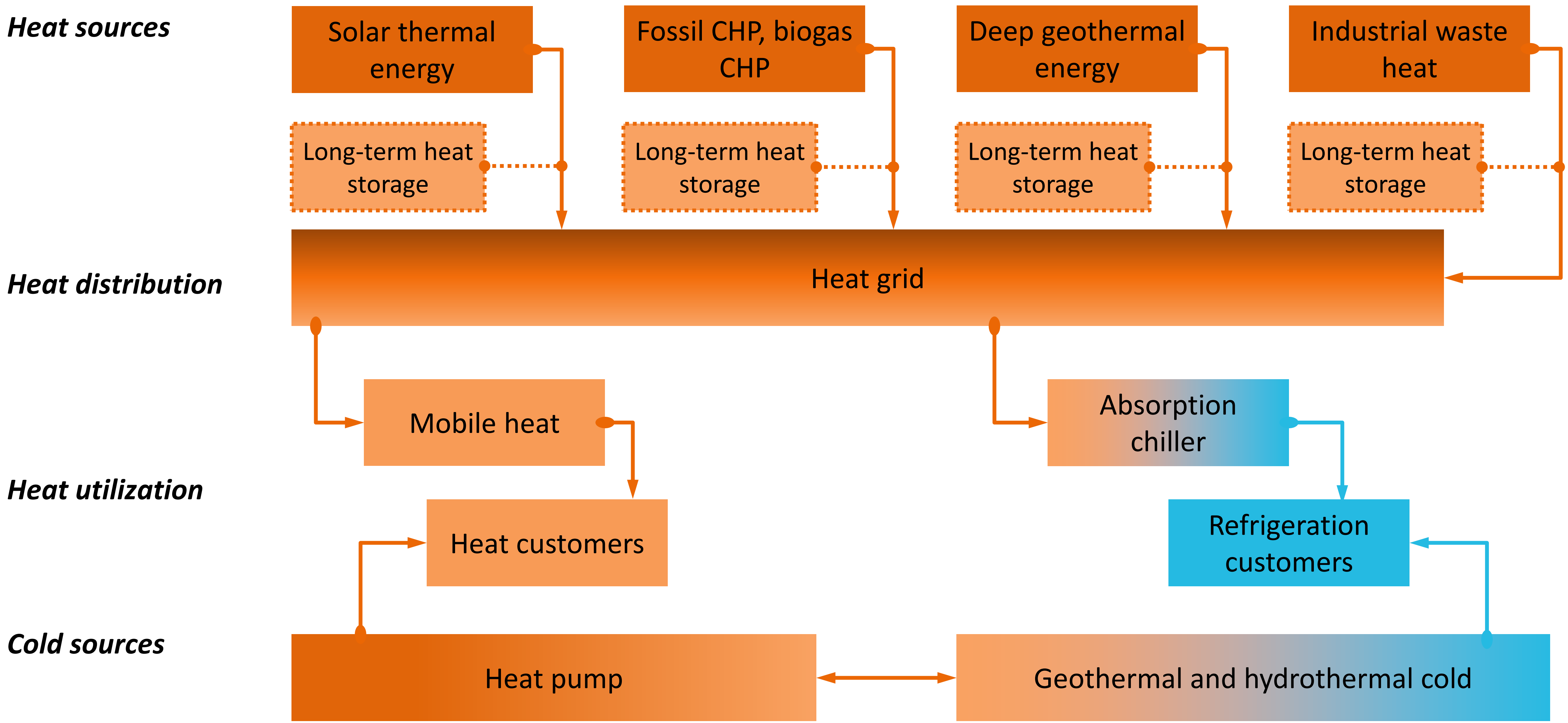
With heating networks and heat storage systems, CHP systems can be made more flexible and
RES can be efficiently integrated into the energy system



Agentur für Erneuerbare Energien e. V.: nach Hamburg Institut. Stand: 02/2015

Overview of battery storage systems

Heat storage and heat grid

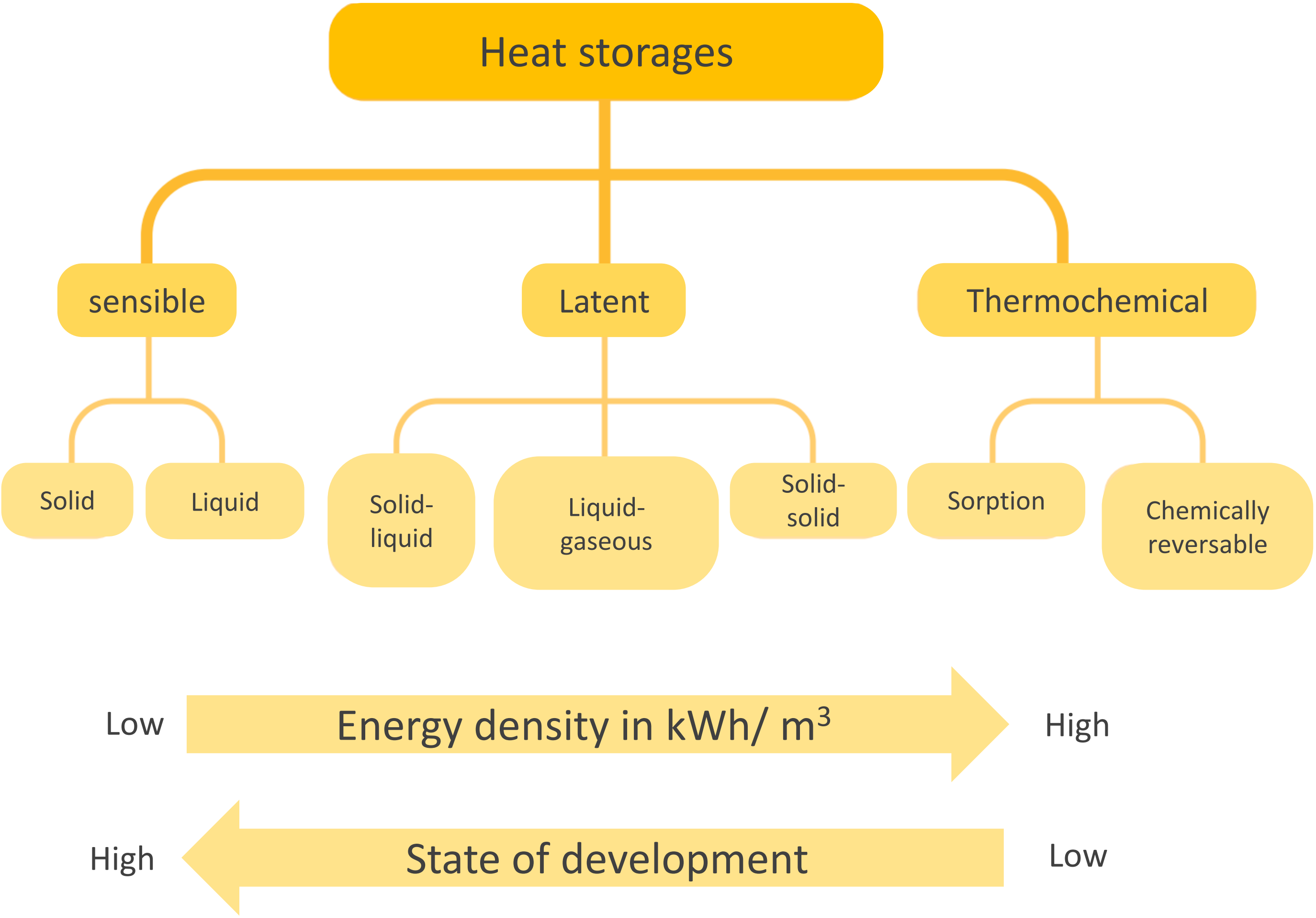


Overview of battery storage systems

Thermal storage - technology overview

- Heat accumulators are based on a storage medium, e.g. a liquid or a solid.
- Differentiation according to three types of storage sensible, latent and thermochemical storage
- Technology differences in energy density and maximum storable temperature
- Thermal energy is defined by heat capacity and mass of the storage medium as well as the usable temperature difference.
- In practice, mostly sensible storage, latent and thermochemical storage, on the other hand, are still in the development phase.
- The advantages of latent heat and thermochemical storage do not lie solely in the significantly higher energy density

Technologies at a glance



Agentur für Erneuerbare Energien e. V. Quelle: Sterner/Stadler: Energiespeicher, Berlin Heidelberg 2014.

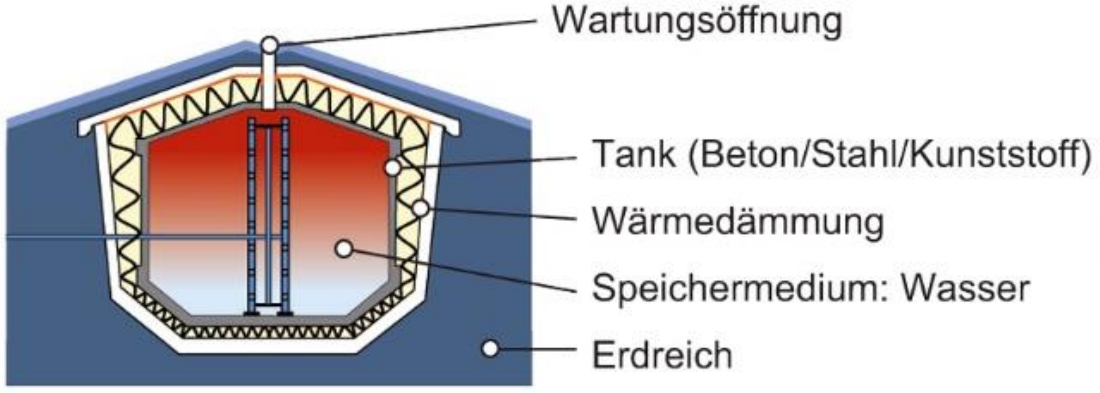
Overview of battery storage systems

Thermal storage - sensible heat and cold storage

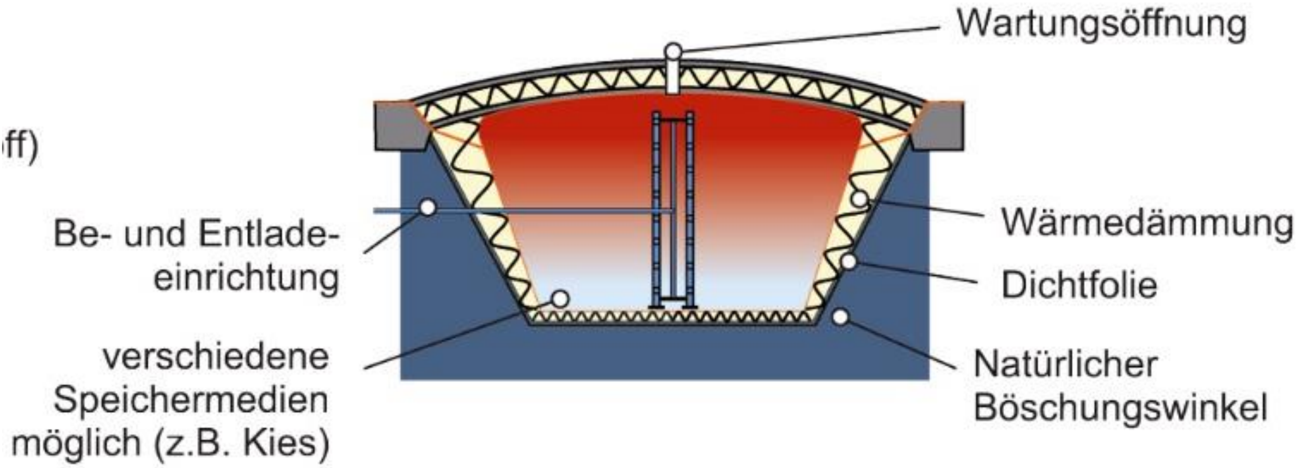
Quelle: EnergieAgentur.NRW

- Construction forms are tank, earth basin, earth probe and aquifer heat accumulators
- Sensible heat accumulators change their sensible temperature during charging and discharging
- Charging corresponds to a temperature increase, discharging to a temperature decrease
- The amount of energy is defined by the heat capacity of the medium
- Heat losses are defined by the temperature difference between the storage and the environment and the thermal resistance
  - Low losses due to good insulation of the storage and optimum surface/volume ratio

Container heat storage



Earth basin heat storage

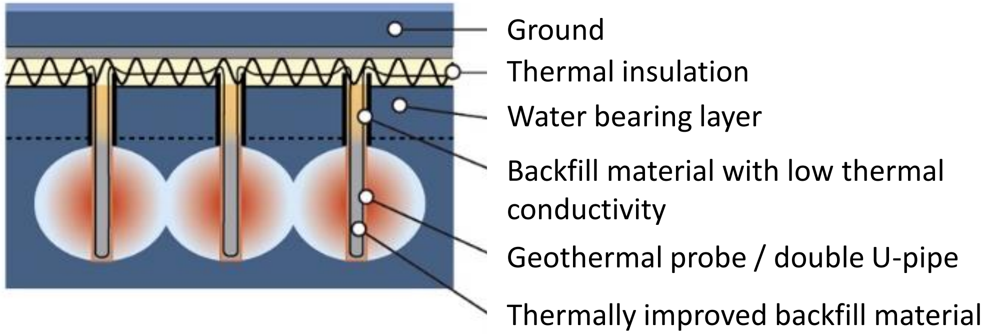


Overview of battery storage systems

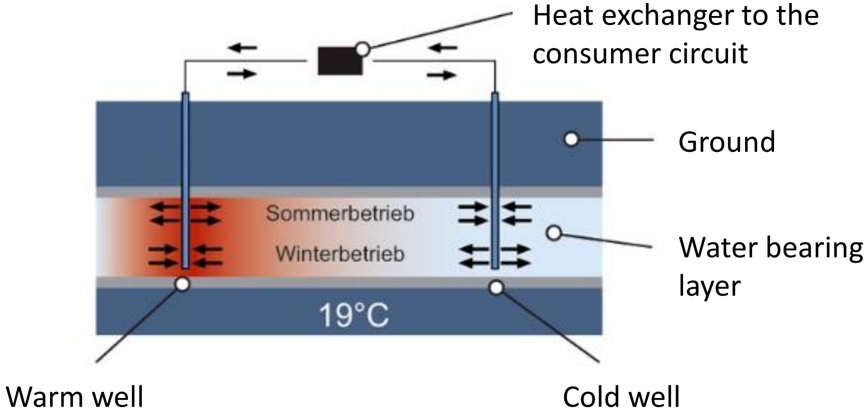
Thermal storage - sensible heat and cold storage

- most used sensible storage are hot water storage tanks in building technology, heating technology in the operation of buffer storage
- Steam accumulators are often used as short-term storage for process heat in industry
- Aber auch über mittlere und lange Zeiträume (saisonal) werden sensible Wärmespeicher verwendet. So finden auch Feststoffe wie Kies oder Eisenoxidsteine bei sensiblen Wärmespeichern Verwendung.
- Hot water storage may only be operated at temperatures below 100°C
- at higher temperatures, other liquids such as liquid salts or solids are used

Earth probe heat accumulator



Aquifer heat storage

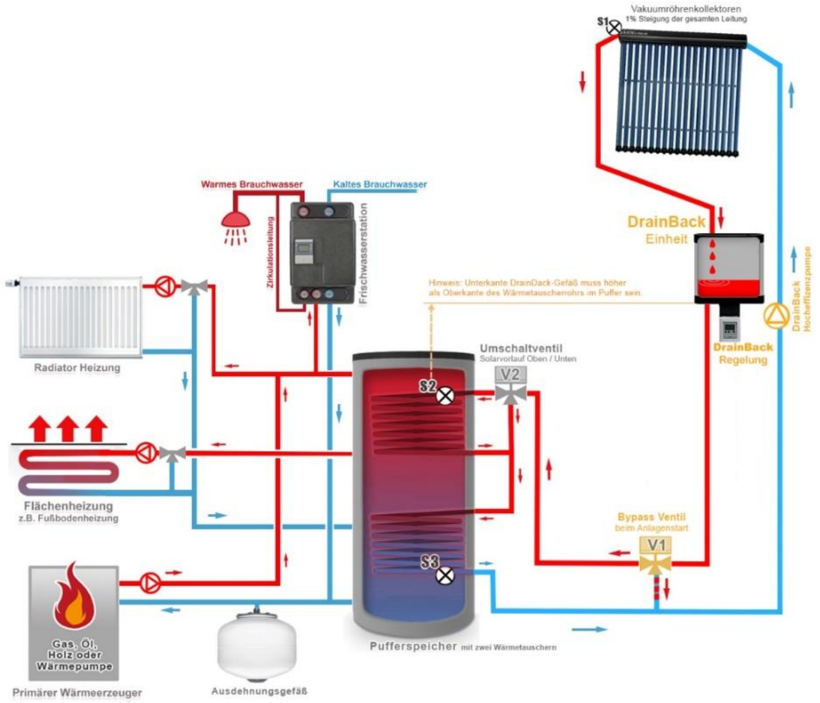


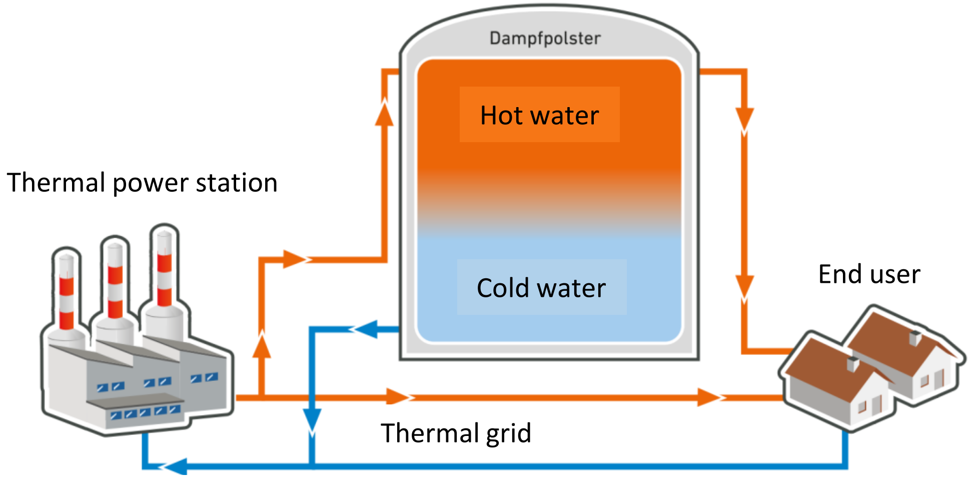
Source: EnergieAgentur.NRW

Overview of battery storage systems

Thermal storage - sensible heat and cold storage

- Type of medium used in sensible storage tanks are fluid or solid storage tanks
- Applications as short- or long-term storage as well as so-called hybrid storage, which implements process combinations. (solids such as gravel or iron oxide bricks).
- One form of hybrid storage is, for example, the gravel-water storage (combination of different media)
- Simple, robust and cost-effective technology, high availability and low cost
- Combination of different heat sources in stratified heat storage systems with multiple heat exchangers
- Established technology, from small storage units in the private sector up to large-scale storage units with several MWh



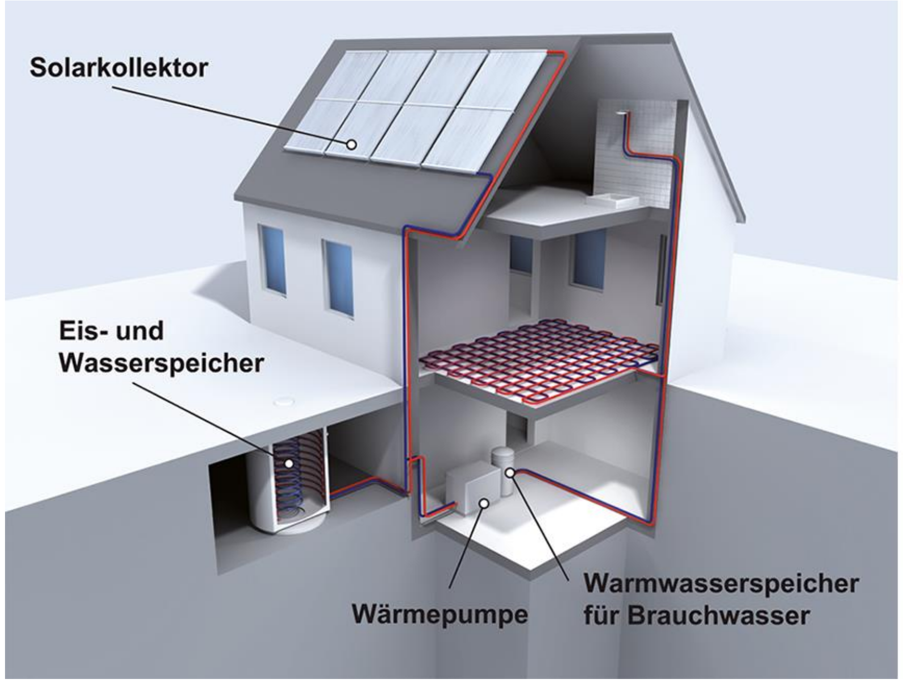


Scheme of a hot water tank for the heating network

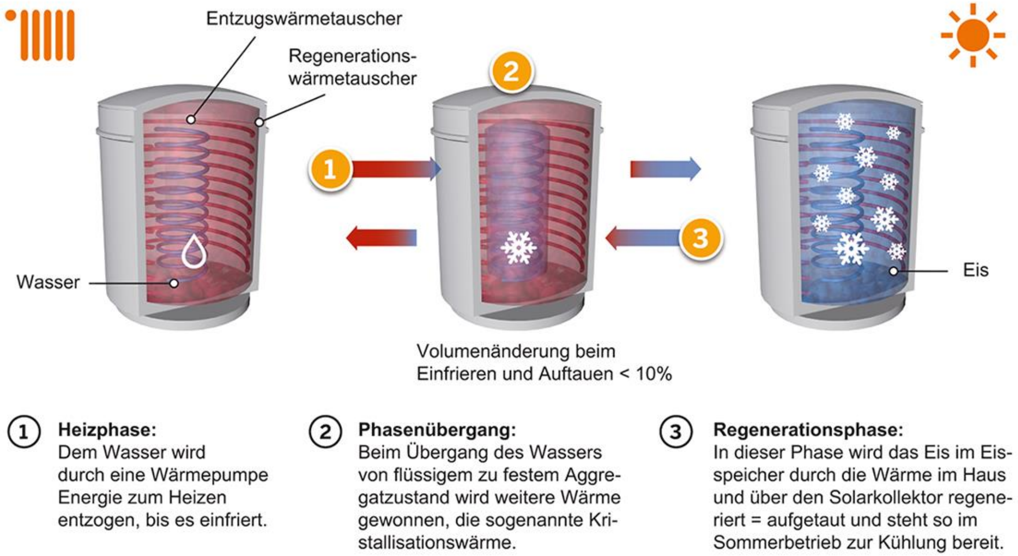
Overview of battery storage systems

Thermal storage - Latent heat storage

- Latent heat accumulators use the phase transition when the aggregate state of the medium used changes
- Phase change material (PCM) storage material enables the absorption of relatively large amounts of heat at high energy densities at a largely constant operating temperature
- Volume change usually less than 10 percent and can therefore be technically controlled
- Melting temperatures depending on material classes from - 40°C to well over 1000°C
- Latent heat storage systems are much more compact
- Excellent for temperature stabilization, temperature peak capping, process stabilization, etc.
- Various PCM products are already ready for the market
- Great development potential



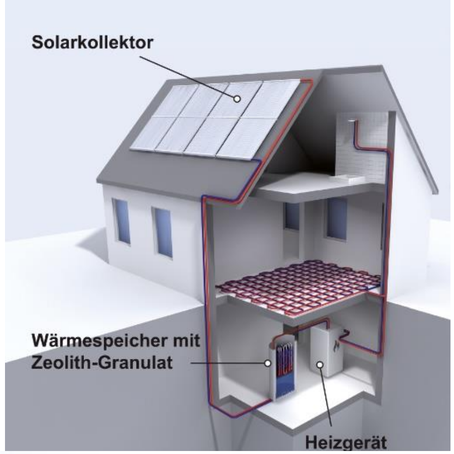
Source: EnergieAgentur.NRW



Overview of battery storage systems

Thermal storage - Thermochemical storage

- Thermochemical storage systems convert heat into chemical energy by endothermic chemical reaction
- The products formed in the reaction (and the chemical energy they contain) can be stored for long periods of time
- Reversal of chemical reaction (exothermic reaction) released again by heat when required
- Thermochemical energy storage systems allow very high energy storage densities
- Low penetration in practice, as this technology is still largely in the basic research stage
- Storage systems are subdivided into storage with reversible chemical bonds and sorption storage, which in turn is subdivided into adsorption and absorption storage.
- Selection of the storage material depends on several factors, such as the desired storage capacity, the charging and discharging performance, and the temperature level of the storage

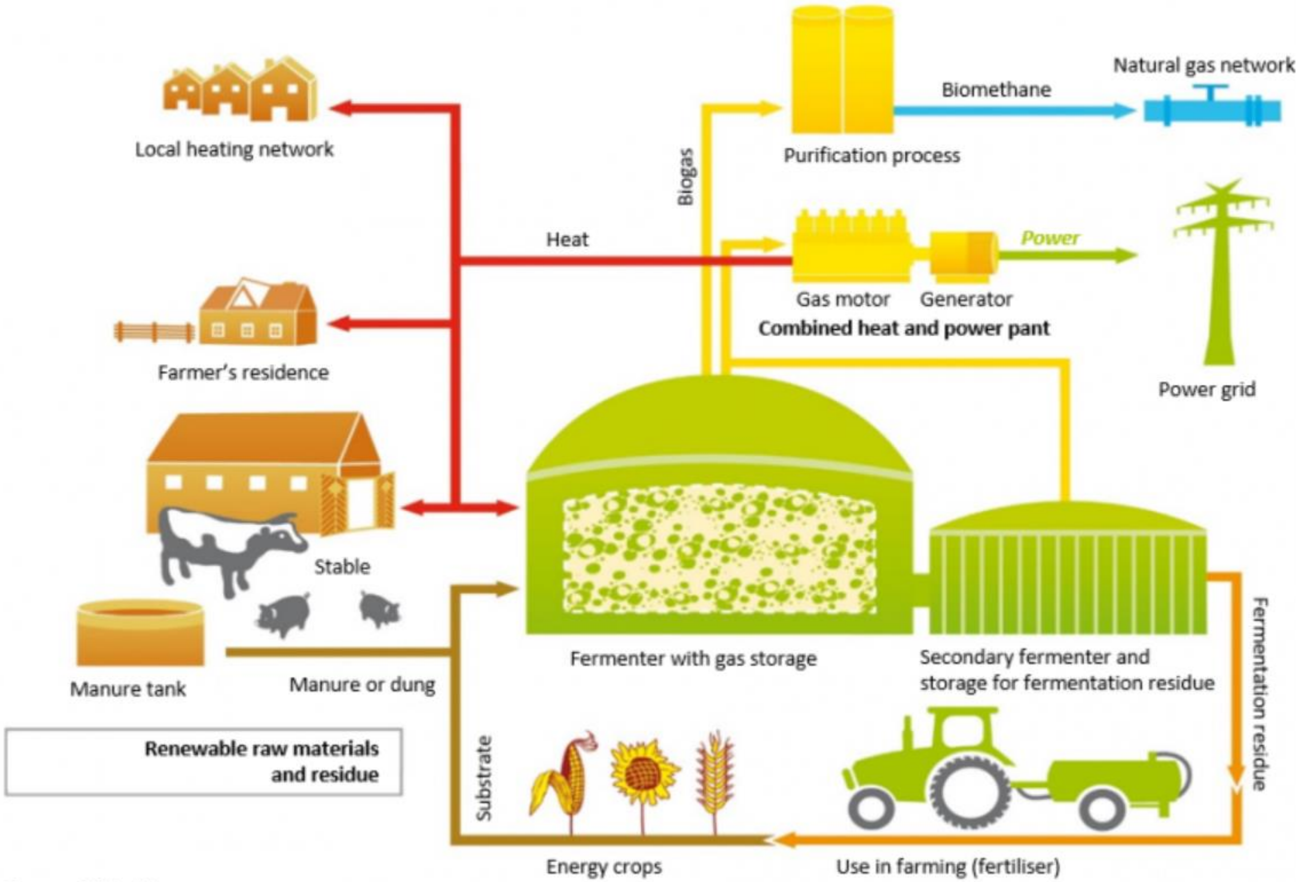


Source: EnergieAgentur.NRW

Overview of battery storage systems

Biochemical storage

- Biomass and biogas (biomethane) can be stored well and used as needed
- For all sectors: heat supply, power generation, CHP or as biofuel in traffic
- In addition to other controllable energy sources such as bioenergy, storage systems also step in to balance the weather and the seasons
- Partly established technologies
- Limited potentials (areas)
- Competition with food, etc.



Source: FNR e.V.

Energy storage technologies in energy supply

Mechanical energy storage
Operating principles and system considerations

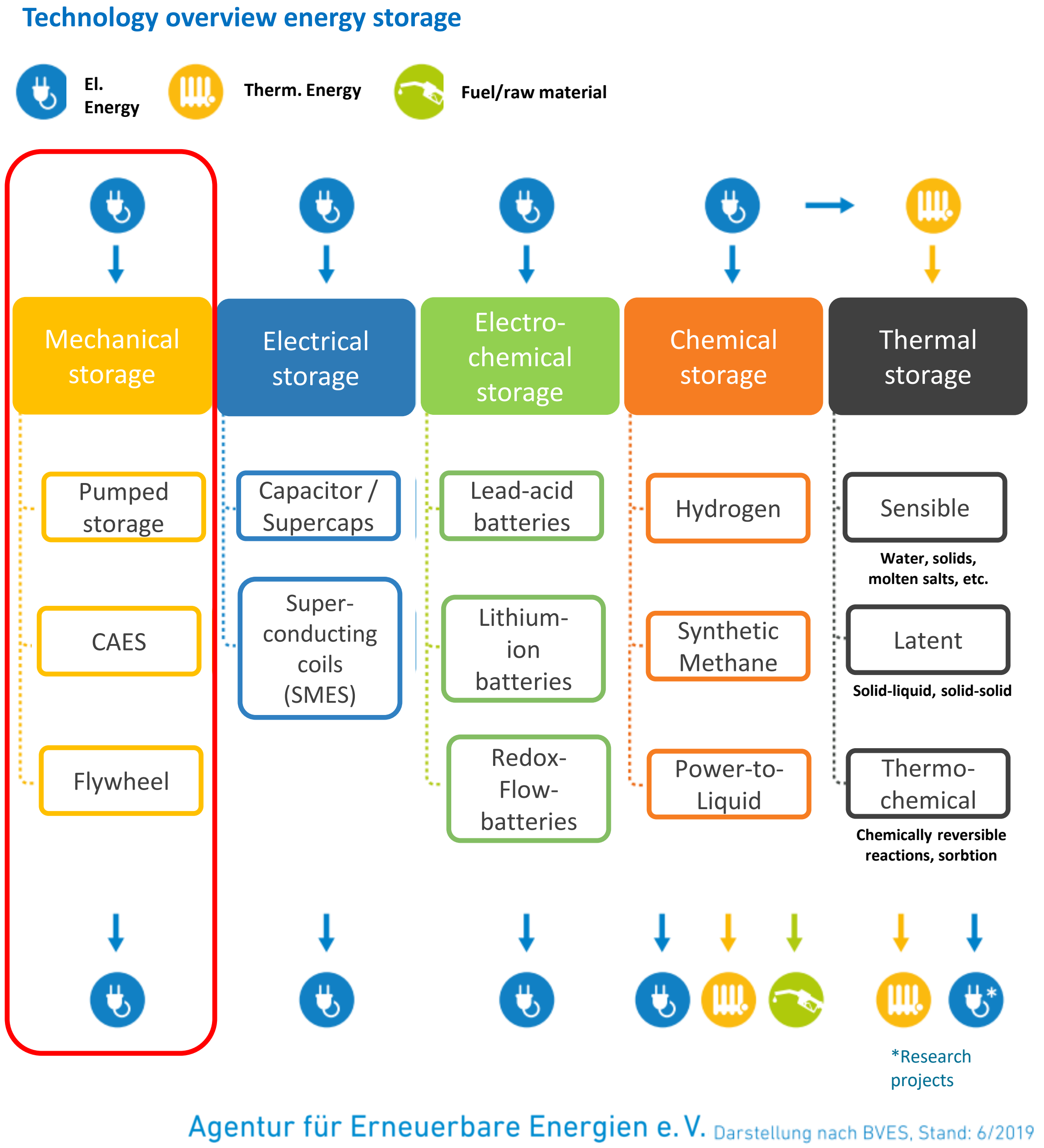
Dr.-Ing. Stephan Balischewski
Prof. Dr.-Ing. P. Komarnicki
Hochschule Magdeburg-Stendal
Fraunhofer IFF Magdeburg

26.03.2022

Overview Mechanical Storage

System overview

- Pumped water storage
- Compressed air energy storage
- Fly wheel storage
- Comparing mechanical storages



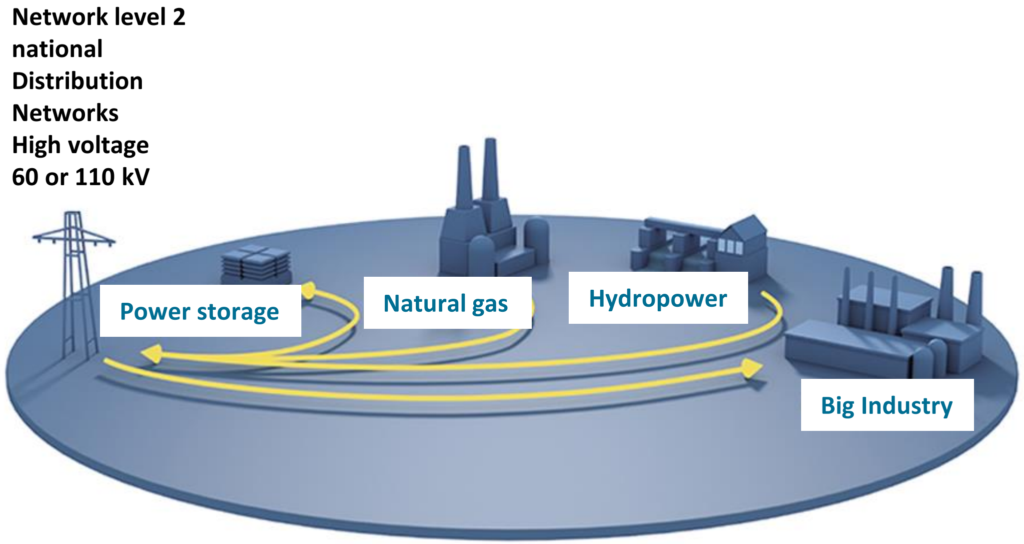
Mechanical storage devices

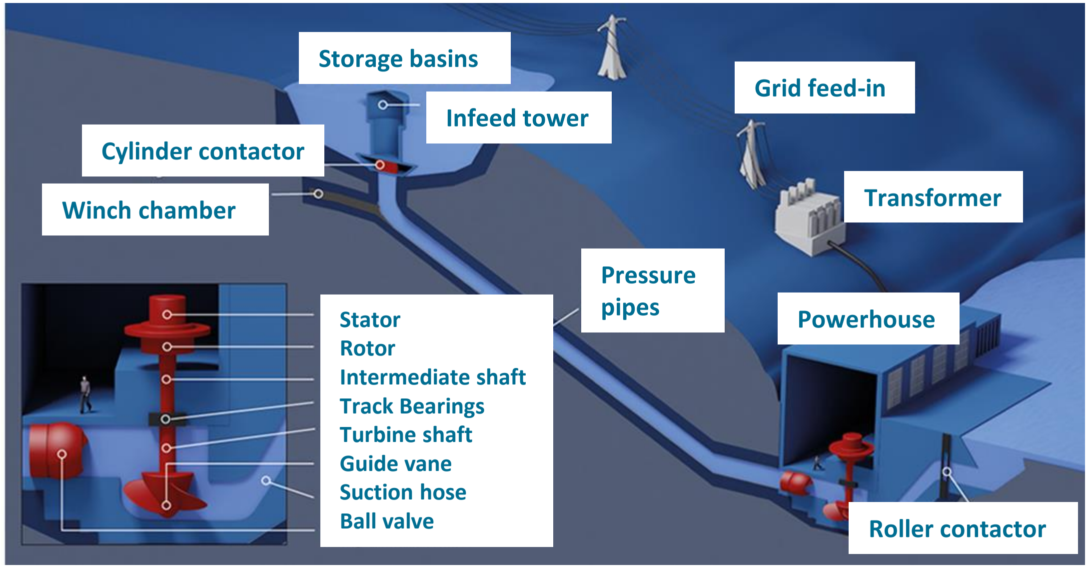
Pumped storage power plants (PWS)

Mechanical storage devices

Pumped storage power plants (PWS)

- Worldwide >99 percent of energy storage type supply grid
- Storage of potential energy by water in the reservoir, energy conversion by pump/turbine and motor/generator
- Limited site potential (height difference, size of reservoirs, short waterways, natural inflows)
- Overall efficiencies of 70 to 80 percent
- Excellent long-term storage (no self-discharge)
- Balancing between peak load and base load (night storage)
- New tasks in the due to volatile feeders arise with:
    - peak load current and to stabilise the grid
    - strengthens control energy provider
    - Black start capability (1-2min. to rated power)
- Alternative locations for hydropower plants
    - Saltwater in pumped storage power plants on steep coasts
    - Pumped storage power plants in disused mining sites





Pumped water storage

Installed power worldwide

- Energy storage in the form of pumped storage hydropower (PSH), the world's 'water battery', supports the needs of changing power systems.
- PSH currently accounts for over 94 percent of installed global energy storage capacity, and over 96 percent of energy stored in grid scale applications.
- During 2019, worldwide pumped storage hydropower installed capacity grew by 304 MW.

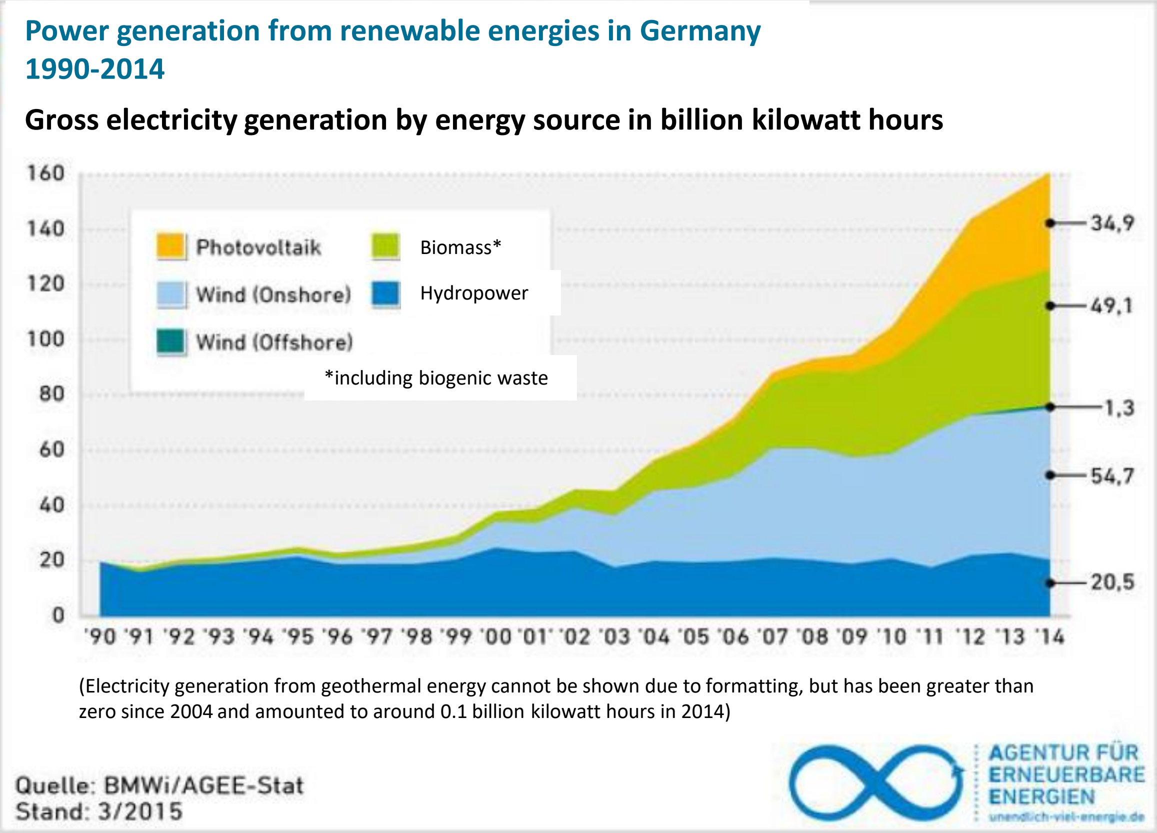
158 GW	
China	30,3
Japan	27,6
USA	22,9
Italien	7,7
Deutschland	6,4
Spanien	6,1
Frankreich	5,8
Österreich	5,6
Indien	4,8
Süd Korea	4,7
Restliche Welt	36,1

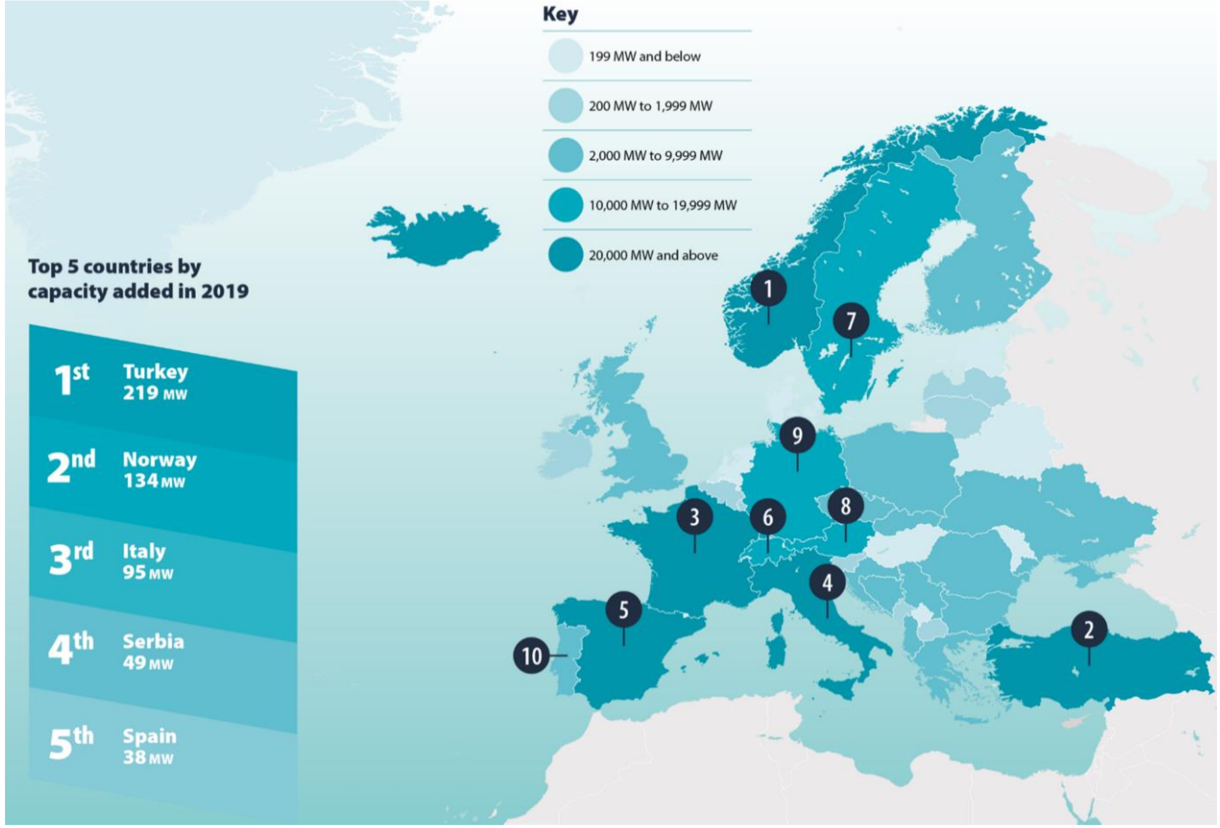
hydropower.org/statusreport

- PWS in use for more than 100 years
- Total global **hydropower** installed capacity reached 1,308 gigawatts
- Technically sophisticated and relatively inexpensive
- New pumped storage facilities have an efficiency of 75% to 80%.
- Pumped electricity consumption is regarded as final consumption, which results in RE apportionment and grid fees
- Due to the geographical conditions mainly in mountainous landscape
- economic difficulties have led to the fact that numerous expansion and new construction projects in Europe have been pushed only cautiously or even postponed in the meantime

Pumped water storage

Installed power in EUROPE





hydropower.org/statusreport

Due to geographical conditions and strong nature conservation restrictions, the potential is very limited.

Source: EAA: Energiewendeatlas Germany 2030

Pumped water storage

Examples of pumped storage power plants

Source: VOITH: Successfully shaping the energy transition: With pumped storage power plants

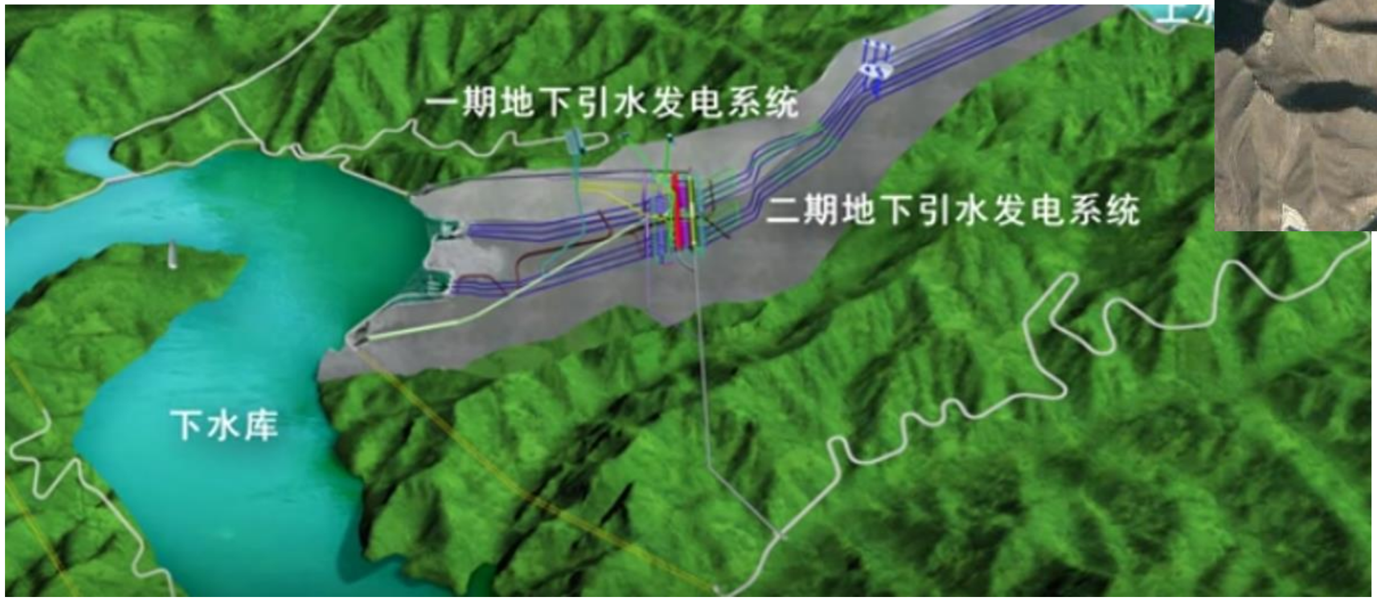
- PWS in Herdecke from RWE in North Rhine-Westphalia
- Contents upper pool 1,600,000m³
- Pumped output: 153.59 MW
- Power in turbine operation: 153 MW
- Electric usable work: 590 MWh

- PWS in Ueno from Tepco in Japan
- 6 x pump turbines
- 6 x motor generators
- Congestion power: 470 MW
- On the grid since 2005

Pumped water storage

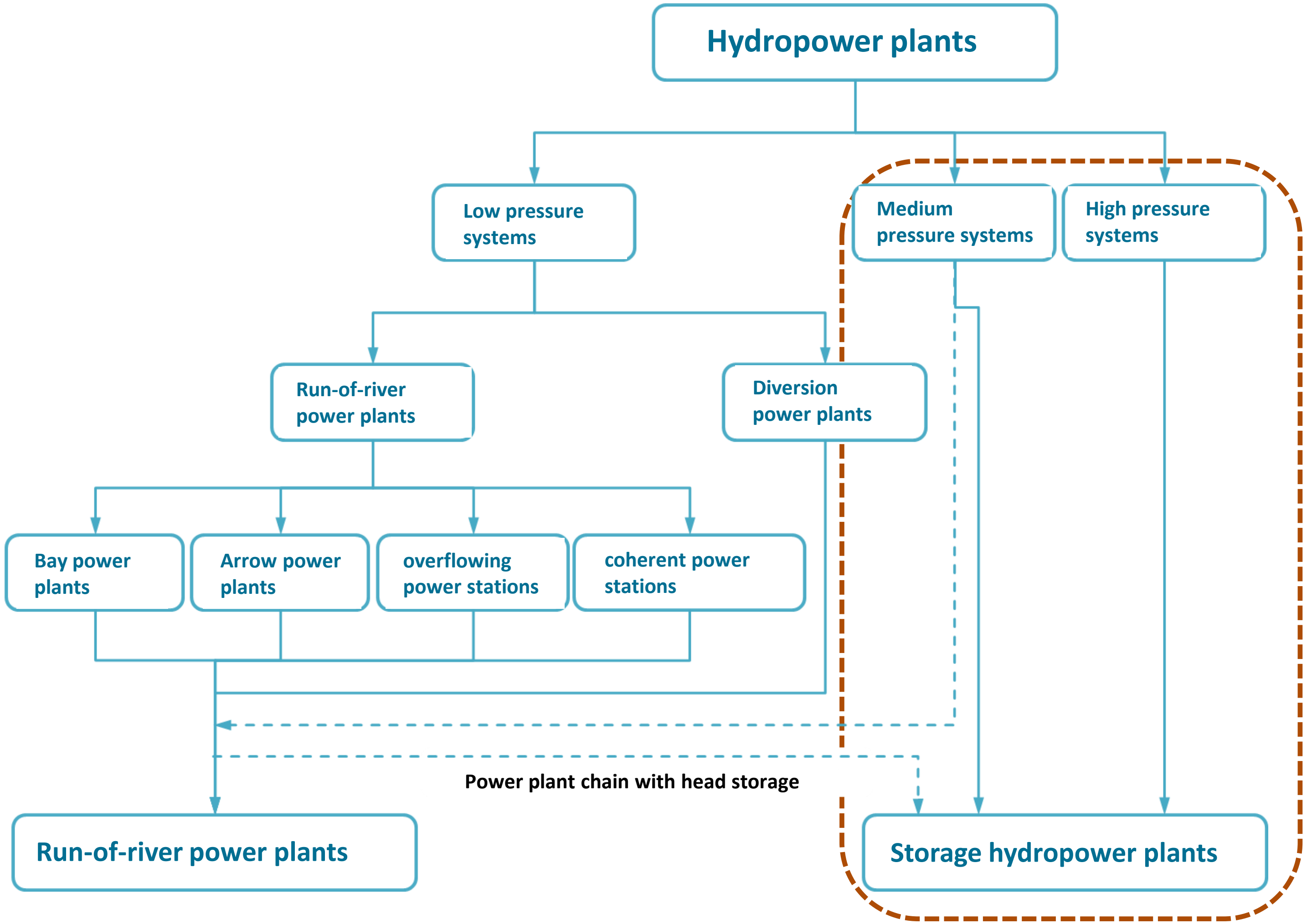
Examples of pumped storage power plants – Biggest Pump Water Storage

- Pump storage system Fengning in China
- Power Output: 3600 MW
- 12 Turbines à 300 MW
- Construction Time: 8 years (2013-2021)



Pumped water storage

Systematic overview of hydropower plants



Pumped water storage

Classification of the potential for hydropower

	Characteristics

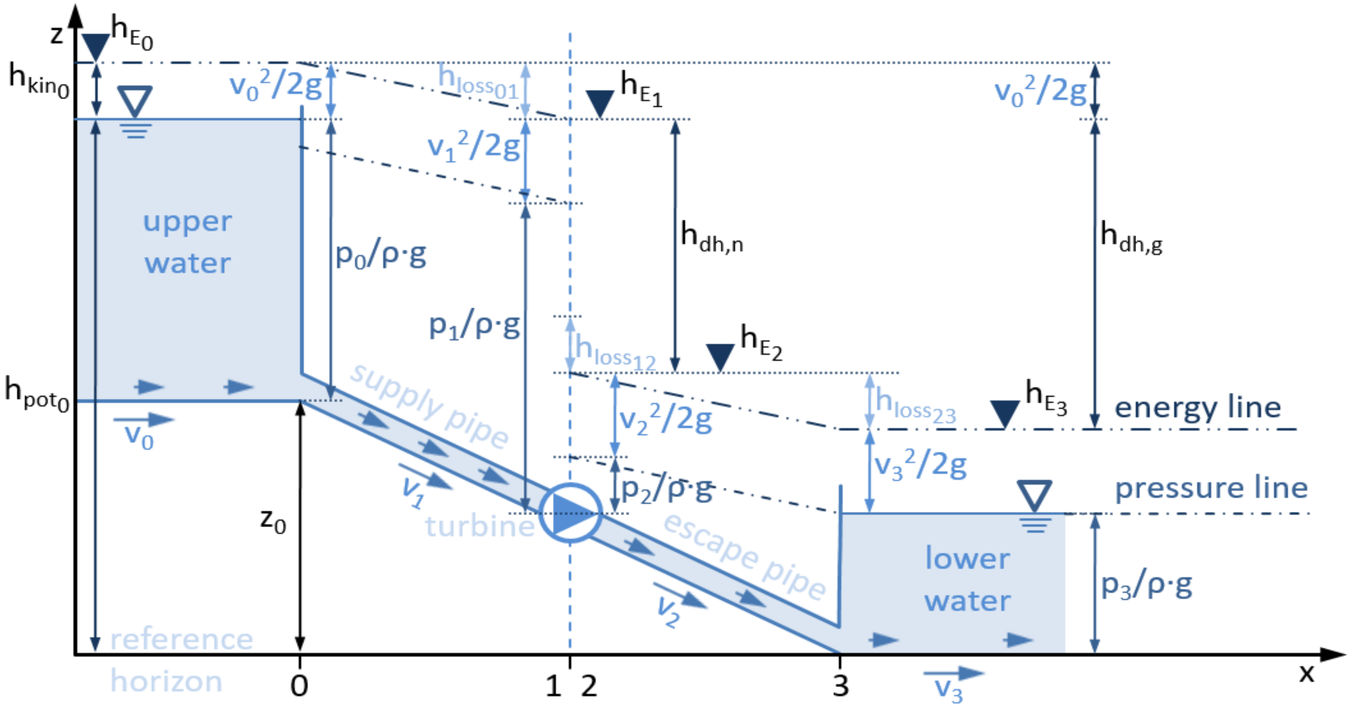
Theoretical area potential	• Upper limit of the theoretical potential
	• Corresponds to the theoretical energy
	  ○ Precipitation minus losses due to evaporation, seepage etc.
	  ○ Contains the height difference between the water surface and the watercourse
	• Insignificant for energy industry purposes

Line potential (Hydropower potential)	• concerns a specific section of a body of water
	  ○ medium drain
	  ○ Height difference
	• Has a certain informative value

Technically usable potential	• Looks at technical, economic and ecological aspects • Is about 40-50% of the theoretical potential, in unfavorable cases only 10%
Economically usable potential	• Benefit / cost ratio considered first, then possibility of technical implementation • Almost always less than the technically usable potential
Utilized potential	• Generated electrical energy within one year

Pumped water storage

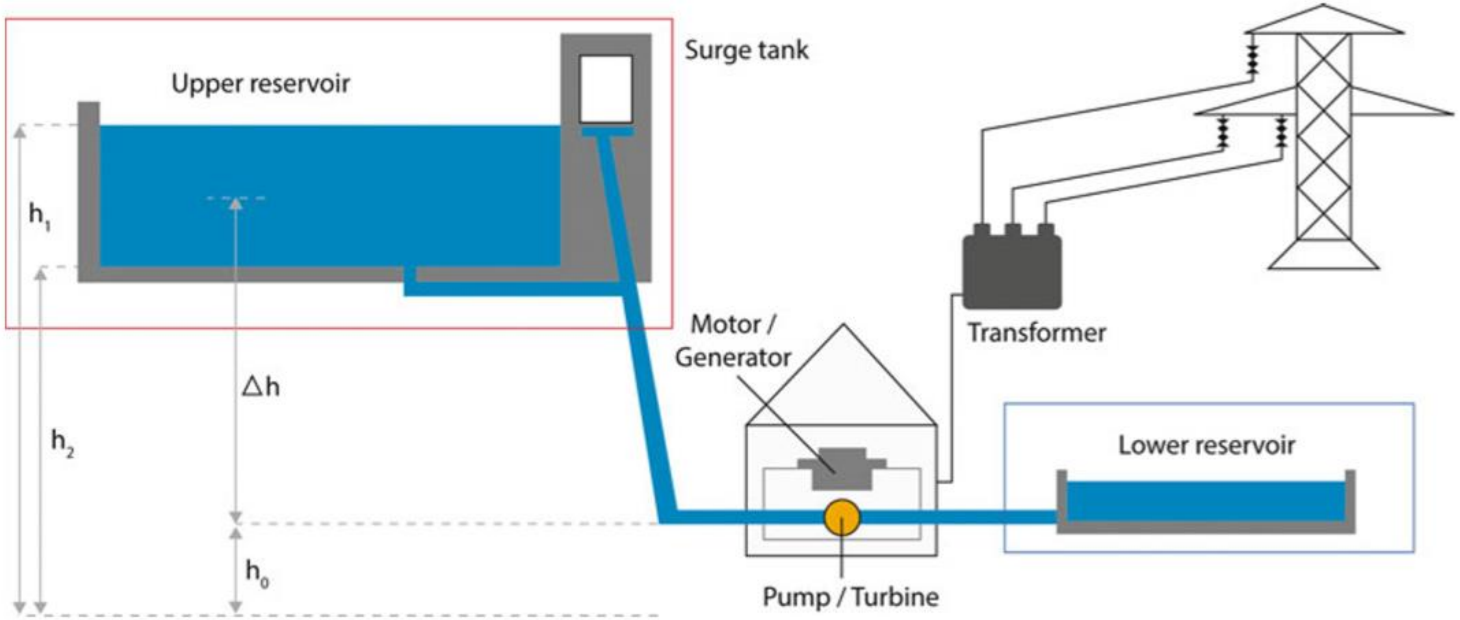
Physical basics



Parameter	unit	formula
Energy	Wh, *J*	$E = V \cdot \rho \cdot g \cdot \Delta h \cdot \eta_{ges}$
Power	*W*	$P = \dot{E} = \dot{V} \cdot \rho \cdot g \cdot \Delta h \cdot \eta_{Ges} = Q \cdot \rho \cdot g \cdot \Delta h \cdot \eta_{Ges},$
Height	*h*	$\Delta h = \frac{h_1 + h_2}{2} - h_0,$
Energy density	*w*	$w = \frac{m \cdot g \cdot \Delta h}{V} = \rho \cdot g \cdot \Delta h,$

Pumped water storage

Design and function

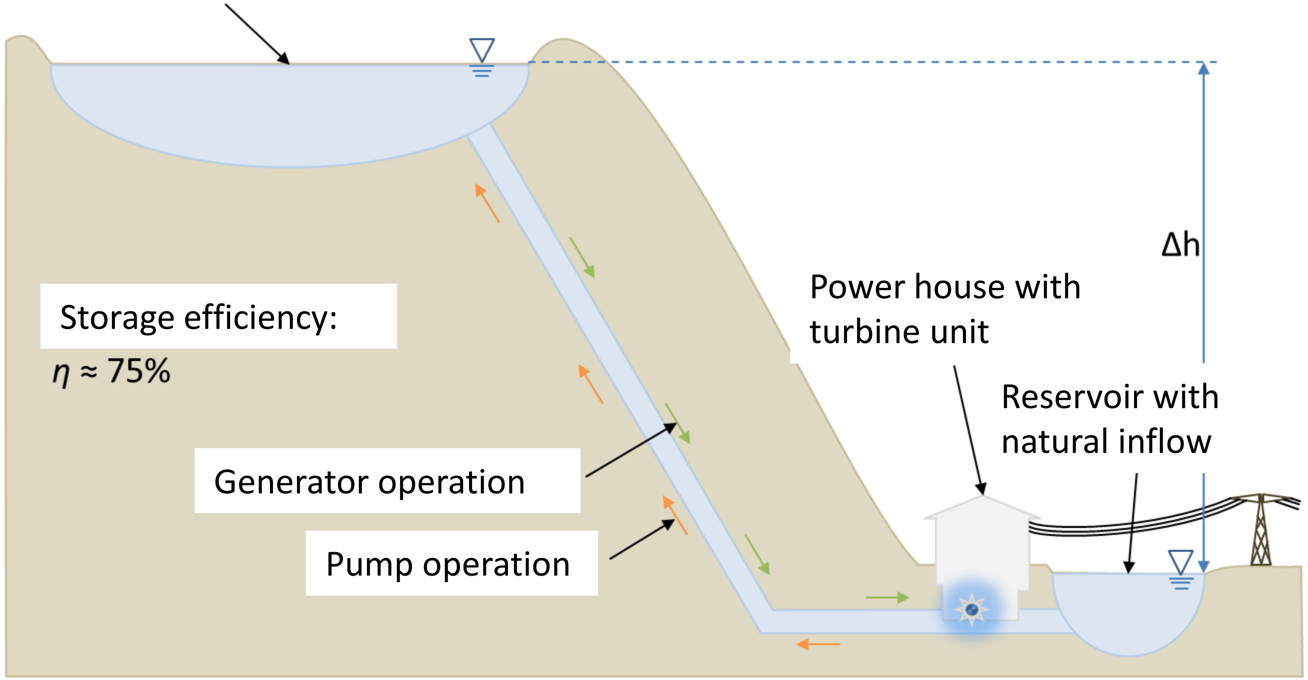


- In the optimum operating mode, the correct ratio of pump to generator operation ensures that as much water as possible is converted. This is therefore a closed circuit. The best power plants have an overall efficiency of more than 70%.
- The following elements are usually installed in pumped storage power plants:
  - Four-machine unit, turbine with separate generator and pump with separate motor,
  - Three-machine-unit, turbine and pump with common generator/motor,
  - Two-machine unit, reversible pump-turbine with generator/motor
  - Furthermore, a small additional run-up turbine is also possible to bring the main turbine to synchronous speed before the water arrives.

Source #2

Pumped water storage

Efficiency chain



- Pumped water storage do not generate "new" energy. Rather, they serve as an electrical energy storage facility, filling the water storage tanks at times of low grid load and emptying them again at peak load times.
- Efficiency chain dependent on operation (turbine/pump)

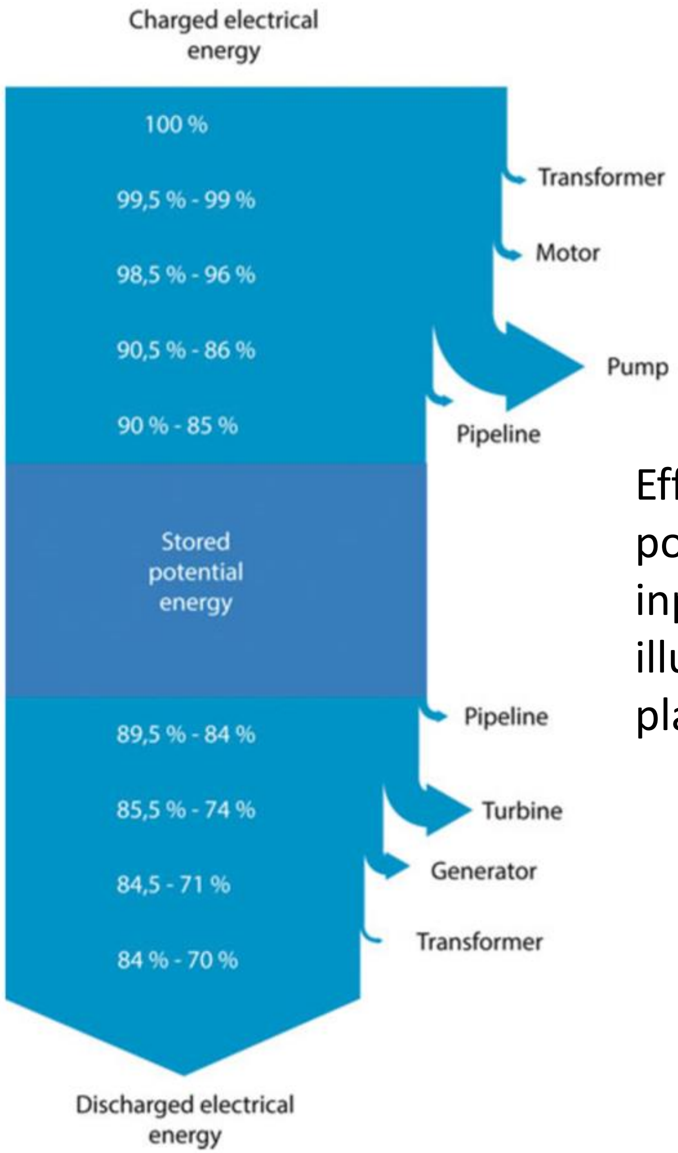
$$\eta_{\mathrm{total}} = \eta_{\mathrm{P}} \cdot \eta_{\mathrm{T,P}} \cdot \eta_{\mathrm{G,M}} \cdot \eta_{\mathrm{Trans}},$$

with

η_{P} – pipeline efficiency,
$\eta_{\mathrm{T,P}}$ – turbine/pump efficiency,
$\eta_{\mathrm{G,M}}$ – generator/motor efficiency,
η_{Trans} – transformer efficiency.

Pumped water storage

Efficiency chain



Efficiency is the ratio of the electrical energy or electrical power output to the electrical energy or electrical power input. The losses and the resulting overall efficiency can be illustrated using the Sankey diagram for the pumped storage plant as an example.

Source #2

Pumped water storage

Physical basics

- Use of the potential energy from the height difference and the kinetic energy of the moving water

$$E_{pot} = m \cdot g \cdot h_{pot} \qquad [J]$$

$$= \frac{1}{3,6 \cdot 10^6} \cdot m \cdot g \cdot h_{pot} \qquad [kWh]$$

$$E_{kin} = \frac{1}{3,6 \cdot 10^6} \cdot m \cdot g \cdot h_{kin}$$

$$= \frac{1}{3,6 \cdot 10^6} \cdot m \cdot \alpha \cdot \frac{v^2}{2} \qquad [kWh]$$

$$E = E_{pot} + E_{kin} = \frac{1}{3,6 \cdot 10^6} \cdot m \cdot g \cdot (h_{pot} + h_{kin}) \quad [kWh]$$

E_{pot}	Potential energy	[kWh]
E_{kin}	Kinetic energy	[kWh]
h_{pot}	Height of potential energy	[m]
h_{kin}	Height of kinetic energy	[m]
m	Mass	[kg]
g	Gravity	[m/s²]
α	Coriolis coefficient, simplified, α = 1	[-]
v	Speed, simply averaged over the cross-section	[m/s]

Pumped water storage

Physical basics

- Use of the potential energy from the height difference and the kinetic energy of the moving water

$$h_{pot} = h_D + z = \frac{p}{\rho_w \cdot g} + z = \frac{p_{abs} - p_{amp}}{\rho_w \cdot g} + z \qquad [m]$$

$$h_{kin} = \alpha \cdot \frac{v^2}{2 \cdot g} \qquad [m]$$

h_{pot}	Height of potential energy	[m]
h_{kin}	Height of kinetic energy	[m]
h_D	Pressure height	[m]
p	Overpressure	[N/m²]
p_{abs}	Absolute pressure	[N/m²]
p_{amp}	Atmospheric pressure	[N/m²]
ρ_w	Water density	[kg/m³]
g	Gravity	[m/s²]
z	Geodetic height	[m]
α	Coriolis coefficient, simplified α = 1	[-]
v	Velocity, simply averaged over the cross-section	[m/s]

Pumped water storage

Physical basics

- Bernoulli equation (for ideal liquids) describes the energy height h_E over a reference horizon:

$$h_E = h_{pot} + h_{kin}$$

- Practice: friction, surface tension, turbulence, etc.
- Introduction of local loss heights $h_{loss,\,i}$ results in the extended Bernoulli equation:

$$h_E = h_{pot} + h_{kin} + h_{loss,i} \qquad h_{loss,i} = \zeta_i \cdot \frac{v_i^2}{2 \cdot g}$$

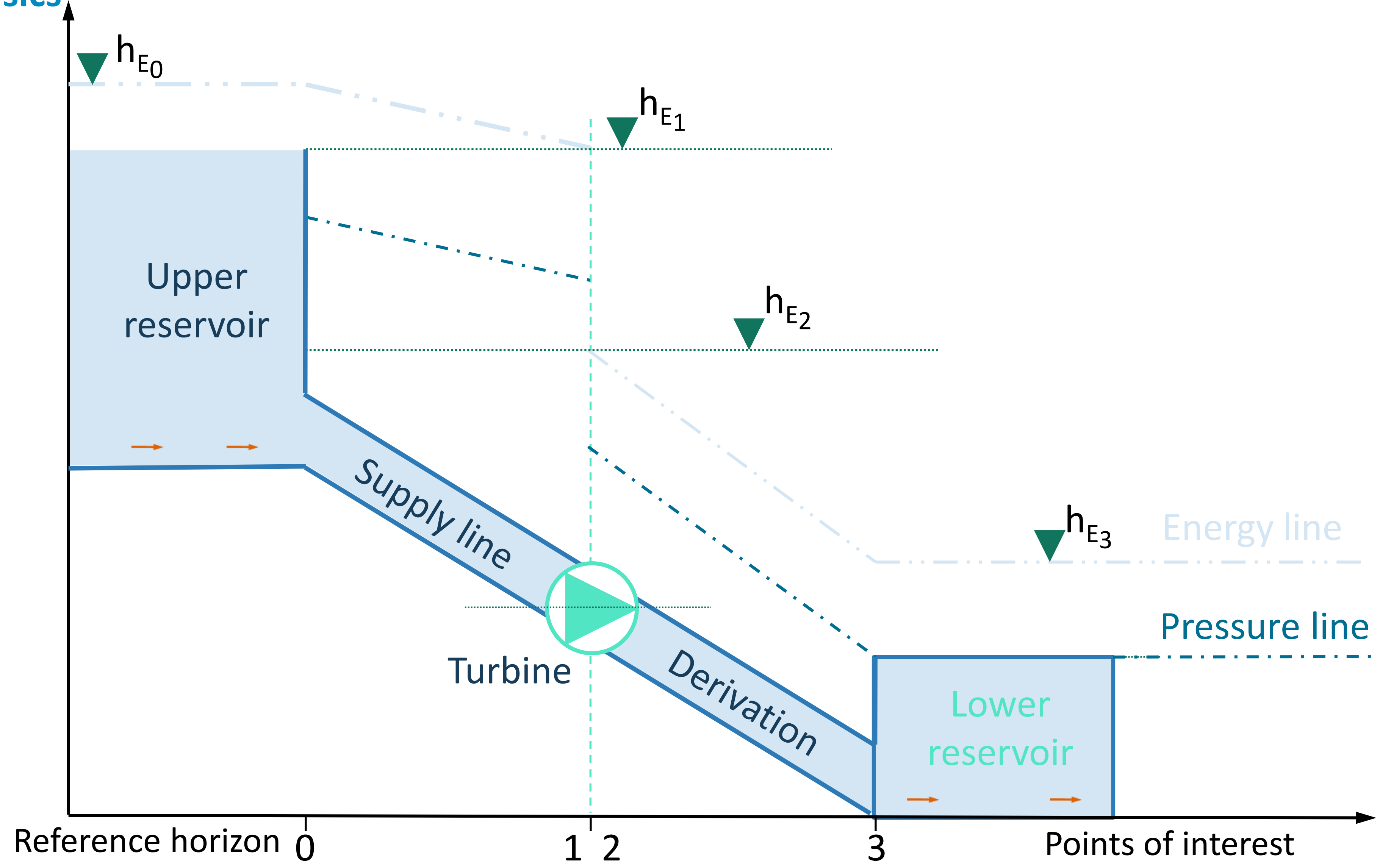
- Continuous losses along a route from point 1 to point n:

$$h_{loss,1n} = \sum_{i=1}^{n} h_{loss,i} = \sum_{i=1}^{n} \zeta_i \cdot \frac{v_i^2}{2 \cdot g}$$

h_E	Energy height	[m]
$h_{loss,\,i}$	local loss height	[m]
$h_{loss,1n}$	continuous loss height	[m]
ζ_i	Loss coefficient	[-]

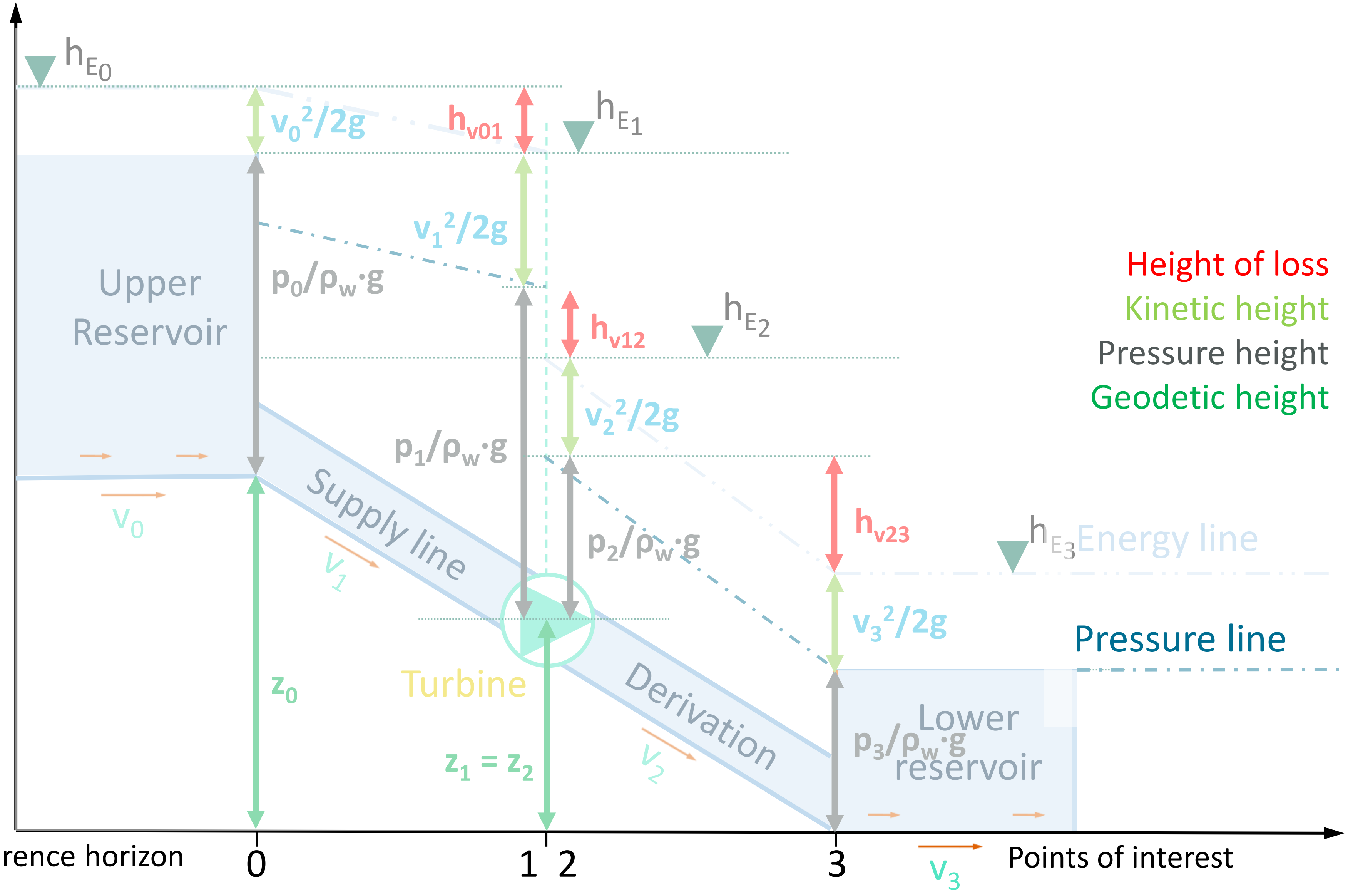
Pumped water storage

Physical basics



Pumped water storage

Physical basics



Pumped water storage

Physical basics

- The continuity equation results from the mass balance between cross-section 1 and 2 (assuming a homogeneous and incompressible liquid):

$$Q = \int_A v \cdot dA = v_1 \cdot A_1 = v_2 \cdot A_2 = const.$$

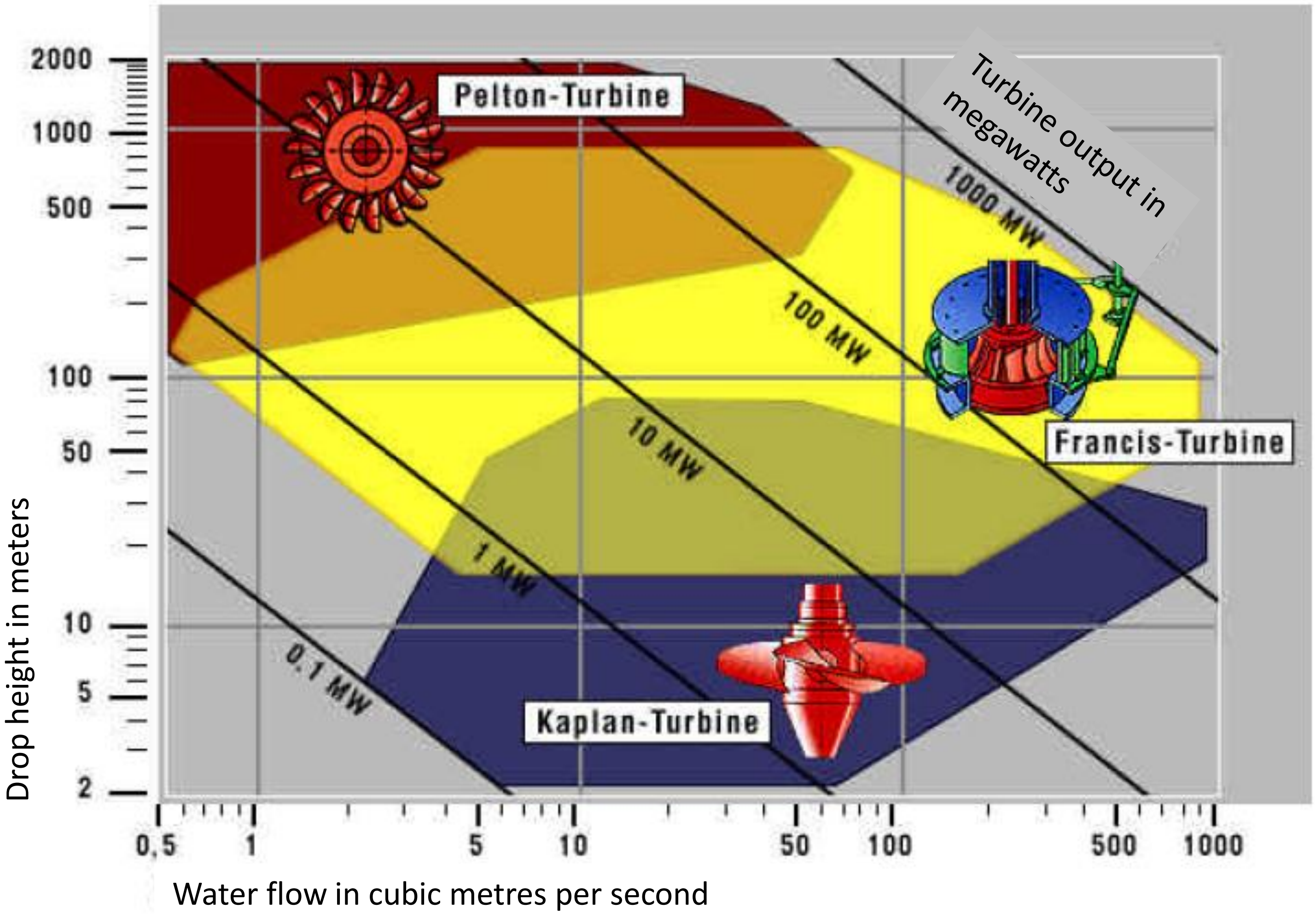
- Electrical Power

$$P = \eta_{ov} \cdot \frac{\rho_W \cdot g}{10^3} \cdot Q \cdot h_{dh} = \frac{\rho_W \cdot g}{10^3} \cdot Q \cdot (h_{dh} - \sum_i h_{loss,i}) = c_P \cdot Q \cdot h_{dh}$$

Q	Flow	[m³/s]
A	Flow cross-section	[m²]
P	Electrical Power	[kW]
η_{ov}	Overall efficiency	[-]
h_{dh}	Height of fall	[m]
$h_{loss, i}$	Local height of loss	[m]
c_P	Power factor (including generator, transformer, etc.) for small hydropower plants: $c_p \approx 8.0$ for medium-sized hydropower plants: $c_p \approx 8.5$ for large hydropower plants (> 50MW): $c_p \approx 8.8$ (lossless: $c_p \approx 9.81$ (not possible))	[m/s]

Pumped water storage

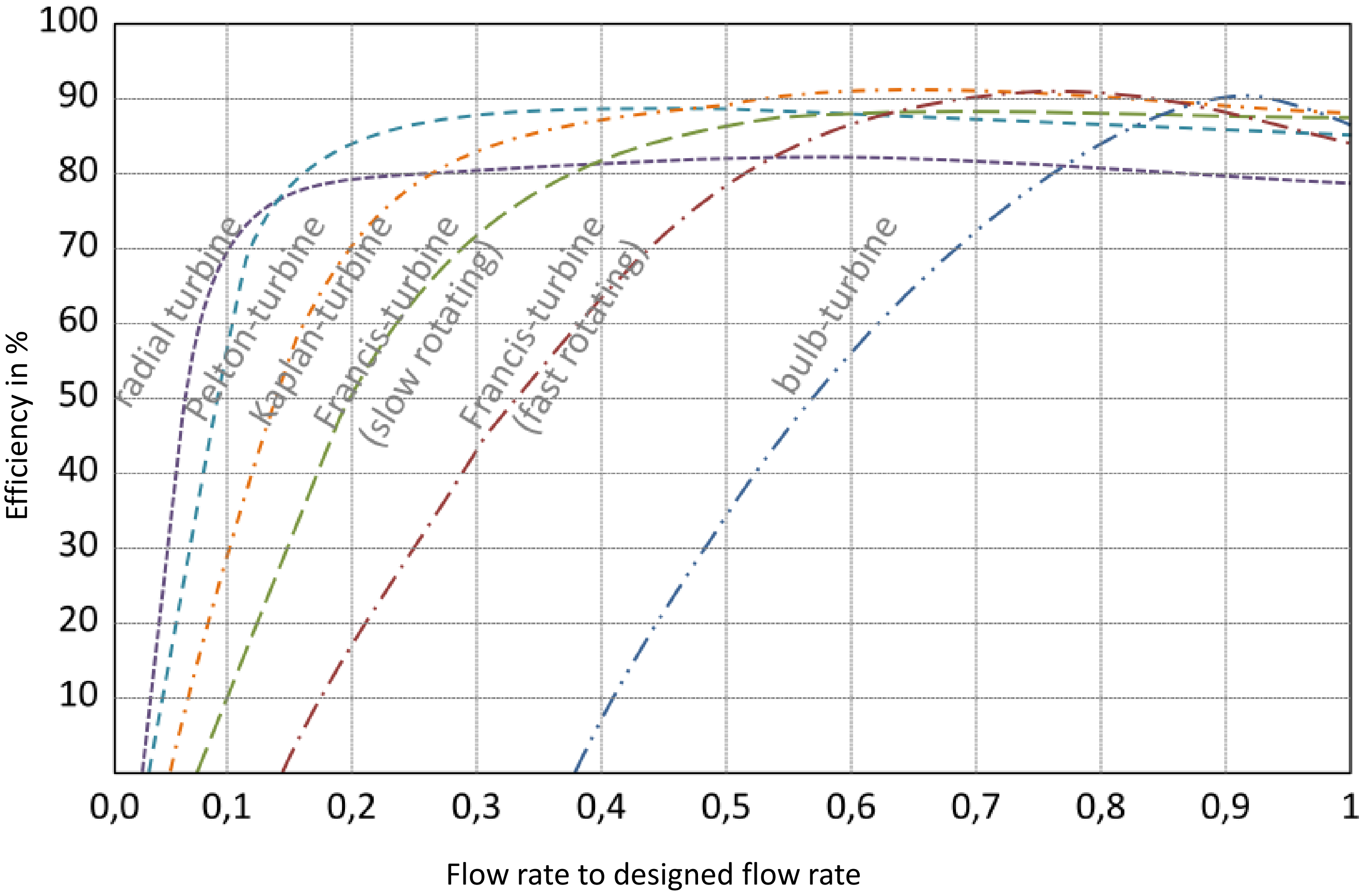
Turbine overview



- Differentiation between equal pressure and overpressure turbine
- Equal pressure: Pelton turbine
  - Pressure-free flow around
- Overpressure: Francis and Kaplan turbine
  - Completely surrounded by flowing water
- Flow control types (simple):
  - Guide wheel control
  - Impeller control
  - Nozzle control
- Flow control types (double)
  - Guide wheel and impeller arrangement
  - Nozzle and jet deflection control

Pumped water storage

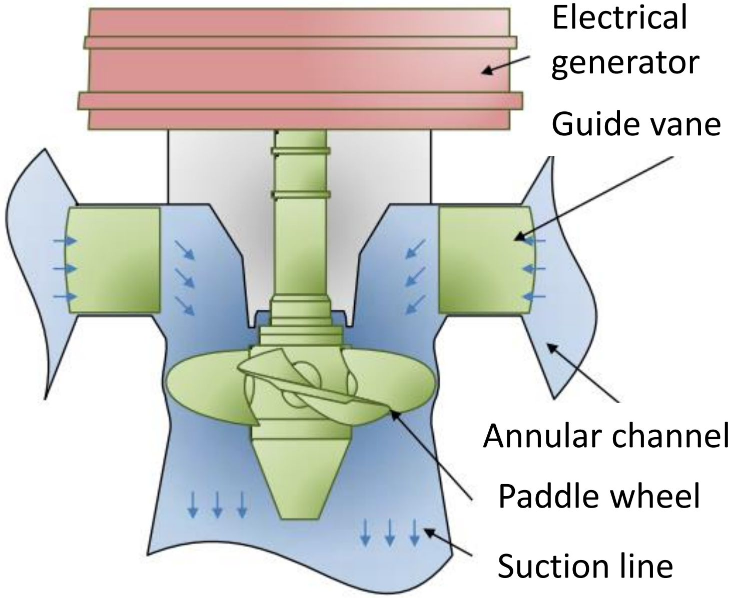
Turbine efficiencies



- Due to losses (e.g. friction losses) theo. Potential energy not usable
- Turbine efficiency $_{\eta T}$ = achievable output / theo. Output
- Influencing the efficiency curve through flow control

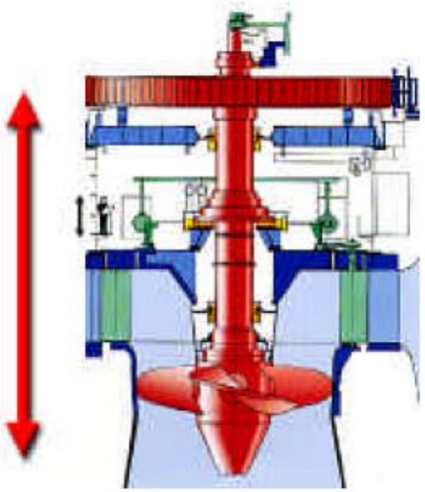
Pumped water storage

Kaplan turbine



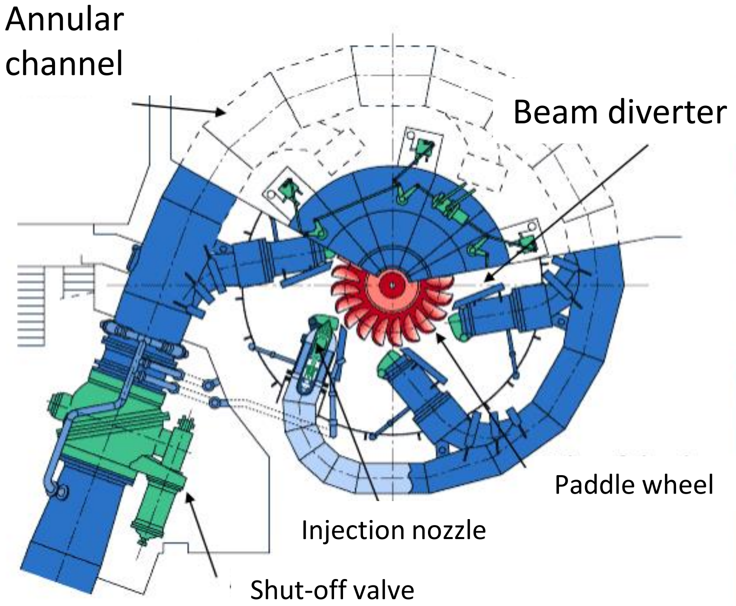
- Inverted propeller
- Few blades (friction)
- Horizontal construction for large plants
- Water flow axial to paddle wheel
- Adjustable paddle wheels -> better water admission

Drop heights up to 65m



Pumped water storage

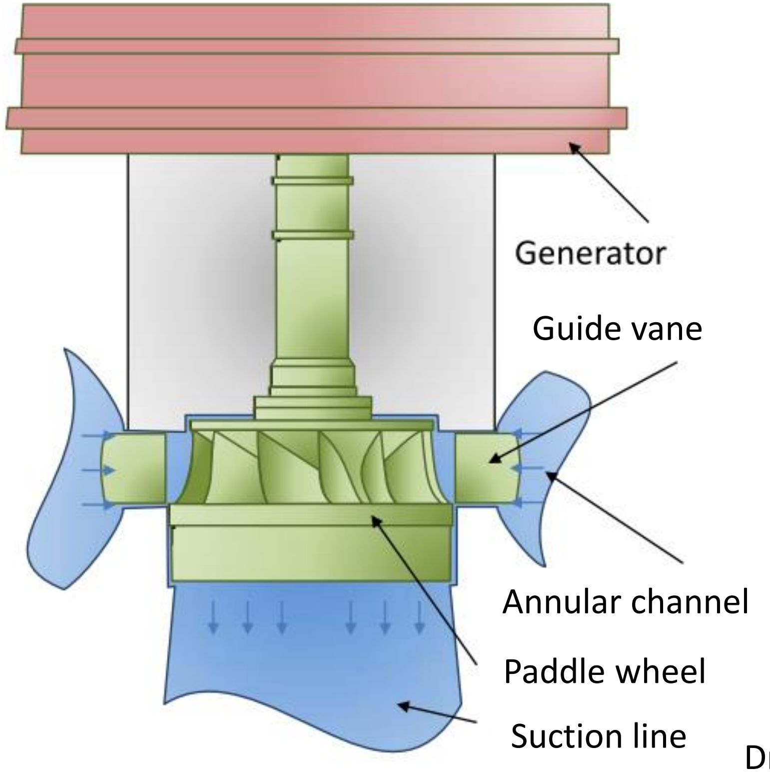
Pelton turbine



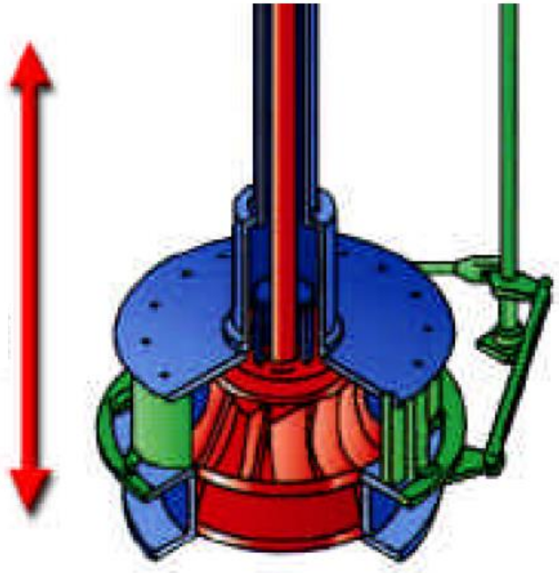
- Highest efficiency at high height of fall and low flow rates
- Use of a free water jet
- Acceleration takes place in controlled injection nozzle (with axially movable needle)
- Water jet deflectors allow the turbine to be switched off quickly (water jet is directed past the blades -> rapid drop in rotor output)
- Large pumped storage power plants have pressure locks to compensate for pressure pulses during shutdown

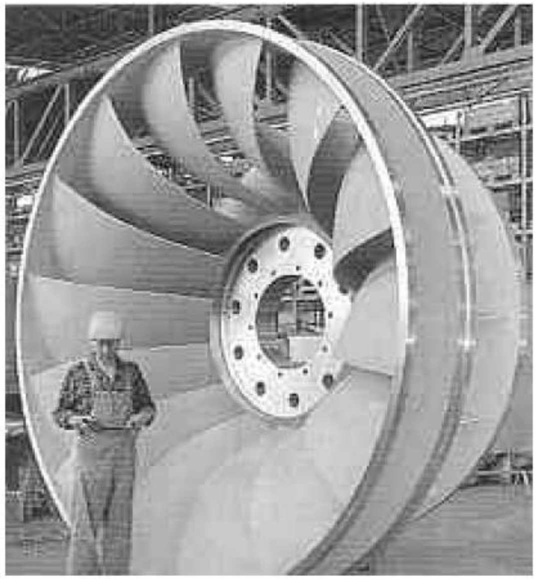
Pumped water storage

Francis turbine



- Drop heights over 100m
- Design as a simple radial or semi-axial turbine
- Repositioning of the guide vanes possible
- Flowed through from outside to inside
  - Annular channel guides water axially symmetrically onto the blade





Pumped water storage

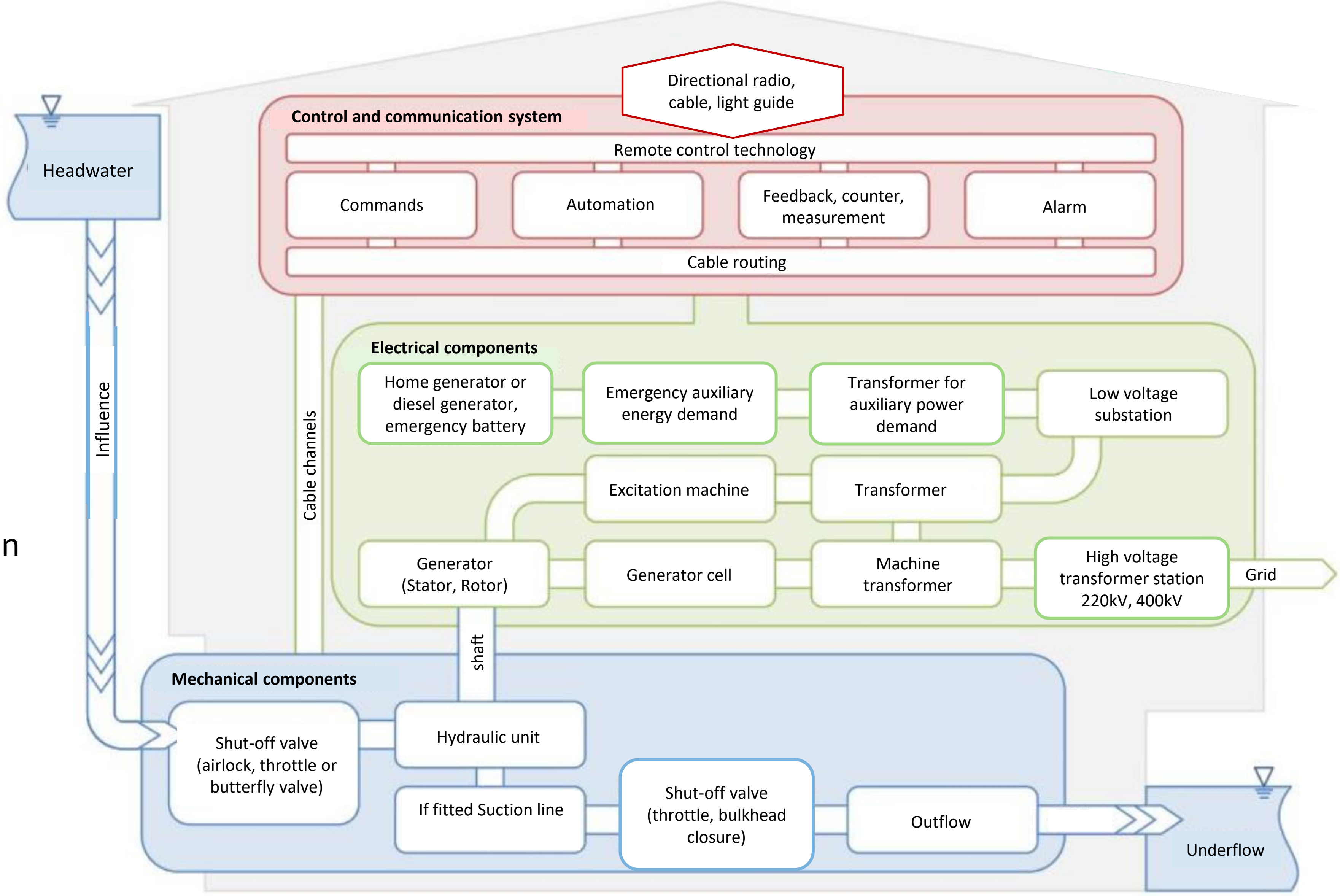
Generators

	Synchronous Generator	Asynchronous Generator
Rotor start up necassary	Yes	No
Independent start from rest	No	Yes
Voltage regulation possible	Yes	No
p control possible	Yes	No
q Regulation possible	Yes	No
Generation in the grid system	Yes	Yes
Generation in isolated operation	Yes	Only certain cases
Synchronization with mains necessary	Yes	No
Efficiency	Higher	Less
Investment/operating costs	Higher / larger	Less / cheap
Structure	complex	easier
Required space	Much	less

Pumped water storage

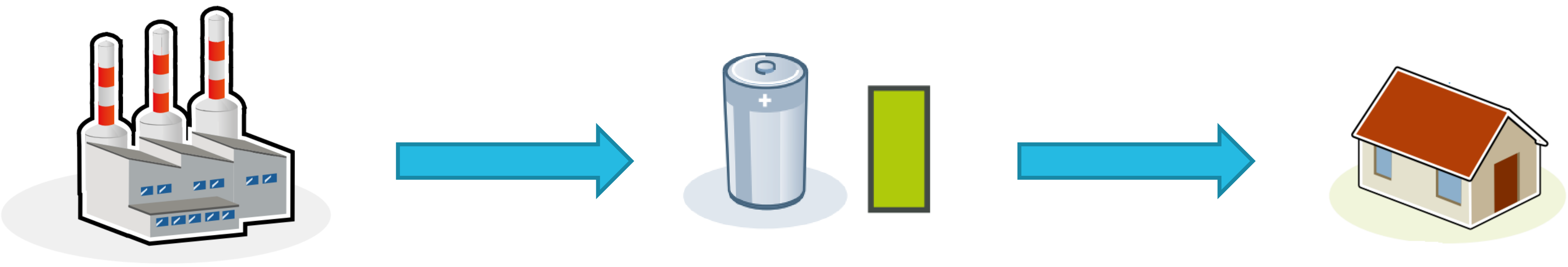
Powerhouse

- Control and monitoring of the operation
- Division of the main competences:
  - Control and communication system (red)
  - Electrical components (green)
  - Mechanical components (blue)



Pumped water storage

Operational concept - Yesterday



Lignite and nuclear power plants

Pump water storage tank

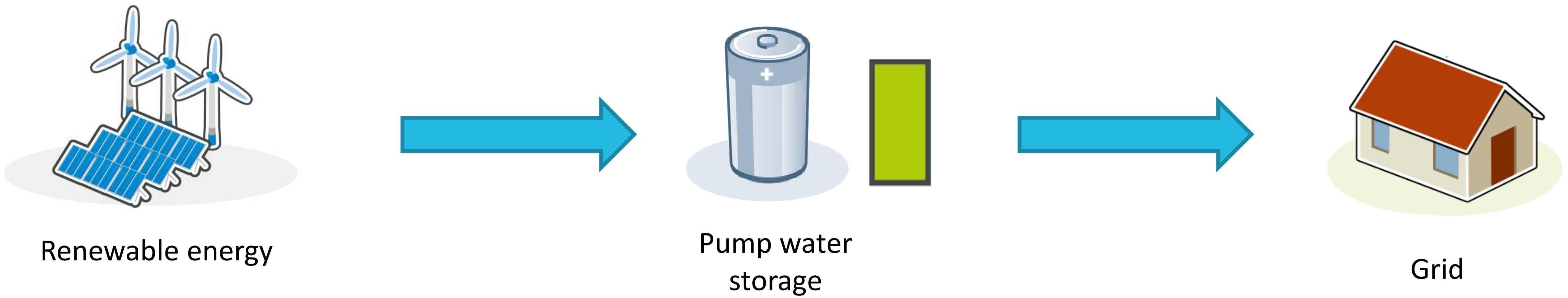
Grid

- Storage operation: pumping up at night charged with inexpensive electricity
- Discharge operation: at midday at peak loads to sell electricity at a high price
- High price difference (spread) between peak and base load prices enables profitable operation
- No longer economical due to increasing share of renewable energies Day-night operation

Pumped water storage

Operational concept - Today

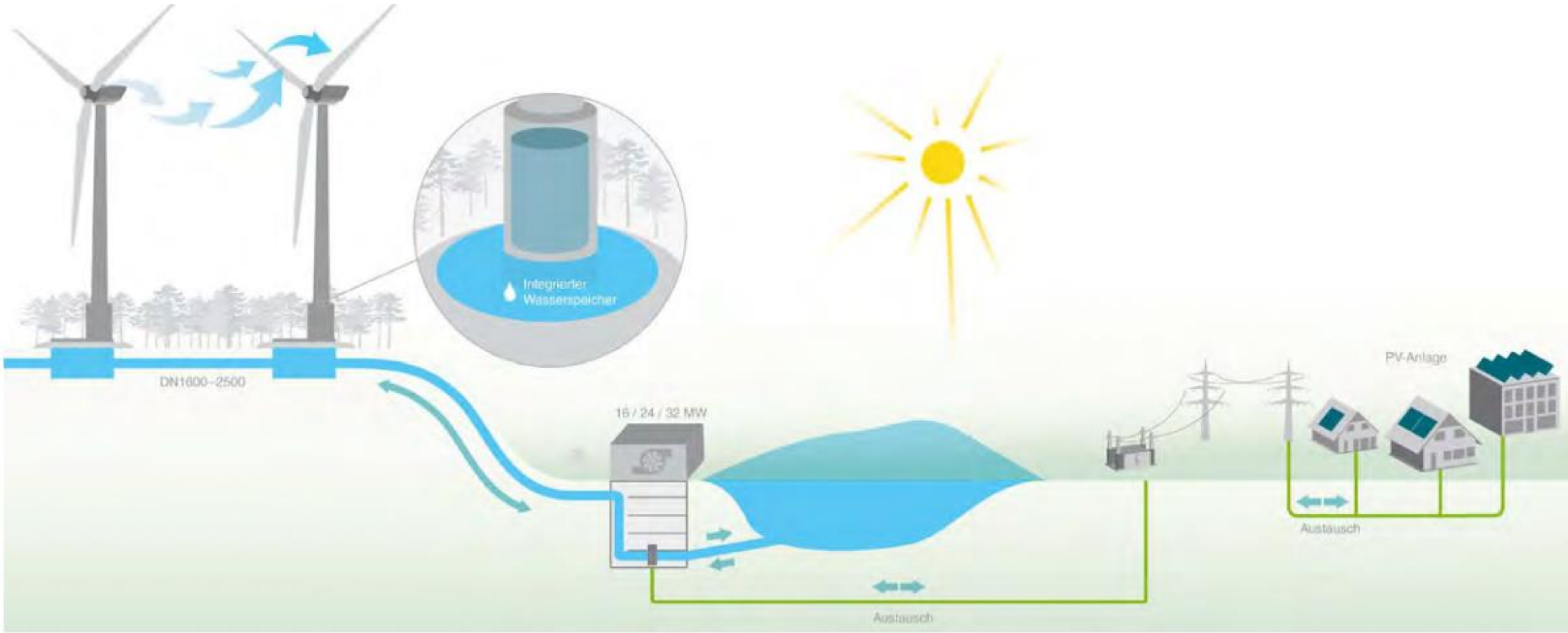
https://www.youtube.com/watch?v=_PH0IJ-_qOI



- PWS gain new importance through energy system transformation
- Storage of "surplus" energy from wind turbines and solar energy systems
- Peak loads at midday are currently largely covered by PV systems

Pumped water storage

Operating concept - Today - "natural power storage"

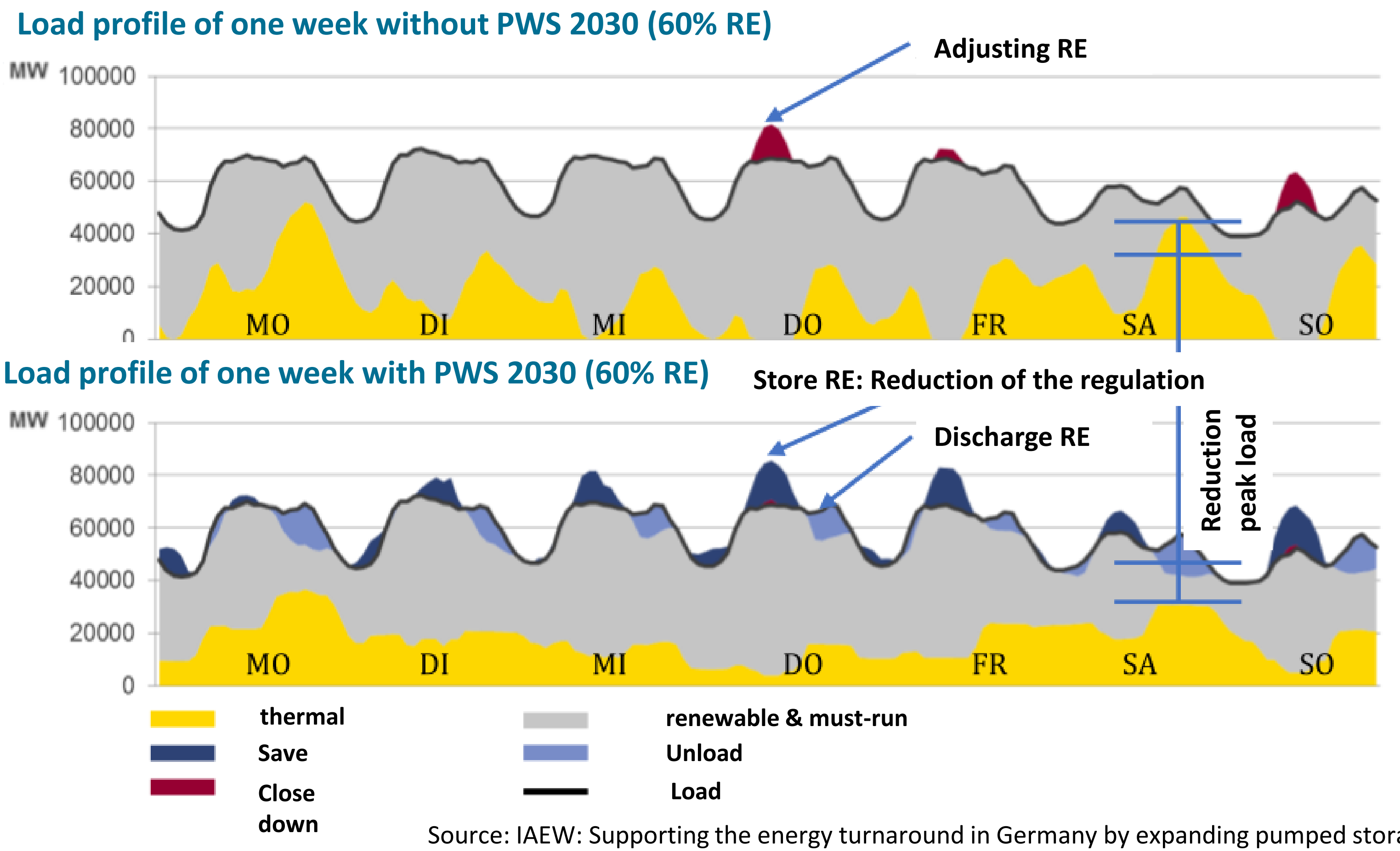


Quelle: Naturspeicher GmbH

- Natural pumped water storage in Gaildorf (Baden-Württemberg)
- 4 wind turbines with an output of 3.4 MW each on the ridges of the Limburg mountains
- In the foundations there are water reservoirs with a pump water storage located 200m deep

Pumped water storage

Operational concept - Tomorrow



Source: IAEW: Supporting the energy turnaround in Germany by expanding pumped storage

By using PWS, thermal power plants (such as coal-fired power plants) can be shut down in their output and energy from renewable energy sources can be used more efficiently without having to regulate RES at times of excess demand for electricity.

The example shows a load curve with and without RE of 60%.

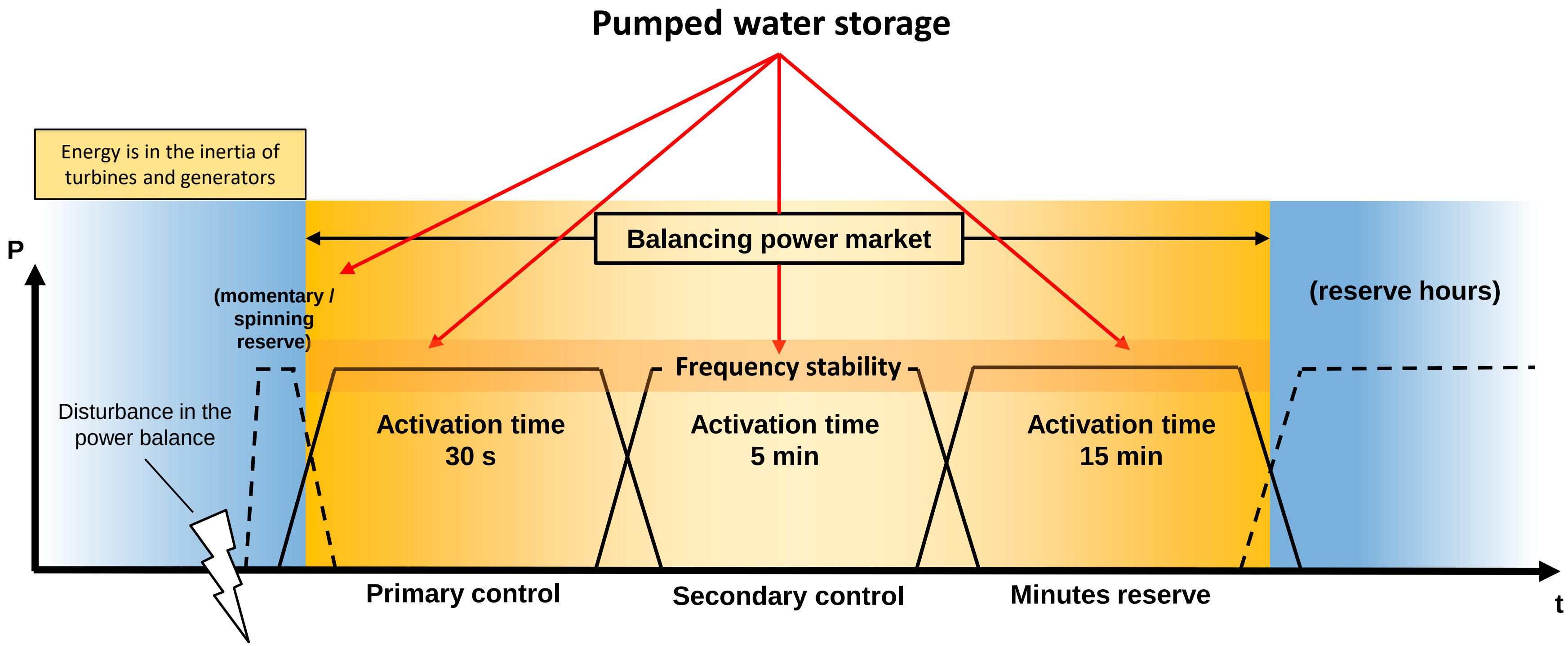
Pumped water storage

System service

Source: https://www.next-kraftwerke.de/wissen/systemdienstleistungen

Pumped water storage

System service - Frequency stability



Source: Bavarian State Ministry of Economic Affairs and Media, Energy and Technology, expert opinion on the profitability of pumped storage power plants

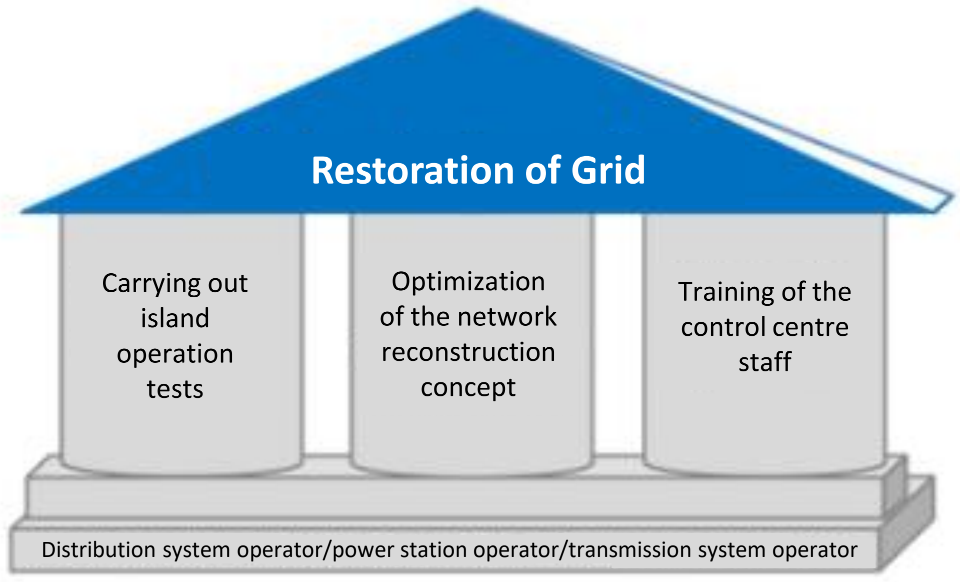
- Prerequisite participation primary control power: time factor and 1 MW
- Prerequisite participation in secondary control power: time factor and 5 MW
- Prerequisite participation minute reserve: time factor and 5 MW

Pumped water storage

System service – Restoration of grid

Characteristics of power plants capable of black starting

- **Short-term** (flexible and fast starting behaviour)
- **Only internal power** (no external power sources)
- **Robustness** (should be able to handle heavy starting current)
- **Stagnation behaviour** (prolonged own operation)



Pumped water storage

Sea water pump storage

Source #2

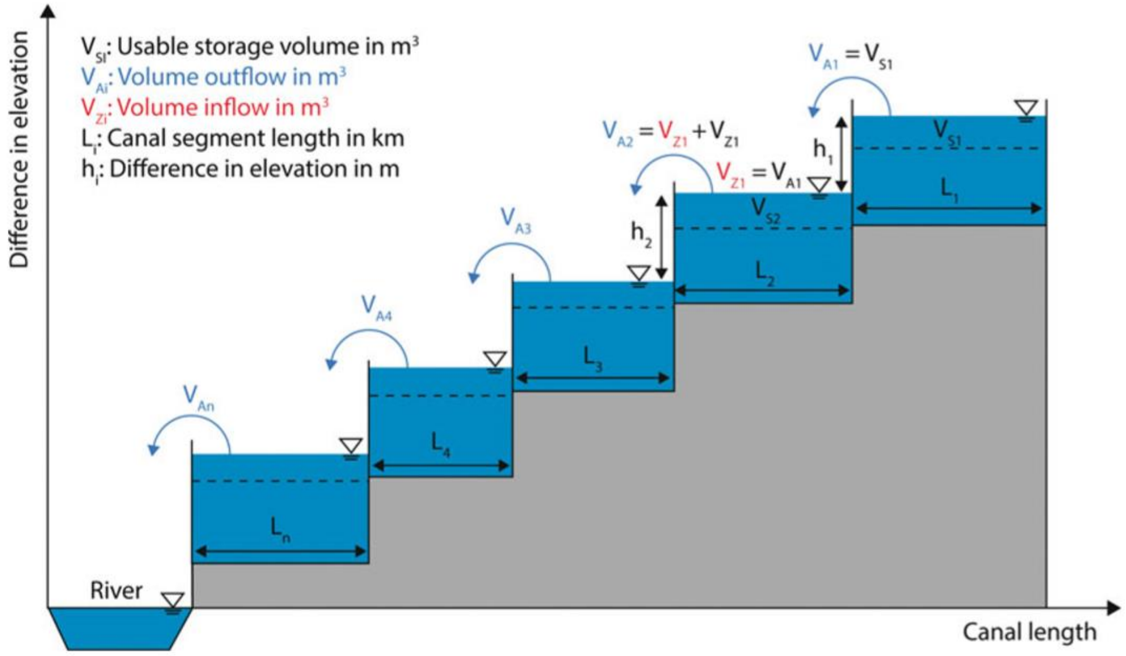
A sea water pumped storage has the following advantages:

1) It is comparatively easy to find a suitable location for the power plant because the wide ocean can be used as a lower reservoir.

2) You can achieve up to 80% efficiency due to the short waterway, which reduces hydraulic losses from 7% to 2%.

Pumped water storage

Barrage storage



Source 2

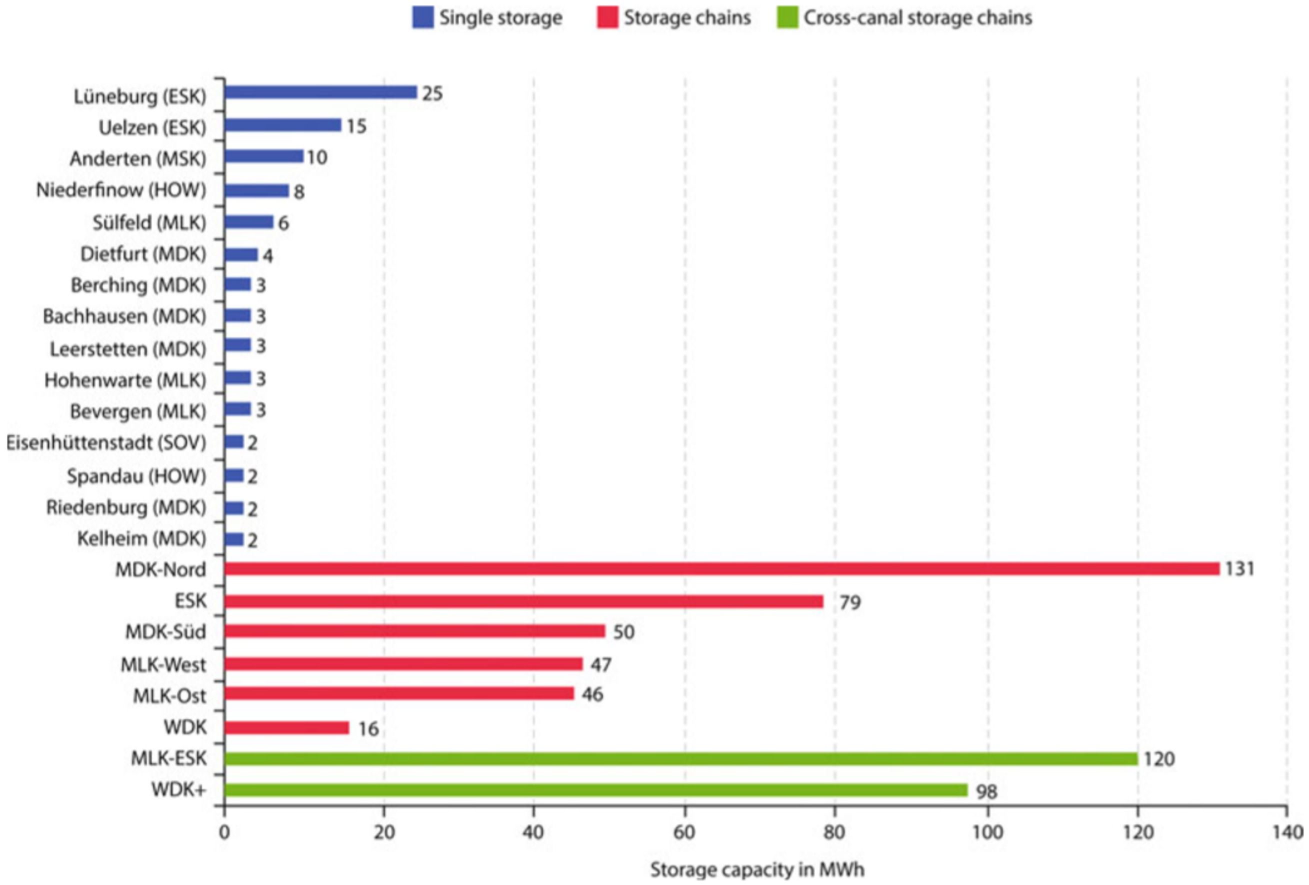
Source 2

- Dams (locks or boat lifts) delimit upper and lower basins and thus ensure a difference in height
- If there is a surplus of electricity, water is pumped from the lower to the upper pool
- If electricity is required, water from the upper basin is fed into the lower basin by a turbine.
- The same principle of action as conventional pumped storage power plants
- Efficiency comparable to conventional PWS
- Germany's waterways are 1340km long, have a total fall height of 611m and are spread over 64 barrages

Pumped water storage

Barrage storage

Source 2

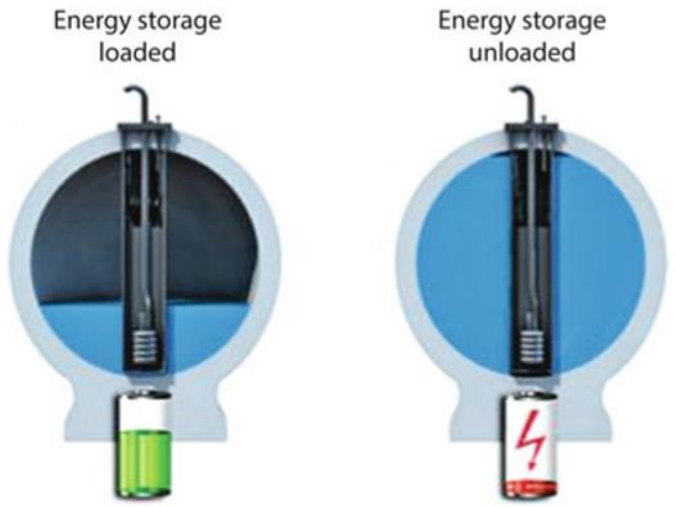


- Lüneburg boat lift (left picture) with the largest potential single storage capacity at a drop height of 38 meters
  - Storage facilities with the highest capacity of 25 MW
- The storage capacity of the usable federal waterways for individual storage, storage chains and cross-channel storage chains (left illustration)
- Not all capacities of the individual storage chains can be added to determine the total storage capacity, since this would result in multiple use of channel sections

Pumped water storage

Ball pump storage

- Function similar to conventional pumped water storages
- Hollow sphere of concrete in deep lakes or on the seabed -> serves as a lower basin
- Sea or lake surface -> serves as upper basin
- Water is pumped out of hollow spheres in the event of a power surplus
- When electricity is required, hollow ball is flooded and thus turbines are driven



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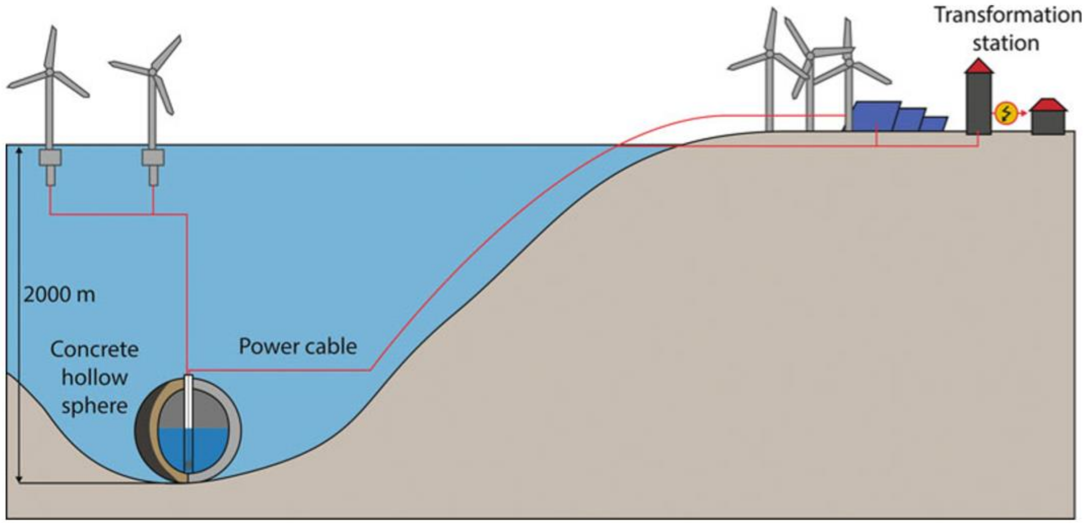


Source 2

Storage capacity of a ball pump reservoir as a function of the depth and diameter of the hollow ball

Depth in m	200	400	800	1.600	3.200
Pressure in bar	19.62	39.24	78.48	156.96	313.92
Energy density in kW h/m^3	0.55	1.09	2.18	4.36	8.72
Diameter in m	20	40	80	160	320
Volume in m^3	4,188	33,510	268,082	2,144,660	17,157,284
Capacity in MW h	2.28	36	584	9,350	149,000

Source 2

Pump storage - Exercise I

The Marmorera - Tinizong power plant stage of the Mittelbünden hydropower plant in Switzerland has a total capacity of 70 MW. A total of 16.7 m^3 per second flows through the turbines from the Marmorera reservoir, 480 m higher up, through a tunnel.

a) Calculate the supplied mechanical power!

b) Calculate the efficiency of the power plant stage!

Source: https://www.tagesanzeiger.ch/die-stromhungrige-stadt-verschluckte-ein-bergdorf-547933244964

Pump storage - Exercise I

a)

$$P = \frac{E_{pot}}{t} = \frac{m \cdot g \cdot h}{t}$$

$$\rightarrow \quad m = \rho_{Water} \cdot V$$

$$P = \frac{\rho_{Water} \cdot V \cdot g \cdot h}{t} = \frac{1000\,\frac{kg}{m^3} \cdot 16{,}7\,m^3 \cdot 9{,}81\,\frac{m}{s^2} \cdot 480\,m}{1s}$$

$$P = 78.636.960\,kg\,\frac{m^2}{s^3} = W$$

$$\underline{P = 78{,}64\,MW}$$

b)

$$\eta = \frac{P_{out}}{P_{in}} = \frac{70MW}{78{,}6\,MW} = 0{,}89$$

➔ $\underline{\eta = 89\ \%}$

Pump storage - Exercise II

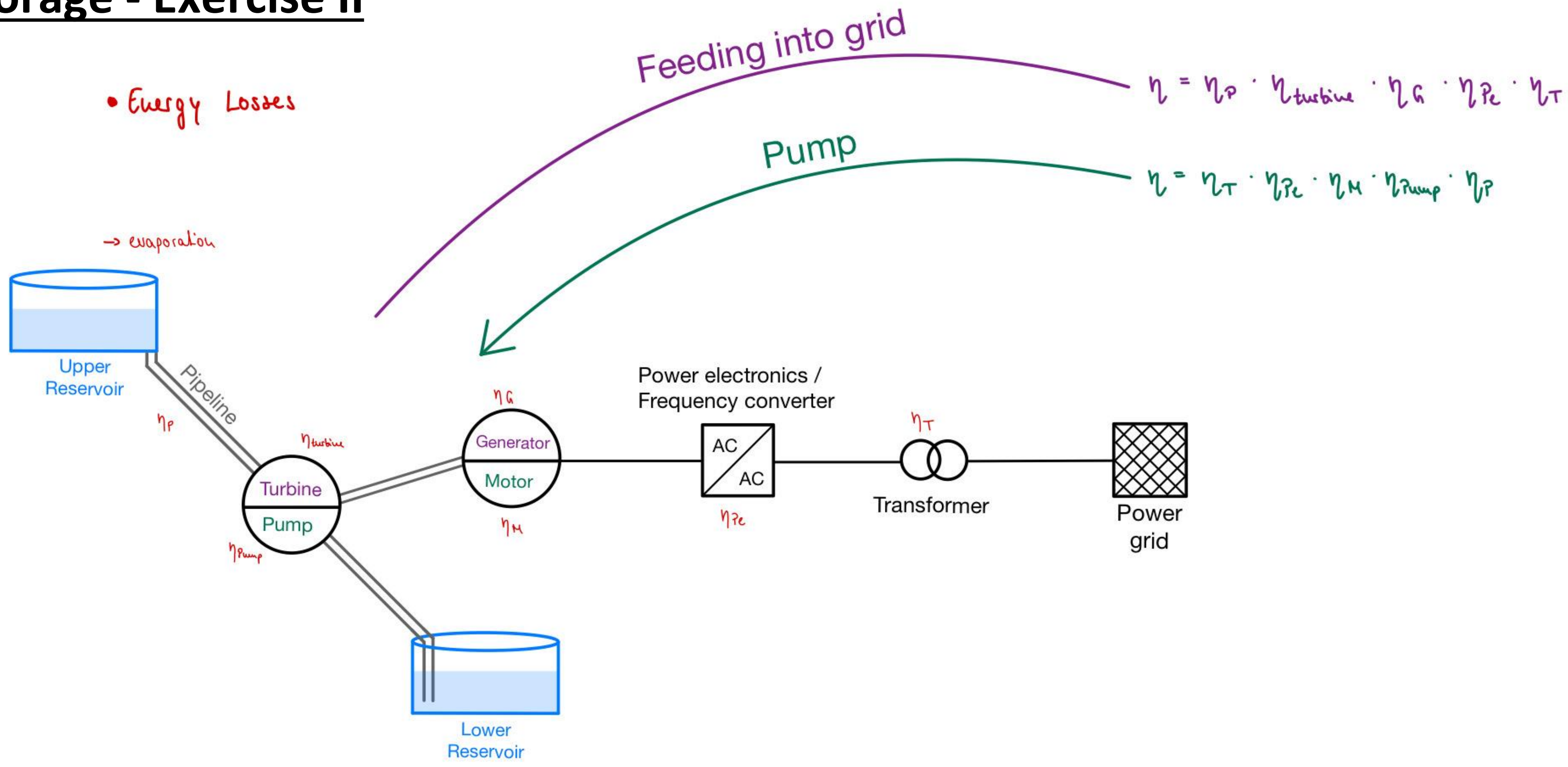
The pumped storage power plant Goldisthal in Thuringia is one of the largest and most modern plants in Europe with a capacity of P_{out} = 1060 MW. In times of low load, when the demand for electrical energy is low, water is pumped from the lower basin to the upper basin 300 m higher, which has a usable volume of $12 \cdot 10^6$ m³.

a) Sketch a pumped storage power plant and name the main components required for its operation. Describe the energy conversion chain.
b) Calculate the energy stored in the water of the upper basin when it is fully filled.
c) Calculate how long it takes to completely fill the empty reservoir at a pumping capacity of 1020 MW if the pumping efficiency is 88%.
d) The water in the storage basin is sufficient for 8 h 20 min turbine operation at maximum power. Calculate the efficiency of the turbine operation.
e) Calculate the overall efficiency of the pumped storage power plant.

Pump storage - Exercise II

a)

• Energy Losses



E_{pot} ⟶ *Pelton-turbine* ⟶ E_{kin} ⟶ *Generator* ⟶ E_{el}

Pump storage - Exercise II

b)

$V_{upper\ reservoir} = V_{UR} = 12 \cdot 10^6\ m^3$

Height: 300 m

$\rightarrow E_{pot} = m \cdot g \cdot h$

$\Lsh\ m = \rho_{Water} \cdot V_{UR}$ $\rightarrow$ *Density assumption:* $\rho_{Water} = 1000\ \frac{kg}{m^3}$

$$E_{pot} = 1000\ \frac{kg}{m^3} \cdot 12 \cdot 10^6\ m^3 \cdot 9{,}81\ \frac{m}{s^2} \cdot 300m$$

$$E_{pot} = 3{,}53 \cdot 10^{13}\ Ws = 9{,}81 \cdot 10^9\ Wh$$

$$\underline{E_{pot} = 9{,}81\ GWh}$$

c)

given: $P_P = 1020\ MW$
$\eta_P = 0{,}88$

Solution: $E = P \cdot t$

$$\rightarrow t = \frac{E}{P} = \frac{\rightarrow \textit{Energy to pump in upper reservoir (as in task b))}}{\rightarrow \textit{Power, with which i can pump the water}}$$

$$t = \frac{9{,}81 \cdot 10^9\ Wh}{P_P \cdot \eta_P} = \frac{9{,}81 \cdot 10^9\ Wh}{(1020 \cdot 10^6 W) \cdot 0{,}88}$$

$$\underline{t = 10{,}93\ h = 655{,}75\ min}$$

Pump storage - Exercise II

d) goal: $\eta_{Turbine}$

given: $P_{out} = 1060\ MW$
$t = 8\ h\ 20\ \text{min} = 8,\bar{3}\ h$
$E_{UR} = 9{,}81 \cdot 10^9\ Wh$

Solution:

$$\eta_{Turbine} = \frac{E_{out}}{E_{in}}$$

$$\eta_T = \frac{P_{out} \cdot t}{E_{UR}} = \frac{(1060 \cdot 10^6\ W) \cdot 8,\bar{3}\ h}{9{,}81 \cdot 10^9\ Wh} = 0{,}9$$

$\underline{\eta_T = 90\ \%}$

e) goal.: $\eta_{overall}$ *of the pumped storage power plant*

solution:

$$\eta_{ovr} = \eta_{Turbine} \cdot \eta_{Pump}$$

$$\eta_{ovr} = 0{,}9 \cdot 0{,}88$$

$\underline{\eta_{ovr} = 0{,}79 \triangleq 79\ \%}$

Pumped water storage

Advantages and disadvantages

Advantages	Disadvantages
An important property of pumped water storage is their black start capability. This means the possibility of being able to start up this power plant without large amounts of electrical energy. This is important, for example, in the event of a large-scale power failure. The small amounts of energy that are required, for example, to open the drain can come from batteries.	The biggest disadvantage of the pumped storage power plant is its large space requirement. The above-ground system of such a power plant usually has a significant impact on the environment.
Pumped water storages can be put into operation quickly. They are therefore well suited to compensate for fluctuations in the energy supply that can occur again and again with renewable energies.	The electricity generated usually has to be transported over long distances, since this power plant is rarely close to settlements. This leads to energy losses and reduces efficiency.
The amount of electricity produced can be influenced by regulating the water flow.	The construction of a pumped water storages is relatively expensive.
The amount of electricity produced can be influenced by regulating the water flow.	

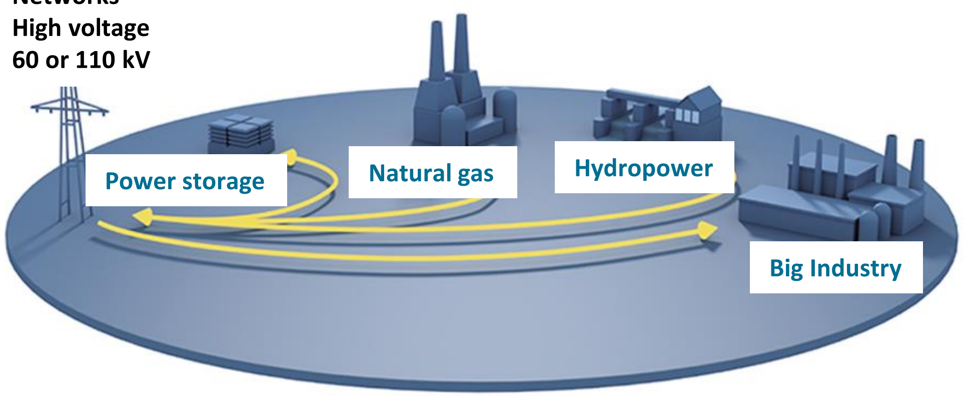
Mechanical storage devices

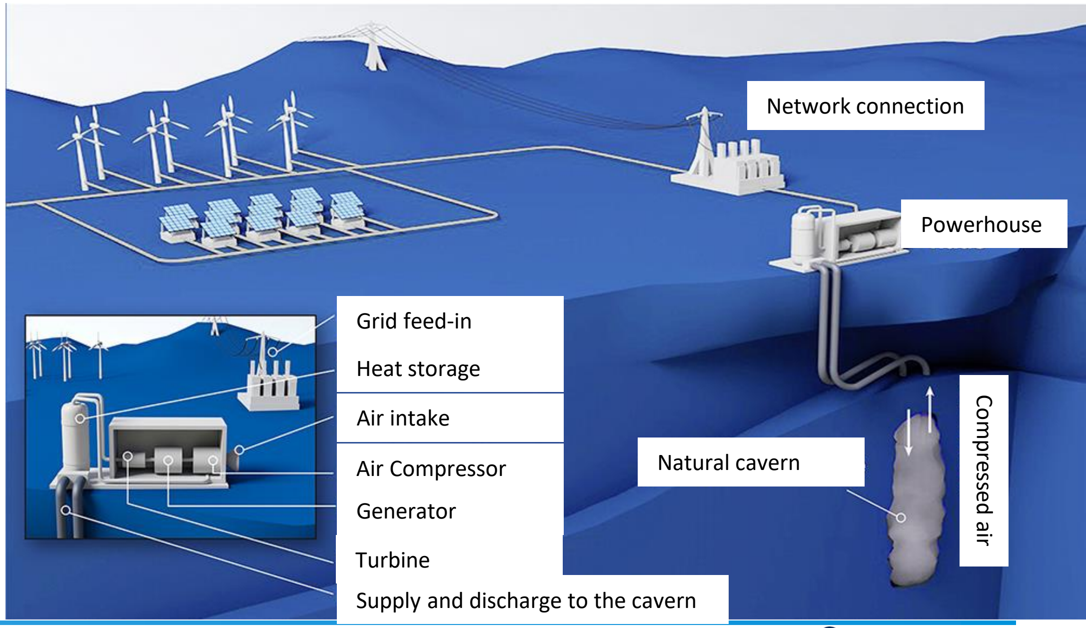
Compressed air energy storage (CAES)

Mechanical storage devices

Compressed air energy storage (CAES)

- Energy conversion into potential energy (internal energy gas)
- Air is forced under high pressure (compressors) into underground cavities and when expanding, the energy is converted back into electrical energy by means of turbines and generators
- CAES power plants are underground compressed air storage facilities in salt caverns (Huntorf Germany 1978; McIntosch USA 1991)
- Due to the complex cooling and subsequent heating, the efficiency is only 40% (Huntdorf) or 54% with waste heat recovery (McIntosh).
- With process integration heat storage/use, theoretically up to 70% efficiency is possible
- Potential locations near the coast were identified. These are very well suited to compensate for the volatile wind supply
- Application area as load balancing, control energy power plant, etc.
- Storage sizes currently several 100MW. In future several GW capacity and GWh storage capacity

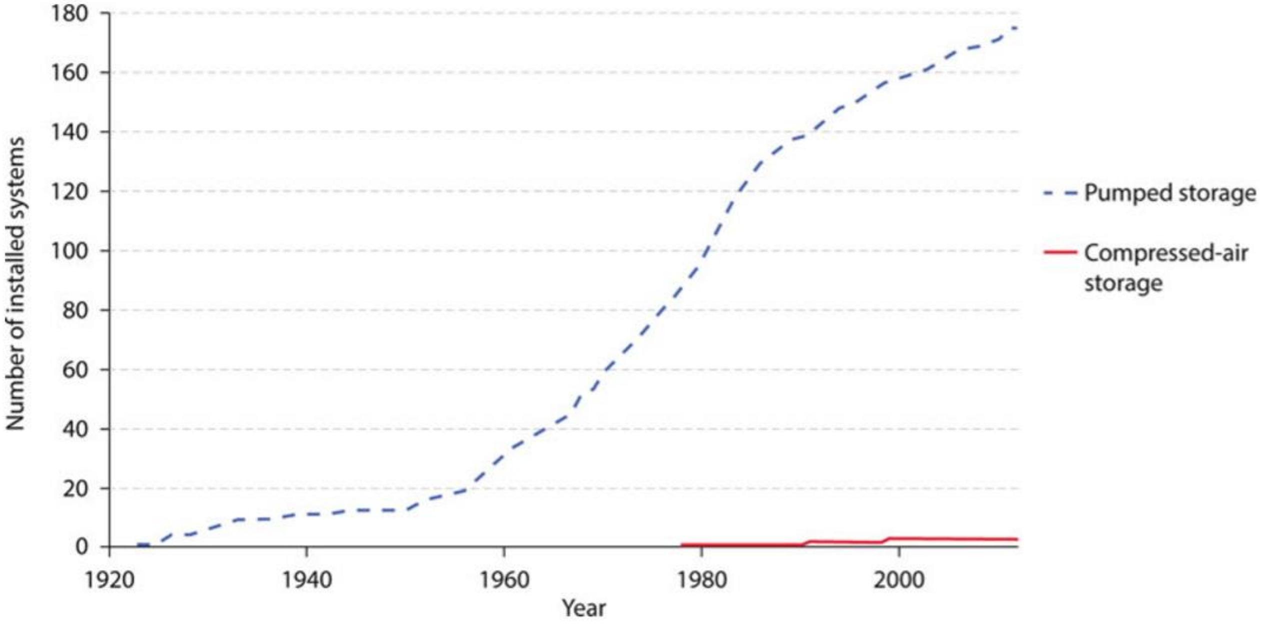




Compressed air energy storage

Installed power

Number of pumped and compressed air storage power plants installed worldwide

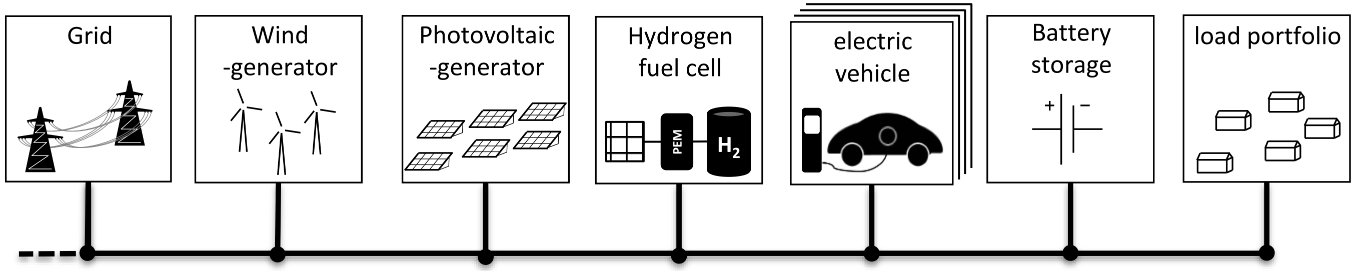


- Just as flexible as pumped storage power plants
- so far there are only two power plants worldwide
  - 1978 Commissioning in Huntorf, Lower Saxony
  - 1991 Commissioning in McIntosh in the US state of Alabama

Source #2

Compressed air energy storage

Potential in Germany



Compressed air reservoirs require the connection as salt caverns!

- Number of all salt domes in Germany: approx. 250
- Storage volume per salt dome: approx. 450 million m^3
- Capacity per m^3:approx. 5kWh/m^3
- Average electricity demand in Germany: approx. 600TWh

- **<u>Theoretically,</u> the use of compressed air storage systems could therefore cover about 90 % of Germany's annual energy demand.**

Quelle: Universität Heidelberg; Druckluftspeicherkraftwerke und ihr Potential

Compressed air energy storage

Trend in Germany

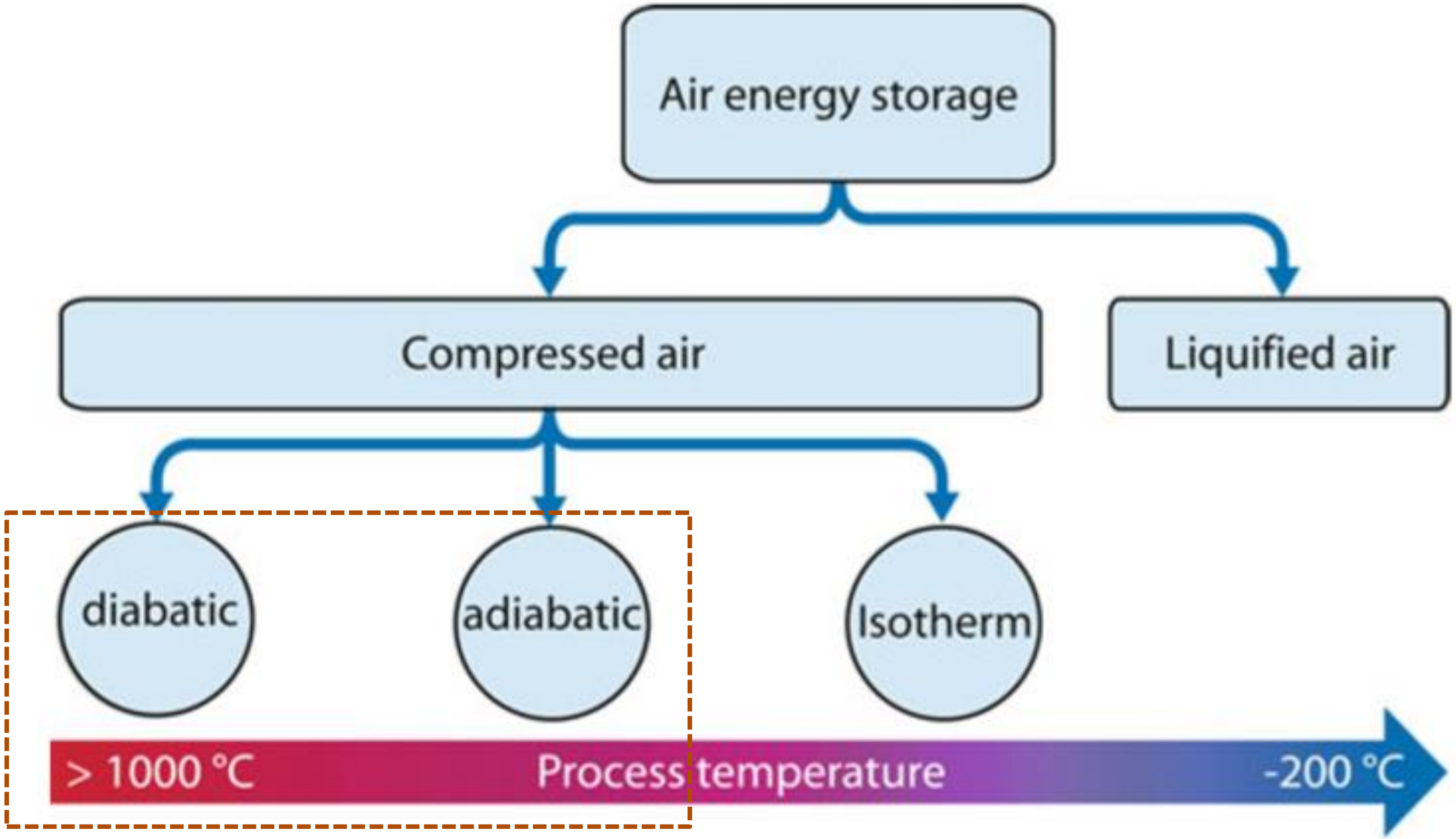
Power plant Adele

Quelle: https://www.bundesregierung.de/breg-de/themen/forschung/adele-koennte-nach-stassfurt-kommen-411972

- Adele stands for "Adiabatic compressed air reservoir for electricity supply".
- planned demonstration power plant near Staßfurt in Saxony-Anhalt
- 2015 Planning rejected due to lack of market prospects
- Coupling with wind power plants planned
- Planned power 90MW
- Planned storage capacity 360MWh

Compressed air energy storage

Classification

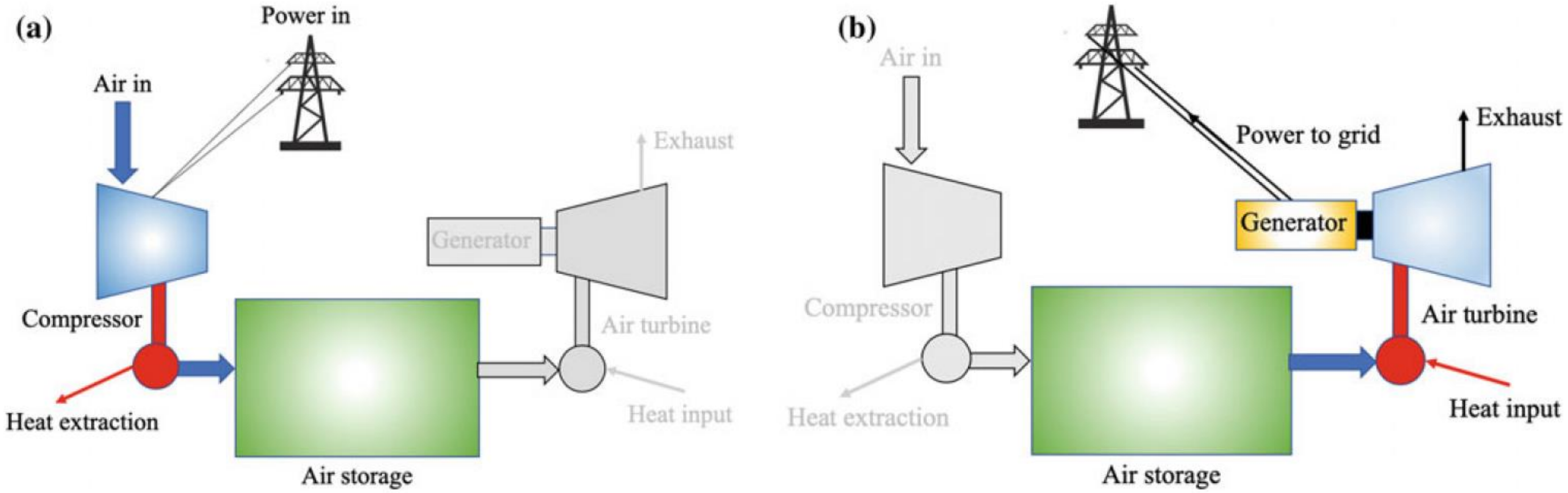


Source #2

Compressed air energy storage

Design and function

Schematic structure of a compressed air reservoir; (a) charging; (b) discharging

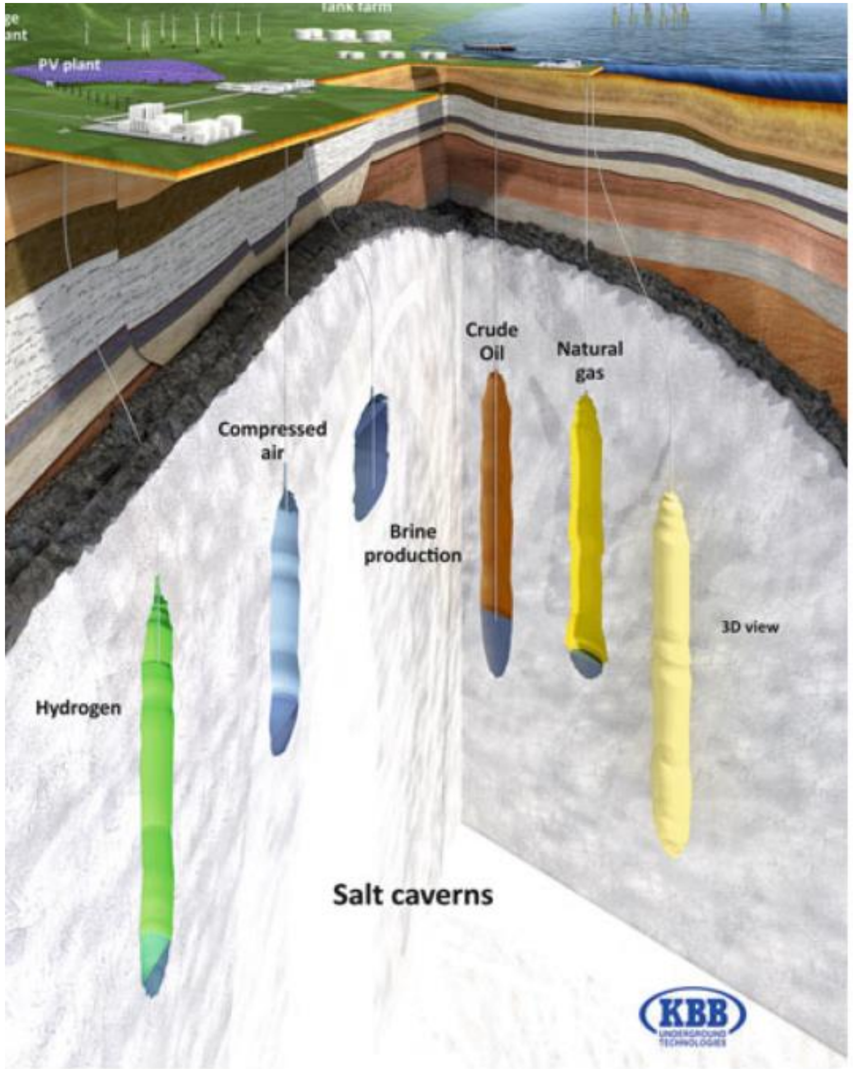


Quelle: Abdul Hai Alami, Mechanical Energy Storage for Renewable and Sustainable Energy Resources

- **Storage process**: Ambient air is compressed by means of electrical energy and stored in gas containers. During the process considerable heat is generated
- **Retrieval process**: The compressed air expands through a pipeline system through a turbine and drives it, which is connected to the generator via a shaft

Compressed air energy storage

Air storage



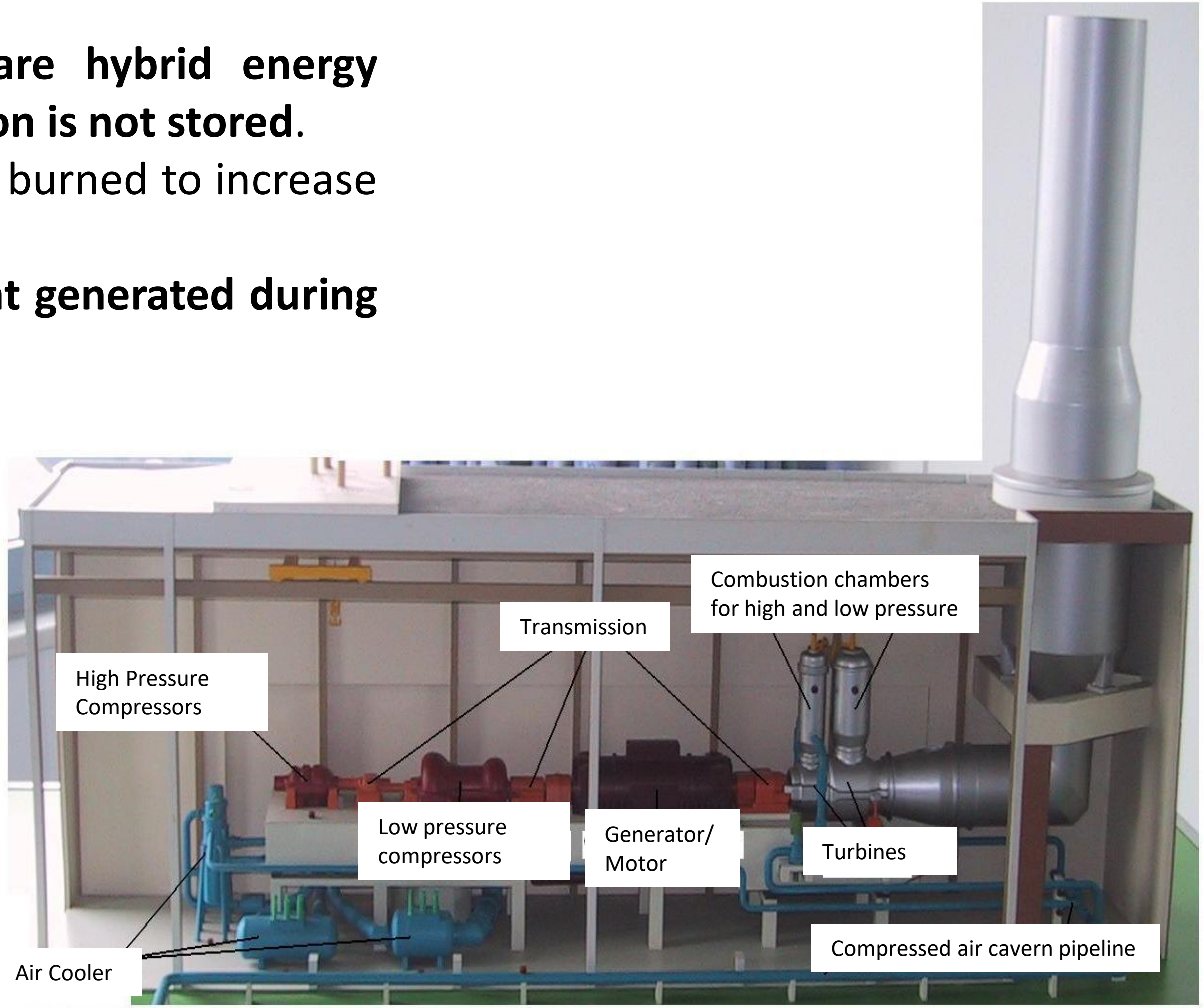
- The storage of compressed air must be airtight and provide sufficient volume
- The air is stored in flushed salt domes in the two known power plants
- These deep storage facilities are called caverns
- In the geological underground, considerably larger storage volumes can be realised at low cost with considerably lower land consumption at the same time
- Due to the depth, pressures of up to 200 bar are possible
- Conventional pressure vessels above ground can hold a volume of approx. 1 million m³, in the case of German underground storage facilities on average with a standard volume of just under 500 million m³.

Source 2

Compressed air energy storage

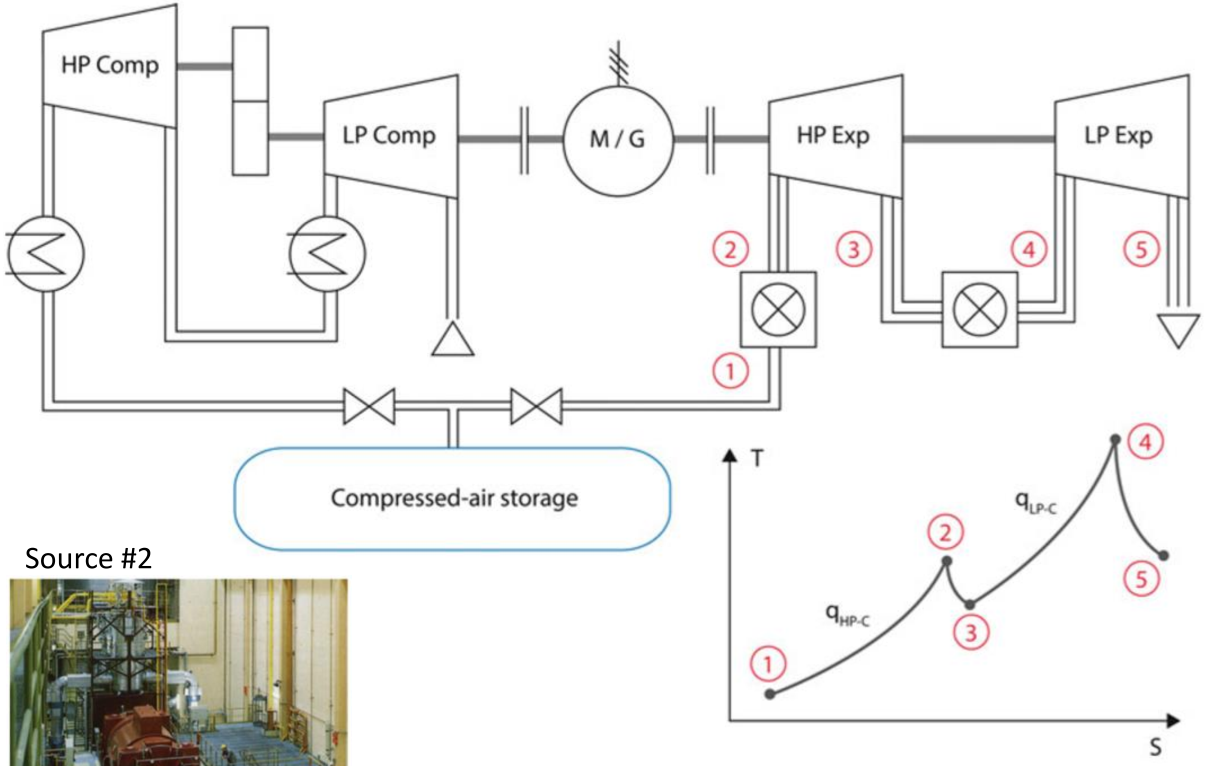
Diabatic vs adiabatic

- **The diabatic compressed air storage systems are hybrid energy storage systems. The heat generated by compression is not stored**.
- When discharged, fossil energy (e.g., natural gas) is burned to increase the temperature of the printed air.
- **In adiabatic compressed air storage tanks, the heat generated during compression is stored in a thermal storage tank.**
- When discharged, the stored thermal energy is released to the printed air so that it increases its temperature and can expand in the turbine.

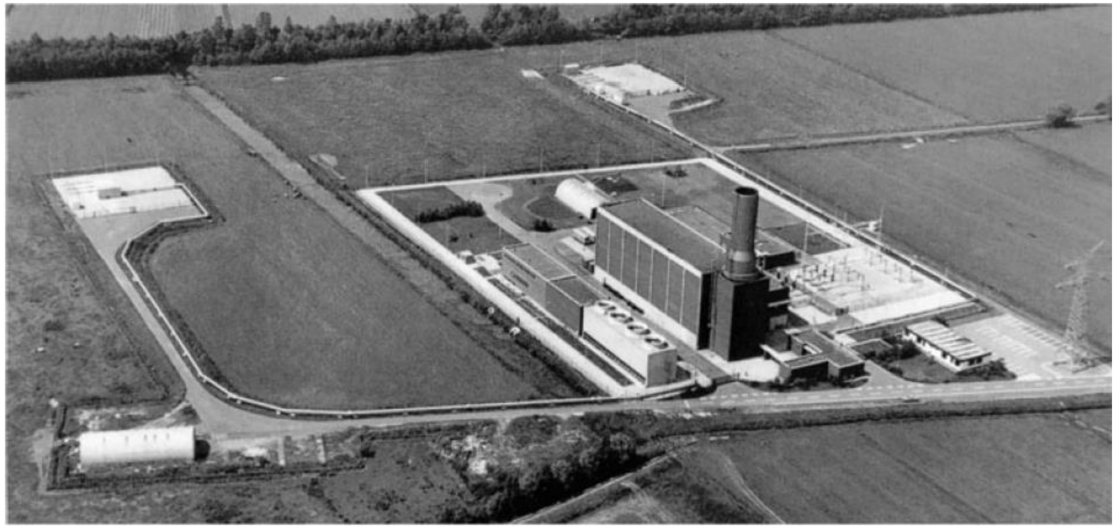


Compressed air energy storage

Diabatic pressure storage (Huntorf)



Source #2

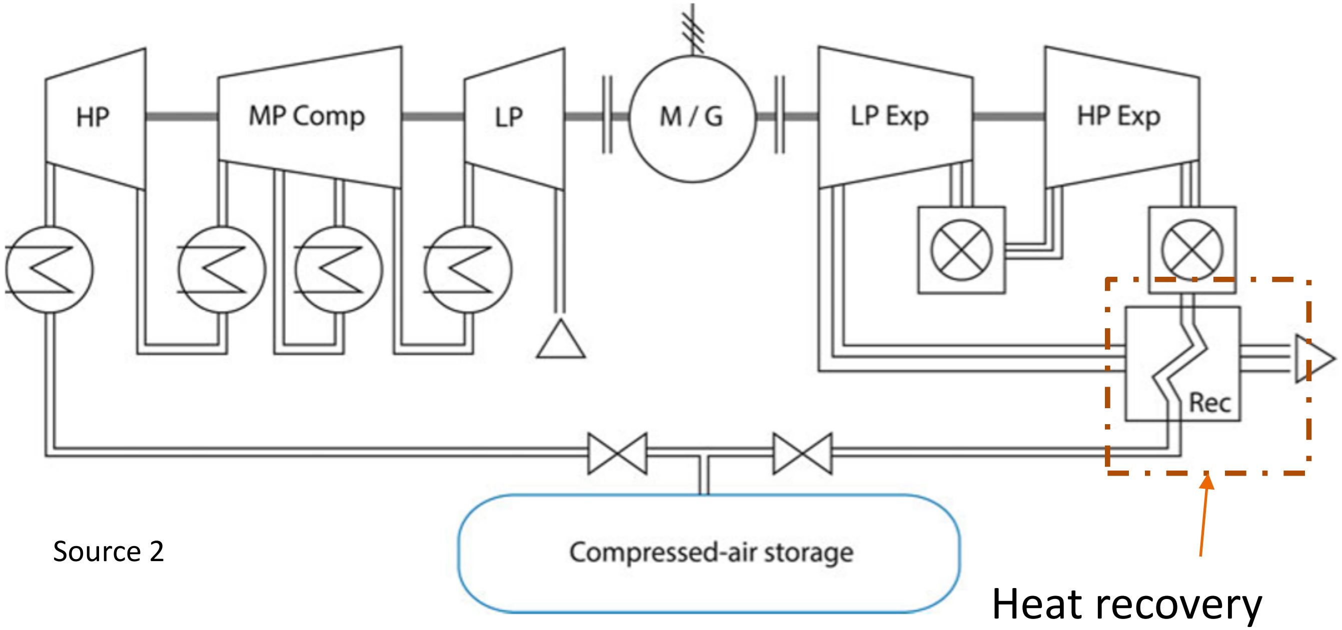


Source: Abdul Hai Alami, Mechanical Energy Storage for Renewable and Sustainable Energy Resources

- The first CAES power plant worldwide (1978)
- Power plant originally had a capacity of 290 MW -> was increased to 321 MW in 2006
- Combined compressed air storage and gas turbine Power plant, i.e. the gas turbine is a combustion engine in which, in addition to energy from compressed air, energy is also converted by burning natural gas

Compressed air energy storage

Adiabatic pressure storages (McIntosh)

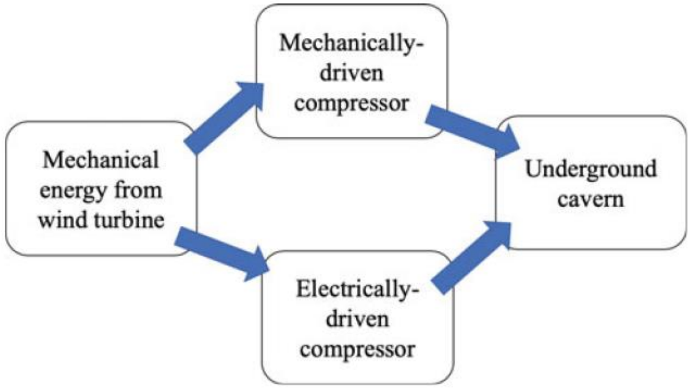


Source 2

Heat recovery
from exhaust fumes

Quelle: Abdul Hai Alami, Mechanische Energiespeicherung für erneuerbare und nachhaltige Energieressourcen

- A recuperator was integrated as a further development of CAES technology
- the hot exhaust gases from the gas turbine are used to preheat the air, thus reducing fuel consumption
- Power plant can provide a capacity of 110 MW over 26 hours
- The long operating time of 26 hours shows that this is not a pure peak load power plant



Compressed air energy storage

Efficiency

Generated electrical energy

$$\eta_{zyk} = \frac{E_{out,el}}{E_{in,el} + E_{in,th}}$$

Chemical energy used (natural gas)

$$\eta_{zyc} = \frac{E_{out,el}}{E_{in,el} + E_{in,th}} = \frac{1}{0.69 + 1.17} = 0.54$$

... for the diabatic compressed air reservoir (McIntosh)

$$\eta_{zyc} = \frac{E_{out,el}}{E_{in,el} + E_{in,th}} = \frac{1}{0.69 + 1.17} = 0.54$$

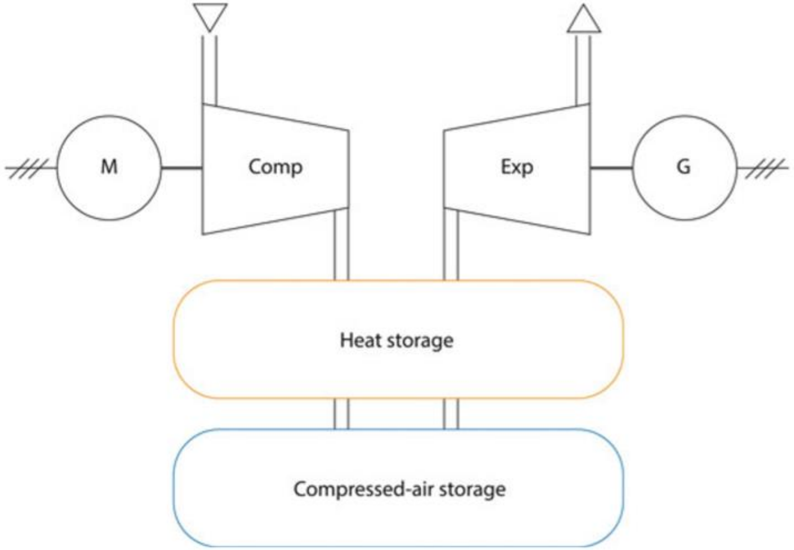
... for the diabatic compressed air reservoir (Huntorf)

0,8 1,6 ⇨ η=0,42

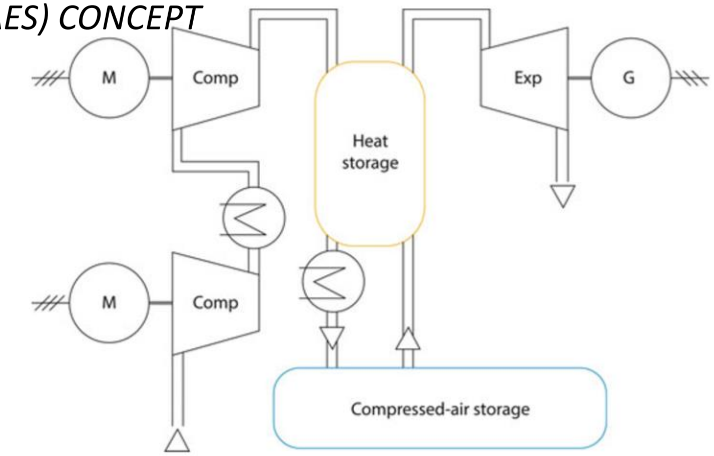
Compressed air energy storage

Adiabatic pressure storage

Adiabatic Compressed Air Energy Storage (ACAES)



Advanced Adiabatic Compressed Air Energy Storage (A-ACAES) CONCEPT

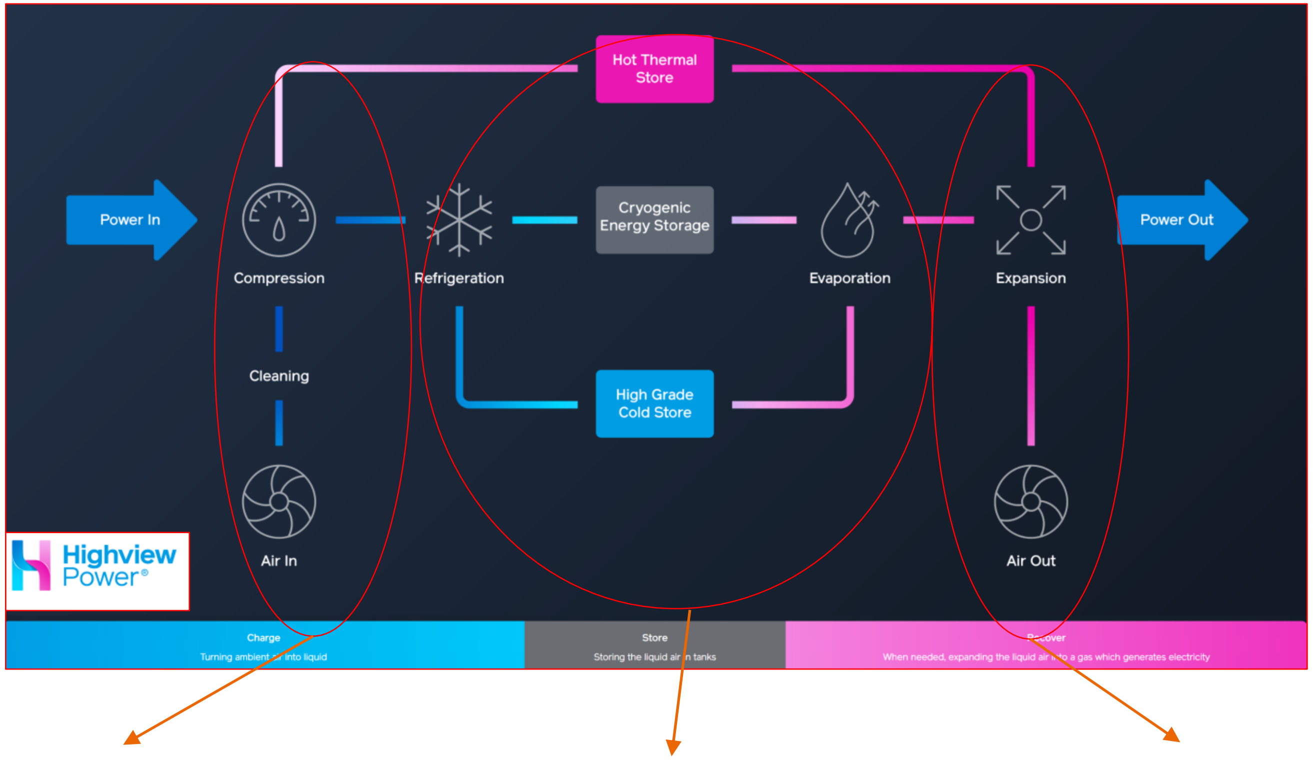


- Two storage systems: compressed air and heat storage
- Heat storage: strong influence on the total system costs (up to 20% of the total investment costs)
- In comparison with diabatic compressed air storage systems: increase in efficiency (no use of fossil energy)
- Lower temperatures and higher pressure in the compressor
- A-ACAES several compressors (axial and radial). Intercooling between the compressors

Source #2

Compressed air energy storage

Liquid air storage - Cryogenic storage



Charge

Storage

Discharge

The LAES (Liquid Air Energy Storage) system consists of three main parts: The charging section, the storage section and the discharge section. The charging section is in operation when electricity is to be stored. The electricity is used to compress air, which is then cooled to -190 °C and liquefied by expansion. The liquid air is then stored in an insulated tank at near ambient pressure with a density more than 700 times that of ambient air. When electricity is needed again, the liquid air is pressurized by a pump, heated and vaporized, and finally expanded in the outlet section in one or more turbines during operation. System efficiency can be increased by storing and reusing the cold air and compression heat and by coupling external heat and fuel to increase efficiency and performance.

Source: Liquid Air in the energy and transport systems; Opportunities for industry and innovation in the UK; Full Report

Compressed air energy storage

Cryogenic storage - Components

https://www.youtube.com/watch?v=kDvlh_aG7iA&t=145s

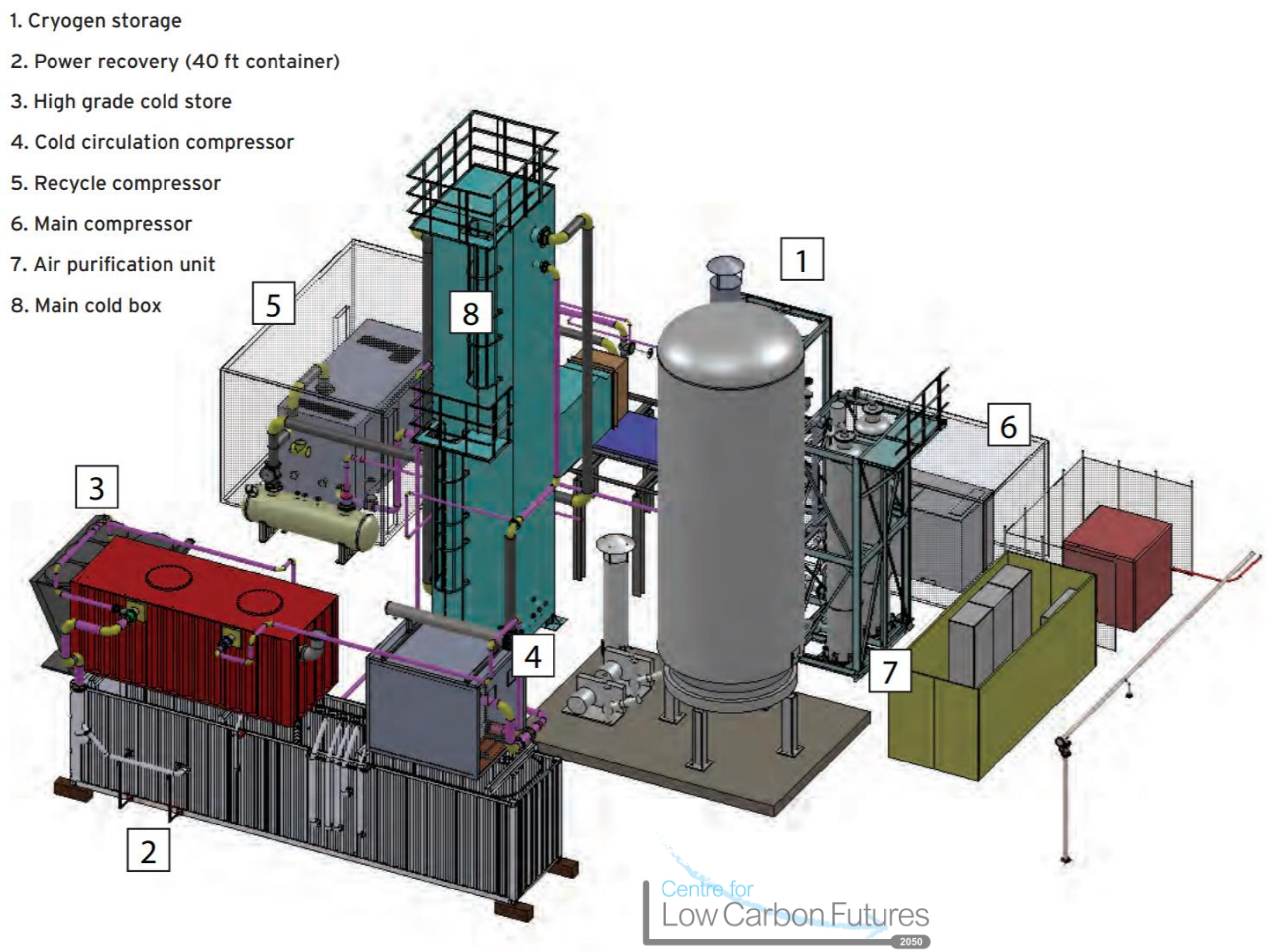
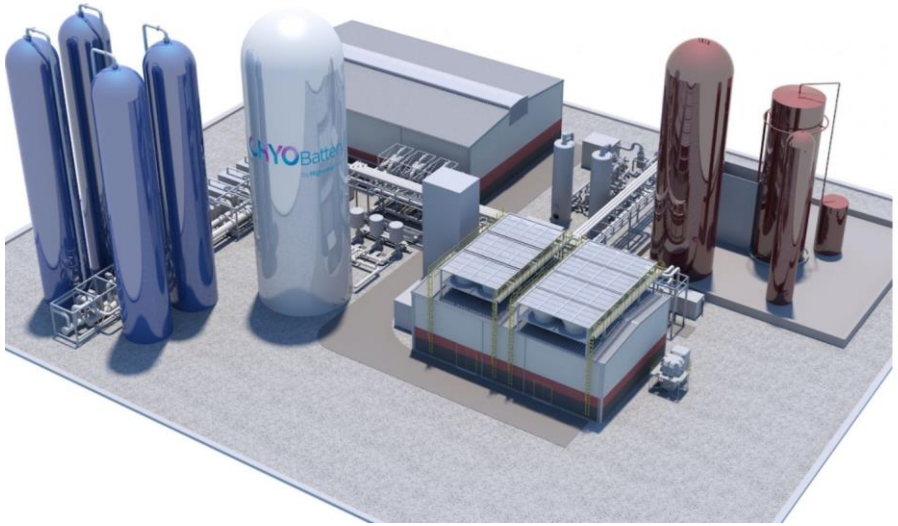


Figure 3.10: Illustration of main components of Liquid Air Energy Storage facility.

A 400MWh US storage follows the conversion of a 250MWh storage into GB.



Source: Liquid Air in the energy and transport systems; Opportunities for industry and innovation in the UK; Full Report

Compressed air energy storage

Cryogenic storage - Comparison

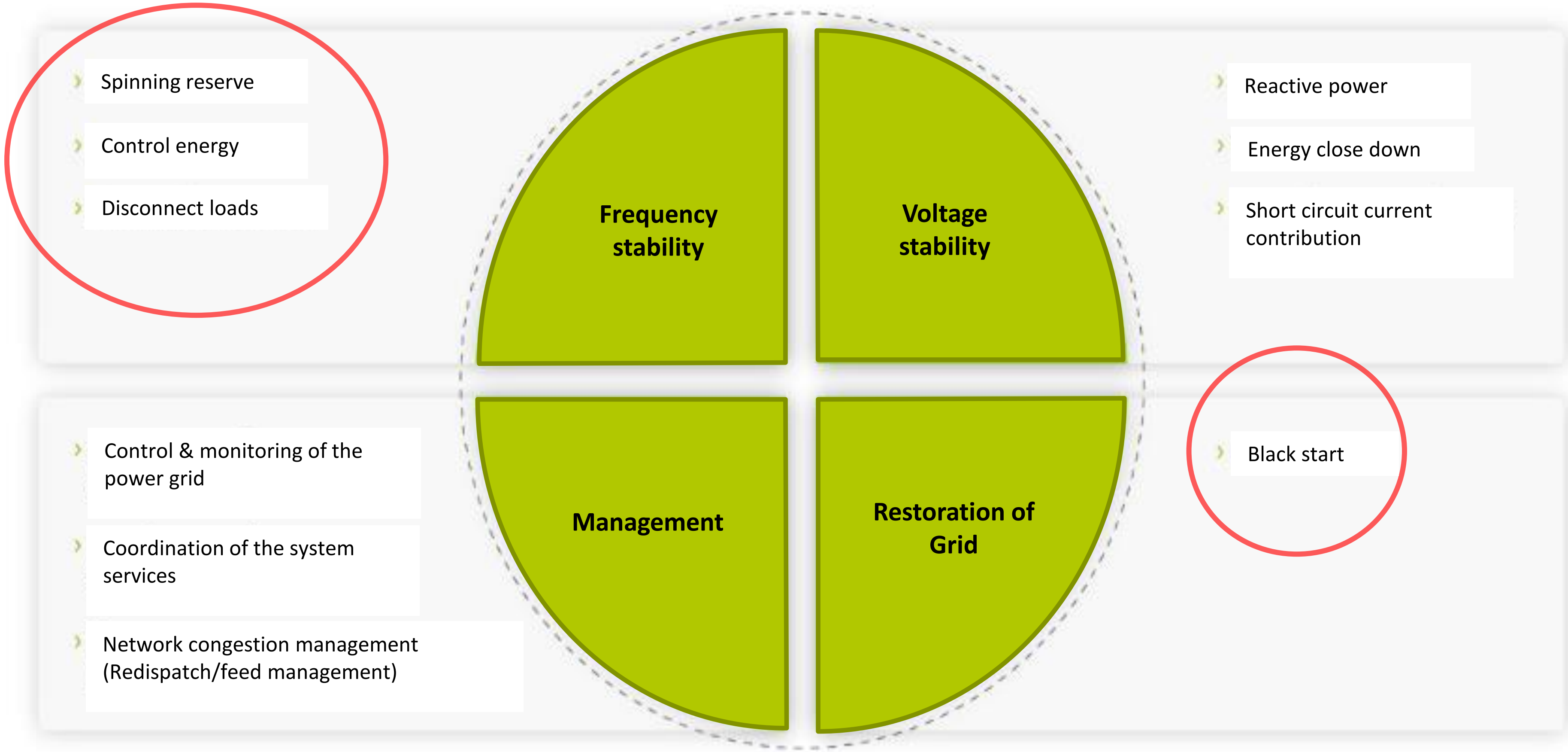
Device type	Low Capital Expenditure	Long life	Low Maintenance	Low through life costs	Fast response (seconds)	High energy storage capacity	Scalable	Geographical constraint	Development Stage
Pumped hydro	N	Y	Y	Y	N	Y	N	Y	3
Compressed air	Y	Y	Y	Y	N	Y	Y	Y	3
Compressed air - adiabatic	Y	Y	Y	Y	N	Y	Y	Y	1
Cryogenic	Y	Y	Y	Y	N	Y	Y	N	2
Flywheels	N	?	N	N	Y	N	N	N	2/3
Capacitors	N	N	N	N	Y	N	N	N	?
Superconducting Magnets	N	Y	N	N	Y	N	N	N	1
Batteries	N	N	Y	N	Y	N	Y	N	3
Fuel Cells	N	Y	Y	N	Y	Y	Y	N	1

Development stage: 1 = R&D 2 = Demonstration 3 = Mature

Source 2

Compressed air energy storage

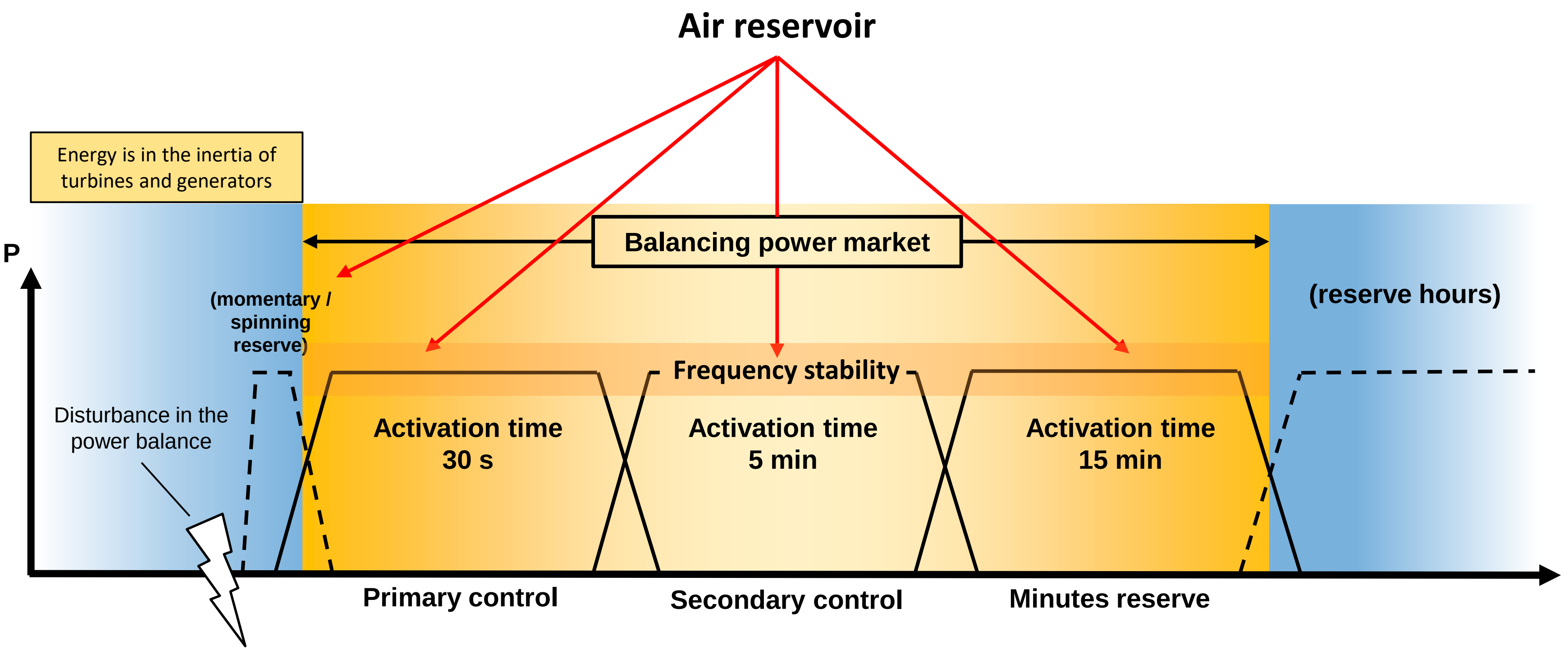
System service



Source: https://www.next-kraftwerke.de/wissen/systemdienstleistungen

Compressed air energy storage

System service - Frequency maintenance



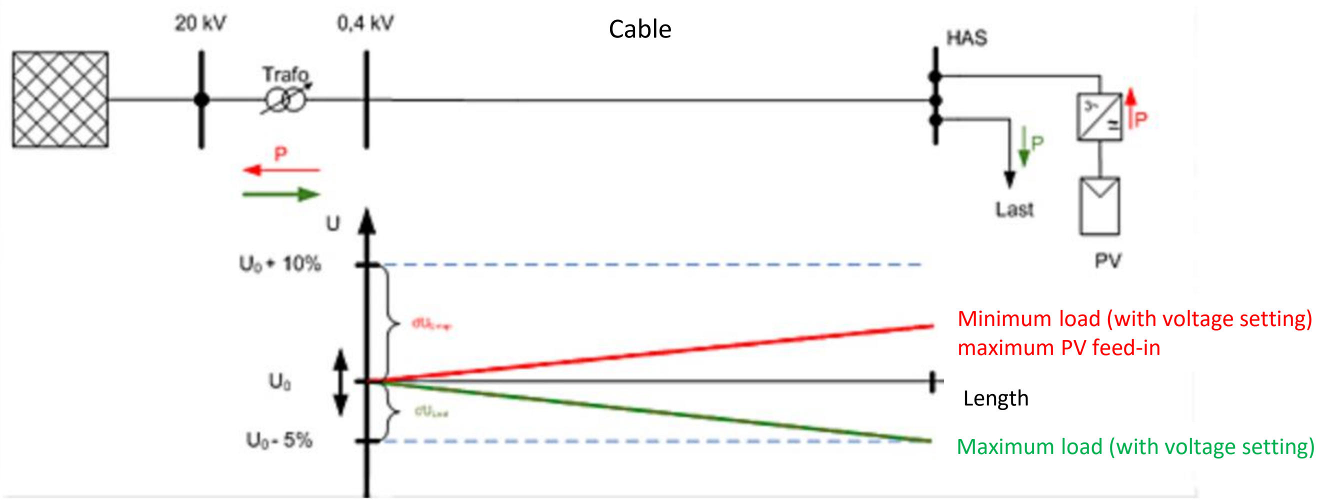
Source: Bavarian State Ministry of Economic Affairs and Media, Energy and Technology, expert opinion on the profitability of pumped storage power plants

- Prerequisite participation primary control power: time factor and 1 MW
- Participation in secondary control power: time factor and 5 MW
- Prerequisite participation minute reserve: time factor and 5 MW

Compressed air energy storage

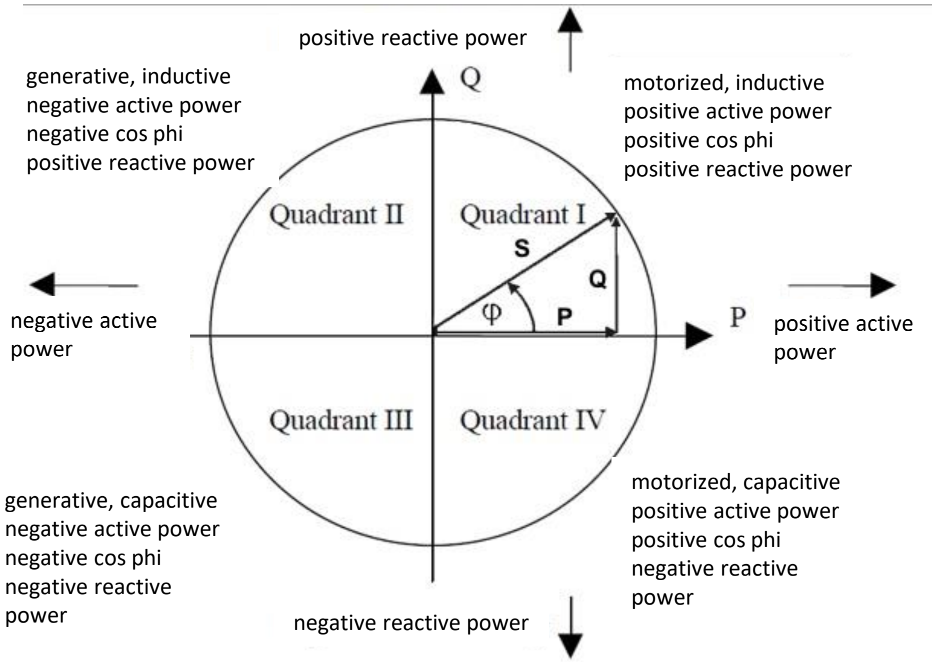
System service - Voltage stability

Voltage setting

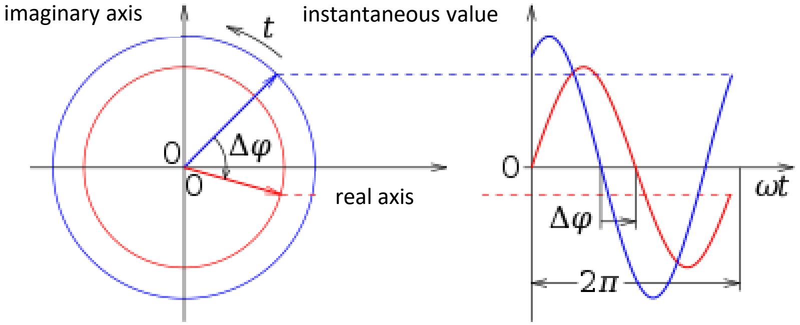


https://www.sma-sunny.com/vom-einspeisen-zur-systemischen-netzbetrachtung-herausforderungen-der-energiewende/

Reactive power control



Control amplitude



Control phase angle

Compressed air energy storage

System service – Restoration of grid

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- **Short-term** (flexible and fast starting behaviour)
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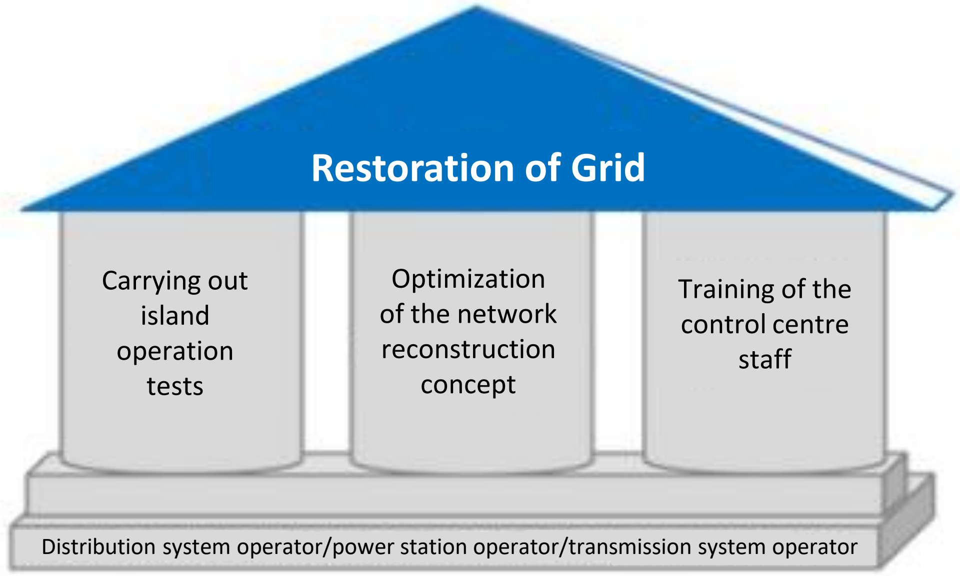
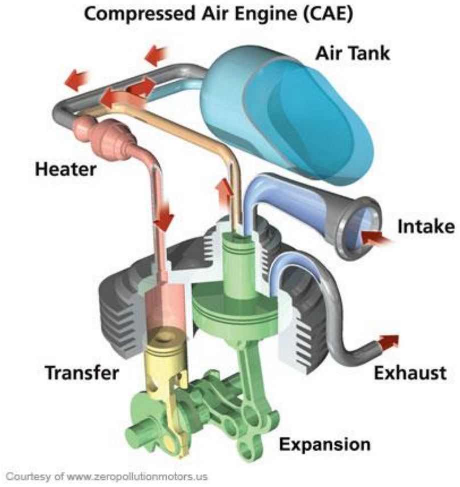
- **Robustness** (should be able to handle heavy starting current)
- **Stagnation behaviour** (prolonged own operation)

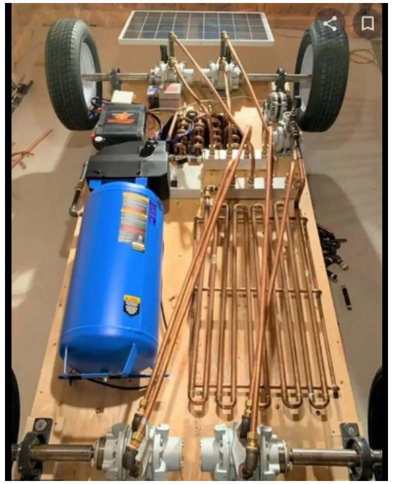


Compressed air energy storage

Mobility sector

- Motor powered by compressed air
- can be powered solely by air, or combined (as in a hybrid electric vehicle) with gasoline, diesel, ethanol, or an electric plant with regenerative braking
- Energy is stored in compressed air tank
- Didn't get out of the prototype stage
- Bad efficiency and short range





Source: Wikipedia.de

Compressed air energy storage

Advantages and disadvantages

Advantages	Disadvantages
As a medium that is available worldwide, independent of location and free of charge, ambient air offers ideal conditions for use as an energy storage medium.	A compressed air reservoir is bound to specific geological locations. According to the state of the art, it must be placed in a salt dome.
Compressed air storage systems have the potential to better match the supply and demand for electricity. In the future, they will be able to function as grid controllers without - like a pumped water strage - seriously interfering with the landscape.	A compressed air storage facility also requires natural gas. Its electricity costs are therefore also linked to the price of this fossil raw material. Electricity from compressed-air storage is rather expensive and is therefore only fed in at peak load times.
A compressed air reservoir is capable of peak loads and its capacity can be available within a few minutes. When the accumulator is full, they are also "black startable", i.e. they do not need a functioning power supply to start up themselves. This is important in order to start up other power plants using electricity from compressed air storage in the event of a power failure.	An air reservoir consumes more electricity than it generates. It can only deliver its power to cover peak loads over a relatively short period of time - the Huntorf power plant only delivers full capacity over two hours, another one in the USA over 26 hours.
Compressed air storage is one way of expanding the share of wind energy, and possibly also photovoltaics, in the electricity mix.	

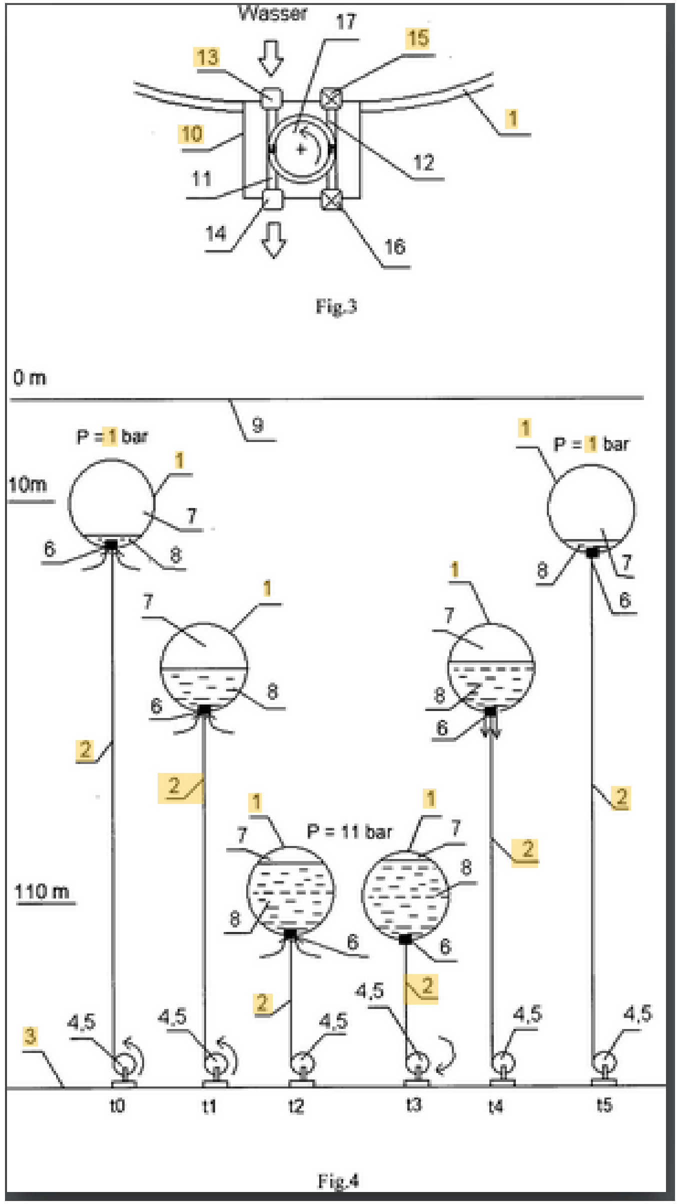
CAES - Exercise I

At a water depth of 50 m (approx. 5 bar gauge pressure), a balloon or pneumatic cylinder is to be filled with compressed air in such a way that 1 kWh of energy is stored in the form of compressed air.

a) What tank volume is required?

   (Assumptions: No losses, isentropic exponent of air = 1,4)

b) Determine the sphere diameter of the balloon at this water depth (As an "energy bag" - gravitational energy storage system - this system can harness the pressure and buoyancy forces).



CAES - Exercise I

given: water depth : 50m

↳ p_W = 5 bar = 500.000 Pa

5 bar overpressure : this means 5 bar above the normal pressure of about 1 bar at the water surface.

p_N = 1 bar = 100.000 Pa $\left(1\ \text{Pa} = \left[\frac{N}{m^2}\right] \right)$

$E = 1\ \text{kWh}$

$\kappa = 1{,}4$

Assumption : $\eta = 1$

goal: V_{Air} at 50m water depth , d_{Ballon}

Solution:

$$W = E = \frac{\dot{m} \cdot \Delta h}{\eta} = \underbrace{\frac{1}{\eta}}_{\to 1} \cdot p_1 \cdot V_1 \cdot \frac{\kappa}{\kappa - 1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}} - 1\right]$$

$p_1 = p_N$ → pressure at water surface

$p_2 = p_W + p_N$ → pressure at 50m water depth

$$E = p_1 \cdot V_1 \cdot \frac{\kappa}{\kappa - 1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}} - 1\right]$$

$$V_1 = \frac{E}{p_1 \cdot \frac{\kappa}{\kappa - 1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}} - 1\right]}$$

↳ V_1 = air Volume at water surface

CAES - Exercise I

$$V_1 = \frac{1\,000\ W \cdot 3600\,s}{100.000\ \frac{N}{m^2} \cdot \frac{1{,}4}{0{,}4} \cdot \left[\left(\frac{600.000\ \frac{N}{m^2}}{100.000\ \frac{N}{m^2}}\right)^{\frac{0{,}4}{1{,}4}} - 1\right]}$$

$$\underline{\underline{V_1 = 15{,}39\ m^3}}$$

→ In order to determine the air volume at 50m water depth, we have to consider the isothermal change of state:

$$p_1 \cdot V_1 = p_2 \cdot V_2$$

$$V_2 = \frac{V_1 \cdot p_1}{p_2}$$ V_2 = air volume at 5 bar overpressure (50m water depth)

$$V_2 = \frac{15{,}39\ m^2 \cdot 1\ bar}{1\ bar + 5\ bar}$$

$$\underline{\underline{V_2 = 2{,}56\ m^3}}$$

↳ with the air volume at 50m depth we now can calculate the required diameter of the ballon

$$V_{ball} = \frac{\pi}{6} d^3$$

$$d^3 = \frac{V}{\frac{\pi}{6}}$$

$$d = \sqrt[3]{\frac{6 \cdot V}{\pi}} = \sqrt[3]{\frac{6 \cdot 2{,}56\ m^3}{\pi}}$$

$$\underline{\underline{d = 1{,}7\ m}}$$

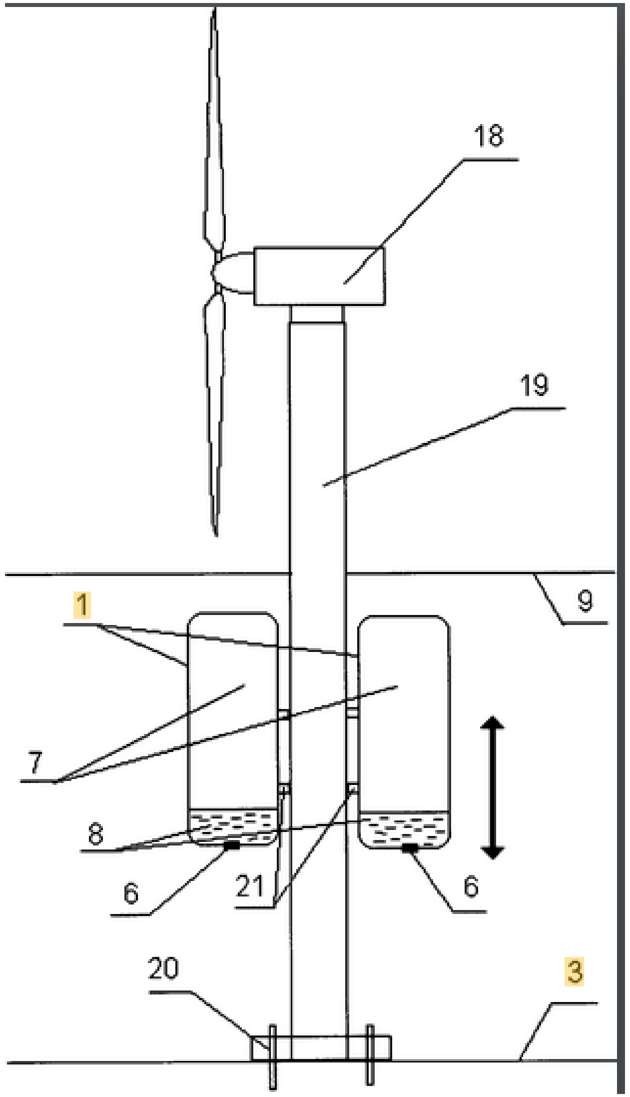
CAES - Exercise II

Wind turbines with a total electrical output of 1000 MW will generate electricity in 1000 full-load hours per year. This is to be temporarily stored with the help of a compressed air storage power plant and then distributed over the year.

(Assumptions: Ideal gas, pressure constant at withdrawal; gas volume 100% withdrawable.)

a) What volume does the cavern storage facility require?

b) How large is the amount of electrical energy that can be fed into the power grid?



CAES - Exercise II

given:

$P = 1000 \cdot 10^6$ W

$t_{full\ load} = 1000$ h

$\eta_{turbine} = \eta_{cva} = 0{,}87$

$\eta_G = 0{,}99$

$\kappa = 1{,}4$

$R = 287{,}05 \frac{J}{kg \cdot K}$

$T = 20°C \rightarrow 293{,}15$ K

$p_1 = 10$ bar | 1 bar = 100.000 Pa

$p_2 = 150$ bar | 1 Pa = $\left[\frac{N}{m^2}\right]$

goal: $V_{storage}$, E_{out} (Energy which can fed into power grid)

Assumptions: ideal gas

pressure constant at withdrawal

gas volume 100% withdrawable

CAES - Exercise II

Solution:

$$V = \frac{m \cdot R \cdot T}{p}$$

$$\Delta H = m \cdot \Delta h_{real}$$

$$\Delta H = m \cdot \frac{\Delta h_{th}}{\eta_{eva}}$$

$$m = \frac{\Delta H \cdot \eta_{eva}}{\Delta h_{th}}$$

ΔH = Enthalpy $\longrightarrow$ heat content

- is the sum of the internal energy U of the system and the product of pressure p and Volume V of the system

It's a calculated quantity and cannot be measured directly.

$\Delta h \rightarrow$ specific enthalpy

$$\Delta H = P_{el} \cdot t_{Fl} = 1000 \cdot 10^6 \ W \cdot 1000 \ h$$

$$\Delta H = 1000 \cdot 10^9 \ Wh = 1 \ TWh$$

$$\Delta h = \frac{\kappa}{\kappa - 1} \cdot R \cdot T_E \cdot \left[\left(\frac{p_2}{p_1} \right)^{\frac{\kappa - 1}{\kappa}} - 1 \right]$$

$$\Delta h = \frac{1{,}4}{0{,}4} \cdot 287{,}05 \ \frac{J}{kg \cdot K} \cdot 293{,}15 \ K \cdot \left[\left(\frac{150 \ bar}{10 \ bar} \right)^{\frac{0{,}4}{1{,}4}} - 1 \right]$$

$$\Delta h = 343.951{,}1 \ \frac{Ws}{kg}$$

$$\Delta h = 95{,}5 \ \frac{Wh}{kg}$$

CAES - Exercise II

$$m = \frac{000 \cdot 10^9\ Wh \cdot 0{,}87}{95{,}5\ \frac{Wh}{kg}}$$

$$\underline{m = 9{,}11 \cdot 10^9\ kg}$$

$$V = \frac{9{,}11 \cdot 10^9\ kg \cdot 287{,}05\ \frac{J}{kg \cdot K} \cdot 293{,}15\ K}{p_2}$$

$\longrightarrow$ searching for the air volume at 150 bar

therefore p_2 is required

$p_2 = 150$ bar $- 150 \cdot 100.000$ Pa

$$V = \frac{9{,}11 \cdot 10^9\ kg \cdot 287{,}05\ \frac{J}{kg \cdot K} \cdot 293{,}15\ K}{15 \cdot 10^6\ \frac{N}{m^2}}$$

$$\underline{\underline{V = 51{,}1 \cdot 10^6\ m^3}}$$

$$W_{grid} = E_{out} = W_{prod} \cdot \eta_{turbine} \cdot \eta_{wa} \cdot \eta_G$$

$$= 1\ TWh \cdot 0{,}87 \cdot 0{,}87 \cdot 0{,}99$$

$$\underline{\underline{E_{out} = 0{,}749\ TWh}}$$

Mechanical storage devices

Flywheel storage

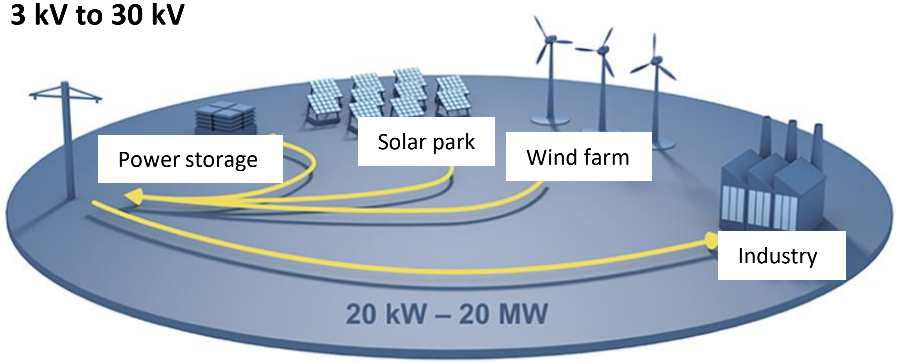
Prof. Dr.-Ing. Przemyslaw Komarnicki

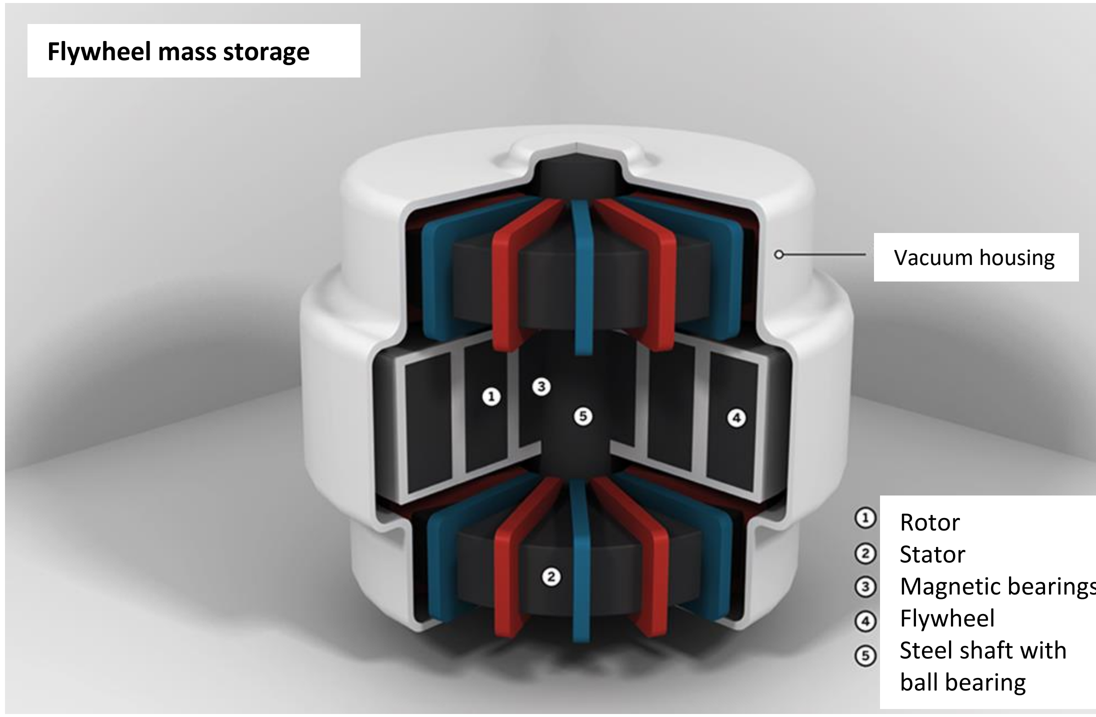
Mechanical storage devices

Flywheel storage

- Energy conversion into kinetic energy (rotational energy)
- Large masses are accelerated to high rotational speeds.
- With superconducting magnetic bearings, maintenance-free and friction-free bearings can be realized, but this is accompanied by very large installation space, high technology expenditure and costs.
- Very high power gradients and power density but low energy storage quantities
- System efficiencies of 80% to 90% are possible and virtually unlimited storage cycles are possible
- Flywheel mass accumulators are only suitable as short-term accumulators due to their high self-discharge
- Storage sizes up to 3MW with up to 15min availability
- applications: Frequency holding in the network, UPS, mobility, load flexibility, etc.

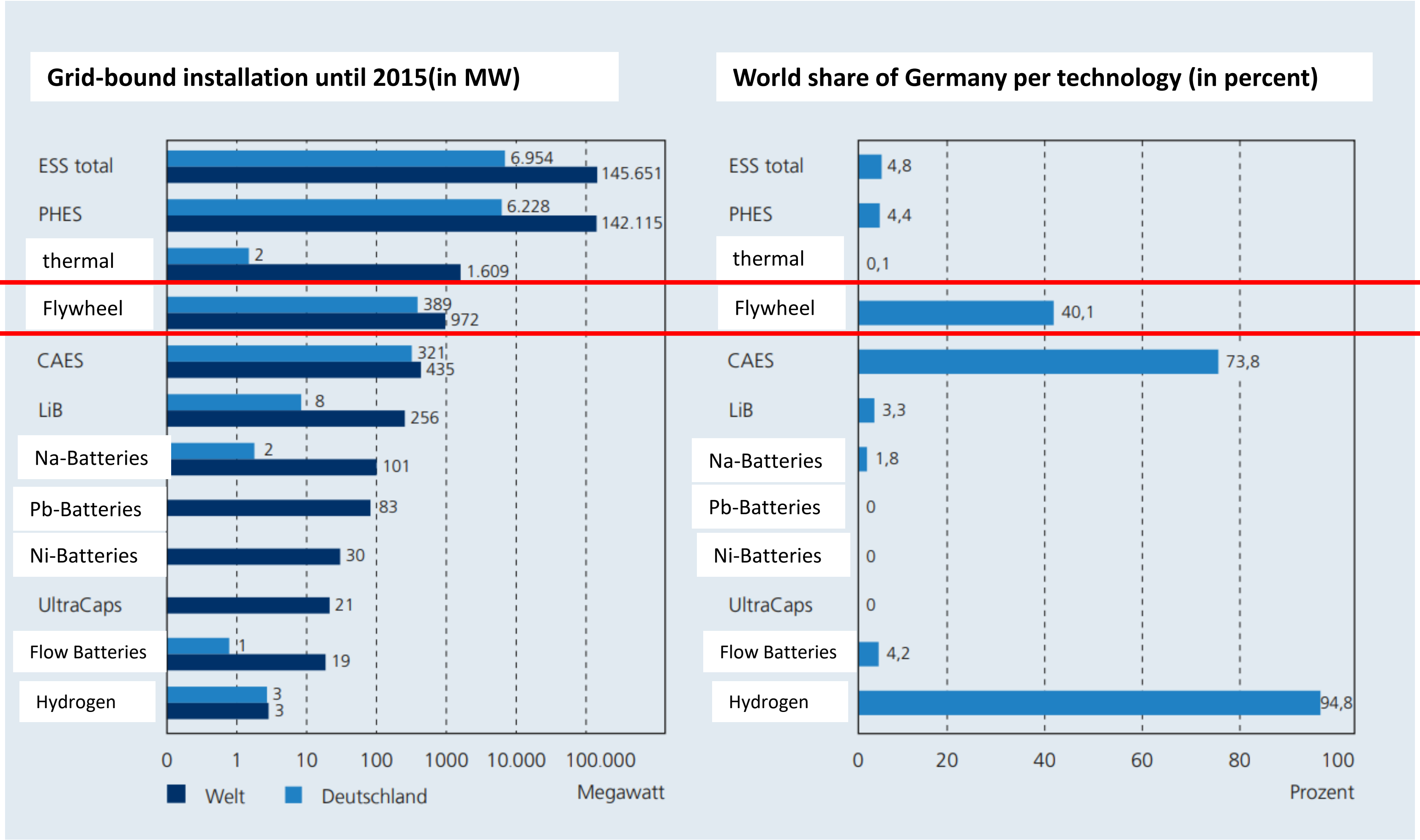
Network level 3
regional distribution networks
Medium voltage
3 kV to 30 kV





Flywheel storage

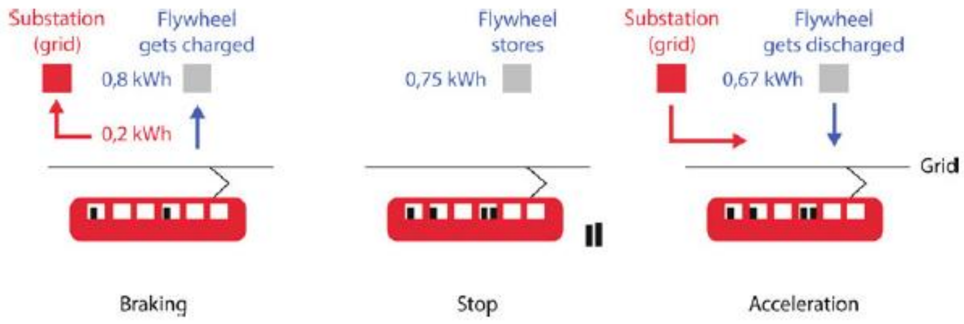
Installed power



Flywheel storage

Potentials

Stationary flywheel storage for the use of braking energy in the tram network



- Recuperation of braking energy from rail vehicles (increase in energy efficiency)
- For motor vehicles, supplement for hybrid vehicles
    - Responds dynamically to recuperation and power allocation

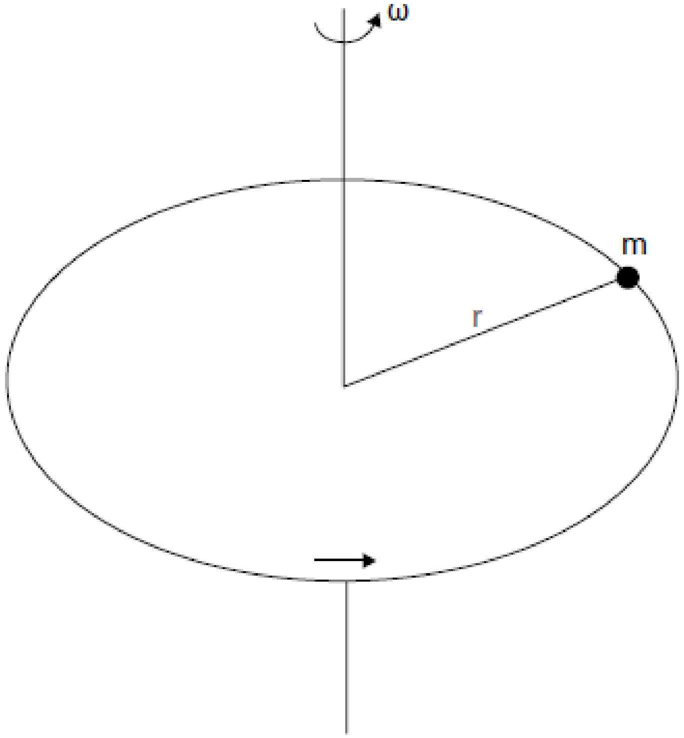
Grid connected flywheel storage for stabilizing the power supply

Source: German Federal Association of Energy Spies, FACT SHEET MEMORY TECHNOLOGIES

- Fast frequency regulation in transmission and distribution networks (e.g. instantaneous reserve and primary control power)
- Stabilization of microgrids and provision of power for peak loads
- Balancing of wind energy (schedule compliance) and ramp management

Flywheel storage

Physical basics



Source ,2

Kinetic energy of a mass *m*, which orbits with an angular velocity *ω* around a fixed axis with distance *r:*

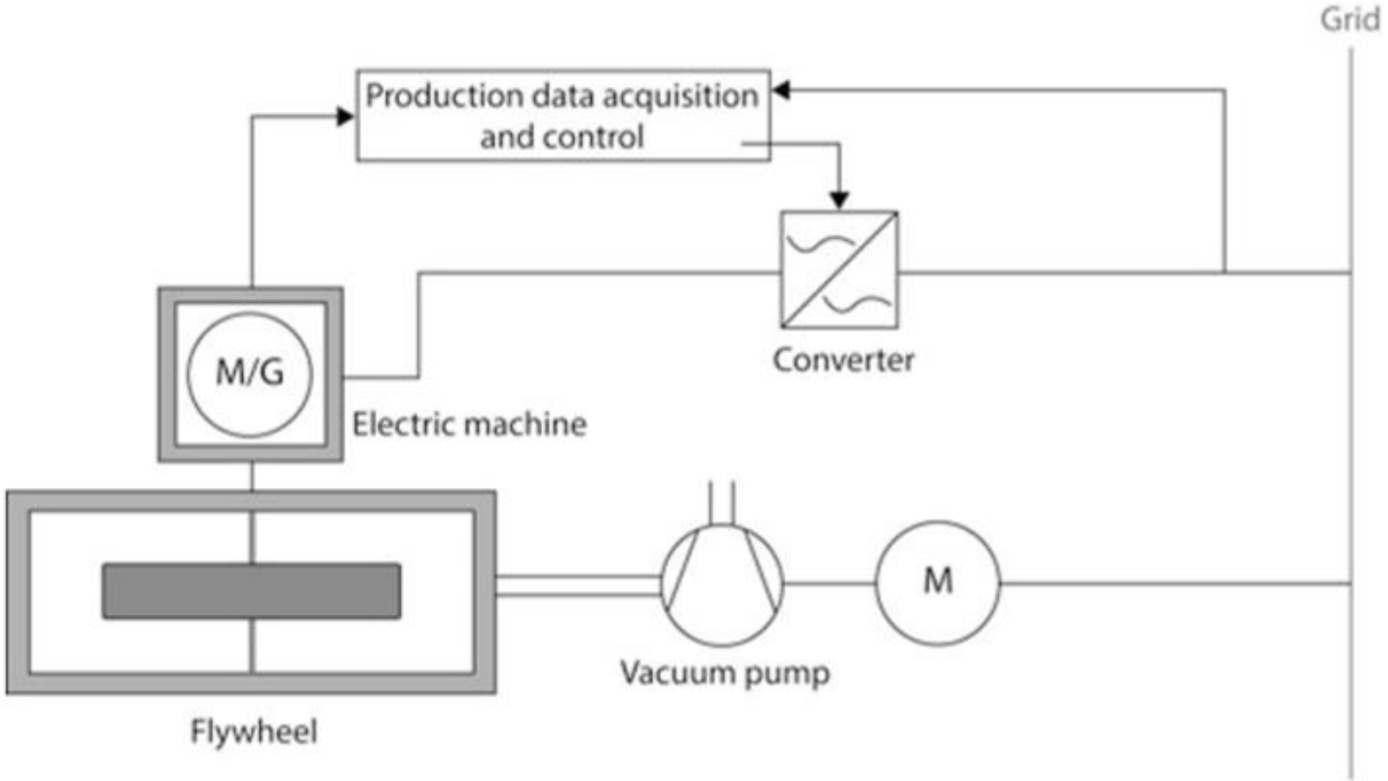
$$E_{kin} = \frac{1}{2} m v^2 .$$ respectiv $$E_{kin} = \frac{1}{2} m (r\omega)^2 .$$

Taking into account the moment of inertia *J* (*J=mr²*), the kinetic energy is calculated as follows:

$$E_{kin} = \frac{1}{2} J \omega^2 .$$

Flywheel storage

Design and function

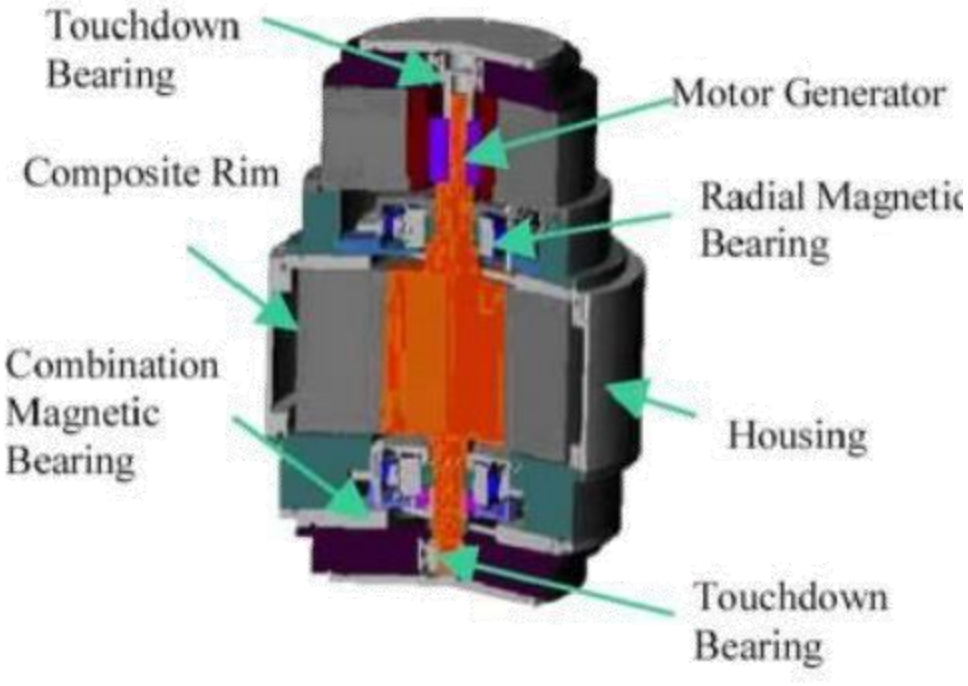


Source 2

Flywheel storage

Design and function

Flywheel storages from Piller for stationary use in Systems for uninterruptible power supply



Rotor	• A rotating mass that stores energy as impulse
Bearing	• Pivot on which the rotor rests
Machine	• Converts mechanical energy into electricity or reverse
Monitoring & control	• System control and monitoring for operational management
Case	• Enclosure for safety, protection, noise reduction and guarantee of an optimal environment (possibly vacuum)

Source: Frank Täubner, Schwungradspeicher in Vision und Realität

Flywheel storage

Components - Electrical machines

Direct current machine

- Operation as generator or motor
- Rotor with armature winding rotates in a fixed magnetic field
- Rotation of the rotor causes a change in the magnetic field, which must be periodically reversed by the commutator
- AC-DC converter required for operation

Asynchronous machine

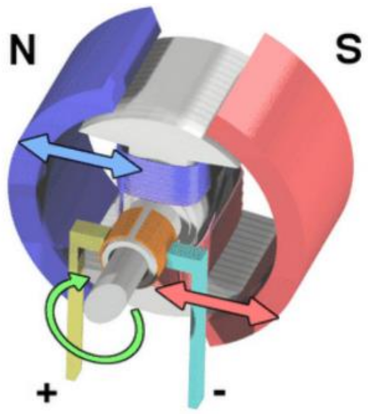
- Operation as generator and motor
- Difference between rotors and squirrel cage rotors
- In motor operation rotating field of the rotor slower than rotating field of the coil
- Speed difference is called slip
- If the frequency is regulated by means of a flywheel on the mains, the rotor speed changes abruptly -> due to the rotor lagging behind in motor operation

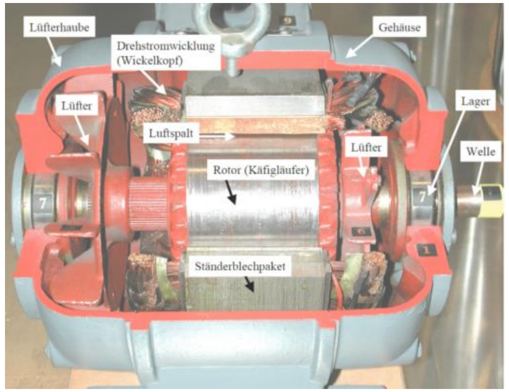
Synchronous machine

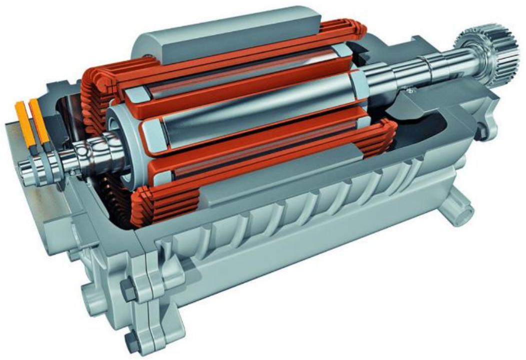
- Operation as generator and motor
- Differentiation between outer and inner pole machine and again between leg and full pole machine
- Rotor speed is synchronous to the magnetic field speed
- Typical star/delta connection
- Can be synchronised with the mains frequency by means of a frequency converter -> even in the event of a power failure, abrupt standstill is prevented

Reluctance machine

- Operation as generator and motor
- Torque generation by reluctance force
- With magnetic excitation by „Lorenzkraft“ no permanent magnet is necessary nor an electrical winding on the rotor -> almost all wearing parts (slip ring or brushes) are omitted
- Compared to magnetically excited electric motors, torque is lower - > thus a larger reluctance machine is required in proportion







Quelle: Continental

Flywheel storage

Components - Rotor

- Rotor
  - Low speed (up to ~ 10.000 rpm)
    - Horizontal shaft
    - Vertical shaft
  - High speed (up to ~ 100.000 rpm)
    - Horizontal shaft
    - Vertical shaft

Source: Satcom Energy System

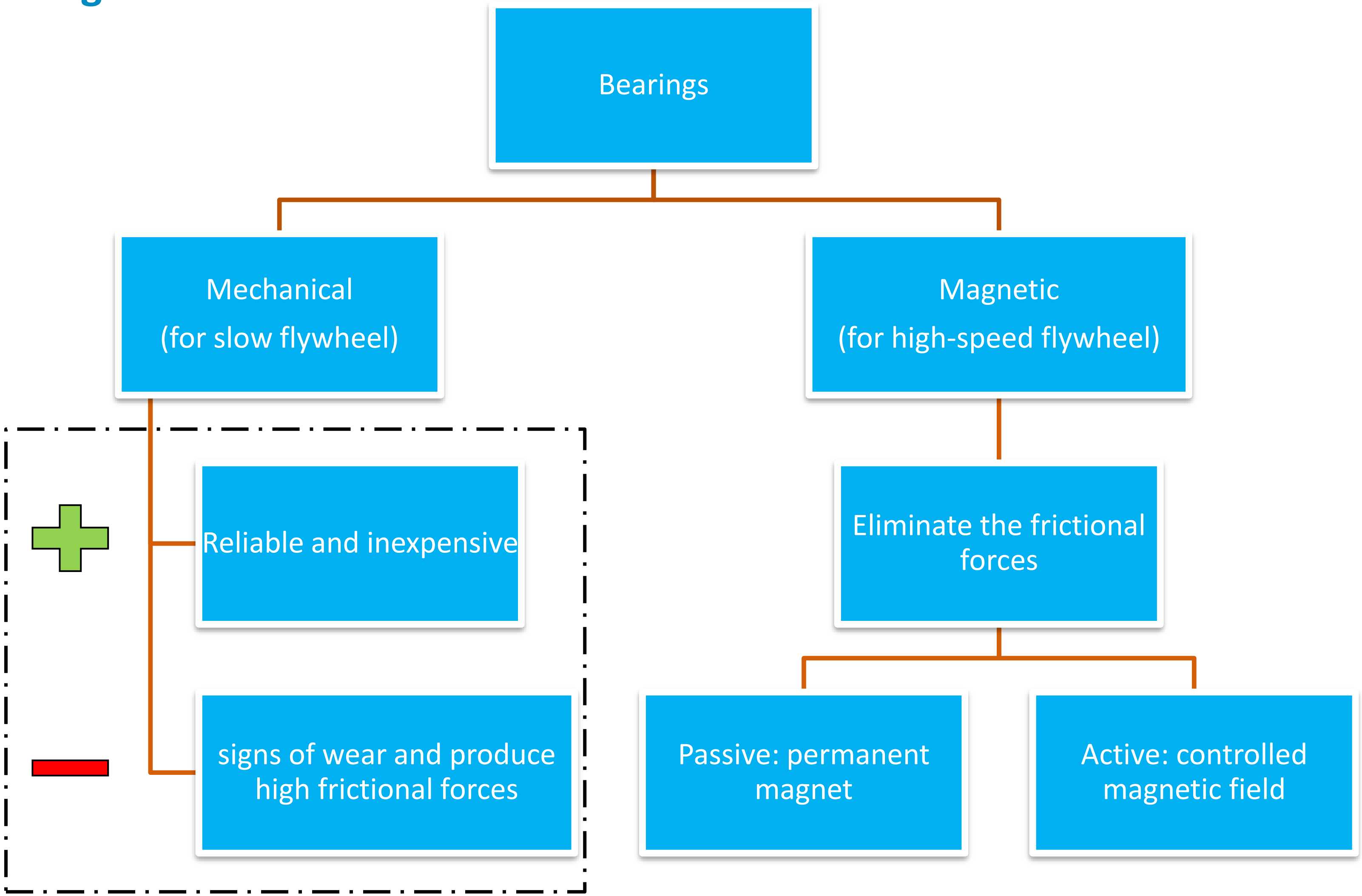
Low speed horizontal shaft flywheel.

High speed flywheel.

Source: Satcom Energy System

Flywheel storage

Components - Bearings



Flywheel storage

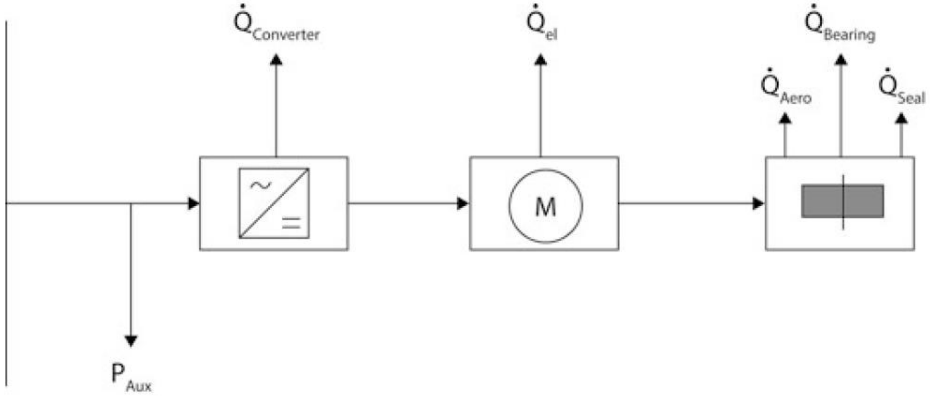
Energy losses

Increases the speed of the flywheel

Charge

Discharge

Reduces the speed of the flywheel



Friction losses

- Rotor environment
- Rotor bearings and supports

Thermal effect

- Losses converted into heat Increased temperature of the flywheel

Solution

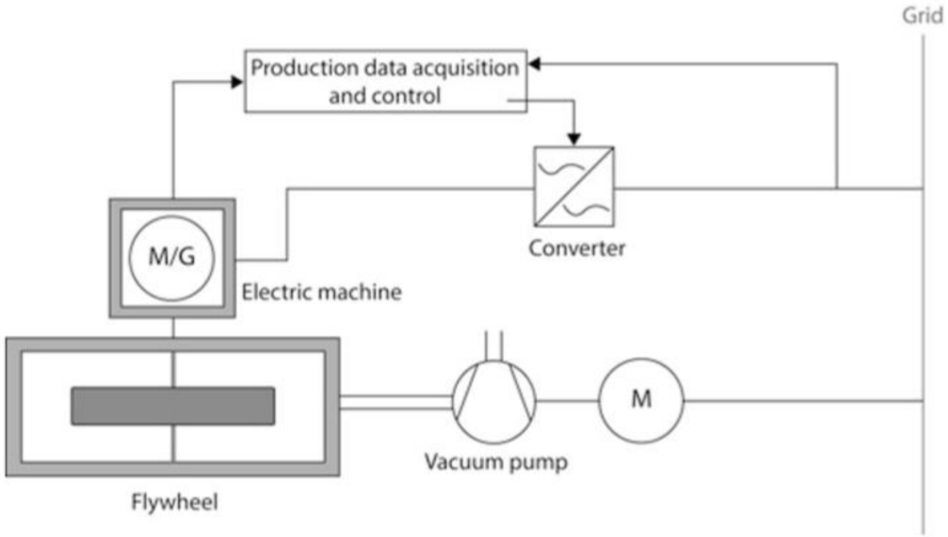
- Heat is extracted from the flywheel
- Vacuum containment and magnetic bearings are used
- Cooling system can be used

Source #2

Flywheel storage

Materials and designs

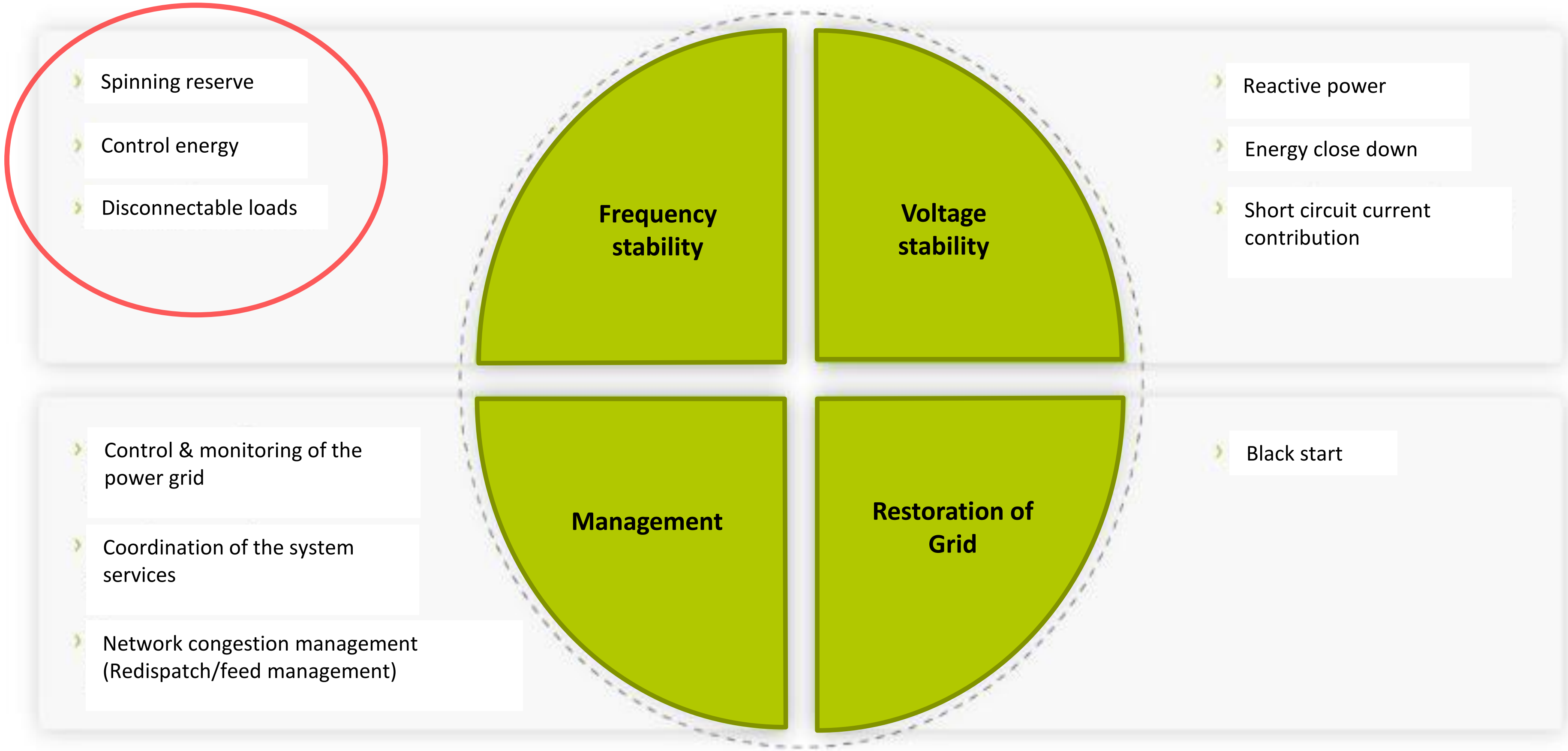
Material	Tensile strength in N/mm^2	Density in kg/m^3	Specific strength in kN m/kg	Maximum circumferential speed in m/s	Potential energy density in kJ/kg
Steel	1,300	7,800	167	410	106
Titanium	1,150	5,100	225	570	143
GFK	1,300	1,900	680	820	335
CFK	6,300	1,546	2,470	1,570	1,570



Source 2

Flywheel storage

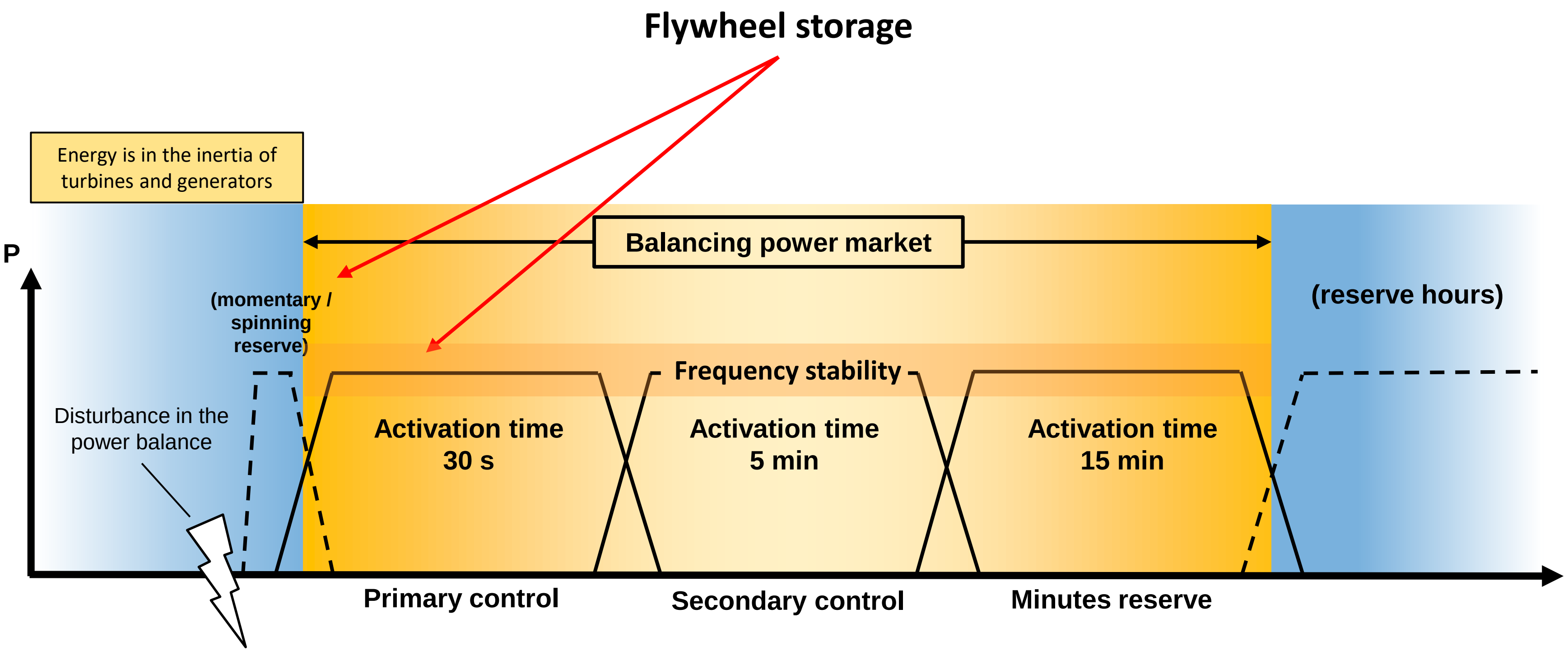
System service



Source: https://www.next-kraftwerke.de/wissen/systemdienstleistungen

Flywheel storage

System service - Frequency maintenance



Source: Bavarian State Ministry of Economic Affairs and Media, Energy and Technology, expert opinion on the profitability of pumped storage power plants

- Prerequisite participation primary control power: time factor and 1 MW
- Prerequisite participation in secondary control power: time factor and 5 MW
- Prerequisite participation minute reserve: time factor and 5 MW

Flywheel storage

Advantages and disadvantages

Advantages	Disadvantages
Both charging and energy extraction can be done at very high power, usually limited by the power of the electric machine(s) used or the charging power available from the power supply system.	Unfortunately, even without energy extraction, losses of the stored energy occur constantly. The resulting *self-discharge* is far greater than with batteries, for example.
The technology used can be quite robust, low-maintenance and durable. Aging of components hardly occurs. The service life also hardly suffers from frequent charging and discharging; thus a very high *number of cycles* (possibly in the range of millions of cycles) is possible. Of course, there are also no problems with deep discharges as known from batteries.	The achievable energy density is comparatively low: e.g. B. in the order of 10 Wh/kg, compared with around 180 Wh/kg for lithium-ion batteries. The low energy density is a major disadvantage, especially in mobile applications; in stationary applications it is less significant, except that it naturally also affects costs.
	When charging and discharging the storage tank, additional losses occur in the electric machine.

Flywheel - Exercise I

A flywheel rotates around its axis at f = 20 Hz. Its moment of inertia with respect to to this axis is $J = 60\ kg\ m^2$. It is then decelerated by a constant torque in one minute until it comes to a standstill.

a) How big is the torque?

b) What power is converted into waste heat by braking?

*c) How often does the wheel rotate during the braking process?

Source: vorweg-net.de/Physik/1.Mechanik/1.7.A.Drehimpulserhaltung.pdf

Flywheel - Exercise I

a) $M = \frac{\Delta L}{\Delta t} = J \cdot \alpha$

$\hookrightarrow \alpha = \frac{\Delta \omega}{\Delta t} = \frac{2\pi \cdot n}{\Delta t} = \frac{2\pi \cdot 20 s^{-1}}{60 s} = \frac{40\pi}{60 s^2} = \frac{2}{3}\pi \, s^{-2}$

$= 60 \, kg \cdot m^2 \cdot \frac{2}{3}\pi \, s^{-2}$

$= 125{,}66 \, kg \frac{m^2}{s^2}$

$\underline{\underline{= 125{,}66 \, Nm}}$

b) $P = \frac{\Delta E}{\Delta t}$ with $E_{rot} = \frac{J\omega^2}{2}$

$= \frac{60 \, kg m^2 \cdot (2\pi \cdot 20 s^{-1})^2}{2}$

$\underline{= 473.741 \, kg \frac{m^2}{s^2}}$

$P = \frac{473.741 \, kg \frac{m^2}{s^2}}{60 s}$

$\underline{\underline{P = 7.895{,}7 \, W}}$

Flywheel - Exercise I

c) $\Delta\varphi = \frac{1}{2}\alpha \cdot (\Delta t)^2$

$\longrightarrow$ from a): $\alpha = \frac{2}{3}\pi \; s^{-2}$

$$\Delta\varphi = \frac{1}{2} \cdot \frac{2}{3}\pi \; s^{-2} \cdot (60\,s)^2$$

$$= 1200\,\pi$$

$$\hat{=} \; N = 600 \text{ revolutions}$$

Flywheel - Exercise II

A flywheel accumulator for a tidal power plant of 1000 kW is proposed in order to steady the periodic energy supply of the tides (according to the figure approx. 12 hrs.). The drawing shows that 10 flywheel accumulators, each 10 m long and 1 m in diameter, are to be placed above the water turbine (material: steel (7.85 kg/dm³)).

given: $P_{out} = 1\,MW$ goal: N (RPM)

$n_{flywheel-storage} = \omega$

$l = 10\,m$

$\rho_{Fe} = 7{,}85\,kg/dm^3 \hat{=} 7850\,kg/m^3$

$t = 12\,h \hat{=} 43.200\,s$

Flywheel - Exercise II

$$E_{rot} = \frac{J\omega^2}{2}$$

1) $E_{rot} = 1.000 \cdot 10^3 \ W \cdot 43.200 \ s$

$E_{rot} = 43.200 \cdot 10^6 \ Ws$

↳ total energy can be seperated to 10 flywheel storages

↓

$E_{pot_1} = 4\,320 \cdot 10^6 \ Ws$

↳ energy to store in one flywheel storage system

Flywheel - Exercise II

2) $J_{cylinder} = \frac{m \cdot r^2}{2}$

$m = V \cdot \rho_{Fe}$

$= \frac{\pi}{4} \cdot d^2 \cdot l \cdot \rho_{Fe}$

$= \frac{\pi}{4} \cdot (1m)^2 \cdot 10m \cdot 7850\ kg/m^3$

$= \frac{\pi}{4} \cdot 10m^3 \cdot 7850\ kg/m^3$

$\underline{m = 61.653,756\ kg}$

↳ weight of a flywheel

$J_c = \frac{61.653,756\ kg \cdot (0,5m)^2}{2}$

$\underline{J_c = 7706,72\ kg\ m^2}$

↳ moment of inertia of a flywheel

Flywheel - Exercise II

3) $\omega^2 = (2\pi \cdot n)^2$

$\omega^2 = 4\pi^2 \cdot n^2$

$$\Rightarrow \quad 4\,320 \cdot 10^6 \ Ws = \frac{7706{,}72 \ kg\,m^2 \cdot 4\pi^2 \cdot n^2}{2}$$

$$2 \cdot 4\,320 \cdot 10^6 \ kg \frac{m^2}{s^3} \cdot s = 7\,706{,}72 \ kg\,m^2 \cdot 4\pi^2 \cdot n^2$$

$$n^2 = \frac{2 \cdot 4320 \cdot 10^6 \ kg \frac{m^2}{s^3} \ s}{7\,706{,}72 \ kg\,m^2 \cdot 4\pi^2}$$

$$n = \sqrt{\frac{2 \cdot 4320 \cdot 10^6 \ \cancel{kg} \frac{\cancel{m^2}}{s^{\cancel{3}2} \cancel{s}}}{7\,706{,}72 \ \cancel{kg}\,\cancel{m^2} \cdot 4\pi^2}}$$

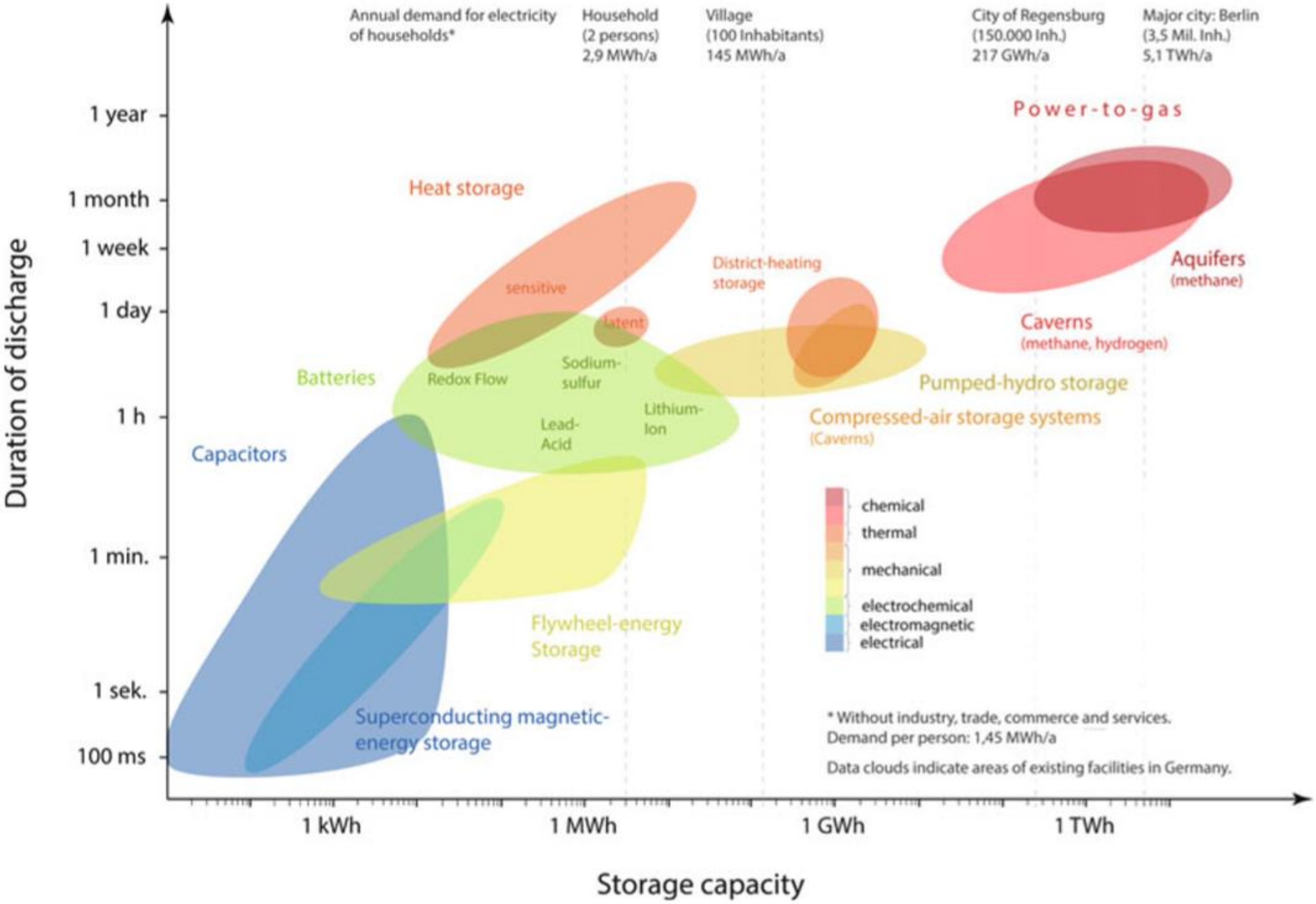
$$n = \sqrt{28.397{,}78 \ s^{-2}}$$

$$n = 168{,}5 \ s^{-1}$$

$$\mathrel{\hat{=}} \underline{\underline{10.100 \ min^{-1}}}$$

Mechanical storage devices

Comparison with other storage technologies



Source 2

Mechanical storage devices

Comparison of capacities with other storage technologies

Capacities of different electricity storage devices

Storage name/use	Discharge time	Storage type	Maximum storage capacity of typical plants and technologies
Short-term storage: grid stabilisation, grid maintenance	less than 1 second to a few minutes	Coils SMES	5,6 kWh
		Capacitors/Super Caps	52 kWh
		Flywheel storage	5 MWh
Long-term storage: peak demand coverage	1 hour to approx. 1 week	Air reservoir	2,86 GWh
		Pumped Storage	8.48 GWh
Electro-chemical storage: reserve storage, electro mobility	1 hour to several days	Lithium-ion batteries	85 kWh
		Redox-Flow-Batteries	12 MWh
		Lead-acid batteries	40 MWh
Chemical storage	Days to one year	Hydrogen	several TWh
		Synthetic methane	several TWh

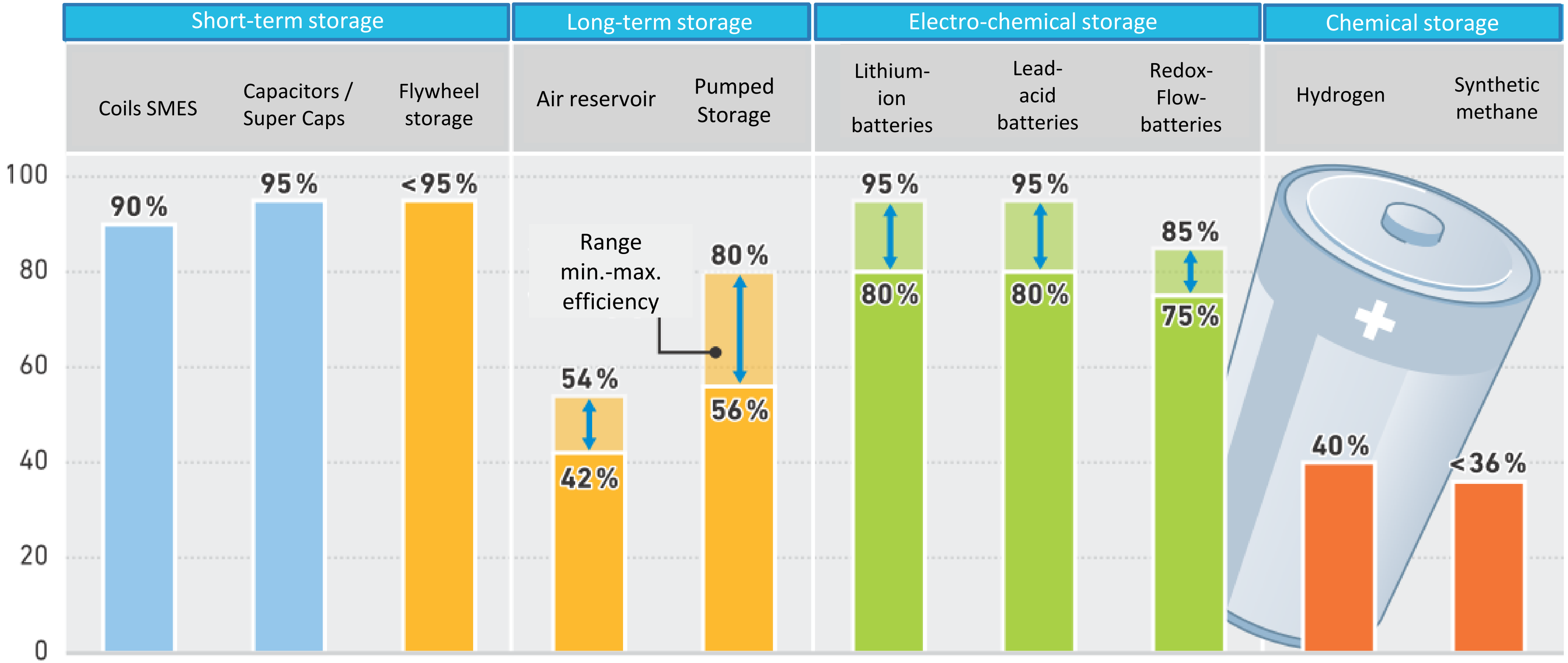
1 10 100 1000 kWh | 1 10 100 1000 MWh | 1 10 100 1000 GWh | 10 TWh

Quellen: EFZN, IfEU, TAB, Sauer, Tesla

Mechanical storage devices

Comparison of efficiencies with other storage technologies

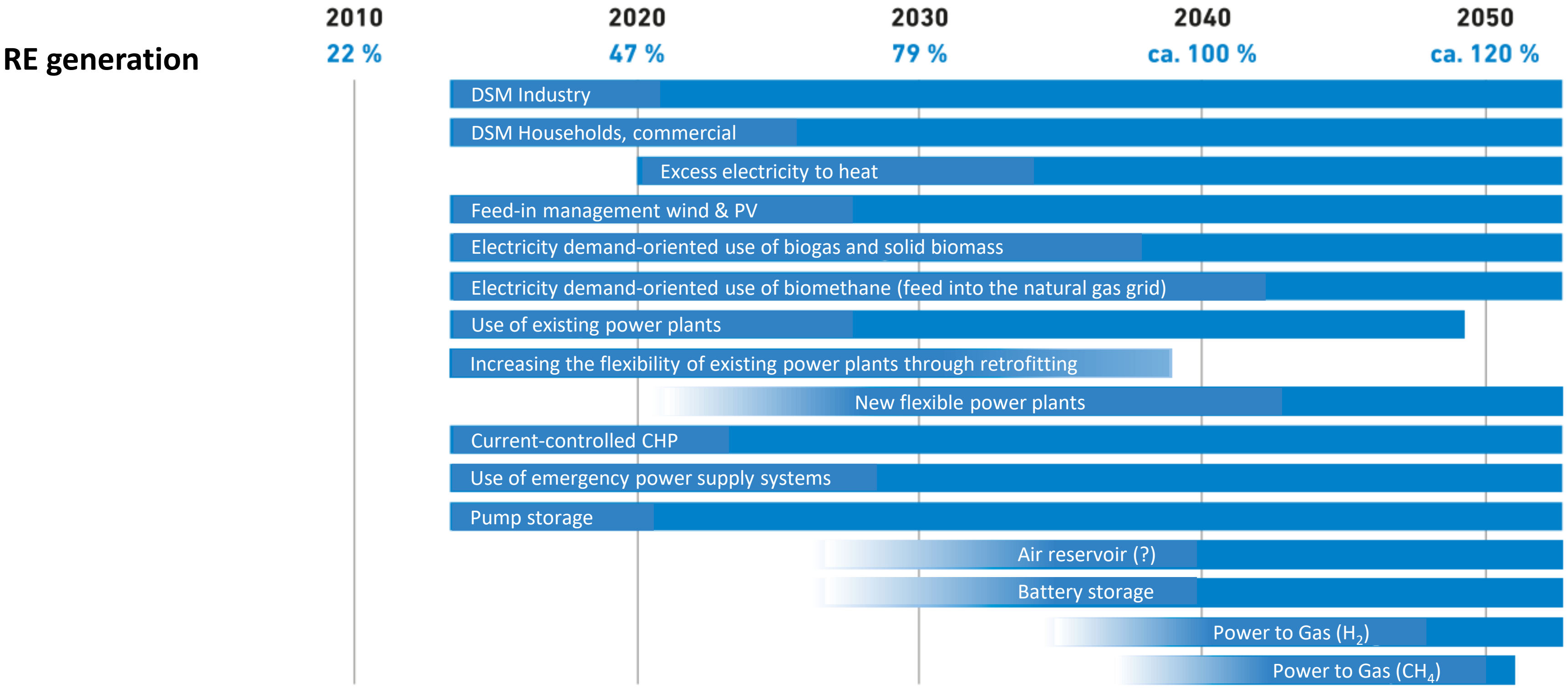
Efficiencies of different electricity storage devices



Quelle: EFZN 2013

Mechanical storage devices

Use of the flexibility options



Thank you for your attention