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Swimming pool thermal energy storage, an alternative for distributed cooling energy storage

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ABSTRACT

The rise in distributed renewable energy generation creates a growing need to find viable solutions for energy storage to match energy demand and supply at any time. This paper evaluates the possibility of using swimming pools as a long-term cooling energy storage solution, i.e., Swimming Pool Thermal Energy Storage (SPTES). This technology allows a small building to store solar energy for cooling purposes in a yearly cycle, by filling the pool with ice slurry in winter and using that ice to cool the house in the summertime. Additionally, the pool can be used as a heat sink for a heat pump to heat the house during the winter. Results show that the energy storage cost of 0.078 US$ kWhe^{-1} is substantially smaller when compared with batteries (125 US$ kWhe^{-1}). This makes SPTES a good alternative to support the development of 100% renewable energy systems in locations where the climate has a highly seasonal variation in temperature and the cooling demand is high in summer.

1. Introduction

The International Energy Agency (IEA) baseline scenario estimates that cooling electricity consumption will increase from 2.200 TWh in 2020 to around 6.200 TWh in 2050, due to population increase, quality of life improvements in developing countries and global warming [1]. Conventional air conditioning could provide the required cooling services to this rising demand. However, due to the rise in variable energy sources, this cooling demand could be coupled with a seasonal thermal energy storage solution to facilitate sustainable development. One thermal energy storage alternative that has gained importance recently is borehole thermal energy storage [2,3] which can provide seasonal energy storage and consists of heating up water or grout 50 to 300 m deep [4,5]. Heat pump systems combined with ice production have been proposed to heat houses during the winter, as the latent heat of water can store large amount of energy [6]. Current status and emerging trends for thermal energy storage can be seen in [7]. Other seasonal energy storage solutions have been proposed with seasonal pumped hydro-storage [8,9] hydropower storage reservoirs [10,11] and biomass [12].

Swimming pools are a common house component of high-income houses in low-density population districts, particularly in locations with average summer temperatures higher than 26 °C. The U.S. is the country with the most pools in the world and Phoenix, Arizona is the city with the most swimming pools in the U.S., one pool per 8,6 inhabitants [13]. Fig. 1 presents the concentration of swimming pools per inhabitant per state in the U.S.

A recent study [14] has shown that the average size of the houses in Phoenix, Arizona does not include enough rooftop area to provide all energy needs for the house during the summer, due to the high cooling demand. Thus, adding daily storage capacity does not substantially increase the fraction of cooling met by solar power during the summer, as most of the electricity generated during the day is already consumed by cooling equipment during the day, leaving no excess electricity to be stored (see Fig. 2). Since there is no viable rooftop area for solar generation, an option is to implement solutions with long-term energy

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storage to store energy during the winter and using that during the summer. In Fig. 2, the change in hours of cooling met by photovoltaics (PV) from 2010 to 2100 is related to the increase in the coefficient of performance of air-conditioners that is foreseen to increase from 3.0 in 2010 to 4.4 in 2100 [15].

Private swimming pools are characterized by relatively low usage rate and substantial maintenance costs. For example, if a swimming pool is used for three hours a week during the summer, the net usage of the swimming pool is only 0.5%. Other households might not use the pool at all. The average cost for maintaining a swimming pool in the USA is 1400 US$ per year. In some households, the swimming pool can demand around half of the energy consumption of the house. These facts could make a swimming pool a costly, energy consuming asset to homeowners. The main objective and contribution of this paper is to estimate the technical potential and financial viability of transforming undesirable swimming pools into a long-term cooling energy storage solution in locations with high seasonal temperature variation.

This technology was named Swimming Pool Thermal Energy Storage (SPTES). This concept was first proposed in 1977 [16,17] but has not received further attention up to the present date due to the lack of need for seasonal cooling storage. Using different storage methods for heating swimming pools has been discussed in the literature [4,18]. Application of swimming pools for storing thermal energy for heating the water is discussed in several studies [19,20]. Ice slurry is a suitable media for cool storage as the phase change between ice and water can provide a significant latent energy for cooling [21]. Cooling demand is one of the major contributors to peak electricity demand on hot summer days [22,23]. Therefore, using swimming pools as a cold storage media can potentially help by reducing the electricity demand during peak time, as well as provide seasonal storage. This paper evaluates the feasibility of using SPTES and maps the world potential for SPTES.

This paper is divided into five sections; Section 2 presents the proposed methodology for transforming swimming pools into long-term cooling energy storage tanks. Section 3 presents the results from a proposed SPTES system installed in a medium sized house in Phoenix, Arizona. Section 4 discusses important aspects of the technology and compares the proposed technology with battery storage. Section 5 concludes the paper.

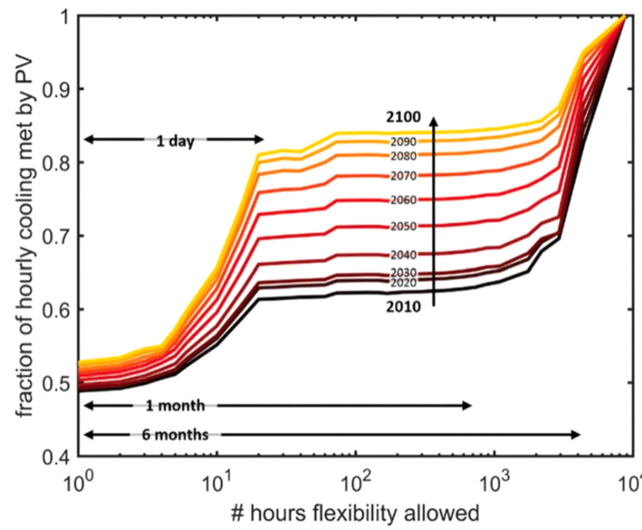

Fig. 2. Different time scales of storage needed to fully power solar PV-based cooling systems during the 21st century [14].

2. Methodology

2.1. 2.1.Swimming pool thermal energy storage: Description and operations

The proposed SPTES system consists of the following main components: a swimming pool, an ice slurry production system, a heat exchanger and an onsite electricity generation source, such as solar panels. The swimming pool will have to go through several modifications to be applicable for cool storage. Firstly, an insulation layer is added to the upper surface of the pool. The ground surrounding the pool acts as a thermal insulator, however, insulation on the sides and bottom of the pool are also required. Additional layers should be added above the pool, such as a wooded or cemented floor, so that the homeowner can use the area for other activities. A roof could also be added above the pool to further reduce heat loss to the environment. This new small building could be connected to the main house so that the cold lost from the pool to the environment can be transferred to the main house. Some excavation is required to lay the pipeline from the pool to the ice slurry

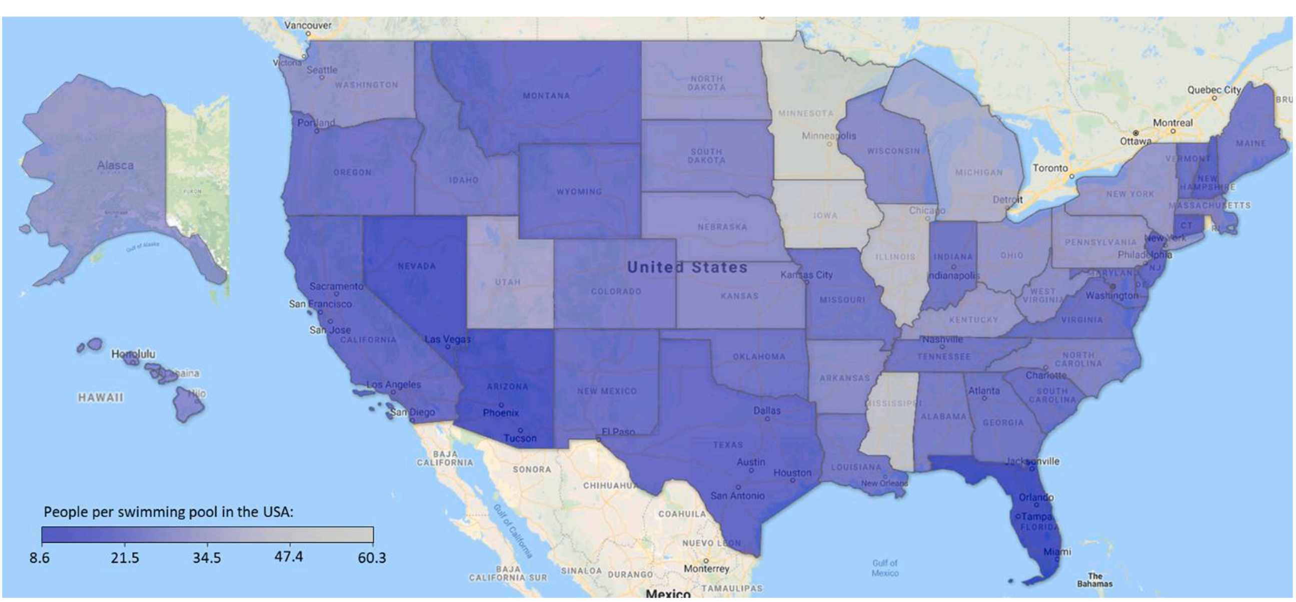

Fig. 1. Number of people per swimming pool in the USA states [13].

production facility and the heat exchanger. A representation of the proposed SPTES system can be seen in Fig. 3.

Ice slurry storage has been selected for this system because it increases the heat transfer, as ice is not built up in the heat exchanger, which reduces the investment cost for freezing the water in the pool. Additionally, the mechanical characteristics of ice slurry facilitates the transport from the ice slurry machine to the pool, with a pipeline, and on the distribution of ice slurry inside the pool. Given the large size of the swimming pool and that it stores energy for long periods of time, mixing the ice slurry in the pool is not an option, as it would increase investment costs and energy consumption. Without mixing, the ice slurry crystals agglomerate into blocks and lose the characteristics required for transportation in pipelines. Given that the pool is close to the house, the costs for pumping cold water to refrigerate the house are low, and water is used as the cooling medium from the pool to the house. The water would enter the heat exchanger at around 0 °C and leave it at 20 to 25 °C. This water would then return to the pool and melt some of the ice slurry in the pool. Ice slurry only serves to store cooling energy in the pool.

A similar rationale applies to the quantity of anti-freeze added to the system. Anti-freeze is convenient to lower the melting point of the ice and, thus, more cooling energy can be transported in the liquid. This improves the efficiency of a cooling distribution system. Using sodium chloride as anti-freeze the freezing temperature would change from −5°C (when the pool has no ice slurry) to −20 °C (when the pool is full of ice slurry). Keeping the pool at −20 °C would negatively impact the coefficient of performance (COP) of the system. Given that the cooling demand of the household is very close to the pool and pumping costs are low, we chose not to add anti-freeze. Ice slurry without anti-freeze is still a good thermal energy storage media and can store an average of 54 kWh m^{-3} of cooling energy [25]. Other benefits of not adding anti-freeze is reduced corrosion, reduced costs of equipment, reduced maintenance costs and reduced impact on the environment in case of spillages. The ice slurry production system can have parts installed underground to reduce heat loss, but a cooling tower needs to be installed above ground to release heat to the environment and condense the refrigerant.

The house should have an existing centralized split air-conditioning system. During periods of high electricity prices or at night with no distributed solar generation, instead of operating the split air-conditioning system, the water from the pool will pass through the heat exchanger cooling down the air passing through the centralized air-conditioning system to the house. A monitoring system should deliver the required flow of water to fulfil the cooling demand of the household.

Four operational modes of the proposed SPTES system are presented in Fig. 4. Fig. 4 a presents the operation of energy storage mode during the beginning of winter with the storage capacity almost empty. This operation happens when electricity is cheap and the COP is 5 because the ambient temperature is low. Cold water in the pool is replaced by ice slurry. Fig. 4b presents the energy storage mode with the storage capacity partially full. This operation happens when electricity is cheap during the summer and cooling demand is at a medium level. The chiller supplies all the cooling load required in the house and the ice slurry machine produce ice (with a COP of 2), which is stored in the pool. Fig. 4c presents the cooling load mode with the storage capacity partially full. This operation happens when electricity is expensive during the summer and cooling demand is at a medium level. The ice in the pool is used to cool the house. Fig. 4d presents the cooling generation mode with the storage capacity partially full. This operation happens when electricity is expensive during the summer and the cooling demand is high. The chiller and the ice in the pool are both used to cool the house.

A design option that substantially reduces the heat losses from the top of the pool is the "Heat Loss Recycle" design presented in Fig. 5. This design proposes the creation of a new layer on the top of the pool, where the warm water coming from the house will have to travel before returning to the pool. This layer does not require a lot of insulation, and substantial heat loss can happen, as the cooling of the water would return anyway to the swimming pool. This warmer intermediate layer is used to reduce the temperature difference between the outside and the pool, reducing the heat losses to the environment. For example, without this intermediate layer, the temperature difference between the surface of the pool would be 40 °C, with the intermediate layer the temperature difference is 20 °C. A thick insulation layer would still be required between the outside and the intermediate layer. This design could be applied around the whole pool, however, the benefits would be smaller to apply this concept on the bottom and sides of the pool.

Table 1 presents an overall review of the operation of a SPTES system

Fig. 3. Main components of a Swimming pool thermal energy storage system [24].

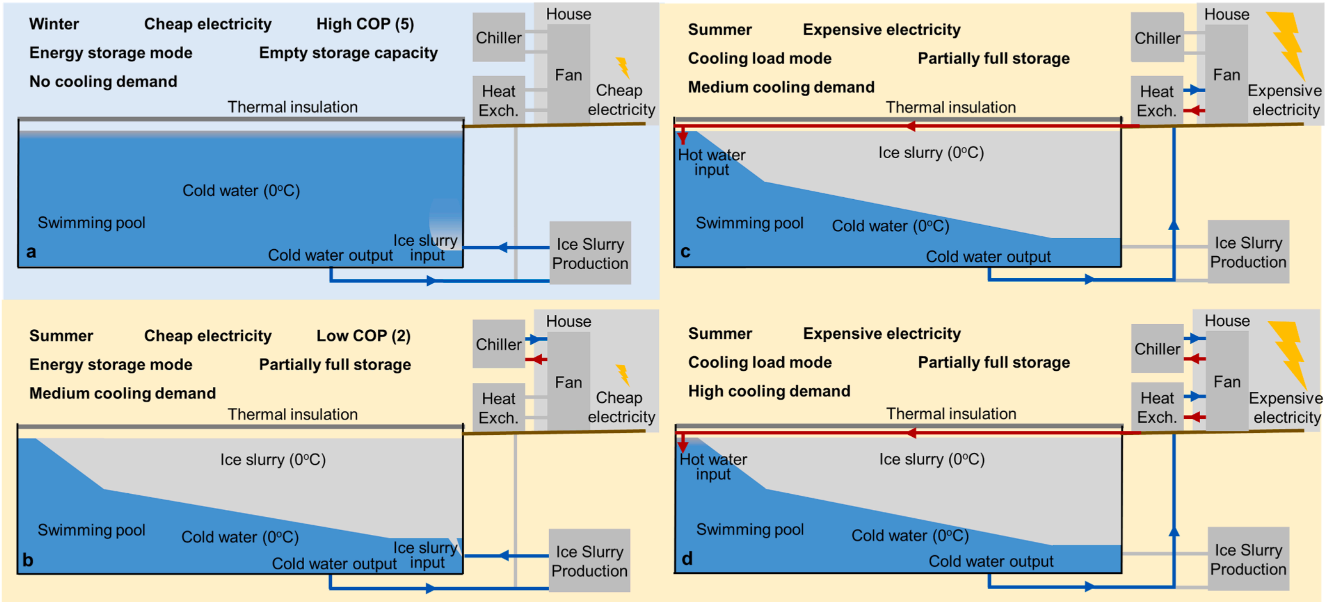

Fig. 4. The operation of Swimming pool thermal energy storage during energy storage mode with cheap electricity in the winter (a) and in the summer (b), and during cooling mode in the summer with medium cooling demand (c) and high cooling demand (d).

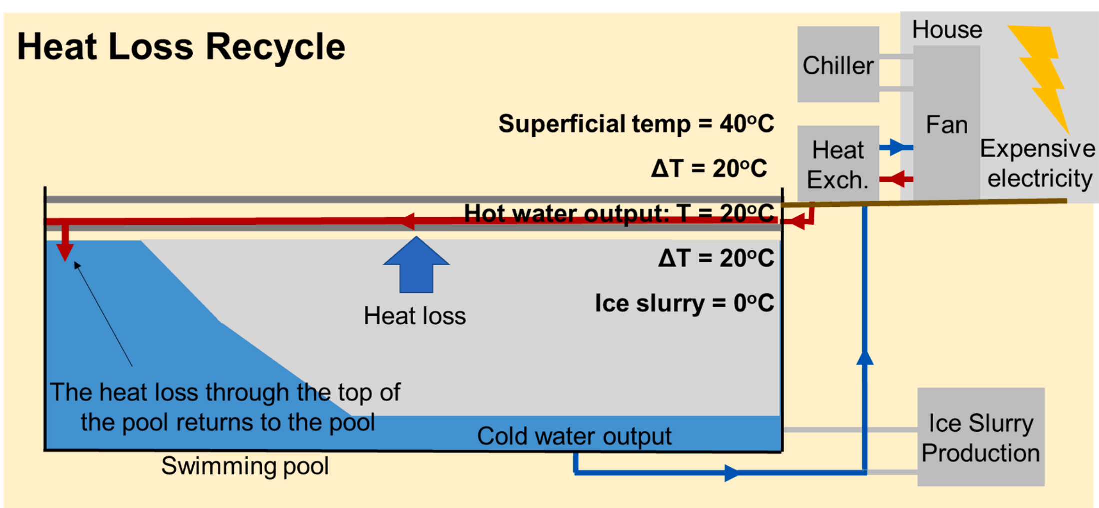

Fig. 5. Heat loss recycle concept for reducing the heat loss from the pool.

Table 1
Thermal energy flows in different operation modes.

Season	Temperature (°C) Ambient	Pool	House	Operation mode	Heating and cooling load capacity factor (%)
Winter	−15 ~ 5 °C	0	20	Heat pump	70% heating
Spring	5 ~ 25 °C	0	22	Heat pump/ Latent cooling	20% heating / 10% cooling
Summer	25 ~ 35 °C	0	25	Latent cooling	50% cooling
Autumn	5 ~ 25 °C	0	22	Latent cooling/ Heat pump	20% cooling

at different seasons. It assumes that the pool at 0 °C is used in as a heat sink for a heat pump system during the winter and spring when the ambient temperature is below 5 °C. Even though it would not be effective to use the pool as the heat sink if the outside temperature is 15 °C looking at the heating aspect, the COP for ice slurry production would be low and the ice produced would also be used for cooling during the summer. The ice production capacity is expected to operate at 70% of its maximum capacity during the winter, an additional heating solution might be required to supply all heating demand during colder days. The ice in the pool is used to cool the house in spring (at 20% of the cooling load capacity), summer (at 50% capacity) and autumn (20% capacity). The cooling load has a lower capacity factor because it provides a flexible cooling load, particularly during the night, when there is no solar power to run the air-conditioning system, replacing the needs for batteries to store solar energy during the day. During autumn, the system does not operate in the heating mode to produce ice because the ice production is more efficient in the winter.

2.2. Sizing of swimming pool thermal energy storage

The thermal energy storage for a standard SPTES site is presented in Eq. (1) below. This paper assumes that the energy storage is performed with the latent heat of melting ice. The change in temperature of water is neglected (specific heat).

$$C = V \times V_i \times V_f \times \rho \times L \quad (1)$$

Where:

C is the available cooling energy stored in the swimming pool (kWh_t).

V is the volume of the swimming pool (m^3).

V_i is the percentage of volume of ice slurry in the swimming, assumed to be 90%.

V_f is the fraction of ice particles within the ice slurry. This fraction depends on the distribution of ice particles in the slurry and is assumed to be 70% [26].

ρ is the density of ice (917 kg m^{-3}).

L is the latent heat of fusion of ice, which is equal to 333 KJ kg^{-1}.

For example, for a pool with the volume of 65 m^3:

$$C = 65m^3 \times 0.9\% \times 0.7\% \times 917kgm^{-3} \times 333KJkg^{-1}/60s/60min = 3.474KWh_t$$

The objective of the SPTES systems is to store energy in the short term (hours, days and weeks) and the long-term (months and year). Thus, the system can store cooling produced when the electricity prices are low, such as at night or during off-season periods, or store the energy generated from distributed energy sources, such as solar energy. The need for storage is also an import aspect of such systems. For example, in Table 2 we present three schemes in which a SPTES could be implemented. In summary, SPTES systems can be used to enhance the capacity of existing refrigeration networks, as a heat source for a heat pump, provide more flexibility of combined-heat-cold-and-power-plants, increase cooling supply reliability, provide cold storage and optimized load management, produce ice during the night, a cold week, or winter, when ambient temperature is lower and COP higher. and integrate cooling with renewable energy generation.

Table 2 shows that the SPTES is most efficient in locations with high seasonal temperature variations and high demand for air-conditioning. This is mainly because during the winter the ambient temperature is low and the production of ice would require less energy, when compared to the summer, given the higher COP of the ice slurry system. The system functions as if the system stores the coldness of the winter and uses it for cooling during the summer. Another benefit of the system is that during the winter the water in the pool could be used as a heat sink for operating a heat pump. In this case, heat is extracted from the pool by producing ice slurry and this heat is "pumped" into the house heating the house during the winter. This is the ideal scenario of a SPTES system.

Given that the pool is designed to store thermal energy seasonally, thermal insulation is a major concern for this technology to guarantee that the cold stored in the winter can be used throughout the summer. Fig. 6 shows the thermal insulation characteristics of vacuum insulation panels, the insulation material proposed for the SPTES system. Fig. 7 shows a representation of the swimming dimensions. Fig. 8 presents a representation of the swimming pool to estimate its thermal insulation. Fig. 9 presents the representation of the swimming pool superficial thermal insulation.

The heat loss estimated for the SPTES plant is presented in Eqs. (2)–(5). These equations are conservative to assume that only the ground and the thermal insulation function as a thermal insulation resistance in the system. The paper assumes that the pool's surface is not hit directly by solar rays, either with the construction of a roof on the top of the pool, or trees surrounding the pool. The estimated yearly heat loss from the pool is 344 KWh_t in this case study, which amounts to around 10% of the total energy stored in the pool.

$$\in L = \sum_{i=0}^{8760} Qt_i + Qs_i + Qb_i \quad (2)$$

Where:

L is the yearly heat loss of the pool, estimated to be 344.9 kWh_t.

i is the hour under analysis, that is 8760 h per year.

Qt_i is the hourly heat lost through the top of the pool.

Qs_i is the hourly heat lost through the side of the pool.

Qb_i is the hourly heat lost through the bottom of the pool.

$$Qt = \sum_{i=0}^{8760} \frac{((Ta_i - Th_i)A_t}{\frac{t_t}{\lambda_i}} if \begin{cases} (Ta_i > 26 \rightarrow Th_i = 20 \\ (Ta_i < 26 \rightarrow Th_i = 0 \end{cases} \quad (3)$$

Where:

Qt is the yearly heat loss of the top of the pool, estimated to be 76.31 kWh_t.

A_t is the area of the top of the pool with insulation in m^2, assumed to be 32.4 m^2.Ta_i is the hourly ambient temperature of the air on the top of the pool in °C in Fig. 10.

Th_i is the temperature of the water coming from the house, assumed to be 20 °C.

λ_i is the thermal conductivity of the insulation layer, assumed to be 0.0022 W m^{-1} K^{-1} [28].

t_t is the thickness of the insulation layer on the top of the pool, assumed to be 120 mm.

$$Qs = \sum_{i=0}^{8760} \frac{(Ts_i - T_p)A_s}{\frac{t_s}{\lambda_i} + \frac{t_{gs}}{\lambda_g}} \quad (4)$$

Where:

Qs is the yearly heat loss of the side of the pool, estimated to be 158.2 kWh_t.

A_s is the area of the sides of the pool, assumed to be 45.6 m^2.

Ts_i is the hourly temperature of the sides of the pool, assumed to be the weekly running average of the ambient temperature in Fig. 10.

T_p is the temperature of the ice slurry and water inside the pool,

Table 2
General applications for Swimming Pool Thermal Energy Storage.

Service	Type of climate	Chance of viability	Summer operation	Winter operation	Comments
Long-term cooling thermalstorage – pool filled with ice (0 °C)	Hot summer (25 ~ 40 °C) and cold winter(-15 ~ 5 °C)	High	- Ice slurry consumption for cooling.- Ice slurry production for short term cooling thermal energy storage.	- Heat source for heat pump.- Ice slurry production for long-term cooling thermal energy storage.	- The advantages of this scheme are that the cooler will operate with a high COP in the winter as the ambient temperature is close to zero. The system can also be used as a heat pump during the winter to heat up the house.
	Hot summer (25 ~ 40 °C) and mild winter (10 ~ 20 °C)	Medium		- Ice slurry production for long-term cooling thermal energy storage.	- The colder the ambient temperature in the winter the higher the COP of the ice slurry machine.
	Hot summer and winter (25 ~ 40 °C)	Low	- Ice slurry consumption for cooling.- Ice slurry production for short term cooling thermal energy storage. - Ice slurry production during the night, when ambient temperature is lower and COP higher.		- There is a low need for seasonal storage as the demand for cooling is similar throughout the year.- Seasonal storage can be implemented if the cost/availability of electricity varies seasonally.

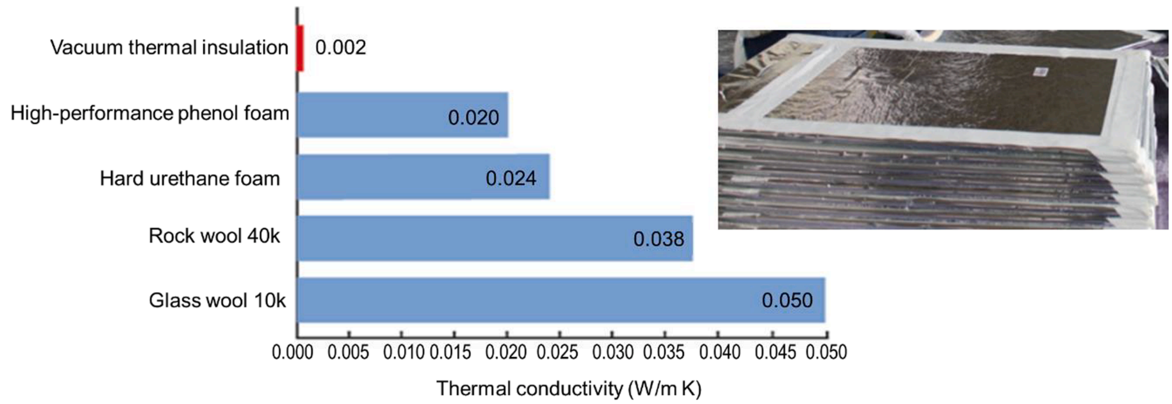

Fig. 6. Thermal insulation characteristics of different material, and image of the proposed insulation material used in the pool (vacuum insulation panels) [27].

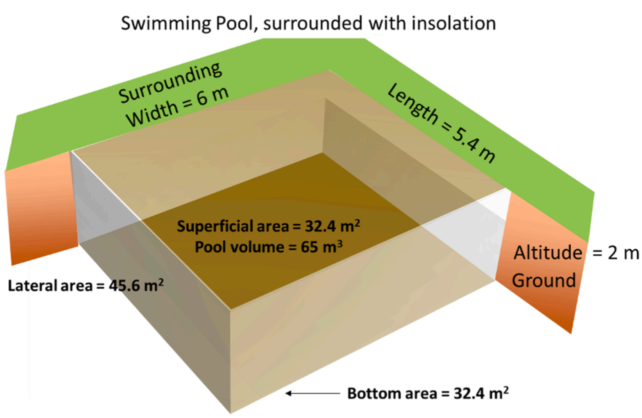

Fig. 7. Representation of the swimming dimensions.

which is equal to 0 °C.

t_s is the thickness of the insulation layer on the side of the pool, assumed to be 120 mm.

t_{gs} is the thickness of the in ground layer on the side of the pool, assumed to be 1 m.

λ_g is the thermal conductivity of the ground, assumed to be 1 W m^{-1} K^{-1}.

$$Qb_i = \sum_{i=0}^{8760} \frac{(Tb_i - T_p)A_b}{\frac{t_b}{\lambda_i} + \frac{t_{gb}}{\lambda_g}} \tag{5}$$

Where:

$Qb_i$is the yearly heat loss of the bottom of the pool, estimated to be 110.4 kWh$_t$.

A_b is the area of the sides of the pool, assumed to be 32.4 m^2.

Tb_i is the hourly temperature of the bottom of the pool, assumed to be the monthly running average of the ambient temperature in Fig. 10.

T_p is the temperature of the ice slurry and water inside the pool, which is equal to 0 °C.

t_b is the thickness of the insulation layer on the bottom of the pool, assumed to be 120 mm.

t_{gb} is the thickness of the in ground layer on the bottom of the pool,

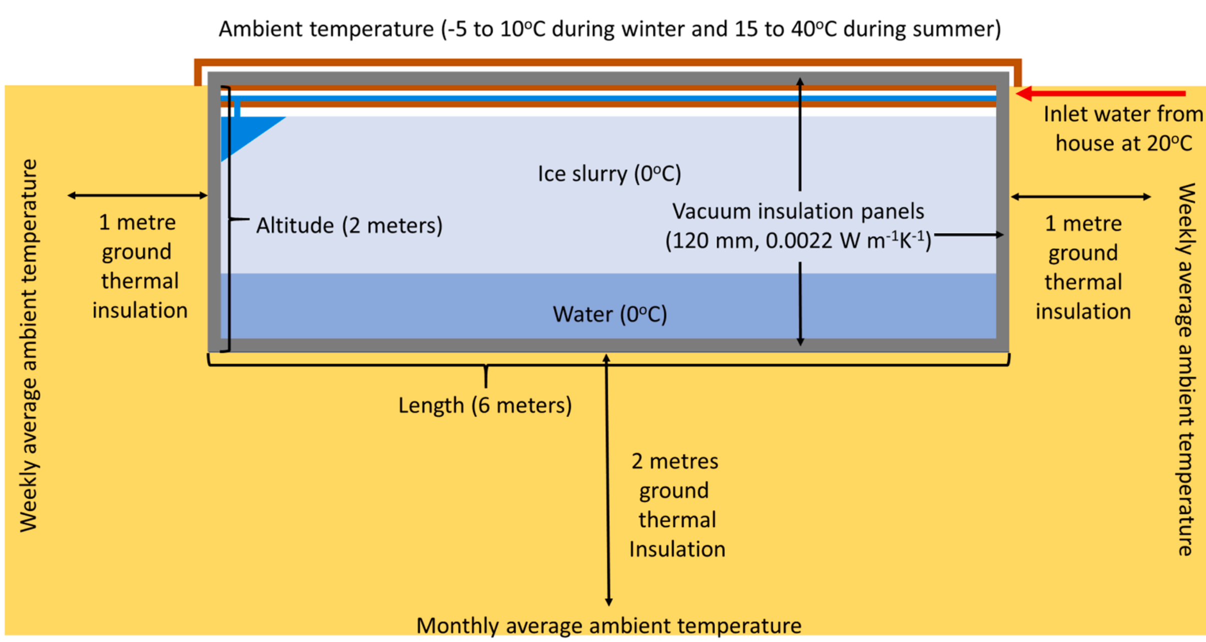

Fig. 8. Representation of the swimming pool to estimate its thermal insulation.

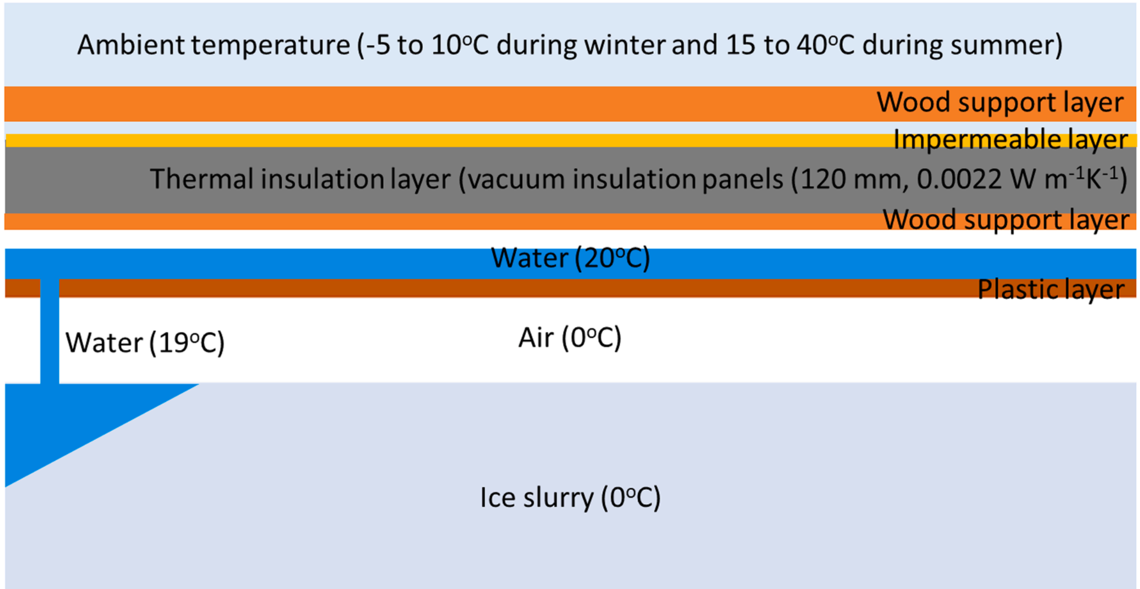

Fig. 9. Representation of the swimming pool superficial thermal insulation.

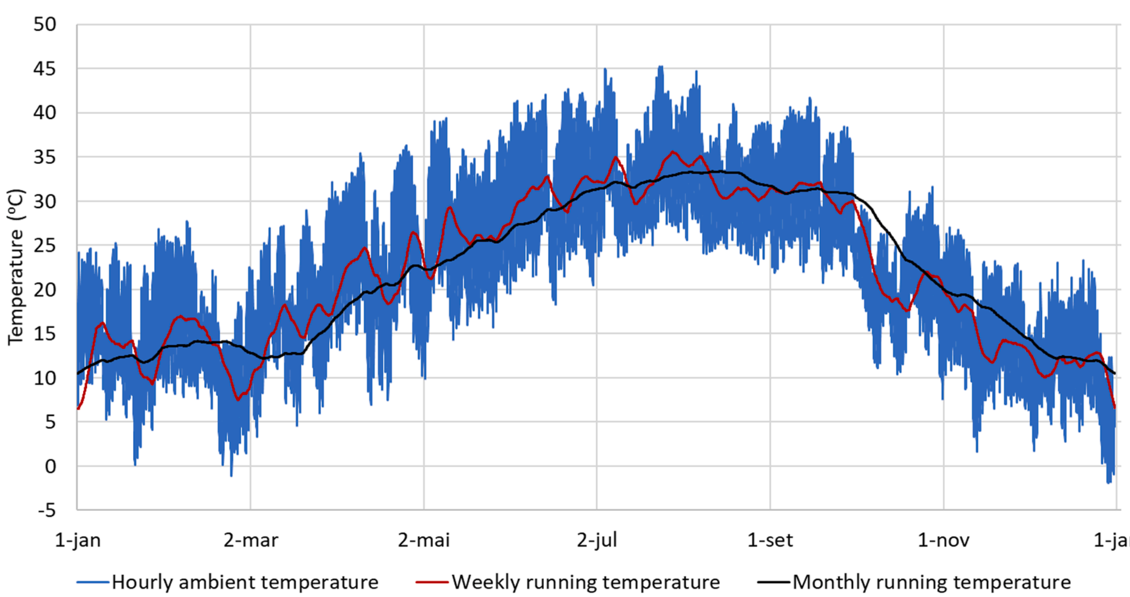

Fig. 10. Hourly ambient temperature, and weekly and monthly running temperature variation in Phoenix, Arizona in 2018 [30].

assumed to be 2 m.

3. Results

3.1. Potential of SPTES for a medium sized house in Phoenix, Arizona

The energy consumption for cooling a medium sized house in Arizona is around 3000 kWh_e per year, which is equivalent to 9000 kWh_t assuming an average COP of 3 for conventional air-conditioning systems in Arizona [29]. This is around three times the amount of energy a standard swimming pool can store (3500 kWh_t). During the summer, some of the cooling is generated directly from a conventional air-conditioning system using daytime solar generation. Additionally, the pool can be partially filled with ice during days with large solar generation and low cooling demand, storing energy from the day to be used during the night. The ice slurry machine should operate at higher capacities during the nights or days when the ambient temperature outside is low, so that the COP of the ice slurry system is higher. In the case study, we assume that the COP for ice slurry production is fixed at 2 and that the ice production is only generated during the day using solar power.

The model applied to estimate the operation of the SPTES cooling system in the case study is an hour-by-hour quasi-steady-state simulation developed in a spreadsheet with Eqs. (6)–(8) applied to estimate the operation of the SPTES in Phoenix, Arizona.

$$D_i = (Ta_i - 25) I C_H if\{T > 25^{\circ}C \rightarrow I = 1 else\{I = 0 \quad (6)$$

Where:

D_i is the hourly cooling demand of the household under analysis in the paper in kW_t.

Ta_i is the hourly ambient temperature in °C in Fig. 10.

I Is the indicator if the cooling system is turned on or off. If on, $I = 1$, if off, $I = 0$.

C_H is the amount of cooling load required to cool the house in one degree, assumed to be 0.364 $kW_t.\ {}^{\circ}C^{-1}$.

$$D_i = C_{SolarAC} + C_{SPTES} + C_{GridAC} \quad (7)$$

Where:

$C_{SolarAC}$ is the hourly cooling performed by AC supplied with solar power in kW_t. If there is cooling demand, the solar power generation in the house is firstly used to operate the AC refrigeration and the C_{SPTES} is conserved. This is because, the COP of AC (3) is higher than in the SPTES (2) solution. The total capacity for solar powered AC assumed in the case study is 2.6 kW_t.

C_{SPTES} is the hourly cooling performed by the SPTES system in kW_t. It is implemented when the demand for cooling cannot be supplied by $C_{SolarAC}$. If the demand is not met with the 4 kW_t SPTES load system. Then energy from the grid is used to generate electricity with AC.

C_{GridAC} is the hourly cooling performed by AC supplied with electricity from the grid in kW_t.

$$Si_i = Sp_i - C_{SPTES} - L_i \quad (8)$$

Where:

Si_i is the total ice slurry store content in the pool in kW_t, during hour i.

Sp_i is the hourly ice slurry produced and stored in the pool in kW_t. In the Phoenix, Arizona case study, the ice slurry production is limited to solar power generation and happens during the winter, when there is no cooling demand and also during the summer, with the intent of storing solar power during the day to produce cooling during the night.

L_i is the hourly heat loss from the pool in Wh_t, estimated with Eqs. (2)–(5).

The solar generation from the selected location for the case study in Phoenix, Arizona, USA (latitude N 33.6347 and longitude W 111.8487) assumes solar irradiation data from 2018 taken from [30]. The ambient temperature assumed to estimate the cooling demand has also been taken from [30] and is shown in Fig. 10. Table 3 represents the technical specifications of the proposed cooling system applied in the case study.

Fig. 11 presents the operation of the SPTES and air-conditioning system for cooling a house in Phoenix. Most of the electricity used to operate the cooling solutions is generated with solar power panels, and a small fraction utilizes electricity from the grid. Ice slurry production takes place throughout the year with a 1.4 kW_e solar generator and a 2.8 kW_t ice slurry capacity. In the beginning of the cooling season (March in Fig. 11), the cooling demand usually happens during the daytime when there is solar power generation. The first alternative to provide cooling is the AC system that operates with a 0.83 kW_e solar generator and 2.5 kW_t AC system. During periods when there is not enough solar power to run the air conditioner, the energy stored in the swimming pool is used to cool the house. If the cooling load from the swimming pool is not enough to fulfil the cooling demand, then electricity from the grid is used to provide the additional cooling demand. The AC system that operates with electricity from the grid has a capacity of 2.1 kW_t.

It turns out that the SPTES provides 76% of the cooling demand from the house, AC using solar generation provides 23% of the cooling demand and AC running with power from the grid provides only 1% of the cooling demand in the house. The SPTES is filled with ice slurry during the winter and it reaches its full capacity (3.474 kWh_t) at the end of May. Over the next months the cold water stored in the pool is consumed and it reaches its lowest value in the beginning of September, when ice starts to be produced again. The system cost is estimated in Table 4.

Assuming that the investment needed to build an SPTES system has an interest rate of 5% a year, that the SPTES would work for 40 years, a discount factor on the investment of 17.16 years, a yearly storage capacity of 3500 kWh_t, an investment of 5000 US$ and an operation and management costs of −200 US$/year (as shown in Table 4), the costs for storing energy with the proposed SPTES system is around 0.026 US$ kWh_t^{-1} (thermal energy). Eqs. (9) and (10) present the equations used to estimate the levelized costs. Assuming that the SPTES solution would replace an AC system with a COP of 3, the cost SPTES is 0.078 US$ $kWhe^{-1}$ (electric energy).

$$C_{SPTES} = \frac{C_I}{S_T D_F} + \frac{C_{O\&M}}{S_T} \quad (9)$$

Where:

C_{SPTES} is the levelized cost of the SPTES system, estimated to be 0.026 U$ kWh_t^{-1}.

$C_I$is the project investment costs, assumed to be 5000 US$.

$C_{O\&M}$ is the sum of the project operation and management cost, assumed to be −200 US$ per year, due to the reduction in maintenance costs of an existing swimming pool.

$S_T$is the energy storage capacity of the SPTES, which is 3500 kWh_t.

$D_F$is the discount factor, assumed to be 17.2.

$$D_F = \frac{(1+i)^t - 1}{i(1+i)^t} \quad (10)$$

Where:

$i$is the interest rate for the project, assumed to be 5%.

t is the estimated life time of the SPTES plant, assumed to be 40 years.

4. World potential of SPTES

Eq. (11) estimates the potential need for seasonal cooling storage with SPTES. It considers the seasonality of the ambient temperature, the cooling degree days (multiplied by weight W_C) and the heating degree days (multiplied by weight W_H). These weights vary with the need for cooling and heating of the location. The cooling and heating weights are set as 4 and 1 because: i) the chances that a swimming pool will be available in locations with high cooling demand is higher than in locations where cooling demand is low. ii) Usually the heating demand in cold locations is higher than its cooling demand in warm places, which creates an imbalance in the need for cooling in the summer and heating

Table 3
Detail technical specifications of the proposed cooling system.

	Cooling energy Capacity (kW_t)	Demand (kWh_t)	Cooling share (%)	COP [Ref.]
Ice slurry production	2.8	6156	–	2 [31]
Ice slurry consumption	4.0	5811	65	2 [31]
AC with solar generation	2.5	2981	33	3 [29]
AC with grid electricity	2.1	159.2	2	3 [29]
Total cooling production	7.4	9296	–	2.32(average COP)
Maximum cooling demand	8.6	8951	100	–
	Electricity Capacity (kW)	Demand (kWh)	Electricity share (%)	COP
Ice slurry production	1.4	3229	76	2 [31]
AC with solar generation	0.8	994	23	3 [29]
AC with grid electricity	0.7	53	1	3 [29]
Total electricity consumption	3	4275	100	2.32(average COP)

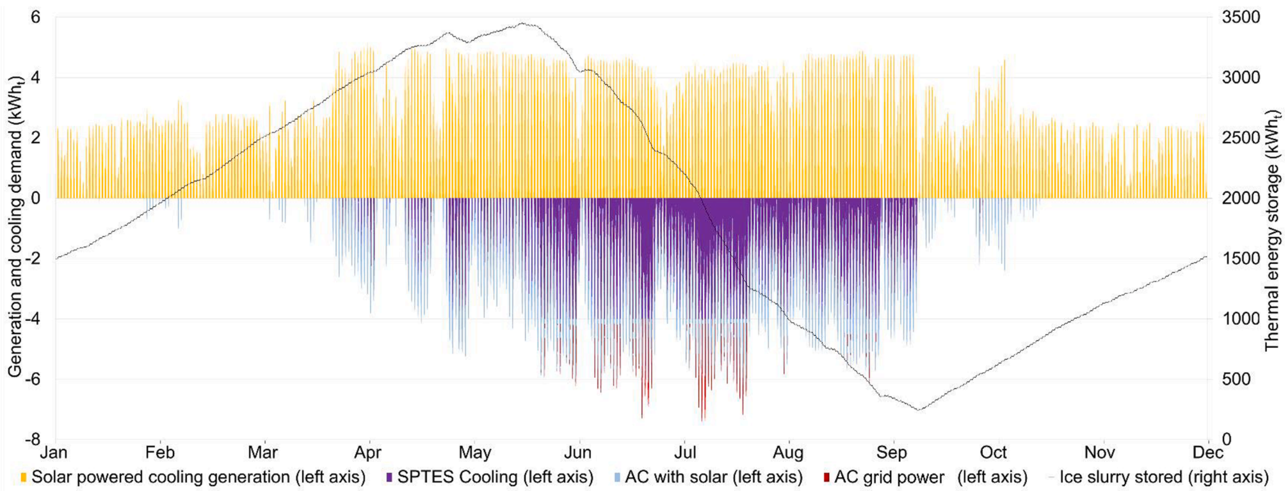

Fig. 11. Hourly operation of solar generation, cooling demand, AC and SPTES systems.

in the winter, and there must be another solution for heating. iii) SPTES is more convenient for cooling than heating. During cooling mode, the temperature of the pool is already 0 °C, which can be directly used to cool the house. During heating mode, the pool is used as a heat sink at 0 °C. There is still the need to "pump" the heat to the house at 30 °C to heat up the house. It also only makes sense energetically to use the pool as a heat sink when the temperature outside is below 5 °C.

The ideal location to install a SPTES system has similar cooling and heating demand patterns. The script used for estimation of the world potential for SPTES will be provided upon request.

$$P = \frac{\sum_{i=0}^{8760} C_D \times W_C + H_D \times W_H) \times S_V}{P_{max}} \quad (11)$$

Where:

P is an index to measure the potential for long term cooling energy with SPTES (unitless index that varies from 0 to 1).

P_{max} consist of the maximum value of P applying the same Eq. (11), however, not dividing by P_{max}. In Fig. 12 the location with the maximum P value is somewhere in Iraq (unitless index).

C_D is the cooling degree hours of the location under analysis above 26 °C.

W_C is the weight of the importance of cooling in the potential, assumed to be 4 (index).

H_D is the heating degree hours that could benefit from a heat sink with 0 °C, that is temperatures below 5 °C.

W_H is the weight of the importance of heating in the potential, assumed to be 1 (index).

S_V is the seasonal temperature variation index, which indicates the temperature variability of the location (see Eq. (13)). The higher the temperature variability, the better performance for SPTES as mentioned in Table 2.

The equation above can be translated into the equation below.

$$P = \frac{\sum_{i=0}^{8760} (4 \times (T_i - 25) \times C + (0 - T_i) \times H) \times S_V}{P_{max}} \; if \begin{cases} T > 25^oC \rightarrow C = 1 \\ T < -0^oC \rightarrow H = 1 \\ P > 0 \rightarrow P = P \end{cases} else \begin{cases} C = 0 \\ H = 0 \\ P = 0 \end{cases} \quad (12)$$

Where:

T_i is the temperature of a given location at hour i (°C);

C is the temperature that the cooling system starts operating (°C);

H is the temperature that the heating system starts operating (°C).

$$S_V = \frac{\sqrt{\frac{\sum_{m \in M} \left(\overline{T}_m - \overline{T}_y\right)^2}{N_m}}}{\overline{T}_y} \; if \{ S_V > 1 \rightarrow S_V = 1 \quad (13)$$

Where:

S_V is the seasonal variation in temperature in °C per location;

$\overline{T}_m$ is the average temperature of a given month (°C);

$\overline{T}_y$ is the average temperature over the year being analyzed (°C);

N_m is the number of months.

The world potential for SPTES (P in Eq. (11)) is presented in Fig. 12. It is a result of applying Eqs. (11)–(13) with 2016 data. It shows that the highest potential for SPTES is in the Middle East, particularly in Iraq. This is because Iraq has a strong seasonal temperature profile and high cooling degree days. Algeria is also a strong candidate; however, the region has a very low population density and cooling demand. Other locations with good potential for SPTES are the USA, Eastern China, Central Australia, Northern India and Pakistan. Locations with some, but low potential for SPTES are Continental Europe, the Southern part of South America, Africa, India and South East Asia. Locations with no potential for SPTES are close to the Equator (due to low seasonal temperature variation) and in high latitudes (due to low cooling demand).

5. Discussion

Long-term cooling thermal storage can have substantial benefits in reducing the costs of providing cooling services. This is because of the possibility of storing the cold water or ice during the winter and using the stored cold in the summer. The SPTES concept presented in this paper is a good solution for cooling storage because of its proximity with the cooling demand (the house) and because district cooling distribution is difficult to implement and requires high investment and pumping costs. It can also be used to reduce peak hour electricity demand and reduce the intermittence of the generation from distributed solar panels.

Note that the results section assumes that the house should be maintained below 26° throughout the whole year. It does not take into

Table 4
Breakdown of cost estimation for SPTES systems.

Component	Cost (US$)	Comments	Ref.
Investment cost			
Ice slurry machine	5000	Power: 1.4 kW; size (L*W*H): 600*650*1250 mm; Voltage: 380 V/3P/50 Hz; Weight: 280 kg; Capacity: 1 ton/day, Content of ice crystals: 40%; Refrigeration gas: R22/R404a; Cooling method air; Cooling capacity (kW): 2.8; COP.	[31]
Swimming pool	0 (already exists)	This paper considers that the pool is already built. The costs of building a private pool in the USA like the one presented in the paper, is around 30,000 dollars.	–
Pump	0 (already exists)	A common private swimming pool pump has a flowrate of around 4 kg s^{-1}. The flowrate required to cool the house with a 4 kW_t capacity is only 0.12 kg s^{-1}. Thus, the existing pump in the pool is more than enough to operate the pool as a thermal energy storage tank.	–
Heat exchanger	500	–	[32]
Insulation	6500	Vacuum insulation panel with double sided adhesive tape, density = 330 kg m^{-3}, Standard temperature range = -70 to 80 °C, thermal conductivity of 0.0022 W $m^{-1}K^{-1}$. Cost of 15.00 $ m^{-2} per 30 mm. We assume a cost of 60 $ m^{-2} for a 120 mm thickness. As the area surrounding of the pool is 110.4 m^2, the cost of insulation is estimated as 6624 dollars. The insulation reduces the volume capacity of the pool. However, the reduction is small and is neglected.	[28]
Wood tile flooring	500	–	[33]
Civil work cost	4000	Includes the excavation for the pipelines, installation costs of the ice slurry machine, heat exchanger, and other equipment.	–
Total investment costs today	16500	–	–
Total investment cost when mature	5000	If SPTES becomes a benchmarked technology for long-term energy storage, the equipment production increases considerably, and the investment costs are reduced by a factor of 3.3.	–
Operation and maintenance cost			
Component	Cost (US$ per year)	Comments	Ref.
Maintenance costs	250	The maintenance cost is assumed to be 5% of the investment costs yearly.	–
Operation costs (pump)	250	Costs for operating the pumps to transport the energy from the pool to the house.	–
Pool maintenance cost	−700	The paper assumes that the reduction in maintenance cost of the pool is accounted in the cost of the SPTES system and assumed to be half of the estimated in [34].	[34]
Electricity for cooling	–	The electricity costs are assumed to be zero, as the SPTES energy storage alternative is compared to the range of electricity prices during the winter and the summer to evaluate if it makes economic sense to store energy seasonally with a SPTES system.	–
Total yearly operation and maintenance cost	−200	–	–

account that the homeowners might not be at home during working hours, which would increase the need for short-term energy storage [35]. This is because most of the solar energy generation happens during the daytime, when the household cooling system is turned off, and most cooling demand will happen at 6 pm when the homeowner returns to the house. Alternatively, the homeowners might take holidays during the summer, which would reduce the need for long-term energy storage.

The cost of batteries is assumed to be 125 $ kWh_e^{-1} [36] and is expected to be reduced in the future. The investment cost of batteries to provide daily storage is 2.3 lower than SPTES [37]. In addition, the COP of daily cooling energy is 3 with batteries and 2 with SPTES. This makes SPTES not an ideal option for short-term energy storage. Thus, SPTES only makes sense if there is the need to store energy seasonally. As the cost of installing 3 kW of solar power generation is around 6.000 US$ [38] it could be a better alternative to install more solar panels and buy more batteries.

The items below present possible scenarios in which the SPTES could make financial sense: i) If solar power is cheap, however the household does not have enough roof area to provide all the energy needs of the house during the summer. In this case, seasonal storage can be used to store cooling energy during the winter to use during the summer. ii) During some summer days the demand for cooling could be so high that solar panels cannot generate all the energy required for cooling in the neighborhood. If a household has SPTES, long-term cooling storage is used, and the solar generation can be sold to the neighbors for a higher price. iii) If the household has high heating demands during the winter, the pool can be used as a heat sink for a heat pump system, where the heat is extracted from the pool by freezing the water and the heat is "pumped" to the house with inverted a refrigeration system. The combination of cooling in the summer and heating in the winter would increase the viability of the system.

This paper assumes an average constant COP for the ice production facility of 2 and a constant COP of 3 for the air conditioning. However, the COP for ice production and air-conditioning will vary with the ambient temperature. Depending on the design of the ice production, the COP could reach as high as 5–6 when the temperature outside is close to zero. The COP could be even higher is the temperature outside is below 0° centigrade. The houseowner could buy a battery and a SPTES system to store energy for cooling demand. In this case, the SPTES would operate only as a long-term energy storage solution, producing ice during the winter, which could increase the COP of the system up to 5. The battery would then focus on storing energy in short-term daily cycles during the summer and operate the AC systems with a COP of 3, instead of producing ice with the SPTES system with a COP lower than 2 in the summer for daily storage. Alternatively, batteries could store solar power during the day, and the SPTES plant would store thermal energy at night, when the outside temperature is lower and the overall COP for battery+SPTES operating at night is smaller than the COP for air-conditioning operating during the day.

An advantage of the SPTES system is that adding additional cooling capacity (kWt) to the system is cheap. This is because the swimming pool pump can pump as much water as needed. The additional cost of the heat exchanger is not high. In other words, it is not expensive to guarantee that the house will be cooled down quickly. Pools with greater depth are more appropriate for SPTES systems as most of the heat loss happens through the pool surface. Another benefit of SPTES systems, particularly in hot and dry regions such as Phoenix, is that cooling the swimming pool and insulating it stops the evaporation of water from the swimming pool and the water consumption of the house.

6. Conclusions

This paper presented the possibility of using existing swimming pools as seasonal thermal energy storage tanks. It shows that an average swimming pool can store around 3500 kWh_t of cooling energy at 0 °C for a cost of 0.078 US$ kWh_e^{-1}. The most optimal operation for the proposed SPTES system is to store the cold ambient temperature during the winter in ice with a high COP, using the pool as a heat sink to heat up the house,

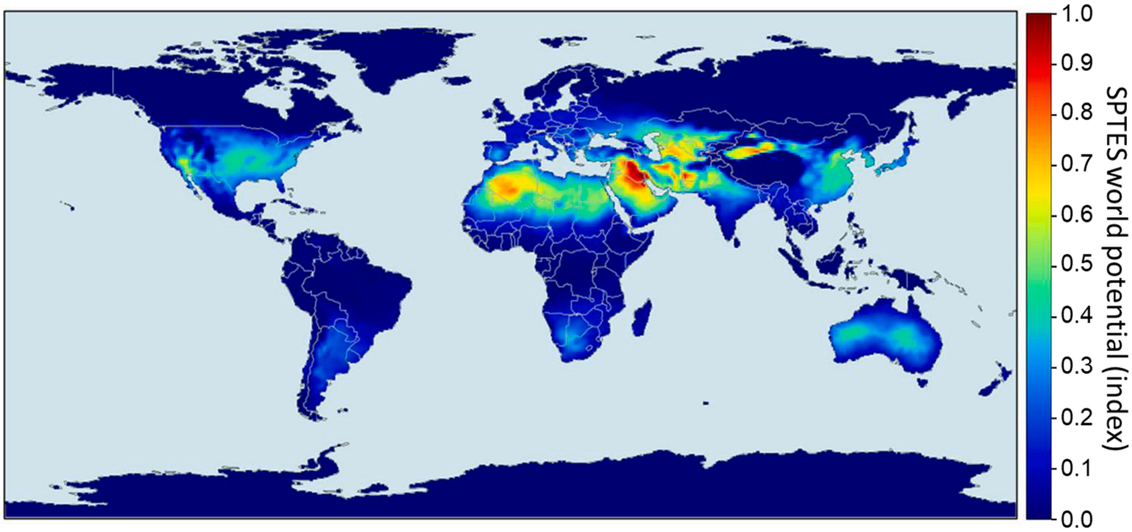

Fig. 12. World potential for seasonal cooling storage with SPTES.

and use the ice for cooling during the summer.

SPTES is more applicable in regions with large seasonal temperature differences and cooling demand. Based on the assessment of the world potential for SPTES, this paper demonstrates that the Middle East has the highest potential, followed by the USA, Eastern China, Central Australia, Northern India, Pakistan, Continental Europe, the southern part of South America, Africa, India and South East Asia. With the increase in decentralized solar power generation worldwide, SPTES offers a viable option for yearly cooling energy storage, supporting the development of 100% renewable energy grids. With increasing demand for cooling services worldwide due to economic development and global warming, SPTES will be an even more important option in the future.

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CRediT authorship contribution statement

Julian David Hunt: Conceptualization, Writing - original draft. **Behnam Zakeri:** Methodology. **Walter Leal Filho:** Project administration. **Paulo Smith Schneider:** Formal analysis. **Natália de Assis Brasil Weber:** Writing - review & editing. **Lara Werncke Vieira:** Software. **Conrado Ermel:** Resources. **Nivalde José de Castro:** Investigation. **Paulo Sergio Franco Barbosa:** Visualization. **Andreas Nascimento:** Funding acquisition. **Alessio Mastrucci:** Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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