

# Feasibility study of $\text{MgSO}_4$ + zeolite based composite thermochemical energy stores charged by vacuum flat plate solar thermal collectors for seasonal thermal energy storage

D. Mahon <sup>a,\*</sup>, P. Henshall <sup>b</sup>, G. Claudio <sup>a</sup>, P.C. Eames <sup>a</sup>

<sup>a</sup> Loughborough University, Loughborough, UK

<sup>b</sup> Oxford Brookes University, Oxford, UK

## ARTICLE INFO

### Article history:

Received 1 December 2018

Received in revised form

23 March 2019

Accepted 31 May 2019

Available online 2 June 2019

### Keywords:

Solar  
Energy  
Storage  
Thermochemical  
Solar-collector  
Feasibility

## ABSTRACT

A primary drawback of solar thermal technologies, especially in a domestic setting, is that collection of thermal energy occurs when solar irradiance is abundant and there is generally little requirement for heating. Thermochemical Energy Storage (TCES) offers a means of storing thermal energy interseasonally with little heat loss. A combination of a Solar Thermal Collector (STC) and TCES system will allow a variety of different heating applications, such as domestic space and hot water heating as well as low temperature industrial process heat applications to be met in a low carbon way. This paper describes and assesses the feasibility of two novel technologies currently under development at Loughborough University; i) an evacuated flat plate STC and ii) composite TCES materials, coupled together into a system designed to store and supply thermal energy on demand throughout the year. Experimental results of composite TCES materials along with predicted performance of STC's are used within a developed model to assess key metrics of conceptual TCES + STC systems feasibility, including; charging time, payback time, cost/kWh, energy savings and CO<sub>2</sub> savings. This paper demonstrates the economic, energy and carbon savings potential of conceptual TCES + STC systems suitable for domestic use.

© 2019 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

Nearly half of the UK's total energy consumption is used for heating purposes [1], with 26% of the UK's total energy consumption used specifically for Domestic Space Heating (DSH) and Domestic Hot Water (DHW) [1]. 88% of the energy for DSH and DHW comes directly from gas and oil with only 2% of the energy required for heating generated from renewable energy sources [1].

Typically supply of thermal energy is high when demand is low (i.e. throughout the summer day time) and vice versa during the winter months. If effective TES is utilised the thermal energy from renewable energy sources (i.e. STC's) can be stored at times of surplus and low demand ready for use when demand is high. This method can utilise thermal energy which would otherwise be unutilised and wasted, increasing the amount of energy generated

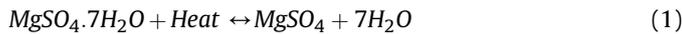
for DSH and DHW from renewable energy sources.

There are three main types of TES, Sensible Energy Storage (SES), Latent Energy Storage (LES) and Thermochemical Energy Storage (TCES) which stores energy in reversible chemical reactions [2]. For TCES heat is applied to a substance until it disassociates into two reactants. When the reactants are recombined energy is released in the form of heat. If the two reactants are kept separate, the energy can be stored indefinitely [3].

Equation (1) shows an example of a reversible chemical reaction which can be used to store heat. Magnesium sulphate ( $\text{MgSO}_4$ ) is an abundant, non-toxic, relatively cheap salt hydrate, with a high theoretical energy density (2.8 GJ/m<sup>3</sup> or 778 kWh/m<sup>3</sup>) which can be utilised as a thermochemical energy storage material [4].  $\text{MgSO}_4$  represents an ideal candidate for domestic interseasonal TCES as it will dehydrate (charge) when exposed to a temperature of 150 °C [4]. Recent research into the potential of  $\text{MgSO}_4$  has demonstrated several drawbacks with its application in TCES [4,5]. The main issue related to  $\text{MgSO}_4$  for use as a TCES material is agglomeration when the material is rehydrated (discharged), any agglomeration that occurs reduces the permeability of the material reducing both the power output and the overall energy output.

\* Corresponding author. Centre for Renewable Energy Systems Technology (CREST), School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough, UK.

E-mail address: [d.mahon@lboro.ac.uk](mailto:d.mahon@lboro.ac.uk) (D. Mahon).



Zeolites are an absorbent material which could potentially be used as a standalone TCES material. Due to their porous structure and typically large surface area [2,6–8], water can be adsorbed by zeolites resulting in the release of hydration heat, making them ideal candidates for domestic TCES. Due to zeolites large internal pore volumes materials (i.e. salt hydrates) can be impregnated inside their structure. Zeolites have been specifically used in attempt to enhance the characteristics of  $\text{MgSO}_4$  [9]. Throughout this paper TCES will be used to refer to sorption materials and thermochemical materials.

STC's are commonly used to heat water to be used for DSH and DHW supply and they usually come in two conventional non-concentrating varieties. The first is a Flat Plate Collector (FPC) which employs a thin metal sheet with a selective surface as a solar absorber, filling a large proportion (>90%) of the gross collector area [10]. A FPC loses energy from the absorber by conduction, convection and radiation. The second main type of non-concentrating STC is an Evacuated Tube Collector (ETC). In an ETC each evacuated tube has an individual absorber dimensioned to fit inside the glass tube without touching the tube walls. The glass tube is evacuated surrounding the absorber by a high vacuum suppressing both convection and gas conduction. ETC's are capable of achieving higher operational temperatures and higher efficiencies based on absorber area compared to FPC's [11]. However, ETC's have less absorber area per gross collector aperture area compared to FPC's.

A recent innovation in STC technology has been the development of Vacuum Flat Plate Collectors (VFPC's) [12]. These types of collectors combine the benefits of FPC's and ETC's via the use of a flat enclosure that surrounds a FPC's solar absorber. The enclosure is designed to be evacuated and robust enough to withstand the exterior atmospheric compression forces resulting from the high vacuum contained within the enclosure [13]. The FPC efficiency is then improved thanks to the thermal insulation properties of the surrounding vacuum layer suppressing conduction and convection in a similar way to an ETC. Furthermore, these types of collectors retain a large absorber area to gross collector aperture area ratio.

Composite materials consisting of zeolite-Y containing various wt% of  $\text{MgSO}_4$  have been created and experimentally characterized using a Differential Scanning Calorimeter (DSC). The generated DSC data was utilised to calculate the feasibility of combined TCES and STC systems for domestic inter-seasonal TES and annual heat delivery.

This study investigates the potential of a combination of a TCES system with a VFPC system for domestic application. Fig. 1 below shows a hypothetical system layout of how the VFPC and TCES system can be integrated into a single system. The diagram illustrates how the VFPC can be used for two purposes, 1) preheating ambient air to the required temperature for dehydration (charging) of the TCES material during the summer period, 2) providing DSH or preheating the household's DHW store at any other period of the year. Throughout the winter, when required, humid ambient air will be pumped directly through the TCES material hydrating (discharging) the store releasing the stored heat. This heat can be used, for either DSH or preheating a DHW store.

The proposed system has the advantage of providing low carbon heat, offering heat security and can potentially be used in off-grid locations. Once the system is dehydrated the heat is stored meaning if the households current space heating system (i.e. typically a boiler) becomes unavailable for any reason the household will still have the TCES + STC system to provide heat.

The objective of this paper is to evaluate the economic, energy and carbon saving potential of conceptual TCES + STC systems

suitable for domestic use. Preliminary results suggest the combination of these two technologies has significant potential for domestic applications.

## 2. Materials and methods

The TCES materials used in this work were  $\text{MgSO}_4 \cdot x\text{H}_2\text{O}$ , zeolite-Y and composite materials consisting of both zeolite-Y and  $\text{MgSO}_4$ . The method for creating the composite materials is an impregnation method which is described in a paper by Mahon et al. [14]. A TA Instruments Discovery DSC was utilised to assess the energy density of the TCES materials. A nitrogen purge gas was used for all DSC measurements where the sample mass used was 6–10 mg. The DSC is not configured to provide a humid air flow; therefore, the hydration of the samples took place in a custom-built microcontroller regulated hydration chamber. The hydration conditions were ~56% ( $\pm 3\%$ ) Relative Humidity (RH) at 20 °C ( $p\text{H}_2\text{O} = \sim 1.3 \text{ kPa}$ ) for a minimum of 18 h. The DSC samples were dehydrated to 150 °C using a double DSC dehydration approach [15] to establish, the effective specific heat capacity, the sensible enthalpy component and the dehydration enthalpy of the TCES samples. The dehydration enthalpy (total enthalpy - sensible enthalpy) was used as the specific energy density of the TCES materials for the model. Each of the TCES materials were tested several times in the DSC to obtain an average value.

### 2.1. Solar collector information

The useful energy gain ( $Q$ ) from a STC is given by Ref. [16]:

$$q = A [S - U_L(T_C - T_a)] \quad (2)$$

where  $A$  is the area of the absorber,  $S$  is the absorbed solar energy per unit area,  $U_L$  is the thermal loss coefficient of the collector,  $T_C$  is the collector output temperature and  $T_a$  is the ambient temperature. The efficiency of a collector in terms of aperture area ( $\eta_a$ ) can be evaluated by:

$$\eta_a = \frac{q}{A_a G} \quad (3)$$

where  $G$  is the local solar irradiance and  $A_a$  is the area of the aperture. The efficiency in terms of gross collector area ( $\eta_c$ ) can be evaluated by:

$$\eta_c = \frac{q}{A_c G} \quad (4)$$

where  $A_c$  is the gross collector area.

From Equations (2)–(4) it can be observed that for a given solar irradiance the efficiency of a STC will reduce as the delta temperature ( $T_C - T_a$ ) of the collector increases and if  $A_c$  is used to calculate efficiency rather than  $A_a$  (as  $A_c > A_a$ ). In order to model and compare the three types of STC's (FPC, ETC, VFPC) previously discussed, the performance parameters of two commercial STC's were used, an FPC [10] and an ETC [17]. The characteristics of the VFPC collector used in this study were derived from the characteristics of both of these commercial collectors, where the VFPC collector has a similar  $U_L$  value to the ETC while having a similar  $A_a/A_c$  ratio as the FPC. Efficiency curves for commercial STC's are usually characterized by an expression similar to Equation (5):

$$\eta = \eta_0 - k_1 \frac{(T_C - T_a)}{G} - k_2 \frac{(T_C - T_a)^2}{G} \quad (5)$$

where the values of constants  $\eta_0$ ,  $k_1$  and  $k_2$  are given by

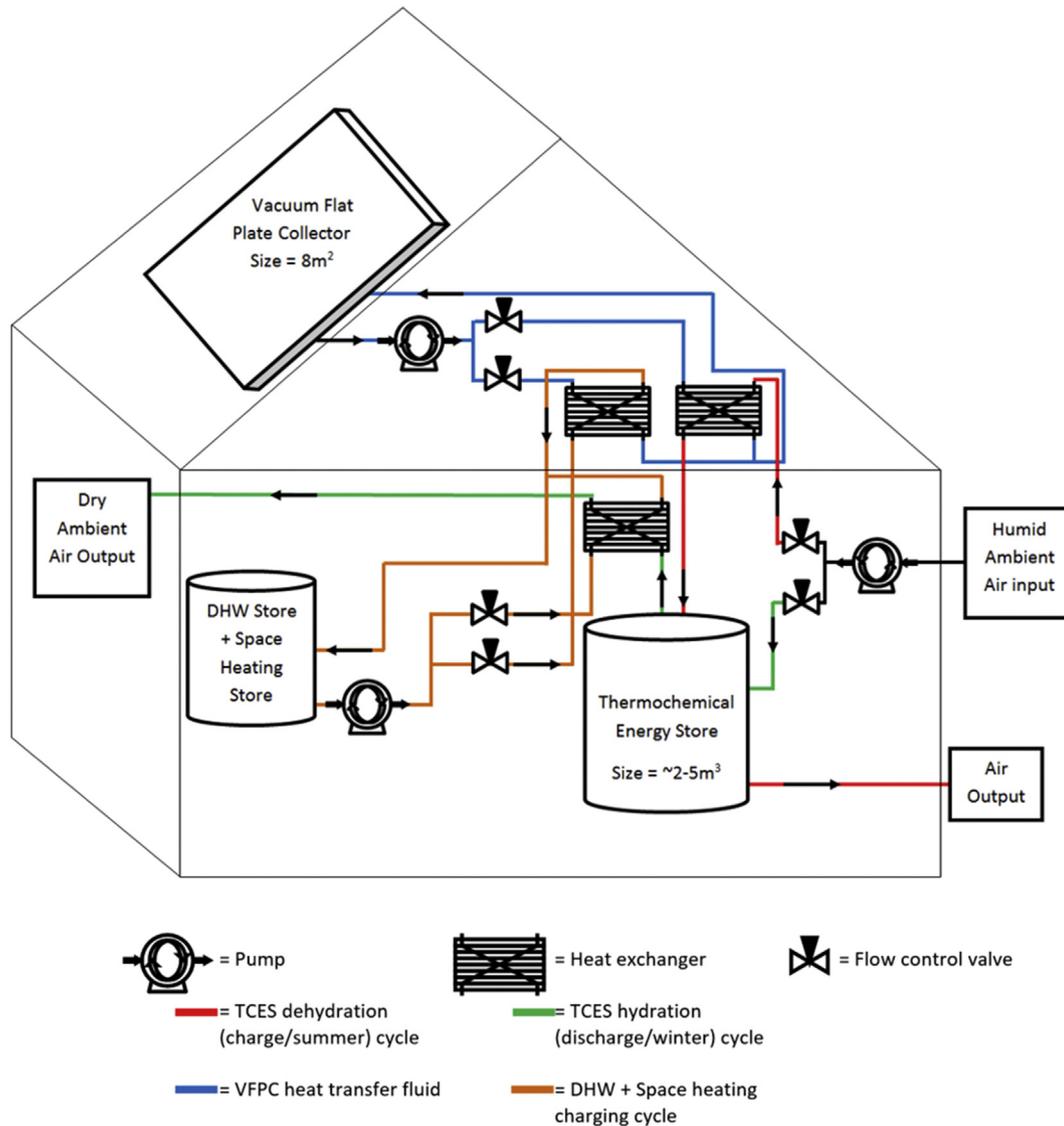


Fig. 1. Schematic of hypothetical TCES + VFPC system.

manufacturers in terms of aperture area.  $\eta_0$  = the maximum efficiency of the STC's when  $T_a = T_c$ ,  $K_1$  and  $K_2$  are constants which are used in Equation (5) to give the efficiency of the STC's dependant on the ambient temperature ( $T_a$ ) (i.e. the constants  $K_1$  and  $K_2$  define the curvature of the efficiency curve), collector output temperature ( $T_c$ ) and local solar irradiance ( $G$ ). The main parameters for the STC's used in this study are given in Table 1. In this study the area available for the STC's was limited to approximately 8 m<sup>2</sup> and the values of  $A_a$  and  $A_c$  are scaled accordingly. Please note references [10] and [17] point to STC's on Kingspan's website where the datasheet on an FPC and a ETC can be found. The data sheets used to obtain the values in Table 1 are no longer available.

TVP Solar have produced a commercially available evacuated flat plate STC designed for industrial process heat applications,

Table 1  
STC parameters.

Collector	$A$ (m <sup>2</sup> )	$A_a$ (m <sup>2</sup> )	$A_c$ (m <sup>2</sup> )	$\eta_0$	$k_1$ (W/m <sup>2</sup> K)	$k_2$ (W/m <sup>2</sup> K <sup>2</sup> )
FPC [10]	2.01	1.97	2.15	0.775	3.73	0.0152
ETC [17]	2.01	2.16	2.77	0.75	1.18	0.0095
VFPC	2.01	1.97	2.15	0.75	1.18	0.0095

which is why the efficiency profile of the TVP panel was not utilised for this study [18]. Currently there are no evacuated STC's designed for domestic use. Fig. 2 shows the efficiency of the TVP panel overlaid with the assumed performance of the VFPC, the values used to calculate the efficiency of the TVP panel were sourced from TUV Rheinland – DIN CERTCO [19]. Fig. 2 clearly shows that the efficiency of the TVP panel is better than the VFPC after a temperature difference of 50 °C which is the temperature difference assumed when calculating the yearly useful kWh gains from the STC when not charging the TCES material, suggesting the results of this analysis in this paper are conservative.

## 2.2. Feasibility analysis and key assumptions

The STC + TCES system was assumed to be charged through the 3 summer months by the STC. Meaning the maximum amount of TCES material that can be charged is calculated based on the summer gains from the STC. The remaining 9 months gains from the STC are set to be utilised directly to pre heat the DSH heat transfer fluid (i.e. in most cases water through radiators) or for DHW.

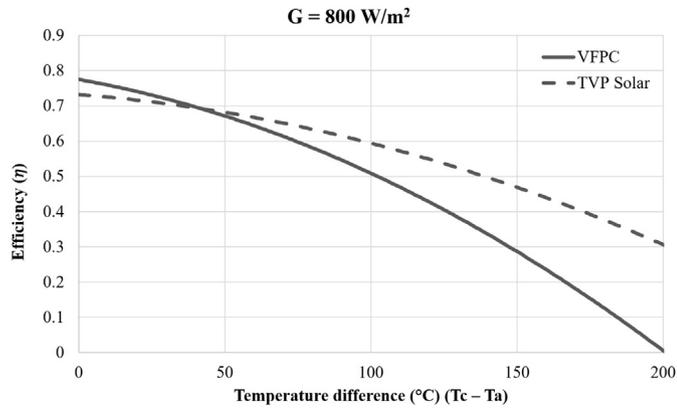


Fig. 2. Predicted efficiency of the VFPC compared to the efficiency of the TVP solar collector for a range of delta T values.

To calculate the yearly average domestic energy consumption for space heating several sources were used [1] and an annual value of 14,373 kWh was obtained. This value is an average value for the UK and not for a specific size of house. To calculate the winter space heating demand (WSHD), degree days [20] for different locations throughout the UK were averaged and the percentage of degree days falling in winter were used to find the proportion of the overall space heating which occurred during this time. The value determined using this approach for the average WSHD was 5,737 kWh. A value of 0.23 kg/kWh was used for the average CO<sub>2</sub> production (kg/kWh) from current space heating sources. This was calculated based on averages of the CO<sub>2</sub> production from each energy source and then calculating an overall average based on the fraction that each energy source contributes to the space heating total.

To calculate the yearly useful kWh gains from the STC's when not charging the TCES (i.e. the non-summer months of the year), it was assumed that the STC's were outputting fluid with an increase in temperature of 50 °C greater than the ambient temperature (i.e. T<sub>c</sub> - T<sub>a</sub> = 50 °C). To do this first Equation (6) was used to calculate the STC hourly kWh gains

$$STC \text{ hourly kWh gains} = (8E_e\eta)/1000 \quad (6)$$

where,  $\eta$  is the efficiency of the STC for each hour calculated using Equation (5) assuming that T<sub>c</sub> - T<sub>a</sub> equals 50 °C and E<sub>e</sub> is the irradiance for that hour of the day. The constant 8 in this equation is required as this is the size of STC used (8 m<sup>2</sup>), 1000 is required to convert the value into kWh's. The value for G used in Equation (5) was the monthly average hourly irradiance value for Loughborough [21]. This process gave the useful gains from the STC for that specific hour of the month and the process was repeated for each hour. The hourly values were then summed to calculate the average gains for each month. The monthly average hourly irradiance is an average irradiance value which changes every hour but is the same for each day of each month. For example the 16th July has 24 average hourly irradiance values; the same 24 values are used for every day for the month of July. The delta T value used (T<sub>c</sub> - T<sub>a</sub> = 50 °C) was set at this high value to reduce the gains from the STC, in comparison to those for a lower delta T value, and therefore make the values calculated in this study conservative.

The results from the TCES DSC dehydration tests were used to calculate the energy density of each of the TCES materials. The DSC tests were also used for calculation of the "effective" specific heat capacity of the TCES materials. The value for effective specific heat capacity used for the TCES materials changed every 5 °C with each value used being the average value within the 5 °C band calculated from the DSC data. It was defined as the "effective" specific heat

capacity as it was a combination of the specific heat capacity of the material and the dehydration enthalpy of the material.

In each of the systems the TCES material was modelled based on a containment within a cylindrical store of which the surface area was minimised. The container was modelled as a stainless steel with a thickness and thermal conductivity of 5 mm and 16 W/mK, respectively. The insulation surrounding the container was assumed to be 200 mm thick with a thermal conductivity of 0.02 W/mK. The temperature within the container was assumed to be in equilibrium and equal throughout the store volume (i.e. assuming there is no temperature gradient within the system). Convective and conductive losses were calculated although, the air surrounding the container was assumed to be stationary, resulting in reduced convective heat losses, because the container will likely be placed within a room or underground in a garden. The losses from the heat exchangers are neglected in this model.

The STC efficiencies for the summer months (TCES material charging period) were calculated using Equation (5) taking into account the monthly average hourly irradiance values for each month. The delta T (T<sub>c</sub> - T<sub>a</sub>) values used in Equation (5) when charging the store, were equal to (the temperature of the TCES + 5 °C) minus T<sub>a</sub>. This means that in the model the TCES material store was always being charged with a temperature 5 °C above the TCES material store temperature. The ambient temperature used was a twenty four average for each month [21]. When the temperature of the TCES material increased the delta T also increased (assuming the ambient temperature remained constant) resulting in a reduced STC efficiency. Hence, at the beginning of the TCES material summer charging period the TCES material is initially at ambient temperature and is heated (charged) over the three summer months. Some of the TCES materials were charged to a maximum dehydration temperature of 150 °C and some were charged to 80 °C. Typically if a TCES material is charged to a lower temperature than the temperature required to completely charge the material the amount of energy stored in the TCES material will be less. However, if a lower maximum dehydration temperature from the STC's is required the efficiency of the STC's will increase resulting in more output energy; this is why both 150 °C and 80 °C maximum dehydration temperatures were investigated.

The charging of the TCES material is also dependant on the specific heat capacity of the material and also the heat losses from the material while it is being charged and when at an elevated temperature, these losses are taken into account in the model.

The heat into the TCES material store is given by Equation (7):

$$Q_{in} = 8E_e\eta \quad (7)$$

where E<sub>e</sub> is the irradiance for that hour of the day and  $\eta$  is the calculated efficiency of the STC using Equation (5) for the predicted delta T (i.e. T<sub>c</sub> = temperature of TCES + 5 °C). The temperature of the store at any given time is determined by Equation (8):

$$T_i = T_{i-1} + \frac{(Q_{in} - Q_{loss}) * 3600}{mC_{p(T)}} \quad (8)$$

where C<sub>p(T)</sub> is the "effective" specific heat capacity at a given temperature of the TCES material, Q<sub>loss</sub> is the heat loss to the surroundings due to conduction and convection while the store is being charged, and m is the mass of the TCES material. The store temperature is calculated hourly over the summer period. The model was used to calculate the maximum amount of TCES material which could be charged and hence, the maximum amount of energy which could be stored throughout the summer period. The energy stored as chemical potential in the TCES material is assumed to be fully utilised and not wasted.

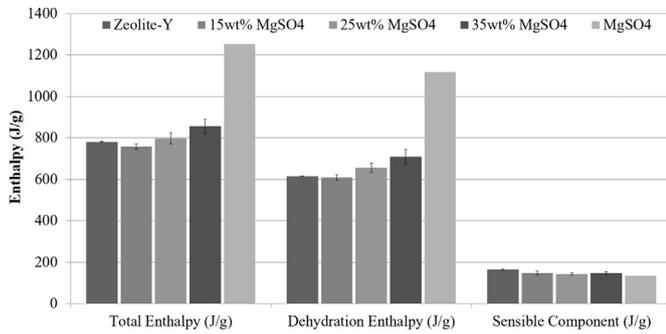


Fig. 3. Average composite dehydration enthalpy, showing sensible component.

To assess the feasibility of the systems compared to traditional energy source costs several assumptions were made. The average cost (£/kWh) for each space heating energy source was compared to the percentage of each energy source used for space heating to get an average cost [22,23], resulting in an average cost for space heating of 5.01p/kWh. A value of 7% was used for the average yearly increase in space heating cost over the next 30 years. This was calculated using 20 years of historic data to find an average yearly increase for each fuel [24] and then calculating an overall average based on the fraction that each fuel is used for space heating. The inflation percentage of 3.6%, which was used to counteract the rising fuel cost, was calculated by averaging the last 30 years inflation data for the UK [25].

The system lifetime was assumed to be 30 years. It assumes the system is fitted alongside the current conventional heating system with only the savings in energy costs taken to assess the financial feasibility of the system, without estimating and offsetting the lifetime savings on a conventional system as the energy demand on it will be lower.

### 3. Results and discussion

To alleviate some of the issues associated with MgSO<sub>4</sub> composite materials of MgSO<sub>4</sub> + zeolite-Y were synthesized in the laboratory and tested. Fig. 3 shows the average dehydration enthalpy for each composite material measured from the DSC dehydration experiments with temperature raised from 20 to 150 °C.

Table 2

Properties of TCES materials.

Material	MgSO <sub>4</sub> -80 °C	MgSO <sub>4</sub> -150 °C	35 wt%-80 °C	35 wt%-150 °C	Zeolite-150 °C
Dehydration enthalpy (J/g)	484	1118	302	708	615
Density (kg/m <sup>3</sup> )	2666	2666	1453	1453	800

Table 3

The system costs used.

Item	Information	Cost (£)	References
Reactor Casing and fabrication	–	£1,440.00	[26]
Cost of piping, fasteners, etc	–	£360.00	[26]
Installation costs	–	£1,000.00	[26]
Maintenance Costs	(2 h/year) x 30years x £50	£3,000.00	Assumed
Heat exchanger costs x3	–	£210.00	[27]
Cost per additional 1000 L	–	£352.24	[28–30]
Cost of MgSO <sub>4</sub>	1000 kg	£64.49	[31–34]
Cost of Zeolite-Y	1000 kg	£280.00	[35]
Cost of Composite 35 wt%	1000 kg	£204.57	Calculated
Flat plate collector (FPC)	8m <sup>2</sup>	£382.67	[36–38]
Evacuated Tube Collectors (ETC)	8m <sup>2</sup>	£416.38	[39–41]
Vacuum Flat Plate Collector (VFPC)	8m <sup>2</sup>	£416.38	Used ETC

The values shown in Fig. 3 were found by conducting a sigmoidal integration of the DSC enthalpy plots. The dehydration enthalpy for each material was derived from the total enthalpy minus the sensible component. The composite materials shown on Fig. 3 are 15, 25 and 35 wt%. These composite materials were created to assess if there was any degradation in the energy density with increasing MgSO<sub>4</sub> wt%. From, Fig. 3, of the three composite materials, the best option is the 35 wt% sample however; more work is required to identify the optimal wt%. The dehydration enthalpy of the composite samples increased with increasing MgSO<sub>4</sub> wt%. As the sample will be dehydrated (charged) in the summer months when, typically, heat is not required all the sensible heat which is stored within the TCES material is assumed to be lost and not utilised leaving the energy stored as chemical potential for use at a later time (i.e. the winter time). The sensible component for the 35 wt% and 15 wt% composite materials was approximately 17% and 20% of the total enthalpy, respectively. The dehydration enthalpy measured for the composite materials is less than the wt% of MgSO<sub>4</sub> and zeolite multiplied by their respective dehydration enthalpy. For example, the maximum calculated dehydration enthalpy for the 35 wt% composite sample is  $(1118 \text{ J/g} \cdot 0.35) + (615 \text{ J/g} \cdot 0.65) = 791 \text{ J/g}$  however, the achieved dehydration enthalpy is 708 J/g. One reason why this occurs is because some of the surface area of the zeolite, which is initially available for water adsorption (and would give off hydration enthalpy when hydrated) is reduced due to the MgSO<sub>4</sub> occupying some of this surface area. For comparison, if water was used to store thermal energy sensibly with a temperature differential of 45 °C between charge and discharge states the specific energy density of the water is 188 J/g. Using water to store thermal energy for long periods will result in significant thermal losses as the water cools losing heat to the ambient environment. Table 2 shows the properties of each of the TCES materials used for the model. The materials are named first with the name of the chemical and then the maximum dehydration temperature. For example MgSO<sub>4</sub>-80 °C represents the chemical used as MgSO<sub>4</sub> and that it is dehydrated to a maximum temperature of 80 °C.

#### 3.1. Feasibility results

The values used for assessing the cost of each system setup are shown in Table 3. The costs are based on bulk prices which are

found from several sources. The cost for each item (i.e. FPC) is an averaged cost from several suppliers. The cost used for the VFPC is the same as the ETC as it is not possible to verify the cost of a VFPC as VFPC's are currently only available commercially for non-domestic applications. Other reasons why this was assumed to be a reasonable assumption is because the materials and processes used to manufacture ETC's is likely to be similar to VFPC's, the installation costs of the VFPC's may be less than the ETC's as there is no need for a manifold therefore, once VFPC's are manufactured on a large scale it is likely the cost of VFPC's and ETC's will be similar. If a system similar to that proposed was manufactured on a large scale it is likely that costs would reduce. This study has deliberately been conservative on cost estimates.

### 3.1.1. TCES store temperature with time

Fig. 4 shows the initial charging of each of the TCES with the different STC over the 3 months of summer. The key shows the volume and percentage of WSHD stored, within only the TCES material, for each system configuration.

The system which stored the highest WSHD (23.9%), with a store volume of 1.66 m<sup>3</sup>, was the MgSO<sub>4</sub> store when charged to 150 °C using a VFPC. Comparatively the 35 wt% composite material when charged to 80 °C using a VFPC was able to store 19.7% of WSHD however, this system required a store size of 9.27 m<sup>3</sup> which makes this unlikely to be a viable choice due to the space constraints within most domestic dwellings. In industrial process applications, where space may not be as much of a constraint this system could represent a viable solution.

As the storage process was thermochemical once the material was in a dehydrated (charged) state the TCES material could be stored at a low temperature and still not lose its hydration energy. This means there is potential for the system to be situated in a garden or even submerged underneath a garden lawn reducing the internal household volume required for installing the system. The only downside to storing the TCES material in an outside space is the average outside ambient temperature in the UK winter is low, 3.9 °C for 2014/2015 [42]. This low temperature could cause issues for the hydration energy output; more work is needed to understand the impact low temperatures have on the hydration of the TCES materials tested.

The reason why the 35 wt% composite material charged to 80 °C was able to store a higher WSHD percentage than when it was charged to 150 °C was due to the efficiency of the VFPC. The VFPC is significantly more efficient than the FPC at higher temperatures but the VFPC becomes less efficient as the output temperature required increases. This means that a higher percentage of the solar energy collected by the VFPC can be used for charging the 35 wt% composite material to 80 °C compared to 150 °C.

The store temperature of the MgSO<sub>4</sub> systems, shown in Fig. 4, had a very slow temperature increase from 50 °C to 70 °C and then increased very quickly after 70 °C. This was due to the large amount of dehydration enthalpy which was required to dehydrate the MgSO<sub>4</sub>·xH<sub>2</sub>O between 50 °C and 70 °C and caused by a significant amount of water loss in this temperature range. For the zeolite-Y and the 35 wt% composite materials the temperature increase was more gradual with time due to these materials not having as large of an endothermic peak, relative to the MgSO<sub>4</sub>·xH<sub>2</sub>O, throughout the dehydration.

The stepped charging profiles of the different system setups shown on Fig. 4 was due to the changing 24-h irradiance values and calculated heat losses used within the model. Throughout the night time the irradiance values used in the model were low or zero however, the store is still losing heat to the ambient which resulted in the store charging temperature profile becoming stepped.

The FPC systems were not able to dehydrate any material up to

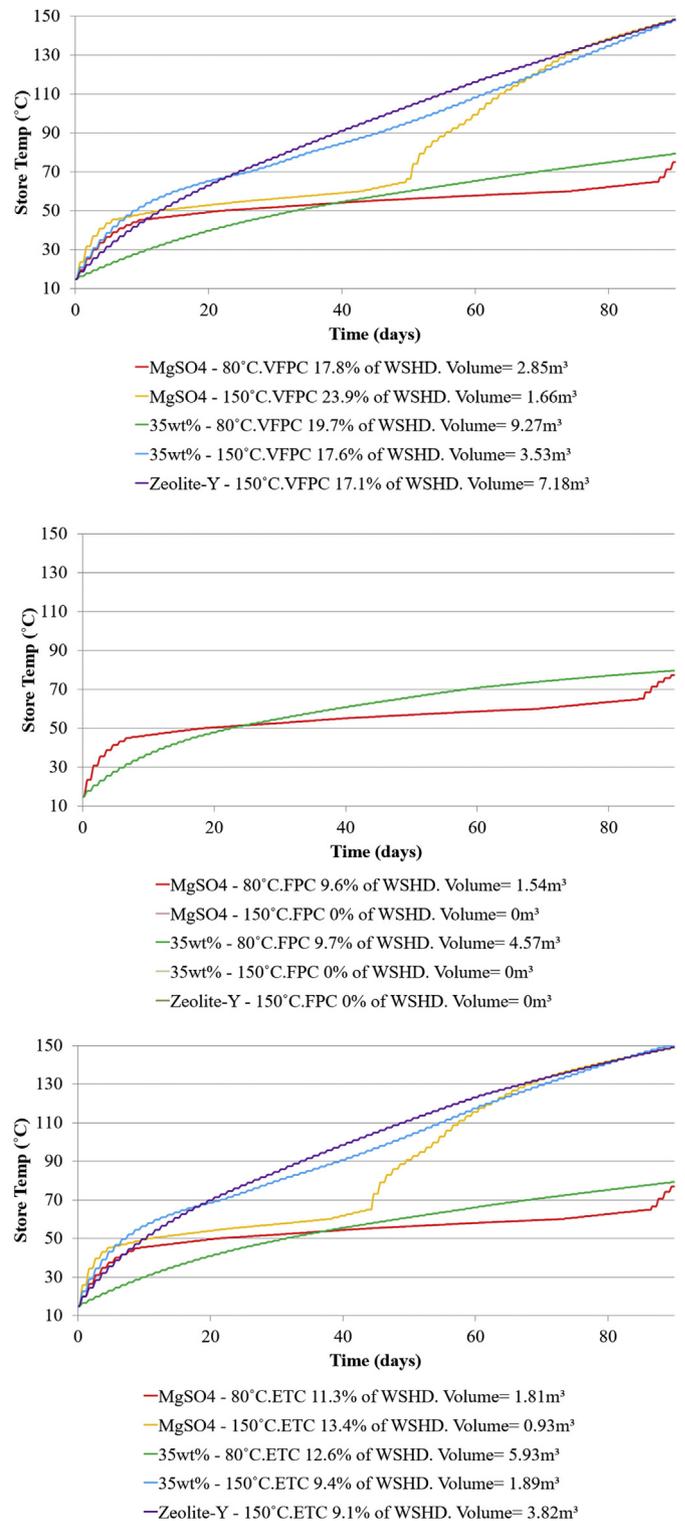


Fig. 4. The initial charging of each of the TCES with different STC over the 3 months of summer (4a = FPC, 4b = ETC and 4c = VFPC).

150 °C due to the low efficiency of the collector at high temperatures. The FPC based systems were able to store a low fraction of the WSHD (7.5% for MgSO<sub>4</sub> using a FPC) when heated at 150 °C if the system is located in Brighton, due to the higher irradiance values for this location.

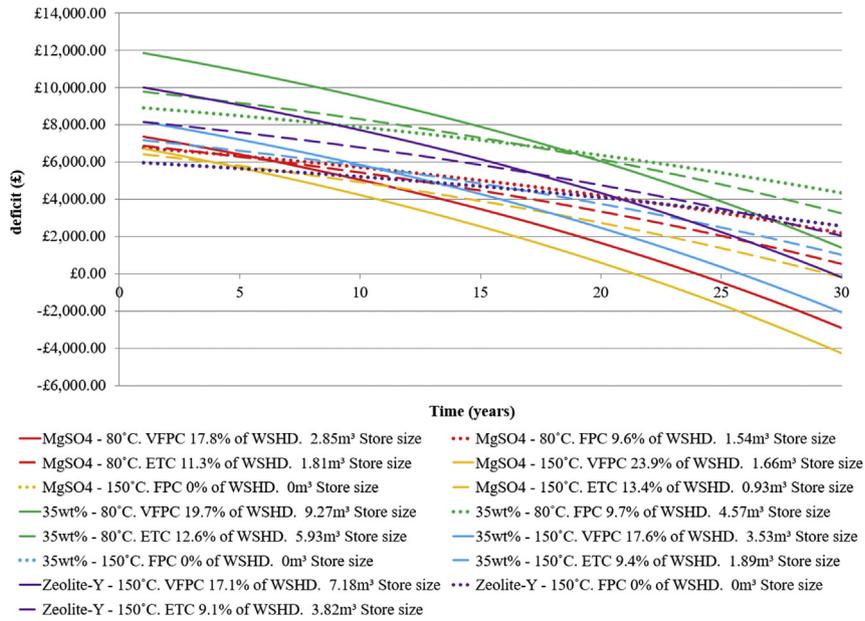


Fig. 5. Predicted payback time of each TCES + STC system.

3.1.2. TCES + STC system payback with time

Fig. 5 shows each of the calculated system payback times and the best system configuration found was the MgSO<sub>4</sub> dehydrated to 150 °C using the VFPC, which also stored the most energy. The predicted payback time for this system was approximately 22 years saving the user over £4,200 over the lifetime of this system. Fig. 5 is colour coded so each material and dehydration configuration has one colour and the type of line (solid, dashed or dots) is what changes to indicate the STC being used for example MgSO<sub>4</sub>-150 °C is an orange coloured line for all three data sets.

Five of the system configurations appeared to be viable. The viable systems were each of the VFPC configurations, not including the 35 wt%-80°C-VFPC system, and the MgSO<sub>4</sub>-150°C-ETC system. The MgSO<sub>4</sub>-150°C-VFPC system and the 35 wt%-150°C-VFPC system had a payback time between 22 and 26 years, meaning these systems would result in savings to the user. Due to the problematic characteristics of the MgSO<sub>4</sub> when utilised over large scales it is likely the 35 wt% composite material would be a more suitable option for a large-scale system.

The calculated initial cost of the 35 wt%-80°C-VFPC system was £12,096 and was able to store 19.7% WSHD. However, this cost was significantly higher than all of the other systems meaning it does not represent a financially viable system.

3.1.3. Initial capital cost per kWh of each TCES + STC system

The initial capital cost per kWh (£/kWh) is shown in Fig. 6. It was defined as the initial capital cost as it was the amount of energy

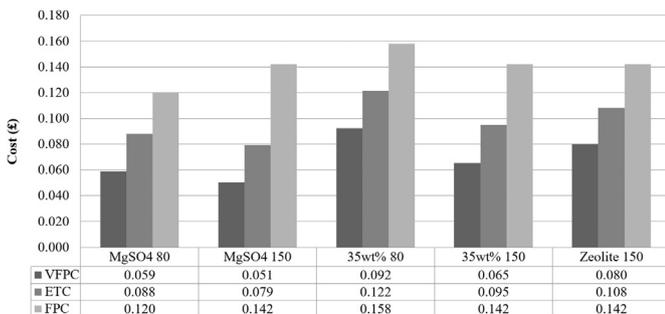


Fig. 6. Initial capital cost/kWh costs for each TCES + STC system.

stored from each system over its 30-year lifetime divided by the cost of the system, this value was used to compare each of the systems.

In all cases the ETC systems had a lower £/kWh cost than equivalent FPC system. All of the ETC systems have a lower £/kWh value than all of the FPC systems other than the MgSO<sub>4</sub>-80°C-FPC against the 35 wt%-80°C-ETC which have £/kWh values of £0.120 and £0.122, respectively. The £/kWh for the 35 wt%-80°C-FPC is higher than the 35 wt%-150°C-FPC system, due to the cost of the 35 wt% material. Each system using a VFPC had a significantly lower £/kWh than the respective ETC or FPC systems. The £/kWh of each system appears to be in line with the current £/kWh from current space heating sources in the UK, suggesting that these systems could be financially viable options to replace or work alongside typical fossil fuel space heating energy systems.

3.1.4. Consideration into the material costs

The systems were compared assuming it was beneficial to store the highest amount of WSHD possible over the 3 summer months of charging. As the fraction of WSHD met increased so too did the CO<sub>2</sub> savings for the systems which was beneficial although, the cost per kWh delivered did not necessarily decrease, due to the material costs.

For the 35 wt%-150°C-VFPC system the initial cost per kWh of the system increased with the fraction of WSHD met. The 35 wt% system being charged to 150 °C coupled with the VFPC was able to

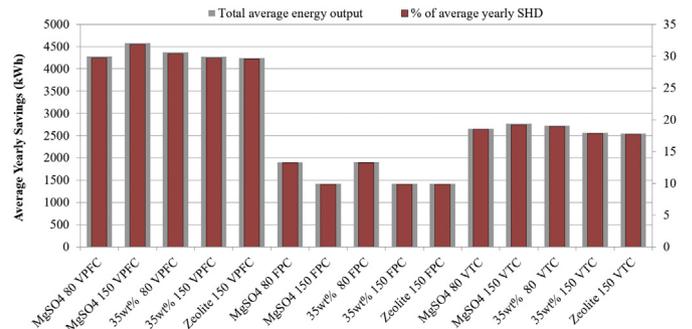


Fig. 7. Total energy output from each TCES + STC system.

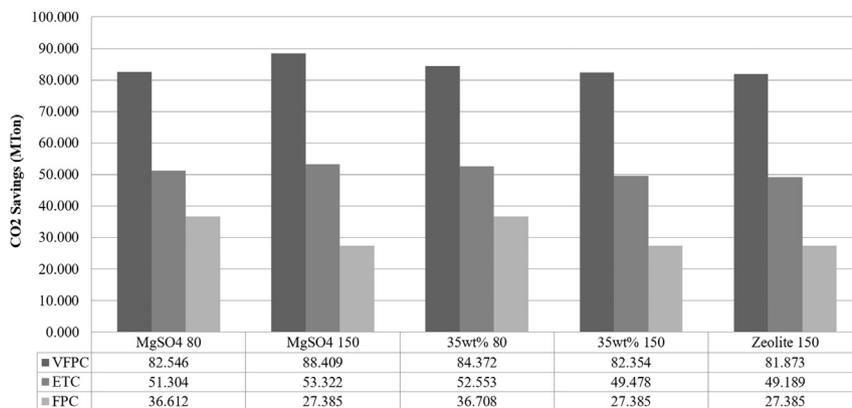


Fig. 8. Predicted CO<sub>2</sub> Savings for each TCES + STC system.

store a maximum of 17.6% of the WSHD, with a cost per kWh of 6.5p and a payback time of 26 years. If the fraction of WSHD met was decreased to 5% the initial cost per kWh reduced to 6.2p, with a payback time of 25 years. Apart from the CO<sub>2</sub> savings of the system, storing the maximum fraction of WSHD for this material does not represent a clear financial gain. Also, if the amount of TCES material charged over the summer months was less than the maximum (i.e. 5% and not the maximum 17.6%, in this case) the extra energy from the STC's which is not being utilised over the summer for charging the TCES material could be utilised for alternate purposes. However, for this model it was assumed that the gains from the STC's over the summer months are typically not utilised and wasted due to low demand.

The 35 wt% material had a dehydration enthalpy of 708 J/g and 10% of WSHD storage (573.7 kWh) required approximately 2917 kg of material. The cost of this material was approximately £597, the extra volume required was 2.01 m<sup>3</sup> which equates to £707. Therefore 573.7 kWh of storage over a 30-year period would cost an extra £1304, which equals 7.6p/kWh. This decision, to add more TCES capacity to the system, would likely be a personal choice of finances against CO<sub>2</sub> reductions however, it is beneficial that a system could potentially become more financially viable if this was the most important characteristic to the user.

3.1.5. Total energy output of the TCES + STC systems

Fig. 7 shows the average energy output of each system over its 30-year lifetime. Clearly the systems using the VFPC were able to output significantly more energy than the other systems. The output from the VFPC systems were able to produce around 30% of the total yearly SHD. Each system using either a FPC or ETC was able to store between 10 and 20% of the yearly SHD.

The choice of material used in the VFPC systems did not have a significant impact on the amount of energy output from the system. This was due to the large gains from the VFPC over the year minus the summer gains. This means that the selection of TCES material to be used with the VFPC will likely be due to the available volume and TCES material properties. This represents a positive factor for the implementation of the developed composite materials which are designed to have much better large-scale characteristics.

3.1.6. CO<sub>2</sub> savings from each TCES + STC system

The UK's Green House Gas (GHG) emissions from the residential sector for 2015, 2016 and 2017 was 67.4, 69.8 and 66.9MtCO<sub>2</sub>e, respectively [43]. A reduction of approximately 4.3% to the residential CO<sub>2</sub> output is achievable if a TCES system using a VFPC is installed in 10% of all UK households.

Fig. 8 shows the cumulative CO<sub>2</sub> savings from each system

configurations assuming 10% of all UK households have a system installed. As the CO<sub>2</sub> savings were directly linked to the amount of energy output from each system, the VFPC systems saved the most CO<sub>2</sub> over their lifetime.

3.1.7. The importance of the TCES + STC system location

The feasibility data values generated for Loughborough were taken and compared with Brighton and Paris. Fig. 9 shows the overall average yearly energy output and the payback time for the MgSO<sub>4</sub>-150°C-VFPC and the 35 wt%-150°C-VFPC systems. Clearly it is advantageous to be located further south thus, resulting in a shorter payback time and therefore more savings to the user.

The cost of energy, energy cost percentage increase and inflation percentage will be different in France compared to the UK however; the location tests were conducted to compare locations with different irradiances under the same constraints, not different economic environments. This means that the payback time may vary if a system is installed in Paris to that shown in Fig. 9.

If a 35 wt%-150°C-VFPC system was installed in a users home in Brighton, the user could expect savings within 24 years after the system was installed opposed to 25 and 26 years if the same system was installed in Paris and Loughborough, respectively.

4. Conclusions

This study has shown that systems combining TCES and VFPC systems for domestic interseasonal heat storage can be financially viable and result in significant CO<sub>2</sub> savings. From a financial standpoint each one of the system configurations using a VFPC produced a saving to the user over its lifetime apart from the 35 wt

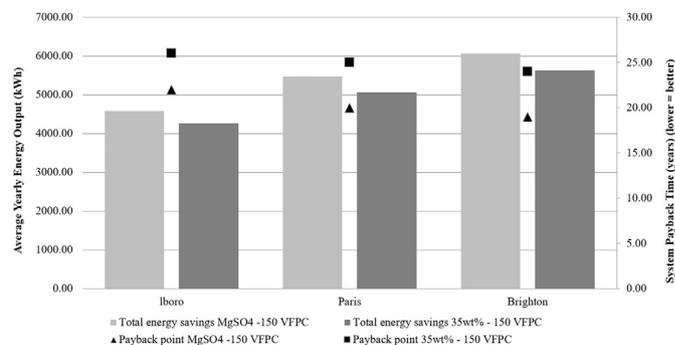


Fig. 9. Comparison, showing the payback time and total yearly energy output from different TCES + STC system configurations for systems located in Loughborough, Paris and Brighton.

%-80°C-VFPC system. Furthermore, the only system using either an ETC or a FPC which was financially viable was the MgSO<sub>4</sub>-150°C-ETC system. The best system choice was one which incorporated a VFPC due to its financial savings, energy output and CO<sub>2</sub> savings. The system which was the most financially feasible was the MgSO<sub>4</sub>-150°C-VFPC system which has the lowest system costs (£6,942), store volume (1.66 m<sup>3</sup>) and outputs the highest average amount of energy per year (4,264 kWh). The 35 wt%-150°C-VFPC system was a financially viable choice and saved the user around £2,080 with a payback time of around 26 years.

This paper has presented a hypothetical system study and the energy density values used are calculated from small scale DSC tests meaning when scaled up the materials are liable to suffer from scaling losses and different characteristics.

In the future the energy consumption of households may change significantly, reducing their energy output, becoming more energy efficient and reducing their CO<sub>2</sub> emissions. If this does happen then the TCES + STC systems will be able to supply a higher fraction of the overall energy demand of the households.

A parameter sensitivity analysis of this study including a more dynamic analysis would be beneficial future work to compare to this study.

## Acknowledgements

This work was supported in full by the UK Engineering and Physical Sciences Research Council (EPSRC) through two grants; i-STUTE (grant number: EP/K011847/1) and High Performance Vacuum Flat Plate Solar Thermal Collectors for Hot Water and Process Heat (grant number: EP/K009915/1) and a Loughborough University PhD studentship. Loughborough University's Research Repository (<http://repository.lboro.ac.uk>) will be the location of data deposited regarding this journal article available for download.

## References

- [1] UK.GOVERNMENT, Estimates of Heat Use in the United Kingdom in 2012, 2013, pp. 73–80.
- [2] I. Dincer, M.A. Rosen, Thermal Energy Storage Systems and Applications, 2011, pp. 109–131.
- [3] C. Bales, et al., 031 - chemical and sorption storage – results from IEA-SHC task 32, in: Eurosun 2008, 2008, pp. 1–8.
- [4] V.M. van Essen, et al., Characterization of MgSO<sub>4</sub> hydrate for thermochemical seasonal heat storage, *J. Sol. Energy Eng.* 131 (2009).
- [5] M. van Essen, H.A. Zondag, R. Schuitema, W.G.J. van Helden, C.C.M. Rindt, Materials for Thermochemical Storage: Characterization of Magnesium Sulphate, 2009.
- [6] J. Janchen, W. Brosicke, D. Ackermann, H. Stach, Studies of the water adsorption on Zeolites and modified mesoporous materials for seasonal storage of solar heat, *Sol. Energy* 76 (2004) 339–344.
- [7] T. Fakin, A. Ristić, A. Horvat, V. Kaučić, Water adsorption study on the zeolite Ita granules, in: 5th Serbian-Croatian-Slovenian Symposium on Zeolites, 2013, pp. 56–59.
- [8] R. de Boer, S.F. Smeding, H.A. Zondag, G. Krol, Development of a prototype system for seasonal solar heat storage using an open sorption process, in: Eurotherm Seminar #, vol. 99, 2014, pp. 1–9.
- [9] S. Hongois, F. Kuznik, P. Stevens, J.J. Roux, Development and characterisation of a new MgSO<sub>4</sub>-zeolite composite for long-term thermal energy storage, *Sol. Energy Mater. Sol. Cells* 95 (7) (Jul. 2011) 1831–1837.
- [10] Kingspan, Kingspan Thermomax FN Flat Plate Collector [Online]. Available: <https://www.kingspan.com/gb/en-gb/products/renewable-technologies/solar-thermal/solar-flat-plate-panels/flat-plate-panels>.
- [11] P. Henshall, R. Moss, F. Arya, P. Eames, S. Shire, T. Hyde, An evacuated enclosure design for solar thermal energy applications, in: Grand Renewable Energy 2014 (GRE2014), 2014.
- [12] F.G.S. Shire, W.R. Moss, P. Henshall, F. Arya, C.P. Eames, T. Hyde, in: "A. Sayigh (Ed.), Renewable Energy in the Service of Mankind Vol II: Selected Topics from the World Renewable Energy Congress WREC 2014, Springer International Publishing, Cham, 2016, pp. 859–866.
- [13] P. Henshall, P. Eames, F. Arya, T. Hyde, R. Moss, S. Shire, Constant temperature induced stresses in evacuated enclosures for high performance flat plate solar thermal collectors, *Sol. Energy* 127 (2016) 250–261.
- [14] D. Mahon, G. Claudio, P. Eames, A study of novel high performance and energy dense zeolite composite materials for domestic interseasonal thermochemical energy storage, *Energy Procedia* 158 (2019) 4489–4494.
- [15] D. Mahon, G. Claudio, P.C. Eames, An experimental investigation to assess the potential of using MgSO<sub>4</sub> impregnation and Mg<sup>2+</sup> ion exchange to enhance the performance of 13X molecular sieves for interseasonal domestic thermochemical energy storage, *Energy Convers. Manag.* 150 (2017) 870–877. <https://doi.org/10.1016/j.enconman.2017.03.080>.
- [16] J.A. Duffie, W.A. Beckman, Solar Engineering of Thermal Processes, third ed., Wiley, New York etc, 1980.
- [17] Kingspan\_Solar, Thermomax HP400 Evacuated Tubes [Online]. Available: <https://www.kingspan.com/gb/en-gb/products/renewable-technologies/solar-thermal/solar-evacuated-tube-collectors/thermomax-hp400-evacuated-tube-collectors>.
- [18] TVP solar, TVP Solar [Online]. Available: <https://www.tvpsolar.com/products.html>.
- [19] TÜV-Rheinland, Annex to Solar Keymark Certificate - Summary of EN ISO 9806:2013 Test Results. License holder TVP Solar SA, TÜV Rheinland - DIN CERTCO, 2016 [Online]. Available: [https://www.dincertco.de/logos/011-751890\\_F.pdf](https://www.dincertco.de/logos/011-751890_F.pdf).
- [20] D.D.D. Limites, Degree Days, 2016 [Online]. Available, <http://www.vesma.com/ddd/welcome.htm>.
- [21] E. Commission, Photovoltaic Geographical Information System, 2016 [Online]. Available, <http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php>.
- [22] E.S. Trust, Energy Prices, 2014 [Online]. Available, <http://www.energysavingtrust.org.uk/corporate/our-calculations>.
- [23] D.of E., C. Change, Average Variable Unit Costs and Fixed Costs for Electricity for UK Regions, 2015.
- [24] D.of E. & C. Change, Consumer Prices Index: Fuel Components.
- [25] S. Morley, Historical UK Inflation Rates and Calculator, 2015 [Online]. Available, <http://inflation.stephenmorley.org/>.
- [26] V.M. Van Essen, P.W. Bach, H.A. Zondag, M. Bakker, An evaluation of the economical feasibility of seasonal sorption heat storage, in: 5th International Renewable Energy Storage Conference IRES, 2010, pp. 22–24. DECEMBER.
- [27] O.F. Supply, Heat Exchanger Costs, 2016 [Online]. Available, <http://www.outdoorfurnacesupply.com/water-to-air-heat-exchangers.html>.
- [28] Alibaba, Bulk Stainless Steel Cost 1, 2016 [Online]. Available, [http://www.alibaba.com/product-detail/430-304-304L-316L-201-310s\\_60254671936.html?spm=a2700.7724838.30.58.43Cxlh](http://www.alibaba.com/product-detail/430-304-304L-316L-201-310s_60254671936.html?spm=a2700.7724838.30.58.43Cxlh).
- [29] Alibaba, Bulk Stainless Steel Cost 2, 2016 [Online]. Available, [http://www.alibaba.com/product-detail/sheet-and-plate-321-316-316Ti\\_60344004321.html?spm=a2700.7724838.30.70.43Cxlh](http://www.alibaba.com/product-detail/sheet-and-plate-321-316-316Ti_60344004321.html?spm=a2700.7724838.30.70.43Cxlh).
- [30] Alibaba, Bulk Stainless Steel Cost 3, 2016 [Online]. Available, [http://www.alibaba.com/product-detail/430-304-304L-316L-201-310s\\_60377911209.html?spm=a2700.7724838.30.80.43Cxlh](http://www.alibaba.com/product-detail/430-304-304L-316L-201-310s_60377911209.html?spm=a2700.7724838.30.80.43Cxlh).
- [31] Alibaba, MgSO<sub>4</sub> Cost 1, 2016 [Online]. Available, [http://www.alibaba.com/product-detail/High-purity-Magnesium-Sulphate-Heptahydrate\\_1885617972.html?spm=a2700.7724838.30.1.atb6e6](http://www.alibaba.com/product-detail/High-purity-Magnesium-Sulphate-Heptahydrate_1885617972.html?spm=a2700.7724838.30.1.atb6e6).
- [32] Alibaba, MgSO<sub>4</sub> Cost 2, 2016 [Online]. Available, [http://www.alibaba.com/product-detail/magnesium-sulphate-MgSO4\\_1768724012.html?spm=a2700.7724838.30.8.atb6e6&s=p](http://www.alibaba.com/product-detail/magnesium-sulphate-MgSO4_1768724012.html?spm=a2700.7724838.30.8.atb6e6&s=p).
- [33] Alibaba, MgSO<sub>4</sub> Cost 3, 2016 [Online]. Available, [http://www.alibaba.com/product-detail/epsom-salt-magnesium-sulphate-MgSo4\\_7H2O\\_60275107256.html?spm=a2700.7724838.30.25.atb6e6&s=p](http://www.alibaba.com/product-detail/epsom-salt-magnesium-sulphate-MgSo4_7H2O_60275107256.html?spm=a2700.7724838.30.25.atb6e6&s=p).
- [34] Alibaba, MgSO<sub>4</sub> Cost 4, 2016 [Online]. Available, [http://www.alibaba.com/trade/search?fsb=y&IndexArea=product\\_en&CatId=&SearchText=magnesium+ sulphate](http://www.alibaba.com/trade/search?fsb=y&IndexArea=product_en&CatId=&SearchText=magnesium+ sulphate).
- [35] Alibaba, Zeolite Cost, 2016 [Online]. Available, [http://www.alibaba.com/product-detail/Molecular-sieve-ball-zeolite-4a-for\\_60336197653.html?spm=a2700.7724857.29.30.Rc11VN&s=p](http://www.alibaba.com/product-detail/Molecular-sieve-ball-zeolite-4a-for_60336197653.html?spm=a2700.7724857.29.30.Rc11VN&s=p).
- [36] Alibaba, Flat Plate Collector Cost 1, 2016 [Online]. Available, [http://www.alibaba.com/product-detail/2015-flat-plate-collector-latest\\_60296647963.html?spm=a2700.7724838.30.12.xSRtny&s=p](http://www.alibaba.com/product-detail/2015-flat-plate-collector-latest_60296647963.html?spm=a2700.7724838.30.12.xSRtny&s=p).
- [37] Alibaba, Flat Plate Collector Cost 2, 2016 [Online]. Available, [http://www.alibaba.com/product-detail/homemade-Flat-Plate-Solar-collector\\_60343112887.html?spm=a2700.7724838.30.29.xSRtny&s=p](http://www.alibaba.com/product-detail/homemade-Flat-Plate-Solar-collector_60343112887.html?spm=a2700.7724838.30.29.xSRtny&s=p).
- [38] Alibaba, Flat Plate Collector Cost 3, 2016 [Online]. Available, [http://www.alibaba.com/product-detail/solar-keymark-SRCC-approved-flat-plate\\_60187825015.html?spm=a2700.7724838.30.49.xSRtny&s=p](http://www.alibaba.com/product-detail/solar-keymark-SRCC-approved-flat-plate_60187825015.html?spm=a2700.7724838.30.49.xSRtny&s=p).
- [39] Alibaba, Vacuum Tube Collector Cost 1, 2016 [Online]. Available, [http://www.alibaba.com/product-detail/Solar-Keymark-Vacuum-Tube-Solar-Thermal\\_60297065372.html?spm=a2700.7724838.30.9.EmgxIN&s=p](http://www.alibaba.com/product-detail/Solar-Keymark-Vacuum-Tube-Solar-Thermal_60297065372.html?spm=a2700.7724838.30.9.EmgxIN&s=p).
- [40] Alibaba, Vacuum Tube Collector Cost 2, EmgxIN&s=p, 2016 [Online]. Available, [http://www.alibaba.com/product-detail/CE-hot-horizontal-vacuum-tube-solar\\_1362174962.html?spm=a2700.7724838.30.28](http://www.alibaba.com/product-detail/CE-hot-horizontal-vacuum-tube-solar_1362174962.html?spm=a2700.7724838.30.28).
- [41] Alibaba, Vacuum Tube Collector Cost 3, EmgxIN, 2016 [Online]. Available, [http://www.alibaba.com/product-detail/Economical-Vacuum-Tube-Vertical-Solar-Collector\\_1704584561.html?spm=a2700.7724838.30.57](http://www.alibaba.com/product-detail/Economical-Vacuum-Tube-Vertical-Solar-Collector_1704584561.html?spm=a2700.7724838.30.57).
- [42] MetOffice, UK Mean Winter Temperature, 2017 [Online]. Available, <http://www.metoffice.gov.uk/climate/uk/summaries/2015/winter>.
- [43] BEIS, 2017 UK Greenhouse Gas Emissions, Final Figures, 2019.