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AN ULTIMATE SOLUTION TO PHASING OUT FOSSIL FUELS - PART I: UTILITY-SCALE UNDERGROUND HOT-WATER STORAGE (USUHWS) FOR POWER PRODUCTION AND HEAT SUPPLY

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ABSTRACT

This paper introduces utility-scale underground hot water storage (USUHWS) systems and evaluates their performance to enable renewable energy sources to produce dispatchable utility-scale power or supply heat with minimized interruption and impact by weather conditions. The USUHWS systems could retain the thermal energy content of the stored hot water for years so that renewable energy can be extracted and stored at any time year-round and be used whenever needed. Another major objective of this paper is to introduce hot-water power and heat internets to interconnect storage systems, power plants, energy sources, and various water and heat users to efficiently manage the demands and supplies of power, heat, and water. Also, the USUHWS can be used to collect, store, and supply fresh water for communities. For more efficient construction of USUHWS systems, tunnel boring machines (TBMs) may be employed. In combination with renewable-energy-based thermal power plants using hot water as the heat-supply fluid, the USUHWS systems could have the potential to phase out most fossil fuels used today through renewable power production and heat supplies to combat global warming.

Keywords: *Underground Thermal Storage System, Hot Water, Solar Energy, Internet of Hot-Water Power and Heat*

1. INTRODUCTION

Energy storage for power and heat is an essential part of renewable energy strategies. Although the development of renewable energies has been underway for decades, they are still playing a supplementary role in total energy supplies, and fossil fuels remain to be the backbone of global energy sources, responsible for more than 80% of global energy consumption. The mainstream predictions indicate that to successfully fight against the global warming trend, major fossil fuels, such as coals, oils, and natural gases, must be displaced by renewable energies. Solar and wind power are the primary renewable energies being developed because of their abundance and limited environmental consequences. However, their inherent intermittence, seasonality, and low-capacity factors are hindering their potential to displace fossil fuels, and the related energy storage is becoming a bottleneck for the future development of renewable energies. It is under this backdrop that we first take a look at the sources of greenhouse gas emissions.

Table 1 summarizes the sources of global greenhouse gas emission and their relevance to energy storage according to EPA (2021). As can be seen from the table, after taking into account the 20% emission deduction due to the ecosystem's removal from the atmosphere in the sector of agriculture/forestry/other land uses, energy storage may play an important role in reducing more than 80% of greenhouse gas emissions into the atmosphere.

One thing notable from the above table is that if transportation is completely electrified, renewable electricity production, which replaces fossil-fuel-burning electricity production, could have the potential to displace up to 49% of the greenhouse gas emissions today because the displacement of fossil fuels for electricity production and transportation could substantially remove the greenhouse gas emission from fuel extraction, refining, and transportation.

The current energy storage systems for power generation include, but are not limited to, pumped-storage hydropower (PSH), compressed air energy storage (CAES), thermal energy storage materials such as molten salts, batteries for renewable power generation, hydrogen, and flywheels (EESI, 2019). However, not all storage systems are feasible for utility-scale storage from the viewpoint of long-term storage capability, large scale, resource availability, efficiency, costs, and environmental impact.

Table 1: Global emissions by economic sectors (EPA, 2021) and their relevance to energy storage

Emission Sources	Percentage	Beak down	Relevance
Electricity and heat	25%	Burning of coal, natural gas, and oils	Yes
Industries including chemical/metallurgical/mineral	21%	Onsite fossil fuel burning for processing heat and for materials transformation	Mostly Yes
Agriculture/forestry/other land uses	24%	Ecosystems removal offsetting 20% of emissions from this sector	Mostly No
Transportation	14%	Fossil fuels mostly gasoline and diesel for road, rail, air, and marine transportation	Yes
Buildings	6%	Onsite burning fuels for heat in buildings or cooking in homes	Yes
Other Energy	10%	Emissions primarily from fuel extraction, refining, processing, and transportation.	Yes

2. CHARACTERISTICS OF FOSSIL FUELS

Before the utility-scale storage potentials of major energy storage systems above are discussed, some characteristics of fossil fuels, which are the targets for displacement, are briefly reviewed. In this paper, the term fossil fuel is referring to major fossil fuels, such as oil, coal, and natural gas, responsible for greenhouse gas emissions. Fossil fuels provide most of the energy we need today, and an equally important fact is that fossil fuels are also among the best energy storage

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substances we can have. In addition to their high energy density or capacity, they have very stable and reliable energy storage characteristics which can store energy for years with little degradation and are ready for power production and heat supply whenever needed. Even with very high energy capacity, the global annual consumption of these fuels is enormous. In 2019 alone, global coal production was nearly 8.0 billion tons (IEA, 2020) and the consumption of petroleum and other liquid fuels was about 100.9 million barrels per day (b/d) (EIA, 2021), or about 5 billion tons in that year in terms of mass. The natural gas demand for the year 2021 was about 4000 billion m^3 (NGI, 2021), or about 3.0 billion tons in terms of mass. These numbers together for the three major fossil fuels would indicate that the total annual consumption of fossil fuels is more than 16 billion tons, and it could keep increasing in the future. This number by any standard is huge, which reflects how much fossil fuels are needed to store energy and used for power and heat globally. The world can afford this huge amount of fossil fuels because they are all-natural substances with abundant reserves, not manmade or chemically synthesized in factories. We produce them through drilling or mining extraction, not through fabrications although they may be processed. One processing example is oil refining which is a thermal separation process, not a chemical synthesizing process.

It is well known that the energy stored in a storage system is directly proportional to the mass of storage media involved. Therefore, it is important to evaluate how much storage materials are needed for renewable energy if all those fossil fuels will need to be replaced by renewable energies, such as solar and wind, which generally have a highly intermittent nature and low-capacity factor. This means that most of the power and heat for customers may need to be generated through storage systems if fossil fuel power plants are prohibited. Take solar energy for example, for a good sunny day, more than 60% of the energy for 24 hours may need to come from storage systems, as the duration to generate power directly from the sunbeams may be less than 10 hours. Yes, solar energy is abundant, and it has the potential to provide all the power and heat needed globally, but most of the energy received must be stored, so that storage systems may pick up the duty for the rest of 14 hours in a day without the backup of fossil fuel energy. On cloudy days, the duty of the storage system may be much longer than 14 hours. Moreover, seasonal rainy days, nationwide rainstorms and snowstorms, or wildfires may last for days, weeks, or even months, and storage systems must be able to store enough energy to provide power or heat for weeks if not for months.

Another hard fact is that except for nuclear fuels, which are not the subject of this paper, fossil fuels discussed above have the highest energy storage capacity per unit mass (energy capacity), and most of the other storage materials or media, as will be shown later in this paper, would have a storage capacity of less than 1% of fossil fuels. If on average, renewable energy storage materials have 1% energy capacity of fossil fuels and in the future, they need to store two weeks of the annual energy release of the fossil fuels today after they are displaced, the total amount of renewable storage materials needed would be: 16 billion tons × (14/365) × 100 = 61.4 billion tons. It is unimaginable if this amount of storage materials would be manufactured, which consumes energy and causes pollution. It is also impractical if we must create new mining industries to supply this amount of storage materials, which, in addition to pollution and environmental impacts, would cause resource shortage. Should this occur, we would get into an endless cycle and never get out of it to attain the net benefit of reducing greenhouse gas emissions through renewable energy sources. Therefore, just like fossil fuels, renewable energy storage materials should be natural and abundant and preferably in a liquid form for reduced storage size and easy transportation. Unlike fossil fuels, renewable energy storage materials should be clean and renewable without causing significant greenhouse gas emissions and adverse long-term environmental impacts, as well as low costs. The only candidate that satisfies the above wish list is water. The water is considered to be renewable because when the water disappears in one place, it may be found in another place. Also, the cost of water compared to other liquid storage media is almost free. Water sustains life on the earth including human beings and should be able to sustain our power and heat needs. The potential energy storage capacity of water is much lower than that of fossil fuels, but its abundance and the lowest costs could well offset the shortcoming of low energy storage capacity. Having discussed some preferred requirements for renewable energy storage materials, several existing storage systems are briefly examined.

3. BRIEF DISCUSSION OF EXISTING STORAGE SYSTEMS

According to the environmental and energy study institute (EESI, 2019), pumped-storage hydropower (PSH) has the largest installed capacity in the U.S. for utility power production, which consists of an upper and a lower reservoir connected via tunnels. Pumped-storage hydropower (PSH) uses the electricity generated by power plants to pump water to the upper reservoir from the lower reservoir to convert the electrical energy to the potential energy of water at a higher elevation. When renewable energy source such as solar or wind power is not available, the stored water is used to generate power through a hydroelectric power plant to convert the potential energy to electricity. The PSH uses water as the storage medium that is natural and abundant as well as clean and renewable. Additional advantages of the PSH include the ability to store a large amount of energy with a relatively high cycle efficiency of about 80%. Major disadvantages include low power storage density, safety considerations, land-use conflict with residents, and high initial investment as well as difficulties in securing permits and construction, which may lead to decade-long development timelines and billion-dollar price tags. Hydraulic dams must hold back large volumes of water at higher elevations and are consequently subject to the risks of construction failure, natural disasters such as flooding and earthquakes, or sabotage. If the water surface is not covered, the depletion of water in the reservoir under drought conditions could occur.

Compressed Air Energy Storage (CAES) has the advantage of providing significant energy storage at relatively low costs and having great flexibility to secure significant load management at the utility or regional levels. The disadvantages include low storage efficiency (EESI, 2019) of about 40-70%, meaning a substantial amount of electricity consumption for the air compression is lost and unable to be converted back into electric power. Another disadvantage is the low air density for storage. To overcome this problem, the air may need to be compressed to high pressure and high temperature. The high temperature could cause significant heat loss during the storage time and heating through the burning of fossil fuels such as natural gas may be required in the expansion process to avoid freezing conditions at the exit of the turbine.

Thermal energy storage materials, particularly molten salts, such as the solar fluid of the eutectic mixture of 60% sodium nitrate and 40% potassium nitrate (Cao and Faghri, 1991 and 1992; Caraballo et al., 2021), have the advantages of stable operation and relatively lower costs and have found a niche application in high-temperature concentrating solar power (CSP) production and thermal energy storage. One of the disadvantages of molten salts is their low energy storage density compared to fossil fuels. For example, if the solar fluid is working over a temperature range of 260-550°C with a maximum temperature drop of 250°C before being recharged to provide thermal energy for power generation, the maximum energy storage capacity is about: $c_p \times \Delta T = 1.53\times10^3$ (J/kg-°C) ×250°C = 0.38 MJ/kg. This is compared to the energy capacity of about 45 MJ/kg of natural gas (ET, 2022), which means that to store the same amount of energy of 1-ton natural gas, more than 118 tons of molten salts are needed. Therefore, for molten salts to play a significant role in replacing fossil fuels, a huge amount is needed. If they are clean and renewable as well as abundant, their use may not be a problem. However, molten salts are hazardous materials (harmful and oxidant) that are mainly used in fertilizers and explosives, and it is unclear if their health and environmental impacts could permit their large-scale uses. Also, it is unclear if a large mining industry needs to be established for its large-scale uses.

Batteries as utility energy storage have the advantages of high energy density, convenience for installation, and great performance in terms of fast energy storage from and release to the power grids. However, their uses as utility energy storage must compete for the resources with the uses for electric vehicles (EVs). Although the uses of batteries for utilities have seen fast growth for the stability of power grids in recent years, the predominant uses or primary markets are in the EV industry, which is considered to be the major approach to electrifying automotive vehicles through the power supplies from renewable energy sources to displace the consumption of oils. Even at the early stage of development of the EV industry with an overall automotive market share of below 5%, a serious batteries/battery materials shortage has emerged (Autoweek, 2021). To maintain the high growth rates of EVs in the coming years, much more minerals such as cobalt, nickel, and lithium must be mined and many more batteries manufacturing facilities must be built for battery production, which causes greenhouse gas emissions and environmental impacts as well as the availability issues of mining resources. Just recently, Serbia scraps the $2.4 billion Rio Tinto lithium mining project after a series of angry protests against the mining on environmental concerns (Reuters, 2022a). As of February 5, 2022, lithium prices have increased by 344.9% year over year (BMI, 2022) and it was predicted that EV growth will be responsible for more than 90% of the demand for lithium by 2030 (CNBC, 2022). Additionally, the long-term environmental impacts of battery disposal and recycling are uncertain. It is not the objective herein to predict the future of the EV markets; the point being made is that even at the early stage of the batteries' primary market, the bottleneck, as well as environmental impacts, have occurred. If batteries are to take a primary role in utility power storage to displace fossil fuels, they could face much more serious challenges, as many times more batteries are needed to store power for renewable power generation. According to EIA (2022), the total US electricity generation in 2021 was 4120 billion kWh, and after the deduction of the generation by nuclear and conventional hydroelectric power, the generation due to fossil fuels and renewable energy is about 3081 billion kWh. If fossil fuel generation is completely displaced by renewable energy and at one point in a year, 5% of that amount needs to be stored, the total electricity storage capacity required would be about 154 billion kWh. According to Reuters (2022b), by February 2022, the accumulated total number of electric vehicles in the U.S. was less than 2.5 million including SUVs and light-duty trucks. Although a substantial portion of that could be hybrids that require a much lower battery storage capacity, assuming that the average battery pack capacity of the EVs is 66 kWh of Tesla model 3, the total capacity of the EV batteries sold so far in the U.S. would be less than 0.165 billion kWh, a very small fraction of the 154 billion kWh discussed above. Furthermore, the costs and lifetime of the batteries could be serious issues. As will be shown later in this paper, the overall costs of utility power storage based on batteries could be more than 100 times more expensive than a preferred energy storage system at the present or in the future.

Based on the above discussions, current energy storage technologies, including batteries, pumped-storage hydropower (PSH), compressed air energy storage (CAES), thermal sensible-heat/phase-change materials, hydrogen technology, and flywheels, have their unique places in renewable energy storage and have found their niche or special applications. However, it is believed they might not be able to serve as the backbone or base load of renewable energy storage to displace the uses of fossil fuels.

4. UTILITY-SCALE UNDERGROUND HOT-WATER STORAGE (USUHWS) FOR POWER PRODUCTION AND HEAT SUPPLY

As discussed in prior sections of this paper, to serve as the storage medium of a backbone renewable energy storage system for displacing fossil fuel-based power and heat, the medium must be natural substance, abundant, low costs, renewable, and clean. The medium should also be readily available without involving mining operations and have a relatively high density in a liquid form for transportation. Even if it could not match the energy density of fossil fuels, the characteristics of abundance, low costs, and renewability could well compensate for the energy density mismatch. It is also understandable that once the fossil fuels are displaced, most of the thermal-energy-related power (such as combustion-based power), as well as industrial heat used at high temperatures (such as heat for mineral transformation) must be electrified. As a result, the global electricity demand could well be more than doubled, and a lot of new renewable energy power plants must be built.

It is hypothesized that storage systems using hot water as a thermal energy storage medium in conjunction with thermal power plants that use the hot water as energy sources could be the only solution to satisfy all the requirements above and be able to function as a backbone of renewable energy storage to enable both reliable energy storage and dispatchable power production. The hot water herein is preferably in a liquid form; however, the hot water could also be in a two-phase liquid-vapor mixture form or superheated vapor although their energy density may be lower. The hot water storage could be underground, in-ground, or above-ground. However, the underground storage, including in-ground storage with top cover and thermal insulation, could eliminate or minimize the risks of hydraulic dam failure, natural disasters such as flooding/earthquakes/sabotage, land use conflict with residents, potential to disrupt river ecosystems, and depletion of water in the reservoir under drought, which are normally associated with the PSH. Also, the underground storage could use earth soil as natural and effective thermal insulation to maintain the desired temperature of the hot water for a long time. Finally, the temperature of the hot water should be low or moderately high to accommodate large storage volumes for utility-scale power production.

To examine the potential of hot-water storage, the performance of a hot-water storage system is compared to its close competitor, the pumped-storage hydropower (PSH), in terms of energy density that is generally the most critical measure for an energy storage system. Since in both cases, the storage substance is water, the energy density, more specifically, work storage potential per unit volume of water for this case, may be used as a yardstick for comparison. In a PSH, if the average water level difference between the upper and lower reservoirs is h, and the combined conversion efficiency, including the pumping from the lower reservoir to the upper reservoir and the conversion from the potential energy of the stored water to mechanical work before the generator in the hydroelectric power plant, is η_P, the work stored by 1 m^3 of the water in the upper reservoir of the PSH system would be:

$$\eta_P \times \rho \times g \times h \qquad (1)$$

Since a lower reservoir of almost the same size as the water stored in the upper reservoir is needed, two cubic meters of volume will be needed for one cubic meter of water stored in the upper reservoir, while a hot water storage system may need only one storage reservoir for operation by taking the advantage of the thermal stratification phenomenon in the reservoir, a factor of 1/2 must be multiplied for comparison. Therefore, the work storage density for the PSH would be:

$$(1/2) \times \eta_P \times \rho \times g \times h \qquad (2)$$

For hot water storage, if the hot water is at a moderate temperature of 120ºC and the temperature drop in the power conversion unit of the thermal power plant before thermal recharging is ΔT, and the

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conversion efficiency of the unit from thermal to mechanical work is η_{th}, the work potential stored by 1 m^3 of hot water would be:

$$\eta_{th} \times \rho \times c_p \times \Delta T \quad (3)$$

For a typical PSH, if the average elevation difference between the two reservoir surface levels is 50 m and the overall conversion efficiency is 85%, while the temperature drop in the hot water thermal to power conversion unit is 40ºC and the thermal efficiency of the power conversion unit is only 10%, the ratio of the work storage density of the hot water storage to the work storage density of the PSH would be:

$$\frac{\eta_{th}\times\rho\times c_p\times\Delta T}{0.5\times\eta_P\times\rho\times g\times h} = \frac{0.1\times1000\times4.2\times10^3\times40}{0.5\times0.85\times1000\times9.81\times50} = 80.60 \quad (4)$$

In the above calculation as well as the following calculations of this paper, constant water density, ρ = 1000 kg/m^3, and constant water-specific heat, c_p = 4.20×10^3 J/(kg-ºC), are used. As can be seen from the above calculation, the hot water storage outperforms the PSH dramatically in terms of storage density. Furthermore, some other issues that may limit the use of the PSH are mentioned in the prior section of this paper and will not be repeated herein.

In addition to water, air also satisfies the conditions of being a natural substance and abundant as well as renewable and clean. However, its low density may be a disadvantage. The performance of hot water storage is compared to that of compressed air energy storage (CAES) under some given conditions. In this case, the compression ratio is assumed to be 3 and there is no heat loss from the compressed air after the compression before the turbine expansion to return the work to the grids. Assume the compression from a standard ambient temperature of 15ºC is isentropic at a constant specific heat ratio, the air temperature after the compression and the associated compression work per unit air mass are respectively calculated using relevant equations from Moran et al. (2011):

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = 288\times3^{0.286} = 394.3K = 121.2^{\circ}\mathrm{C}$$

$$\left(\frac{\dot{W}_{CV}}{\dot{m}}\right)_{rev} = \frac{k\times R_a\times T_1}{k-1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}-1\right] = \frac{1.4\times287\times288}{0.4}\times(3^{0.286}-1) = 106.8\ kJ/kg$$

The density of the air after compression is:

$$\rho_2 = \frac{p_2}{R_a\times T_2} = \frac{3\times10^5}{287\times394.3} = 2.65\ kg/m^3$$

Under idealized conditions where there is no heat loss during the storage time and the expansion process in a turbine to produce mechanical work is also isentropic, the produced work would be equal to the compression work calculated. However, in reality, the irreversible losses could be significant, and the losses can be evaluated through an overall efficiency that is about 40-70% (EESI, 2019). Assume that the overall efficiency (compression and expansion to power generation) is at the high end of 70%, the work-storage per 1 m^3 of the compressed air, or the energy density, would be:

$$\eta_{CAES}\times\rho_2\times\left(\frac{\dot{W}_{CV}}{\dot{m}}\right)_{rev} = 0.7\times2.65\times106.8\times10^3 = 198.1\times10^3\ J/m^3$$

Subsequently, the ratio of the energy density of the hot water storage system to that of the CAES would be:

$$\frac{\eta_{th}\times\rho_{water}\times c_p\times\Delta T}{198.1\times10^3} = \frac{0.1\times1000\times4.2\times10^3\times40}{198.1\times10^3} = 84.8 \quad (5)$$

In the above calculations, the hot water storage is at a pressure of about 2 bar corresponding to a temperature of 120ºC while the compressed gas is at a higher pressure of 3 bar. It could be recognized that the air could be compressed to a much higher pressure to increase its storage density through a higher compression ratio. However, a high compression ratio will result in significantly higher pressure for the storage container and substantially higher temperature after the compression, and significant heat loss may not be avoided. If this would occur, preheating for the compressed air using fossil fuel is needed before the expansion to avoid frozen conditions at the outlet of the expander.

It should be emphasized that the 10% thermal efficiency of the thermal power plant related to the hot water storage is the thermal efficiency of the heat-to-work conversion unit, not the overall efficiency of the entire power plant. The Carnot cycle efficiency of the conversion unit between a low temperature of 15ºC and a high temperature of 120ºC can be calculated as follows:

$$\eta_{Carnot} = 1 - \frac{15+273}{120+273} = 26.7\%$$

A second law efficiency in terms of the ratio of the actual efficiency over the corresponding Carnot efficiency would be 10/26.7 = 37.5%, which is generally achievable. Furthermore, a recent innovation revealed that at a hot-water temperature of about 100ºC as the heat source of a new thermal power plant, the utility-scale power production of more than 300 MW could be achieved with a thermal efficiency of above 15% (Cao, 2022a).

Like other energy storage approaches, hot water storage is subject to limitations. A major limitation is the pressure of the water because of the large storage volume needed. When an amount of water is stored in a closed container with substantial removal of air from the container, the pressure at the free surface of the water is close to the saturation pressure corresponding to the temperature of the water (thermodynamic pressure) in conjunction with hydrostatic pressure near the bottom of the container. Table 2 shows the gauge pressure of the thermodynamic pressure at different temperatures (Moran et al., 2011):

Table 2: Storage gauge pressure as a function of temperature.

Temperature, ºC	Gauge Pressure (bar)
≤ 100	0.0
110	0.423
120	0.975
130	1.691
140	2.603
150	3.748
160	5.168
200	14.53

It is well known that the Carnot cycle principle favors a higher heat source temperature. As the temperature increases, the power plant performance could improve. However, the Carnot principle only dictates a higher efficiency of the thermal-to-work conversion unit at a higher operating temperature. With an increased temperature, the storage pressure would increase exponentially, accompanied by much higher structural costs. For solar energy applications, a higher temperature would reduce the efficiency of the solar collectors significantly, which are used to produce hot water. It is also known that as the operating temperature is increased, the materials costs, heat losses, and operation costs could increase exponentially. As a result, a higher operating temperature may not necessarily produce an increased overall efficiency of a power plant, but with a high-cost penalty. Therefore, for present applications, the storage temperature is preferably maintained at a temperature below 150ºC, although higher temperature applications are still possible. When the storage water temperature is equal to or below 100ºC, the container can be maintained

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near the ambient pressure, which could be the best-case scenario for an underground large storage facility in terms of structural penalty.

In the following, some utility-scale underground hot water storage (USUHWS) facilities are introduced, and their feasibility and potential are demonstrated. Figure 1 shows schematically a top view of a USUHWS system and Fig. 2 is a schematic sectional view taken along line A-A in Fig. 1. For hot water temperatures meaningfully above 100ºC with a significant thermodynamic gauge pressure, the hot water may be contained in a container vessel, which may be concrete, steel-reinforced concrete, carbon fiber reinforced concrete, or metals, with a length *L* and a width *W*, as shown in Fig. 1, and a depth *H* as shown in Fig. 2. The external walls of the container are being held against by surrounding earth. Because of the large size of the utility scale under pressure, the top wall (not shown in Fig. 1, but partially shown in Fig. 2) of the container may be the most vulnerable part. For this reason, a plurality of internal supports (or internal walls) may be installed inside the reservoir, as shown in Figure 1, which divides the reservoir into smaller segments for pressure management and supporting the roof of the container. The water in the reservoir is interlinked through the openings in the internal walls, and water temperature and pressure at the same level of the reservoir can be approximately uniform even though thermal stratification would occur in the vertical direction. For safety considerations, at least a pressure relief valve may be installed as seen in Fig. 1. The span of the section would depend on the pressure loading and rooftop construction of the reservoir, among others. For hot water with a temperature of 100ºC or less, the construction of the reservoir can be simplified, and the costs significantly reduced due to zero-gauge pressure. As one of the choices in this zero-gauge pressure situation, the reservoir can be constructed similar to the construction of an in-ground swimming pool and the container can be replaced by pool walls or panels. The roof ceiling of the reservoir can be flat in conjunction with sufficient support. In either the container vessel or pool constriction, the land on top of the reservoir can be used for other purposes. For example, the land on top of the reservoir can be used for solar collectors, as shown schematically in Fig. 2. Because the hot water stored may be used as the heat source for power plants under open cycles, no chemical treatment on the water may be required other than simple filtration, which reduces costs.

For maintenance and lower cost considerations, the distance between the rooftop of the reservoir and the ground surface may be limited. Thermal insulation is critical to the present application to minimize the heat loss from the hot water to the ambient to achieve sufficient storage duration. Because the storage operation is supposed to be long-term, the heat losses through the external walls and reservoir bottom surfaces can be rather small due to the very thick surrounding earth that serves as natural and ideal insulation to these walls or surfaces. However, the insulation on top of the reservoir could be critical due to the limited earth soil thickness between the reservoir top and the ground surfaces. Engineered insulation layers may be employed to provide excellent insulation with a rather limited thickness (Cao, 2022b). However, earth soil under general conditions has a rather low thermal conductance of about 0.5 W/(m-ºC) (Kusuda, 1981 and Bergman et al., 2011), and natural insulation with moderate soil thickness may be sufficient to achieve the desired insulation goal.

After the USUHWS is introduced, the storage capacity of useful work for a given size of USUHWS is demonstrated. The thermal storage capacity of the USUHWS facility as shown in Fig. 1, E_{th}, can be calculated by the following relation:

$$E_{th} = L \times W \times H \times \rho \times c_p \times \Delta T \tag{6}$$

where ΔT is the average temperature drop of the hot water in the reservoir before being thermally recharged. If the efficiency of the thermal-to-work conversion of a power plant is η_{th}, the useful work stored would be:

$$E_w = \eta_{th} \times L \times W \times H \times \rho \times c_p \times \Delta T \tag{7}$$

If the power generation capacity of the power plant is *P*, which extracts the thermal energy from the storage system and converts it into power, the maximum duration in hours that the storage system can enable the continuous full power generation is:

$$P \times 3600 \times t_{hr} = E_w$$

$$t_{hr} = \frac{\eta_{th} \times L \times W \times H \times \rho \times c_p \times \Delta T}{P \times 3600} \tag{8}$$

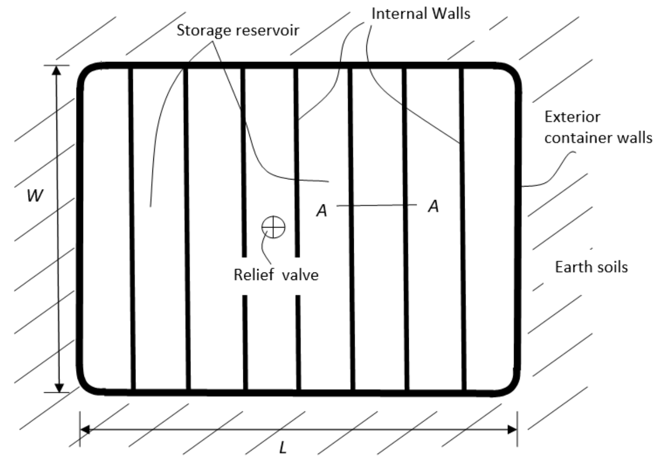

Fig. 1: A schematic top review of a hot-water storage reservoir with interior supporting structures (or walls) for the roof of the container.

If the size of the USUHWS reservoir is *L* = *W* = 500 m and *H* = 15 m, the power plant capacity is *P* = 100 MW, the thermal to work conversion efficiency η_{th} is again 10%, and water temperature drop before recharge ΔT = 40ºC, then

$$t_{hr} = \frac{0.1 \times 500 \times 500 \times 15 \times 1000 \times 4.2 \times 10^3 \times 40}{100 \times 10^6 \times 3600} = 175 \text{ hr} = 7.30 \text{ days}$$

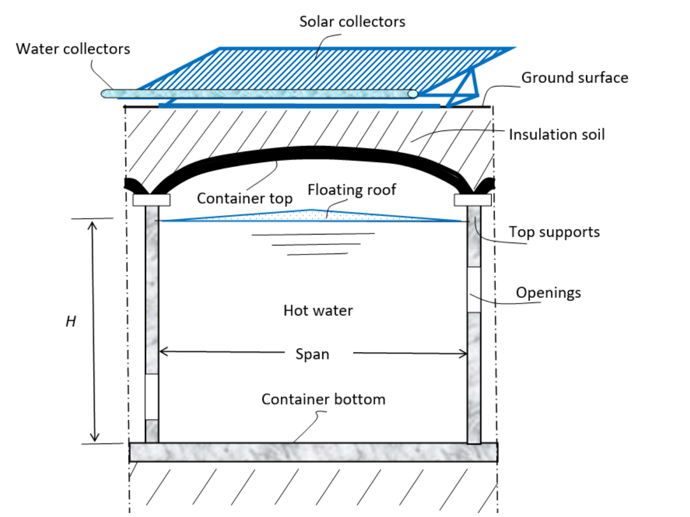

Fig. 2: A schematic sectional view of a segment of hot-water storage reservoir with soil insulation on top of the water container.

For a smaller power plant capacity of 10 MW, the results would be t_{hr} = 1750 hr = 73.0 days = 2.43 months. Furthermore, for an even longer power generation duration, the size of the reservoir can be simply increased without significant restrictions. For example, if the length and width of the reservoir are doubled, the power production durations for 100 MW and 10 MW could be more than 29 days and 9.7 months, respectively. The relatively large reservoir is used here to

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demonstrate the potential of hot-water storage that could deal with extreme weather conditions causing the unavailability of renewable energy sources for an extended time. From the above demonstration, the USUHWS could approach the characteristics of fossil fuels to produce electricity continuously and reliably over a long period of time. On the other hand, if the operation time duration is specified, the power capacity of a power plant that the hot water storage facility could enable would be calculated by Eq. (9) as follows:

$$P = \frac{\mu_{th}\times L\times W\times H\times\rho\times c_p\times\Delta T}{t_{hr}\times 3600} \tag{9}$$

Using Eq. (9) and under the condition that by working with other renewable energy systems such as solar PVs, winds, and geothermal, the storage system will only need to provide the heat source to the power plant for 14 hours a day before recharging, the power generation that the storage system could enable would be:

$$P = \frac{0.1\times 500\times 500\times 15\times 1000\times 4.2\times 10^3\times 40}{14\times 3600} = 1250\text{ MW} \tag{10}$$

The result above indicates that under the given conditions, the storage system could enable a huge power plant.

As mentioned earlier in this paper, one of the best advantages of fossil fuels is their stable storage characteristics with little energy losses over time. In the following, the storage stability of the hot-water storage is evaluated in terms of its potential as a backbone of renewable energy storage means. Appendix 1 derived a relation for the stable-storage duration as follows:

$$t_s = \frac{2R(1-\alpha)E_o}{(1+\alpha)(T_o-T_{am})} \tag{11}$$

where t_s is defined as the stable storage duration in seconds; R is the total thermal resistance related to the heat loss between the hot water and the ambient; α is the critical ratio of the usable energy storage E_s at t_s to the initial usable energy storage E_o at time t = 0; T_o is the initial temperature of the hot water, and T_{am} is the ambient temperature. The usable energy is defined based on the difference between the hot water energy at a given temperature and water energy at ambient temperature. Since the thermal energy of the hot water is directly related to its temperature, the ratio, or called critical ratio, is defined based on the following relations:

$$E_o = L\times W\times H\times\rho\times c_p\times(T_o-T_{am}) \tag{12}$$

$$E_s = L\times W\times H\times\rho\times c_p\times(T_s-T_{am}) \tag{13}$$

$$\alpha = \frac{E_s}{E_o} = \frac{T_s-T_{am}}{T_o-T_{am}} \tag{14}$$

If the critical ratio, for example, is 0.9, the period, during which the stored energy is equal to or greater than 90% of the initially stored energy, is defined as the stable storage period.

Consider the thermal insulation case as shown in Figs. 1 and 2 with the same dimensions used earlier in the calculation. Because of the large surface area, the edge effect is neglected. Also, due to the slow temperature change, the soil insulation layer on top of the storage reservoir is treated as a flat plate under quasi-steady-state conditions. If the earth layer on top of the reservoir has a thermal conductance of k_s = 0.5 W/m-^{o}C (Bergman et al., 2011), and an average thickness of insulation L_{in} = 2.5 m, the total thermal resistance would be:

$$R = \frac{L_{in}}{k_s A} = \frac{2.5}{0.5\times 500\times 500} = 2\times 10^{-5}\text{ W/}^o\text{C}$$

Again, use the same initial temperature of T_o = 120^{o}C and ambient temperature T_{am} = 15^{o}C, as well as the same underground reservoir size, 500× 500 × 15 m^3, one would have:

$$E_o = 500\times 500\times 15\times 1000\times 4.2\times 10^3\times(120-15)$$
$$=1.650\times 10^{15}\text{ J}$$

$$t_s = \frac{2R(1-\alpha)E_o}{(1+\alpha)(T_o-T_{am})} = \frac{2\times 2\times 10^{-5}(1-0.9)\times 1.65\times 10^{15}}{(1+0.9)\times(120-15)}$$

$$= 1.05\text{ year}$$

If the soil insulation thickness is increased to 5 m, then

$$t_s = 2.1\text{ years} \tag{15}$$

It should be mentioned that the soil thermal conductivity is sensitive to the type of soil and water content in the soil; therefore, soil selection and soil moist management for the earth surrounding the storage vessel should be considered. When the solar collector system is installed on a land surface on top of an underground hot water storage system and when earth soil is used as a thermal insulation means, the water collector mechanism, as representatively shown in Fig. 2, could have a function to reduce the moisture level of the insulating soils on top of the underground hot water storage system to maintain an acceptably low soil thermal conductivity for higher thermal insulation effectiveness in addition to collecting water for storage.

For a further reduced distance between the reservoir top and the ground surface with an even longer stable-storage duration, engineered insulation layers may be employed. Figure 2 also shows schematically the deployment of a floating cover at the free surface of the hot water. The floating cover minimizes the evaporation of water at the free surface and subsequent condensation at the inner surface of the top container walls, which cuts off a major heat transfer path between the hot water and roofing of the storage and could further increase the storage duration, although this benefit has not been taken into account in the above calculations.

The long storage duration feature of hot water storage is very significant to solar energy. Solar energy can be extracted and stored at any time and in any season year-round, and then stored heat can be used to produce power or provide heat whenever needed. In the current oil age, the national oil reserve has been established to deal with unexpected oil supply snags. Similarly, with the long-term storage potential of the hot water as demonstrated above, national hot water storage reserves can be established to deal with unexpected renewable energy shortfalls.

The USUHWS in Fig. 1 has a rectangular shape; however circular shapes such as cylindrical shapes may be employed, which could tolerate a higher thermodynamic pressure. Figure 3 shows schematically a plurality of underground circular hot water storage tanks for higher temperature applications including those providing industrial process heat at relatively high temperatures.

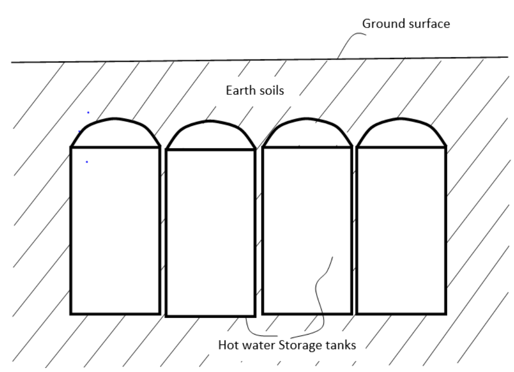

Fig. 3: A schematic view of multiple underground hot water storage tanks for higher pressure applications.

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The USUHWS could also be an integral part of the global freshwater strategy because the USUHWS would conserve the water that would otherwise be depleted due to the evaporation into the open air. According to WWF (2022), “Clean freshwater is an essential ingredient for a healthy human life, but 1.1 billion people lack access to water and 2.7 billion experience water scarcity at least one month a year.” Understandably, the storage capacity requirement for power and heat may vary substantially under different weather conditions or demands. At times, some of the water storage capacity may be used for other purposes. In this regard, some underground water storage may be part of drinking water or other freshwater water facilities to store water for residents with sufficient redundancy of storage capacity or when the hot water storage requirements for power generation and heat are reduced. Alternatively, because of the thermal stratification, the top hot water can be used for power generation, while the bottom of the reservoir would store colder water for freshwater purposes. Some of the storage may be used to collect rainfall water for feed water purposes or may be used to store excessive rainfall water to prevent local flooding. Yet some of the storage may provide needed water to the surrounding communities under drought conditions. Finally, if the power plant is decommissioned, the roofs may be removed, and the water storage facility would become an open-air lake. In summary, underground water storage, one way or another, is always beneficial. It causes no significant environmental impact on or risk to the surrounding communities and could benefit their ecological systems in the long run. In fact, underground water tanks have been installed for fire protection, drinking water, water irrigation, and water collections (Pmengineer, 2022 and Plastic-Mart, 2022), although of relatively small size.

5. COSTS CONSIDERATIONS

Using the same size and temperature drop before recharging the storage reservoir, the useful work storage potential in kWh can be calculated as below:

$$E_w = \eta_{th} \times L \times W \times H \times \rho \times c_p \times \Delta T$$
$$= (0.1 \times 500 \times 500 \times 15 \times 1000 \times 4.2 \times 10^3 \times 40)/10^3/3600$$
$$= 1.75\times 10^7 \text{ kWh} \qquad (16)$$

If this amount of work is to be stored by battery packs, the costs of the battery system are estimated. According to DOE estimation (Cole et al., 2021), the four-hour battery capital cost of utility-scale battery storage of lithium-ion systems in 2020 is about $340 per kWh. The medium projected price by 2030 is about $200 per kWh. If the projected cost is used, the future capital cost of the battery system to store the same amount of useful work as the hot water storage system above, with a round trip efficiency of 0.85, would approximately be:

$$(1.75\times 10^7 \text{ kWh}/0.85) \times \$200/\text{kWh} = \$4.12 \text{ billion}$$

If the price of 2020, which may be close to the current price, is used, the capital cost would be:

$$(1.75\times 10^7 \text{ kWh}/0.85) \times \$340/\text{kWh} = \$7.0 \text{ billion}$$

The present hot water storage system may be based on simple steel-reinforced concrete frames that are commonly used in ordinary building construction. For the hot water storage system having a maximum temperature of 120°C and a gauge pressure of 1 bar with natural thermal insulation of earth soils, the order of magnitude of the capital costs could be less than $100 million. Therefore, the costs of the hot water storage system could be two orders of magnitude lower than the corresponding battery system. More importantly, the lifetime of the battery system is only about 10-15 years, while the underground hot water storage system could function and last hundreds of years with necessary maintenance. It is well known that some ancient underground structures had survived for thousands of years. Also, the hot water storage is completely clean, while the long-term environmental impacts related to mining, recycling, and disposal of battery materials could be significant. As discussed in Section 3 of this paper, if fossil fuels are phased out, at one point in a year, 154 billion kWh of work in the U.S. may need to be stored. Assuming that the stored work (or electricity) of the average unit storage facility is equal to that from Eq. (16) with a capital cost of $50 million per facility and it would take 15 years to build the total storage capacity needed, the annual costs would be:

$$\frac{154\times 10^9\ kWh}{1.75\times 10^7\ kWh} \times \frac{1}{15\ year} \times \$0.05 \text{ billion} = 29.35 \text{ billion/year}$$

The capital costs above are not low but should be affordable, and the costs of other considerations such as batteries may exceed $4.0 trillion/year.

6. CONSTRUCTION OF HOT-WATER STORAGE SYSTEMS USING TUNNEL BORING MACHINES (TBMs)

For mountainous or hilly regions, flatlands may be scarce and their uses as hot water storage may compete with the uses for other purposes. To overcome this problem, the hot water storage facilities may be built inside the mountain or hills as tunnel hot water storage (THWS) facilities (Cao, 2022b), as schematically shown in Fig. 4. In this case, although other construction means may be used, popular Tunnel Boring Machines (TBMs) that are used to construct high-way tunnels and metro subways may be used to build the hot water storage in conjunction with related tunnel linings cost-competitively. Although the diameter of the tunnel may be limited to the order of 10 to 20 m, the length of the tunnel may be on the order of kilometers because of the automation of TBMs, and multiple tunnels can be made in the same mountain or hill to achieve a utility-scale for power and heat. An advantage of the tunnel storage is its circular shape which could accommodate a higher pressure under a higher temperature. Also, due to the very high length/diameter ratio, the heat loss from the entrance may be negligible, so the ideal thermal insulation could maintain the thermal energy of the hot water for many years. To reduce the water leakage out of the tunnel in case of an accident, a cavity may be made at the entrance of the tunnel to accommodate leaked water under accident with surrounding protection walls, so that most of the water could remain in the tunnel in such an event. To prevent the cavity from being flooded, it may be covered by roofing. Also, the relief valves may be installed although they are not shown in the figures.

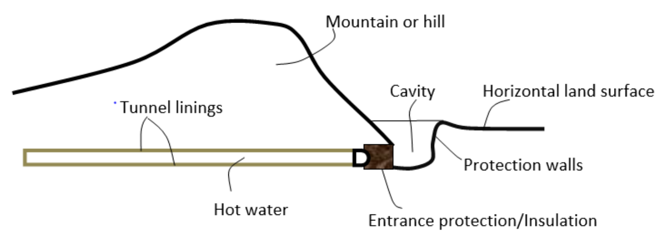

Fig. 4: Schematic illustration of a tunnel hot water storage facility in mountains or hills.

TBMs may also be used to construct tunnel hot water storage (THWS) on relatively flat lands, similar to the ways to construct subways. Figure 5 is a schematic illustration of an underground tunnel hot-water storage facility with tunnel linings as well as entrance protection and thermal insulation under the land surface. Similar to the case in Fig. 4, for reducing the water leakage out of the tunnel in case of an accident as well as the operation of TBMs and tunnel maintenance, a cavity may be made at the entrance of the tunnel to accommodate leaked water under accident with surrounding protection walls, so that most of the water could remain in the tunnel in such an event. To prevent the cavity from being flooded, the cavity may be covered by roofing. A plurality of the underground tunnel hot-water storage facilities may be constructed to attain utility-scale hot water storage

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capacity. For example, a number of the underground tunnel hot water storage facilities may be constructed in a direction generally perpendicular to the paper and the storage facilities may share the same cavity or roofing. Furthermore, the left end of the tunnel may tilt down and most of the water may remain in the tunnel if leakage were to occur from the entrance.

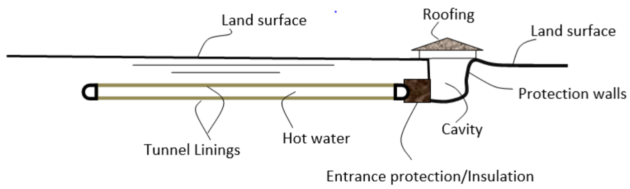

Fig. 5: Schematic illustration of an underground tunnel hot-water storage facility.

7. HEAT ACQUISITION FROM SOLAR ENERGY SOURCES

Based on the discussion earlier in this paper, enormous renewable energy storage is needed to displace fossil fuels. It is believed that solar energy is in a good position to provide the needed energy for storage as well as power and heat because of its abundance. In this regard, solar collectors are employed to collect solar energy in terms of heat and store it in hot water to generate power or provide heat for industrial and domestic consumers. Non-concentrating hot water heating solar collectors that could collect both direct and diffusion components of the solar flux, such as commercial hot water solar collectors, are the starting point for the present applications. Hot water solar collectors are well-developed non-concentrating solar collectors mainly for domestic hot water and home heating applications. With its low costs, high collector efficiency, and enormous popularity in emerging countries, its world installation has increased dramatically in the past 20 years. The global accumulated installed capacity of solar water heating collectors reached about 472 GW thermal in 2017 (SWH, 2022). In comparison, in the same year, the accumulated installed capacity of photovoltaics (PVs) was 401 GW electric (PV, 2022) and the accumulated installed capacity of concentrating solar power (CSP) was about 4.9 GW electric (CSP, 2022). The CSP also converts solar energy into heat, but it collects the direct component of the solar flux only and would miss the diffusion component that is normally 25-50% of the total solar flux. CSP concentrators work at a high temperature, and the cost level could be an order of magnitude higher than that of the water-heating solar collector.

The current trend of water heating solar collectors has moved towards evacuated tube collectors (ETC) on the basis of the heat pipe or U-tube configuration (Laurence et al., 2016; Jafarkazemi et al., 2016; and Sokhansefat et al; 2018). Because of the special applications of domestic hot water and home heating, its working temperature is often around 70^{o}C. At a higher temperature, the conventional non-concentrating solar collector may incur significant heat loss with substantially reduced collector efficiency. However, for the power generation and industrial applications of his paper, the collector's output temperature can be increased to above 100^{o}C with still good collector efficiency by using high-performance evacuated flat plate solar collectors (EFPSCs) for hot water production.

The non-concentrating EFPSC includes a flat absorber within an evacuated enclosure with a top glass cover and an array of pins to support the glass cover against atmospheric pressure loading (Moss et al, 2018), and the collectors have the potential to attain sufficiently high operating temperatures up to 250^{o}C with still reasonable collector efficiency. According to the performance curves for a commercially developed EFPSC by Benvenuti (2013), at an operating temperature of about 100^{o}C, the collector thermal efficiency is greater than 60% under a solar flux of 800 W/m^2. Under the same solar flux, the efficiency is about 54% when the operating temperature is increased to 150^{o}C. Benz and Beikircher (1999) developed a prototype collector for process steam production based on a commercially available evacuated flat-plate collector to achieve higher thermal efficiencies at temperatures up to 150^{o}C. According to the test results, at a steam temperature of about 115^{o}C, a collector efficiency of 62% was achieved while at about 165^{o}C, the efficiency was still about 45%. Low-cost commercially available EFPSCs are offered by TVP Solar (TVP, 2022). According to the company's product datasheet, at an ambient temperature of 30^{o}C and an operating temperature of about 120^{o}C, the collector efficiency is about 64%, while at 150^{o}C, the efficiency is still about 57%. EFPSCs are also being offered by some other companies. For example, SunMaxx (2022) and Indiamart (2022) offer flat plate solar collectors and customers can order the products online.

A competing solar water-heating collector category for a higher operating temperature is the concentrator augmented tubular solar collector. To attain an operational temperature range of 70–120^{o}C, Nkwetta and Smyth (2012) developed and tested a concentrator augmented solar collector module. The module was comprised of four evacuated tube heat pipe solar collectors. A compound parabolic trough collector (CPC) was added to the fourth heat pipe collector where the water temperature is highest at the outlet of the collector module. The experiment results showed at an outlet temperature of about 101^{o}C, the average collector efficiency was about 58%. Commercial solar collectors that combined ETC and CPC technologies had also been developed, such as Microtherm SK-6 and Thermomax DF-100-20 (Freeman et al., 2015). For Microtherm SK-6, the ETC-CPC collector efficiency could approach 60% at the collector mean temperature of 100 ^{o}C under a solar flux of 1000 W/m^2, while for Thermomax DF-100-20, the collector efficiency was about 50% at a collector average temperature of 84 ^{o}C under a solar flux of 875 W/m^2. It should be mentioned that the outlet water temperature is more important than the mean collector temperature for the application of this paper, which could be significantly higher than the average temperature. More recently, CPC heat pipe solar collectors are on the market (CPC, 2022a). According to the company's product description, the collector can reach 130^{o}C quickly and is cost-effective with stable performance and long service life. According to indiamart.com, in recent years, several startups have developed CPC-based solar collector systems for industrial applications with operating temperatures close to or above 100^{o}C (CPC, 2022b).

Another renewable energy source is geothermal energy. Although a thermal power plant may directly interact with a geothermal source without involving a hot water storage system, the hot water generated through the geothermal source may store in the storage system as needed. In the case that the temperature of the hot water generated by non-concentrating solar collectors is too low for efficient power production, while the hot water generated by the geothermal source is high, the water from the geothermal source may be used to boost the temperature of the hot water from the solar collectors. A similar boost may also be provided by solar concentrators commonly used in CSP.

8. INTERNET OF HOT-WATER POWER AND HEAT

Transportation of hot water between solar farms and storage systems as well as between the storage systems and power plants is essential to the operation of renewable energy systems. However, during transportation, some thermal energy associated with the hot water may be lost. In the following, the energy loss along a pipeline for how water transportation is evaluated. Figure 6 shows schematically an underground pipeline transporting hot water over a distance of L_p. If the heat loss per unit length along the distance is assumed to be the same, the total heat loss from the pipeline to the surrounding earth soil can be calculated by Eq. (17) (Kusuda, 1981).

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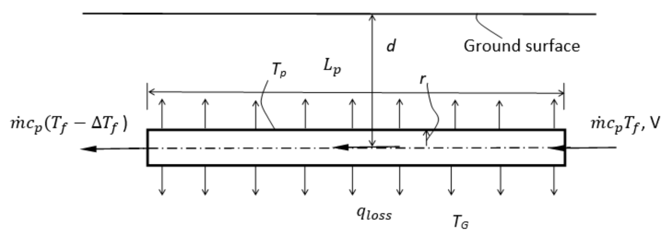

Fig. 6: Schematic of an underground pipeline transporting hot water over a distance L_p.

$$q_{loss} = \frac{2\pi k_s L_p (T_p - T_G)}{\ln\left(\frac{d}{r} + \sqrt{\left(\frac{d}{r}\right)^2 - 1}\right)} \tag{17}$$

where k_s is the effective soil thermal conductivity, L_p is the pipeline length, T_p is the pipeline surface temperature (for simple conservative calculation, it can take the inlet temperature T_f of the hot water), T_G is the undisturbed surrounding earth temperature that can take the ambient air temperature for simple calculation (Kusuda, 1981), d is the distance from the ground surface to the centerline of the pipe, and r is the radius of the pipeline.

With reference to Fig. 6, a heat balance over the entire pipeline would give:

$$\dot{m}c_p T_f = \dot{m}c_p(T_f - \Delta T_f) + q_{loss} \tag{18}$$

where ΔT_f is the temperature drop between the inlet and outlet of the pipeline. Solving the above equation for ΔT_f, one would have:

$$\Delta T_f = \frac{q_{loss}}{c_p \dot{m}} = \frac{2\pi k_s L_p (T_p - T_G)}{\ln\left(\frac{d}{r} + \sqrt{\left(\frac{d}{r}\right)^2 - 1}\right)} \frac{1}{c_p \dot{m}}$$

The hot water mass flow rate can be calculated by the following relation:

$$\dot{m} = \rho \frac{\pi}{4} (2r)^2 V$$

where V is the cross-sectional average velocity of the hot water in the pipeline. If k_s= 0.5 W/(m-°C), L_p = 100 km, $T_p = T_f$ = 120°C, T_G = 15°C, d = 3 m, r = 0.5 m, and V = 1 m/s, then

$$\dot{m} = 1000 \times \frac{\pi}{4} \times (2 \times 0.5)^2 \times 1 = 785.4 \text{ kg/s}$$

$$\Delta T_f = \frac{2\pi \times 0.5 \times 100 \times 1000 \times (120 - 15)}{\ln\left(\frac{3}{0.5} + \sqrt{\left(\frac{3}{0.5}\right)^2 - 1}\right)} \frac{1}{4.2 \times 10^3 \times 785.4} = 4.04^{\circ}\text{C} \tag{19}$$

Since the temperature drop is directly related to the energy loss of the hot water over the distance, the above result shows that only about 3.8% energy loss would occur over a long distance of 100 km, which gives a certain degree of freedom for transporting hot water between different users over distances. The above results are based on a simple underground pipe with natural insulation. With additional engineered insulation or a deeper layout, the above heat loss can be further reduced. A simple calculation of the pumping power requirement has also been undertaken with acceptable results. In general, a higher water transportation rate favors the reduction of heat loss, but a slower transportation rate favors a reduction in pumping power.

So far in the paper, hot water storage for power generation is emphasized. However, it is also essential to store hot water to provide heat for other uses. Therefore, the hot water storage facilities should be multifunctional. In addition to the purpose of displacing fossil fuel uses for power production, multi functionalities could make hot water storage more attractive as the costs of the storage system can be shared by several important uses. Since the energy storage density of hot water is much lower than that of fossil fuels, a large number of utility-scale storage facilities must be built. The multi-functionalities could provide additional incentives for the storage constructions with shared costs. In general, hot water storage could serve many purposes including, but not limited to, the following:

1. Replace fossil fuel as a backbone of renewable energy storage for power grids to generate power stably and reliably whenever needed.
2. Provide process heat for various industries with reduced burning of fossil fuels.
3. Deliver hot water to metropolitans or cities for home heating `that may require hot water at a relatively low temperature.
4. Provide hot water for domestic uses such as dishwashing, showering, and laundry.
5. Supply hot water for agricultural communities including food processing.
6. Store water for water treatment facilities of metropolitans or cities when surface water is not available or in short supplies to produce drinking water or for other freshwater uses of the communities.

The multi-functionalities of the storage systems would require interaction and interconnection of different sources and users through fluid-transportation pipelines. Therefore, the internet of hot-water power and heat is introduced (Cao, 2022b). Figure 7 is a schematic illustration of a local area of hot-water power and heat internet.

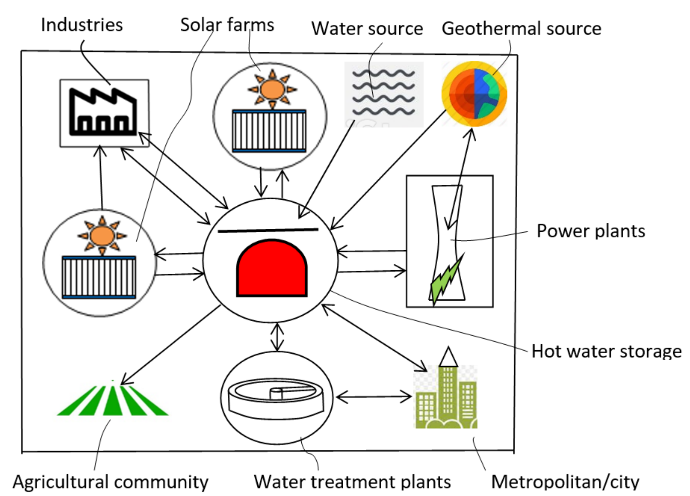

Fig. 7: Concept of a local area of hot-water power and heat internet.

Referring to Fig. 7, a hot-water storage facility is interconnected with various users and suppliers through one-way or two-way fluid transportation lines (the lines with at least an arrow) including, but not limited to, power plants, solar collector farms, geothermal heat sources, industries, metropolitan/cities, water treatment plants, agricultural communities, and water resources. The interconnected system is centered around the storage facilities and may serve a given area for power production, heat supplies, and water uses, which may be referred to as a local area of hot-water power and heat internet. The interconnection could facilitate the sharing of hot water storage systems and power plants as well as the heat and water resources and make the operation of a given area more efficient and more reliable. The interconnection with industries has second importance. In addition to providing process heat to some industries, some other industries could use water to recover some thermal energy from relatively high-temperature waste-heat sources generated by those industries, which would otherwise be discharged into the ambient without recovery. The

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hot water generated through the heat recovery would be delivered to the storage system and be used to produce power or for other heat uses.

It should be pointed out that additional systems may be added to the internet. Interconnections that bypass the storage facility, such as the direct connection between the solar farm and industries and the direct connection between the power plant and geothermal source in Fig.7, can also be included. Also, the internet could be centered around a different system other than the storage system. Furthermore, several local areas may be interconnected through pipelines to form a large area, as schematically shown in Fig. 8. The interconnection could facilitate the sharing of hot water storage systems and power plants as well as the heat and water resources and make the operation of a large area more efficient and more reliable.

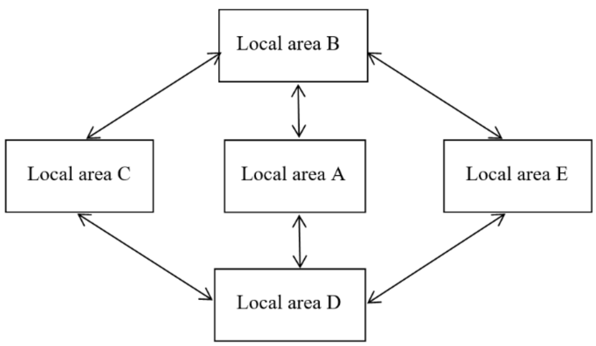

Fig. 8: A larger area of hot-water power and heat internet comprising several local areas.

Although at the higher end of temperatures, the process heat for industrial uses could be largely electrified, oil, molten salts, and other thermal energy storage (TES) materials or phase-change materials (PCMs) may be used as a storage medium as they may not require high storage pressure to reduce the costs. The use of heat at high temperatures for industries should be more economical than the use of electricity. As a result, the hot water storage system may include some oils, molten salts, or other TES materials and PCMs as high-temperature storage media to more fully address the demands for industrial heat. Also, CSP may be an important component of overall renewable power generation. Therefore, TES, PCMs, and CSP may also be part of the hot-water power and heat internet although they are not explicitly shown in Fig. 7.

9. CONCLUSIONS

1. In this paper, the performance characteristics of major fossil fuels currently being used for utility-scale power and heat were discussed and it was concluded that to match the performance merit matrix of fossil fuels for their displacement, the energy storage media for renewable energy must satisfy the conditions of being a natural substance, abundance, renewability, low costs including for transportation, and no significant long-term environmental impacts. The only storage medium that meets the above conditions is water. After examining existing storage systems and considering practical constraints, it was hypothesized that utility-scale hot-water storage systems in conjunction with thermal power plants are the only global solution to provide a backbone of renewable energy storage for producing dispatchable power and supplying heat reliably without involving fossil fuels.
2. The performance of utility-scale underground hot-water storage (USUHWS) systems was evaluated against the PSH and CAES, and the results showed that USUHWS could outperform the PSH and CAES by more than 80 times in terms of work storage density. It was found that USUHWS could provide hot water to thermal power plants as the heat source to produce power on a utility-scale of more than 100 MW for long time periods. The USUHWS can also maintain the thermal energy content of the stored water for years; therefore, renewable energy can be extracted and stored at any time year-round and be used whenever needed.
3. The concept of hot-water power and heat internets was proposed, which could interconnect storage systems, power plants, energy sources, and various water and heat users to efficiently manage the demands and supplies of power, heat, and water.
4. Modern construction technology of tunnel boring machines (TBMs) can be used for tunnel hot-water storage (THWS) systems. In particular, the hot-water thermal storage systems can be built into mountains or hills, which provides some ideal thermal insulation and structural integrity.
5. The solutions outlined here in this paper may represent an example of Nature-Based Solutions (NBS). In the current society featured by modern technologies, there could be a tendency to employ complex technologies to solve a problem, even a nature-related problem. Global warming is a nature-related problem, there could be underlying nature-related, simple solutions to this problem. It is believed that USUHWS could be one of such solutions. However, this paper missed an essential component of the solution: the thermal power plant. Please read Part II of this paper: Air-Water Thermal Power Plants (Cao, 2022c) to close the loop of this solution.

NOMENCLATURE

A	Heat transfer surface area, m^2
CAES	Compressed air energy storage
c_p	Specific heat of hot water, J/(kg-^{o}C).
d	Distance from the pipeline to the land surface, m
E_{th}	Thermal storage capacity of the USUHWS facility, kJ
E_w	Useful work storage capacity of the USUHWS facility, kJ
E_s	Usable energy storage at t_s, kJ
E_o	The initial stored usable energy of the hot water reservoir at t = 0, kJ
H	The height of the USUHWS reservoir, m
h	The average liquid level difference between the upper and lower reservoirs of a PSH, m
k	Specific heat ratio of air
k_s	Thermal conductivity of insulation soil, W/(m-^{o}C)
L	The length of the USUHWS facility with a rectangular cross-section, m
L_{in}	Insulation thickness, m
L_p	The length of a pipeline, m
$\dot{m}$	Air or water mass flow rate, kg/s
P	Thermal power plant capacity, MW
p	Pressure, Pa
p_1	Air pressure before compression, Pa
p_2	Air pressure after compression, Pa
PSH	Pumped-storage hydropower
q_{loss}	Heat loss from the pipeline, W
R	Thermal resistance of the insulation layer, ^{o}C/W
R_a	Gas constant, J/kg-K
r	Pipeline radius, m
T_{am}	Ambient temperature, ^{o}C
T_G	Undisturbed surrounding earth temperature, ^{o}C
T_o	The initial temperature of the hot water, ^{o}C
T_p	Pipeline surface temperature, ^{o}C
T_f	Water temperature in the pipeline, ^{o}C
T_1	Air temperature before compression, K
T_2	Air temperature after compression, K

t_o	Initial time, s
t_s	Hot-water stable storage duration, s
USUHWS	Utility-Scale Underground Hot Water Storage
V	Water flow velocity, m/s
W	The width of the USUHWS facility with a rectangular cross-section, m
$\dot{W}_{cv}$	Compression power consumption, kW

Greek Symbols

α	The ratio of the energy storage at t_s to that at t_o
η_{CAES}	The efficiency of the CAES
η_{Carnot}	Carnot efficiency
η_P	The efficiency of pumped-storage hydropower (PSH)
η_{th}	Thermal efficiency of the thermal to mechanical work
ρ	Density of water or air, kg/m^3 conversion unit of a power plant
ΔT	Temperature drop of the hot water in the power conversion unit, °C
ΔT_f	Water temperature drop along the pipeline, °C

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Appendix 1 - Derivation of Eq. (11)

The heat loss of a hot water storage system to the ambient can be calculated by using the temperature difference between the storage temperature and the ambient temperature and the total thermal resistance as follows:

$$\dot{Q} = \frac{dQ}{dt} = \frac{T - T_{am}}{R}$$

where Q is the heat loss or the heat transfer from the hot water storage to the ambient, T is the average hot water temperature at a given time t, T_{am} is the year-round average ambient air temperature, which is often used to approximate a ground surface temperature, and R is the total thermal resistance associated with the insulation of the storage system. The heat loss over a time period between $t = 0$ and t can be evaluated by the following integration:

$$\mathrm{Q} = \int_0^t \frac{T - T_{am}}{R} dt$$

Assuming between $t = 0$ and t the change of the temperature difference is a linear function of time of t, with two constants a and b to be determined, which is a good assumption with little error for a large storage system due to the slow water temperature change under a given ambient temperature:

$$T - T_{am} = a + bt$$

At t = 0, $T = T_o$, then $a = T_o - T_{am}$

At $t = t_1$, $T = T_1$, then, $b = \frac{(T_1 - T_{am}) - (T_o - T_{am})}{t_1}$

Therefore, the heat loss between $t = 0$ and $t = t_1$ by substituting the relations for a and b into the integration would be:

$$\mathrm{Q} = \int_0^t \frac{T - T_{am}}{R} dt = \frac{1}{R}\int_0^{t_1} (a + bt) dt = \frac{t_1}{2R}[(T_o - T_{am}) + (T_1 - T_{am})]$$

The hot water energy storages at initial time $t = 0$ and t_1 would be calculated, respectively, by the following two relations:

$$E_o = mc_p(T_o - T_{am})$$
$$E_1 = mc_p(T_1 - T_{am})$$

Where m is the mass of the hot water stored. The ratio of the energy storage at t_1 to that at t_o would be:

$$\alpha = \frac{E_1}{E_o} = \frac{T_1 - T_{am}}{T_o - T_{am}}$$

or

$$T_1 = \alpha(T_o - T_{am}) + T_{am}$$

Through energy balance

$$E_o - E_1 = E_o(1 - \alpha) = Q = \frac{t_1}{2R}[(T_o - T_{am}) + (T_1 - T_{am})]$$

Solve the above equation for t_1, one would have

$$t_1 = \frac{2R(1 - \alpha)E_o}{(1 + \alpha)(T_o - T_{am})}$$

Because of the heat loss from the storage to the ambient, E_1 is less than E_o or α is less than 1. However, if at t_1 the energy storage is equal to or more than 90% of the initial storage amount at $t = 0$, the time period $t_1 = t_s$ may be defined as the stable storage period:

$$t_s = \frac{2R(1 - \alpha)E_o}{(1 + \alpha)(T_o - T_{am})}$$

with $\alpha = 0.9$.