DANUBE REGION
strategy
Energy

ENERGY STORAGE

1.

THE NEED FOR ENERGY STORAGE

For many years, energy storage was not considered as a priority in energy systems, partly because the technologies were not yet economically viable, partly because the benefits of storage were valued less in centralised fossil fuel-based energy systems. Nevertheless, this situation is rapidly changing due to the cost-performance improvements in energy storage technologies and the global and EU political commitment to the transition of a low-carbon economy with a significant increase of share of renewables in the electricity generation.

Policy background

The EU's energy and climate policies have become increasingly ambitious over the past 10–15 years.

Building on the 20/20/20 Climate & Energy Package objectives - 2007 (20% cut in greenhouse gas emissions from 1990 levels; 20% of energy from renewables; and 20% improvement in energy efficiency), even more ambitious EU climate and energy targets for 2030 were accepted in 2014: a 40% cut in greenhouse gas emissions (compared to 1990 levels); at least a 27% share of renewable energy consumption; and at least 27% energy savings compared with the business-as-usual scenario. The Paris Agreement (2015) further strengthened these goals and endorsed the objective of net-zero greenhouse gas emissions in the EU by 2050 and directed the global energy community as well on a path to decarbonisation.

The Energy Union Strategy (2015) and the "Clean Energy for All Europeans" package (2016) further addressed key policies areas – energy security, internal energy market, energy efficiency, decarbonisation of the economy, and research, innovation and competitiveness – in a comprehensive manner, some of the aspects touching on energy storage. The European Parliament published a report in 2020 on a wide-ranging European approach to energy storage (2019/2189(INI)), in which highlights the needs for energy storage, calls on the Member States to fully explore their potentials in this matter and calls on the Commission to develop a comprehensive strategy on energy storage. It states that *"a cost-efficient energy transition towards a highly energy-efficient and renewable-based energy system for a climate-neutral economy requires a well-developed and smart energy grid, advanced storage and flexibility technologies, backup generation and demand response in order to secure a constant, affordable and sustainable power supply, as well as the application of the 'energy efficiency first' principle".*

In line with these European policies, energy storage is also one of the key areas of the Priority Area 2 of the EU Strategy for the Danube Region ("Sustainable Energy"), as highlighted in its recently revised Action Plan: *to promote new and innovative low-carbon solutions, including energy storage applications.*

Drivers for Energy Storage

Various energy scenarios all predict the significant restructuring of the global energy systems in the coming decades (Fig.1).

As shown in Fig. 1, the energy mix of primary energy consumption is expected to be rearranged and power consumption will significantly intensify by the end of 2030s. According to the BP Energy Outlook 2019, if the transition continuously tends towards a lower-carbon energy system, renewables and natural gas will play major roles in the decarbonisation process. These two energy sources will account for almost 85 % of the total growth by 2040. Furthermore, renewable energy is the fastest-growing source: its share in primary energy consumption will increase from 4 % today to around 15 % by 2040. Natural gas consumption rises massively due to increasing availability and widespread use. Another reason that drives the growth is the expansion of liquefied natural gas (LNG) supply, which will overtake inter-regional pipeline shipments in the late 2020s. There is a

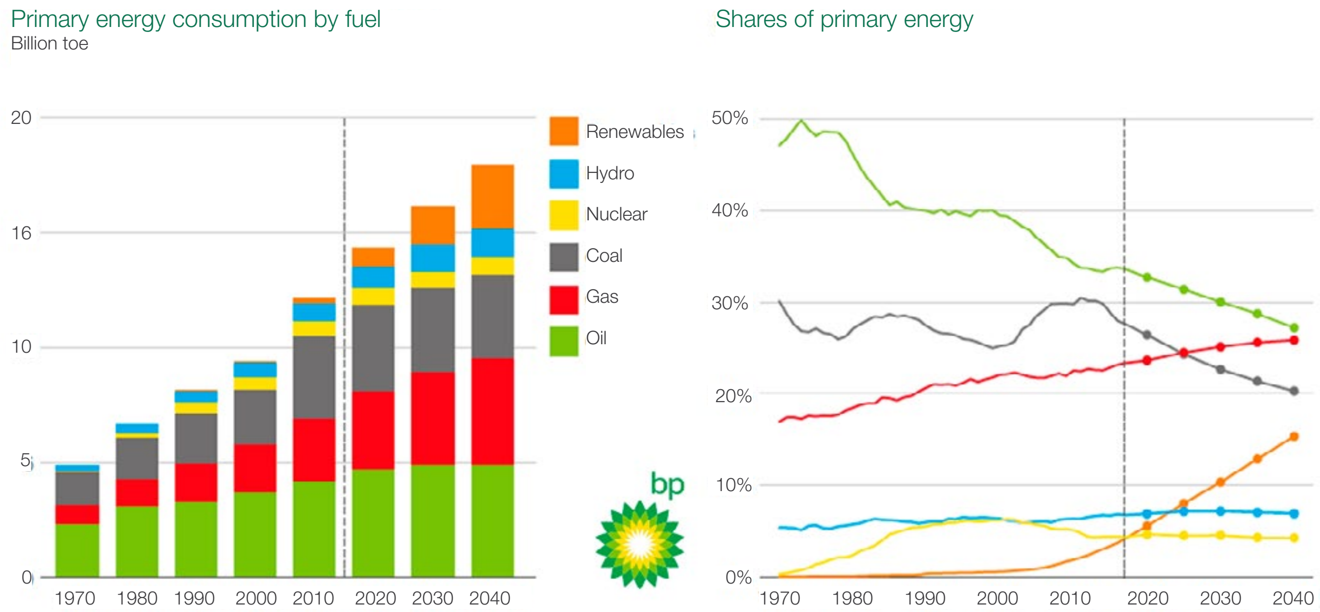

Primary energy consumption by fuel
Billion toe
Shares of primary energy

Fig. 1: Primary energy consumption by fuel and shares of primary energy (source: BP Energy Outlook 2019)

noticeable contrast in coal consumption in the global market. While OECD countries switch coal or lignite to cleaner, lower-carbon (or almost carbon-neutral) fuels, the overall figure stagnates, because it is offset by the increasing consumption demand of the Asian countries, especially India. Despite the expansion of natural gas and renewable sources, the share of oil consumption continues to dominate (especially in the transportation sector), plateauing in primary energy consumption after 2030.

Nevertheless the transition of energy supply from mainly fossil sources to renewable energy sources is essential for mitigating climate change effects and preparing for a future of sustainable energy systems.

However, energy supply from renewable sources like wind, or solar power is subject to strong natural temporal fluctuations and therefore frequently does not match the instantaneous energy demand and energy base load (Figs. 2, 3). Energy storage is thus required to dampen these fluctuations and to compensate for times of low power production. By taking up surplus power, energy storage also contributes to grid stability in times of high renewable energy production. Energy storage will therefore play a fundamental role in future energy systems with a significant contribution to the future envisioned carbon-neutral and environmentally friendly society. It will enable to optimize the integration of renewable energies into the electricity and heat systems. It will also facilitate grid interconnectivity and flexibility, and development of demand response functionalities. Furthermore it can also contribute to the decarbonisation of the transport sector by producing green fuel and can produce green raw materials for the chemical industry, like hydrogen. Energy storage methods therefore offer sustainable, predictable and long-term solutions to achieve the EU 2030 energy targets in line with the goals of the Paris Agreement. The International Energy Agency estimated that limiting global warming to below 2°C will necessitate globally installed energy storage capacity to increase from 140 GW in 2014 to 450 GW in 2050.

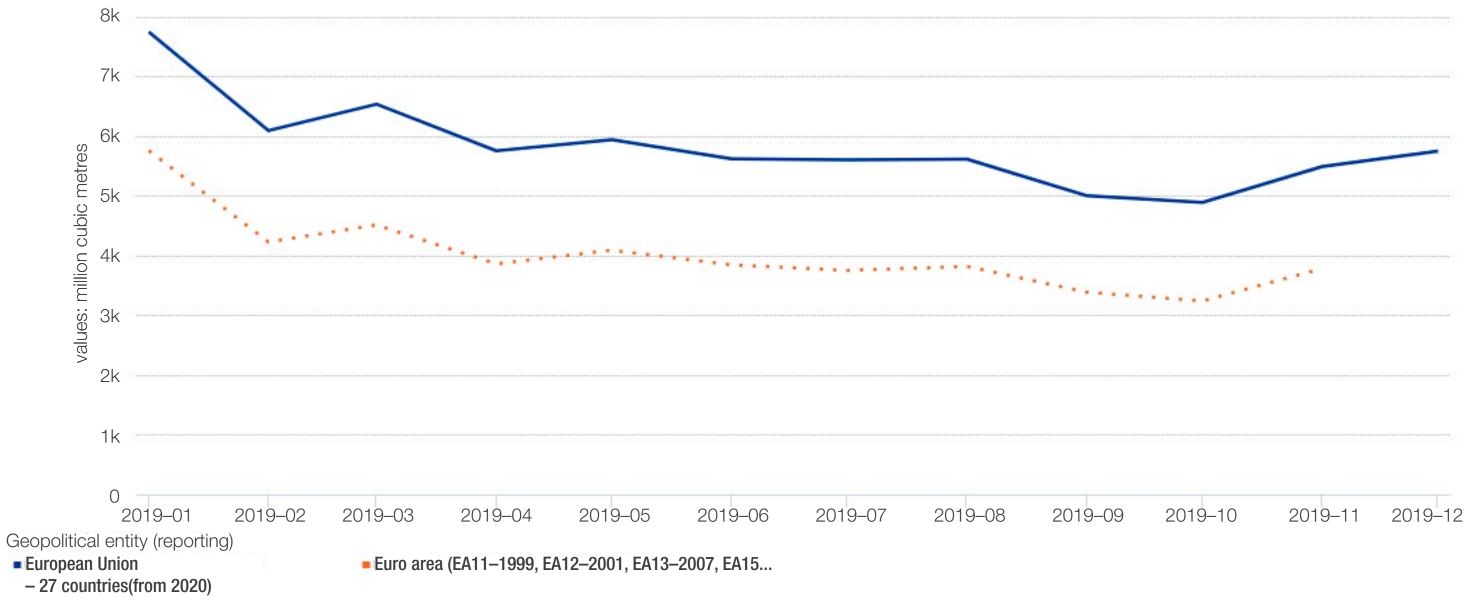
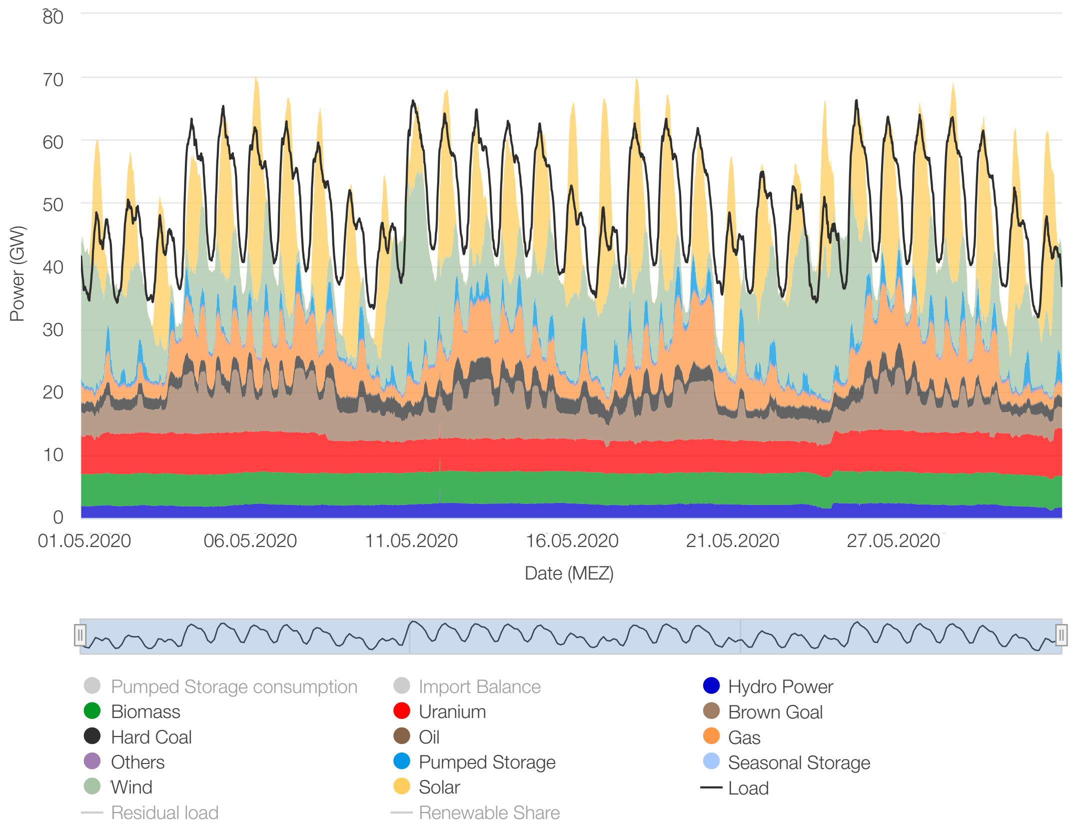


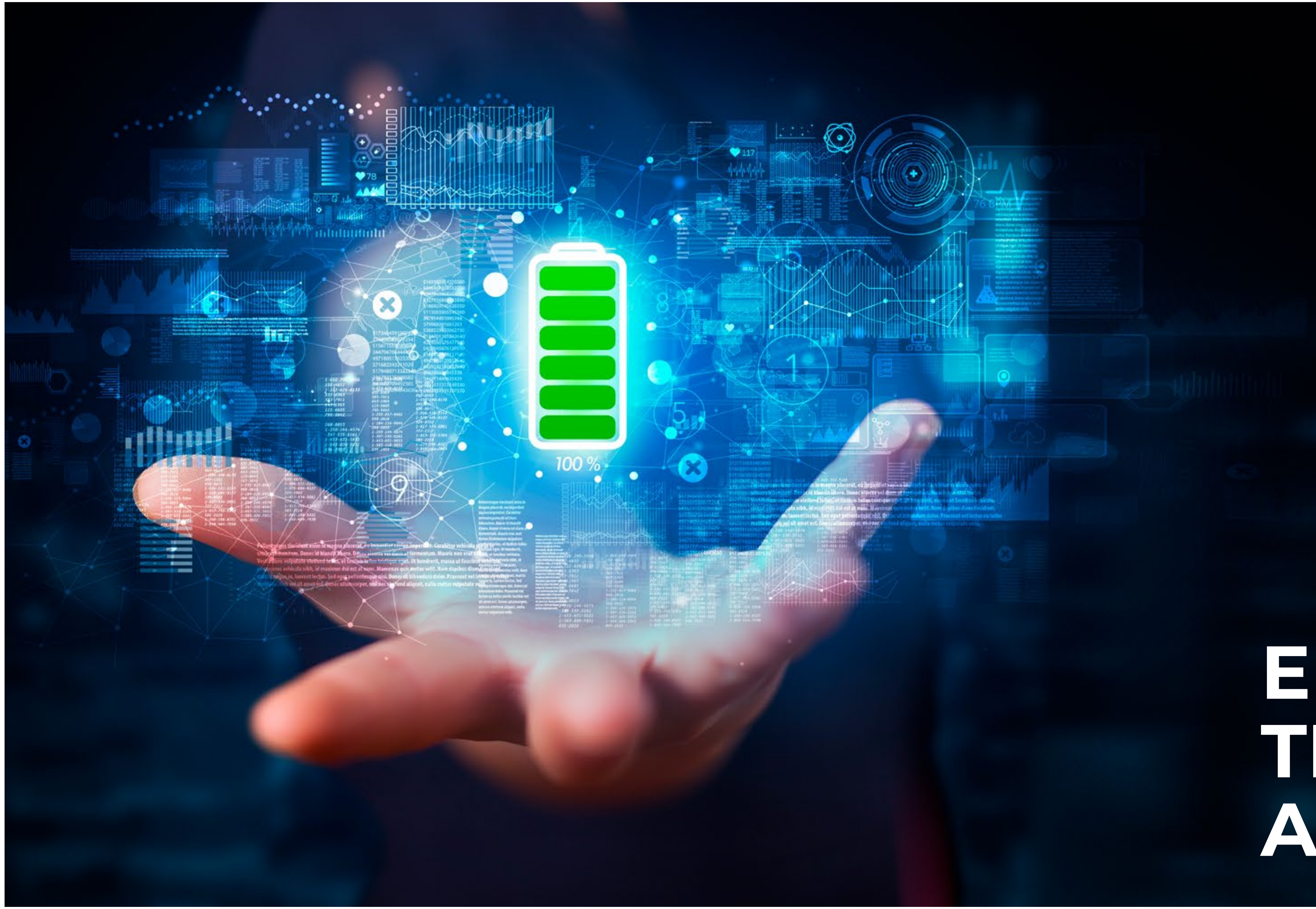
Fig. 2: Seasonal fluctuations of gas demand (source: Eurostat)

Electricity generation in Germany in May 2020



Energy–Charts.info; Data Source: 50 Hertz, Amprion, Tennet, TrasnetBW, EEX, ENTO–E; Last Update: 19.09.2020, 19:45 MESZ

Fig. 3: Intermittent renewable electricity production highlighting daily fluctuations of solar and wind energy (source: Fraunhofer, https://energy-charts.info/)



2.

ENERGY STORAGE TECHNOLOGIES AND APPLICATIONS

Due to the fluctuating nature of renewable power production, storage is required on a wide range of time scales, ranging from seconds to months, as well as storage sizes, ranging from tens of kWh to tens of GWh (Fig. 4).

Five main available groups of energy storage technologies can be distinguished (EASE 2016) which vary according to their discharging time and storage capacity (Fig. 4)

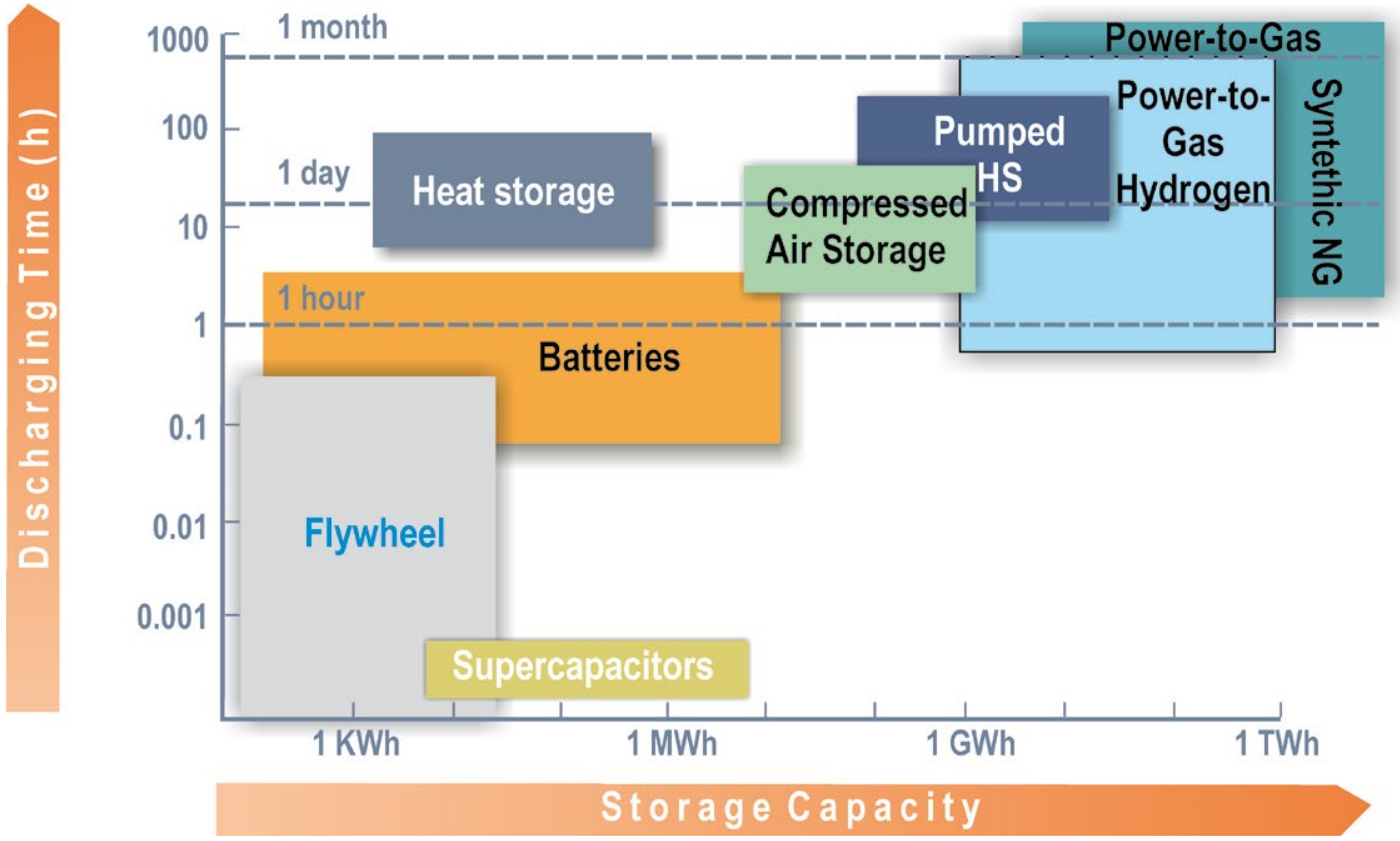


Fig. 4: Discharge times vs. storage capacities of various storage technologies

2.1. Mechanical energy storage

2.1.1. COMPRESSED AIR ENERGY STORAGE (CAES)

CAES is a technology where excess electricity is used to drive compressors in adiabatic, diabatic, or isotherm way to pressure air. The compressed/pressurised air can be stored in underground caverns, or other (above surfaces) tank(s). During discharging, the air from the cavern or tank(s) is released and drives a turbo, or piston expander.

CAES plants can be used to provide grid scale storage services on a daily, or even weekly basis. There are only 2 such plants existing worldwide (USA and Germany), which makes these small-scale applications expensive. Moreover, these plants use natural gas for preheating of the compressed air before expansion, thus producing some amounts of CO_2. Furthermore CAES has a relatively low round-trip efficiency (40 to 54%).

2.1.2. KINETIC ENERGY STORAGE (FLYWHEEL)

This is a fast energy storage technology, where electricity is stored as kinetic mass in a rotating flywheel. It can be installed at any location, and is characterized by high power and energy densities. Flywheel is a mature technology completely introduced in the industrial market. Nevertheless, it is a short-term solution to store energy with low storage capacity and short discharging time.

2.1.3. HYDROPOWER (PUMPED HYDRO STORAGE)

This proven technology – which uses the potential energy of water – is the most efficient and flexible largescale means of storing energy available today. There is about 1000 GW of hydropower installed worldwide with an average annual production of about 3500 TWh, where 480 TWh are produced in Europe from an installed capacity of 160 GW. Even though more than 50 per cent of the technical potential for hydropower in Europe is still not developed, major untapped opportunities are in the mountain regions. In pumped hydro storage, water is pumped from a low level reservoir via turbines to an uphill reservoir with the help of surplus electricity during off-peak periods (Fig. 5). When power consumption increases, water flow direction is reversed, and in turn, the uphill reservoir water drives the turbines to regain electricity. The estimated efficiency ranges from 70 % to 85 %. Capacity is between 1-10 GWh per cycle and is a massive storage method in both the short and medium term.

Fig. 5: Pumped hydro station

2.2. Electrochemical energy storage (also known as Battery-storage)

Batteries are based on single electrochemical cells that use chemical reaction(s) to create a flow of electrons – electric current. Each cell has voltages in the range from below 1 V up to about 4 V that can be combined in series to yield very high voltages if required (Fig. 6). Today the most commonly used technologies on the market available are Lead-based, Lithium-based, Nickel-based and Sodium-based batteries, which are used and tailored for a variety of different applications, most commonly as uninterruptible power supplies in grid balancing and mobile applications (e-cars). Batteries are also important strategic components in several key functions of the modern society, such as communication, mobility and defence.

Fig 6: Battery storage

Although batteries are still not very efficient as to their price/capacity ratio, and they also raise environmental degradation concerns (mining processes, waste prevention and recycling), as well as supply of critical raw materials (lithium), they are viable enough to be used on a large scale. Conventional (lead-acid and alkaline) batteries may provide even up to 40 MW_h for load levelling. Advantages of batteries include flexibility and efficiency (in some cases near 100%); while its disadvantages are limited stored energy and power performance, lifetime, charging capabilities and costs.

2.3. Chemical energy storage

This well-established technology uses renewable electricity to create chemical materials, mostly gases (Power-to-Gas) (Fig. 7). A hydrogen-based chemical storage system is a three-step process of (1) converting surplus renewable electricity to hydrogen using electrolysis; (2) storing the chemical energy as hydrogen, or synthetic methane (or if convenient in the form of ammonia) in either the natural gas pipeline, local storage tanks, or even subsurface in salt caverns, or well-sealed porous formations; and (3) discharging the stored energy for mobility (hydrogen fuelled electric vehicles), or power through a gas turbine generator, or for various industrial applications. The main advantages of Power-to-Gas are the rapid, dynamic response of the electrolyser to integrate intermittent renewable sources of generation, and the unparalleled massive storage capacity of the existing natural gas infrastructure. Surplus electricity can be stored on short- (days) to long- (weeks/months) term without the need to discharge it, providing a seasonal storage capacity and the flexibility to discharge the stored energy wherever and whenever it is needed. It also provides an opportunity for sector-coupling (a bridging technology between electricity and natural gas markets).

The efficiency of the complete conversion chain from renewable energy via electrolysis to hydrogen/methane, or other fuels and back to electricity can amount up to 40%, a level that is also typical for conventional coal fired steam power plants.

Chemical storage is not a mature technology yet; the major challenges for its uptake include the (1) high CAPEX especially of the electrolysers, (2) system integration of the electrolyser, (3) safe and compact storage of hydrogen and the admixing limit in the natural gas grid, (4) improvement in efficiency.

The Power-to-Gas applications are best suited to large- very large scale systems (10-100 MW capacity) with seasonal storage capability.

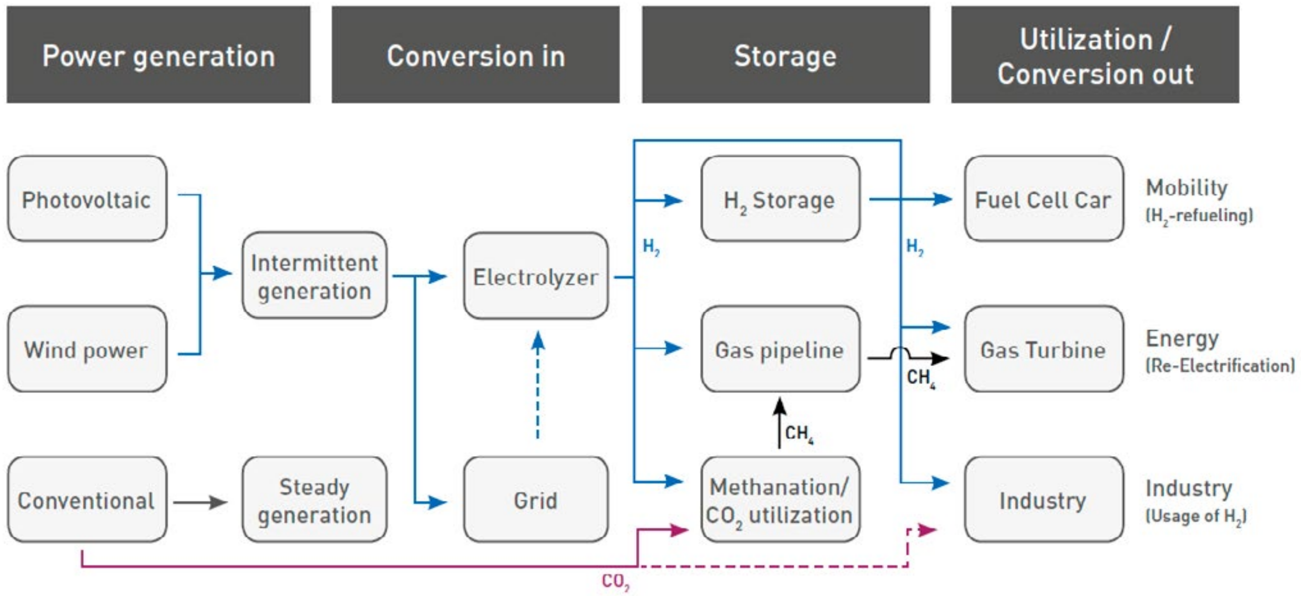


Fig. 7: Schematic overview of chemical storage pathways. Source: EASE / EERA Energy Storage Technology Development Roadmap 2030

2. 4. Thermal energy storage

Thermal energy storage (TES) is a key element for effective generation and utilisation of heat, where heat supply and heat demand do not match in time, space, temperature and power. Heat sources may come from waste combustion, waste water, combined heat and power, as well as from other sources of surplus heat (geothermal, industry, datacentres, etc.). There is a wide range of diverse applications that require different temperatures, energy/power levels and use of different heat transfer fluids. Each storage concept has its best suited materials and these may occur in different physical phases: liquids (mostly water), molten salts, and solids are used as heat storage media. The thermal conductivity of the materials is important for the charge and discharge power of the storage system.

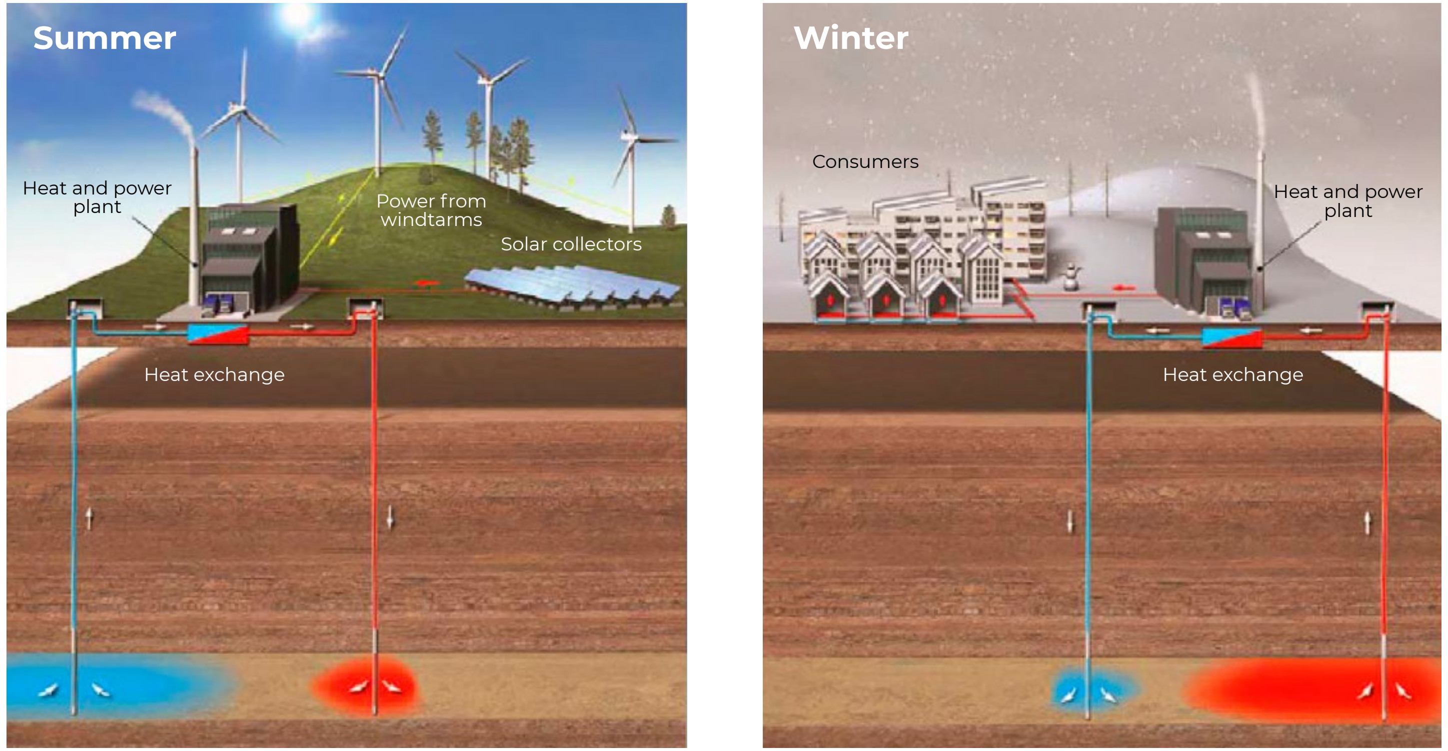


Fig. 8: The concept of aquifer thermal energy storage (ATES)

By use of underground thermal energy storage (UTES) systems, excess heat during summer is stored in the ground, to be extracted during winter (seasonal storage). One typical and relatively widespread application is a combination of a ground-source heat pump with aquifers (Fig. 8) for space heating and for sanitary hot water generation in the winter and for cooling in summer. High-temperature ATES systems use aquifers, as storage media, where storage temperature range between 50 and 150 ˚C and the storage depth between <100 to >500 m. Storage capacities are in the range of a few thousand MW_h up to 20 000 MW_h.

Thermal energy can be also stored in the subsurface in specially designed single-, or double U-tubes or coaxial pipes placed in boreholes (Fig. 9), these closed-loop systems use the soil volume as storage media. Storage temperature range between 45 and 80 ˚C, and the storage depth between 30 and 150 m. Storage capacities range from 100 to 3800 MW_h. Storage efficiency is between 45 and 60%.

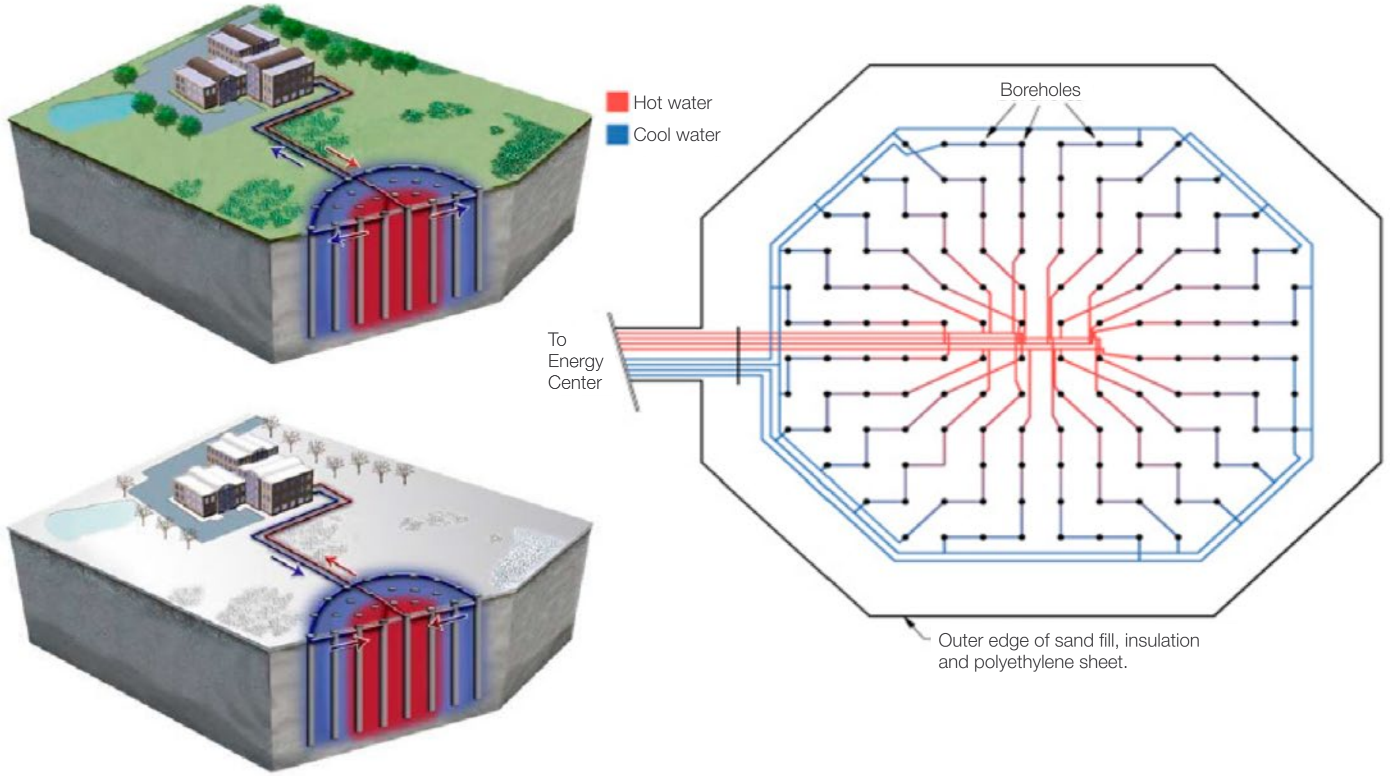


Fig. 9: The concept of borehole thermal energy storage (BTES)

The third way of storing thermal energy in the subsurface is the utilisation of mine water of abandoned and flooded mines, as low-temperature energy source for heating buildings. This method is used so far in Germany and the Netherlands.

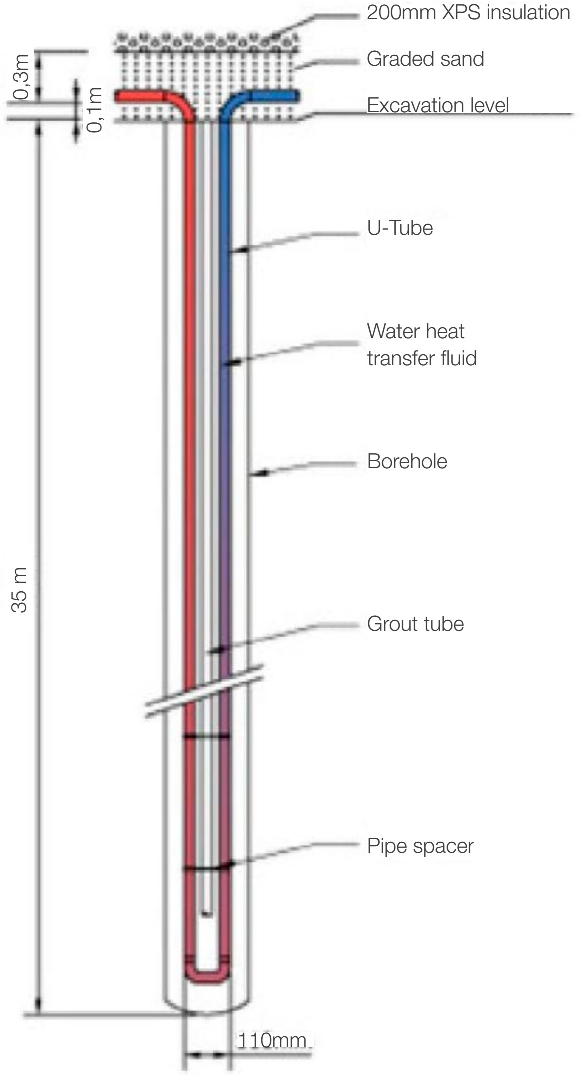
A special case is where thermal energy is stored in water, displaced on the surface in large, properly insulated pits (pit thermal energy storage – PTES), as in some cases in Denmark. Storage temperatures are up to 90 °C and storage capacities range from 3000 to 12000 MW_h. Storage efficiency may be up to 90% (both on short- and long-term), and these systems have high charge/discharge capacities.

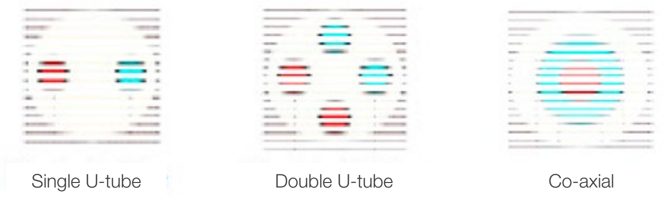
In addition to water (liquids), natural materials in the form of rocks and pebbles are suitable for low-temperature ground storage, while manufactured solid materials (various ceramics) may be widely used for higher temperature storage.

Due to the potential to store thermal energy within a solar thermal power plant, heat storage is currently one of the hot topics to increase the share of solar thermal electricity generation in the future. Furthermore, heat storage application may be highly relevant for small scale heating and cooling in the private sector, large scale heating and cooling in the public and industrial building sector, industrial waste heat storage, as well as heat storage for decentralised CHP systems.

2.5. Electrical energy storage

Electrical energy storage stores electrons. In a capacitor, the electricity is stored in the electrostatic field between two electrodes. In superconducting magnetic energy storage (SMES) the electricity is stored in the magnetic field of a coil. The energy capacity is limited, but the reaction time is fast, while the power and efficiency are very high. These methods are still in research and development phase.





3.

SUBSURFACE ENERGY STORAGE

Greater deployment of energy storage is required at different scales, i.e. from low power (kW to MW level), fast response (seconds to minutes) solutions, to high power (towards GW), longer-term (hours and far beyond) balancing needs for the grid. Large-scale and centralized energy storage can provide flexible bulk power management services for electricity, gas and heat commodities, and also offers essential services to society in the form of strategic energy reserves. Subsurface energy storage plays a substantial role in large-scale energy storage.

Whilst various ways for the above ground energy storage are relatively well established, energy storage in the subsurface represents a complex and broadly evolving field of research and a vast range of emerging technologies, as it covers multiple scales of application, a variety of end-user profiles, and different types of energy carriers. Subsurface storage capacities are present in many types of geological formations, each of which has its own criteria for identifying techno-economic viability.

Research and technological development related to subsurface energy storage is already well advanced in some European countries (e.g. Germany, France, The Netherlands, Austria), however rather in its infancy in Central and Eastern Europe.

Regarding the different subsurface storage media, the most common are (1) depleted hydrocarbon reservoirs (mainly gas fields) and other porous media, (2) salt caverns, and (3) other excavated tunnels, abandoned mines.

3.1. Depleted gas fields and aquifers

Storing energy in hydrocarbon reservoirs (depleted gas or oil fields) is a widely used mature technology for underground (natural) gas storage (UGS), which has been implemented in many locations in Europe. The main characteristics of this storage type are as follows (Fig. 10):

- Surface and subsurface technologies are well developed, proven, and tested during long operational times of former hydrocarbon production, and are available for storage (e.g. natural gas preparation technology, wells, etc.)
- Easy integration into the national gas transmission (and distribution) grid
- Technically and economically viable according to feasibility studies
- Huge amount of potential working gas capacity suitable for seasonal storage and network balancing with high demand periods of several weeks, or even months
- During the withdrawal period (mostly in autumn and winter), natural gas is produced from the reservoir through gas wells to the surface equipment. The gas withdrawn through the wells is usually accompanied with water and liquid hydrocarbons from the reservoir, which is also brought to the surface. The removal of these liquid components is essential to fulfil standards and regulations, so the gas must first be separated to liquid and gaseous phases in separators. Following this, the gas flows through a dehydration equipment, where with the help of a special treatment, the rest of the water content is absorbed and separated from the gas. In some cases, the gas also contains liquid hydrocarbons, which must be removed as well: either by cooling via expansion, or refrigeration. From this point on, the gas becomes ready to be directly fed into the high-pressure transmission pipelines.
- During the injection period, natural gas is transported from the transmission system to the UGS site, where it is measured and compressed. Since pressure increase also raises the temperature of the gas, it must be cooled down. Following this, it travels through the flowline manifold and the field lines and then the gas enters through wellheads and wells into the storage formation.

Within the EUSDR countries the most commonly used subsurface hydrocarbon reservoirs are in Germany, Austria, Hungary, Ukraine and Serbia.

Hydrogen Energy Storage also has a potential in depleted gas fields with adequate sealing rock capacity. Aquifers may also be used as storage media for underground heat storage.

3.2. Caverns

Cavern storage utilizes typically salt caverns, which host rocks have been formed by the evaporation of saline waters in the geological record resulting in

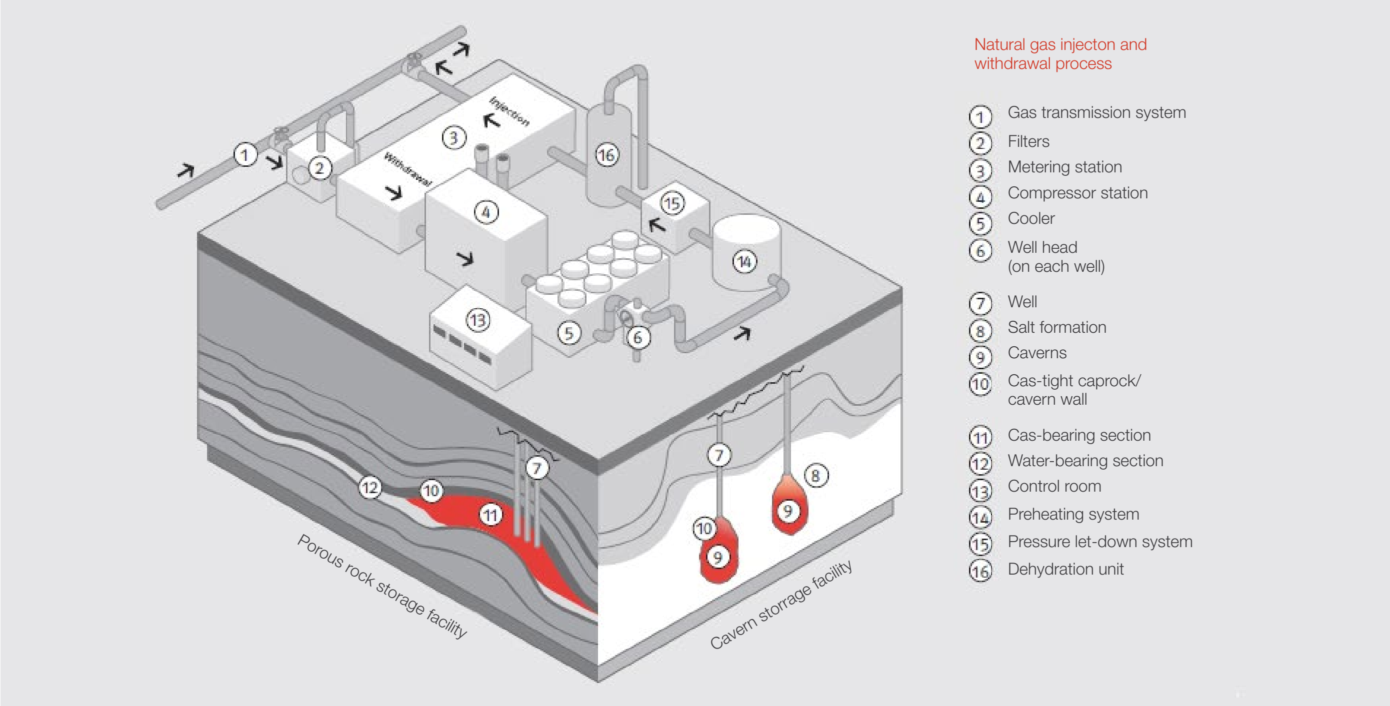


Fig. 10: Typical withdrawal and injection cycle of natural gas

the deposition of alternating gypsum and carbonate strata. The cap-rock above these deposits usually has low permeability and can be considered impermeable. This impermeable layer prevents the flow of fluids and gases to the layers above.

Salt caverns are also often used for underground gas storage. Similarly to UGS concepts described above, when natural gas consumption is low, usually during the summer, gas is injected into the storage site from transmission pipelines. The entering volume is metered and compressed (if necessary), and then flows through a gas manifold and is distributed into buried pipelines that feed it into wells. These wells lead into artificial caverns leached out by injecting fresh water into a totally impermeable salt layer to form cylindrical shaped caverns (100-300 meters in height and several tens of meters in diameter). When natural gas consumption is increasing, gas flow direction is reversed and natural gas flows back into the well and passes through the buried pipes to the manifold. The produced natural gas is then dehydrated to have water and fluids removed. Cavern storage has high flexibility to inject/withdraw into/from the high-pressure gas grid.

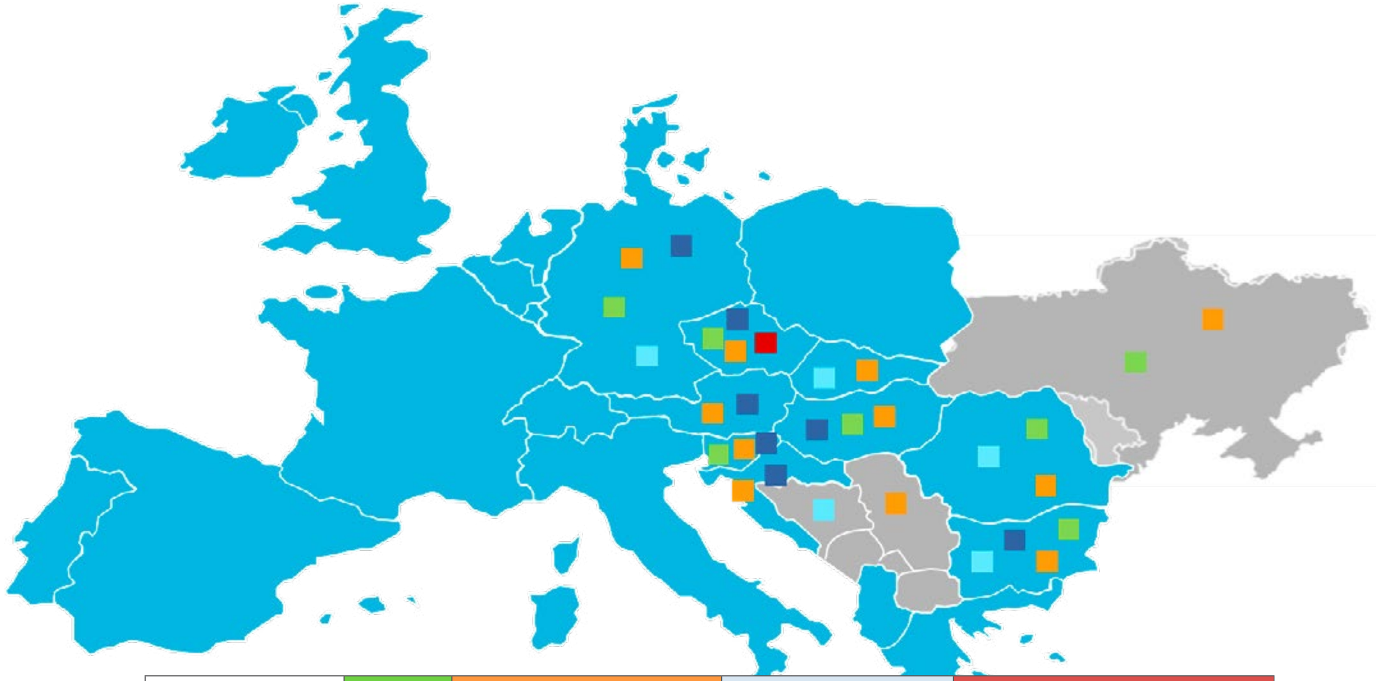
Salt caverns are currently suitable for natural gas storage based on decades of operational experience and there is a proven technology for this geological formation. Some pilot projects have already been launched to test these facilities for hydrogen storage as well. Nevertheless for storage safety and integrity, suitability of materials against hydrogen resistance and durability, microbiological activity, laboratory and experimental assessment and in-situ tests are required to understand the long-term interaction between salt and hydrogen.

Salt formations also have a great feasibility potential for CAES, because of the high purity of the reservoir (when caverns are created, fresh water is injected through the wellbore and contamination cannot enter the reservoir).

3.3. Abandoned mines or mined rock caverns

These facilities have slight impact on the energy storage methods due to their capacity limitations. This technology counts on tight caverns and should be designed to ensure that they are free of fractures and permeable sections to minimize leakage. The subsurface rock must be strong enough and uniform to use it as a storage method. Shale and siltstone are the most preferred rock types. Abandoned mines are considered a main target for UTES as an energy storage possibility.

The various energy storage methods in the Danube Region are summarized on Fig. 11.



	Aquifers	Hydrocarbon reservoirs	Salt formations and caverns	Host rock,caverns, mines
Austria		X		
Bulgaria	X	X	X	
Czech Republic	X	X		X
Croatia		X		
Germany	X	X	X	
Hungary	X	X		
Romania	X	X	X	
Slovakia		X	X	
Slovenia	X	X		
Bosnia and Herzegovina			X	
Montenegro				
Moldova				
Serbia		X		
Ukraine	X	X		

Fig. 11: Common energy storage methods in the Danube Region (source: ESTMAP project)

3.4. Underground energy storage in the context of subsurface planning

Although the geological subsurface offers large potential storage capacities, large achievable loading and unloading rates and a variety of suitable settings, also other ways of using the subsurface are already in place. These include shallow or deep geothermal applications for various heating and cooling purposes, as well as power production, groundwater abstraction for drinking water purposes, mining of ores, coal or other geo-materials, hydrocarbon production, disposal of hazardous materials or waste (Fig. 12). Also protected entities, such as groundwater reservoirs, flora and fauna, and ultimately humans, have to be safeguarded when utilizing the geological subsurface, which may put restrictions on the implementation of certain types of subsurface use. In addition, competition for subsurface space, i.e. suitable geological formations, may impair their use as storage sites, as other types of use may already be in place or prohibit the use as storage site due to induced effects. Therefore a subsurface planning approach should be applied that allocates specific types of use to individual subsurface formations and assign for each type of use the corresponding subsurface spatial demand, determines priorities, assesses interactions between different types of use. Only by such an approach, a reliable and sustainable use of the subsurface will be achieved.

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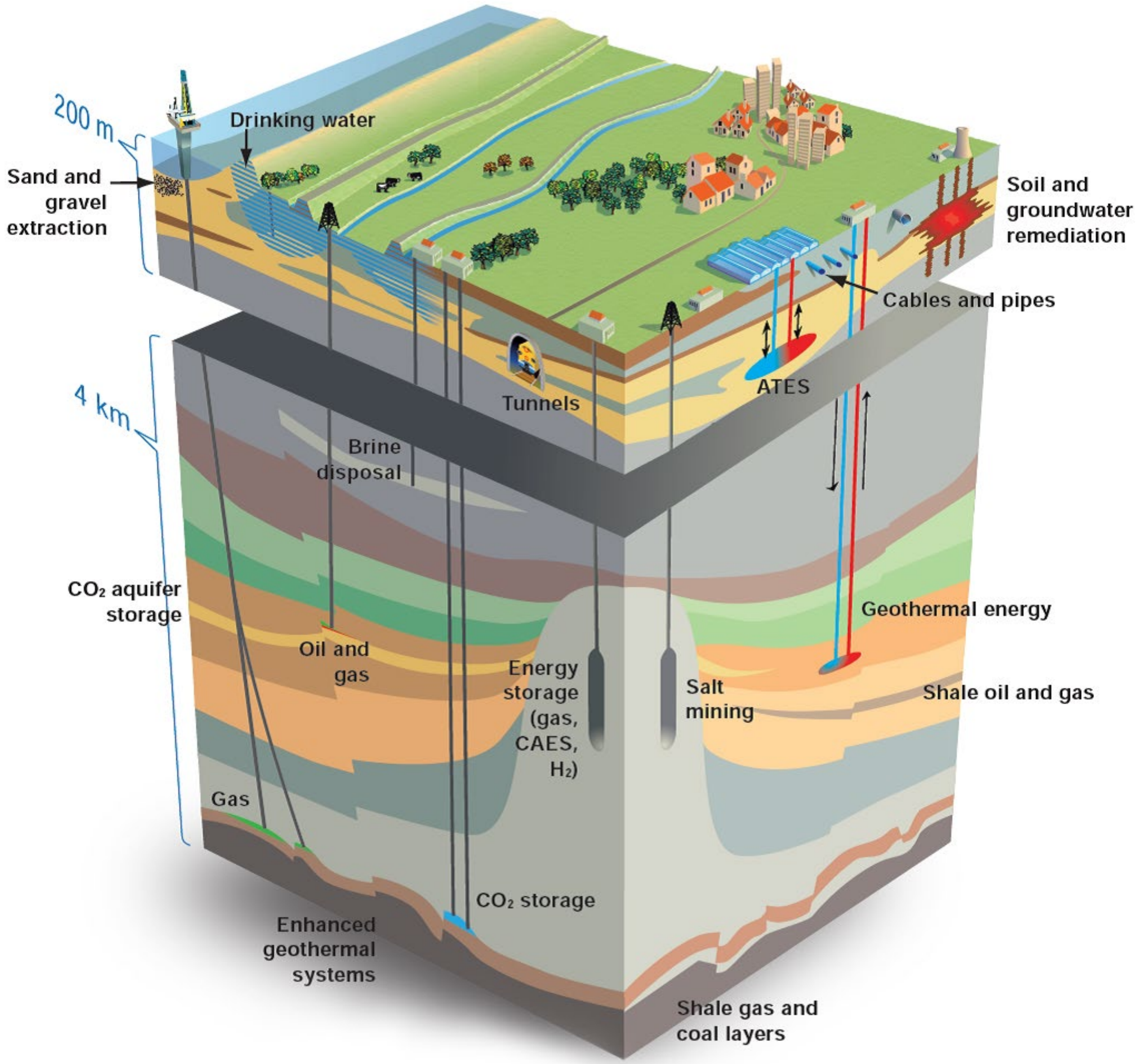

Fig. 12: The concept of integrated use of the subsurface (source: TNO)

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