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Decarbonising Heating and Hot Water Using Solar Thermal Collectors Coupled with Thermal Storage: The Scale of the Challenge

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Abstract

This paper explores the feasibility of using renewable solar thermal energy linked to a salt hydrate thermochemical store (reversible chemical reaction involving the addition / removal of water from a salt) to provide a zero-carbon heating and hot water option for an average UK home. Volumetric absorption based on diluted colloidal suspensions or nanofluids containing wavelength tuneable plasmonic silver nanoparticles are a possible means for enhancing solar thermal capture. To make full use of this captured energy, it requires inter-seasonal storage in a suitable energy dense, high efficiency thermal store. As such even the potentially highest energy density obtainable for a salt hydrate thermochemical store would still need a store of greater than 35 m^3 (10 MWh) to nearly meet current winter heating and hot water demands (with 1 discharge cycle per annum). With a possible increase in collector efficiency to over 70% such a system would collect enough solar energy annually to become viable for homes with a greater than average (>15 m^2) roof area, a lower than median consumption (<12,000 kWhyr^{-1}) and enough space for a large thermochemical store (≤46 m^3). This paper concludes by detailing the significant additional research efforts required to bring this possible decarbonising solution to a prototype level of maturity.

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Nomenclature

A	*Area / m*^{2}
DASC	Direct absorption solar collector
ETC	Evacuated tube collector
FPC	Flat plate collector
HW	Hot water
ISTES	Inter-seasonal thermal store
I	*Solar Irradiation / kWhm*$^{-2}$
LTS	Latent heat thermal storage
PCM	Phase change material
PV	Photovoltaic
Q	*Energy / kWh*
STS	Sensible heat thermal storage
TCS	Thermochemical storage
TES	Thermal energy store
V	*Volume / m*^{3}
ρ	*Volumetric storage density / kWhm*$^{-2}$
η	*Efficiency / %*

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Subscripts and superscripts

AA	Average Annual
C	Collector
TES	Thermal energy store
Ts	Total for storing
D	Demand
HW	Hot water
H	heating

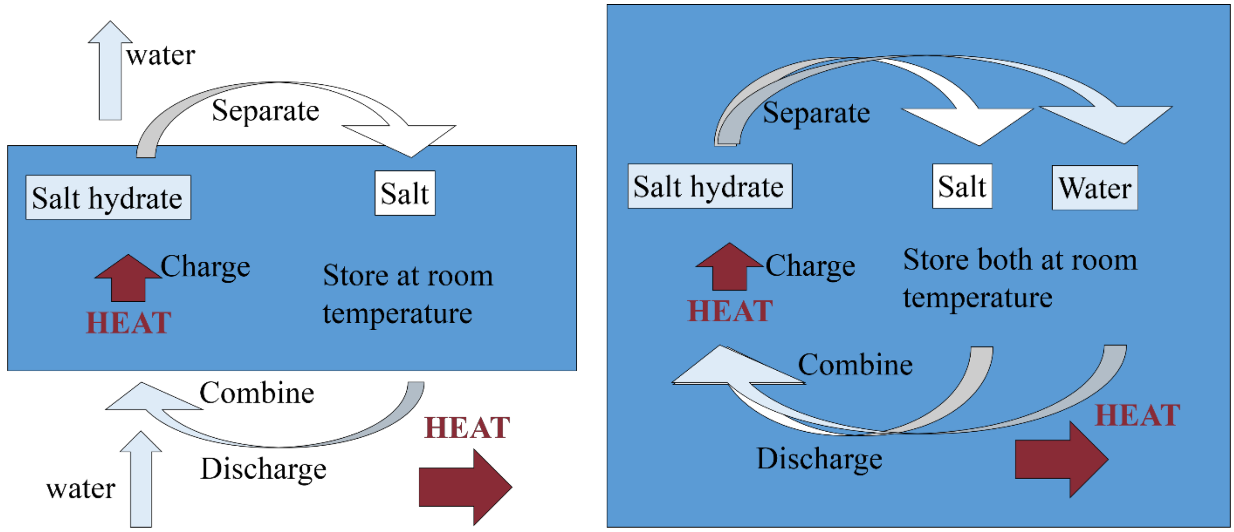
1. Introduction

The UK is making slow progress on decarbonising heating and hot water, which accounts for 24% of energy use (Department for BEIS, 2017b), to meet the 2008 Climate change act obligations (Department for BEIS, 2017a; UK Government, 2008). It is unlikely to meet the 12% renewable heat target by 2020 (House of Commons Energy and Climate Change Committee, 2016). The European Union also has a lack of change in the CO_2 emissions from buildings with two opposing trends occurring: improved efficiency versus increased floor area per person (Climate Action Tracker, 2016). Currently the main source of emissions is from gas used to provide heating, hot water and cooking. Electrification of this would cause major issues for the electricity grid with a possible peak demand of 330GW and a minimum demand in summer of less than 30GW (Sansom, 2012). To provide enough electricity to meet this heat demand would require more than doubling of the UK electricity generation capacity with much of this enhanced capacity only needed in the winter. In addition, the electricity grid would need reinforcing to cope with the additional seasonal power levels (Sansom, 2012). Despite these issues, the use of heat pumps in 19 million UK homes by 2050, has been suggested as the best decarbonising solution for the UK to reach the more ambitious target of nearly 100% reduction in CO_2 emissions by 2050 recently proposed (Committee on Climate Change, 2019).

This paper explores the feasibility of an alternative but less technically mature solution, namely enhanced solar thermal energy capture connected to an inter-seasonal thermal store (ISTES) as a means of providing a zero-carbon heating and hot water (HW) option for an average UK house.

1.1. Types of thermal energy storage

There are three main types of thermal energy store (TES) that could be used for ISTES. These include (i) a sensible thermal store (STS) based on using a materials heat capacity as the storage principle, (ii) a latent heat thermal store (LTS), which uses a phase change material (PCM) to store more energy, and (iii) a thermochemical store (TCS). An efficient ISTES must be able to store the thermal energy generated in the summer for later use in the winter. As such, TCS is ideal, as it allows the separate room temperature storage of two components of a reversible chemical reaction, and hence has negligible losses with time. The principle is shown in Figure 1 along with two examples of potentially suitable salt hydrate reaction for an open system (only one component stored) and a closed system (due to potential formation of H_2S in this example (de Jong et al., 2016)). The material storage density obtained with a TCS system based on salt hydrates is related to the number of water molecules present in the hydrate, the salt hydrate density and whether an open or closed system is used. In addition, system design plays an important part in the final size of the TCS, with significant volume being required for effective operation of the store.



A) Open

B) Closed

$$\text{OPEN}\quad K_2CO_3.1.5H_2O_{(s)} \rightleftharpoons K_2CO_{3(s)} + 1.5\,H_2O_{(g)} \rightleftharpoons K_2CO_3.1.5H_2O_{(s)} \tag{1}$$

$$\text{CLOSED}\quad Na_2S.5H_2O_{(s)} \rightleftharpoons Na_2S.0.5H_2O_{(s)} + 4.5H_2O_{(g)} \rightleftharpoons Na_2S.5H_2O_{(s)} \tag{2}$$

Figure 1 Principle of TCS A) -open where only the salt is stored and B) closed system where both components are stored. The reaction of potassium carbonate (1) and sodium sulphur (2) given as examples of A) and B) respectively as potentially suitable reversible salt hydrate reactions (de Gracia and Cabeza, 2015; de Jong et al., 2016; Donkers et al., 2017)

1.2. Enhanced solar thermal capture

Developed during the 1970s, direct absorption solar collectors (DASCs) use a volume of liquid as the working-fluid to collect solar thermal energy. Compared to selective absorbing surface solar collectors such as flat plate (FPC) and evaporated tube collectors (ETC) (Gupta et al., 2015), DASCs exhibit advantages such as simpler manufacturing, saving raw material (in particular copper) (Otanicar and Golden, 2009; Otanicar et al., 2010; Tyagi et al., 2009), improving heat transfer (Iyahraja and Rajadurai, 2015; Lee et al., 2016) and generating an even distribution of the rising temperature through the fluid system, which reduces overall heat loss (Luo et al., 2014; Xu et al., 2015). These factors lead to an increasing in efficiency of ~10% (Nasrin et al., 2015; Turkyilmazoglu, 2016). Using a dilute colloidal suspension or nanofluid as the working fluid can potentially improve this efficiency even further. This can allow the DASC to be placed in front of a photovoltaic (PV) collector, if the absorption wavelength of the nanofluid is tuned to allow light of the right wavelength to reach the PV collector with some loss of PV electrical efficiency but a gain in thermal efficiency (Hjerrild et al., 2016). As such, wavelength tuneable plasmonic nanofluids are of interest. Of these plasmonic nanofluids based on silver nanoparticles provide a high level of absorption at a very low nanoparticle concentration, which can be readily tuned to absorb solar radiation at different wavelengths just by changing the shape and size of the silver nanoparticles used. Efficiencies obtained by other researchers for a number of different nanofluids in small-scale experimental studies are given in Table 1. Even the lowest efficiency of 56% obtained for an non-optimised DASC configuration is approximately 10% greater than a commercial FPC (efficiency = 46% (Ayompe and Duffy, 2013)).

Table 1. Efficiencies obtained using nanofluids in experimental DASCs.

Nanofluid investigated	Type of work	Comments	Efficiency obtained / %
Graphite in water (Gorji and Ranjbar, 2016)	Numerical and experimental using small flow cell	Efficiency dependent on flow rate	50 - 80
Gold, copper and carbon black (Zeiny et al., 2018)	Small experimental static cell	Depth of nanofluid ≈ 3mm	≤ 70
Silver, graphite and carbon nanotubes in water (Otanicar et al., 2010)	Experimental with small flow cell	Silver (20 nm) best performing. Low depth of fluid employed. Steady state collector efficiency quoted	56 - 58
Plasmonic (Qin et al., 2017)	Modelling	Nature of nanofluid not specified	≤ 75
Various (O'Keeffe et al., 2018)	Modelling	Concentrated system with a parabolic trough	70 - 80

2. Calculations

In order to assess the feasibility of collecting enough solar energy and then storing it for subsequent use in a suitable ISTES it is necessary to calculate the total volume of the thermal store required and the amount of thermal energy needed to be captured to change this store. To this end, six different scenarios were considered (Table 2). A demand reduction of 21 – 25% is considered feasible by others (Committee on Climate Change, 2019) hence in this work a conservative value of 20% was used for scenarios 5 and 6. The values for storage efficiency η_{TES} used were the top and bottom of the range for TCS given in Table 3. Scenario 1 represents the 2015 median UK gas usage in the UK (Department for BEIS, 2017c) and has hence been included although it represents an impossible η_{TES} of 100% (likewise Scenario 2). The value of η_{TES} of 75% for the other 4 scenarios is more realistic and represent the bottom end of the range reported in Table 3. Scenarios 5 and 6 represent likely future scenarios for capture and storage respectively. Scenarios 2, 4 and 6 that exclude summer HW would need a more complicated system design to allow for a summer bypass to the TES.

Table 2. Scenarios considered.

Scenario	η_{TES} / %	Excluding summer HW / yes or no	Demand reduction / %	Energy to be stored annually Q_{Ts} / kWh
1	100	No	0	12,000
2	100	Yes	0	10,400
3	75	No	0	16,000
4	75	Yes	0	13,867
5	75	No	20	12,800
6	75	Yes	20	11,093

The volume of the thermal store V_{TES} in m^3 is given by:

$$V_{TES} = \frac{Q_{Ts}}{\rho_{TES}} \tag{3}$$

where ρ_{TES} is the volumetric storage density of the TES store in $kWhm^{-3}$. The total energy to be stored Q_{Ts} in kWh is:

$$Q_{Ts} = Q_D \frac{\eta_{TES}}{100} \tag{4}$$

where η_{TES} is the efficiency of the TES in % and the energy demand Q_D in kWh is:

$$Q_D = Q_H + Q_{HW} \quad (5)$$

where Q_H is the heating energy requirement and Q_{HW} is the HW energy demand both in kWh. Typical values for volumetric storage density ρ_{TES} and η_{TES} for the three types of TES are given in Table 3. Values for Q_H and Q_{HW} are given in Table 4. These values were used in conjunction with (3), (4) and (5) to calculate the maximum size of TES required for the six scenarios. During sunny periods the heat from the solar thermal panels is used (via a heat exchanger) to heat the store or dehydrate the salt hydrate in the case of TCS. For all three storage types it was assumed that the store would be charged and discharged completely only once per annum. In reality, it is likely that the store will be partially discharged and recharged on numerous occasions throughout the year, so the assumption of one discharge per annum represents the worst-case scenario and hence maximum store size needed. Also excluded from the calculation is any electrical energy required to operate the thermal store, such as for pumps and heat exchangers. The electrical energy need for this is likely to be low (<5%) compared to the total needed for heating and hot water.

The energy output from the solar collector Q_c in kWh is:

$$Q_C = I_{AA} A_C \frac{\eta_C}{100} \quad (6)$$

where I_{AA} is the average annual solar Irradiation per unit area in kWhm^{-2}, A_c is the area of the collector in m^2 and η_c is the collector efficiency (%). Values for the solar and demand parameters used in this study are given in Table 4. Equation (6) in conjunction with the values in Table 4 were used to calculate the size of collector needed to collect enough energy in a year to satisfy scenarios 1,3 and 5 for a range of different values of collector efficiency η_c. In addition, the reverse calculation was carried out, starting with the collector efficiency and hence determining the amount of energy captured Q_c for a range of collector areas. These results were then compared to the average UK roof area available of 15 m^2 to assess the feasibility of capturing enough solar energy from an average UK home to meet the storage energy demand Q_{Ts} (plus summer HW demand). Again, any electrical energy required to operate the pump for the collector are excluded from the calculations. η_c is also related to the input and output temperature of the collector and system and the flow rate of the fluid through the collector. At high flow rates, the temperature rise through the collector is lower and hence thermal losses are reduced. However, the output temperature from the collector may then not be high enough to provide hot water (65°C). These factors have not been considered in this feasibility study as they are hard to generalize and depend on the final system and collector design but they can be significant at nearly 20% in some cases (Ayompe and Duffy, 2013). Good design, with short well-insulated pipe lengths, close proximity of the collector and store, an efficient heat exchanger, and as low an output temperature as practicable will all help to minimise but not in reality eliminate these losses.

Table 3. Typical TES parameters. * - top value of 100% impossible but quoted directly from IRENA and ETSAP (represents top of likely range)

Parameter	STS	LTS	TCS
Storage density ρ_{TES} / kWhm^{-3}(IRENA and ETSAP, 2013)	25	100	300
Efficiency η_{TES} / %	50 - 90	75 -90	75 – 100* (IRENA and ETSAP, 2013)
Assumptions / comments	No loss of heat with time (unless very large and super insulated this is unlikely (de Jong et al., 2016))	Active PCM has a suitable transition temperature and the majority of the store contains active material	Salt hydrate used gives an output temperature suitable for HW (65°C) (Donkers et al., 2017)

Table 4. Values for other parameters used in this study.

Parameter	Value used	Comment	Reference
Annual Energy demand Q_D / kWhyr^{-1}	12,000	Median UK gas value from 2015	(Department for BEIS, 2017c)
Annual HW demand Q_{HW} / kWhyr^{-1}	3,200	Value from literature actually 3216 kWhyr^{-1}. Summer HW taken as ½ Q_{HW}	(Greening and Azapagic, 2014)
Average annual solar irradiation I_{AA} / kWhm^{-2}yr^{-1}	1,100	Average value from two sources = 1093.5 kWhm^{-2}yr^{-1}in a temperate climate for inclined (≥30°) south facing collectors with no shading. Area is actual surface area	(Ayompe et al., 2011; Greening and Azapagic, 2014)
Current solar collector efficiency η_c for a FPC / %	45.9	Average of two values (46.1 and 45.6%)	(Ayompe and Duffy, 2013; Ayompe et al., 2011)
Current solar collector efficiency η_c for an ETC (heat pipe) / %	60.7	Commercial system in temperate climate	(Ayompe et al., 2011)
Average UK roof area available for solar collectors A_c / m^2	15	Estimated value	(Freeman et al., 2015)

3. Results and discussion

Using the storage density values for the three different TES types given in Table 3, the size of the store needed for the six different scenarios investigated (see Table 2) is shown in Figure 2. Even with the impossible assumption of no losses with time STS is not a viable option for ISTES. LTS becomes a more viable option but would still require a storage volume of 111 m^3 for scenario 6 (for illustrative purposes this equates to a cube with a side length of 4.8 m) this would only be feasible if the store was located underground and well insulated. The storage volume required for a TCS store is much more feasible with a storage volume of 37 m^3 for scenario 6 (cube side length = 3.33 m). Although still large this store could be located above ground and hence becomes more viable for retrofitting to existing housing stock. To meet current demand with a feasible η_{TES} of 75% even TCS would require a store size of 46.2 m^3 (scenario 4) which equates to a cube side length of 3.6 m. Hence, demand reduction is vital to make ISTES viable even if TCS is used.

To determine the potential size of thermal collector required to capture enough solar energy to charge this TCS, only Scenarios 1, 3 and 5 were considered as the collector would still need to capture enough energy to meet summer HW demand even if this energy does not need subsequent storage. The calculated area of collector needed versus the efficiency of the collector for the three scenarios considered is shown in Figure 3 along with Q_c versus roof area for various different values of η_c. The UK average roof area of 15 m^2 is highlighted for illustration. A value of $\eta_c \geq 78\%$ is required to capture the energy required for Scenario 5. This value is at the top of the range of η_c obtainable for DASCs utilising nanofluids (Table 1). As such it is optimistic to suggest that the average roof area in the UK can capture enough energy to fully meet the total heating and HW demand even with a demand reduction of 20% (scenario 5). With the highest current η_c for a heat pipe ETC of 61% an area of >19 m^2 of collector would be required for Scenario 5. For current FPCs the position is even worse with 15 m^2 only capturing 7590 kWh and > 25 m^2 required to capture enough for Scenario 5. A more realistic possible η_c = 70% for DASCs would need a roof area of slightly less than 16 m^2, marginally above the UK average for Scenario 5.

If energy demand remains at current levels an unattainable efficiency of 97% is needed with a roof area of 15 m^2, a η_c of 70% would need a roof area of about 21 m^2 and current heat pipe ETCs would need an available roof area of ≈24 m^2. Hence, demand reduction is again vital to facilitate the feasibility of capturing enough solar energy in combination with improving η_c to ≥70 % potentially by the use of nanofluid DASCs. In reality therefore capturing enough thermal energy and placing it in a TCS ISTES for subsequent winter use is hence only likely to become viable for homes in the UK if the following three conditions are met;

1. A below median demand of < 12,000 kWhyr^{-1}

2. An above average roof area of > 15 m^2
3. Enough space to house a large ($\leq$ 46 m^3) TCS ISTES

If the amount of solar radiation was much lower (for example a property in North Scotland) the amount of roof area required would be larger, unless the demand was also reduced or the efficiency improved to compensate for the lower amount of sunlight available. Hence, the conclusions that a less than median demand and above average roof area is needed would still be valid but the exact numbers would be slightly different. There will also in reality be losses throughout the system in the pumps, pipes and heat exchangers. These losses would have the same effect as a reduction in solar radiation leading to a need for a larger collector area, a more efficient collector or a greater reduction in demand.

For the store, assuming only one charge / discharge cycle leads to a larger store size than might actually be the case. In contrast, any reduction in storage efficiency or storage density would lead to a smaller TCS ISTES size being proposed than is actually achievable. These factors effectively cancel each other out so would not dramatically affect the conclusion that a large TCS ISTES is needed of about the size suggested here.

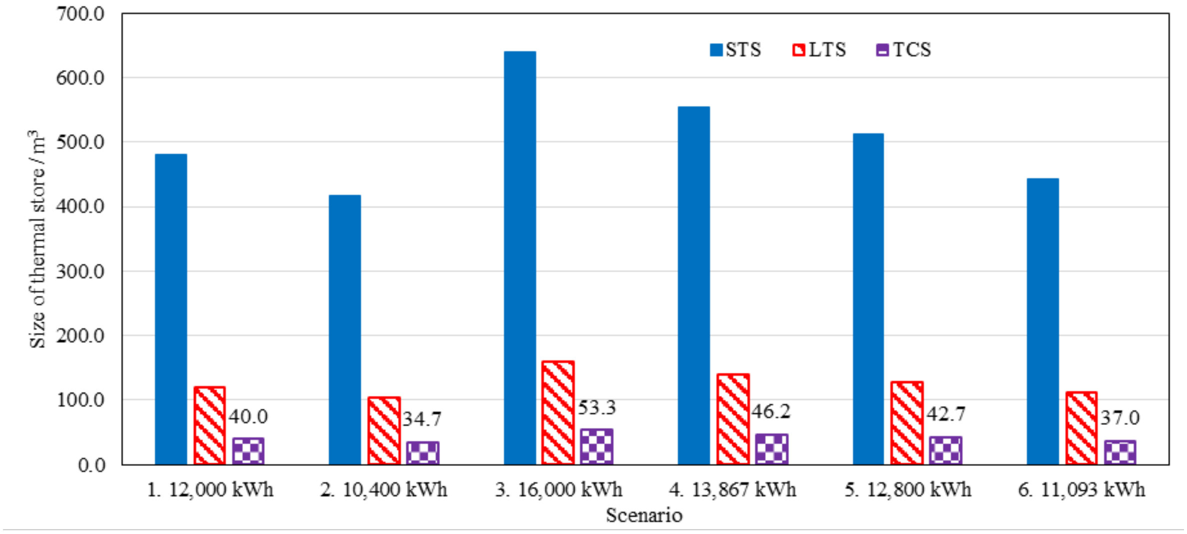


Figure 2 Size of store required for the six different scenarios

As mentioned in the introduction as well as potentially improving η_c to $\geq$ 70% one of the other potential advantages of using a nanofluid DASC would be the ability to retrofit the DASC above any pre-existing PV panels provided a suitably wavelength tuned plasmonic nanofluid is used (for example a nanofluid containing silica coated silver nanodiscs (Crisostomo et al., 2017)). This would make such a system an option for houses, which have already utilised their available roof space for PV panels. However, depending on the optical properties of the nanofluid employed, this could reduce the electrical output from the PV cells by as much as 66% (Crisostomo et al., 2017) so would only make practical sense if the heat output was more important than electricity generation (not currently normally the case).

However, considerable technical challenges need to be overcome before plasmonic nanofluid based DASCs become a viable option. For a nanofluid to be suitable for use in a DASC it must be able to remain stable over the lifetime of the collector (≈20 years) whilst being subjected to multiple daily heating / cooling cycles, solar radiation and shear forces associated with pumping. For wavelength tuneable plasmonic nanofluids this can be especially challenging as any change in size and shape of the nanoparticles in the nanofluid can significantly affect the absorption wavelength profile of the nanofluid (Jin et al., 2001). Other challenges include current significant production limitations for these research stage nanofluids and optimisation of the design of the collector, which needs undertaking in conjunction with the actual proposed nanofluid as each different type of nanofluid will have different absorption /

stability considerations. The technical challenges and research efforts needed are detailed in Table 5. In addition, the collector output temperature will need to be tailored to meet the temperature requirements for the TCS.

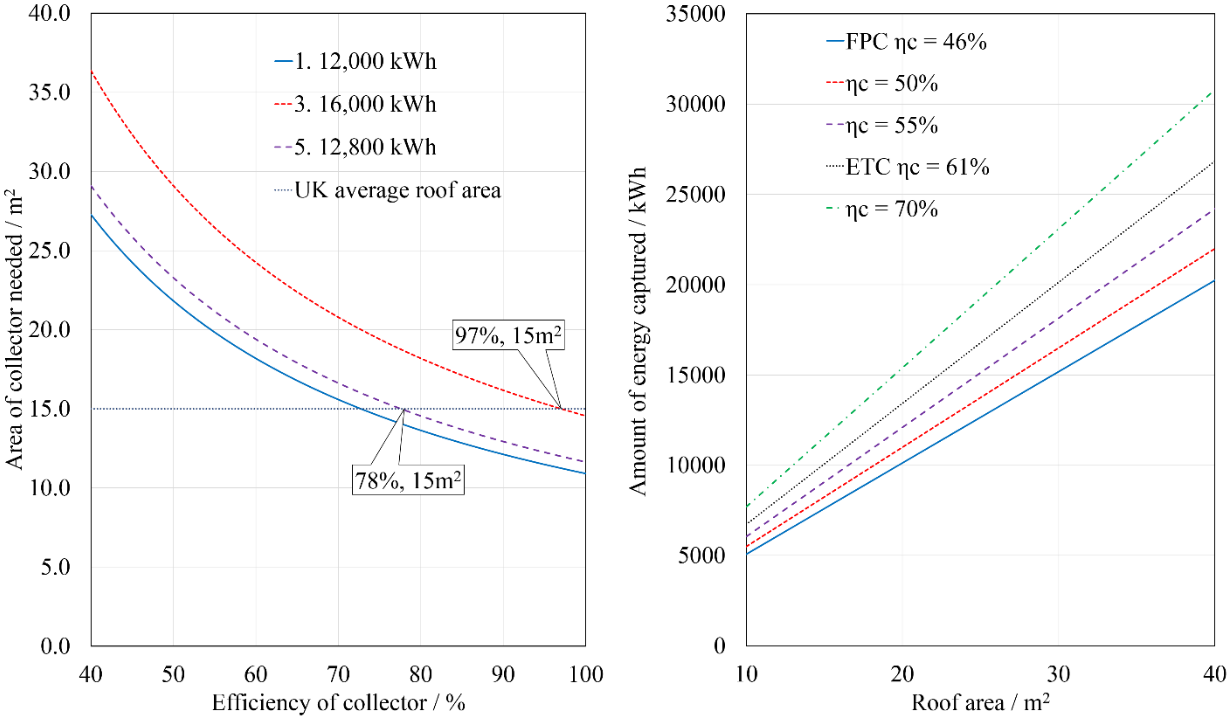


Figure 3 Area of collector required for Scenarios 1.3 and 5 (left) and amount of energy captured at different values of η_c (right). All assume I_{AA} = 1100 kWhm^{-2}yr^{-1}

The level of maturity of TCS is also in its infancy. One of the major technical challenges is selection / evaluation and modification of a suitable active material. For a salt hydrate the TCS output temperature is related to the partial pressure of the water and for an open system (potentially higher storage density), this severely restricts the output temperature obtainable for a given salt hydrate making only a handful of salt hydrates potentially suitable (Donkers et al., 2017), especially for HW (output temperatures of ≈ 65°C needed). In addition, the active material storage density is related to the number of hydrate water molecules in the reaction again limiting the potential material choices. Other material considerations include the presence of unwanted side reactions producing toxic / corrosive materials and depletion of active material, any potential deliquescence during hydration, sluggish kinetics and material cost.

On a systems level there needs to be a better knowledge and understanding of reaction design factors. Hence, significant work is required on optimisation of the reactor design to ensure high levels of actual storage density and efficiency (Aydin et al., 2015). For example a prototype pilot scale closed TCS system based on (2) in Figure 1 at present gives a system storage density of 50 kWhm^{-3} but could reach a storage density of 278 kWhm^{-3} with further optimisation according to the authors (de Jong et al., 2016), which is comparable with the value for ρ_{TES} in Table 3. This optimisation is mainly around the packing arrangement of the salt hydrate and heat exchangers within the module design, which for the pilot scale demonstrator was far from ideal (i.e. rectangular heat exchangers in a circular cross-section).

Table 5 Additional research efforts required to reach prototype maturity level

Nanofluid / collector	TCS
Improved / scaled up production methods for nanofluid (Muhammad et al., 2016)	Further active material research to find and quantify a suitable active material with sufficient energy density, stability and a suitable output temperature for HW (Donkers et al., 2017)
Assessment and improvement of nanofluid stability under application realistic conditions	Assessment of cyclability / reversibility / stability of reaction (Scapino et al., 2017)
Understanding long term toxicity (Gorji and Ranjbar, 2017)	Understanding of reaction kinetics / potential side reactions / toxicity and corrosion
Optimisation / testing of collector design for specific nanofluid / nanofluids and output temperature range required for TCS	TCS design, optimisation including energy, exergy and efficiency measurements
Life cycle and economic evaluation	Research scale trials
	Life cycle and economic evaluation
Research / pilot scale collector trials	Scale up of reactor design and pilot scale trials
Integration with TCS and subsequent system trials	Integration with collector and subsequent system trials and optimisation

4. Conclusions

A decarbonising solution, based on enhanced solar thermal capture connected to a suitable ISTES comprising a TCS, has been proposed for providing a zero-carbon heating and HW option for the average UK home. This solution is only feasible for homes with a less than median demand (< 12,000 kWhyr^{-1}), a larger than average roof area (> 15 m^2) and enough space for a large TCS (≤ 46 m^3). If the size of the store could be reduced to 10,000 kWh (10 MWh) this would still equate to a storage volume of 35 m^3 for a TCS store with ρ_{TES} = 300 kWhm^{-3}. A realistic increase in collector efficiency potentially obtainable by using a nanofluid DASC to 70% could capture enough solar energy from 16 m^2 to meet the storage requirements for a 20% reduction in demand (12,800 kWh).

However, significant further research mainly initially into the active materials both for the proposed DASC collector and the TCS are needed before this solution is at a level of technology readiness to be implemented on a pilot scale. The main challenges for the nanofluid DASC is the long-term stability under application realistic conditions , especially for tuneable plasmonic nanofluids, whereas for the TCS the main material challenges are associated with selection and modification of a suitable active material to give a suitable output temperature, energy storage density and performance.

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