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Energy Geotechnology

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Energy Geo-Storage − Analysis and Geomechanical Implications

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Abstract

The increasing energy demand, the mismatch between generation and load, and the growing use of renewable energy accentuate the need for energy storage. In this context, energy geo-storage provides various alternatives, the use of which depends on the quality of surplus energy. In terms of power and energy capacity, large mechanical energy storage systems such as Compressed Air Energy Storage (CAES) and Pumped Hydro Storage (PHS) are cost-effective and suitable for centralized power generation. In contrast, sensible and latent heat storage are appropriate for distributed applications when excess heat is involved. Energy density estimations highlight the advantages of compressed air over elevated water, and latent heat over sensible heat storage. From a geotechnical standpoint, the operation of geo-storage systems exerts complex effective stress, temperature, wet-dry, and freeze-thaw cycles. Although these excitations may not cause monotonic failure, they lead to ratcheting or shakedown behavior, both of which must be carefully analyzed to ensure the proper long-term cyclic response of energy geo-storage systems.

Keywords: *energy storage, cyclic loading, compressed air energy storage, pumped hydro storage, thermal energy storage, wet-dry, cyclic temperature*

1. Introduction

Fossil fuels are the product of solar-driven photosynthesis accumulated for almost a billion years and they account for nearly 85% of the total primary energy consumption in the world (EIA, 2010). Unfortunately, the accelerated consumption of these resources over the past two centuries will eventually lead to supply limitations and ecosystem damage. In this context, the more extensive use of renewable energy sources is gaining relevance as part of a sustainable long-term energy strategy.

Renewable energy sources such as solar, wind, wave, and tidal energy often fluctuate anti-cyclically with electricity demand. For example, solar energy yields maximum output in the daytime whereas the electrical load usually peaks at night. Hence, the use of intermittent renewable energy sources for electric power generation underscores the need for energy storage (Cavallo, 2007; Denholm and Margolis, 2007; Mason *et al*., 2008). Large-scale storage systems are needed to accommodate the excess off-peak generation and to deliver high power during peak load (Ibrahim *et al*., 2008; McLarnon and Cairns, 1989). In addition, energy storage allows the operation of power plants at their highest efficiency throughout the year.

The most promising energy geo-storage systems are pumped hydro storage (Garg *et al*., 1985; Ter-Gazarian, 1994), compressed air energy storage (Allen *et al*., 1985; Giramonti *et al*., 1978; Succar and Williams, 2008), thermal energy storage (Hepbasli, 2004; Novo *et al*., 2010; Sanner *et al*., 2003), and stored energy in waste (Williams *et al*., 2003). Large-scale compressed air energy storage and pumped hydro storage have suitable storage capacities to satisfy current urban demands. On the other hand, distributed small-scale systems, such as thermal energy storage, are attractive for residential-scale applications.

Geo-materials involved in geo-storage systems experience complex cyclic loading that varies with the type and periodicity of the imposed boundary conditions. Generally, these excitations do not cause monotonic failure, but their repetitive application can gradually deteriorate the properties of geo-materials and affect the performance of geo-storage systems.

In this manuscript, we review geo-storage systems, provide simple analyses to assess their capacity and cost, and highlight the most important geotechnical challenges in their implementation. In addition, we identify cyclic loadings on geo-materials, investigate their behavior, and attempt to anticipate emergent phenomena and coupled processes that may compromise the long-term performance of energy geo-storage systems.

2. Energy Storage Systems

The requirements for an energy storage system depend on the type and the extent of the mismatch between energy supply and

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demand. The system must satisfy the transient capacity gap and the rate of energy delivery, or power. As a result, hourly, daily, and seasonal storage systems may be needed.

The volume V [m^3] of a storage system is a function of the stored energy density e_V [J/m^3], either the stored energy E[J] or the delivered power P[W], and the time of supply t [s] as follows:

$$V = \frac{E}{e_V} = \frac{P \cdot t}{e_V} \tag{1}$$

The duration of the energy storage is a function of the time delay between energy surplus and deficiency. Yet, storage is limited by stability constraints. For example, energy stored as fuel lasts decades whereas energy stored as heat and high pressure air is conduction- and diffusion-loss limited.

Energy storage depends on energy quality. High-grade mechanical, electrical, magnetic, and chemical energy can be readily converted into other forms of energy with high efficiency. For example, the commercial efficiency of an electric generator, defined as the electrical power output over the mechanical power input, can reach 95%. In contrast, thermal energy is low-grade energy since its transformation into a higher form of energy is limited by the Carnot efficiency:

$$\eta_C = 1 - \frac{T_L}{T_H} \tag{2}$$

where T_L [K] and T_H [K] are the low and high temperatures of the cycle. The storage process must prevent the conversion of high-grade energy into low-grade form. Table 1 summarizes the efficiency of typical energy conversion devices.

Examples of energy geo-storage in chemical form include national emergency fuel storage in underground caverns (e.g., Strategic Petroleum Reserve maintained by the United States Department of Energy and the Federal Oil Reserve in Germany),

Table 1. Energy Conversion Efficiency

From	To	Devices	Efficiency
Thermal	Mechanical	Heat engine	$\eta = \frac{\text{useful work output}}{\text{heat input}}$ Limited by Carnot efficiency$^{(1)}$ $\eta_C = 1 - \frac{T_L}{T_H}$ Eq. (2)
Electric	Mechanical	Electric motor	$\eta = \frac{\text{mechanical power output}}{\text{electric power input}}$ $\eta_{max} = 95\%$ $^{(2)}$
Chemical	Electric	Fuel cell	$\eta_{ideal} = \frac{\text{change in Gibbs free energy}}{\text{change in enthalpy}}$ $\eta_{ideal} = 83\%$ $^{(3)}$
Mechanical	Electric	Electric generator	$\eta = \frac{\text{electric power output}}{\text{mechanical power input}}$ $\eta_{max} = 95\%$

Note: (1) Cengel and Boles (2001); (2) USDOE (2004a); (3) thermal efficiency of an ideal fuel cell operating reversibly on pure hydrogen and oxygen (USDOE, 2004b)

and the commercial storage of natural gas, butane, propane, propylene, and gasoline in salt caverns, aquifers or depleted reservoirs (Bary *et al*., 2002; Katz, 1973; Thoms and Gehle, 2000). Liquefied natural gas and liquefied petroleum gas may also be stored in refrigerated caverns under very low temperatures; these extreme conditions require an adequate understanding of the behavior of geo-materials under freeze-thaw cycles (Glamheden and Lindblom, 2002).

2.1 Thermal Energy Storage

Thermal energy storage is recommended only when the available energy surplus is heat, for example, from solar water/air heating systems. The design of a thermal energy storage system mainly depends on the required heat output and the available space. Thermal energy can be stored as sensible heat or latent heat. Latent heat is preferred when the storage size is limited, but it is typically more expensive than an equivalent sensible heat storage system. In both cases, heat is recovered from the storage medium with a transfer fluid and a heat exchanger. Energy recovery increases with the thermal conductivity and the heat transfer coefficient of the medium. The main cost components of a thermal energy storage system are the cost of the heat storage material, the cost of the space of storage, and the cost of the heat exchanger.

2.1.1 Sensible Heat Storage

The energy density e_V [kJ/m^3] stored as sensible heat in a given material is a function of the material mass density ρ [kg/m^3], its specific heat capacity C_p [kJ/kg/K], and the change in temperature ΔT [K]:

$$e_V = \rho \cdot C_p \cdot \Delta T \tag{3}$$

Values of specific heat capacity and mass density for several substances are listed in Table 2. For example, the energy density of water subjected to ΔT=10ºC is e_V=42 MJ/m^3. The use of water as sensible heat storage is preferred over other materials, despite the limited range of operating temperatures, because of its low cost, wide availability, large heat capacity, low environmental impact, and the advantages of convective and conductive heat transport. Other advantages include simple heat exchanger geometry, simultaneous heat charging and discharging, direct integration with solar heating/cooling water systems, low cost of pumps and fans, and low corrosion with conventional materials (Farid *et al*., 2004; Sharma *et al*., 2009). In contrast, the use of rocks as sensible heat storage is more limited due to their low heat capacity, low thermal conductivity, and unknown response to long-term thermal cycling (Farid *et al*., 2004).

Underground thermal energy storage systems typically refer to large-scale sensible heat storage systems that combine the use of water with an underground reservoir. The system rejects or absorbs heat at the surface using a heat exchanger, and may be coupled to an aquifer, a cavern, or a gravel filled space (Novo *et al*., 2010). These systems are suitable for seasonal storage of

Table 2. Specific Heat, Thermal Conductivity, and Mass Density of Different Substances

Substance	Specific heat capacity C_p	Thermal conductivity λ	Mass density ρ
	[kJ / kg / K]	[W / m / K]	[kg / m^3]
Air (dry, 20ºC)[(1)]	1.0	0.03	1.2
Air (dry, 100ºC)[(1)]	1.0	0.03	0.9
Water (80ºC)[(1)]	4.2	0.67	972
Water (20ºC)[(1)]	4.2	0.60	998
Ice (0ºC)[(1)]	2.1	2.14	917
Ice (-80ºC)[(1)]	1.5	3.30	927
Quartz (0ºC)	0.7	6.8 to 11.4[(2)]	2650
Quartz (100ºC)	0.8	4.9 to 8.0[(2)]	2650
Granite[(3)]	0.9	2.9	2600
Salt rock	0.9	6.6[(2)]	2160
Paraffin wax	2.9[(4)]	0.17 (liquid)[(5)] 0.34 (solid)[(5)]	790 (liquid)[(5)] 916 (solid)[(5)]
Asphalt[(6)]	0.92	1.2	2200

Note: data from (1) Lide (2010); (2) Clauser and Huenges (1995); (3) Heuze (1983); (4) El-Dessouky and Al-Juwayhel (1997); (5) Zalba *et al.* (2003); (6) Chadbourn *et al.* (1996)

solar energy since low surface area to volume ratio reduces heat losses.

2.1.2 Latent Heat Storage

Materials absorb heat to change from solid to liquid or from liquid to gas, and release heat during the reverse phase change. The energy density e_V [kJ/m^3] in a latent heat storage system is proportional to the material specific latent heat for phase transformation L [kJ/kg] and the material mass density ρ [kg/m^3].

$$e_V = L \cdot \rho \tag{4}$$

The latent heat of transformation is large in many materials. For instance, the latent heat of fusion of water, 333 kJ/kg or e_V= 305 MJ/m^3 (properties of ice at 0ºC - Table 2), is equivalent to the sensible heat corresponding to a temperature increase from 5ºC to 78ºC (properties of water at 20ºC - Table 2). Figure 1 summarizes the melting point and specific latent heat of fusion for several phase change materials. In the temperature range between 10ºC and 60ºC, the latent heat of fusion of most materials ranges between 75 and 300 kJ/kg.

The desired properties of phase change materials include: for thermal properties, phase transition temperature in the range of operating temperatures, high latent heat for phase transformation, and high thermal conductivity; for physical properties, congruent melting in order to avoid composition differences between the solid and liquid phase, high density, small volume change during phase transition, and low vapor pressure; for kinetic properties, no supercooling during freezing and a high crystallization rate;

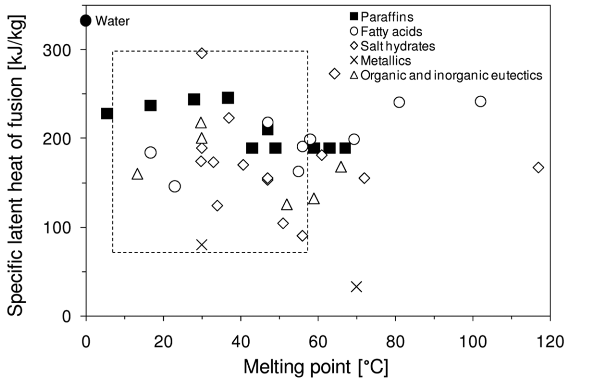

Fig. 1. Possible Phase Change Materials: Melting Point and Latent Heat of Fusion (Data from Sharma *et al.* 2009; and Zalba *et al.* 2003)

and for chemical properties, long-term chemical stability, compatibility with container materials, non toxic, and non flammable. Phase change materials generally have low thermal conductivity and expand upon melting (Garg *et al*., 1985; Sharma *et al*., 2009).

Phase change materials are classified into three main groups: organic, inorganic, and eutectic. Organic materials can be subdivided into paraffin and non-paraffin compounds. Paraffin compounds are among the most reliable in latent heat storage systems due to their availability, cost, and safeness. They also have a wide range of melting points, are chemically inert (stable below 500ºC), and exhibit volume change upon melting on the order of 10% (Dincer and Rosen, 2011; He and Setterwall, 2002). The latent heat of fusion of paraffins is about L=200 kJ/kg (Fig. 1). For a mass density ρ= 850 kg/m^3 (Table 2), the approximate energy density of paraffin is e_V= 170 MJ/m^3. However, paraffin compounds have low thermal conductivity and are chemically incompatible with some plastic containers.

The stability of the phase change material under thermal cycling (Farid *et al*., 2004) and the long-term stability of the surrounding geo-materials under induced chemical stresses (Wang *et al*., 1998) may limit latent heat storage. Other inherent difficulties arise from the solid-liquid interface movement as the phase change material melts: heat exchange decreases because the heat transfers through the low thermal conductivity liquid phase (see values for paraffin wax in Table 2) and a more complex heat exchanger configuration is required.

2.1.3 Geothermal Heat Pump

A geothermal or ground-coupled heat pump is a sensible heat storage system that combines a heat pump with a ground heat exchanger in a closed or open loop system configuration to extract thermal energy stored underground during the summer surplus. The heat pump exchanges heat with the soil mass via a fluid that circulates in pipes either placed directly in vertical boreholes or horizontal trenches or incorporated into foundation elements such as piles and basement slabs (Brandl, 2006; Hepbasli, 2004; Omer, 2008).

The number and size of heat exchangers depend on the thermal properties of the soil, the radius of influence and the interaction between neighboring systems, and the thermal coupling between the fluid, the pipe, the grout, and the soil in the borehole. Geothermal heat pumps can be used in combination with phase change materials to enhance thermal storage.

2.2 Mechanical Energy Storage

Large energy geo-storage systems are pumped hydro storage and compressed air energy storage.

2.2.1 Pumped Hydro Storage

Pumped hydro systems store potential energy using low-cost off-peak electric power to elevate water from a lower to a higher reservoir. The stored water is then discharged to run turbines and generate electric power during peak demand periods (Deane *et al*., 2010). The potential energy density e_V [kJ/m^3] of a fluid with unit weight γ [kN/m^3] raised to an elevation ΔH [m] is:

$$e_V = \gamma \cdot \Delta H \tag{5}$$

The energy density of water elevated $\Delta H = 100$ m is $e_V = 1$ MJ/m^3 (mass density of water at 20ºC - Table 2). This relatively small value can only justify large-scale storage, which requires large inundation areas.

The total stored energy can be expressed as a function of the discharge rate q [m^3/hr] and the duration of discharge t [hr]

$$E = \eta \cdot q \cdot \gamma \cdot \Delta H \cdot t \tag{6}$$

where the efficiency coefficient η accounts for energy losses during discharge. Approximately 70 to 85% of the electrical energy used to elevate the water is recovered during the generation stage. To avoid large inundation areas, pumped hydro storage systems are built using lakes as reservoirs or operated with underground, sealed mines (Uddin and Asce, 2003). Geographical constraints and high capital cost are the main drawbacks of these systems (Yang and Jackson, 2011).

2.2.2 Compressed Air Energy Storage

A conventional compressed air energy storage power plant utilizes excess low cost electricity generated during off-peak periods to compress and store a large volume of air in an underground cavity or reservoir. The stored air is later released and expanded with heat provided by fossil fuels to drive turbines that generate electricity during peak periods. Alternative adiabatic concepts couple compressed air energy storage with thermal energy storage to reduce fuel consumption using the heat generated during the compression stage to expand the air as it is released from storage to drive the turbines (Bullough *et al*., 2004; Najjar and Jubeh, 2006; Zaloudek and Reilly, 1982). The construction and operation of compressed air energy storage plants have less of an environmental impact and similar land use compared to conventional electrical generating facilities. In addition, locating a compressed air energy storage project is more flexible than a pumped hydro storage (Beckwith and Associates, 1983).

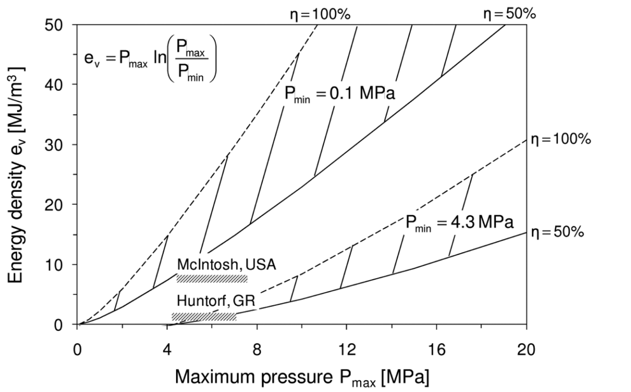

Fig. 2. Energy Density of Compressed Air in Isothermal Conditions (The energy density is a function of the maximum P_{max} and minimum P_{min} storage pressures, and the recovery efficiency η. Dotted and continuous lines represent 50 and 100% efficiency, respectively. The energy density of the CAES projects shown was calculated dividing their energy output (total electric energy minus the thermal energy used in the generation stage) by the total volume of the salt caverns.)

An ideal gas compressed in isothermal conditions has an energy density e_V [kJ/m^3] that is a function of the cycle's minimum and maximum pressures P_{min} and P_{max} [kPa]:

$$e_V = P_{\max} \ln\left(\frac{P_{\max}}{P_{\min}}\right) \tag{7}$$

For instance, the energy density in air compressed from $P_{\min} = 4$ MPa to $P_{\max} = 7$ MPa is $e_V = 4$ MJ/m^3. The energy density of an isothermal compressed air system is plotted versus the maximum air pressure for two efficiency values in Fig. 2. Moreover, the energy density of the existing compressed air energy storage power plants is shown in the range of working pressures.

Consider a hollow foundation of volume $V = 2$ m^3 and compressed air pressure ranging from $P_{\min} = 0.1$ MPa (atmospheric pressure) to $P_{\max} = 8$ MPa. The energy density is $e_V = 35$ MJ/m^3 (Eq. (7)). From Eq. (1), and assuming a recovery efficiency $\eta = 0.75$, the energy stored is 53 MJ. Taking a house power consumption of 2 kW, this distributed compressed air energy storage can provide 7.3 hours of power supply.

Various underground storage concepts have been considered for compressed air projects including solution-mined salt caverns, excavated rock caverns, existing porous rock formations, and abandoned limestone or coal mines. Salt domes can be economically excavated by solution mining (Allen *et al*., 1982b). Moreover, these formations tend to be homogeneous, impermeable, and self-healing (Chan *et al*., 2000; Fuenkajorn, 2006; Munson *et al*., 1999). The only two operating compressed air energy storage power plants in the World operate in salt caverns. One is installed in Huntorf, Germany (Crotogino *et al*., 2001) and the other is in McIntosh, Alabama, U.S. The operating air pressure ranges between 4 MPa and 7 MPa. The air temperature and relative humidity increase during compression (Landsbaum *et al*., 1955). Moisture, temperature, and the in-situ geothermal gradient determine the creep behavior of the salt rock (Note: air may be dried before storage). Salt caverns may fail due to creep, cavern roof collapse, subsidence, loss of cavern integrity, leakage, and salt fracture. These failure mechanisms must be considered to design the cavern geometry (e.g., shape, depth, diameter, height, and separation distance) and to define operational variables, such as the working pressure, the loading/unloading rate, and the air flux humidity (Allen *et al*., 1985; Thoms and Martinez, 1978).

Hard rock caverns involve expensive mining processes. Thus, some abandoned mines have been evaluated for potential storage (EPRI-DOE, 2003). In fact, an abandoned mine in a limestone formation with a shale caprock will be used as a storage reservoir in Ohio, U.S. This power plant will generate 2700 MW with a 30 hr supply duration (van der Linden, 2006). Hard rock caverns can sustain larger air pressure fluctuations (e.g., 7 and 8 MPa). Their design must account for fluctuations of the phreatic level and the chemical composition of the underground water, changes in the rock strength, the development of fractures and sliding blocks, and thermo-chemo-mechanical weakening of the rock mass (Allen *et al*., 1982a). Typical requirements for the host rock are low permeability ($<10^{-8}$ m/s), limited faulting and jointing to prevent instability and air leakage, thermal stability between 4 to 80°C, unconfined compressive strength larger than 25 MPa, limited creep and shrink/swell to control unexpected jointed rock behavior, and in-situ stress anisotropy smaller than 1.5 (Allen *et al*., 1982a).

Injected compressed air in aquifers displaces the in-situ underground water, which later provides the reaction pressure to recover the compressed air. This scheme can be regarded as a constant volume system because the movement of the air-water interface is negligible for daily cycles compared to the initial displacement of the interface (Allen *et al*., 1983; Katz and Lady, 1976). An appropriate underground reservoir requires large dimensions (e.g., the generation of 200 MW in 8 hours requires a 16 ha × 100 m reservoir), the presence of a confined aquifer, an impermeable cap rock, compatible underground water regime, high porosity, and high permeability of the rock formation (Allen *et al*., 1983). A new compressed air energy storage power plant is under development in a sandstone aquifer with these characteristics in Iowa, U.S. (Fortner, 2008). Fast, cyclic, multidirectional fluid flow, mixed fluid composition, and cyclic loading take place in the reservoir during operation. These processes can result in cementation loss, fines production, migration and clogging, accelerated dissolution, and mineral precipitation and oxidation. Anticipated problems include the enhancement of wellbore corrosion due to biological activity; turbo-machinery damage due to fine sand production and migration; and changes in permeability, corrosion, and flammability due to the presence of residual hydrocarbons (Katz and Lady, 1976).

The long-term performance of mechanical energy geo-storage systems requires continuous monitoring of the storage integrity. Volume reduction and subsidence induced by creep in salt caverns (Bérest and Brouard, 2003; Munson and Myers, 2000; Wierczeyko, 1983), and leakage of the stored substance caused by changes in hydraulic conductivity (Bérest *et al*., 2007; Fossan, 1979; Hinkebein *et al*., 1995) can be identified and mitigated with proper monitoring.

2.3 Stored Energy in Waste

Biomass accounts for nearly 65% of the total municipal solid waste stream in the U.S (including paper, food scraps, wood, and yard trimmings) (EPA, 2009). Biomass can be converted into energy through thermochemical, biochemical, and physico-chemical methods (Williams, 2007). Thermochemical conversion methods are suitable for low moisture-content materials and include combustion (incineration), gasification, and pyrolysis.

The potential energy density of waste e_V [kJ/m^3] regarding combustion can be quantified using the higher heating value HHV [kJ/kg] of the burnt waste multiplied by its mass density ρ [kg/m^3]:

$$e_V = HHV \cdot \rho \tag{8}$$

Higher heating values of some generic waste materials are listed in Table 3. For a mass density ρ=1200 kg/m^3 (Zekkos, 2005) and a higher heating value HHV=11 [MJ/kg] (based on the composition of municipal solid waste), the energy density of municipal solid waste is about e_V=13200 MJ/m^3.

Biochemical conversion methods are recommended for high moisture-content materials and include anaerobic digestion, aerobic conversion, and anaerobic fermentation. Both methods produce gas, which is later used to generate electricity or is converted into a biofuel, such as methane or ethanol. The potential ethanol extractable from paper/cardboard and wood & green is approximately 0.3 m^3 per dry ton of biomass. This estimation assumes that 50% of paper/cardboard and 40% of wood & green

Table 3. Higher Heating Value of Waste Materials (Williams *et al*., 2003)

Type of municipal solid waste	Higher heating value HHV [MJ / kg]
Paper/cardboard	16
Food	4.2
Leaves and grass	6
Other organics	8.5
Construction and demolition lumber	17
Prunings, trimmings, branches, and stumps	11.4
All non-film plastic	22
Film plastic	45
Textiles	17.4
Hydrogen	142

Note: Higher heating values of waste as received from the landfill stream can be recovered for fuel production (Williams, 2007).

2.4 Capacity and Cost Analysis

The design of an energy storage system accounts for the required energy E [kJ], the power P [kW], the time duration of supply t [s], the available volume V [m^3], and the energy density e_v [kJ/m^3] according to Eq. (1). Table 4 provides simple guidelines to estimate the energy density, the energy stored, the power delivered, and the costs of various energy storage systems. In addition, Fig. 3 highlights the energy stored and the power capacity of existing compressed air energy storage and pumped hydro storage power plants compared to other distributed storage systems.

Table 4. Energy Storage Systems: Guidelines to Estimate Energy Density, Power, and Cost

System	Energy density e_V [kJ/m^3]	Costs C_C
Sensible Heat Storage	$\rho \cdot C_p \cdot \Delta T$ Eq. (3)	Storage material Underground space Heat exchanger system
Latent Heat Storage	$L \cdot \rho$ Eq. (4)	
Pumped Hydro Storage (PHS)	$\gamma \cdot \Delta H$ Eq. (5)	Energy capacity Power capacity Balance of plant Power conversion Fuel/electricity Operation and maintenance
Compressed Air Energy Storage (CAES)	$P_{\max}\ln\left(\frac{P_{\max}}{P_{\min}}\right)$ Eq. (7) (isothermal conditions)	
Stored energy in waste	$HHV \cdot \rho$ Eq. (8)	Containment space Lining and cover system Gas recovery system

Note:
(1) Stored energy $E = V \cdot e_V$, where V is the volume of the energy storage system
(2) Power $P = E/t$, where t is the supply time duration
(3) Reference costs for CAES and PHS in Bradbury (2010), and Schoenung and Hassenzahi (2003)

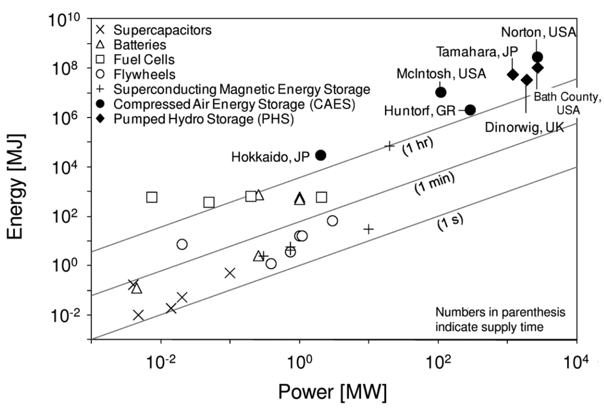

Fig. 3. Energy and Power Capacity of Storage Systems (Based on Schoenung 2001 with additional data from EPRI-DOE 2004, electricity storage association, Power Plants Around the World, and First Hydro Company.)

We use the levelized annual cost to compare various energy storage alternatives (Masters and Wiley, 2004; Schoenung and Hassenzahi, 2003). The levelized annual cost LAC [\$/kW/yr] is estimated with the fixed charge for capital equipment C_{FC} [\$/kW/yr], the levelized fixed operation and maintenance costs C_{OM} [\$/kW/yr], the levelized cost for replacement parts C_{RP} [\$/kW/yr], and the levelized costs for energy generation C_{EG} [\$/kW/yr] according to:

$$LAC = C_{FC}+C_{OM}+C_{RP}+C_{EG} \tag{9}$$

The fixed charge for capital equipment is calculated with the fixed charge rate FCR [1/yr] and the total capital cost C_C [\$/kW]:

$$C_{FC} = FCR \cdot C_C \tag{10}$$

Given the required time duration of supply t [s], the total capital cost C_C [\$/kW] is estimated using the energy storage cost C_E [\$/kJ], the power cost C_P [\$/kW], the balance of plant costs C_{BOP} [\$/kW], which includes the cost of the components and structures not considered in the other costs, and the power conversion system costs C_{PCS} [\$/kW] (Bradbury, 2010; EPRI-DOE, 2003; Schoenung and Hassenzahi, 2003):

$$C_C = C_E \cdot t + (C_p+C_{BOP}+C_{PCS}) \tag{11}$$

Figure 4 provides estimates of energy and power capacity costs for various energy storage systems.

The levelized fixed operation and maintenance costs are computed with the fixed operation and maintenance cost C_{OMF} [\$/kW/yr] and the levelizing factor for operation and maintenance cost LF_{OM} [−]:

$$C_{OM} = C_{OMF} \cdot LF_{OM} \tag{12}$$

The levelized cost for replacement parts is calculated using the

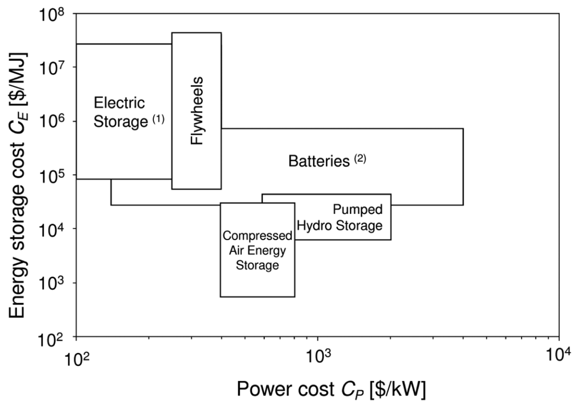

Fig. 4. Energy and Power Costs for Various Energy Storage Systems (Note: (1) Electric storage includes standard electrostatic capacitors, electrochemical capacitors, and superconducting magnetic energy storage; (2) Batteries include conventional, molten salt, lead-acid, and flow batteries (Data from Bradbury, 2010).)

annualized replacement cost C_{AR} [$/kW/yr] and the levelizing factor for operation and maintenance cost:

$$C_{RP} = C_{AR} \cdot LF_{OM} \tag{13}$$

Finally, the levelized costs for energy generation includes the cost of fuel and electricity charge:

$$C_{EG} = \left(C_{fuel} \cdot HR \cdot LF_{fuel} + C_{el} \cdot \frac{1}{\eta_{el}} \cdot LF_{el} \right) \cdot t_{year} \tag{14}$$

where C_{fuel} is the unit cost of fuel [$/kJ], HR is the heat rate [kJ/kJ], LF_{fuel} [−] is the levelizing factor for fuel, C_{el} is the unit cost of input electricity [$/kJ], η_{el} [kJ_{out} / kJ_{in}] is the storage efficiency, LF_{el} [−] is the levelizing factor for electricity, and t_{year} [s/yr] is the annual operation time (Schoenung and Hassenzahi, 2003). The variable operation and maintenance cost C_{OMV} [$/kWh-delivered] is generally neglected for energy storage systems (Bradbury, 2010).

The levelizing factors are calculated with the real discount rate d [−], the equivalent discount rate d' [−], and the levelization period n [−] (Masters and Wiley, 2004):

$$LF = \left[\frac{(1+d')^n - 1}{d' \cdot (1+d')^n} \right] \cdot \left[\frac{d \cdot (1+d)^n}{(1+d)^n - 1} \right] \tag{15}$$

The equivalent discount rate is calculated with the total escalation rate e_T [−]:

$$d' = \frac{1+d}{1+e_T} - 1 \tag{16}$$

The total escalation rate is a function of the real escalation rate e_R [−] and the inflation rate i_R [−] (Drbal *et al*., 1996):

$$e_T = (1+i_R) \cdot (1+e_R) - 1 \tag{17}$$

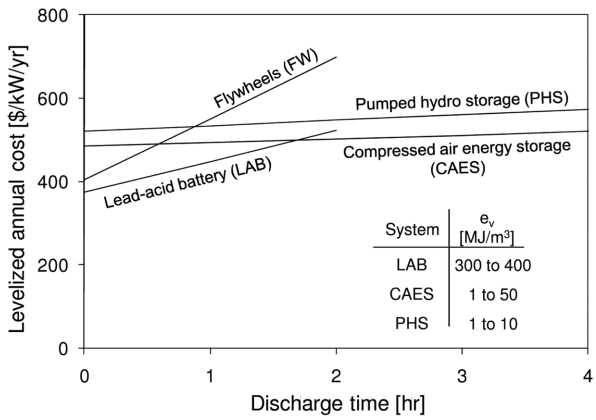

Fig. 5. Average Levelized Annual Cost of Energy Storage Systems (Flywheels and lead-acid batteries have less than two hours of discharge time according to Fig. 3 (Data from Bradbury, 2010, Schoenung and Eyer, 2008, and Schoenung and Hassenzahi, 2003).)

Figure 5 compares the average levelized annual cost of compressed air energy storage, pumped hydro storage, lead-acid batteries, and flywheel energy storage obtained following the described methodology. The results indicate that levelized annual costs of compressed air energy storage and pumped hydro storage are lower than those of other systems for discharge times longer than two hours.

3. Geotechnical Implications: Cyclic Response of Geo-materials

The long-term performance of energy geo-storage systems depends on the cyclic behavior of geo-materials. Periodic storage and release exert cyclic changes in effective stress, temperature

Table 5. Energy Storage Systems, Frequency and Type of Excitation

System	Frequency	Cyclic excitation	Coupled processes and emergent phenomena
Compressed Air Energy Storage (CAES)	Daily	Effective stress Temperature Relative Humidity	- Cyclic air flow causes fines production and migration clogging aquifers - Warm, compressed air enhances creep in salt cavern
Pumped Hydro Storage (PHS)	Daily/Seasonal	Effective stress Wet-dry	- Water flow through rock joints dissolves filling materials
Geothermal Heat Pump (GHP)	Daily	Temperature Relative Humidity	- Heat front dries soil reducing thermal conductivity - Vapor migration induces hygrothermal stresses
Sensible Heat Storage	Daily	Temperature	- Substance thermal expansion induces stress in heat exchanger system
Latent Heat Storage	Daily/Seasonal	Temperature Freeze/thaw	- Substance thermal expansion induces stress in container and heat exchanger system - Storage substance induces chemical stresses on geomaterials
Stored energy in waste	Months - years	Depends on the method	- Gas migration and fluid percolation induces dissolution of geomaterials and chemical stresses

(including freeze-thaw), and relative humidity (wetting and drying). In this section, the main characteristics of the behavior of geo-materials under cyclic excitations are discussed. Table 5 summarizes the type and the frequency of possible cyclic excitations, and anticipates emergent phenomena caused by coupled processes for every storage system.

3.1 Effective Stress Cycles

The change in effective stress around an underground cavern in an elastic medium as a result of cycles of internal pressure is illustrated in Fig. 6. The figure shows the mean and shear stress fields and the stress path of two points as the internal pressure increases from 4.5 MPa to 7 MPa.

The material response to cyclic loading can be described within the framework of the shakedown theory, which includes elastic response; elastic shakedown; plastic shakedown, or alternating plasticity; and ratcheting, or incremental collapse (Koiter, 1960; Melan, 1938; Sharp and Booker, 1984).

The elastic response refers to low-magnitude loads that do not cause plastic deformation, i.e., the strain level is below the linear threshold strain (Dobry and Swiger, 1979; Vucetic, 1994). Even in the small strain regime, the impact of repetitive loading on material properties and long-term behavior can be detrimental if the number of cycles is large. Elastic shakedown refers to loads above the "elastic limit load" and below the "shakedown limit load." In this regime, plastic deformation develops during a finite number of early cycles; thereafter, the material recovers elastically. If the applied load is larger than the shakedown limit, the material reaches a stable hysteretic cycle of deformation after several cycles of permanent deformation. This state is called "plastic shakedown," or "alternating plasticity." Finally, ratcheting, or incremental collapse, is a process in which the material continues to accumulate plastic deformation under loads larger than the shakedown limit and the material cannot adapt to cyclic loading. The long-term behavior of a system subjected to cyclic loading is determined by its ability to reach a state of shakedown.

The average state of stress, the imposed strain amplitude, the initial density, and the characteristics of the geo-material determine its long-term behavior under cyclic loading (Wichtmann, 2005). Figure 7 depicts the development of shear and volumetric strains during cyclic drained loading. Soil elements with an initially high stress obliquity mostly exhibit shear strain whereas elements subjected to an initial isotropic stress condition mainly develop volumetric strain. The figure also emphasizes that soil elements with high stress obliquity exhibit ratcheting in the long-term. In all cases, sediments reach a terminal density under repetitive loading (Narsilio and Santamarina, 2008).

Rocks subjected to cycles of effective stress may experience fatigue as shown in the stress-number of cycle space in Fig. 8. As the cyclic stress amplitude increases, the number of cycles required to cause failure decreases (Haimson, 1978; Scholz and Koczynski, 1979; Xiao *et al*., 2010). Fatigue in rocks is related to the development of intergranular cracks and their growth in preferential orientations (Kobayashi *et al*., 2009). It is enhanced by the presence of pre-existing cracks (Prost, 1988), and it is usually accompanied by volumetric strain, which is a function of the confining stress (Hadley, 1976; Scholz and Koczynski, 1979; Zoback and Byerlee, 1975). When the rock is saturated, the

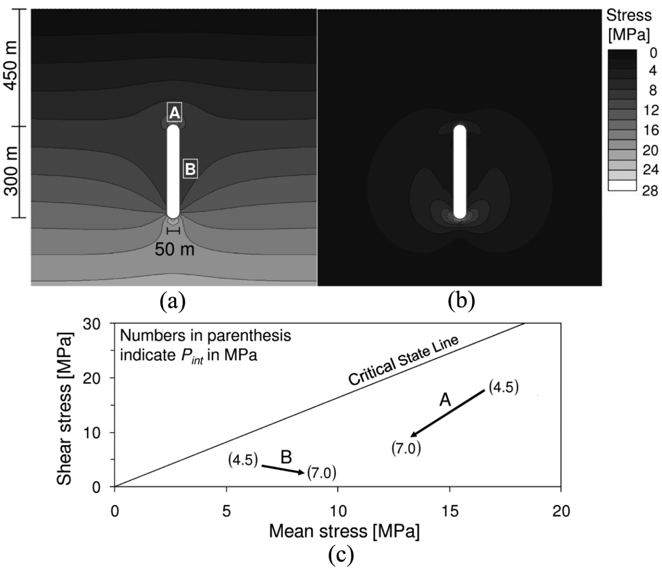

Fig. 6. Underground Cavity in Elastic Medium Subjected to Cyclic Internal Pressure P_{int} from 4.5 to 7 MPa: (a) Mean Stress, (b) Shear Stress for Internal Pressure of 7 MPa, (c) Stress Paths of Points A and B (Stress field computed using a gravitational stress field and plane strain conditions. Simulated conditions correspond to McIntosh salt cavern.)

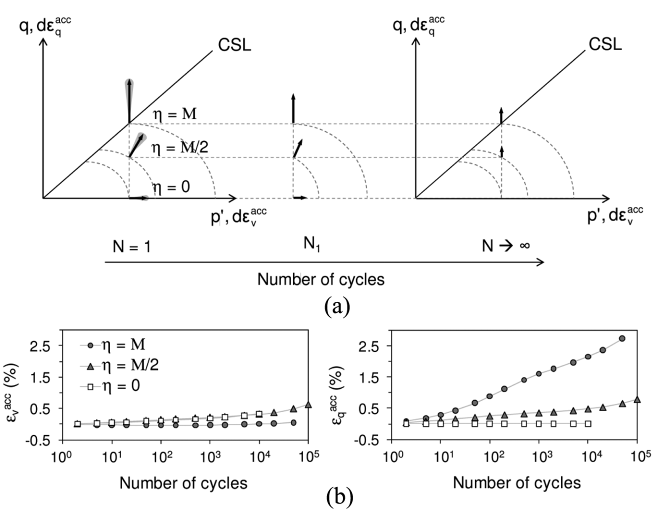

Fig. 7. Cyclic Behavior of Granular Materials: (a) Schematic Representation of the Increments of Volumetric ε_v^{acc} and Shear Strain ε_q^{acc} with the Number of Cycles for Soil Elements at Three Different Average State of Stress (The arrows represent the direction and magnitude of the accumulated strain.), (b) Measured Accumulated Volumetric and Shear Strain in Sand with the Number of Cycles for Each Average State of Stress (Data from Wichtmann, 2005)

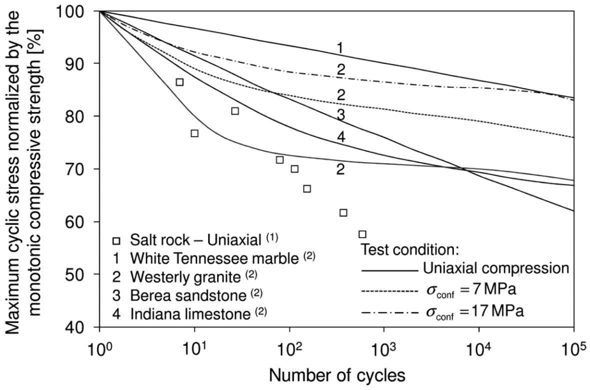

Fig. 8. Fatigue Strength of Various Types of Rock Subjected to Cyclic Loading in Uniaxial and Triaxial Compression (Note: data from (1) Fuenkajorn and Phueakphum, 2010; and (2) Haimson, 1978.)

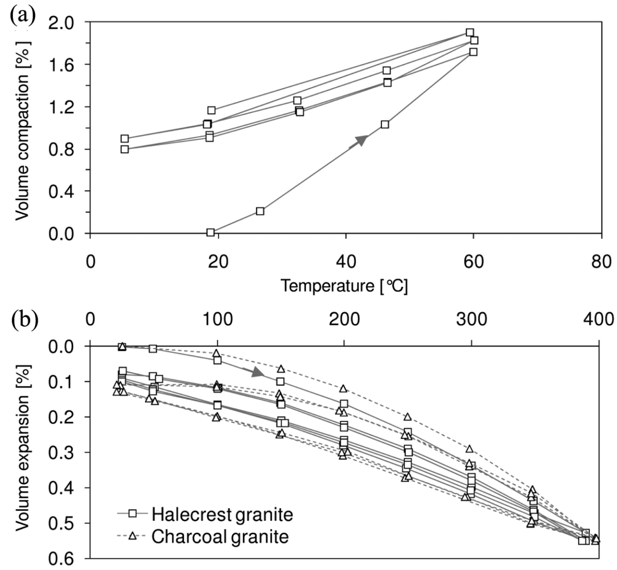

Fig. 9. Thermal Cycling on Geo-materials: (a) Sediments: Consolidation of Remolded Illite (Campanella and Mitchell, 1968), (b) Rocks: Expansion of Granite (Thirumalai and Demou, 1974)

opening and closing of cracks and the variation of porosity generates changes in pore-fluid pressure (Tien *et al*., 1990).

3.2 Temperature Cycles

A temperature change can cause sediment consolidation (Campanella and Mitchell, 1968; Towhata *et al*., 1993), swelling, an increase in pore water pressure (Abuel-Naga *et al*., 2007), a decrease in strength, and creep (Demars and Charles, 1982). Water drainage takes place if the rate of temperature increase and volume expansion is lower than the rate of drainage. Otherwise, temperature increase induces excess pore water pressure. The sediment response is analogous to consolidation due to changes in effective stress (Fig. 9a), and high plasticity soils are more sensible to temperature changes (Demars and Charles, 1982). When the temperature decreases, water and mineral volume contraction trigger suction and water absorption.

Subjecting a soil to cyclic thermal loading is similar to overconsolidation. Even though the volume change induced by the first cycle is more pronounced than the change induced by subsequent ones, cyclic thermal excitation can cause damage accumulation in the long-term. In particular, thermal cycles can lead to thermal ratcheting (Carson, 2000; Carson and Holmes, 2003) and the gradual rearrangement of grains due to differential thermal expansion (Chen *et al*., 2006).

Mineral heterogeneity and different thermal expansion may cause damage accumulation in rocks subjected to thermal cycles (Fig. 9b). A transition from brittle to ductile behavior is expected (Tullis and Yund, 1977). In jointed rocks, temperature cycles enhance relative movement of the joint faces and affect the properties of the filling materials (Thirumalai and Demou, 1974; Wong, 1982).

3.3 Freeze-Thaw Cycles

Freeze-thaw cycles exacerbate the effects of thermal cycling. Most sediments experience volume expansion during freezing and consolidation after thawing, resulting in net volume contraction. Sediments eventually reach a residual void ratio after a certain number of freeze-thaw cycles regardless of the initial void ratio (Viklander, 1998b). In addition, freeze-thaw cycles enhance particle segregation (Viklander, 1998a; Viklander and Eigenbrod, 2000).

Other consequences of freeze-thaw cycles are changes in permeability (Eigenbrod, 1996; Viklander, 1998b), liquid limit, grain size distribution (Qi *et al*., 2006), consolidation behavior (Graham and Au, 1985), shear strength (Leroueil *et al*., 1991), and stiffness (Simonsen *et al.*, 2002).

3.4 Wet-dry Cycles

Fine grained sediments subjected to wet-dry cycles develop volumetric swell/shrink changes. Eventually, these volumetric changes can lead to plastic deformations and desiccation cracks (Albrecht and Benson, 2001; Boardman and Daniel, 1996; Herrera *et al*., 2007; Lin and Benson, 2000).

Specific surface determines the pore size and the suction magnitude in fine grained soils. The matric suction $u_g - u_w$ [Pa] can be calculated with the surface tension T_s [N/m], the mass density of the soil particle ρ_s [kg/m^3], the void ratio e, and the specific surface S_s [m^2/kg]:

$$u_g - u_w = \frac{T_s \cdot S_s \cdot \rho}{e} \tag{18}$$

Suction and stiffness M [Pa], which is mainly controlled by compaction, determine the strain amplitude:

$$\varepsilon_{amplitude} = \frac{u_g - u_w}{M} \tag{19}$$

Most volumetric changes occur during the first few wet/dry

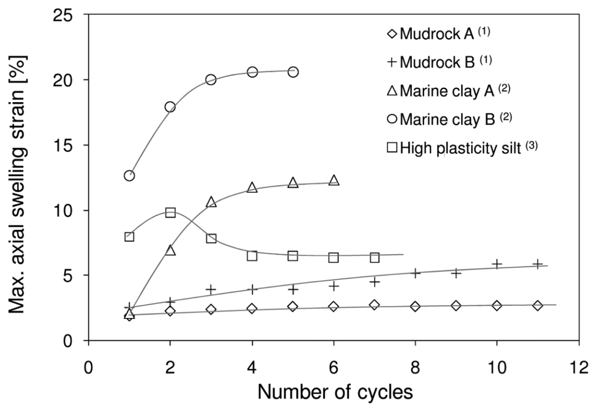

Fig. 10. Maximum Axial Swelling Strain of Sediment and Mudrock Samples Subjected to Wet-dry Cycles (Mudrock and marine clay samples tested in odometer cells under free swelling conditions. High plasticity silt tested in odometer cells with vertical surcharge of 50 kPa. Note: Data from (1) Pejon and Zuquette, 2002, (2) Osipov *et al.* 1987, and (3) Tripathy and Subba-Rao, 2009.)

cycles (scaly clays in Farulla *et al*., 2007; and expansive soils in Tripathy and Subba Rao, 2009, and Tripathy *et al*., 2002). Clay rocks, such as shales, also experience swelling due to the hydration of clay minerals, which are more susceptible to expansion (Harper *et al*., 1979). Figure 10 illustrates the vertical strain of soil and rock samples subjected to wet-dry cycles in odometer cells.

4. Conclusions

The increase in both energy demand and the use of intermittent renewable energy sources underscores the need for energy storage. Surplus electric power generated from fossil fuels or renewable energy must be stored as high-grade energy (e.g., mechanical and electric energy).

Energy geo-storage provides multiple alternatives for the storage of surplus electric power. The cost analysis of energy geo-storage systems indicates that mechanical energy storage, such as compressed air and pumped hydro, is suitable for large scale power systems since it has a lower levelized annual cost for high discharge times compared to batteries, flywheels, and electric storage systems.

Nominal energy density values for typical storage implementations rank as follows: 100 to 300 MJ/m^3 for latent heat, 10 to 300 MJ/m^3 for sensible heat, 1 to 50 MJ/m^3 for compressed air, and 1 to 10 MJ/m^3 for elevated water. Although thermal heat storage can reach higher energy densities, energy recovery is limited by the Carnot efficiency.

A compressed air energy storage system uses less volume than an equivalent pumped hydro storage system because higher energy density can be achieved in compressed air than in elevated water under typical conditions. In addition, the underground space of compressed air energy storage has a lower environmental impact.

Thermal energy storage either as sensible or latent heat is recommended when the available surplus energy is heat. These systems can be coupled with solar water/air heating systems. Under volume restrictions, latent heat systems are preferred because of their higher energy densities in the range of working temperatures.

It is worth noting that distributed geo-storage systems may also satisfy economic criteria, especially thermal energy storage systems. Distributed compressed air energy storage is limited by its low energy density compared to batteries and its higher levelized annual cost at low discharge times.

Energy geo-storage systems exert cyclic changes in effective stress, temperature (including freeze-thaw), and moisture on geo-materials. Although these excitations may not cause monotonic failure, their repetitive application can gradually deteriorate the properties of geo-materials and affect the long-term performance of geo-storage systems. Shakedown and ratcheting behavior can be developed in long-term cyclic storage systems.

The use of energy geo-storage systems enhances conventional power generation and optimizes the use of renewable energy sources. Therefore, energy geo-storage must be considered as an integral component of a sustainable energy strategy.

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