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Theoretical analysis of the potential for thermochemical heat storage under Mediterranean climate conditions: Northern Cyprus Case

Devrim Aydin, Sean P Casey* and Saffa Riffat

Abstract

Thermal energy storage systems are gaining attention in recent years as they are now seen as one of the most promising solutions in order to increase utilisation of solar energy and reduce greenhouse gas emissions. On the other hand in the last decade, thermochemical versions of these systems have been widely researched for 'seasonal' storage of solar energy as they have the potential to store heat at ambient temperatures for extended periods of time without any degradation or heat loss. In this study a theoretical analysis of the thermochemical heat storage potential in Mediterranean climate conditions is conducted. A theoretical building located in the northern part of the island of Cyprus is considered as a case study and analysis done using real building data from a site located on the west region (Morphou) of North Cyprus. The analysis results showed that the required heat storage volume to fully compensate heating demand of the building in winter (December to February) is 8 m^3 whilst the time required for charging the THS material (Vermiculite-$CaCl_2$) with 8 m^2 solar air collectors is slightly more than a month (*i.e.* 35 days during May and June) An analysis of thermochemical heat storage's economical and greenhouse gas savings compared against gas heaters, electrical heaters and air sourced heat pumps, which are the popular methods for space heating in North Cyprus, is also presented. It was found that payback period of the thermochemical heat storage is 6 years whilst total CO_2 emissions savings over 25 years life is 47.9 tonnes.

Keywords: North Cyprus; Solar energy; Heat load; Thermochemical heat storage; Theoretical analysis; CO_2 savings

Introduction

Due to the ever increasing drive in technological and industrial developments coupled with increases in human population, environmental pollution is worsening. This phenomenon, alongside the rise in prices of fossil fuels has increased a large portion of current research towards new and improved renewable energy sources (Chiasson et al. 2000). For most populations across the world, whether low density (*i.e.* traditional rural) or high density (*i.e.* current or future cities), solar energy is considered as a primary energy source for the future however, there are issues with its supply and demand which serve to limit its usability. Storing solar energy in a suitable way can provide some level of equilibrium between supply and demand. Energy storage systems can improve utility of solar energy and also:

- contribute to energy conservation
- provide economical usage of fuel
- reduce the amount of wasted energy

Storage of solar energy in an appropriate way and developing systems to make it available on-demand must be a key mission of today's energy researchers (Sharma et al. 2009). Fossil fuels, which many national energy networks, including Cyprus are largely dependent on, are now limited and are predicted to be an insufficient and expensive energy source in the future (Grätzel 2001). In addition to this, domestic energy demand continues to rise year on year. Increased energy demand is not only dependant on the rise in energy consumption,

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but also on environmental impacts such as climate change and atmospheric pollution (both are increasing).

Within this context, various international agreements such as the Kyoto Protocol seek to address this problem (Zhou et al. 2012). As a result of the increasing awareness on the importance of renewable sources for reducing dependency on fossil fuels, the EU commission aims to increase the share of renewables to 20 % by 2020 in member countries (Böhringer et al. 2009a; Böhringer et al. 2009b). Whilst Southern Cyprus is a member of EU, Northern Cyprus (NC) is not but there is still an onus on NC to develop infrastructure and strategies to increase usage of renewable sources as it has the potential to be a part of EU in the near future.

The island of Cyprus (see: Fig. 1) has a remarkable solar potential (see: Fig. 2) when compared with most of the developed EU countries such as Germany and UK. This abundance of dense solar radiation should be fully utilized, especially during the summer months when it is at its peak. Due to historically insufficient economical outlay, alongside the technical and managerial background of the country, usage of solar energy is largely limited to flat plate solar collector technology for water heating purposes (Ibrahim & Altunc 2012). Generally, these systems can only be used from March to November as the solar availability in winter is inadequate to heat the water to a usable level (>40 °C). There are some cases where small size water storage tanks are used to store heat sensibly however, these tanks are rarely insulated and thus provide little or no advantage in utilizing the solar resource effectively. In NC, it is traditionally direct electrical heaters that are employed for space heating purpose. Whilst water heating accounts for 45 % of end energy usage, space heating constitutes the second highest energy share (28 %) in the residential sector (Atikol & Güven 2003; Atikol 1996). The reason for this can be due the large total area of residential buildings which, in general, can be 150 to 200 m^2 and usually consist of many uninsulated building components (*i.e.* walls, floors and roofs) with common usage of low efficiency single glazed windows.

There are currently no residential or commercial applications for utilizing solar energy for space heating during the winter months in NC (Evcil 2012) and, even with the abundance of energy during the summer period, it cannot be employed in winter for this purpose because of the seasonal mismatch. Thermal heat storage (THS) systems should be the main driving force for seasonal storage of solar energy and usage of it during winter conditions. This will significantly contribute to reducing the usage of electricity and thus fossil based fuels in the residential sector for space heating applications. THS systems bring the advantage of storing summer heat, densely with very low heat loss and space requirements (Aydin et al. 2015; Yu et al. 2013).

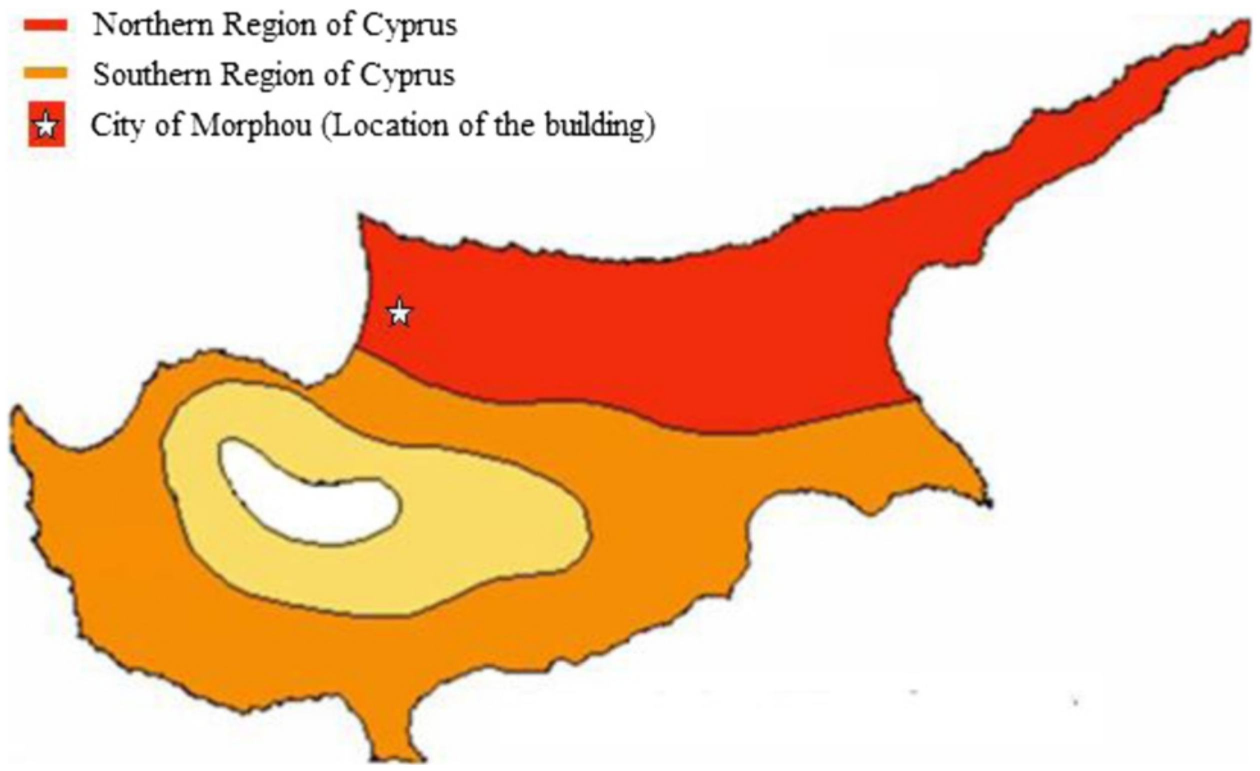

Fig. 1 Map of Cyprus showing the geographical occurrence of solar radiation and location of the test building. Adapted from: (Evcil 2012)

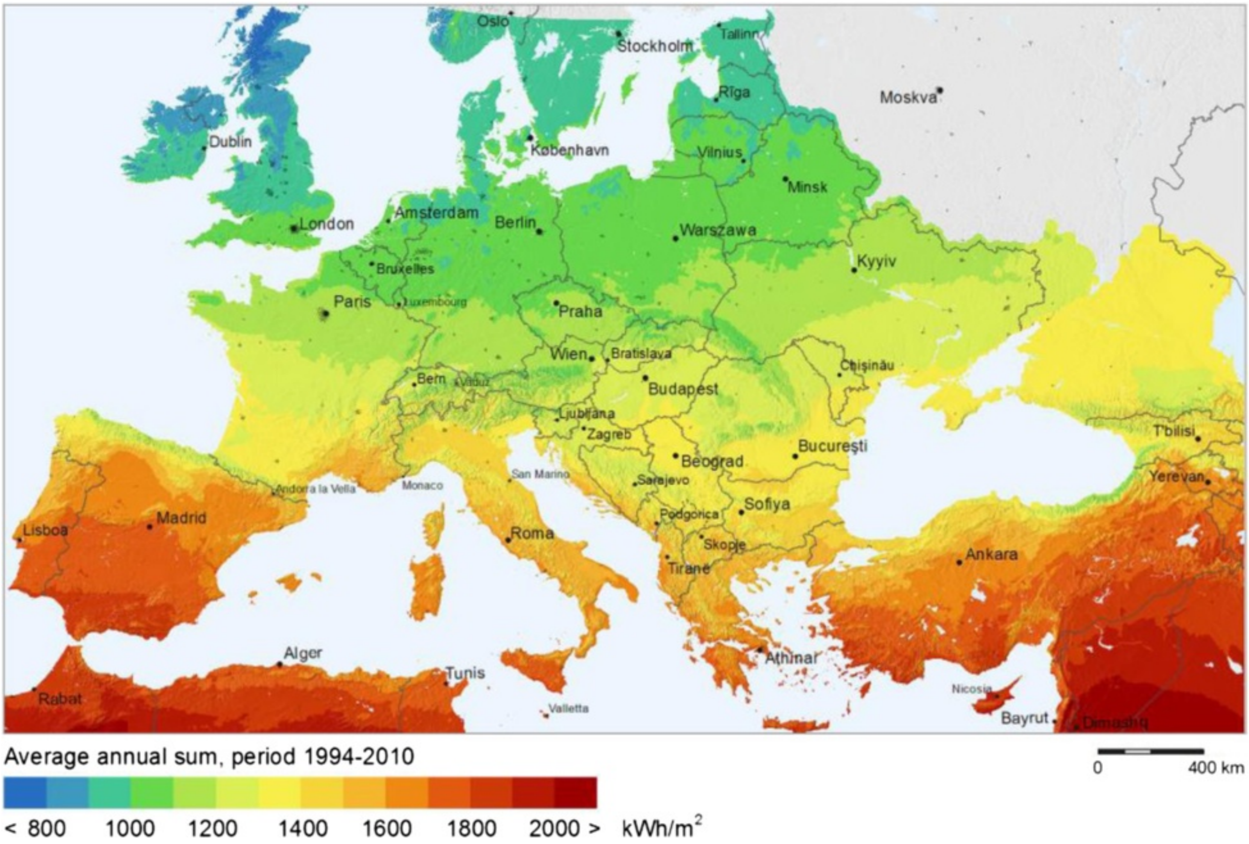

Fig. 2 Global horizontal irradiation in European countries (http://solargis.info/doc/_pics/freemaps/1000px/ghi/SolarGIS-Solar-map-Europe-en.png)

In this study, the suitability of THS for increasing the solar share in space heating applications for NC climate conditions is investigated. Within this context, firstly, energy trends in NC (past and future) are discussed. THS potential is evaluated through the analysis of material based experimental results (*i.e.* COP, output temperature, temperature lift and heat storage density) of a selected THS material called SIM-3a. The year round heating load of a selected building in NC with the solar heat gain of the same building from 8 m^2 solar air collectors is simulated. In the final part of the present research, an integrated solar THS system applicable to NC conditions is proposed and discussed in terms of its technical and economic feasibility.

Energy trends in Northern Cyprus

North Cyprus is part of a small island located in the eastern Mediterranean Sea. According to the census carried out in 2006 by the NC government the population is circa 265,000 with a total number of residential customers of ≈ 80,000 (http://www.kibtek.com/Santrallar/santrallar.htm). The rate of increase in demand for electricity has doubled from ≈ 7 % in 2004 to > 30 % during recent years due to population and construction growth in all geographical regions. The total energy consumption, E_c in 2009/2010 for NC was 913 GWh whereas for 2011/2012 it was 1256 GWh corresponding to a 37 % increase as shown in Fig. 3.

By 2012 the installed capacity of power plants in NC was 329 MW with a total energy generation, E_g of 1349 GWh (http://www.kibtek.com/Santrallar/santrallar.htm). Electricity generation is spread between steam turbines (35 %) and diesel generators (65 %) where gas turbines are used as backup (http://www.kibtek.com/Santrallar/santrallar.htm). Recently, a large scale solar photovoltaic (PV) power plant was installed with the support of the EU however, utility of this power plant is still not sufficient due to the low generating efficiency (<10 %) of PV cells. This has been attributed to high ambient temperatures in summer and grid connection problems. The installed plant capacity, P and energy generation, E_g of all NC units for 2012 are presented in Fig. 4.

The residential sector in NC currently accounts for ≈ 35 % of total national energy consumption (see: Fig. 5a) with the share of water and space heating being the two heaviest loads at 45 % and 28 % respectively (see: Fig. 5b). In total, 73 % of the energy demand of a building in NC is thermal (*i.e.* space heating and hot water). As seen in Fig. 2, the remarkable solar potential of Cyprus could be utilized to reduce fossil fuel consumption for space heating and hot water purposes. Feasibility studies on thermal energy

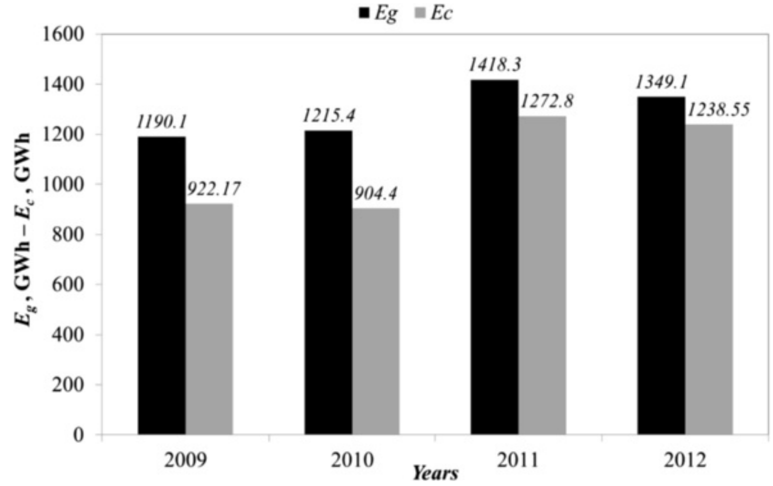

Fig. 3 Total energy consumption and generation trend for Northern Cyprus

storage systems for NC should be carried out as this technology has the potential to store solar energy and increase the solar fraction for building thermal energy consumption. Furthermore thermochemical heat storage (THS) brings an advantage of storing solar energy in summer and using it in winter without any heat loss or degradation.

The high share of overall energy consumption attributed to the residential sector is primarily due to the dependency on fossil fuels for domestic activities such as space and water heating with the majority of water heating in NC provided by either electricity or Liquefied Petroleum Gas (LPG). Central or district heating systems are rarely used in NC as a high percent of buildings are detached and winter climate conditions are not extremely cold. For this reason mainly air sourced heat pumps (HP) or direct electrical heaters are used to provide heating to each room of a dwelling separately. Additionally, in some dwellings, LPG sourced single heating units are also used. Although wood burning stove or fireplaces were popular in the past, these units are currently rarely used due to health and safety issues, environmental pollution and user heavy operating conditions such as temperature control.

NC does not have any oil or natural gas based fossil sources and imports all fuels types required for electricity generation, residential and commercial needs from other countries. Increases in population and recent industrial developments have caused a significant rise in demand for electricity and fossil fuel consumption (http://www.kibtek.com/Santrallar/santrallar.htm). There has also been a sharp rise in electricity unit prices. In 1990 electricity was 0.0008 €/kWh whereas the current unit price of electricity is 0.22 €/kWh, representing an increase of 275 %. Energy consumption in residential buildings has also increased almost 4 fold from 112 GWh to 435 GWh over the same period (see: Fig. 6).

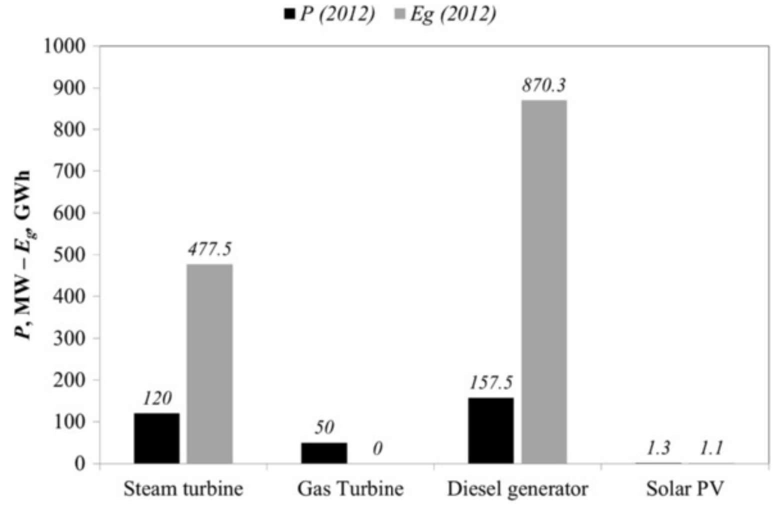

Fig. 4 Installed plant capacity and energy generation spread in NC for 2012

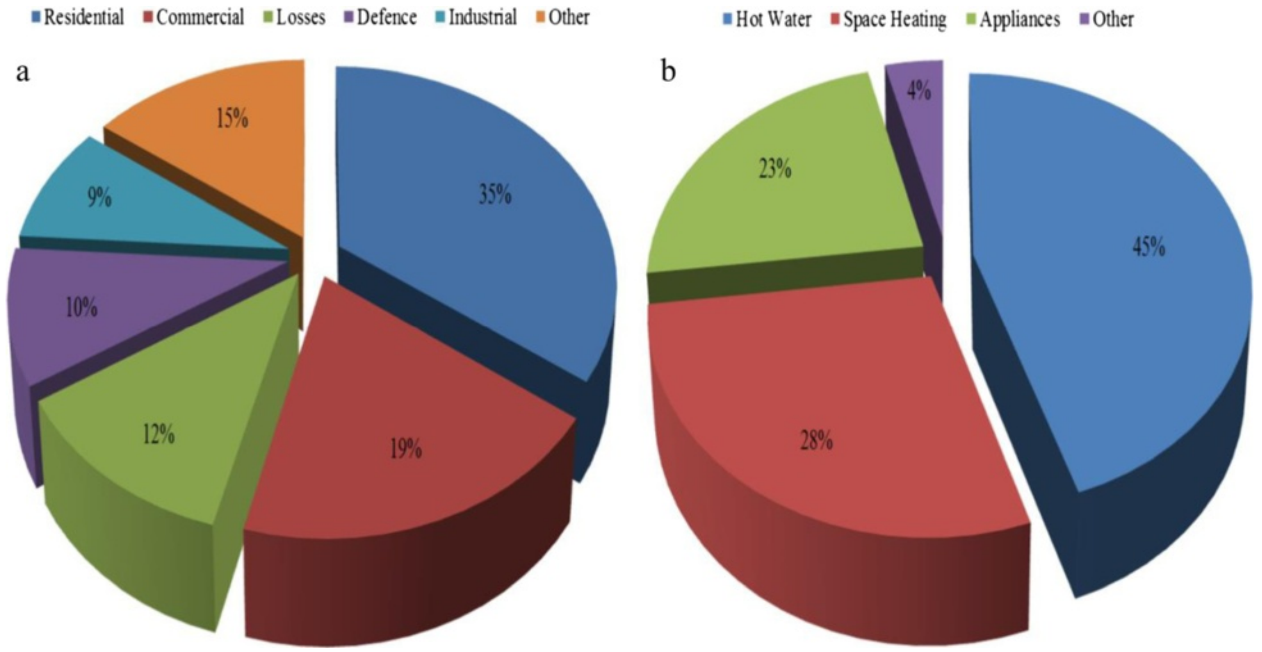

Fig. 5 **a** Share of national energy consumption in NC and (**b**) Share of energy consumption in the residential sector in NC (Atikol & Güven 2003)

NC has very good solar potential which should enable up to 100 % of thermal energy demand of a building to be met. Therefore the importance of the link (and mismatch) between solar energy and the heat load of a building should be understood and innovative methods to store heat with THS materials developed. This will start a transformation in NC towards a 'green' island and a cleaner and safer environment to live.

Materials and methodology

To evaluate the technical, economic and environmental feasibility of 'open' THS systems under NC climate conditions, initially, the annual heat load of a real residential building was simulated. The annual solar heat gain was obtained assuming a total collector surface area, A_{coll}, = 8 m^2. The THS material was selected as SIM-3a (*i.e.* Vermiculite impregnated with $CaCl_2$) from previous research carried out by the authors (Casey et al. 2014). This absorbent composite has many remarkable properties such as a high experimental heat storage density, $E_d = 165$ kWh/m^3, good cyclic ability with little hysteresis, low regeneration temperature, $T_r <$ 90 °C and is non-toxic. The storage density of SIM-3a is used to calculate the overall dimensions of the proposed TES system.

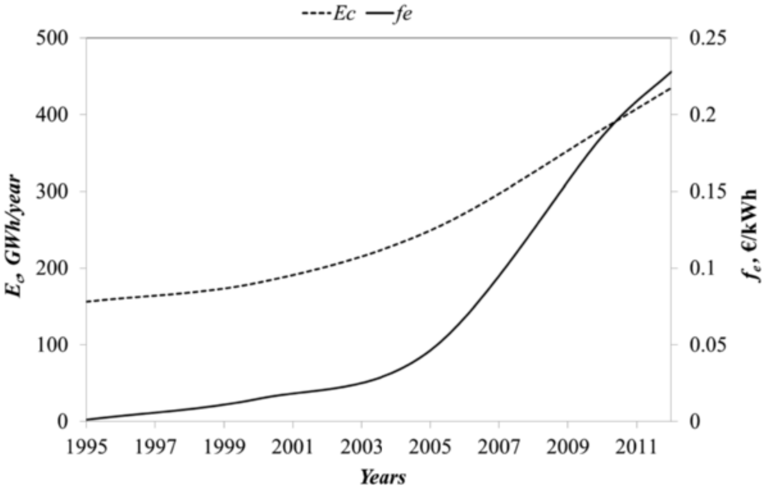

Fig. 6 Energy consumption in residential sector and unit price trend for Northern Cyprus

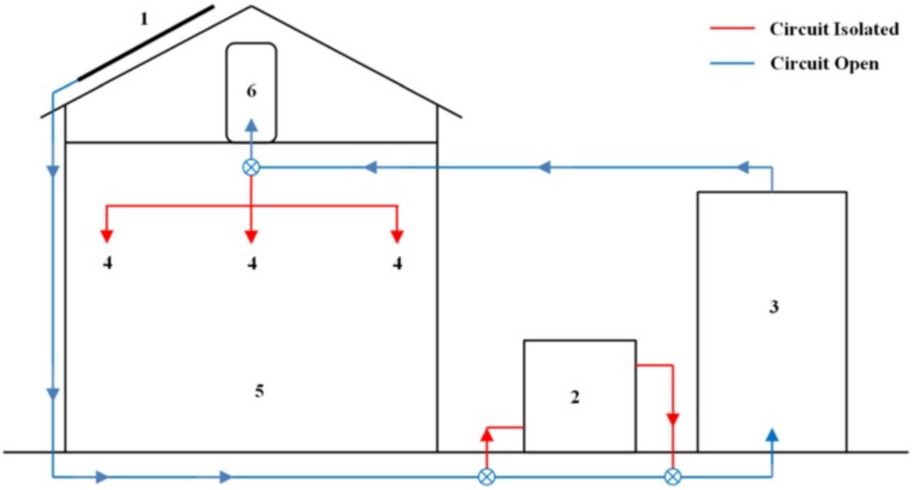

Fig. 7 Schematic of the seasonal solar driven THS in charging mode

System description

A schematic diagram of the proposed THS system is shown in Fig. 7. The system is comprised of solar air collectors (1), an evaporative humidifier (2), an over or underground THS unit (3) and internal heat outlets (4) in the building (5). In the summer period (*i.e.* June to August), the system operates in charging mode, as an open cycle, where the solar collectors supply hot and dry air to the THS ($T_r = 80 \rightarrow 90$ °C). The hot air charges the system by heating the THS material and removing any moisture. The outlet air from the THS during charging is moist and warm ($T_{out} = 50 \rightarrow 55$ °C). Although there is not any heating demand in summer conditions, there is a requirement for hot water, particularly after sundown. Therefore any heat from the outlet air can be transferred to a hot water tank (6) via a heat exchanger before dumping waste heat to the ambient air.

During the winter (*i.e.* December to February), the available solar energy is not sufficient to meet the total heating demand of the building during the day. In addition after sundown when heating demand peaks, solar energy is not available. In this instance (*i.e.* discharging mode) the THS is used to supplement any heat gained from the collectors providing adequate heat to the building. Placing the store underground would also minimize heat loss to the surroundings enabling longer heat generation or dwell times, t_{dwell} from the THS whilst also minimizing space usage inside or around the building. In this setup, the system operates in 'closed' cycle mode to minimize any waste heat (see: Fig. 8). As an evaporative humidifier is used to introduce moisture to the input airstream, heat pipes can be used to gain some heat from the ground to ease evaporation of water

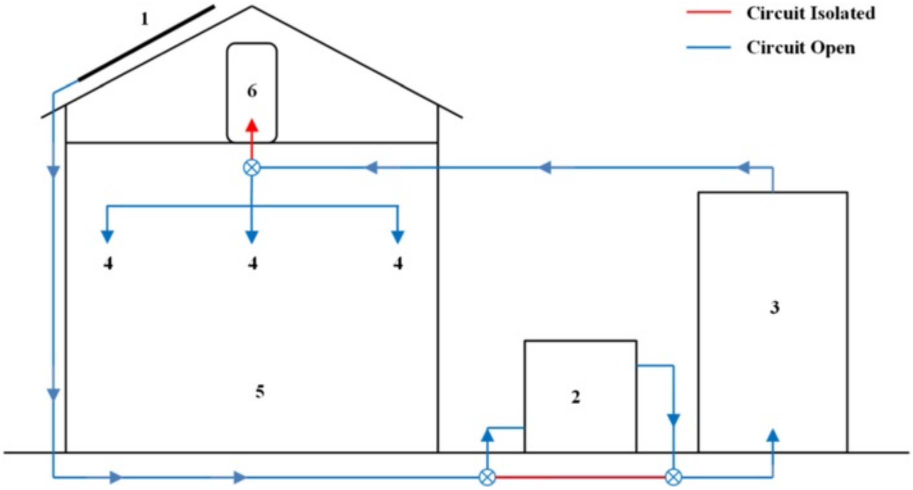

Fig. 8 Schematic of the seasonal solar driven THS in discharging mode

Fig. 9 View of the investigated building

in the humidifying tank. The relative humidity (*RH*) of the input air is increased to $RH = 80$ % and blown to the THS.

The THS system consists of divided units with perforated diffusion tubes in each unit as schematically described in Figs. 7 and 8. The perforated tubes enable air to diffuse throughout the absorbent uniformly which is crucial for the maximising reaction performance. The tubes overcome the issue of increased air resistance at the front surface of the material due to the thickness of the absorbent bed. This resistance can slow down the reaction kinetics whilst also causing a pressure drop which results in high fan energy

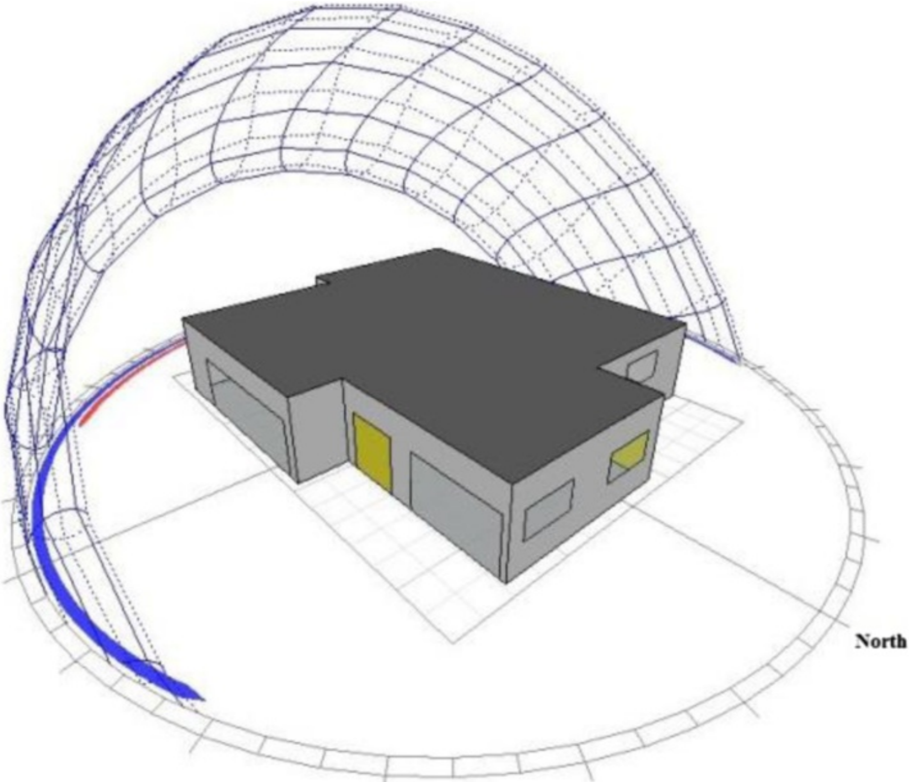

Fig. 10 3D model of the building created in Ecotect

Table 1 The properties of the building components with their applicable surface areas

Building component	Material	Total surface area (m^2)	Thickness (mm)	Schematic view	U-Value (W/m^2K)	Admittance (W/m^2K)	Solar absorption coefficient
Wall	Brick plaster	138.3	Brick: 110 Plaster: 20		2.62	4.38	0.42
Door	Solid oak timber	7.31	40		2.26	3.19	0.46
Window	Single glazed- aluminium frame	38.8	6		6.0	6.0	0.94
Roof	Concrete roof-Asphalt	185.5	Asphalt: 6 Concrete:150 Plaster: 20		0.89	2.30	0.90
Floor	Concrete slab-on ground	185.5	Soil:1500 Concrete:100		0.88	6.0	0.47

consumption and low temperature lift. Similarly to the diffusion tubes, perforated collector pipes are connected to the outlet side of the reactor. This allows the humid air to diffuse through the material and the hot air to be collected via outlet pipes. This concept increases the contact area of air and absorbent providing one possible solution to non-uniform HAM transfer in larger scale applications.

Building thermal analysis

The chosen dwelling is a 40 year old, single floor building with a floor area, $A = 180\ m^2$ (see: Fig. 9). The building is located near the west coast of the island where the weather is hot and humid in summer and mild in spring and autumn. Although Cyprus does not suffer extremely severe winter conditions, ambient temperature is below comfort conditions (18 → 20 °C) during most of the winter, and top-up heating is required. The chosen dwelling uses three types of heating systems to provide this;

1. Radiative electrical heaters are installed in the bedrooms
2. A gas heater is used in kitchen and one of the living rooms
3. Air conditioning units are used for the remaining rooms

To simulate the heat load of the building the software package Ecotect Analysis 2011 was used. The software allows user to create annual simulations using a 3D model of the building with imported building properties

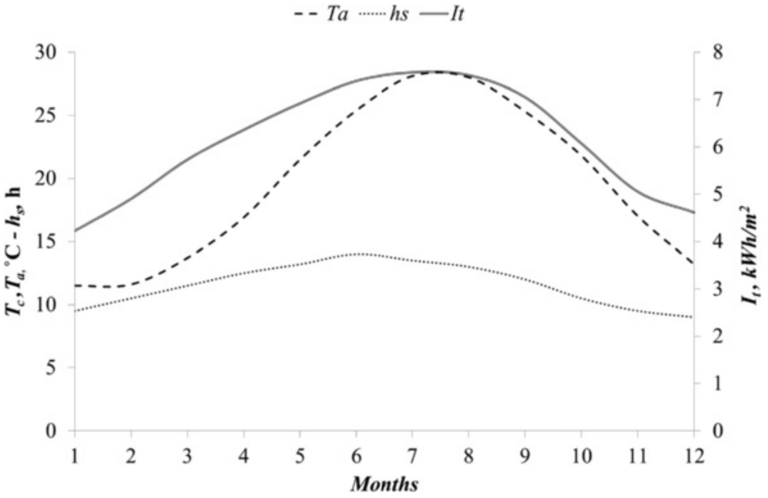

Fig. 11 Year round ambient temperature, hours of sunshine and total solar irradiation in NC

Table 2 Properties of the solar collectors

Constant	Unit	Value
Total collector area, A_c	m^2	8
Collector heat exchanger efficiency, F_r	–	0.86
Absorption-Transmission coefficient, $\tau\alpha$	–	0.8
Heat loss coefficient, U_L	W/m^2 °C	6.9

(*i.e.* dimensions, *U*-Values, ventilation etc.). The software also provides the user with several adjustable settings. For this work the heat gain from occupants was set at 70 W (*i.e.* 4 adults living in the building), the air conditioning type was set on 24 h heating mode whilst sensible and latent heat gains were set at 5 W/m^2 and 2 W/m^2 respectively. The 3D model created in Ecotect, using the original dimensions of the building is illustrated in Fig. 10.

In NC, insulation of external building envelope elements is not considered important and is rarely utilised, whilst winter heat load is not as high as other northern countries such as UK, Norway or Finland, increased application of insulation could provide huge monetary and energy savings. The building case here is primarily of a concrete type construction with uninsulated brick masonry walls however, the roof is minimally insulated using an asphalt coating to the exterior. The buildings windows are of single glazed construction with an unbroken aluminium frame. The properties of the building components with their applicable surface areas are presented in Table 1 and the data used in Ecotect to perform the thermal analysis. Comfort conditions for the building were chosen as 18 °C for the heat load analysis.

The annual total solar radiation, I_t on an optimally inclined solar collector, hours of sunshine, h_s and average ambient temperature, T_a, are presented in Fig. 11. The comfort temperature, T_c used for analysing the heat load of the building, was set as 18 °C. As can be seen year round solar irradiation is in the range of 4 → 7.5 kWh, ambient temperature is 12 → 28 °C and daily sunshine is in the range of 9.5 → 14 h. According to these data, it is clear that Cyprus has a remarkable year round solar availability to utilize in thermal

Table 3 General properties of dwellings in NC

	Percentage of total, %				
Number of occupants	1	2	3	4	>5
	1.7 %	13.9 %	27.7 %	45.4 %	11.3 %
Type of houses	Detached	Semi detached	Flat	–	–
	52.6 %	5.3 %	42.1 %	–	–
Age of houses	<5 years	5–10 years	10–20 years	>20 years	–
	10.4 %	20.8 %	38.1 %	30.7 %	–
Area of houses	<100 m^2	100–200 m^2	>200 m^2	–	–
	10.8 %	81.8 %	7.4 %	–	–
Type of external walls	Terracotta brick	Concrete blocks	Others	–	–
	91.3 %	8.4 %	0.3 %	–	–
Insulation-external walls	Glass wool	Polystyrene	Air gap	No insulation	–
	1.3 %	3.5 %	1.7 %	93.5 %	–
Frames of windows	Wood	Aluminium	PVC	–	–
	16.9 %	78.4 %	4.7 %	–	–
Glazing	Single glazing	Double glazing	–	–	–
	84.8 %	15.2 %	–	–	–
Type of roof	Flat Concrete	Inclined concrete w tiles	Flat concrete, tiles on wood	–	–
	73.6 %	8.7 %	17.7 %	–	–
Insulation-roof	Glass wool	Polystyrene	No insulation	Asphalt	–
	4.4 %	7.1 %	88.5 %	–	–
Means of heating	Central heating	Heaters	Air-conditioners	–	–
	2.2 %	53.0 %	44.8 %	–	–
Energy source for heating	Wood	Electricity	LPG	Kerosene	Diesel
	1.3 %	65.8 %	27.7 %	3.9 %	1.3 %
Number of air conditioners	None	1	2	3	>4
	30.7 %	21.2 %	23.8 %	16.5 %	7.8 %

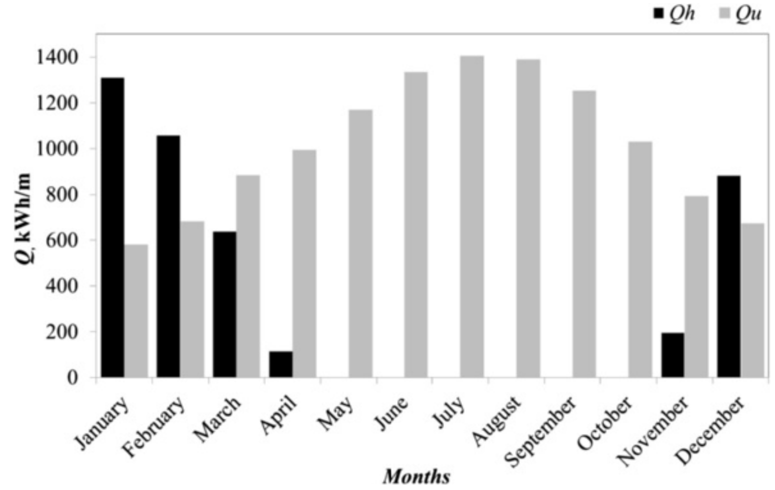

Fig. 12 Monthly heat gains and heating demand for the building

applications. Data obtained from the European Commission's web site (http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?lang=en&map=europe. [Accessed on 10.01.2015], http://photovoltaic-software.com/pvgis.php) was used to calculate the solar thermal heat gain, Q_u (W) using Eq. 1:

$$Q_u = A_c \cdot F_r \cdot \left[(H_t \div h_s) \cdot (\tau\alpha)_{net} - U_L \cdot \left(T_{fi} - T_a \right) \right] \quad (1)$$

Where A_c is the collector area (m^2), H_t is the solar radiation (J/m^2), h_s is the radiation time (s), $\tau\alpha$ is the absorption-transmission coefficient of solar collectors, U_L is the heat loss coefficient of solar collectors (W/m^2 °C), T_{fi} is the collector surface temperature (°C) and T_a is ambient temperature (°C). The properties of the solar collectors that were used in the calculation are given in Table 2.

A survey was conducted by Evcil (Evcil 2012) to demonstrate the general properties of dwellings in NC with the results given in Table 3. The dwelling for this study was chosen as its properties are representative of the average dwelling in NC as described in the Evcil study. The survey consisted of multiple choice questions and results demonstrate the share of different options provided in questions. The properties of the building considered in this study are highlighted in the table.

Results

The main aim of the analysis was to determine the storage volume, V_s of THS required to assist the buildings normal solar gains and fully meet building heat demand. As a 'seasonal' heat storage approach is proposed, the

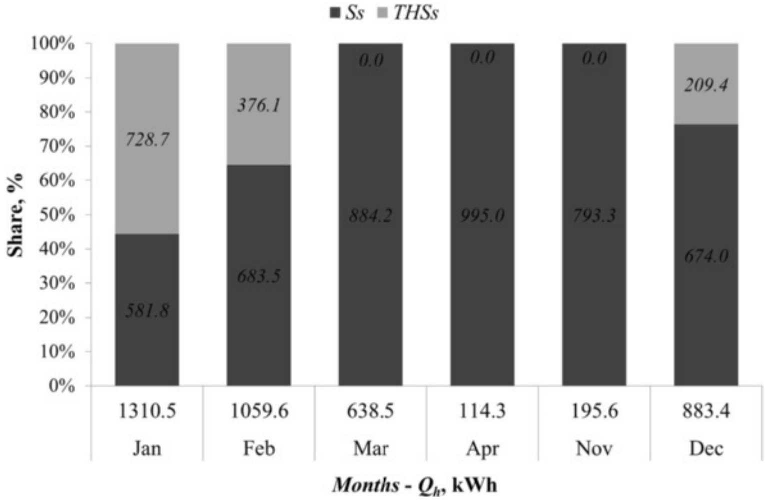

Fig. 13 Share of THS required to meet heating demand during heating months

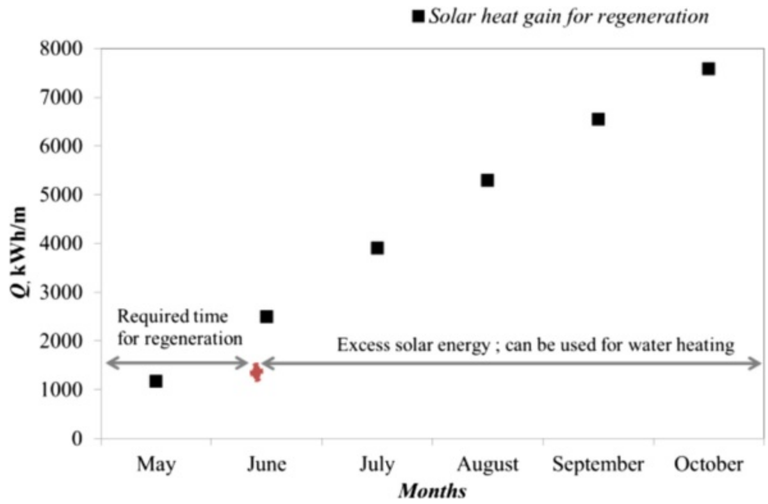

Fig. 14 Regeneration time of the absorbent with solar energy in summer conditions

potential of solar energy for absorbent regeneration was also investigated. The absorbent material selected was the SIM-3a (V-CaCl$_2$) composite as discussed in previous section with the E_d used in order to determine V_s.

In the dual hybrid model proposed here, integrated THS and solar air collectors are considered as the heating unit. In Fig. 12 the annual heat load and solar heat gain for NC climate conditions is presented. There is no heat load from May to October as the average temperature is higher than 18 °C (*i.e.* chosen comfort limit) during this period. The heating period begins in November and lasts until April.

However in November, March and April solar heat gains still exceed the building heat demand, $Q_u > Q_h$ therefore there is no necessity for any THS in these months. THS is only required in December, January and February where heat loads, Q_h are greater than heat gains are (*i.e.* $Q_h = 883$, 1310 and 1060 kWh whilst $Q_u = 674$, 582 and 683 for Dec, Jan and Feb respectively).

These results indicate that an auxiliary heating source is required to assist solar energy for full compensation of heat load of the building. The peak difference, ΔQ between Q_u and Q_h occurs in January with 729 kWh with February and December having ΔQ of 376.2 kWh and 209.3 kWh (see: Fig. 13). The total additional thermal energy required for the three heating months is 1314 kWh and, based on the energy density of the absorbent ($E_d = 165$ kWh/m^3), the THS volume required to meet the total thermal demand was calculated as $V_s = 8$ m^3. The specific required storage volume for each month is calculated as 4.41, 2.28 and 1.26 m^3 in January, February and December respectively.

From May onwards, when there is no building heat load and the moist absorbent can be regenerated using

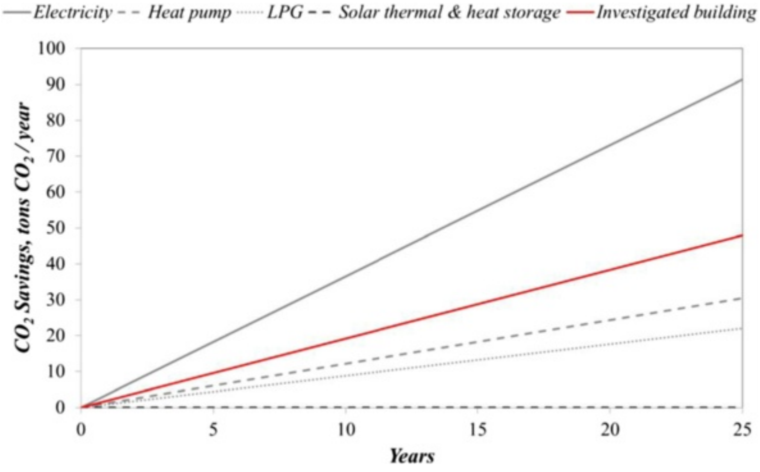

Fig. 15 Total CO$_2$ savings using THS in comparison with traditional heating methods

Table 4 Cost of system components

System component	Price (€)
Ducting pipes, fittings, vents	200
Solar panels (8 m^2)	600
Heat storage tank (8 m^3)	400
Fan	50
Heat storage material (8 m^3)	800
Evaporative humidifier	100
Insulation	100
System built and installation costs	500
Total	2750

solar energy. From the second half of spring to the first half of autumn (April–September) solar radiation is at its maximum level (> 6 kWh/m^2) and the notional 8 m^3 absorbent can be regenerated in a time period of slightly more than one month as presented in Fig. 14. The theoretical amount of energy required for regeneration is equal to the energy supplied by the material during the discharging process (*i.e.* $Q_c = 1314$ kWh $= Q_d$) and is indicated in Fig. 14. From May to October, the potential cumulative solar gain is 7582 kWh and thus only 17 % of this would be sufficient for regenerating the 8 m^3 of SIM-3a. Any remaining heat can be used for water heating purposes, if required.

CO_2 savings and economic evaluation of the system

Control of GHG and CO_2 emissions and methods for reducing them have been gaining importance in recent years as they have been shown to have a significant effect on both Ozone depletion and global warming. Utilizing new, clean and renewable energy sources is one of the most promising solutions to this problem. In the domestic sector of NC, electricity, natural gas, fuel oil, LPG or solid fuel sourced systems are mostly preferred for space heating purposes due to their advantages for consumers such as lower prices, steady and easy operating conditions, low space requirements and long operational lifetime in comparison with renewable sourced heating systems.

Space heating applications however do not require high temperature. For example the heat pump blowing temperature is $35 \rightarrow 45$ °C in air conditioning applications or water circulation temperature is $35 \rightarrow 40$ °C for wall or ground heating methods. Using high temperature combusting fossil fuels for low temperature applications like space heating is a waste of the high quantity and quality of this energy (*i.e.* as a result of exergy destruction). In addition this is the waste of the fuel potential, which could be used for more appropriate applications such as electricity generation. The potential contribution of THS systems would facilitate this move away from high temperature fuel wastage by meeting the space heating demand with solar energy.

The conversion factor, ς is a coefficient used to determine the CO_2 emissions from energy generation or consumption processes and varies in the range of $0 \rightarrow 1$ depending on several factors (*e.g.* fuel type used etc.). The conversion factor of electricity per kWh consumption, ς_e, in Cyprus is 0.87 whilst for LPG, including residual heat or power generation $\varsigma_{LPG} = 0.21$. According to a recent IEA report however, solar thermal and THS systems do not have CO_2 emissions and therefore $\varsigma_{THS} = 0 \rightarrow S_{CO_2,THS} = 0$.

According to these assumptions the CO_2 savings per year in compliance with usage of an AC heat pump

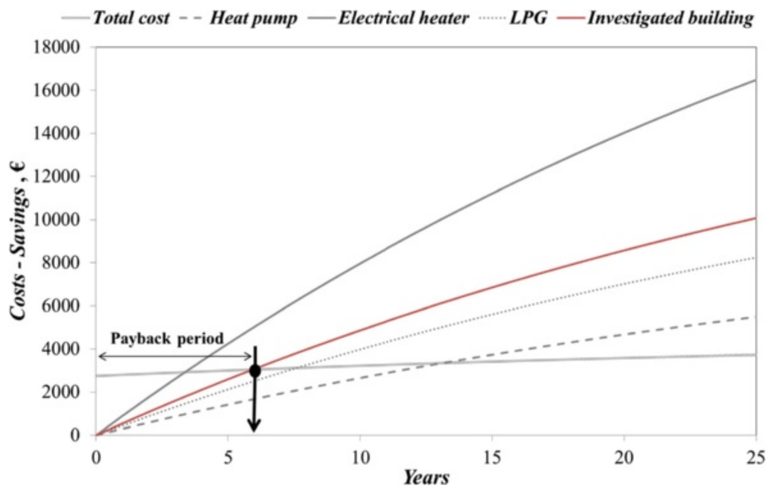

Fig. 16 Payback period of the integrated solar assisted THS

(HP), electrical heater (EH) or gas heater (GH) are given in Equations 2, 3 and 4 respectively;

$$S_{CO_2,HP} = \sum\nolimits_{N=0}^{N=25} \xi_{HP} \times \varsigma_e \tag{2}$$

$$S_{CO_2,EH=} \sum\nolimits_{N=0}^{N=25} \xi_{EH} \times \varsigma_e \tag{3}$$

$$S_{CO_2,GH} = \sum\nolimits_{N=0}^{N=25} \xi_{GH} \times \varsigma_{LPG} \tag{4}$$

Based on these calculations, utilizing solar assisted THS for space heating would allow for a saving of 3.65, 1,21 and 0.88 ton CO_2 per year compared with usage of EH, GH and HP respectively (see: Fig. 15). The building investigated here uses all of these systems. The living room and one of the bedrooms are heated using a HP, the kitchen and other living room are heated with GH and rest of the rooms are heated with EH. For this reason CO_2 savings for the investigated building are determined as an average of the CO_2 savings achieved for all three heating methods. Therefore yearly CO_2 savings of the investigated building with the usage of solar assisted THS, is estimated at 1.91 ton per year. As the system lifetime is assumed to be 25 years and during that period savings of 47.9 ton CO_2 are expected.

In addition to the environmental effect of the proposed system, the economical evaluation of it should also be discussed in order to form a complete picture of solar assisted THS systems. The total cost of the system is estimated at €2750 based on the information provided in Table 4. Cost estimations are made based on component and material retail prices in NC at the time of printing.

For analysis of the total savings of the proposed system, the present worth method is used. According to this method The rate of interest, *r*, can be found using Equation 5:

$$r = \frac{(i + g)}{(1 - g)} \tag{5}$$

where i is inflation rate (14.5 %) and g is discount rate (11.4 %). Therefore r is calculated as 2.7 %. The present worth factor (PWF) is expressed as in Equation 6 to determine the present value of the money for the N^{th} year;

$$PWF = \frac{1}{(1 + r)^N} \tag{6}$$

The potential savings against using the HP, EH and GH over the 25 year period are analysed using Equations 7, 8 and 9 respectively where γ is the total operational cost, ξ the total yearly energy consumption and f_e, the unit price of electricity in NC which is currently €0.22/kWh for domestic usage.

$$\gamma_{HP} = \sum\nolimits_{N=0}^{N=25} \xi_{HP} \times \frac{fe}{3} \times PWF \tag{7}$$

$$\gamma_{EH} = \sum\nolimits_{N=0}^{N=25} \xi_{EH} \times fe \times PWF \tag{8}$$

$$\gamma_{GH} = \sum\nolimits_{N=0}^{N=25} \xi_{GH} \times f_{LPG} \times PWF \tag{9}$$

The total cost of the THS, γ_{THS}, through the 25 year period including capital cost, operational and maintenance costs is calculated using Equation 10 where subscripts O, M and C represent operational, maintenance and capital respectively.

$$\gamma_{THS} = \gamma_C + \sum\nolimits_{N=0}^{N=25} (\gamma_O + \gamma_M) \times PWF \tag{10}$$

The total yearly operational and maintenance costs of the system are expected to be very low with the annual sum assumed as 2 % of the total capital costs (see: Equation 11);

$$(\gamma_O + \gamma_M) = (2\% \times \gamma_C) \tag{11}$$

The payback periods of HP, EH and GH are determined as follows;

$$N_{\rho HP} \rightarrow \gamma_{HP} = \gamma_{THS}$$

$$N_{\rho EH} \rightarrow \gamma_{EH} = \gamma_{THS}$$

$$N_{\rho GH} \rightarrow \gamma_{GH} = \gamma_{THS}$$

The economic analysis results are presented in Fig. 16. Similar to the environmental analysis, this is conducted based on the savings of solar assisted THS compared with the operating costs of usage of the current systems/methods (HP, EH and GH) and the average. It was found that the solar assisted THS system could provide a saving of €550/year whilst cumulative savings exceed the sum of total (capital, maintenance and operating) cost of system, (3081 > €3050) at the end of year 6 years. Over the full 25 years the cumulative total saving would be €10,077 whereas the total cumulative cost of the system would be €3731 over the same period corresponding to a €6346 profit with the usage of THS compared to HP, GH and EH. The average annual energy consumption (e.g. appliances, heating cooling, hot water) of the investigated building is ~5600 kWh whilst the energy (electricity, gas) consumed for space heating is ~ 1900 kWh. Therefore the average annual energy saving rate is found to be 34 %. The floor area of the building investigated is 180 m^2 whereas the floor area of dwellings in NC is generally 100–150 m^2 and therefore, in NC conditions the average annual energy saving rate and payback period is expected to be somewhat less than the investigated building *i.e.* 25–30 % and 5–7 years respectively.

Conclusions

In this study the applicability of thermochemical heat storage (THS) under Northern Cyprus climate conditions is theoretically investigated. An underground THS system, integrated with 8 m^2 solar air collectors placed on the roof of a flat roof, detached building is considered. In addition, an evaporative humidification unit for humidifying the air during the discharging process is assumed. It was found that 8 m^3 of absorbent was required to meet the mismatch between solar energy supply and building heat load where the total solar heat gain and heat load are 1939 kWh and 3253 kWh respectively. On the other hand with 8 m^2 of solar air collectors, 35 days in the summer period (May/June) where the solar irradiation is in the range of $6 \rightarrow 7$ kWh/m^2 are required to regenerate the absorbent.

Gas heaters, electrical heaters and heat pumps are widely used in North Cyprus for space heating. The results of an economic and environmental comparison showed that payback time would be 6 years based on the capital and operational costs of THS compared to the average operational costs of GH, EH and HP. Similarly, CO_2 savings would be 47.9 tonnes.

According to the theoretical analysis, THS was found to be a feasible method to utilize for space heating purposes in Northern Cyprus. It has very good potential to replace electrical and gas sourced heating systems which have negative effects on the environment and economy. The remarkable solar potential in Northern Cyprus, which is > 6 kWh in summer should be harvested to meet the heating demand in winter by utilizing THS. In this respect, the Northern Cyprus government should raise the public awareness and promote a transformation away from traditional space heating systems for a sustainable future.

Nomenclature

A_c	collector area	m^2
E_c	energy consumption	kWh
E_d	energy density	kJ/kg
f_e	electricity unit price	€/kWh
F_r	collector heat exchanger efficiency	–
g	discount rate	–
H_t	total solar irradiation	J/m^2
I_t	total solar irradiation	kWh/m^2
i	inflation rate	–
P	thermal power	kW
Q_u	solar heat gain	kWh
Q_h	heat load of the building	kWh
r	rate of interest	–
S	savings	kg/m^3
t	time	s
T	temperature	°C
U_L	collector heat loss coefficient	W/m^2K
V_s	storage volume	m^3
$\tau\alpha$	absorption-transmission coefficient	–
ς	conversion factor of electricity per kWh consumption	–
ξ	total yearly energy consumption	kWh
Υ	total operational cost	€/kWh

Indices

a	ambient
c	comfort, collector, charging, capital cost
d	discharging
e	electricity
fi	collector surface
g	generation
m	maintenance cost
o	operational cost
out	outlet
r	regeneration
s	sunshine, storage
t	total

Abbreviations

COP: Coefficient of performance; EH: Electrical heater; EU: European Union; GH: Gas heater; HAM: Heat and mass transfer; HP: Heat pump; HSM: Heat storage material; HTF: Heat transfer fluid; LHS: Latent heat storage; LPG: Liquefied petroleum gas; NC: North Cyprus; RH: Relative humidity; PWF: Present worth factor; SIM: Salt impregnated matrix; SHS: Sensible heat storage; TES: Thermal energy storage; THS: Thermochemical heat storage.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

DA performed the theoretical analyses and drafted the manuscript.
SPC participated in the preparation of figures also critically revised the manuscript. SR has supervised the presented research, done the final revision of the manuscript and given final approval of the version to be published.
All authors read and approved the final manuscript.

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