LARGE SCALE UNDERGROUND ENERGY STORAGE FOR RENEWABLES INTEGRATION: GENERAL CRITERIA FOR RESERVOIR IDENTIFICATION AND VIABLE TECHNOLOGIES

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ABSTRACT

The increasing integration of renewable energies in the electricity grid contributes considerably to achieve the European Union goals on energy and Greenhouse Gases (GHG) emissions reduction. However, it also brings problems to grid management. Large scale energy storage can provide the means for a better integration of the renewable energy sources, for balancing supply and demand, to increase energy security, to enhance a better management of the grid and also to converge towards a low carbon economy.

Geological formations have the potential to store large volumes of fluids with minimal impact to environment and society. One of the ways to ensure a large scale energy storage is to use the storage capacity in geological reservoir. In fact, there are several viable technologies for underground energy storage, as well as several types of underground reservoirs that can be considered.

The geological energy storage technologies considered in this research were: Underground Gas Storage (UGS), Hydrogen Storage (HS), Compressed Air Energy Storage (CAES), Underground Pumped Hydro Storage (UPHS) and Thermal Energy Storage (TES). For these different types of underground energy storage technologies there are several types of geological reservoirs that can be suitable, namely: depleted hydrocarbon reservoirs, aquifers, salt formations and caverns, engineered rock caverns and abandoned mines.

Specific site screening criteria are applicable to each of these reservoir types and technologies, which determines the viability of the reservoir itself, and of the technology for any particular site. This paper presents a review of the criteria applied in the scope of the Portuguese contribution to the EU funded project ESTMAP – *Energy Storage Mapping and Planning*.

KEYWORDS

Energy Storage; Underground Reservoirs; Geological Formations; Storage Technologies; Reservoir Selection Criteria.

1. INTRODUCTION

The European Union (EU) 2030 Climate Change and Energy strategy, regulated by the European Council, sets as targets for Europe a 40% reduction of greenhouse gas emissions compared to 1990, an increase of 27% of renewable energy, and an improvement of 27% in energy efficiency [1].

The increasing integration of renewable energies in the electricity grid is expected to contribute considerably to achieve the EU goals on energy and GHG emissions reduction. However, it also brings problems to grid management, because the electricity generated using renewable sources is difficult to adjust in response to the demand needs [2]. As a consequence, electric grids face challenges in the physical balances between supply and demand and also in the adequacy of power.

Electric power is a commodity that may be wasted if it is not preserved or consumed [2]. So, one of the possible solutions in order not to waste the energy that is being generated at low demand periods and also to solve the difficulties in grid management, is energy storage.

In essence, energy storage increases the flexibility of the way we generate, deliver and consume electricity. It provides the ability to balance power supply and power demand, making power networks more resilient, efficient and cleaner than before [3], being used to level the load in different time frames.

The article addresses large scale energy storage in geological formations, which has several advantages, including a better management of the grid, ensure energy security, balance supply and demand and converge towards a low carbon economy [4,5]. Thus, large-scale energy storage can be the key for integration of large amounts of renewable resources like wind and solar into the power grid [4,5,6].

The article also addresses both the geological reservoirs that can be used for energy storage, as well as the compatible energy storage technologies and their suitability for each type of underground reservoir.

This conference article results from the Portuguese contribution to the EU funded project ESTMAP – Energy Storage Mapping and Planning - which aims to contribute to strengthen the basis for long term strategic planning, optimizing the future energy system and defining potential bottlenecks at an early stage [7].

2. GENERAL CRITERIA FOR SELECTING GEOLOGICAL ENERGY STORAGE RESERVOIRS

The utilization of geological formations to store energy carrying fluids is in essence replicating the process of storage of hydrocarbons in nature.

Long term storage of fluids in geological formations is routinely conducted by the hydrocarbon industry for several decades, with low quality formation water produced with oil being reinjected in saline formations to minimise environmental impacts, or in acid-gas injection techniques to reduce the H_2S and CO_2 stripping from natural gas.

The volume provided by geological formations to store fluids can range from hundreds of m^3 for cavities excavated in rocks, to tens of km^3 for storage in porous sedimentary rocks.

There are mainly two types of suitable geological formations for large scale energy storage:

i) **Engineered cavities** which refers to the construction of underground caverns with a well-defined geometry, usually taking an area of hundreds of m^2, where the stored fluid may occupy all the available space in the cavity. Cavities may be created by dissolution of an evaporite rock, such as **salt**, by excavation of **hard-rocks**, such as granites or basalts, or soft-rocks such as shales or unfractured limestones, or they may reuse cavities in abandoned underground mines.

ii) **Porous media**, which takes advantage of the voids existent in virtually any rock type and aims at filling those voids with energy carrying fluids injected in the target rock – the reservoir – through small diameter wells connected to surface facilities. The reservoir types considered are usually in sedimentary rocks such as **saline aquifers** or **depleted hydrocarbon reservoirs.**

Thus, in general the geological formations adequate for underground energy storage technologies are (fig. 1): Salt rocks (bedded salt and leached salt caverns); Host rocks such as poorly fractured igneous rocks (engineered cavities or even abandoned mines); and Porous rocks (saline aquifers or depleted hydrocarbon reservoirs).

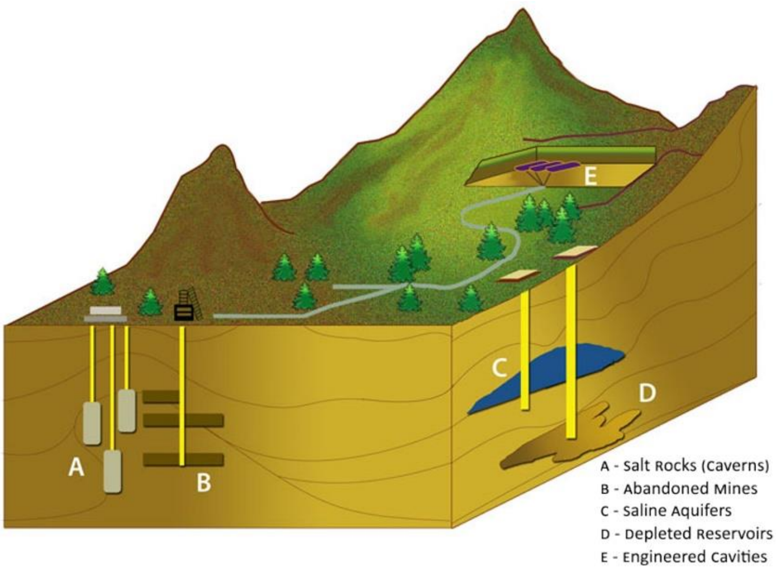

Figure 1. Geological reservoirs for underground energy storage. Adapted from [8].

2.1. Salt

Salt rocks may occur underground as extensive horizontal beds with thickness ranging from a few centimeters to hundreds of meters, or as vertical structures (domes, pillars, walls) when a deep salt bed intrudes vertically into surrounding rock strata [7].

Salt is characterized by very low permeability and it is considered impermeable to most substances, which ensures a very high-quality containment for fluids [7], and is also easily extracted by dissolving it with water. This means that, it is relatively simple to create huge artificial underground caverns by solution mining (Fig. 2). This process is characterized by the fresh or low salinity water injection into the salt rock, through a borehole, with the salt being progressively dissolved (leaching) and the resulting brine extracted, shaping a cylindrical cavern.

Three basic conditions must exist, if solution mining is going to be used, for cavern construction [9]:

1) A sufficient thickness of structurally competent salt at a proper depth, without an excess of interbedded insolubles;

2) An adequate supply of fresh water for leaching the salt;

3) An environmentally acceptable and economical means of brine disposal.

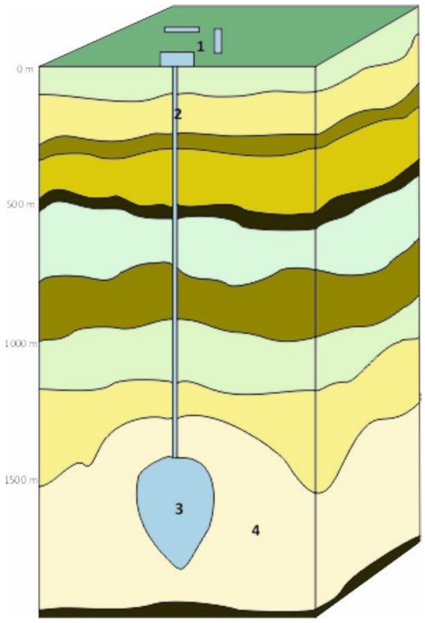

Figure 2. Schematic representation of a salt cavern storage facility.
1- Storage Plant, 2- Storage Well, 3- Salt Cavern, 4- Salt Dome Formation.

At depth intervals less than ca. 2000 to 1500 metres, salt becomes more stable and suitable for development of caverns, with minimal risk of leakage [7,10]. The range of acceptable depths for underground storage ranges from 200 to 2000 meters, which guarantees higher stability and less risks. Higher depths would allow to store more gas or air, but it would also increase the development costs and the risk of structure closure due to temperature and overburden pressure.

Thickness should be at least 300 meters and cavern diameter of 70 meters are recommended [7, 11]. The caverns are usually vertically elongated in shape - several hundred metres in height and several tens of metres in diameter - and may have a volume of several hundred thousand cubic metres [7]. In a field with more than one salt cavern, it is safer to leave at least 300 meters between caverns [11,12].

Each cavern can have a storage volume from 300 000 to 750 000 m^3 or more [11], with an average volume of 500 000 m^3.

Salt caverns are suitable for underground energy storage technologies like: Natural Gas (UGS), Hydrogen (H2S) and Compressed Air Energy Storage (CAES) [7].

2.2. Host Rocks

Host rocks are poorly fractured and fissured rocks, where energy storage can be done in mined or engineered rock cavities; or in abandoned mines.

An engineered mined rock cavern consists of one or more galleries excavated in rock from a vertical shaft or inclined drift (Fig. 3) [7].

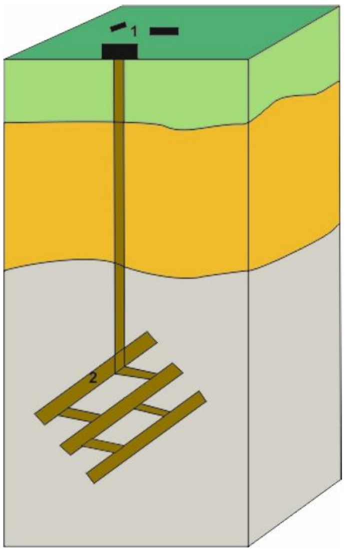

Figure 3. Schematic representation of mined rock cavern storage. 1- Surface facilities, 2- Galleries.

The types of host rocks that can be considered are [7,13]:

a) Igneous and Metamorphic rocks, like granite/granodiorite, quartzite, massive gneiss;
b) Sedimentary rocks, like shales and siltstones.

Sites are selected essentially on the basis of geological criteria like very low permeability to ensure containment, stability, level of fracturing, and hydrostatic equilibrium [7,13].

One of the general criteria that should be taken into account is depth, which should vary from 70 to 200 m.

Engineered mined rock caverns can be suitable for energy storage technologies such as: Natural Gas, Hydrogen, Compressed Air Energy Storage and Underground Pumped Hydro Storage with an underground reservoir.

Some of the abandoned mine shafts and galleries may be also suitable for storage functions and technologies like: Compressed Air Energy Storage, Underground Pumped Hydro Storage with an underground reservoir, and Thermal energy storage.

2.3. Porous Media

A porous media is a geological formation which has a reasonable storage volume and permeability provided by the intergranular voids, and that can be used as a reservoir for energy storage. These types of formations may be aquifers saturated with high salinity formation water, or depleted oil or gas fields (Fig. 4).

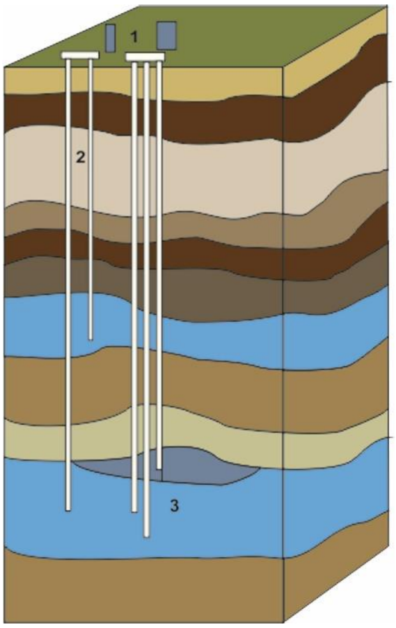

Figure 4. Diagram of a porous rock storage (Aquifer). 1- Storage Plant, 2 – Storage Wells, 3- Saline Aquifer.

These formations should be [14]:

- Overlain by an impermeable stratum (the cap-rock or seal) to prevent any upward migration of the injected fluids;
- Present a geological structure adequate to ensure lateral containment, for example in the form of an anticline;
- Placed at depths, between 500 and 2000 meters.

A reservoir in a porous and permeable geological formation can be used to store Natural Gas, CO_2, Compressed Air Energy Storage, Hydrogen or even Thermal Energy in the case of Aquifers.

3. LARGE SCALE UNDERGROUND ENERGY STORAGE TECHNOLOGIES

Large scale energy storage aims, typically, at storage of hundreds of MW of power capacity, for long term storage applications (fig. 5), and is more appropriate at the utility scale (e.g. large scale generation level, transmission and distribution levels).

Electric energy storage technologies involving the use of underground geological reservoirs offer large storage capacities and discharge rates [15], bringing all the advantages of a large scale energy storage system while minimising environmental and social impacts, and the need for surface space.

Storage technologies such as Pumped Hydro Energy Storage, Compressed Air Energy Storage, Underground Hydrogen Storage and Underground Natural Gas Storage, both with Power-to-Gas technologies and Underground Thermal Energy Storage, are considered large scale energy storage technologies because they can store large amounts of energy (hundreds to thousands of MW) and supply that energy in periods of hours to days (fig. 5).

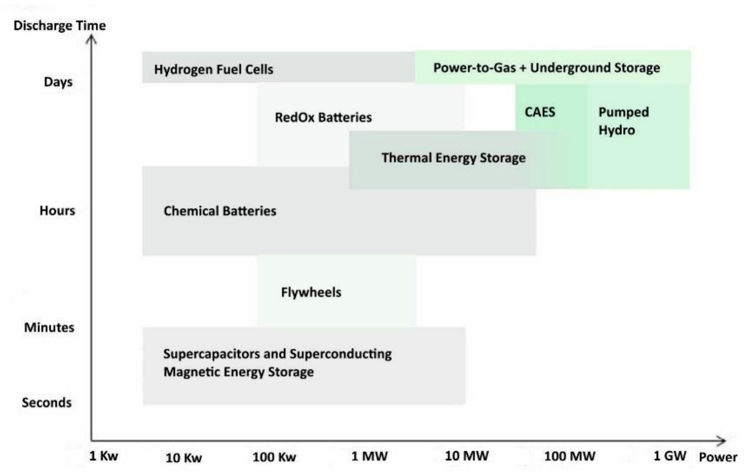

Figure 5. Electrical storage technologies according to discharge time and power capacity. Technologies adequate for geological storage are marked in green. Adapted from [15].

3.1. Underground Gas Storage (UGS)

Storage of natural gas in geological formations is a mature technology which has been used to meet load variations, maintaining a balance between demand and supply of gas, eliminating the daily peak demand, or even hours, thus mitigating fluctuations in volumes consumed [8].

The UGS technology applied to the generation of energy from renewable sources, is based on the Power-to-Gas (P2G) technology. P2G converts electrical power to a gas fuel, for instance methane, which can be stored underground and then used to generate electricity when there is a demand peak (fig. 6).

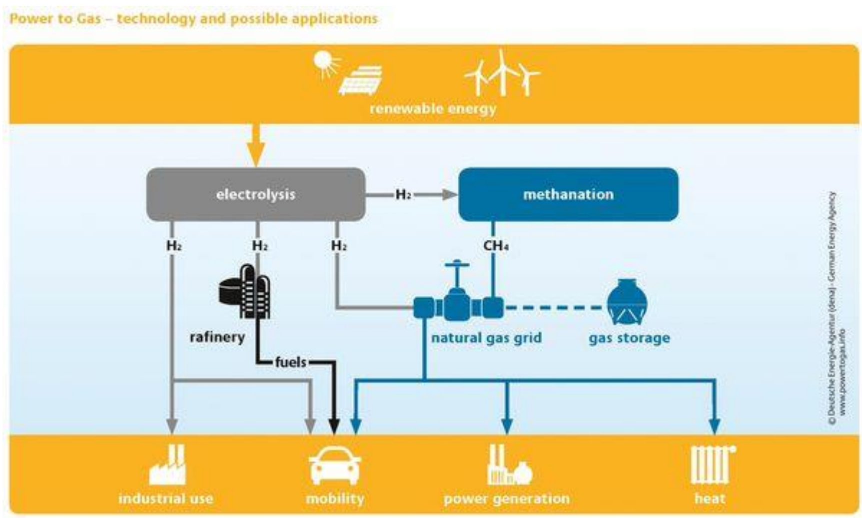

Figure 6. Diagram of Power-to-Gas technology and its applications, in [16].

The main types of reservoirs for UGS currently used are mainly depleted oil and gas reservoirs, aquifers, salt caverns [12,17,18]. However there are other reservoirs that have been developed in engineered cavities, abandoned coal mines and salt mines, but are more expensive than the main types.

3.2. Underground Hydrogen Storage (UHS)

Underground hydrogen storage is useful to provide grid energy storage for intermittent energy sources, like wind power [19,20,21], as well as providing fuel for electricity generation and for transports [19,22].

Hydrogen for energy storage purposes can result from using excess power from intermittent sources to produce hydrogen in high pressure electrolysis of water and electricity [20]. It has the potential to be injected into the regular gas grid and it is also a P2G process [7] (fig. 7).

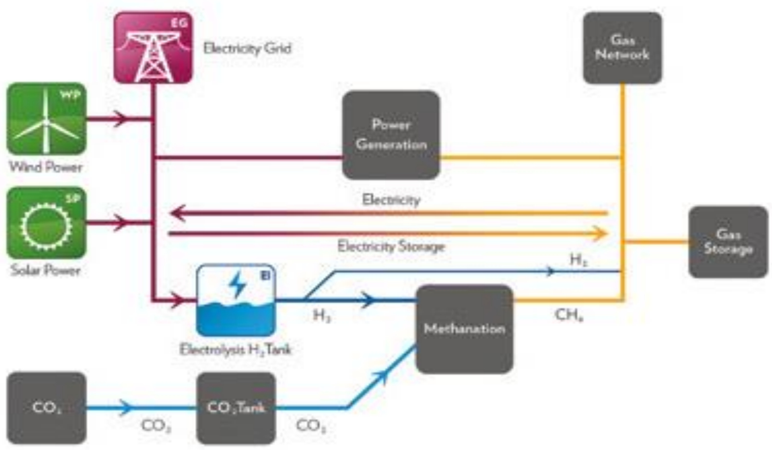

Figure 7. Methods for Hydrogen Storage, which use electricity to split water into hydrogen and oxygen by means of electrolysis, in [23].

The underground storage options for hydrogen are similar to those used for natural gas storage (depleted gas fields, saline aquifers and salt caverns) [7,19].

3.3. Compressed Air Energy Storage (CAES)

Compressed Air Energy Storage (CAES) converts electrical energy into mechanical energy by using electrical pumps to compress air [7,9,24]. In a CAES plant (fig. 8), ambient air is compressed and stored under pressure in a geological reservoir or underground cavern or even in surface reservoirs as tanks or pipes; when electricity is required, the pressurized air (which may be heated) is expanded in a turbine, driving a generator for power production [3].

The geological formations suitable for CAES are salt formations and salt caverns (Figure 6), depleted hydrocarbon fields, aquifers and also abandoned mines and engineered rock caverns in host rocks [5,10,24].

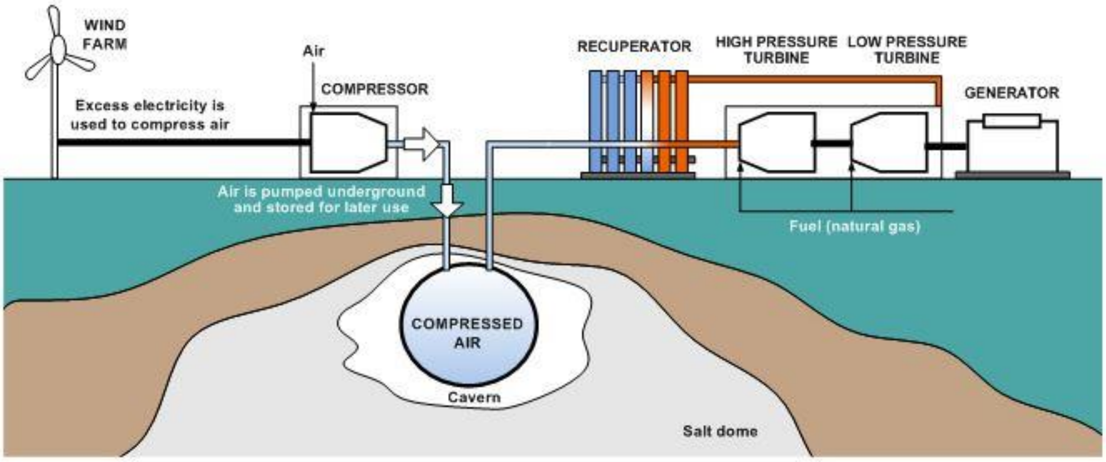

Figure 8. Possible configuration of a CAES system, using a salt dome reservoir, in [25].

There are two commercial CAES plants in the world, Huntorf in Germany and McIntosh in USA [5,10,24].

The Huntorf CAES plant, in Germany, was built in 1978 in two salt caverns (310,000 m3 total). It has a power capacity of 290 MW and 2-3 hours discharge period [7,26].

The McIntosh CAES plant, in Alabama, USA, has been operating since 1991, using a salt caverns for storage (560,000 m3), with a power capacity of 110 MW, and approximately 29 hour discharge period [7].

3.4. Underground Pumped Hydro Storage (UPHS)

The Underground Pumped Hydro Storage (UPHS) system is an adaptation of the Pumped Hydro Storage (PHS) concept with the integration of the lower water reservoir in an underground cavity or cavern (fig. 9) [5,15]. The gravitational energy is either established by elevation differences between the two reservoirs/basins or by using large pistons [7].

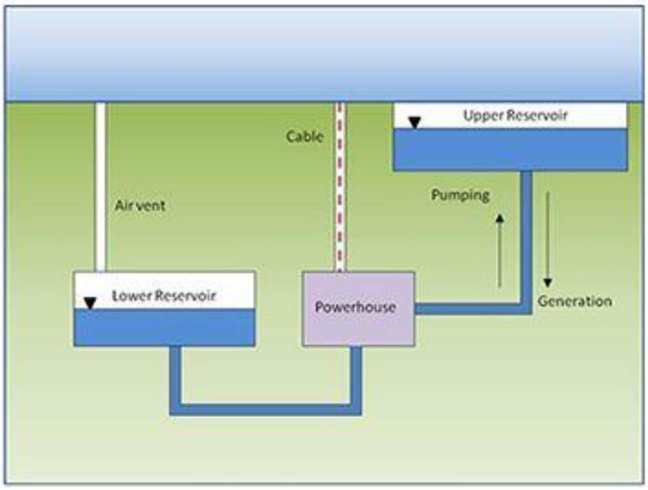

Figure 9. Schematic diagram of an Underground Pumped Hydro Storage (UPHS), in [27].

The suitable underground reservoir types that can be used for large-scale UPHS (0.5 to 3000 MW) are specifically mined cavities or abandoned mines. Non fractured igneous rocks under low lateral stress are considered ideal, however igneous extrusive rock, metamorphic rock, or sedimentary rock can also be used if its geotechnical and hydraulic characteristics are adequate [28]. The capacity of a large UPHS plant would, in theory, range from 1000 to 3000 MW [29].

3.5. Underground Thermal Energy Storage (UTES)

Underground Thermal Energy Storage (UTES) is a form of energy storage that provides large-scale seasonal storage of cold and heat in natural underground sites. Geological formations are suitable for thermal energy storage due to their high thermal inertia. If undisturbed, the ground temperature below 10-15 m depth is weakly affected by local climate variations and maintains stable temperature slightly above the local annual mean air temperature [30,31,32].

UTES can efficiently store thermal energy for long periods of time. The thermal energy can come from several sources including the summer and winter ambient air, solar energy and by-product waste heat from industrial and other cooling processes. During demand periods it can supply space cooling/heating, ventilation air precooling/preheating and process cooling [32,33].

There are three types of reservoirs for UTES: Aquifers (ATES), Boreholes (BTES) and Rock Caverns (CTES) (fig 10). The suitability of each type depends on the local site conditions including geological and hydrogeological conditions [32,34]. However, BTES is not limited to large-scale energy storage, it is suitable for both small- and large-scale energy applications, depending on the number of installed heat exchangers.

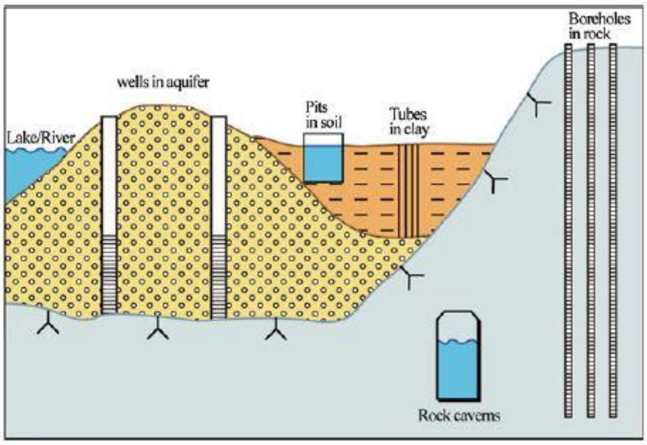

Figure 10. Schematic representation of the most common UTES systems, ATES, BTES, and CTES, in [30].

4. DISCUSSION AND CONCLUSIONS

In order to store large amounts of energy available during periods of excess wind or sun, underground reservoirs may potentially provide the storage capacity required for daily, weekly or even seasonal energy storage [18,35].

Some of underground energy storage technologies previously described can be applied in all of the defined reservoir types, but others are strict in terms of the acceptable criteria of the geological reservoirs and can only be applied in specific reservoir types (Table 1). Therefore, there is a “competition” for suitable storage formations, as one storage formation may be suitable for a number of uses, especially if surface uses and installations are considered [35].

The storage technologies are currently at different stages of development and present a wide range of Technology Readiness Level (TRL), from mature technologies with wide implementation, to just conceptual designs. Each type of underground reservoir has also different stages of techno-economic feasibility and maturity within each type of underground storage technology (Table 1).

Table 1. Suitability and currently known techno-economic feasibility and maturity of each underground storage technology within the different types of reservoirs. Adapted from [7].

STORAGES	Reservoirs	Natural Gas	Hydrogen	CAES	UPHS	UTES
Salt	**Salt Caverns**	●	○	●		
Host Rocks	**Engineered Cavities**	○	◊	◊	◊	
	Abandoned Mines			◊	◊	○
Porous Media	**Aquifers and Traps**	●	◊	◊		●
	Depleted Hydrocarbons Reservoirs	●	◊	◊		

Legend:

●: Mature technology, widely implemented;

○: Proven technology, sparsely implemented;

◊: Prospective technology, pre-commercial pilots and conceptual designs.

A sustainable planning of the use of the geologic subsurface is required to ensure that storage capacities are available where needed and not blocked by other types of use, either in the same location or in neighbouring locations. The planning of the subsurface also has to consider the conditions at the land surface and the available infrastructure, as well as protection areas e.g. for groundwater [35].

Specific site screening criteria determines the viability of the reservoir itself, and of the technology of underground energy storage chosen for that site.

Thus, in order to evaluate each type of technology for each possible type of compatible reservoir detailed site-scale geological studies need to be conducted to assess the suitability of a specific rock unit or site for a certain type of energy storage.

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